COMPUTER-AIDED CLOTHING THERMAL FUNCTIONAL ENGINEERING DESIGN

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Computer-aided Clothing Thermal Functional Engineering Design

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CERTIFICATE OF ORIGINALITY

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毛爱华 (Signed)

Mao Aihua (Name of student)

TO MY FAMILY

For their constant love, support and encouragement

ABSTRACT

This thesis presents and realizes a strategy of computer-aided clothing thermal engineering design. By the application and integration of multidisciplinary knowledge, a computational simulation-based and computer-aided technique is developed to quantify the thermal performance of clothing and its impact on the thermal biology of the human body in various wearing situations. Theoretical framework has been developed with simulation models, computational schemes, software architecture and CAD software systems. With the achievements of the research, this strategy has been realized in a systematical and scientific way and can be delivered to the user as a user-friendly computer-aided design tool.

Clothing thermal engineering design is an innovative application of engineering principles in clothing design and involves the knowledge across a range of disciplines, including physics and biological mechanisms, computational simulation models, computational and CAD technologies. The requirements on thermal functions of clothing are identified by revealing the relationships between the thermo-physiology of human body and physical mechanisms governing the heat and moisture transfer in clothing. A systematical definition of clothing thermal engineering design is presented and an innovative multi-disciplinary framework derived from different disciplines is proposed to apply and integrate involved knowledge and data. In the framework, two central components in clothing thermal engineering are identified as computational simulation and computer-aided design system.

In order to utilize the capability of computational simulation models, a set of multi-scale simulation models is selected and assessed by using a set of engineering design criteria to model the thermal behaviors involved the clothing system. The data availability of the parameters in the models is investigated and made clear for engineering applications. To generate the numerical solutions of the simulation models, multi-structural computational schemes are developed to implement the numerical algorithms of computational simulation for the purpose of clothing thermal engineering design. Furthermore, the influence of various coefficients on the simulation results is studied to control the accuracy of simulation results.

In order to achieve the aim of computer-aided clothing thermal engineering design, an innovative software architecture is proposed and developed with the identification of user requirements, and the functional components and their relationships in the architecture. The computer-aided design system is developed using objected-oriented method to make the system an open and flexible structure so that it can be easily and economically maintained and updated. An engineering database is designed and developed to support the engineering design process with the software system.

Under the designed architecture, two software systems are developed for clothing multi-layer design and multi-style design corresponding to different application requirements. The functionalities and interfaces provided by the systems enable the user to design, simulate, preview and analyze the thermal performance of clothing during the wearing period. Design cases carried out using the software systems are illustrated to show the design procedures and system functionalities. The accuracy of the systems is validated by comprising simulation results with the experimental measurements derived in wear trials using human subjects.

In summary, the strategy of computer-aided clothing thermal engineering design has been presented with systematical definition and multi-disciplinary framework, which is realized by the design and development of multi-scale computational simulation structures and a computer-aided design system. Using the software systems, users can carry out dynamic iterative design and engineering of clothing, which are supported by database, data visualization software to preview the thermal performance of clothing with scientific data presentation, as well as communicative 2D and 3D visual illustrations.

RESEARCH OUTPUT

Referred Articles in Journals:

1. **A.H Mao**, Y. Li, Y.P. Guo, X.N. Luo, R.M. Wang, Life-oriented software engineering for clothing thermal functional design, *Computers in Industry*, 2008 (SCI, submitted).
2. **A.H Mao**, Y. Li, Numerical heat transfer coupled with multi-dimensional liquid moisture diffusion in porous textiles with a measurable-parameterized model, *Numerical Heat Transfer Part A,* 2009, Vol.56, pp.246-268 (SCI, **Impact factor 1.32**).
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6. **A.H Mao**, Y. Li, Y.P. Guo, X.N. Luo, A computational bioengineering system for thermal functional design of textile products, *Journal of Fiber Bioengineering and Informatics*, Vol.2, 2008, pp.27-36.
7. Y.P. Guo, **A.H Mao**, W.R. Wang, Y. Li, Predicting Thermal Functional

Performance of Protective Clothing Through Computer Simulations, *Journal of Fiber Bioengineering and Informatics*, Vol.2, 2008, pp.51-70.

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2. **A.H Mao**, Y. Li, W.R. Wang, X.N Lou, Computational Models and Engineering Design of Textile Products, *Recent Advances in Systems Engineering and Applied Mathematics in WSEAS conference*, 2008, Istanbul in Turkey, pp.128-133.
3. **A.H Mao**, Y. Li., R.M Wang, X.N Luo, Y.P Guo, Virtual thermal bioengineering system for life-oriented design of textile products, *The 1st Textile Bioengineering and Informatics Symposium*, 2008, Hong Kong, pp. 201-207.
4. Y.P Guo, **A.H Mao**, R.M Wang, Y. Li, Predicting Thermal Functional Performance of Protective Clothing through Computer Simulations, *The 1st Textile*

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5. M.L Cao, **A.H Mao**, R.M Wang, Y. Li, Visualization of Thermal Effects of Clothing in Virtual Space, *The 1st Textile Bioengineering and Informatics Symposium*, 2008, Hong Kong, pp.252-259.

Patent and Copyright:

1. Y. Li, **A.H. Mao**, R.M Wang, X.N Luo, Z. Wang, Computer simulation system for clothing thermal functional design, *USA Patent*, RIP-09, Filing date: 8/18/2008, Filing No.: 61/136,188
2. Y. Li, **A.H. Mao**, R.M Wang, X.N Luo, A simulation software system for functional textile products development, *Software copyright*, China, 2008

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1. **Outstanding Student Paper** of the *1st Textile Bioengineering and Informatics Symposium*. 2008, Hong Kong
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SYMBOL NOMENCLATURE

Symbol	Definition	Symbol	Definition
B_n	Heat loss by blood flow in each node [W]	R_t	Heating resistance [Ω]
C_a	Water vapor concentration in the air filling the inter-fiber void space [kg/m^3]	R	Gas constant [J/mol K]
c_b	Thermal capacity of the blood in each node [J/K]	R_e	Evaporation heat resistance on the skin surface [m^{2}Pa/W]
c_{pbl}	Specific heat at constant pressure of blood [J/Kg/K)]	R_{esk}	Evaporation resistance of the skin in N [m^{2}Pa/W]
c_{vf}	Volumetric heat capacity of the fabric [J/ (m^{3}K)]	R_n	Heat transfer resistance of waterproof membrane [m^{2}K/W]
c_{vl}	Volumetric heat capacity of the liquid water [J/ (m^{3}K)]	R_{esk}	Evaporation resistance of the skin [m^{2}Pa/W]
c_{va}	Volumetric heat capacity of the air [J/ (m^{3}K)]	S	Liquid water volumetric saturation (liquid volume/pore volume)
c_n	Thermal capacity in each node [J/K]	S_i	Skin area of the ith segment in N [m^2]
C_f	Water vapor concentration in the fibers of the fabric [kg./m^3]	S_v	Specific area of the fabric [1/m]
C_n	Heat loss by convection in each node [W]	$SKINR(6)$	Fraction of all skin receptors in segment I
C_{sk}	Water vapor concentration of the skin surface [kg/m^3]	$SKINS(6)$	Fraction of sweating command applicable to skin of segment I
$C(25)$	Heat capacity of each node [J/K]	$SKINV(6)$	Fraction of vasodilatation command applicable to skin of segment I
c_v	Volumetric heat capacity of the fabric [J/ (m^{3}K)]	$SKINC(6)$	Fraction of vasoconstriction command applicable to skin of segment I
D_f	Vapor diffusion coefficient of fiber [m^2/s]	SWR_{max}	Maximum sweating rate [mg/m^2/s]
D_a	Vapor diffusion coefficient of air [m^2/s]	SHV_{reg}	Regulative shivering constant [W/m^2]
D_l	Liquid diffusion coefficient in fabric [m^2/s]	SWR	Pow sweating rate [mg/m^2/s]
d_c	Largest effective radius of the pore in fabrics [m]	R_{ea}	Evaporation heat resistence on the skin surface in [m^{2}Pa/W]
D_{fab}	Vapor diffusion coefficient of fabric [m^2/s]	R_n	Heat loss by thermal radiation in each node [W]

E_n	Heat loss by evaporation through the skin surface in each node [W]	R_f	Radius of fiber [m]
E_{res}	Latent respiration heat loss in each node [W]	R_m	Radius of micro-spheres [m]
E_{sk}	Total evaporative heat transfer from skin [W/m$^{2]}$	RH	Relative humidity [%]
$EB(25)$	Basal evaporative heat loss from N [W]	T	Temperature of the fabric [K]
$BFB(25)$	Basal effective blood flow to N [1/h]	T_0	Initial temperature of fabric [K]
$QB(25)$	Basal metabolic heat production in N [W]	T_{env}	Temperature of environment [K]
$HC(6)$	Environmental convective heat transfer coefficient for segment I	T_{cr0}	Neutral core temperature [degree]
L	Fabric thickness [m]	T_p	Melting point of PCM [K]
M_n	Metabolic heat generation in each node [W]	T_{sk}	Temperature of skin [degree]
$M_{CHIL}(6)$	Fraction of total shivering occurring in muscle of segment I	Tcr	Temperature of core [degree]
M_g	Mole mass of gas [kg/mol]	$T_{SET}(25)$	Set point or reference point for receptors compartment N [degree]
m_{rsw}	Regulatory sweating in each node [g/s^1/m^2]	$TC(25)$	Thermal conductance between N and N+1 [W/°C]
m_s	Sweating accumulation on the skin surface [g/m^2]	WVP	Water vapor permeability [g/m^2/day]
G_a	Coefficient of pressure gradient to water vapor flux	W	Work rate [W/m^2]
G_l	Coefficient of pressure gradient to liquid water flux	W_n	Moisture transfer resistance of waterproof membrane [s/m]
Gs	Coefficient of pressure gradient to dry air flux	p_m	Proportion of moisture vapor from the skin at the clothing-covered area
l	Air space between the skin and the inner side of the fabric next the skin [m]	p_h	Proportion of dry heat loss at the clothing-covered area
h_{vap}	Evaporation heat of water [J/kg]	p_A	Proportion of clothing-covered area
h_{lg}	Mass transfer coefficient for evaporation and condensation [m/s]	τ_a	Vapor diffusion tortuousity, actual diffusion path deviated from the straight distance
h_m	Convection mass transfer coefficient [m/s]	τ_l	Liquid diffusion tortuousity, actual diffusion path deviated from the straight distance
h_t	Convection heat transfer coefficient [J/m^{2}K]	a	The effective angle of the capillaries in the fabric [degree]

h_T	Heat transfer coefficient between the micro-spheres and the flows surrounding them [W/m^2 K]	μ_a	Dynamic viscosity of vapor [kg/ms]
K_t	Effective thermal conductivity of the fabric [W/m/K]	μ_l	Dynamic viscosity of liquid water [kg/ms]
K_n	Heat loss by thermal conduction in each node [W]	μ_s	Dynamic viscosity of gas [kg/ms]
K_l	Thermal conductivity of the liquid water [W/m/K]	ε	Porosity of the fabric
K_a	Thermal conductivity of air [W/m/K]	ε_m	Volume proportion of PCM in fabric
K_{fab}	Thermal conductivity of the fabric [W/m/K]	ε_f	Volume proportion of fibers in fabric
K_{ml}	Thermal conductivity of liquid PCM [W/m ^{o}C]	ε_l	Volume proportion of liquid moisture in fabric
K_{ms}	Thermal conductivity of solid PCM [W/m ^{o}C]	ρ_a	Density of dry air [kg/m^3]
K_{min}	Minimum thermal conductance of body tissue [W/m^2/K]	ρ_l	Density of liquid water[kg/m^3]
m_{rsw}	Regulatory sweating [g/s/m^2]	ρ_m	Density of PCM [kg/m^3]
m_s	Sweat accumulation on the skin surface in [g/s/m^2]	ρ_f	Density of fiber [kg/m^3]
P_{ea}	Water vapor pressure of ambient temperature [Pa]	ρ_w	Density of liquid water [kg/m^3]
P_{sat}	Saturation water vapor pressure on the skin temperature [Pa]	λ_{1g}	Latent heat of evaporation of water [J/kg]
P_{sk}	Water vapor pressure on the skin surface [Pa]	λ_v	Latent heat of sorption or desorption of vapor by fibers [kJ/kg]
P_f	Vapor pressure of the inside of the fabric next to skin [Pa]	λ_l	Latent heat of sorption or desorption of liquid water by fibers [kJ/kg]
p_s	Pressure of gas phase[Pa]	λ_m	Latent heat of fusion of PCM [kJ/kg]
p_{env}	Air pressure of environment [Pa]	ϖ_a	Proportion of the sorption of water vapor at fiber surface
U	The voltage of the electric supply system [V]	ϖ_l	Proportion of the sorption of liquid water at fiber surface
σ	Stenfan-Boltzmann constant	γ	Surface tension of liquid moisture [J/m]
β	Radiation absorption constant of the fiber [1/m]	θ	The contact angle of the liquid moisture with fiber surface [degree]

CHAPTER1 INTRODUCTION

1.1 INTRODUCTION

1.1.1 Clothing thermal engineering design

Clothing plays a very important role in the daily lives of human beings, as it contributes to biological health and psychological happiness in our lives. More and more modern consumers understand the importance of textiles and thus have come to prefer the apparel products with high added values in terms of functional performance [1]. Currently, clothing design focuses on not only the pattern and fashion design, but also pays more attention to the functional performance of the clothing, making the clothing more smart and satisfying human needs in various environments.

From the points of view of biology and physiology, people will be aware of discomfort in terms of warmth or coolness if the temperature of any part of the skin changes by more than 4.5 °C, and will be fatal if the core body temperature rises or falls by more than 1.5 °C [2]. Actually, there is a thermoregulatory system inside the human body to maintain the body thermal comfort or even being survived in various external environments. When the body temperature drops or rises, the human body must generate or dissipate heat to allow the body temperature to remain in the reasonable range. However, when people are exposed in an extremely hot or cold environment, the thermoregulatory system is not strong enough to maintain the balance between the rates of heat loss and heat generated inside the body.

The clothing, as the barrier between the body and environment, needs to be sensitive enough to take the outside environment into consideration and generate a reasonable thermal microenvironment around the body to help it deal with/cope in extreme weather conditions. Recently, with the successful multidisciplinary teamwork, more and more innovative textile materials and structures are developed for the study of biology and health [2]. Heat generating/storing fiber/fabrics, micro and nano-composite materials, smart phase change material and intelligent coating/membrane are developed and available for clothing functional design [3]. The clothing with superior thermal performance is being known to consumers and regarded as an important concern in their buying decision.

Clothing thermal engineering design is an effective and economical solution of designing clothing with superior thermal performance for people to live in various environments with a feeling of comfort. To achieve desirable thermal functions, the clothing design process is not traditional trial and error but a functional engineering process which involves multi-disciplinary knowledge and computer-aided design (CAD) technologies to investigate, simulate and preview the physical thermal behaviors in the clothing. Clothing designers can thus scientifically evaluate with computer before the produce of real products that if their design concepts are achieved and suitable for the expected wearing environment.

1.1.2 CAD systems for clothing thermal engineering design

The application of CAD technologies for clothing design is a significant sign of revolutionary advancement in the development of computerization and automation in the clothing industry. Clothing designers/engineers are offered a number of flexibilities in their design with CAD systems, such as the usage of textile material, exploration of new design methods and products display [4].

Currently many CAD packages are available, targeting at pattern design, garment construction, fashion design and physical fitting simulation, which have made many achievements in catering for different requirements of the clothing industry [5-11]. They are helpful to shorten the design cycle and save time and money on the prototypes preparation as well as improve productivity considerably. Recently, 3D clothing design and visualizations have been developed to simulate and visualize the physical performance of the clothing wear on the body in 3D virtual ways [12, 13], which enable the designs to be more realistic and make detailed analysis and evaluation of the clothing mechanical performance. However, these pioneer achievements are mainly focused on the mechanical behaviors of clothing.

The newest interest in the CAD system for clothing functional design places the focus on the thermal behaviors of clothing. The CAD system for clothing thermal engineering design aims to create a virtual platform to achieve textile products with superior thermal performance, which offer designers the ability to conceive their products using the engineering method. With this CAD system, designers can simulate the thermal behaviors of the clothing, human body and environment system in specified scenarios, preview and analyze the thermal performance of the clothing, and iteratively improve their designs for desirable thermal functions of clothing.

This new application of CAD technologies demonstrates great potentials in the clothing thermal engineering design, because the capacity of simulating and predicting the thermal performance of clothing is indispensable for designing clothing for thermal protection and comfort. While physical fit and a good-looking fashion style are crucial aims of clothing design, the thermal performance of clothing is another critical aspect that relates to the survival, health and comfort of human beings living in various environmental conditions. As more and more consumers want to wear clothing with higher functional and comfort performance, there is an urgent need for a CAD system to design clothing and analyze its thermal performance effectively and efficiently.

1.1.3 Involved knowledge

Clothing thermal engineering design is a systematic approach which considers the whole wearing situations, including not only the clothing material, but also the biological behaviors of human body and the wearing environments. Figure 1.1 illustrates all the key issues to be considered in the clothing thermal engineering design. The final product of clothing is supposed to be achieved considering all the physical and physiological phenomena involved during the wearing process. For instance, the design of clothing worn in the hot environment or the activity situations should consider the hot sensitive parts of the body which easily accumulate sweat. The design of clothing worn in the cold environment should consider the cold sensitive parts of the body which need more thermal protection. The thermal performance of the designed clothing needs to be suitable for the wearing situations.

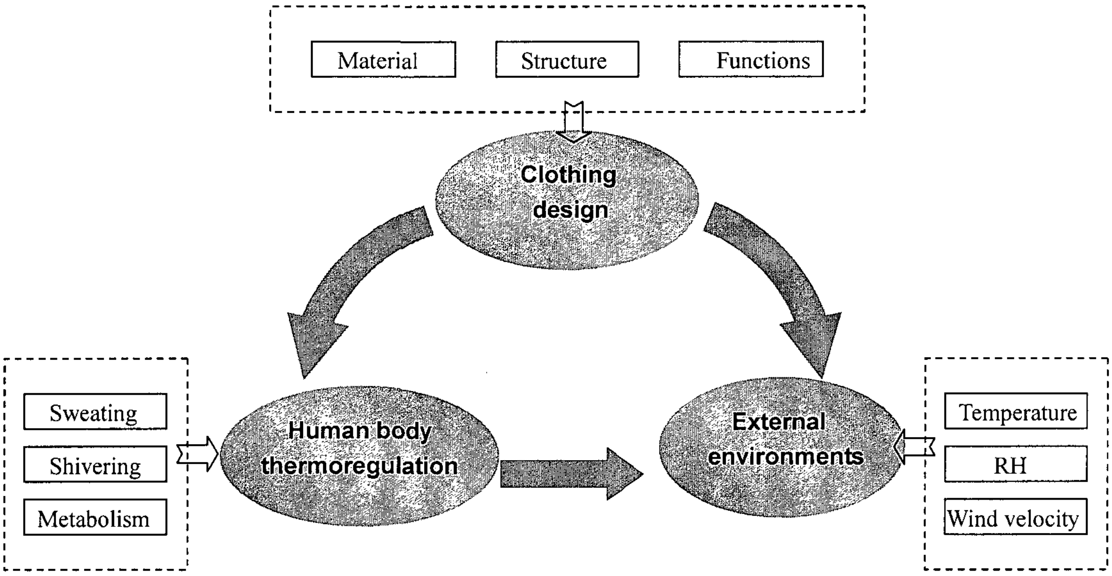


Figure 1.1 Key issues in clothing thermal engineering design

The computer plays a critical role in the clothing thermal engineering because it offers a virtual platform for the users to perform their design in the following ways: 1) the rapid provision of numerical and graphic representation to the traditional qualitative trial-and-error method of clothing design; 2) detailed product design, which is manually practiced in design/workshop office in traditional way; 3) and modeling the involved behaviors/mechanisms and visualizing product performance. This computerized engineering method makes a great advance in both the computer applications and functional clothing engineering design. However, it can not be taken for granted that this method can be realized individually by computer technologies or engineering design or their simple combination. It is an engineering application of multi-disciplinary knowledge which makes effective communications and integration between the research studies in different areas.

In order to establish a theoretical understanding of the knowledge behind this computerized engineering system, it is necessary to investigate the physical and physiological behaviors involved in the wearing system and their mathematical representations in the virtual environment. Also it is necessary to devise effective strategies to diffuse the computer technologies into the clothing thermal engineering design. The fundamental knowledge acquired for this research includes the following scientific areas:

1) Thermal behaviors and their interactions involved in the clothing wearing system;

2) Mechanism and theoretical models of the thermal behaviors in the clothing wearing system;

3) The computational and CAD technologies in clothing thermal engineering design and simulation.

1.2 LITERATURE REVIEW

The fundamental knowledge acquired for this research can be obtained by literature review as follows:

1.2.1 Thermal behaviors in the clothing wearing system

Clothing is one of the most intimate objects in people's daily life since it covers most of the human body most of the time. People may keep having subjective psychological feelings of the clothing and consciously judging the warm/cold/comfort sensation during the wearing time. On the basis of wearing experience, people can make a rough evaluation of the thermal function of clothing and choose suitable clothing for their daily activities. However, as projected in the thermoscopic world, the wearing situation of people can be regard as a complex and interactive multi-component system. Figure 1.2 shows the components of the clothing wearing system. The thermal behaviors involved in the wearing situation may be categorized as [14]:

1) Heat and moisture transfer in the textile materials. This is the physical behavior mainly deciding the thermal performance of clothing. It can be regarded as the following physical process to have deep investigation:

- The heat transfer process in the textile material in terms of conduction, convection and radiation;
- The vapor moisture transfer process in the textile material in terms of diffusion and convection;

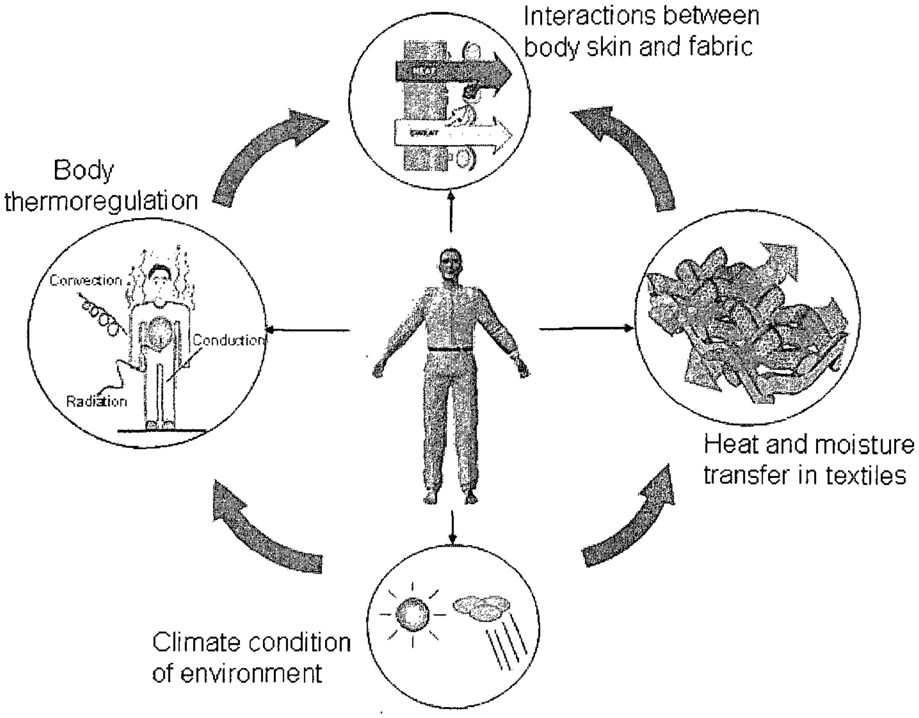


Figure 1.2 Components of the clothing wearing system

- The liquid water transfer process in the textile material;
- Phase change process in the textile material. It is an approach allowing the heat and moisture transfer in a coupled way, including moisture condensation/evaporation in the fabric air void volume, moisture absorption/desorption of fibers, and micro-encapsulated phase change materials;
- Influence of functional treatments of textiles on the heat and moisture transfer process, such as waterproof fabric, moisture management treatment, PCM coating and heating fabrics.

2) Thermoregulatory behaviors of the human body, such as sweating, shivering and biological metabolism, and heat and moisture exchange of body skin and environment.

3) Interactions between the inner clothing and body skin.

4) The climatic conditions of wearing situation in terms of temperature, relative humidity and wind velocity, which influence the heat and moisture behaviors of textile materials and the human body.

1.2.2 Theoretical modeling of the clothing wearing system

1) Heat and moisture transfer in the textile materials

Normally, the heat and moisture transfer processes in the textile material occur when there are gradients of temperature and water vapor pressure across textile structures, and these two processes are often coupled accompanying with the appearance of phase change process.

Heat transfer process

The overall heat transfer in textile materials is the sum of contributions through the fiber and interstitial medium, which may involve multiple transfer mechanisms in terms of conduction, convection and radiation. Theoretically, conduction heat transfer always occurs in the solid fiber material and the medium trapped in the spaces between the fibers as long as a temperature gradient is presented. Convection heat transfer will be obviously observed if the medium is gaseous and if the space is large enough, that is to say, the more porous the textile material is, the more effectively convection takes place. Radiation heat transfer can be ignored when the temperature gradient is small.

Consequently, the heat transfer via conduction is the most dominant transfer mechanism.

In the engineering applications, thermal conductivity is usually adopted to express the thermal properties of materials because thermal conduction is better documented and mathematically analyzed [15]. Unlike other porous materials, in textiles the air filled in the space between fibers has substantially bigger proportion than that of the fibers and the thermal conductivity of fiber is much smaller than air [16]. The heat flow by thermal conduction at any position (x) inside the textile structure can be expressed by the Fourier's law [17]:

$$Q_k(x)_c = -K\frac{dT(x)}{dx} \tag{1.1}$$

$$K = (1-\varepsilon)K_f + K_a \tag{1.2}$$

Where, Q_k is conductive heat flux, T is the temperature and K is the effective thermal conductivity of the textile structure, which is the combination of the conductivities of the air (K_a) and the solid fiber (K_f). ε is the porosity of textile material.

The heat transferred by convection when there is temperature difference between the fabric and the surrounding gas is calculated by Newton's law [18],

$$Q_c = h_c \cdot \Delta T \quad , \tag{1.3}$$

Where, Q_c is the convective heat flux, h_c is heat transfer coefficient, and ΔT is the temperature gradient across the fabric.

The radioactive heat transfers in the ways of emitting or absorbing electromagnetic waves when the standard temperature of the textile material is above zero. The intensity of radioactive is depended on the ratio between the radiation penetration depth and the thickness of textile material, besides the temperature difference between the two surfaces of textile material. Farnworth reported that when the radiation depth is similar to the thickness of fabric, the amount of radiation should be taken into account as it is comparable to the amount of the conduction heat flow, and the radiation heat flux in fabric can be expressed by [17]:

$$\frac{\partial F_R}{\partial x} = -\beta F_R + \beta \sigma T^4 \quad , \quad \frac{\partial F_L}{\partial x} = \beta F_L - \beta \sigma T^4 \qquad (1.4)$$

$$\beta = \frac{(1-\varepsilon)}{r} \varepsilon_r \qquad (1.5)$$

Where, β is the radiation absorption constant for textile materials, σ is the Boltzmann constant, F_R and F_L respectively is the total thermal radiation incident traveling to the right and left way.

Moisture transfer process

Thanks to the porosity of the fabric, the interstices between fibers provide the space for moisture to flow away. There are four ways of moisture (in the phase of water vapor or liquid) transfer occurring in textile materials as summarized by Mecheels [19]: (1) Diffusion through the space between the fibers, (2)Absorption/desorption by the fiber materials, (3)Transfer of liquid water through capillary interstices in yarns/fibers, and (4) Migration of liquid water on the fiber surface.

There are many similarities between heat conduction and moisture diffusion in the textile material. When the system scale, material properties and initial and boundary conditions are similar, the governing equations, analysis methods and results would be analogous for these two processes [20]. When there is a difference between the water vapor concentration on the fibers' surface and that of the air in the fiber interstices, there will be a net exchange of moisture. The water vapor diffusion through the textile material can be described by the First Fick's law [20]:

$$Q_w = D_a \frac{\Delta C}{L}, \qquad (1.6)$$

Where Q_w is the moisture transfer rate, D_a is the diffusion coefficient of water vapor through the textiles, L is the thickness of the fabric sample, and ΔC is the vapor concentration gradient of two fabric sides.

Since the fiber has a small proportion of volume in the fabric, the main contribution of moisture flux is from the diffusions process through the air in the fiber interstices. However, it was identified by Wenhner et al. that absorption of moisture by the fiber also importantly affected the response of fabric to the moisture gradient [21]. The water vapor concentration on the fiber surface, theoretically, depends on the amount of absorbed moisture onto the surface and the local temperature of the fiber. The fiber will keep absorbing as much moisture as it can until it reaches a saturated status with respect to the absorption rate. And when the fiber becomes saturated, additional vapor moisture may condense into liquid phase onto the fiber surface. With regard to the physic nature of fibrous materials, condensate water may be held on the surface of the fiber and be relative immobile, or may be transferred across the textile structure by capillary actions.

The moisture absorption capacity of fibers is described by the property of hygroscopicity (also called moisture regain), which means the amount of moisture that the fiber contains when placed in an environment at certain temperature and relative humidity. In 1967, Nordonb land David [22], on the basis of Henry's work [23], proposed an exponential relationship to describe the change rate of water content of the fibers, and developed a numerical solution with computer technology at that time. Li and Holcombe, in 1992, devised a new absorption rate equation by analyzing the two-stage sorption kinetics of wool fibers and incorporating it with more realistic boundary condition [24]. They assumed the water vapor uptake rate of fiber is composed by two components associated with the two stages of sorption which is firstly experimentally identified by Downes and Mackay [25] and later described by Watt [26]:

$$\begin{aligned} &\frac{\partial C_f}{\partial t} = (1-\alpha)R_1 + \alpha R_2 \quad 0 \le \alpha \le 1 \\ &R_1 = \frac{\partial C_f}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\frac{(rD_f \partial C_f)}{\partial r} \end{aligned} \tag{1.7}$$

Where, R_1 and R_2 are the moisture sorption rates in the first and second stages respectively, α is the proportion of uptake occurring during the second stage. R_1 can be obtained by regarding the sorption/desorption process as Fickian diffusion. R_2 is identified by experimental data and related to the local temperature, humidity and sorption history of the fibers.

Li and Luo in the 1999 year improved the model by presenting the two-stage sorption/desorption process as a uniform Fickian diffusion equation by valuing the diffusion coefficient of the fabric D_f individually at different stages [27], as shown in Equas.2.6 . This improved model was available for both hygroscopic and non-hygroscopic fibers [28].

$$\begin{aligned} &\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{\partial r}(r \cdot D_f(x,t) \cdot \frac{\partial C_f(x,r,t)}{\partial r}) \\ &C_{fs}(x,R_f,t) = f(H(x,t),T(x,t)) \end{aligned} \tag{1.8}$$

Liquid transfer process

When liquid water transfers across the textile material, it will experience wetting and wicking stages, in which wetting of textile is prerequisite for the wicking process [29]. Both wetting and wicking are determined by surface tensions between the solid-vapor-liquid interfaces. In view of the macroscopic world, these tensions are the energy that must be supplied to increase the surface/interface area by one unit. The liquid water put in touch with fibrous material comes to an equilibrium state with regard to minimization of interfacial free energy on the surface. The force involved in the equilibrium can be expressed with the well-known Young's equation:

$$\gamma_{LV} \cdot \cos\theta = \gamma_{SV} - \gamma_{SL} \tag{1.9}$$

Where, γ_{sv}, γ_{sl}, γ_{lv} respectively represents the interfacial tensions that exits between the solid-vapor, solid-liquid and liquid-vapor interfaces. And the term γ_{lv} is also usually regarded as the surface tension of the liquid. θ is equilibrium contact angle, which is the consequence of wetting instead of the cause of it. The term $\gamma_{LV} \cdot \cos\theta$ is defined as adhesion tension or specific wettability of textile material. This equation shows that wettability increases with the decreased equilibrium contact angle θ. The equilibrium contact angle is an intrinsic value described by the Young equation for an ideal system. However, precise measurement of surface tension is not commonly possible. The experimentally measured contact angle between the fiber and the liquid can be observed on a macroscopic scale and is an apparent physical property.

When textiles surface is fully wet by the liquid, the wicking process will happen spontaneously, where the liquid water transports into the capillary space formed between fibers and yarns by capillary force. The fibrous textile assembly is a complex non-homogeneous capillary system due to irregular capillary spaces. These spaces have various dimensions and discontinuous radius distributions. The practical engineering field, an indirectly determined effective capillary radius, is adopted to represent the no-uniform capillary spaces in yarns and fabrics. If the penetration of liquid is limited to the capillary space and the fiber does not absorb the liquid, the wicking process is called capillary penetration, and the penetration is originally driven by the wettability of the fiber, which is decided by the chemical nature and geometry structure of its surface [29]. Ito and Muraoka pointed out that the wicking process will be suppressed with the decreased number of fibers in the textiles [30]. When the number of fibers becomes greater, water moves along the void spaces even between the untwisted fibers, which indicates that sufficient number of continuity of pores is very important to the wicking process.

Coupled heat and moisture transfer

The research of the heat transfer and moisture diffusion in textile materials was initially regarded as independent under the assumption that the temperature and moisture concentration of the clothing is steady over a period of time. In this steady-state condition, there is no need to address the interactions between heat and moisture transfer process [31]. However, under some transient situations where some phase change processes happen, such as moisture sorption/desorption and evaporation/condensation, these two processes are coupled and interact significantly [22, 32].

The moisture absorption/desorption capability of the solid fiber depends on the relative humidity of the enclosed air in the microclimate around the fiber and the type of fiber material. When fibers absorb moisture, heat is generated and released. Consequently, the temperature of fiber will rise and thus results in an increase of dry heat flow and a decrease in latent heat flow across the fabric [25]. The absorbed/desorbed moisture of fibers and the water vapor in the enclosed microclimate in textiles compose the water content of the textile material, which can originate from the wicking process or result from condensation in case of the fully saturated water vapor in fibrous materials [27].

Similar to the phase change process of moisture sorption/desorption, liquid condensation/evaporation pose an impact on the flow of heat and moisture across the textiles by acting as a heat source or be merged into the heat transfer process. Condensation is a physical phenomenon which commonly takes place when the fibrous material is exposed to a large temperature gradient and high humid source, both of which cause the local relative humidity to attain 100% or full saturation [33]. And provided that there is still extra moisture diffusing into the fibrous material, condensation continues. The condition of condensation is different from the transient process of moisture sorption/desorption [34]. When the relative humidity of surrounding microclimate is less than 100%, evaporation occurs.

The first model describing the transient heat and moisture transfer process in porous textile material was developed by Henry (1939) in terms of two differential equations respectively for mass and heat governing formulation [35], as listed in the following. A simple linearity assumption was made in this model to describe the moisture absorption/desorption of fibers to obtain analytical solution. This modeling work established a basic framework of modeling the complicated coupled process of heat and moisture transfer through the textiles material.

$$\varepsilon \cdot \frac{\partial C_a}{\partial t} = \frac{D_a \cdot \varepsilon}{\tau_a} \cdot \frac{\partial^2 C_a}{\partial x^2} - (1-\varepsilon) \cdot \Gamma_f \tag{1.10}$$

$$C_v \cdot \frac{\partial T}{\partial t} = K_{fab} \cdot \frac{\partial^2 T}{\partial x^2} + (1-\varepsilon) \cdot \lambda_v \cdot \Gamma_f \,. \tag{1.11}$$

$$\Gamma_f = \frac{\partial C_f}{\partial t} = const. + a_1 C_a + a_2 T \qquad (1.12)$$

Where, α_1 and α_2 are coefficients. Henry assumed the moisture sorption rate Γ_f to be a linear relationship between temperature and moisture concentration, allowing him to solve the equations analytically.

Nordon and David (1967) proposed an exponential relationship to describe the change rate of water content in fibers and relaxed some assumptions by adopting experimental adjustable parameters for the two stages of moisture absorption/desorption of fibers based on the experimental observation from Downes and Mackay (1958) [25] and Watt (1960) [26], and generated a numerical solution with computer computation [22]. Ogniewicz and Tien (1981) proposed a model considering the heat transport that happened by the ways of conduction, convection and condensation in a pendular state [36]. That model ignored moisture sorption and was lack of a clear definition of the volumetric relationship between the gas phases and the liquid phase. Motakef (1986) extended this analysis to describe mobile condenses, in which the moisture condensation was taken into account with simultaneous mass and heat transfer process [37].

$$\frac{\partial C_a}{\partial t} = D_a \frac{\partial C_a}{\partial x} + \Gamma_{\mathrm{lg}} \qquad (1.13)$$

$$c_v \frac{\partial T}{\partial t} = K \frac{d^2 T}{dx^2} - \lambda_{\mathrm{lg}} \Gamma_{\mathrm{lg}} \qquad (1.14)$$

$$\rho_c \varepsilon \frac{\partial \theta}{\partial t} = \rho_c \varepsilon \frac{\partial}{\partial x}\left(D_l(\theta) \frac{\partial \theta}{\partial x} \right) - \Gamma_{\mathrm{lg}} \qquad (1.15)$$

In Motakef's model, a concept of critical liquid content (CLC) was introduced to address the liquid diffusivity. When the liquid content θ is below the CLC, the liquid is in the pendular state and has no tendency to diffuse. When the liquid content θ is beyond the CLC, a liquid diffusivity $D_l(\theta)$ was introduced to describe the liquid transfer by surface tension force from regions of higher liquid content to the drier regions. $D_l(\theta)$ is a complicated function of the internal geometry and structure of the medium.

Gibson et al. modified the model developed by Whitaker for mass and energy transport through porous media [32] and conducted testing of the coupled heat and moisture transfer through a porous textile by considering the steady diffusion of liquid transport and accumulation and gas flow convection effects [38]. They applied Volume-Averaging approach [39] to simplify the complex transient heat and mass transfer through hygroscopic porous media. This model was also applied to study the interactions between human thermoregulation and the clothing layers [27]. Farnworth in 1986 year first developed a numerical model for coupled heat and moisture transfer with considerations of the condensation/evaporation and absorption/desorption by hygroscopic materials. The conductive and radiative heat transfer and diffusion vapor transfer were included in this model without convective heat and mass transfer [40]. This model was simplified and applied for the multi-layered clothing in which the temperature and moisture content in each clothing layer were assumed to be uniform, as listed in the following:

$$C_i \frac{dT_i}{dt} = \frac{T_{i-1} - T_i}{R_{Hi-1}} - \frac{T_i - T_{i+1}}{R_{Hi}} + Q_{ci}, \tag{1.16}$$

$$\frac{dM_i}{dt} = \frac{P_{i-1} - P_i}{R_{Vi-1}} - \frac{P_i - P_{i+1}}{R_{Vi}}, \tag{1.17}$$

Where, T_i and P_i are the temperature and vapor pressure of the clothing layer. M_i is the total mass per unit area of water present in the clothing layer. R_{Hi} and R_{Vi} are the resistance to heat and vapor flow. Q_{ci} refers to the heat source inside a layer by the process of moisture absorption or condensation. C_i is the heat capacity per unit area of the layer. A proportional relation was used in this model to describe the fabric regain with regard to the relative humidity in each layer to address the effect of moisture absorption.

Fan and Luo (2000) incorporated the new two-stage moisture sorption/desorption model of fibers [27] into the dynamic heat and moisture transfer model for porous clothing assemblies [41]. They considered the radiation heat transfer and the effect of water content of fibers on the thermal conductivity of fiber material. Further, Fan and his co-workers improved the model by introducing moisture bulk flow, which was caused by the vapor-pressure gradients and super-saturation state [42-44]. This improvement made up for the ignorance of liquid water diffusion in the porous textile material in previous models. The equations of the model are listed as follows:

$$\varepsilon\frac{\partial C_a}{\partial t}=-\varepsilon\mu\frac{\partial C_a}{\partial x}+\frac{D_a\varepsilon}{\tau}\frac{\partial^2 C_a}{\partial x^2}-\Gamma(x,t) \tag{1.18}$$

$$\rho(1-\varepsilon)\frac{\partial(W-W_f)}{\partial t}=\rho(1-\varepsilon)D_l\frac{\partial^2(W-W_f)}{\partial x}+\Gamma(x,t) \tag{1.19}$$

$$\mathrm{C_v}(x,t)\frac{\partial T}{\partial t}=-\varepsilon\mu\mathrm{C_{va}}(x,t)\frac{\partial T}{\partial x}+\frac{\partial}{\partial x}\left(k(x,t)\frac{\partial T}{\partial x}\right)-\frac{\partial F_R}{\partial x}+\frac{\partial F_L}{\partial x}+\lambda(x,t)\Gamma(x,t) \tag{1.20}$$

Where, $\Gamma(x,t)$ accounts for moisture change due to absorption/desorption of fibers and the water condensation/evaporation; W-W_f is the free water content in the fibrous material; D_l is the diffusion coefficient of free water in the fibrous batting, which is assumed with a constant value with reference to some previous work. C_v is the effective volumetric heat capacity of fibrous material.

In 2002 year, Li and Zhu reported a new model for simulation of coupled heat and moisture transfer processes, considering the capillary liquid diffusion process in textile [45], which developed the liquid diffusion coefficient as a function of fiber surface energy, contact angle, and fabric pore size distribution. In subsequent research, they analyzed the effect of the pore size distribution, fiber diameter [46], as well as thickness and porosity [47] in the heat and moisture transfer processes. Based on this new model, Wang et al. considered more the radiative heat transfer and moisture sorption and condensation in the porous textile, achieving more accurate simulation for the realistic situation [48]. The governing equations of the model are shown as follows:

$$\frac{\partial(C_a\varepsilon_a)}{\partial t}=\frac{1}{\tau_a}\frac{\partial}{\partial x}\left(D_a\frac{\partial(C_a\varepsilon_a)}{\partial x}\right)-\varepsilon_f\xi_1\Gamma_f+\Gamma_{\mathrm{lg}} \tag{1.21}$$

$$\frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l(\varepsilon_l)\frac{\partial(\rho_l \varepsilon_l)}{\partial x}\right) - \varepsilon_f \xi_2 \Gamma_f - \Gamma_{lg} \tag{1.22}$$

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_{mix}(x)\frac{\partial T}{\partial x}\right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + \varepsilon_f \Gamma_f(\xi_1 \lambda_v + \xi_2 \lambda_l) - \lambda_{lg}\Gamma_{lg} \tag{1.23}$$

In the above equations, the dynamic distributions of liquid and water vapor in the fabric space are specified by a relationship of volumetric fractions:

$$\varepsilon_l + \varepsilon_a = 1 - \varepsilon_f \tag{1.24}$$

The diffusion coefficient for liquid water in porous textile media is calculated by the capillary pore distribution d_c, fiber surface energy γ, contact angle φ and the liquid volumetric fraction ε_l:

$$D_l(\varepsilon_l) = \frac{\gamma \cos\theta \sin^2 \alpha d_c \varepsilon_l^{\frac{1}{3}}}{20\eta \varepsilon^{\frac{1}{3}}} , \tag{1.25}$$

And the moisture phase change process of condensation/evaporation is defined as:

$$\Gamma_{lg} = \frac{\varepsilon_a}{\varepsilon} h_{lg} S_v \left(C^*(T) - C_a\right) , \tag{1.26}$$

Where, $C^*(T)$ is the water concentration on the fiber surface, C_a is the water concentration in the adjacent air, h_{lg} is the mass transfer coefficient at the fiber surface, and S_v is the specific volume of the fabric.

Recently, Li. et al improved the model by considering the factor of atmospheric pressure which has a significant impact on the heat and moisture transfer process in textile [49], and provided insights into the thermal process of textile in windy weather and sports situations. It is assumed that the heat and mass transport mechanisms include movement of liquid water due to the capillarity and atmospheric pressure gradient, diffusion of vapor within inter-fibers due to the partial pressure gradient of vapor and total gas pressure gradient, diffusion of vapor into fiber, evaporation and condensation of water.

$$\frac{\partial[\varepsilon((1-S)\rho_v)]}{\partial t}+\frac{\partial[C_f(1-\varepsilon)]}{\partial t}-\varepsilon(1-S)S_v h_{l\to g}[\rho_{vs}(T)-\rho_v]=div\left(-\overline{m}_v^D\right)+div\left(-\overline{m}_v\right) \quad (1.27)$$

$$\frac{\partial[\varepsilon S\rho_w]}{\partial t}+\varepsilon(1-S)S_v h_{l\to g}[\rho_{vs}(T)-\rho_v]=div(-\overline{m}_w) \quad (1.28)$$

$$c_v\frac{\partial T}{\partial t}-\lambda(1-\varepsilon)\frac{\partial C_f}{\partial t}+h_{vap}\varepsilon(1-S)S_v h_{l\to g}[\rho_{vs}(T)-\rho_v]=div[K_{mix}(gradT)] \quad (1.29)$$

$$\frac{\partial[\varepsilon((1-S)\rho_a)]}{\partial t}=div\left(\overline{m}_v^D\right)+div(-\overline{m}_a) \quad (1.30)$$

Where, ρ_v is water vapor concentration; ρ_a is the concentration of dry air; ρ_w is the density of liquid water; C_f is the water vapor concentration in the fibers; ρ_{vs}(T) is the concentration of saturated water vapor at the temperature (T); m_v is the mass flux of vapor under total atmospheric pressure gradient; $\overline{m}_v^D$ is the diffusion mass flux of water vapor; $\overline{m}_v$ is the mass flux of dry air under total atmospheric pressure gradient; $\overline{m}_w$ is the diffusion mass flux of liquid water;

The previous research about the heat and moisture transfer in textile material limited their focus on a single layer of porous textiles. Li and Wang extended the model for coupled heat and moisture transfer to multilayer fabric assemblies [50]. They described the geometrical features, layer relationships and blend fibers of the multilayer fabric assemblies by the following definitions:

$$l_{(i-1)0} = l_{i1} \quad (2 < i < n) \tag{1.31}$$

$$Contact_{in} = \begin{cases} 1 & l_{ij} = 0 \\ 0 & l_{ij} \neq 0 \end{cases} \quad (1 \leq i \leq n, j = 0,1) \tag{1.32}$$

$$\overline{p} = \sum_{ti=1}^{tn} f_{ti} p_{ti} \quad (tn \geq 2) \tag{1.33}$$

l_{i0} and l_{i1} are defined as the thickness of the left and right gap between neighbored layers. Contact is defined to express the contact situation at boundaries between layers, which determines the heat and moisture transfer behavior at the layer boundary. The symbol of $\overline{p}$ is the weighted mean property of all blend fibers in the fabric based on their fractions f_{ti}. In addition, they individually developed boundary conditions for different fabric layers to achieve the numerical solutions.

Waterproof fabric

Waterproof fabric, which is laminated or coated with micro-porous or hydrophilic films, is frequently used in the design of functional clothing for the weather of low temperature, wind, rain, and even more extreme situations [51, 52]. With waterproof fabric, the clothing can effectively protect the body from the wind and water; as well as reduce the heat loss from the body to the environment. These functions of waterproof fabric, scientifically, are achieved by significantly affecting the processes of heat and moisture transfer through the textile products.

The term 'water vapor permeability' (WVP, g.m-2.day-1) is commonly used to measure the breathability of the fabric, which indicates the moisture transfer resistance in the heat and mass transfer processes. This property can be obtained by the experimental measurement with the Evaporation and Desiccant methods [53]. The calculation formulation is expressed according to the first Fick's law of diffusion [12]:

$$WVP = \frac{Q_w}{tA} = \frac{\Delta C}{W_n} \, , \tag{1.34}$$

Where, Q_w is the weight loss/gain in grams over a period time t through an area A, W_n is the water vapor resistance and ΔC is the difference of water vapor concentration on the two surfaces of the fabric sample.

Meanwhile, R_n is employed to express the thermal resistance of the waterproof fabric. Thus, the simulation of the thermal effect of the waterproof fabric can be realized by specifying the heat and moisture transfer coefficients at the boundaries, as shown by the following formula [54]:

$$H_{mn} = \frac{1}{W_n + \frac{1}{h_{mn}}} \tag{1.35}$$

$$H_{cn} = \frac{1}{R_n + \frac{1}{h_{cn}}} \tag{1.36}$$

Where, h_{mn} and h_{cn} are respectively the mass and heat transfer coefficients of the inner and outer fabric surface. When the fabric is laminated or coated with microporous or hydrophilic films as being waterproof, the combined mass and heat transfer coefficients H_{mn} and H_{cn} (n = 0,1) can be obtained by integrating the water vapor resistance W_n and the thermal resistance R_n of the waterproof fabric.

Phase change material (PCM) fabric

The phase change material (PCM), which has the ability to change its phase state within a certain temperature range, such as from solid to liquid or from liquid to solid, is micro-encapsulated inside the textile fabrics in the functional clothing design in recent years to improve the thermal performance of clothing when subjected to heating or cooling by absorbing or releasing heat during a phase change at their melting and crystallization points. With PCM technology, the temperature of clothing is able to gain a change delay due to the energy released/absorbed from the PCM when exposed to a very hot/cold environment [55].

In the textile application, the PCM is enclosed in small plastic spheres with diameters of only a few micrometers. These microscopic spheres containing PCM are called PCM microcapsules, and are either embedded in the fibers or coated on the surface of the fabric. Research on qualifying the effect of the PCM fabric in clothing on the heat flow from the body was experimentally conducted by Shim [56]. He measured the effect of PCM clothing on heat loss and gain from the manikin which moved from a warm environment to a cold environment and back again. Ghali et al. analyzed the sensitivity of the amount of PCM inside the textile material on the fabric thermal performance [57]. The percentage of PCM in the fabric was found to influence the length of time period during which the phase change occurs. Also, they drew a conclusion that under steady-state environmental conditions, PCM has no effect on the thermal performance;

while when there is a sudden change in the ambient temperature, PCM can delay the transient response and decrease the heat loss from the human body.

In order to investigate the mechanisms of thermal regulation of the PCM on the heat and moisture transfer in textiles, Li and Zhu developed a mathematical model to describe the energy loss rate from the micro-spheres which is considered to be a sphere consisting of solid and liquid phases [58], as shown in the following equations:

$$\frac{\partial T_{ms}(x,r,t)}{\partial t} = a_{ms} \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 \frac{\partial T_{ms}(x,r,t)}{\partial r}) \quad \textit{spherical core} \qquad (1.37)$$

$$\frac{\partial T_{ms}(x,r,t)}{\partial t} = a_{ms} \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 \frac{\partial T_{ms}(x,r,t)}{\partial r}) \quad \textit{spherical shell} \qquad (1.38)$$

Where, T_{ms} and T_{ml} respectively are the temperature distributions in a sphere containing solid and liquid PCM. These energy governing equations are developed on the radial coordinate. r denotes the radius of the latest phase interface in micro-PCM The smaller is the radius of the micro-spheres, the more significant is the effect of the PCM.

Heating fabric

When people are in an extremely cold environment or some other special conditions, they need substantially more energy to survive. Considering these needs, the heating fabric is developed by applying the electrical heating technology in the fabric design [59, 60] in the recent years. In the design process of fabric, a set of thin electric wires are placed and connected to battery supply equipment. When the switch is triggered at certain specified temperature point, these wires will be electrified and release heat to increase the temperature of fabric.

The heat release by the electric heating system can be evaluated by [61]:

$$W = \frac{U^2}{R} t \tag{1.39}$$

Where, W is the heat release volume from the electric wires in fabric, R is the resistance of the electric wires, and U is the voltage of the supply system. With the evaluation of the electric heat release W, the models for coupled heat and moisture transfer in textiles can be extended for the heating fabric by adding the factor of W to the energy balance equation.

Summary

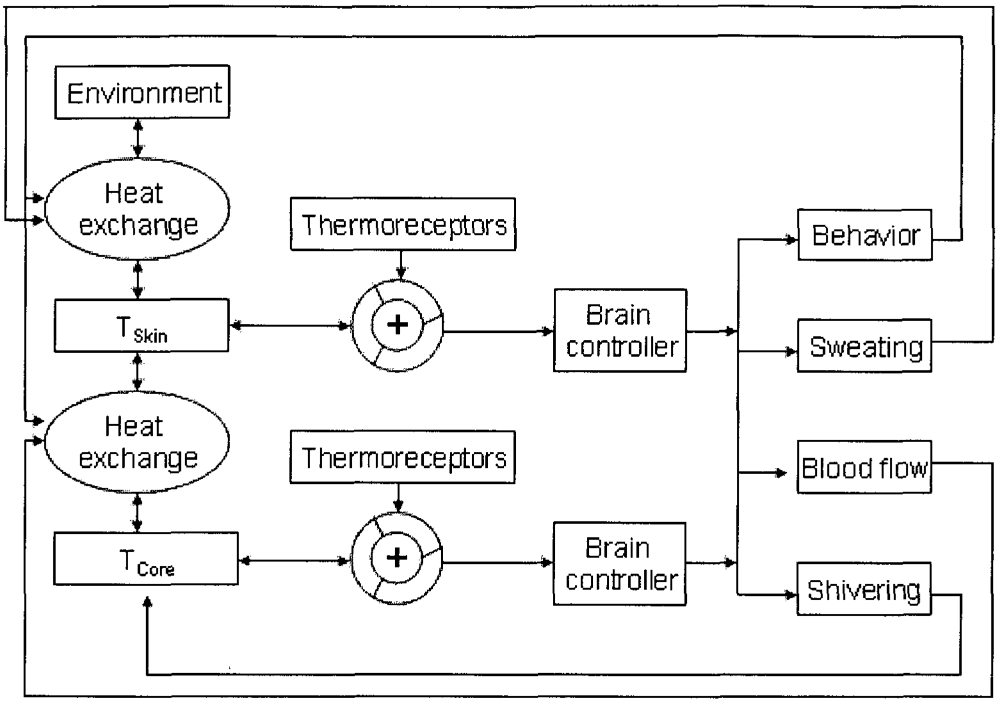
In this section, the physical models with mathematical descriptions for modeling the thermal behaviors in textile materials have been reviewed. Basically, the thermal behaviors happening in the textiles involve heat transfer process, moisture transfer process, moisture absorption/desorption by fibers and, phase change processes. The innovative textile materials, such as waterproof fabric, fabric with PCM, heating fabric, naturally achieve their thermal performance by influencing the heat and moisture transfer in textile materials and thus can be modeled and integrated into the model of heat and moisture transfer. The research studies examining the thermal performance of clothing have been developed gradually from investigating the mechanism of heat transfer or moisture transfer in the textile statically to considering the dynamically coupled interactions and simultaneousness between the thermal behaviors in the clothing.

These models have laid substantial foundations in simulating and predicting the thermal performance of textile materials in various climatic situations. With these models, the researchers are able to develop scientific strategies and tools for computational simulation, and even design of the clothing with the aid of computers.

However, due to the complexities of these theoretical models, people without sufficient expert knowledge will have difficulty in directly applying these modes to gain benefits from the model simulation. Meanwhile, in various potential applications, the limitations of the models need to be taken into account, such as the distances between the ideal assumptions and reality conditions, the ignorance of important involved physical phenomenon, and the unavailability of values of the parameters in the models.

2) Human body thermoregulatory system

To sustain life in various environments, the human body must have the ability to keep the temperature of core and skin at a reasonable range under a variety of external conditions, that is, the core body temperature should be maintained at 37.0±0.5 °C, and the skin temperature should be managed at approximately 33° C. In the human body, the regulation of the body temperature is implemented by the thermoregulation system, which responds to produce/dissipate heat when the body core temperature drops/rises [62, 63]. The basic mechanism of the body thermoregulation system involves two processes: (i) when the body feels warm, the blood vessels react with vasodilatation and the glands begin to perform the sweating process; (ii) when the body feels cold, the blood vessels reduce the blood flow to the skin and increase the heating production by muscle shivering [64]. The schematics of thermoregulatory system of the human body can be seen in Figure 1.3.



T_{skin}—mean temparature of body skin

T_{core}— core temperature of body

Figure 1.3 Schematic diagram of the thermoregulatory system of human body

The research into developing models for describing the thermal regulation system of the human body based on the physiology, thermodynamics and transports processes has been carried out over a long period of time. Due to the limitation of the computer capacity, the early models were relatively simple, such as the thermal models of Smith [65] and Brown [66]. Hand in hand with the development of computer technologies, the development of thermal models of human body has become more and more detailed and complex, such as the models reported by Gagge [67], Stolwijk [68, 69] and Wissler [70].

The thermal mathematical models for human body can be classified for a single part and/or for the entire body. The models for a single part of the body, which was usually developed by physiologists, most of them are too complicated to simulate the physiological and anatomical details of the specific parts. It seems that these partial models theoretically can be added together to form a complete representation of the thermal exchange of the whole body. However, Fu [71] claimed that such methods were not practical due to the fact that the connection between these models is very difficult, and adding the models together would need a supercomputer even if the connection between models is feasible. The thermal models for the entire body, reviewed by Fu [71], can be characterized by the following classifications: 1) one-node models, 2) two-node thermal models, 3) multi-node models, and 4) multi-element models.

Though most of these models are likely to produce acceptable simulation results under the condition that the temperature is relatively uniform throughout the body, the multi-node and multi-element models perform better when large temperature gradients exist within the body because of the greater amount of details provided about the body temperature fields.

One-node thermal models

One-node thermal models, in which the human body is represented by one node, are also called empirical models. They usually depend on experiments to determine the thermal response of the human body, and therefore, are not mathematical models in a phenomenological sense. A well-known empirical prediction model for the entire human body was reported by Givoni and Goldman (1972) [72]. It was derived by fitting curves to the experimental data obtained from the subjects exposed to various environments.

Two-node thermal models

Two-node thermal models tend to divide the entire human body into two concentric shells of an outer skin layer and a central core representing internal organs, bone, muscle and tissue. The temperature of each node is assumed to be uniform. The energy balance equations are usually developed for each node and solved to produce the skin and core temperature and other thermal responses.

The early two-node models, such as Machle and Hatch's model [73], were not widely used by people due to the lack of sufficient consideration of the complicated physiological phenomena of the human body. Gagge et al. (1971) introduced a more complete two-node model for the entire body [67], which includes the unsteady-state energy balance equation for the entire human body and two energy balance equations for the skin node and core node, as listed in the following:

$$S = M - E_{res} - C_{res} - E_{sk} - R - C - W \qquad (1.40)$$

$$S_{cr} = M - E_{res} - C_{res} - W - (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) \qquad (1.41)$$

$$S_{sk} = (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) - E_{sk} - R - C \qquad (1.42)$$

Where, S_{cr} and S_{sk} respectively are the heat storage of core and skin shell, M is the metabolic heat, E_{res} and C_{res} respectively is latent and dry respiration heat loss, W is moisture transfer resistance, R is radioactive heat loss, C is convective heat loss, V_{bl} is skin blood flow rate and c_{pbl} is specific heat at constant pressure of blood.

Gagge et al. later (1986) improved their two-node model by the development of the thermal control functions for the blood flow rate (V_{bl}), the sweat rate (RSW), and the shivering metabolic rate (M) [74].

$$V_{bl} = [6.3 + 200(WARM_{cr})]/[1 + 0.1(COLD_{cr})] \qquad (1.43)$$

$$RSW = 4.72 \times 10^{-5} \cdot WARM_{bm} \cdot e^{(WARM_{sk}/10.7)} \qquad (1.44)$$

$$M = 58.2 + 19.4 \cdot COLD_{cr} \cdot COLD_{sk} \qquad (1.45)$$

Due to the two-node nature of this model, it is able to be applied easily and simply with the straightforward numerical solution. Smith pointed out that Gagge's model was applicable for situations with moderate levels of activity and uniform environment conditions[75]. However, due to the limitation imposed by only two nodes, Gagge's model can only be applied under uniform environmental circumstances.

The multi-node models

Multi-node models divided the entire human body into more than two nodes and developed energy balance equation for each node as well the control functions for blood flow rate, shivering metabolic rate, and so on.

Crosbie (1963) firstly reported a multi-node model for the entire human body, in which the human body was considered to have three layers consisting of core, muscle and skin [62]. This model is considered to be the first to simulate the thermal regulation of the entire human body on an analog computer. Jones, based on Gagge's model, presented a multi-node model with the concept of keeping the core node single while dividing the skin node into arbitrary number of segments [76]. The balance equation for the skin node in Gagge's model is applied to each skin segment, and the energy and control equations are identical to those in Gagge's model.

Stolwijk et al. (1971) presented a more complex multi-node mathematical thermal model of the entire human body, in which many efforts are made to the statement of the thermal controller [68]. This model firstly divided the body into six cylindrical parts of head, trunk, arm, hands, legs and feet and a spherical body part comprising the head. Each part is further divided into four concentric shells of core, muscle, fat and skin tissue layers. Specifically, in this model all the blood circulation in the human body is regarded as a node called the central blood pool, which is the only communication connecting each body part. Therefore, Stolwijk's model is also called a 25-node model, and energy balance equations are developed for each node with the assumption of uniform temperature in each layer, which includes heat accumulation, blood convection, tissue conduction, metabolic generation, respiration and heat transfer to the environment. There are several descriptions for these equations. Li et al. presented these equations as follows [77]:

$$\text{Core layer}: C(i,1)\frac{dT(i,1)}{dt} = Q(i,1) - B(i,1) - D(i,1) - RES(i,1) \tag{1.46}$$

$$\text{Muscle layer}: C(i,2)\frac{dT(i,2)}{dt} = Q(i,2) - B(i,2) + D(i,1) - D(i,2) \tag{1.47}$$

$$\text{Fat layer}: C(i,3)\frac{dT(i,3)}{dt} = Q(i,3) - B(i,3) + D(i,2) - D(i,3) \tag{1.48}$$

$$\text{Skin layer}: C(i,4)\frac{dT(i,4)}{dt} = Q(i,4) - B(i,4) + D(i,3) - E(i,4) - Q_t(i,4) \tag{1.49}$$

Where, $C(i,j)$ is the heat capacity of each node, $T(i,j)$ is the node temperature, $Q(i, j)$ is the sum of the basic metabolic rate, $B(i,j)$ is the heat exchanged between each node and central blood compartment, $D(i,j)$ is the heat transmitted by conduction to the neighboring layer with the same segment. $E(i,j)$ is th evaporative heat loss at skin surface.

Similar to Gagge's model (1971), Stolwijk et al (1986) also developed the thermal control functions in terms of tissue temperature signals, in which the warm signal (WARMS) and cold signal (COLDS) are corresponding to warm and clod receptors of the skin and are calculated by the error signal (ERROR). These controller equations produce the signals to drive the regulator, including total efferent sweat command (SWEAT), total efferent shivering command (CHILL), total efferent skin vasodilation command (DILAT), and total efferent skin vasoconstriction command (STRICT), as shown below.

SWEAT = CSW* ERROR(1) + SSW* (WARMS-COLDS) + PSW* WARM(1)* WARMS (1.50)
DILAT = CDIL* ERROR(1) + SDIL* (WARMS - COLDS) + PDIL* WARM(1)* WARMS (1.51)
CHILL = -CCHIL* ERROR (1) + SCHIL* (COLDS-WARMS) + PCHIL* COLD(1) COLDS (1.52)
STRIC = -CCON ERROR(1) + SCON (COLDS - WARMS)+ PCON *COLD(1)* COLDS (1.53)

Stolwijk's model has made much advancement compared to pervious multi-node models as it is not only capable of calculating the spatial temperature distribution for each node, but also has improved the representation of the human's circulatory system since the blood circulation is the most important function of human body. This model has been validated with the good agreements between the experimental and predicted results of most cases. The limitation of this model is that it can not be used for the highly non-uniform environmental situations caused from the negligence of spatial tissue temperature gradients.

Multi-element models

The greater difference between the multi-element thermal models and the two-node or multi-node models is that it divides the human body into several parts or elements without further division, and the temperature of each part or elements is no longer assumed as uniform. With the lifting of node uniform assumption, the mathematical descriptions of thermal functions, circulation, respiration etc. have also become more detailed to correspond with the detailed temperature filed.

Wissler (1961) developed a multi-element model for the entire body by dividing the human body into six elements: head, torso, two arms and two legs, which were connected by the heart and lung where venous streams were mixed [31]. Later on, Wissler improved his model and divided the human body into 15 elements to represent the head, thorax, abdomen, and the proximal, medical, and distal segments of the arms and legs, which were connected by the vascular system composed of arteries, veins and capillaries [78]. Energy balance equations for each element and the arterial and venous pools were developed with the assumption that the blood temperature of arteries and veins in each element were uniform, and the thermal control equations for blood flow rates, the shivering metabolic rate and the sweat rate were built up. The limitations of this model are that it is not applicable to the situations where a large internal temperature gradient or highly nonuniform environmental conditions exist. Additionally, the effect of the vasodilation and vasoconstriction was not included in the model. Finally, the parameters and constants used in the control equation are not easy to determine.

Smith (1991) developed a 3-D, transient, multi-element thermal model for the entire human body with detailed control functions for the thermoregulation system [75]. Compared to the previous models, the improvements were that he: 1) developed a 3-D temperature description of the human body; 2) provided a detailed description of the circulatory system, the respiratory system and the control system; and 3) employed the finite-element method to get the numerical solutions of the model, which made a 3-D transient model for the entire human body possible. The model divided the human body in 15 cylindrical body parts: head, neck, torso, upper arms, thighs, forearms, calves, hand and feet. Each body part is connected only by the blood flow and without tissue connection. The simulation results showed this model works well for situations of human thermal response during sedentary conditions in both uniform and non-uniform environments for either hot or clod stress conditions. However, the behaviors of the model during cold or hot exercising conditions were less satisfactory.

George Fu (1995) summarized the limitations of the previous models and developed a 3-D transient, mathematical thermal model for the clothed human to simulate the clothed human thermal response under different situations [71]. The main improvement of this model is the addition of the subcutaneous fat layer, the accumulation of moisture on the skin, and the blood perfusion and blood pressure to Smith's model. The development of the human model includes the thermal governing equations of the passive and control systems.

The passive system of humans was defined as including the tissue system, the circulatory system and the respiratory system, which determines the heat and mass transfer processes in the human body.

Tissue energy governing equation

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + w_b \rho_b c_{p,b}(T_a - T_v) + q_m + q_a + q_v + \alpha q_{res} \tag{1.54}$$

The energy governing equation of macro-circulation system

$$\rho_b c_{b,p} \frac{\partial T_b}{\partial t} = k_b \frac{d^2 T_b}{dZ^2} - \rho_b c_{b,p} v_b \frac{dT_b}{dZ} + \frac{q_{bd}}{A_b} \tag{1.55}$$

The energy governing equation of respiratory system

$$\rho_b c_{b,p} \frac{\partial T_{res}}{\partial t} = k_b \frac{d^2 T_{res}}{dZ^2} - \rho_b c_{b,p} v_{res} \frac{dT_{res}}{dZ} + \frac{q_{res}}{A_b} \tag{1.56}$$

The control system in the thermoregulatory system of the human body includes the vasomotor, sudomotor and metabolism. In Smith's model, the thermal control governing equations for the vasomotor response, the sweat rate, the shivering metabolic rate and the cardiac output were developed [75].

Vasomotor response

$$r_{o,dil} = \begin{cases} r_{o,basal} & T_{core} \leq 36.8\ ^\circ\mathrm{C} \\ \dfrac{T_{core} - 36.8}{37.2 - 36.8}(r_{o,\max dil} - r_{o,basal}) + r_{o,basal} & 36.8^\circ\mathrm{C} \leq \mathrm{T_{core}} \leq 37.2^\circ\mathrm{C} \\ r_{o,\max dil} & \mathrm{T_{core}} \geq 37.2^\circ\mathrm{C} \end{cases} \tag{1.57}$$

$$r_{o,con} = \begin{cases} r_{o,\max con} & T_{skin} \leq 10.7\ ^\circ\mathrm{C} \\ \dfrac{T_{skin} - 10.7}{33.7 - 10.7}(r_{o,bascal} - r_{o,\max con}) + r_{o,\max con} & 10.7^\circ\mathrm{C} \leq \mathrm{T_{skin}} \leq 33.7^\circ\mathrm{C} \\ r_{o,bascal} & \mathrm{T_{skin}} \geq 33.7^\circ\mathrm{C} \end{cases} \tag{1.58}$$

Sudomotor response

$$T_{sweat} = \begin{cases} 42.084 - 0.15833 T_{skin} & T_{skin} \leq 33.0\ ^\circ\mathrm{C} \\ 36.85 & \mathrm{T_{skin}} \geq 33.0^\circ\mathrm{C} \end{cases} \tag{1.59}$$

$$m_{sw} = 45.8 + 739.4(T_{core} - T_{sweat}) \qquad T_{core} > T_{sweat} \tag{1.60}$$

Metabolic response

$$T_{shiver} = \begin{cases} 35.5 & T_{core} \leq 35.8\ ^{\circ}\mathrm{C} \\ -1.0222\times10^{-4} + 570.97T_{core} - 7.945T_{\mathrm{core}}^{2} & 35.8^{\circ}\mathrm{C} \leq T_{\mathrm{core}} \leq 37.1^{\circ}\mathrm{C} \end{cases} \quad (1.61)$$

$$m_{shiv\max} = -1.186\times10^{9} + 6.552\times10^{7}T_{core} - 9.04\times10^{5}T_{core}^{2} \qquad T_{core} < 37.1^{\circ}\mathrm{C} \quad (1.62)$$

$$m_{shiv} = m_{shiv\max}(1 - (\frac{T_{skin} - 20}{T_{shiver} - 20})^{2}) \quad (40^{\circ}\mathrm{C} - T_{shiver}) \leq T_{skin} \leq T_{shiver} \quad (1.63)$$

George Fu improved 3-D transient model has a good ability of simulating the human body thermoregulatory system in situations where there exists high temperature vibration and even in the extremely atrocious weather conditions.

Though the multi-elements models can predict the thermal status of the human body in more detail, however, it should be noticed that there are many difficulties in applying the multi-element models into clothing engineering design due to the following considerations: 1) the multi-element model requires the clothing to be 3D meshed and modeled, which may cause great complexity in the integration of the models of clothing and human body, and the computation load is very intensive; 2) the many parameters involved in the multi-element models have high demanding on the data availability in the engineering application.

Summary

In this section, the physiological mechanism and the mathematical models of the thermoregulatory system of human body have been reviewed. The classification suggested by Fu [71] states that the mathematical models include one-node models, two-node models, multi-node models and multi-element models. The representative models of each classification have been discussed in terms of the mathematical description and the development process. With a greater number of nodes dividing the human body, more detailed and complex information in the thermoregulatory system could be considered. In addition, the multi-nodes model is able to provide more accurate simulation results for applications in more dynamic and extreme environments. Whether or not the evolution of the models can increase the body nodes significantly depends on the computing capacity provided by the computer.

When these models are employed to express the body thermoregulatory system and generated thermal response during various climatic conditions, both the advantages and limitations of the model should be taken into consideration so that a balance can be achieved between the simplicity and complexity, between the easy-usability and intricate configurations, between the effective computation and result accuracy.

3) Interfaces between the body skin and clothing

In the daily life, the clothing acts as an important barrier for heat and vapor transfer between the skin and the environment, protecting against extreme heat and cold, but meanwhile hampering the loss of superfluous heat during physical effort. This barrier is formed by the clothing materials themselves and by the air they enclose as well as the still air bound to the outer surfaces of the clothing [79].

Some researchers (Stuart et al., De Dear et al.) experimentally observed the phenomena of heat and moisture that exchange actively between the clothing and skin, and found the exchanged amount is considerable compared to the total increase/decrease volume [80, 81]. The maximum heat flow from the skin to clothing depends on the heat conductivity of the inner layer of clothing and covering area of skin. Also, the heat exchange between the human body and clothing is dependent on the external parameters, such as air temperature, air humidity, and wind speed [82]. The clothing with the least porous, greatest thickness and lowest permeability will provide the greatest protection to heat and perspiration from the skin to environment provided with least porous and thickest thickness and [83].

Shitzer and Chato (1985) reported on a significant development in the study of simultaneous heat and mass transport through the skin-fabric system [84]. Jones et al. (1990) reported a model to describe the transient response of clothing system and later on they combined this model with Gagge's two-node model to investigate the interactions between the body and clothing [85, 86]; however, the data for validating their model has not been reported. Li and Holcombe (1998) reported a new model by interfacing the model for a naked body with a heat and moisture transfer model of a fabric. They developed the boundary condition between the body and clothing by quantifying the heat and mass flow [87].

At the fabric-skin interface

Heat: $M_t = h_{ti}(T_{sk} - T_{fi})$ (1.64)

Mass: $M_d = h_{ci}(C_{sk} - C_{fi}) + L_{sk}\dfrac{\partial C_{sk}}{\partial t}$ (1.65)

At the interface between fabric and ambient air

Heat: $K\dfrac{\partial T}{\partial x}\Big|_{x=L} = -h_t(T - T_{ab})$ (1.66)

Heat: $D_a\dfrac{\partial C_a}{\partial x}\Big|_{x=L} = -h_c(C_a - C_{ab})$ (1.67)

Where, M_d is the moisture flow from the skin and M_t is the heat flow from the skin.

Since the air spacing between the skin and the fabric continuously varies in time depending on the level of activity and the location, the thermal transfer processes are influenced by the ventilating motion of air through the fabric initialed from the relative motion between the body and surrounding environment, such as in the walking situations. Ghali et al. developed a 1D model of the human body. The oscillating trapped air layer gap width and the periodically-ventilated fabric predict the effect of walking on exchanges of heat and mass [88]. Murakami et al presented a numerical simulation of the combined radiation and moisture transport for heat release from a naked body in a house where continuous slight air flow exists by considering the thermal interaction between the human body and the environment and the intrinsic complex air situation in the real world [89]. Recently, Li et al. integrated the simulation of thermal interactions between human body and clothing with regard to six body parts by employing the Stolwijk's multi-node model to simulate the human physiological regulatory response [77].

Though much attention has been paid to the simulation of the thermal behaviors in the integrated system of human body, clothing and environment, and some numerical algorithms were reported for the simulation, these research studies put their focuses only on the scientific exploration and investigation. Few are developed systemically with a user-oriented purpose and used for clothing functional design.

1.2.3 Computer tools for clothing thermal functional design

The clothing thermal design, if following the traditional way of the clothing design and production, begins from the conception design and the prototypes making. As a result, a series of testing configured with experimental protocols will be performed by employing wearing subjects or by thermal manikins [90], and related thermal data will be measured using various equipment during the experiments. Based on the analysis of experimental data, designers attempt to find the difference of measured thermal functions of clothing and their design concepts to obtain feedback to improve their design. After the iterative trial and error process, the final products can be put on the market. This traditional design process is very expensive, time-consuming and tedious due to the real prototypes making, experimental testing and burdensome data analysis.

These shortcomings of the traditional design method make it difficult to satisfy the requirements of designers and manufacturers. People come to resort to the powerful capacity of the computer in the design process of thermal functional clothing. Antunano et al. (1992) employed a computer model and heat-humidity index to evaluate the heat stress in protective clothing [91]. Tan et al. (1998) presented a design and evaluation approach to develop thermal protective flight suits in which they adopted commercial software tools to develop fabric patterns [92]. Schewenzferier et al. (2001) optimized thermal protective clothing by using a knowledge bank concept and a learning expert system [93]. Computer has acted a role in the clothing thermal functional design. However, it still can not directly help the designer to preview the thermal performance of clothing, which is a crucial function for clothing thermal functional design.

James et al. applied the commercial software of computational fluid dynamics (CFD) in their strategy to simulate the heat and moisture diffusive and convective transport as well as effect of sweating to predict the performance of chemical and steam/fire protective clothing [94]. Kothari et al. simulated the convective heat transfer through textiles with the help of computational fluid dynamics (CFD) to observe the effects of convection on the total heat transfer of the fabric. can be simulated [95]. The software tools like CFD provide a possible pathway for the user to simulate the heat and fluid distribution in the clothing. However, these tools do not take into account the structural features of the textile materials and the special features of the heat and moisture transfer process in textile materials that are related to the physical properties and chemical compositions of the textile materials. They can not reflect the practical wearing situation and preview the true complex thermal behaviors in clothing.

In order to obtain scientific simulation of clothing thermal performance, some researchers have made efforts to apply the theoretical models describing the complex heat and moisture behaviors in clothing wearing system to the clothing thermal functional design. Parsonin 1995 adopted thermal models for the clothed body including human thermoregulation and clothing to work as tools for evaluating clothing risks and controls [96]. Prasad et al. in 2002 constructed a detail mathematical model to study transient heat and moisture transfer through wet thermal liners and evaluated the thermal performance of fire fighter protective clothing [97].

These researches have made good exploration in clothing thermal functional design with the computer tools. Design and evaluation models, experts systems, applications of CFD software, and theoretical simulation models have been utilized to help to carry out clothing thermal functional designs. They either simply focus on evaluating certain thermal properties of clothing or need specialized knowledge to understand. They are very difficult to be applied as engineering tools for the general designers.

1.3 PROBLEM STATEMENT

The literature review above has explored the fundamental research in the theoretical models and computational simulation of the clothing wearing system. However, there has been no any systematic strategy of computer-aided clothing thermal engineering design yet and there is a need to fill in the knowledge gaps.

The literature review has covered the following areas:

1) The thermal behaviors of clothing wearing system and their interactions;
2) The physical mechanism of the thermal transfer processes in textiles and their mathematical models, including the heat transfer, moisture transfer, liquid transfer, phase change and the influence of innovative technologies with reference to membrane fabric, PCM and self-heating fabric;
3) The biological mechanisms and mathematical models of the thermoregulatory system in the human body, including one-node models, two-node models, multi-node models and multi-element models. The representative models of each classification were addressed in term of the mathematical description and governing equations;
4) The interface between the clothing and human body and the frontward research work about the simulation of the integrated human body and clothing system; and
5) The state-of-the-art of the computer tools in clothing thermal functional design.

In the above areas, the clothing wearing system has been reviewed in terms of thermal behaviors and interactions involved, but there has been no theoretical framework which addresses the knowledge and technologies involved in the strategy of clothing thermal engineering design; The physical mechanisms and theoretical models of the thermal behaviors in the clothing materials and the human body thermoregulation system have been available in many publications, but few of them are developed for the purpose of engineering applications, and can systematically simulate all the thermal behaviors involved in the clothing wearing system for clothing thermal engineering design. There are some software tools and computational methods for evaluating the thermal performance of the clothing, but they either simply focus on evaluating certain thermal properties of clothing or require specialized knowledge to understand them. It is therefore very difficult for the users who do not possess sufficient expert knowledge to directly apply these findings to their designs.

The observations above have suggested that there is an urgent need for a systematic and scientific approach of computer-aided clothing thermal engineering design, which enables users to effectively carry out clothing thermal functional design with desired thermal functions. With the CAD system for engineering design, potential users with or without background knowledge will be provided the capacity to design, preview, analyze and evaluate the thermal performance of clothing, and make correct and useful decisions in the process of product design or purchase. In order to realize this engineering approach, the following knowledge gaps have been identified:

1) A systematic description of clothing thermal engineering design and a framework that integrates the knowledge and technologies involved and their relationships/communications are still lacking;

2) The simulation models for engineering application purposes to scientifically

simulate the thermal behaviors of the clothing wearing system has not been integrated, and the algorithm for obtaining numerical solution of these models has not been systemically developed;

3) The software architecture of the CAD system for clothing thermal engineering design, which includes clothing thermal functional design capacity, software engineering principles and the support of an engineering database, has not been established; and

4) The CAD system for clothing thermal engineering design is not yet available for general users.

1.4 OBJECTIVES OF THIS RESEARCH

In order to address the problems described above, this research aims to develop a systematic and scientific approach of computer-aided clothing thermal engineering design by integrating the required multi-disciplinary knowledge of physical mechanism, mathematical models, engineering principles, computational algorithms, and CAD technologies. Specifically, the objectives of this research can be described as follows:

1) To build a multi-disciplinary framework of thermal engineering design of clothing, which is a model-based and simulation-based engineering solution for desirable thermal functions of clothing. The key issues in this framework are computational simulation of the involved physical and physiological mechanisms, and

the CAD system for general users to access this new engineering method;

2) To integrate multi-scale computational models to express the thermal behaviors in clothing wearing system for functional engineering design. The models are provided with effective approaches to measure the parameters for engineering purposes;

3) To develop multi-structural computational scheme to implement the computational simulation for clothing thermal engineering design. The simulation results can be generated during the iterative computational simulation.

4) To build a software architecture of clothing thermal engineering CAD systems, which is featured with a life-oriented clothing design procedure, object-oriented system design, and the support of an engineering database; and

5) To develop CAD systems by which the users can effectively and economically achieve the thermal engineering design of clothing in multi-layer or multi-style levels.

1.5 RESEARCH METHODOLOGY

To achieve the above mentioned objectives, the research of this thesis was carried out according to the following methodology:

1) Develop a multi-disciplinary framework of the thermal engineering design of clothing

- Summarize the factors of thermal comfort of the human body and the thermal functional requirements of clothing;
- Analyze the thermal behaviors and their interactions/relationships involved in the wearing system in terms of physical mechanisms and mathematical models;

- Present a framework that addresses the knowledge and technologies involved in clothing thermal engineering design and the scientific and effective combination of multi-disciplinary knowledge;
- Identify the key parts of knowledge and techniques in the framework

2) Integration of computational multi-scale models for numerically expressing the thermal behaviors in the clothing wearing system;

- Develop criteria for model selection for the purposes of engineering application and analyze the existing representative models;
- Develop multi-scale models for clothing wearing system from the nano-meter scale to the meter-scale corresponding to the thermal behaviors in micro-encapsulation PCM, fibers, multi-layer fabrics to the body-clothing system;
- Provide the data availability of the parameters in the models for engineering applications

3) Development of the computational scheme for the simulation in clothing thermal engineering design;

- Develop numerical solutions for the multi-scale models;
- Develop multi-structural computational schemes for clothing thermal engineering design; and
- Analyze the influence of various variables on the simulation accuracy and convergence.

4) Development of the architecture of computer-aided engineering system;

- Analyze the user requirements of computer-aided clothing thermal engineering design;

- Develop the software architecture for clothing thermal engineering CAD system;
- Create a life-oriented design procedure for the users to perform finish their design effectively and easily;
- Design the system with object-oriented technology to enable an open and flexible structure for easy maintenance and updating; and
- Develop an engineering database to support the clothing thermal engineering design

5) Development of the computer aided engineering systems

- To develop two computer-aided engineering systems respectively for clothing multi-layer design and multi-style design in order to satisfy different application requirements;
- To realize the systems with friendly functionalities and graphic user interfaces according to the developed architecture. The two CAD Systems with different capacities will be provided to the user to perform design, simulation, preview and analysis; and
- To prepare and illustrate design cases using the software systems to show the design procedure, to demonstrate functionalities and to validate the accuracy of the system by the comparisons between the experimental and predicted results.

1.6 THESIS OUTLINE

This thesis consists of eight chapters to report the research and outputs of this study.

Chapter 1 reports on extensive literature review in relevant disciplinary areas that cover related knowledge in order to: 1) introduce research background; 2) identify knowledge gaps; and 3) determine the objectives and methodology of the research project.

Chapter 2 presents a multi-disciplinary framework of clothing thermal engineering design. In this chapter, the thermal functional requirements of clothing are first identified and discussed. A systematic definition of clothing thermal engineering is presented, which involves multi-disciplinary knowledge of physical, chemical, mathematical, and computational and software engineering sciences and engineering principles. An innovative multi-disciplinary framework of clothing thermal engineering design will be proposed and explained.

Chapter 3 and Chapter 4 focus on the computational simulation strategy for clothing thermal engineering design.

In Chapter 3, the multi-scale models systematically expressing the thermal behaviors in the clothing wearing system are selected and accessed with reference to a set of engineering criteria, and the data availability of the parameters in the models are investigated for engineering applications.

Chapter 4 reports on the development of multi-structural computational scheme to perform computational simulation for clothing thermal engineering design. The computational scheme is developed on the basis of the solutions of the multi-scale models, which are incorporated with different dimensional thermoregulatory models of the human body.

In Chapter 5, an innovative software architecture of computer-aided system is proposed and developed for clothing thermal engineering design. With the identification of user requirements, the software architecture is proposed to address the required functionalities and their relationships in the system. This computer-aided system is designed with the object-oriented method for a flexible and open structure and supported with an engineering database.

With this architecture and the proposed computational simulation strategy, Chapter 6 and Chapter 7 report on two software systems developed to enable the end users to carry out their thermal engineering design of clothing corresponding to different application requirements.

In Chapter 6, a computer-aided system for multi-layer clothing thermal engineering design is developed and described. With this system, the end user can perform multi-layer clothing thermal engineering design and preview the overall thermal performance of clothing and the thermal responses of the human body. The functionalities and prediction accuracy of the system are discussed and shown by the design cases.

In Chapter 7, a computer-aided system is developed and described to allow the designer to carry out multi-style clothing thermal functional design. This system enables the designer to investigate the effects of clothing with different materials and styles for different body parts by simulating and previewing the thermal performance of clothing pertaining to multi-parts. Two design cases illustrate the functionalities of this system and the simulated results are compared with the experimental results.

Finally, Chapter 8 draws conclusions of the research of this study and makes recommendations for directions of future studies.

CHAPTER 2 MULTI-DISCIPLINARY FRAMEWORK OF CLOTHING THERMAL ENGINEERING DESIGN

2.1 INTRODUCTION

Engineering design has been successfully applied in a number of engineering areas such as civil engineering, machine manufacturing, and electronic products design by linking the scientific discoveries with commercial applications to develop feasible solutions of practical issues. It has become an economical and effective approach to advance fundamental knowledge and create new concepts and technology. Recently, with the development of thermodynamics and its rapid applications in specific fields, some tools and CAD systems have been developed for products thermal engineering design. For instance, in 1995 Bonani et al. presented a thermal CAD system for the thermal analysis of compound semiconductor devices and integrated circuits based on a computationally efficient 3D large-scale thermal simulator [98]. A virtual thermal comfort engineering method for vehicle design was introduced by Han et al. to manage the thermal comfort of human body [99]. Kuo et al. in 2004 reported using a real-time animated thermal CAD system in the design of electronics multilayer structures integrated with a compact cold plate [100], which is composed of a pre-processor subsystem, a thermal analyzer, a post-processor subsystem, and relevant user interfaces and databases.

The study reported in this thesis is an original piece of work to develop a thermal engineering strategy for clothing design with desirable thermal performance due to the complex structure of textile materials and diverse thermal behaviors in the clothing wearing system. In this chapter, the requirements of thermal functions of clothing are identified and described to reveal the relationships between the functions and theoretical mechanisms; a systematic definition of clothing thermal engineering design is presented; and then an innovative multi-disciplinary framework of clothing thermal engineering design is proposed and explained. This framework combines multi-disciplinary knowledge including physical, biological, mathematical, and computational and software engineering sciences and engineering principles. The two central parts of this framework are computational simulation and computer-aided system. Computational simulation is enabled by simulation models, characteristic data, and numerical algorithms. Based on the capacity of computational simulation, the computer-aided system aims to provide a new engineering design tool for end users through a series of functionalities including design and engineering interfaces, support of engineering database, simulation and prediction, visualization and evaluation.

2.2 CLOTHING THERMAL FUNCTIONAL REQUIREMENTS

Clothing functions as a protective insulation between the body and environment in the energy balance process by reducing or controlling energy loss from the body and ensuring that the physical conditions around the body are comfortable. Clothing is hence usually regarded as an extension and modification of the body itself or called “the second skin” [3]. On the apparel market, comfort has been identified as one of the key attributes when consumers choose clothing and textile products [101].

However, comfort is such a complex and subjective concept that it is difficult to be quantitatively defined. In the research on comfort, Fourt and Hollies surveyed the literature and found that comfort involves thermal and non-thermal components and is related to the wearing situations [102], on which important research findings have been published and applied to solve practical problems [18, 103]. Thermal comfort has become a predominant requirement in the clothing design and the thermal performance of clothing during wearing time is a fundamental factor to determine the thermal comfort. Wearing clothing without suitable thermal performance for a particular environment may result in discomfort and physical strain, and in extreme cases, even heat or cold injury or illness. For instance, an evening dress is not suitable for a snowing environment and skiwear can not be worn in hot summer. Before a multi-disciplinary framework of thermal engineering design of clothing is developed, it is essential to understand the theories that underpin the requirements of thermal comfort of human body and the thermal performance of clothing, which are consistent with the findings drawn from the physical and physiological fields.

2.2.1 Factors of thermal comfort of human body

According to ASHRAE standard, thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding thermal environment [104]. Thermal environment refers to those characteristics of the environment which affect the heat loss from the human body. From the physiological viewpoint, thermal comfort will occur when there is a thermal equilibrium in the energy exchange between the human body and environment, and will maintain when the heat generated by normal human metabolism or external activities is allowed to dissipate to keep such a thermal equilibrium. Regarding the ways that govern energy exchange between the human body and the environment as seen in Figure 2.1, thermal comfort in physical mechanism is theoretically affected by heat loss as a result of conduction, convection, radiation and evaporation.

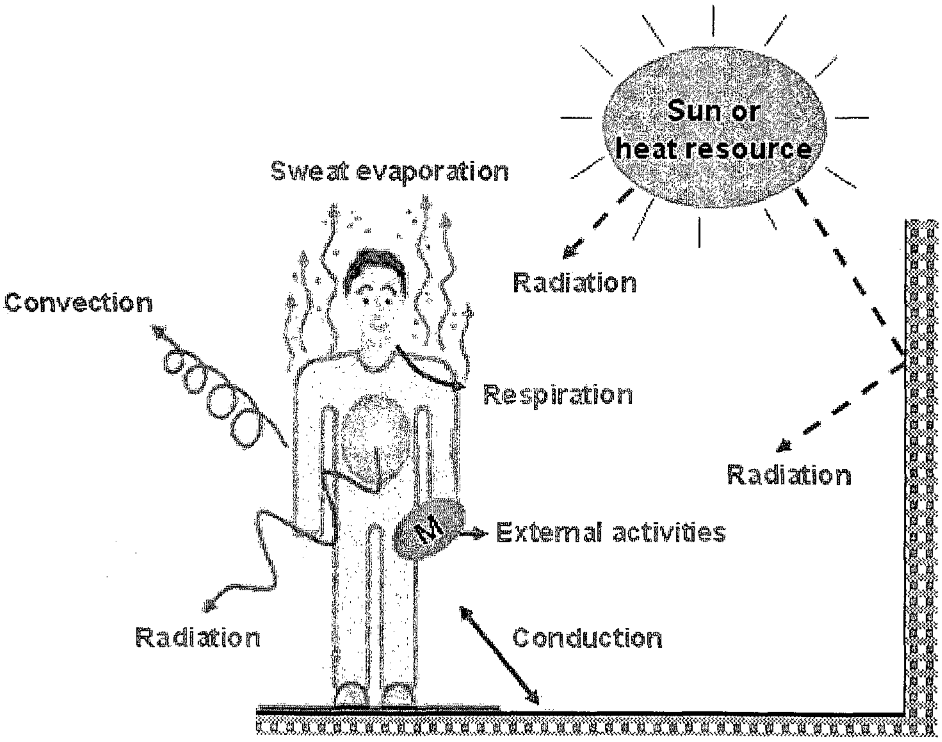


Figure 2.1 Schematics of heat balance of the body with the environment [105]

From the macroscopic view, it is significant to find out the factors of thermal comfort, which are controllable and can be managed so as to improve thermal comfort. The factors have been identified as climatic conditions, physical activity levels and clothing insulation [79], which are elaborated in Figure 2.2 and explained in the following:

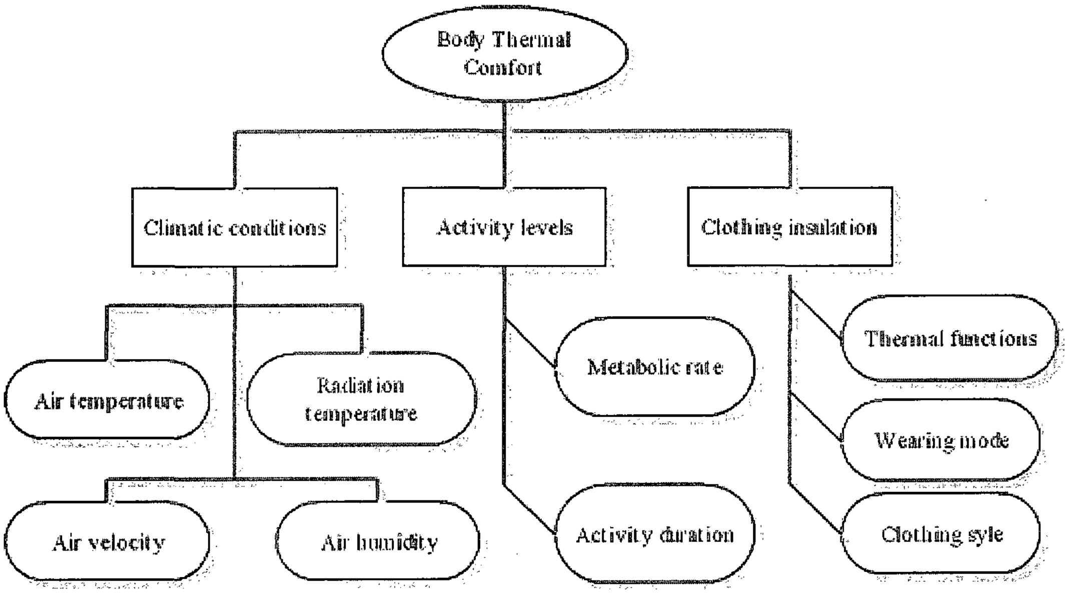


Figure 2.2 The factors of thermal comfort of the human body

1) Climatic conditions

The climatic conditions influence the thermal comfort of human body by the factors of air temperature, radiation temperature, air velocity and air humidity.

Air temperature directly determines the convective heat loss/gain of the human body through the environmental air flow along the skin and the breath in the lungs. The higher the air temperature is, the less heat loss from the body. However, if the air temperature increases to be higher than skin temperature, the body will gain heat from the environment instead of dissipating heat away.

The mean radiant temperature is used to express the radiant environment of a specific situation, and in practical cases is usually regarded as the mean temperature of the surrounding walls or objects in the wearing situations. In the case of thermal balance of the human body, it is generally used to take account of the heat exchanged by radiation between skin and environment. In an environment with heat sources, such as a stove with flame, heating facilities and the sun, the body covered by clothing usually receives radioactive heat from the heat source since the temperature of these heat sources easily exceeds the skin temperature.

Air movement/velocity commonly refers to the wind speed of an environment, which physically influences both convective and evaporative heat loss if there is sweat or other liquid moisture on the skin. The higher the wind speed, the more amounts of convective and evaporative heat loss. When the body feels hot, it is sensible for it to get access to a windy environment to obtain a cooling sensation due to the enhanced evaporation. Also because of that, the body usually feels cool, or even cold, after sweating in such situations. However, in the cold environment, the presence of wind may accelerate the heat loss from the body and cause a sensation of discomfort.

The amount of moisture contained in the air called moisture concentration or expressed as air humidity determines the intensity of the moisture flow between the skin and environment. Generally, the moisture concentration on the skin will be higher than that of the environment which makes the evaporation of sweating on the skin possible, and the body can thus dissipate the surplus heat to keep a thermal balance between energy production and loss. However, if the moisture concentration of the skin is lower than that of the air, the thermal balance will be upset and the body will feel discomfort. In theory, the higher temperature leads to higher moisture content at the same relative humidity, so that even the skin is at 100 % relative humidity, the sweat will always be able to evaporate from the skin provided that the skin temperature is above that of the air temperature.

2) Activity levels

The heat produced in the body depends on the metabolic rate and the activity duration. In the resting situation, the metabolic rate of the body means the generated heat needed for the basic functions in the body, such as respiration and blood circulation, to provide the body cells with nutrients and oxygen to maintain life. In the active situation, with the increasing oxygen and nutrients consumed by muscles, the metabolic rate will increase to generate more energy for the body. During the nutrients burning process, most energy will be released in the muscles and the body temperature will subsequently be increased. The metabolic rates of the body engaged in different activities have been studied and measured [106], as listed in Table 2.1, which shows the trends that when engaged in more vigorous activities, the body has a higher metabolic rate.

Table 2.1 Metabolic rates of the body when engaged in different activities

Activity	Body metabolic rate

	(W/m^2)	(Met)
Reclining	46	0.8
Sitting, relaxed	58	1.0
Standing, relaxed	70	1.2
Sitting activity (office work, school etc.)	70	1.2
Standing activity (shop, laboratory etc.)	93	1.6
Moving activity (house work, work at machines etc.)	116	2.0
More vigorous activity (hard work, sports activities etc.)	165	2.8

3) Clothing insulation

Clothing acting as the insulation between the body skin and the environment is a direct obstruction to the heat and moisture exchange between the skin and the environment. Clothing itself is a complex system where various heat and moisture behaviors happen and interact with internal and external environments, such as the human body and the surrounding environment. The thermal functions of clothing are therefore significantly important for the body to obtain and maintain thermal comfort. The thermal functions of clothing will be discussed in detail in the next section. Besides, the wearing mode (open or close, loose or tight) determining the fraction of heat and moisture transferred by clothing and the style of clothing determining the area of human body covered by clothing also importantly influence the thermal comfort of the body.

In conclusion, the factors of climatic conditions, activity levels and clothing insulation influence the thermal comfort of the human body. The findings show that the body is able to theoretically achieve thermal comfort through actions in the following three forms: 1) move to a different thermal environment making use of controllable thermal conditions (air temperature, humidity and velocity) to change the current environment;

2) change to a different active status (resting, light, hard) to obtain a different metabolic rate; and 3) wear different types of clothing to obtain comfort sensation, which is the most simple response people usually take in their daily lives. All of these actions are under conscious control and activate the unconscious physiological reactions of the body to enter a comfort state.

2.2.2 Thermal functions of clothing

Clothing covers most of the body skin most of the time. It provides substantial protection against extreme cold or hot environment and, at the same time, hampers the loss of surplus heat from the body. Due to the shield function of clothing, the range of environment where the body has thermal comfort is considerably widened. For instance, the body wearing light clothing at a low activity level will expand the climatic temperature range for thermal comfort by about 3.5°C [107]. It is quite important to be aware that clothing is not just a passive cover on the skin, but that it interacts with and even modifies the thermal regulating functions of the body. For example, when a person senses a change in climatic conditions, he or she will make conscious actions such as wearing other clothing, adjusting the clothing fitting status (loose or tight), and shifting the wearing mode (open or closed). The thermal environment for the human body to maintain thermal balance and thermal comfort is achieved by the microclimate around the skin which is mostly covered by clothing. The thermal functions of clothing are hence to create a comfort microclimate and provide environmental protection for the body. Specifically, they can be classified into heat protection, moisture protection and wind protection, as seen in Figure 2.3. In these different aspects of protection, clothing has different features of thermal functions, which are explained as follows:

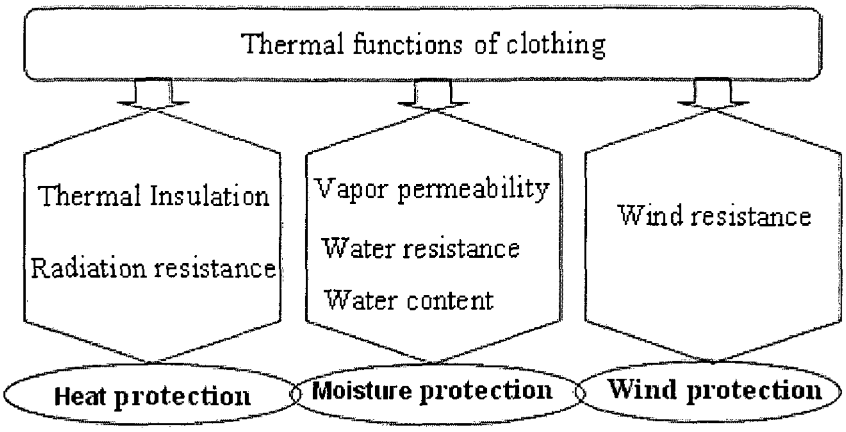


Figure 2.3 Clothing thermal functional requirements

1) Heat protection

Basically, clothing has the function to provide thermal protection for the human body by minimizing the hot or cold stress imposed by the environment. Being a barrier of the heat transfer in terms of conduction, convection and radiation, clothing more or less has the capacity of thermal insulation to reduce the heat loss from the human body to the environment. This capacity is described as the property of thermal resistance of clothing and textile material, which can be measured with the unit 'clo', and many measurement methods have been available [15, 108]. This property is also alternatively expressed as the property of thermal conductivity. Speakman and Chamberlain have carefully studied and pointed out that fiber type, fabric density and fabric thickness are important contributors to the thermal insulation capacity of clothing [109]. However, the textile material is a mixture of air and fibers, and usually the volume of air is greater than that of fibers. Considering the thermal conductivity of air is much lower than that of the fibers, the thermal insulation of clothing hence depends much on fabric thickness and fabric density and less on the fiber material. The fabric with even gossamer thickness adds resistance to heat and moisture transfer across textile structures. In the case that clothing consists of multi-layered fabrics, the thermal insulation of clothing should also be concerned with the air layer between the fabrics due to the noticeable thermal conductivity of air. Therefore, clothing with a multi-layer assemble usually has total thermal insulation much greater than the sum of the thermal insulation of individual fabrics.

The human body may experience long exposure to environments with strong radiation in some situations. Clothing is also expected to extend its ability to protect the skin against the harmful effects of ultraviolet radiation. The ultraviolet protection factor (UPF) rating is a measure of the protection provided by clothing. The contributors of UPF of clothing may include the UV radiation-absorbing properties of textile material, the construction of fabric (less UV radiation passes through tightly woven or knitted fabrics), and the thickness and weight of fabric (heavier weight fabrics usually block more UV radiation than light fabrics of the same type).

2) Moisture protection

Clothing composed of porous textile materials can be regarded as a specific medium for the moisture to diffuse to and away from the body skin. However, the human body is continually losing water mostly by evaporation and diffusion. The passage of moisture through clothing is one of the most important factors for the microclimate to maintain thermal balance and thermal comfort. The moisture protection of clothing for the human body, which transiently interacts with thermal protection, can be characterized as water vapor permeability/breathability, water resistance and water content.

Water vapor permeability is a property of clothing which indicates its capability of allowing the water vapor to permeate through the clothing material. Since it is easy for the human body to have perspiration accompanied with sweat evaporation in the hot environment or during activity time, the amount of moisture that passes through the clothing has much contribution to the level of thermal comfort. The meaning of clothing with good water vapor permeability is that in the situations where there is perspiration, even sweat accumulation on the skin, the inner layer of clothing does not become wet and the natural evaporative cooling effects can be achieved. A higher degree of water vapor permeability of clothing leads to more moisture vapor passing from the skin through the fabric layers to the environment and more substantial guarantee of thermal comfort.

Even clothing with good moisture permeability capacity becomes wet when it is in touch with liquid water. Water resistance is another function of moisture protection of clothing which protects the wearer in rainy and other wet conditions by preventing the leakage of water into clothing while still allowing perspiration to evaporate from the wearer to the atmosphere. It has been investigated that wetted fabrics in contact with the skin will change the hydration state, the speed of capillary blood flow, and the temperature at skin surface, which, consequently, will lead to coolness and damp sensations, resulting in thermal and moisture discomfort [110]. There are direct relationships between damp sensation and the skin wetness caused by the amount of sweat or water accumulated in the clothing. Water resistance is measured by the amount of water seeped through the fabric with the unit of mm (the water is suspended above the fabric). According to the different capacity levels of resisting water, fabrics with the function of water resistance are further categorized as water resistant, water repellant and waterproof [111].

Water resistant fabrics are characterized as shedding water, which is affected by the weave method or functional treatment. However, they will still soak through in heavy rain. Water repellent fabrics, which are either tightly woven or coated with a finish, are more effective than water resistant fabrics. The water is forced into little beads when hitting the fabric rather than going through it. Waterproof fabrics are completely impermeable to water even in heavy rains since the water stays outside of the clothing. They may be coated with a finish or be laminated, resulting in the covered body becoming hot and uncomfortable. Instead of coatings, membranes, or laminates, fabric construction, which directs water away from the body, is encouraged to be used to keep the wearer dry. In recent years, many manufacturers have included this information of moisture protective function on their product labels.

The water content of clothing is also an important function of moisture protection of clothing. Keeping moderate water content in the clothing helps to obtain a cool and damp sensation and thermal comfort. The water content of clothing is decided by many factors, including the water transport within the fabric, moisture regain of fibers, the drying speed of water which is mostly decided by the interactive factors of evaporation, water resistance, and sweat accumulation. The variations of the textile material, such as fiber type, yarn size, twist and weave, and especially chemical finishes, affect the water content of clothing [112]. The speed of water loss from clothing, which is related to the water content contained and the material structure or treatment, has been identified as a critical functional index of clothing, especially sportswear and outerwear.

3) Wind protection

The wind speed, even the relative air motion caused by the body's movement, has a greater influence on the clothing insulation and air permeability. The combined physical effect of wind, body movement and clothing fit has been investigated, and it has been found that it can reduce the insulation of the surface air layer by up to 80% and the total clothing insulation by up to 53% [113]. Later reports have revealed that the heat and vapor resistance of clothing will be reduced by an increased subject movement and wind [82, 114]. Wind can quickly take away the air enclosed in the clothing system, speed up sweat evaporation, and dissipate the warm vapor [115]. However, if the wind speed reaches a noticeable level, it may result in superfluous heat loss of the body by convection and evaporation and cause the body to suffer from discomfort or cold sensation. This phenomenon frequently happens in winter or in the windy and rainy conditions.

The wind protection function of clothing is to provide wind resistance to prevent strong ventilation caused by the wind in the microclimate between the skin and clothing, since strong ventilation may take away much heat from the skin and reduce the body temperature to below comfort level. The great importance of clothing functions, such as water repellant and windproof, have been recognized and has received positive response from the consumers especially at the sportswear market [116].

In summary, the requirements of thermal functions of clothing may include heat protection, moisture protection and wind protection according to the wearing situations and application fields. With the rapid development in textile material and technologies, people are paying greater attention to the thermal functions clothing, which can provide substantial thermal protection for the human body.

2.3 DEFINITION OF THERMAL ENGINEERING DESIGN OF CLOTHING

The above section has discussed the factors influencing the thermal comfort of human body and the thermal protection functions of clothing provided to guarantee thermal comfort. The theoretical developments of physics, chemistry related to textile and clothing, physiological thermoregulations of the human body, and the dynamic interactions between the clothing and body lead to thermal engineering design of clothing to achieve desirable thermal functions. Thermal engineering design of clothing is the application of a systematic and quantitative way of designing and engineering of clothing with the inter-disciplinary combination of physical, physiological, mathematical, computational and software science, and engineering principles to meet with the thermal biological needs of protection, survival and comfort of human body.

In the concept of clothing thermal engineering design, the achievement of thermal functions of clothing needs a clear understanding of the physical and biological mechanisms of the complex clothing wearing system. From this point of view, it is important to identify the relationships between the functions and corresponding physical behaviors. Figure 2.4 shows the corresponding relationships between the thermal functions of clothing and physical behaviors. All the thermal functions are directly related to the physical mechanisms of moisture and heat transfer processes. For instance, the water content as discussed in Section 2.2.2 is related to the behaviors of liquid transfer, moisture sorption/desportion, and moisture condensation/evaporation, and the thermal insulation is influenced by conductive heat transfer in most cases, convective heat transfer in intensive ventilation conditions, radioactive heat transfer in the domain of strong radiation resource, and the water content of textile which may reduce the thermal insulation.

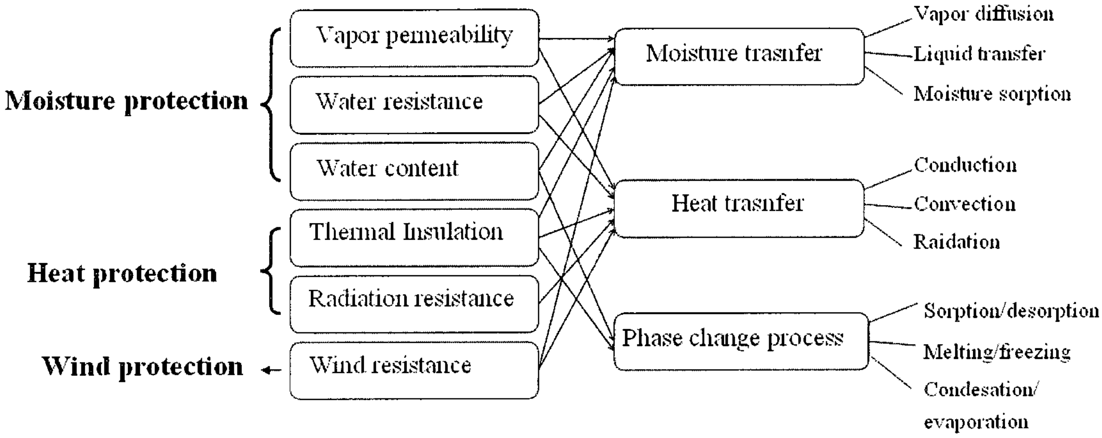


Figure 2.4 Relationships between the thermal functions and thermal physical behaviors

However, in the practice, all the thermal functions of clothing are realized by using the textile material and construct method. The flexibility but complexity of clothing lies in the use of different materials and treatments and multiple layers in which each is possibly designed for a specific function and works in conjunction with adjacent layers. There may be various design schemes to achieve similar thermal performance while the most appropriate one should be easily achieved and make a good balance between flexibility and complexity. Due to this concern, the attributes of clothing, which may influence its thermal performance, need to be summarized. Table 2.2 lists the attributes of clothing in terms of geometrical, structure, fluid and physical and their features in design process.

Table 2.2 Attributes of clothing

Features of clothing	**Properties**	**Design notes**
Fiber properties	• Fiber diameter • Fabric thickness • Maximum pore radius • Fabric density • Fabric Weight	Controllable
Structure feature	• Number of fabric layers • Air thickness between fabrics • Phase change material coating volume • Waterproof membrane	Controllable
Fluid feature	• Contact angle of liquid • Surface tension • Vapor tortuosity • Liquid tortuosity • Effective angle of capillaries • Dynamic viscosity of liquid	Intrinsic
Fabric feature	• Thermal conductivity • Specific heat • Latent heat • Thermal emissivity of fibers • Fiber regain (hygroscopicity)	Intrinsic
Wearing features	• Style (body covering area) • Fitting (loose, tight) • Mode (open, close)	Controllable

The fluid and physical features of clothing listed in Table 2.2 are intrinsic. The relevant properties of clothing of these two features are decided by the intrinsic nature of the material, such as thermal conductivity, thermal emissivity, fiber regain, contact angle of liquid and vapor/liquid tortuosity. They are constant in the design scheme, and the designer needs to select different textile materials if different values of these properties are hoped. The geometrical, structural and wearing features are controllable, which means these features can be designed in the design scheme to control the thermal performance of final clothing product.

Though the above discussion has recognized that the thermal functions of clothing are theoretically associated to the physical behaviors and practically realized by the construct method and textile materials characterized by geometrical, structure, fluid, physical and wearing features with a variety of properties. It is still very difficult to design clothing product with desirable thermal functions without effective tools. A promising solution is provided in the strategy of thermal engineering design of clothing. It utilizes the capability of computer to input the design scheme with selected textile material, construct method and wearing scenarios and output the thermal performance of clothing and thermal status of human body in terms of various thermal and moisture distributions for the designer to make analysis and decisions, as shown in Figure 2.5.

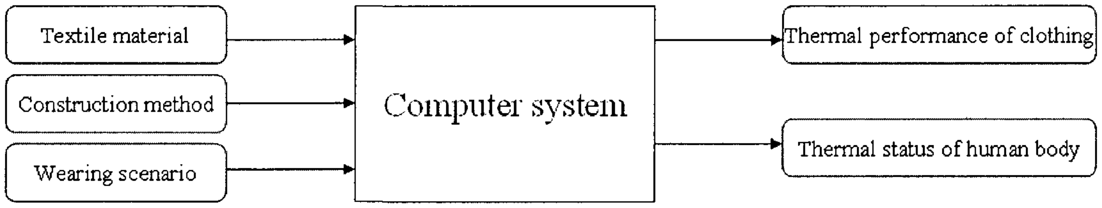


Figure 2.5 Computer system in thermal engineering design of clothing

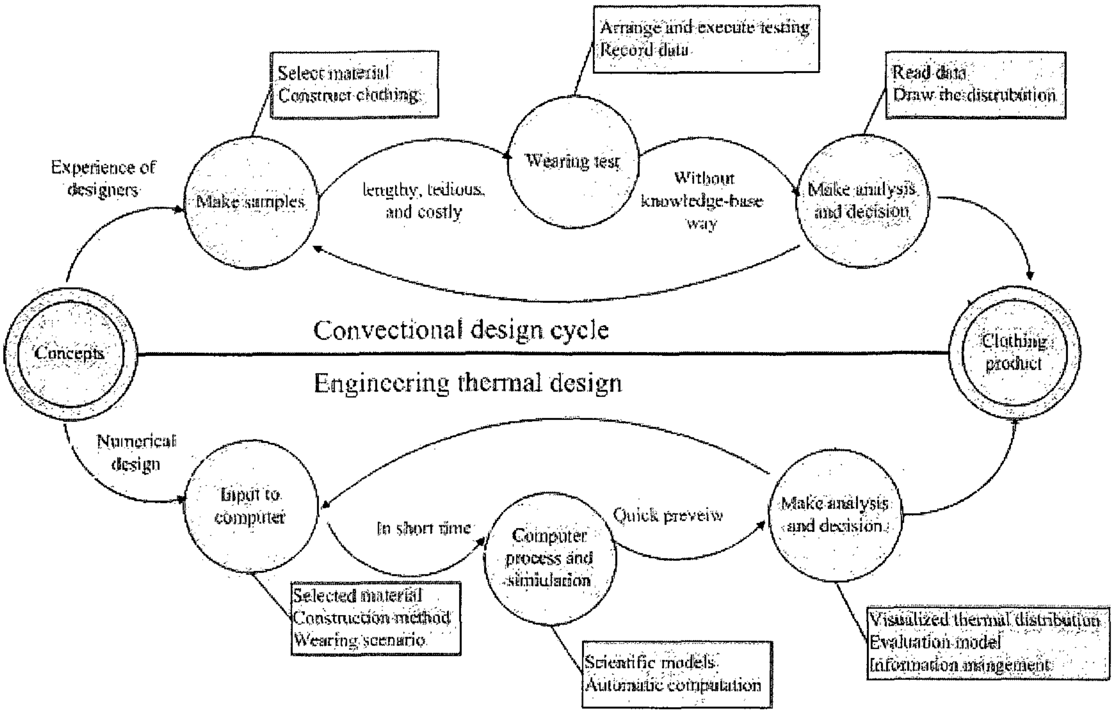


Figure 2.6 Comparison between the convectional design and engineering thermal design

This computer-aided method can benefit the design procedure with many advantages, which can not be obtained from the conventional design approach. Figure 2.6 illustrates the design cycle of clothing with thermal functions from concepts to final products in terms of conventional design procedure and thermal engineering design. From the comparison between the sectors throughout the design cycle, the thermal engineering design strategy has the following characteristics:

1) The engineering design procedure is based on the scientific model and computer simulation and management, which offers much more reliance than the experience-based conventional approach. This model-based design procedure provides the means to integrate interdisciplinary knowledge to achieve design

concepts in a scientific way.

2) The engineering design procedure greatly speeds up the design cycle by virtual simulation and preview of the thermal performance of deigned clothing in specified wearing scenarios before making any real samples, which only take a short time on the computer system, while it is a lengthy, tedious and costly process to iteratively make samples, test and verify the thermal functions of samples in the conventional approach.
3) The designer is provided with friendly visualized ways to observe and analyze the thermal distributions of the clothing and thus shorten the decision-making process to improve the design scheme. Parametric analysis of the thermal performance of clothing becomes feasible with the aid of computer tool. Meanwhile, multiple sets of predicted thermal data are effectively managed and recorded.
4) Much more freedom is offered to the designers with the engineering design strategy where they can try any materials and construct methods through numerical design, and simulate the designed clothing in any possible wearing scenarios to make explore new designs. That ability is limited in the convectional approach due to the real iterative trial of sample making and experimental testing.

2.4 MULTI-DISCIPLINARY FRAMEWORK

2.4.1 Development of the framework

The thermal engineering strategy for clothing design with specified functions is to numerically design clothing and specify wearing scenarios, scientifically analyze the predicted thermal results, iteratively make decision and improve their designs to achieve desirable functions, and then produce real products. In order to give a substance to this strategy, it is imperative to scientifically integrate the multi-disciplinary knowledge including physical, physiological, mathematical, computational and software science, and engineering principles as defined in section 2.2, and offer a friendly computer-aided system to the user. Therefore, a multi-disciplinary framework needs to be developed to facilitate the knowledge integration and relationships across different disciplines.

Before building such a framework, it is necessary to have an overview on the thermal behaviors that happen in the clothing wearing system, which is illustrated in Figure 2.7. As reviewed in section 1.2.1, the following thermal behaviors involved in the clothing wearing system need to described with mathematical models to be simulated by the computer system.

1) Heat and moisture transfer behaviors in fibers, fabrics and garments including their interactions and the influence from phase change materials and various functional treatments;
2) Thermoregulatory behaviors of human body responding to various external

environments;

3) Interactions between the boundaries of clothing, human body and environment;

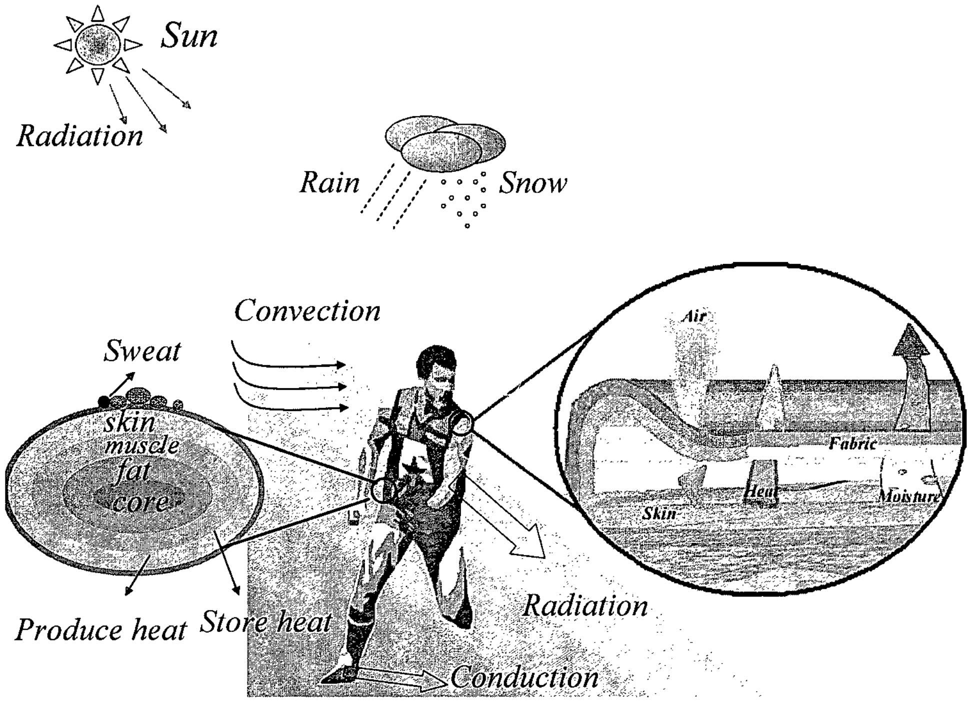


Figure 2.7 Thermal behaviors of clothing wearing system

With the numerical expression of these thermal behaviors, the thermal performance of clothing can be previewed by the computational simulation, and the CAD technologies are applied to enable this engineering design strategy to become a friendly and powerful tool for the general user who may have little specialized knowledge.

Figure 2.8 shows the multi-disciplinary framework of clothing thermal engineering design, which demonstrates the relevant knowledge and technologies initiating from diverse fields and their roles and relationships. It can be observed that the computational simulation and computer aided system are the two predominating sectors in the central position.

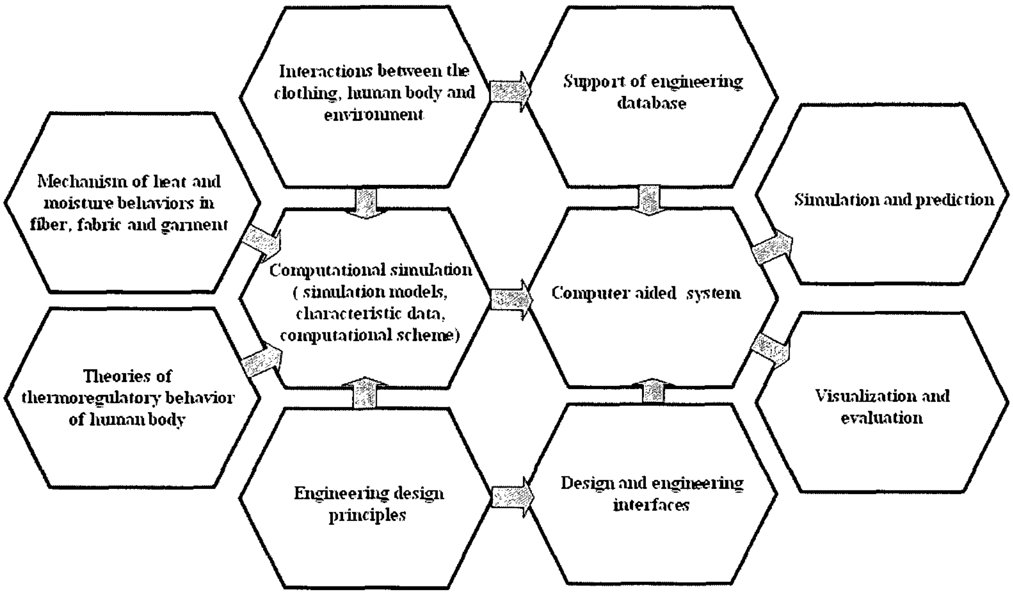


Figure 2.8 Multi-disciplinary framework of clothing thermal engineering design

Computational simulation is on the basis of the development of mechanisms, theories and models to describe the thermal and moisture behaviors of fibers, fabrics and garments and thermoregulatory behaviors of human body as well as the dynamic interactions between clothing/human body/environment. Meanwhile it incorporates the design principles into the simulation which is the laws, standards, practices and codes mostly coming from the experience of designers in the decision making process. This sector consists of the charactering data, simulation models and computational algorithms to implement the computational simulation of clothing wearing system.

The computer-aided system in this framework is to offer a friendly and easy-to-use tool for end users to access the thermal engineering design of clothing. This system realized by CAD technologies encapsulate the complex theories and models behind the engineering design and provide a series of functionalities with graphic user interfaces to end users. This benefit greatly widens the range of potential end users who have different level of background knowledge but only understanding of simple computer operations, including scientists and academic researchers in the correlative fields, industrial designers and engineers with abundant experience of design and operation, as well as common consumers who have interest in making a wise choose for themselves when they need to buy some thermal functional products or try a functional design tour in the DIY way.

2.4.2 Computational simulation

1) Simulation models

The computational simulation of the clothing wearing system is implemented with the precondition of simulation models, which enable the numerical expression of the thermal behaviors of clothing wearing system in a computer platform. However, the simulation models applied for engineering design need to be developed considering scientific supposition, clear physical meaning and available characteristic data for robust simulation of general applications. The available descriptive models in the literature, when employed for engineering simulation, are required to be conformed to some criteria, which will be discussed in Chapter 3.

The simulation models in the strategy of clothing thermal engineering design should include descriptive models for all the thermal behaviors that happen in the clothing wearing system, as reviewed in section 2.4.1. Clothing worn on the body consists of complicated fabric assemblies, which can be hierarchically regarded in most cases as multi-garment, multi-layer fabrics, fabrics and fibers. Theoretically, the simulation models in this engineering strategy are multi-scale from the molecular level to the body-clothing system level. The multi-scale models for clothing thermal engineering design will be developed in Chapter 3

2) Characteristic data

The characteristic data of the properties of clothing, human body, environment and their relationships plays a significant role in the simulation models of the thermal behaviors and interactions in the clothing wearing system as input parameters. The successful development of the simulation models is to some extent dependent upon the characteristic properties of fibers, fabrics and garments, human body and environment and upon the characteristic variables describing the relationships between them.

The characteristic data of clothing includes the properties related to the geometrical, structure, fluid, physical and wearing features of fibers, fabric and garments, as discussed in section 2.2. The characteristic data of the human body includes the physical, physiological and psychological properties, such as the height, weight of body shape, blood flow of skin, sweating rate, core temperature and skin temperature. The interactions between the clothing, human body and environment are realized through boundary conditions which are developed with the characteristic data, including the heat and moisture exchange coefficients, thermal status of the body skin (skin temperature, sweating accumulation on skin, air pressure at skin), the inner layer of clothing (fabric temperature, fabric vapor pressure, fabric relative humidity) and air condition of environment (air temperature, air pressure, air velocity). Due to the importance of characteristic data for the description models, it is important to ensure scientific or standard methods to obtain these data.

3) Computational scheme

It is necessary to develop a computational scheme to implement numerical algorithms for the computational simulation and obtain the numerical solutions of the simulation models. Before this can happen, the numerical method to solve the simulation models involved in the scheme should be investigated and performed. For instance, the simulation models of clothing consists of a series of partial differential equations and need to be discretized with appropriate method to obtain the numerical solution.

Concerning the multi-scale models describing the thermal behaviors of clothing wearing system and the multi-layered clothing, the computational scheme will be built with multi-structure for iterative computation. Furthermore, when the clothing models are incorporated with the human body models which have different dimensions, the computational scheme is featured as being multi-dimensional. The accuracy of the simulation results is highly dependant upon the methods, the variables involved in the simulation, and the strategy applied in controlling the results accuracy. Detailed information about the computational scheme will be discussed in Chapter 4.

2.4.3 Computer-aided system

1) Design and engineering interfaces

The computer-aided system is the final tool delivered to end users to execute engineering design. It is required to provide a series of friendly design and engineering interfaces. These interfaces are developed graphically to offer direct communication between the system and the end users. Through these interfaces, the users should be able to define their problems, perform the system functionalities, and view and analyze the solution results. In order to enable the end users to effectively and easily define their problem, the design principle of clothing, such as the flow of fiber→fabric→garment, should be expressed with the interfaces, and the wearing scenario involving the factors of clothing, wearer, wearing environments and wearing activity schedule should be considered and presented to the end users through the interfaces in a life-oriented way. Namely, the user can perform the software tool in the thinking way of choosing or designing clothing just as that in their lives. Meanwhile, the input data on the interface should be provided with physical units and a valid value range to obtain a meaningful engineering value. The interfaces are also required to display the output results of the computer system to the user.

2) Support of engineering database

In the engineering design process, it is important to allow the design and specification activities to happen in a systematic way with various types of information. The support of engineering database for the computer-aided system has become crucial and significant to store, manage and utilize these types of information. An engineering database is different from a traditional database since the engineering design is based on multi-disciplinary knowledge and the engineering database needs to deal with the design principles and various types of data information (strings, numerical data, equations, diagrams, images etc.).

The engineering database supporting for this computer system should be available for the clothing design, wearer definition and scenario specification. The design principle of the garment is the hierarchical structure from fiber, fabric to garment, and this principle should be considered in the database development. The database is able to input, store and query the fundamental technical specifications of the raw materials, semi products and final products of clothing. With this engineering database, the wearer can be classified under gender, age and race, and even given the values of his or her physical and physiological parameters. And with this engineering database, the user can also specify the wearing scenarios in any expected place and time by querying the climatic information from the database. That extends the ability of the designer to custom-make thermal functional clothing for different people and different environments.

3) Simulation and prediction

With the completed clothing design and wearing scenario specification, the computer aided system will automatically configure the interior modules and implement the computational simulation. In order to enable the computational simulation, the computational scheme needs to be applied in the interior modules of the system and to automatically solve the simulation models involved in the clothing wearing system. The simulation will take a period of time, which is determined by the duration of simulated scenarios, the dimension of computational scheme, the required level of accuracy of results, and the computational capacity of computer. During the iterative computational simulation process, simulation results are continuously generated by the simulation models. These simulation results are the important basis of the computer-aided system to predict the thermal performance of the clothing and the thermo-biological response of human body during the wearing process. The thermal variables of clothing, such as the temperature, water vapor concentration, liquid water volume fraction of all the fabric layers in the clothing, and the thermal variables of human body, such as skin temperature, skin relative humidity and core temperature, can be previewed and analyzed by the end user. Due to the huge volume of simulation results, the data management in this virtual system is quite important, and also, hard work. The simulation results will be stored in a data file with a case ID and a structured file format.

4) Visualization and evaluation

Though the end user has the ability to store and retrieve simulation results, it is still a big challenge that large amounts of information can be easily generated and stored, but can not be easily turned into useful information and even knowledge. The computer-aided system requires the capacity to convert tedious result data into useful information, and to retrieve it in a timely and efficient manor. The visualization functionality of the system is hence needed to interpret the simulation results through graphical presentation to make end users easily see and understand the tedious output data. Both 2D/3D graphic charts and 3D animation can be applied to present the simulation results. With 2D/3D graphic charts, the simulated distributions of the thermal variables of fiber, fabric and human body can be observed in temporal or/and spatial coordinates. With 3D animation, the values of the thermal variables of clothing and human body are dynamically mapped onto the 3D objects with corresponding colors in real-time and the user can easily compare the thermal distributions of clothing and human body by color changing. Through these graphic presentations of the simulation results, the user is able to evaluate if the thermal performance of designed clothing is suitable for the specified wearing scenarios, and scientifically obtain feedback to iteratively improve the design before the production of the real clothing.

2.5 CONCLUSION

In this chapter, the thermal comfort of human body and thermal functions of clothing is systemically analyzed before the development of the framework of clothing thermal engineering design. The thermal comfort of the human body, resulting from the thermal biological balance between the body and environment is related to environment (air temperature, mean radiant temperature, air velocity, air humidity), activity level and insulative clothing. Clothing is the most common and frequent choice in the daily life by the wearer to achieve substantial thermal comfort. That requires the clothing to have various thermal functions to protect the human body from various wearing environment, including thermal protection, moisture protection and wind protection. However, these functions of clothing are quite difficult to be achieved only by the iterative trial and error method and without any scientific analysis. It requires a strategy of clothing thermal engineering design based on multi-disciplinary knowledge to achieve the final products with superior thermal functions. By the analysis of the association of the thermal functions of clothing with the physical thermal behaviors and the textile features, a clothing thermal engineering design system is required to remove the distance from complex theories to final products and deliver a friendly platform for the general end users who have difference levels of background knowledge to access the engineering strategy with many advantages.

The multi-disciplinary framework of clothing engineering design is developed to fill the knowledge and technologies gaps and work out the relationships and communication between them. From the framework structure, it can be found that the computational simulation and computer-aided system play central roles in the engineering design. The computational simulation is based on the mechanisms, theories and models of the relevant thermal behaviors and significantly dependent on the charactering data, simulation models and numerical algorithms. The computer-aided system encapsulating the complex knowledge provides a series of user-friendly interfaces and functionalities to end users to easily achieve their design, including design and engineering interfaces, support of engineering database, simulation and prediction, visualization and evaluation.

CHAPTER 3 MULTI-SCALE MODELS FOR CLOTHING THERMAL ENGINEERING DESIGN

3.1 INTRODUCTION

In Chapter 2, the strategy of clothing thermal engineering design has been systematically described and the multi-disciplinary framework of clothing thermal engineering design has been proposed by building up communication/relationship between different disciplines involved. It has been identified that the computational simulation and the computer-aided system are the key components in the strategy. The simulation models, which express the theories and mechanisms of the thermal behaviors in the clothing wearing system, enable the computational simulation in clothing thermal engineering design, and the clothing thermal performance during various wearing scenarios is thus possible to be predicted and previewed numerically. This makes a big difference from the convectional design approach, in which the thermal performance of clothing can not be evaluated without making the real garment and testing its performance.

Many theoretical mathematical models have been developed for investigating the mechanisms of thermal behaviors in textile and clothing, human body and also the clothing-human body system, as reviewed in Chapter 1. However, these models are confined to individual physical processes or topical interactive phenomena, and there is still a long way to go before they are effectively applied to engineering design. The description models for clothing thermal engineering design should be able to symmetrically express all possible thermal behaviors in the clothing wearing system and model this complex multi-scale system from the molecular to the body-clothing level.

In this Chapter, a set of criteria is first developed and discussed for selecting the models to be applied to clothing thermal engineering design. These criteria will be used to evaluate the existing models to find out whether they are suitable for engineering applications. Subsequent to that, the multi-scale models expressing the thermal behaviors involved in the clothing wearing system are integrated, and the data availability of the parameters in the models are investigated and realized for engineering applications. Finally, the boundary conditions and initial conditions of the models are built up for obtaining the models' solution.

3.2 CRITERIA FOR MODEL SELECTION

The mathematical models create the possibility to simulate the thermal behaviors of clothing wearing system with characteristic data and controllable configuration, and to output the values of thermal variables of interest in temporal and spatial coordinates. With the power of computer, mathematical models gradually build up their important roles in various engineering fields through the execution of numerical simulation. However, the feasibility and accuracy of numerical simulation in engineering applications depends upon which description models are employed, and not all the models can be utilized in the engineering design purpose to perform numerical simulation or are suitable for the framework of the engineering design. During the development process of these models, a number of hypotheses and assumptive conditions have been made to address the special issues, which may result in that the model is confined to the special situations. Furthermore, if the hypotheses and assumptive conditions are not scientific and clear, it is difficult for the models to generate reliable simulation results and deal with practical problems. Meanwhile, the models without available input data can only be used by the readers as reference rather than applied to their own situations. The capacity of the models will not benefit the readers in solving engineering problems.

It is necessary to develop a set of criteria to evaluate the potential/suitability of the models for being directly applied to engineering design or being selected as the component of integrated models for the clothing wearing system. Following paragraphs report on the criteria respectively for selecting the models of heat and moisture transfer processes in the textile and clothing, the models of the thermoregulatory system of the human body and the models of the integrated clothing-human body system.

For the models of the heat and moisture transfer processes in textile and clothing, the criteria include the following aspects:

1) Are the physical models developed with clear physical meanings such as reasonable

scientific hypotheses? Are the parameters in the models related to the real structural and physical properties/process of the materials? Are the parameters involved in the models measurable in industrial engineering processes?

2) Is the development of the models standardized in terms of correct and scientific definitions of variables and units?
3) Are the numerical simulations in fact related to the real industrial practices or are they just academic assumptions?
4) Can the models and simulations results be verified / validated by independent third parties?
5) Are the simulation programs suitable for industrial participants to use in designing and engineering their products and validating their predictions and simulation results? This concern is specially responding to the models which are provided with simulation programs.

For models of the thermoregulatory system of human body, the criteria include the following aspects:

1) Are the models standardized and do they have clear physical and physiological meanings? Can they be validated and used by independent third parties?
2) Can the models interact closely with the clothing models in term of the boundary conditions and fully respond to the dynamic heat and moisture transfer processes in the clothing such as the temperature and relative humidity of the clothing?
3) Can the output variables of the models and the detailed level of information reflect

the thermo-physiological status of the body that can be utilized to analyze the thermal performance of the clothing?

4) Is the computation load of the models integrated with the clothing models reasonable for allowing computer simulation in the capacity of personal computer?

For the models of integrated clothing-human body system, the criteria include the following aspects:

1) Are the simulation algorithms/programs user-oriented/user-friendly as simulation tools?
2) Are the simulation programs developed with a clear engineering design framework and industrial specific language?
3) Are the simulation programs supported by a good engineering database that contains the fundamental technical specifications of the raw materials, semi products and final products?

From the above description, it can be seen that the main focuses of the criteria are placed on the model hypotheses, data availability and application feasibility of the models. According to these developed criteria, a critical analysis of the well-known models of textile and clothing, human body and integrated clothing-human body system is performed as respectively illustrated in Table 3.1~3.3. As shown in Table 3.1, the models describing different thermal mechanisms in textile and clothing, including the basic heat and moisture transfer in the fabric, moisture sorption in the fiber, condensation/evaporation, liquid transfer in the fabric, pressure effect, membrane thermal function, phase change material thermal process and radiation process, have been reviewed and can get the view of their performance under the criteria. Some of them, for example, Li and Luo's model for moisture sorption in the fiber, Li and Zhu's model for liquid transfer in the fabric, Li et al.'s model for pressure model, Wang and Li's model for membrane and Li and Zhu's model for phase change material, are more suitable to be employed for engineering design. Similar analyses have been made for the thermoregulatory models of the human body, as shown in Table 3.2. The differences among the thermoregulatory models of Gagge, Stolwijk and George are mainly the division of the human body and the performance of the model in cooperation with the clothing model. The critical analysis in Table 3.3 shows the existing models of integrated clothing-human body system are difficult for the general user in engineering design. It is necessary to select the models for clothing thermal engineering design in a systematic way under these criteria.

Table 3.1 Critical analyses of the description models relevant to textile materials

Models	Hypotheses /application limitations	Key governing equations	Availability of parameters /variables	Models validation and application
Basic heat and moisture transfer in the fabric				
Henry's model[35]	• Coupled heat and moisture transfer • Ignored fiber moisture sorption	$\frac{\partial C_f}{\partial t} = const. + a_1 C_a + a_2 T$	• C_f is linearly dependent on T and C_a • Const a_1 and a_2 are used to adjust the prediction results and are empirically evaluated	Only valid over small ranges of the conditions

Farnworth's model[40]	• Multi-layered clothing systems • Enclosed air layer act as resistances to heat and moisture flow • Sorption and condensation were considered	$\frac{dM_i}{dt}=\frac{P_{i-1}-P_i}{R_{Vi-1}}-\frac{P_i-P_{i+1}}{R_{Vi}}$ $\frac{M_{ai}}{M_{fi}}=\gamma_i\frac{P_i}{P_s(T_i)}$	• Absorbed water is steadily related to pressure by fabric regain • The fabric regain is supposed with a simple approximate form in the model	• Validated with data measured from apparatus • Inherited into other research work • The model is linear and can not applied to transient dynamic process
Gibson's model [38]	• Pressure drop and RH varies across the fabric • The steady diffusion and convection process was investigated	$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{v})=0$ $\rho\frac{D\vec{v}}{Dt}=\rho\vec{g}+\nabla\cdot T$ $\rho\frac{Dh}{Dt}=-\nabla\cdot\vec{q}+\frac{Dp}{Dt}+\nabla\vec{v}:\tau+\phi$	• Volume-averaged approach is applied and three volume averages are defined	Obtained good agreement with the experimental temperature profiles of the materials
Moisture sorption in the fiber				
Nordon and David's model [22]	• Based on Henry's model • Exponentially describe the change rate of water content in fibers	$\frac{1}{\varepsilon}\frac{\partial C_f}{\partial t}=(RH_a-RH_f)\chi$ $\chi=k_1\left(1-e^{k_2\|RH_a-RH_f\|}\right)$	• k1, k2 are adjustable parameters and evaluated by comparison between prediction and measured moisture content of fabric	First generated numerical solution with computer computation
Holcombe, Li and Luo's models [9-10]	• Coupled heat and moisture transfer • Water vapor two-stage sorption of wool fiber	$\frac{\partial C_f(x,r,t)}{\partial t}=$ $\frac{1}{r}\frac{\partial}{\partial r}(rD_f(x,t)\frac{\partial C_f(x,r,t)}{\partial r})$ $D_f(x,t)=f(W_c)$	• *Wc* is the water content of fibers and can be calculated from C_f • D_f is clearly defined with physical meanings and can be measured through a sort of experimental apparatus • The moisture sorption by fibers (*Wc*) can be measured	• Validated by comparison between simulation and experimental results • Applied in other models
Condensation/evaporation models				
Ogniewicz and Tien's model [36]	• Heat is transported by conduction and convection • The condensate is in pendular state • Ignored fiber moisture sorption	$\rho_a u\frac{dW}{dx}=\rho_a D_0\frac{d^2W}{dx^2}-\Gamma$ $\rho_l\Phi\frac{\partial\theta}{\partial t}=\Gamma$	• The condensate rate (Γ) and the accumulated liquid saturation (θ) are identically zero in dry zone • In wet zone vapor concentration is given with saturation relation	Not applicable for the case with frosting and small moisture accumulation
Murata's model [34]	• The condensate falling under gravity and convective heat transfer were consider	$\frac{d}{dy}(\rho_L v_{LF}\delta_{LF})=(\rho_G u_G)_i$	• At the boundaries of the fibrous slab, $\delta_{LF}=\delta_{LF,cr}$ • δLF,cr is critical film thickness	a steady state model; prediction agrees well with the experimental one

			with condensation	
Fan and Luo's model [41]	• Heat and moisture transfer with sorption and condensation • Heat transfer by conduction and radiation is built into the mode	$\Gamma(x,t)=(\frac{D_a}{\tau}\frac{\partial^2 C_a^*(x,t)}{\partial x^2}$ $-\frac{\partial C_a^*(x,t)}{\partial t})$ $\partial C_a^*(x,t)=216.5\times Vap(T(x,t)\times 10^6)$ $/T(x,t)$	• C^*_a is saturated water vapor concentration of the fabric • T is the temperature of fabric • Vap is the vapor pressure under certain temperature	Distinguished from the fiber sorption and adsorption process
Liquid transfer models in the fabric				
Motakef's model [37]	• Immobile and mobile condensate in porous slab • Critical liquid content as the phase change condition	$\rho_c\varepsilon\frac{\partial\theta}{\partial t}=$ $\rho_c\varepsilon\frac{\partial}{\partial x}\left(D_l(\theta)\frac{\partial\theta}{\partial x}\right)-\Gamma_{\mathrm{lg}}$	• Immobile condensate, D_l is equal to 0 • Mobile condensate: D_l is set a mean value for mathematical simplicity	• Validated for immobile and mobile condensates • Inherited into other research work
Fan and Wen's model [117]	• Coupled heat and moisture transfer • Radiation effect existing • Liquid diffusion coefficient is constant	$\rho(1-\varepsilon)\frac{\partial(W-W_f)}{\partial t}=$ $\rho(1-\varepsilon)D_l\frac{\partial^2(W-W_f)}{\partial x}$ $+\Gamma(x,t)$	• D_l is assumed with a constant value referred to previous research • The diffusive equation can be only applied when $W>Wf$	Validated by the comparison with results of Farnworth's model
Li and Zhu's model[118]	• Coupled heat and moisture transfer • Liquid diffusion by capillary actions • Condensation/evaporation • Ignored radiation effect	$\frac{\partial(\rho_l\varepsilon_l)}{\partial t}+\varpi_2\frac{\partial(C_f\varepsilon_f)}{\partial t}$ $+h_{l\to g}S_v^{'}[C^*(T)-C_a]=$ $\frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l(\varepsilon_l)\frac{\partial(\rho_l\varepsilon_l)}{\partial x}\right)$ $D_l(\varepsilon_l)=\frac{3\sigma\cos\phi\sin^2 ad_c\varepsilon_l}{20\eta\varepsilon}$	• D_l has clear physical definition and is a function of the properties of fiber, liquid and fabric structural properties • The liquid transfer process can be characterized and measured with MMT equipment	Validated by comparison between simulation and experimental results
Pressure effect models				
Li et al's model[49]	• Pressure gradient influences the movement and diffusion of liquid water in void space of inter-fibers	$\frac{\partial p_c}{\partial x}=-\frac{2\sigma\cos\phi\varepsilon}{\varepsilon_l^2 d_c}\frac{\partial\varepsilon_l}{\partial x}$	• P_c has direct relationship to capillary action • The value of parameters can be obtained	Validated by comparison with the experiments results in reference
Membrane model				
Wang and Li's model[54]	• Waterproof breathable fabric • Decrease the heat and moisture transfer at the out boundary	$H_{mn}=\frac{1}{W_n+\frac{1}{h_{mn}}}$ $H_{cn}=\frac{1}{R_n+\frac{1}{h_{cn}}}$	• W_n and R_n are measure properties of waterproof membrane	Validated with different waterproof fabric and analyzed its effect on heat and moisture transfer
Phase change material model				

Li and Zhu's model [58]	• Micro-PCM microcapsules are embedded in porous textiles • Micro-PCM is considered as a sphere consisting of solid and liquid phases	$\dot{q}(x,t)=\frac{-\frac{3\varepsilon_m}{R_m}h_T K_m\left(T_p-T(x,t)\right)}{h_T R_m\left(\frac{R_m}{r_l(x,t)}-1\right)+K_m}$ $\dot{r}_l=\frac{h_T\frac{K_{ml}R^2{}_m}{\rho_m\lambda_m}\left[T_p-T(x,t)\right]}{h_T R_m^2 r_l+\left(K_{ml}-h_T R_m\right)r_l^2}$	• $\dot{q}(x,t)$ is the heat rate from PCM microcapsules • R_m, K_l,, h_T, R_m, T_p are measurable properties of PCM material	Validated with different amounts of PCM using the finite volume method
Radiation model				
Fanworth' model [17]	• When the radiation depth is similar to the thickness of fabric, the radiation heat can not be ignored and is comparable to conductive heat	$\frac{\partial F_R}{\partial x}=-\beta F_R+\beta\sigma T^4$ $\frac{\partial F_L}{\partial x}=\beta F_L-\beta\sigma T^4$	• F_L and F_R is the total thermal radiation incident on the element traveling to the left and right direction • β and σ are radiation constant	• Validated with experimental data • Applied in other models

Table 3.2 Critical analyses of the thermoregulatory models of the human body

Models	Hypothesis /application limitation	Parameters/data availability in the models	Cooperation with clothing model	Model validation and application
Gagge's model [119]	• Body is composed by two nodes • The two nodes communicate by blood flow • The thermal status of body is in whole level	• Physical data of body can be directly measured • Neutral physiological data can be obtained form the reference	• One-dimensional interactions by temperature and air pressure • Computational load is small • Give a overall view of clothing performance	• Validated with published experimental data • multiply employed in other model and research
Stolwijk's model [68]	• Body is composed by six sections and each section have four layers • The thermal status of body is extended to 6 sections • The thermal status of each section is uniform	• Listed out the used geometrical and physiological parameters and constants	• Multi-part interactions by temperature and air pressure • Computational load is moderate • Give a multi-part view of clothing performance	• Validated by simulation of the experiments with a man • Employed in the model of thermal comfort evaluation
George Fu's model [71]	• Body is composed by multi-elements • The thermal status of body is detail to each element • The thermal status of body is not uniform on each element any more	• Got the geometrical and physiological parameters and constants from Smith's model and listed out	• 3D interactions by temperature and air pressure • Computational load is large • Give a 3D view of clothing performance	• Validated with the data from others' experiments

Table 3.3 Critical analyses of the models of integrated clothing-human body system

Models	User-friendly	Developed with framework	Supported with engineering database
Jones's model [85]	Data is not available	NO	NO
Li and Holcombe's model [87]	Difficult for general user	NO	NO
Li et al's model [77]	Difficult for general user	NO	NO

3.3 MULTI-SCALE MODELS ASSEMBLY

The thermal behaviors of clothing wearing system, as summarized in Section 1.2.1, actually are in different scales, namely, the heat storage process of PCM micro-encapsulation is in nm-scale, fiber moisture sorption/desorption is in μm-scale, the fabric heat and mass transfer process is in mm-scale, and the thermal regulation of human body and thermal interactions between the human body and fabric is in m-scale. The models for describing the behaviors in clothing wearing system are therefore multi-scale, whose scale structure is illustrated in Figure 3.1. It can be observed that the differences in scale are 1000 times between the levels. This section focuses on the integration of multi-scale models for clothing thermal engineering design.

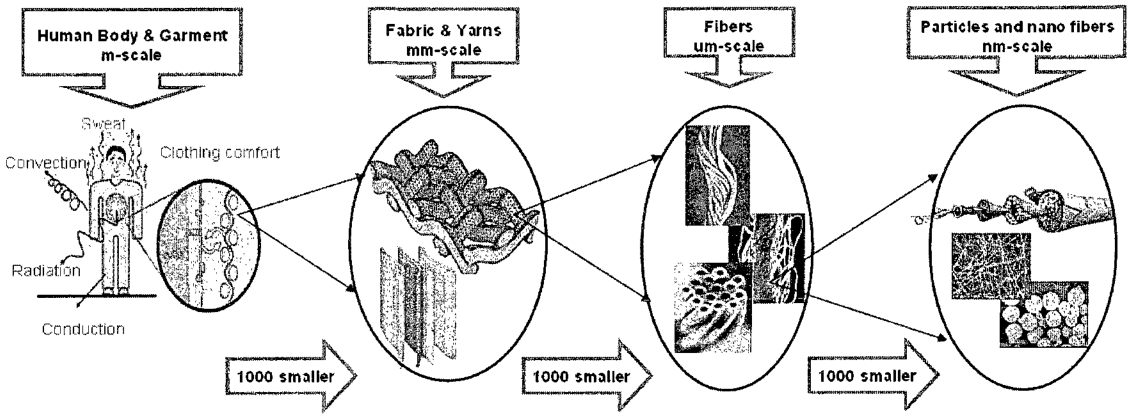


Figure 3.1 Multi-scale models for clothing thermal engineering design

3.3.1 Micro-encapsulated PCM heating model

The incorporation of micro-encapsulated PCM in textile fabrics by wet spinning process or coating on the fabric surface aims to improve the fabric's thermal performance during temperature change in different environmental conditions [120]. As reviewed in Section 1.2.2, the PCM is able to release/absorb energy by phase change between solid and liquid to prevent the temperature of the fabric dramatically changing when the fabric is exposed to a clod/hot environment. Once the PCM has been completely crystallized/melted, the thermal effect on the fabric can not sustain any more. The contribution of PCM micro-encapsulation to the thermal performance of fabric depends on the phase change temperature, the amount of encapsulated PCM and the energy generated/consumed during the phase change process. The amount of encapsulated PCM can be taken into account in the structural properties of fabric, which will be discussed in Section 3.3.3. The micro-encapsulated PCM can be regarded as a sphere consisting of solid and liquid phases and the rate of energy released/absorbed by PCM can be modeled in the radial coordinate with reference to Li and Zhu' model [77].

$$\dot{q}(x,t)=\frac{-\frac{3\varepsilon_m}{R_m}h_T K_{ml}\left(T_p-T(x,t)\right)}{h_T R_m\left(\frac{R_m}{r_l(x,t)}-1\right)+K_{ml}} \qquad \textit{Crystallization process} \qquad (3.1)$$

$$\dot{q}(x,t)=\frac{-\frac{3\varepsilon_m}{R_m}h_T K_{ms}\left(T_p-T(x,t)\right)}{h_T R_m\left(\frac{R_m}{r_l(x,t)}-1\right)+K_{ms}} \qquad \textit{Melting process} \qquad (3.2)$$

$$r_l(x.t)= h_T\frac{K_{ml}R_m^2}{\rho_m\lambda_m}\left[T_p-T(x,t)\right] \Big/ \left[h_T R_m^2 r_l+\left(K_{ml}-h_T R_m\right)r_l^2\right] \qquad (3.3)$$

Where, the parameters used in the thermal model of PCM can be obtained their values as illustrated in Table 3.4.

Table 3.4 Parameters in PCM heating model

Parameters	Physical meaning	Data availability	Unit
ε_m	Volume proportion of PCM in fabric	Technical parameter	Percentage
R_m	Radius of micro-spheres of PCM	Measurement [121]	m
h_T	Heat transfer coefficient between the micro-spheres and the flows surrounding them	Determined by the internal geometry and the structure of the fabric	W/m^2 K
K_{ml}	Thermal conductivity of liquid PCM	Property of material	W/m °C
K_{ms}	Thermal conductivity of solid PCM	Property of material	W/m °C
T_p	Melting point of PCM	Property of material	K
ρ_m	Density of PCM	Property of material	kg/m^3

λ_m	Latent heat of fusion of PCM	Property of material	kJ/kg

3.3.2 Fiber moisture absorption/desorption model

Textile fabrics consist of solid fibers, gaseous mixture of water vapor and dry air, and liquid water in the void space, which, regarded in microscope view, have many microclimates for moisture exchange between the fibers assemblies and the surroundings. The moisture in the air will be continuously absorbed onto the fiber surface and into the fiber material until the fiber becomes saturated with respect to its hygroscopicity, as reviewed in Section 1.2.2. In the saturated state, the additional moisture may condense as liquid on the fiber surface. The amount of absorbed/desorbed moisture by fibers depends on the relative humidity of the surrounding microclimate and the fiber type. Meanwhile, a certain amount of energy will be released during the process of water vapor absorbed onto the fiber surface. Similarly, the same amount of energy must be consumed when moisture is desorbed from the fiber. The absorption/desorption behaviors of fibers make the heat and moisture transfer in fabric coupled during the transient process. It has been identified that the moisture absorption/desorption is a two-stage process, in which the first stage can be represented by Fickian diffusion and the second-stage is much slower and follows an exponential relationship[25]. The uniform mathematical expression of the absorption/desorption process can be given by adopting Li and Luo's model [27].

$$\begin{aligned} &\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rD_f(x,t)\frac{\partial C_f(x,r,t)}{\partial r}) \quad \textit{fiber interior point} \\ &C_{fs}(x,R_f,t) = f(H(x,t),T(x,t)) \quad \textit{fiber surface point} \end{aligned} \qquad (3.4)$$

Where, r denotes the radius of fiber in radial coordinate, H and T respectively are the relative humidity and temperature in the surrounding microclimate, whose values are decided by the relative humidity and temperature contributions of the fabric. The value of other parameters can be obtained as illustrated in Table 3.5.

Table 3.5 Parameters in fiber moisture sorption/desorption model

Parameters	Physical meaning	Data availability	Unit
R_f	Radius of fiber	Property of material	m
D_f	Diffusion coefficient of water vapor in fibers	Calculation	m^2/s
ρ_f	Density of fiber	Property of material	kg/m^3

The diffusion coefficient of water vapor in fibers (D_f) in the two sorption stages can be calculated corresponding to a quadratic function and a attenuates function of the water content (W_c), which is the product of moisture concentration of fiber (C_f) and fiber density (ρ_f).

$$\mathrm{D_f}(x,t) = \begin{cases} 1.04 + 68.2W_c - 1342.592W_c^2 \times 10^{-14} & t < 540s \\ 1.6164(1 - \exp(-18.163 \times \exp(-28 \times W_c))) \times 10^{-14} & t \geq 540s \end{cases} \qquad (3.4)$$

3.3.3 Fabric dynamical heat and moisture transfer model

The heat and moisture transfer processes in textile fabrics continually happen when there is temperature difference and moisture pressure gradient across the fabric structure. The behaviors involved and their occurrence forms have been reviewed in Section 1.2.2. The heat and moisture transfer processes in the transient process are dynamically coupled resulting from the phase change phenomena that are associated with the presence of micro-encapsulated PCM in the fabric, the moisture absorption/desorption behavior of fibers, and the moisture condensation/evaporation in the air in the void space. The micro-encapsulated PCM thermal model and the fiber moisture absorption/desorption model have been respectively developed and discussed in Section 3.3.1 and Section 3.3.2.

Condensation in the fabric medium will take place anywhere when the local vapor pressure exceeds the saturation vapor pressure at that location temperature. However, if the vapor pressure of the boundary formed between the liquid and air in void is higher than that of the air, evaporation may occur. It has been found that there is a linear relation between saturated water vapor pressure and temperature, and higher temperature leads to higher saturated vapor pressure [122]. Due to this reason, condensation is more likely to occur in the colder location of the fabric. Concerning this physical mechanism, Li and Zhu's model can be used to mathematically express of the condensation/evaporation rate [45]:

$$\Gamma_{lg} = \frac{\varepsilon_a}{\varepsilon} h_{lg} S_v \left(C^*(T) - C_a\right) \tag{3.5}$$

Where, Γ_{lg} is the rate of condensation/evaporation, $C^*(T)$ is the saturated water vapor concentration at the local temperature and C_a the water vapor concentration at the fiber surface. The other parameters in the expression can be obtained as illustrated in Table 3.6.

Table 3.6 Parameters in condensation/evaporation model

Parameters	Physical meaning	Data availability	Unit
ε_a	Volume proportion of vapor moisture in fabric	$\varepsilon_f + \varepsilon_a + \varepsilon_f + \varepsilon_m = 1$	Percentage
ε_f	Volume proportion of fibers in fabric	$\rho_{fabric} / \rho_{fiber}$	Percentage
ε	Porosity of fabric	$1\text{-}\varepsilon_f$	Percentage
h_{lg}	Mass transfer coefficient for evaporation and condensation	Physical coefficient [47, 123]	m/s
S_v	Surface volume ratio of the fiber	$2/R_f$	1/m

The condensation/evaporation phenomena have a close relation with the temperature, water vapor and liquid distribution of the fabric. Meanwhile, the volume of water vapor/liquid phase caused by condensation/evaporation and the energy released/consumed in this process turns out to be an important source in the heat and moisture governing equation. The dynamical heat and moisture model of textile fabrics, when taking account of the effect of atmosphere pressure gradient, will include the governing equations of vapor moisture, liquid water, heat transfer and dry air pressure.

Vapor moisture governing equation

The vapor moisture diffusion in textile fabrics is determined by the resultant of behaviors of fibers and the air in voids. Under certain vapor concentration and total gas pressure gradients, the moisture flux across the textile material is contributed by the diffusion process through the air voids, which basically decides the vapor moisture concentration of the textile fabrics. The moisture absorption/desorption behaviors of hygroscopic fabric also affect the vapor moisture concentration of the fabric, taking account of the absorbed/desorbed vapor moisture. The governing equation of the vapor moisture transfer process is given based on the First Fick's law [20] and the Li and Luo's two-stage absorption model [24] and Li et al.'s pressure model [49].

$$\frac{\partial\ (\varepsilon_a C_a)}{\partial t}=\frac{D_a \varepsilon_a}{\tau_a}\frac{\partial^2 C_a}{\partial x^2}+G_a\frac{\partial^2 p_s}{\partial x^2}+\varpi_a \varepsilon_f\frac{\partial C_f}{\partial t}+\Gamma_{\mathrm{lg}} \tag{3.6}$$

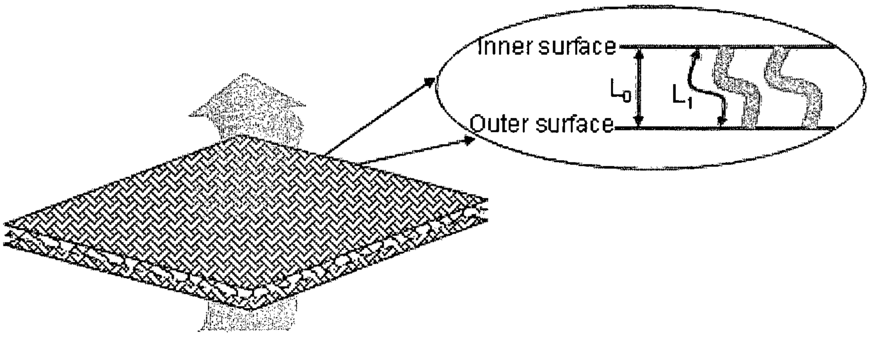
Where, $G_a\frac{\partial^2 p_s}{\partial x^2}$ is the mass flux of water vapor under total atmospheric pressure gradient. $\frac{\partial C_f}{\partial t}$ is the moisture sorption/desorption rate of fibers, which has been formulated in Equation 3.4, Γ_{lg} is the condensation/evaporation rate, which has been given in Equation 3.5. The parameters of this equation can be obtained their values as illustrated in Table 3.7.

Table 3.7 Parameters in vapor moisture conservation equation

Parameters	Physical meaning	Data availability	Unit
ε_l	Volume proportion of liquid moisture in fabric	$\varepsilon_l+\varepsilon_a+\varepsilon_f+\varepsilon_m=1$	Percentage
ϖ_a	Proportion of the sorption of water vapor at fiber surface	$\frac{\varepsilon_a}{\varepsilon}\cdot\varepsilon_f$	Percentage
τ_a	Vapor diffusion tortuousity, actual diffusion path deviated from the straight distance	Effective value	Ratio
D_a	Vapor diffusion coefficient	Constant property [124]	m^2/s

	of air		
G_a	Coefficient of pressure gradient to water vapor flux	$C_a \frac{3\varepsilon sin^2 ad_c^2}{80\mu_a}\left(1-\left(\frac{\varepsilon_l}{\varepsilon}\right)^3\right)$	
a	The effective angle of the capillaries in the fabric	Effective value	degree
d_c	Largest effective radius of the pore in fabrics	Material property [46, 125]	m
μ_a	Dynamic viscosity of vapor	Constant property	kg/ms
D_{fab}	Vapor diffusion coefficient in fabric	$\frac{WVP \cdot L}{\Delta C}$	m^2/s
WVP	Water vapor permeability	Measurement method [53]	$g/m^2/day$
L	fabric thickness	Material property	m
ΔC	Water vapor concentration between the two sides of fabric	Measurement method [53]	g/cm^3

Due to the complex structure of textile fabrics, the properties of vapor diffusion tortuosity (τ_a) and effective angle of the capillaries in fabric (a) are difficult to be directly measured or calculated. Considering this, their effective values are specified with other measurable properties by analyzing the relative physical mechanisms. The effective angle of the capillaries in fabric (a) will be discussed and described its calculation method in next subsection. The vapor diffusion tortuosity (τ_a) is assumed to be equal to the ratio of vapor moisture diffusivity in air (D_a) to that in fabric (D_{fabric}) which can be calculated by the measurable property of fabric water vapor permeability (WVP).



$$\tau_a = \frac{L_1}{L_0} = \frac{D_{fab}}{D_a} \qquad (3.7)$$

Liquid water governing equation

The liquid water diffusion in textile fabrics is typically a wetting and wicking process, namely, the liquid will wet the fabric surface before being transported by capillary action through the fabric [29]. Wetting of fibrous assembly is a complex process, which is completed with the condition depending on the geometrical parameters of fibers and liquid body, the number of fibers, and the liquid surface tension. The transport of a liquid into a fibrous assembly in a spontaneous way is caused by capillary forces. The interstices between fibers are usually regarded as a large number of parallel capillaries which are interconnected and have a continuous distribution of radius. These capillaries can suction the liquid into the fiber material by capillary force. When the wetting process happens, the liquid water fills the smallest millipores first, then fills smaller ones and gradually fills large pores [46]. The capillary action is influenced by the interaction between the liquid and textile fabrics through liquid properties (viscosity,surface tension) and the geometric structure of the pores. Meanwhile, the size and shape of the fibers, as well as their alignment determine the geometry of the pores.

The governing equation of the liquid transfer process in textile fabrics can be expressed with reference to Li and Zhu's model which first gave the definition of liquid transfer coefficient as a function of the properties of fiber, liquid and fabric structural properties [118] and the pressure model of Li et al [49].

$$\frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l \frac{\partial(\rho_l \varepsilon_l)}{\partial x}\right) + G_l \frac{\partial^2 p_s}{\partial x^2} + \varpi_l \frac{\partial C_f}{\partial t} - \Gamma_{\mathrm{lg}} \qquad (3.8)$$

Where, $G_l \frac{\partial^2 p_s}{\partial x^2}$ is the mass flux of free liquid water under total atmospheric pressure gradient. The value of the parameters in this equation can be obtained as illustrated in Table 3.8.

Table 3.8 Parameters in liquid water conversation equation

Parameters	Physical meaning	Data availability	Unit
ρ_l	Density of liquid water	Constant property	kg/m^3
ϖ_l	Proportion of the sorption of liquid water at fiber surface	1-ϖ_l	Percentage
τ_l	liquid diffusion tortuousity, actual diffusion path deviated from the straight distance	Effective value	Ratio
D_l	Liquid diffusion coefficient in fabric	$\frac{3\gamma\cos\theta\sin^2\alpha d_c\varepsilon_l}{20\mu_l\varepsilon}$	m^2/s
G_l	Coefficient of pressure gradient to liquid water flux	$\rho_l\frac{3\varepsilon\sin^2\alpha d_c^2}{80\mu_l}\left(\frac{\varepsilon_l}{\varepsilon}\right)^3$	
γ	Surface tension of liquid moisture	Constant property [126-128]	J/m
θ	The contact angle of the liquid moisture with fiber surface	Effective value	degree
a	The effective angle between the capillaries in the fabric	Effective value	degree
μ_l	Dynamic viscosity of liquid water	Constant property [129]	kg/ms

For the parameters of τ_l, θ, a, though having conceptual physical definitions, there is still a lack of an effective measurement method to measure their practical values due to the complex textile structure and multifarious liquid transfer process. In the previous research, their values are often referred to as empirical values or limited samples, which are not applicable for the general engineering purpose. To resolve this difficulty, it is expected to obtain their effective values by utilizing other measurable properties and make the model valid for various application cases.

A standard testing method provided with equipment and software has now been available to measure the liquid diffusion capacity of porous textile material [130]. Ten indices (seen in Table3.9) characterizing the dynamic multi-dimensional liquid diffusion property are provided and measured with values [131]. Provided with these measurable data, these parameters may be given new definitions and obtain an effective value for the model parameterization by analyzing the physical mechanism involved.

Table 3.9 Measurable indices of moisture management capacity

Evaluation index	Explanation of definition
Wetting time of top /bottom (WTT/WTB)	Time period from starting to wet to that the slope of water content on top/bottom surface exceed than tan(15 deg)
Maximum wetted radius of top/bottom (MWRT/MWRB)	The maximum wetted ring radius at the top/bottom surface
Absorption rate of top/bottom (ART/ARB)	The moisture absorbing time of the top/bottom surface
Spreading speed of top/bottom (SST/SSB)	The accumulative spreading speed from the center to the maximum wetted radius at the top/bottom surface
Accumulative one-way	The difference of the accumulative moisture content between

transport capacity (R)	the top and bottom surfaces
Overall moisture management capacity (OMMC)	The overall capacity of the textile composites to manage the transport of liquid moisture

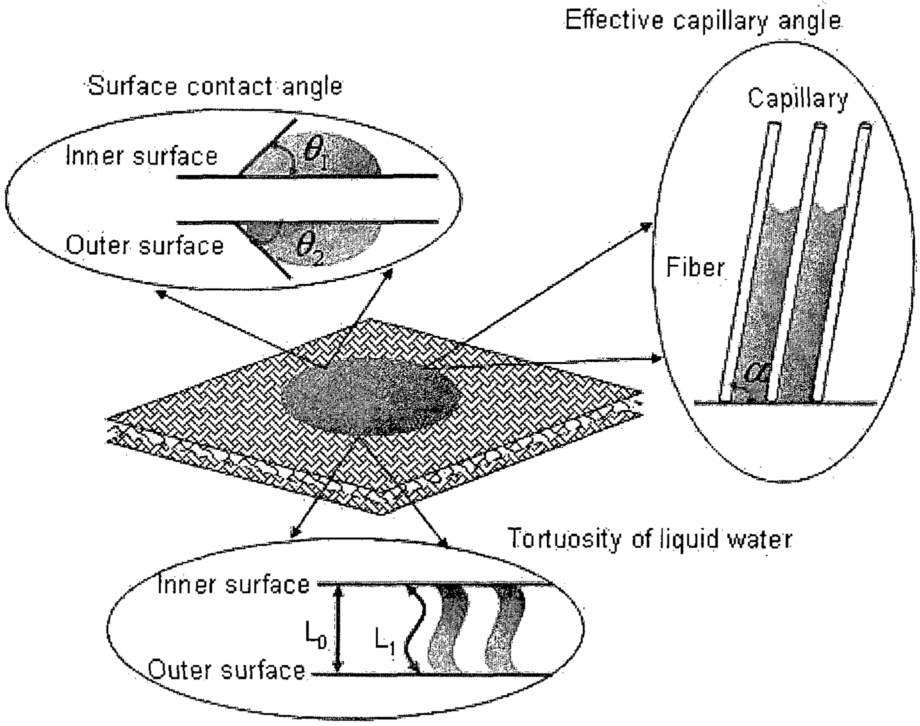
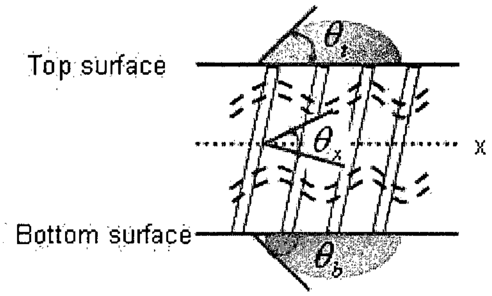


Figure 3.2 Physical schematics of liquid diffusion in textile fabrics

Figure 3.2 shows the physical meaning of the parameters including surface contanct angle (θ), effective capillary angle (α) and tortuosity of liquid water (τ_l). The new definition of these parameters with an effective value can be expressed as follows:

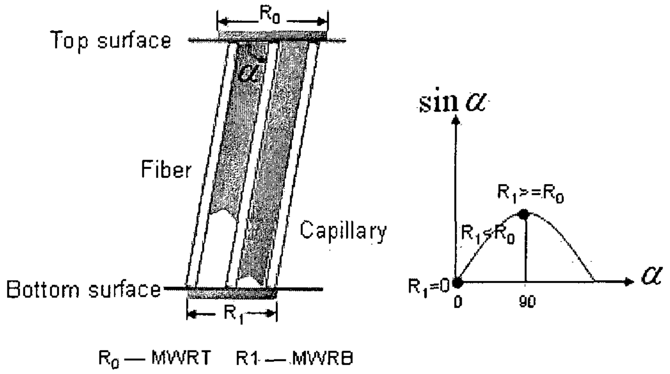
(1) The liquid contact angel on the two surfaces of the textile material can be measured using the drop shape method [132], while the measurement of the liquid contact angel at the internal position is very difficult due to the structural complexity and the liquid uptake in the capillaries. The contact angle of the textile material through the thickness ($\theta(x)$) is assumed to have a linear distribution between the contact

angle of top surface (θ_t) and bottom surface (θ_b) regarding the texture continuity in the fibrous batting.



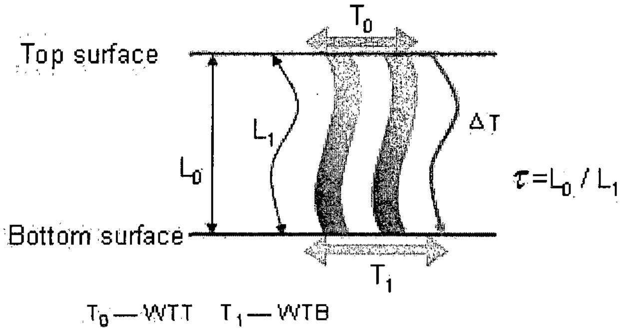
$$\theta\ (x) = \frac{x}{n} * (\theta_t + \theta_b) \quad (0 \le x \le n) \quad (3.9)$$

(2) The interstices between fibers are usually regarded as a large number of parallel capillaries which are interconnected and have a continuous distribution of radius. The effective angle (α) between the capillaries and the surface of the fiber can not be directly measured but can be determined with an effective value by analyzing its potential relationship with the wetted maximum radius of top and bottom surfaces (MWRT, MWRB). When MWRB=0, it means no moisture is transferred to the bottom surface from the top surface and α is equal to 0; When MWRB>=MWRT, it means the textile material has transverse wicking and good longitudinal wicking so that the liquid can be transferred quickly from the top surface to the bottom surface and α is supposed to be close to 90 oC; When MWRB<MWRT, the liquid moisture is partially transferred from the top surface to the bottom surface, and α is assumed as in the sin function of MWRB/MWRT. Thus, a conditional function is given to calculate the effective value of the effective contact angle (α):



$$\sin\alpha=\begin{cases}\dfrac{\text{MWRB}}{\text{MWRT}}, & 0\le \text{MWRB}\le \text{MWRT}\\ 1, & \text{MWRB}>\text{MWRT}\end{cases}\tag{3.10}$$

(3) The tortuosity of liquid moisture expresses the tortuous path of the liquid flow through textile material. However, it is known that the tortuous path in a transported material, microscopically, is very complicated. In an analytical solution, the tortuosity of liquid moisture is defined as the ration of the straight length or thickness of a sample/unit cell to the actual length of flow path [133]. Considering the difficulty in measuring the actual flow path through textile material, the effective value of tortuosity of liquid moisture is assumed to be equal to the ratio of the wetted time of top surface to that of top and bottom surface (WTT, WTB), as listed in Eqs.8. When WTB=0, it means no liquid transferred cross the textile material, and the tortuosity of liquid moisture through the textile material is supposed to be infinite large. The larger the WTB is, the more liquid moisture is transferred to the bottom surface, and the smaller the tortuosity of liquid moisture through the textile material should be.



$$\tau_l = \frac{WTT}{WTB} \tag{3.11}$$

Heat transfer governing equation

The heat transfer process in textile fabrics, in most practical situations, relies on two or even three modes occurring together in terms of conduction, convection and radiation. It has been recognized that conductive and radioactive heat are the predominate contributions to the heat flux across the fabric material, and the connective heat is not observable through experimental investigation even in very low-density battings [17]. The heat conduction process in textile fabrics is similar to the moisture transfer process since both of these processes are governed by statistical behaviors of micro-particles (molecules, atoms and electrons) random movement in the system. The governing equation of thermal conduction thus is in the same form to that of the moisture diffusion. In addition, the radiation heat exchanges between fibers and other surfaces often can not be neglected especially in the textile fabrics with low density or with high temperature gradients. Therefore, the basic structure of the heat transfer governing equation can be referred to Henry's model[35] and Farnworth's model[17]. Considering the innovative technologies used to improve the thermal performance of fabric, including PCM micro-encapsulation and self-heating fabric, they are modeled into the governing equation acting as a resource item to reflect their influence on the heat transfer process. The general governing equation for heat transfer process is written as:

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_t \frac{\partial T}{\partial x} \right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + (\omega_a \lambda_v + \omega_l \lambda_l)\varepsilon_f \frac{\partial C_f}{\partial t} - \lambda_{\mathrm{lg}} h_{\mathrm{lg}} \Gamma_{\mathrm{lg}} + \dot{q}(x,t) + W \quad (3.12)$$

Where, $\dot{q}(x,t)$ is the energy released/absorbed rate which has been mathematically expressed in Section 3.3.1. c_v is the dynamic volumetric specific heat of the fabric and is defined as:

$$c_v = \varepsilon_l c_{vl} + \varepsilon_f c_{vf} + \varepsilon_a c_{va} \quad (3.13)$$

K_t is the effective thermal conductivity for the porous fabric, and is defined as:

$$K_t = \varepsilon_a K_a + (\varepsilon_l + \varepsilon_f) K_{fab} \quad (3.14)$$

F_R and F_L respectively is the total thermal radiation incident in a tiny volume element traveling to the right and left way, they are further governed by the following equation:

$$\frac{\partial F_R}{\partial x} = -\beta F_R + \beta \sigma T^4, \frac{\partial F_L}{\partial x} = \beta F_L - \beta \sigma T^4 \quad (3.15)$$

W is the heat production rate of the self-heating fabric, which is technically driven on when the fabric temperature is lower than a specified bottom point (T_l) and is driven off when the fabric temperature is higher than a specified top point (T_h), the detail expression can be given as:

$$W = \begin{cases} \dfrac{U^2}{R_t} & T < T_l \\ 0 & \mathrm{T} > \mathrm{T_h} \end{cases} \quad (3.16)$$

The parameters and properties involved the equations 3.12~3.16 can be obtained their values as listed in Table 3.10.

Table 3.10 Parameters in heat conservation equation

Parameters	Physical meaning	Data availability	Unit
c_{vl}	Volumetric heat capacity of the liquid water	Constant property	kJ/m^3/K
c_{va}	Volumetric heat capacity of the air	Constant property	kJ/m^3/K
c_{vf}	Volumetric heat capacity of the fiber	Linear to water content of fiber [134]	kJ/m^3/K
K_l	Thermal conductivity of the liquid water	Constant property	W/m/K
K_a	Thermal conductivity of air	Constant property	W/m/K
K_{fab}	Thermal conductivity of the fabric	Experimental measurement [135]	W/m/K
β	Radiation absorption constant of the fiber	Constant property	1/m
σ	Stenfan-Boltzmann constant	Constant property	W/m^2/K
λ_v	Latent heat of sorption or desorption of vapor by fibers	Experimental measurement [136]	kJ/kg
λ_l	Latent heat of sorption or desorption of liquid water by fibers	Experimental measurement [136]	kJ/kg
λ_{lg}	Latent heat of evaporation of water	Constant property	kJ/kg
U	The voltage of the electric supply system	Setting specification	V
R_t	Heating resistance	Setting specification	Ω

Dry air pressure governing equation

In the situation where the atmospheric pressures are different at the two sides of the fabric, the caused ventilating motion of air through the fabric may enhance the heat and moisture transfer processes. For instance, the clothing worn in running situation or windy weather are easy to decrease its temperature due to that the induced airflow across the fabric strengthens the evaporation and adsorption behaviors in textile material and thus increases the lost heat. The direct influence of atmospheric pressure on the moisture diffusion process has been considered in the water vapor and liquid mass governing equation. In order to enable the solution of equation assemblies, it is necessary to develop a governing equation of the pressure of dry air (p_s) which fill in the void space of fabric together with the water vapor. The expression of the governing equation comes from Li's model [137].

$$\frac{M_g \varepsilon_a}{RT}\frac{\partial p_s}{\partial t} - \frac{p_s \varepsilon_a M_g}{RT^2}\frac{\partial T}{\partial t} - \frac{M_g p_s}{RT}\frac{\partial \varepsilon_l}{\partial t} = \frac{\partial}{\partial x}\left[G_s \frac{\partial p_s}{\partial x}\right] - \varpi_1 \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{lg} \quad (3.17)$$

Where, the involved parameters can be found their definition in Table 3.11 and Tables 3.8.

Table 3.11 Parameters in dry air model

Parameters	Physical meaning	Data availability	Unit
M_g	Mole mass of gas	29.0 [138]	kg/mol
R	Gas constant	8.31*1.0e+7 [138]	J/mol K
Gs	Coefficient of pressure gradient to dry air flux	$\frac{M_g p_s}{RT}\frac{3\varepsilon \sin^2 \alpha d_c^2}{80\mu_s}\left(1-\left(\frac{\varepsilon_l}{\varepsilon}\right)^3\right)$	
ε	Porosity of fabric	1-ε_f	Percentage
d_c	Largest effective radius of the pore in fabrics	Material property [46, 125]	m
μ_s	Dynamic viscosity of gas	Constant property	kg/ms

3.3.4 Human body thermoregulatory models

The heat and moisture model of textile fabrics in the above Section 3.3.3 is developed with regard to the heat and mass conservation on the unit of tiny volume, and the fabric is divided into numerous such tiny units in the spatial coordinate. In the clothing wearing system, the thermoregulatory system of human body is generally modeled in a large-scale with meter view due to the symmetrical thermal regulations of body and the complex body constitution which has difference biological responses to the external environment at different body parts.

As reviewed in Section 1.2.2, the developed models of human body thermoregulatory system in the literatures were categorized as one-node, two-node, multi-node and multi-element models with accordance to the node division of human body. The more nodes regarding the body as, more detail behaviors can be addressed and more accurate results can be obtained, as well as more complex and dynamic environments can be applicable with the model. However, the model with more nodes requires more detail input information and cause more intensive calculation load. That consequence, meanwhile, is the limitation of the model promoted to be applied for effective engineering application. With concerning a balance between the benefit and limitation, this project employs a 2-node and a 25-node model with some updates to be more smoothly incorporated with the heat and moisture transfer model of textile fabrics. The dimension of the thermoregulatory model of human body employed in numerical representation of the clothing wearing system directly determines the dimension of clothing thermal functional design and simulation. In order to offer alternative solutions for different design requirements, these two types of thermoregulatory models are respectively incorporated in the multi-scale model assemblies to achieve one-dimensional and multi-dimensional thermal engineering applications.

2-node thermoregulatory model

In the assumption of this model presented by Gagge [67], the entire human body is regarded as two concentric nodes, namely skin node and core node to simply represent all the internal organs, bone, muscle and tissue in the body. The thermal information of these two nodes such as temperature, relative humidity and vapor pressure are uniform. The energy balance equation of each node and the thermal control functions are given with reference to Gagge's model [67]:

$$S_{cr} = M - E_{res} - C_{res} - W - (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) \qquad (3.18)$$

$$S_{sk} = (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) - E_{sk} - R - C \qquad (3.19)$$

$$V_{bl} = \left[6.3 + 200(WARM_{cr})\right] / \left[1 + 0.1(COLD_{cr})\right] \qquad (3.20)$$

The involved parameters can obtain their values as listed in Table 3.12

Table 3.12 Parameters in the two node model

Parameters	Physical meaning	Data availability	Unit
M	Metabolic rate of human body	User specification	Met.
E_{res}	Latent respiration heat loss	$1.73\times10^{-5}M(5.87\times10^{3} - P_{env})$	W/m^2
P_{env}	Air pressure of	Climatic data	*pa*

	environment		
C_{res}	Dry respiration heat loss	$0.0014M(307.6-T_{env})$	W/m^2
T_{env}	air temperature of environment	Climatic data	°C
W	Work rate	User specification	W/m^2
K_{min}	Minimum thermal conductance of body tissue	Physiological measurement [67]	W/m^2/K
c_{pbl}	Specific heat at constant pressure of blood	Physiological measurement [67]	W.hr/L/C
Warmcr/Coldcr	Warm/cold control signal of core	$T_{cr}-T_{cr0}$	
T_{cr0}	Neutral core temperature	Physiological measurement [67]	°C

25-node thermoregulatory model

In order to enhance the model prediction capacity with more detailed thermal responses of the body and more applicable environmental situations, the human body is further divided into more nodes to express the thermoregulatory system. The 25-node model developed by Stolwijk consists of passive system and controlling system [68]. In the passive system the body consists of head, trunk, arm, hands, legs and feet segments which are subdivided into four concentric layers representing the core, muscle, fat, and skin layers. An additional node denoting the central blood pool is counted to represent the large arteries and veins in the body, which uptakes the responsibility to execute communications between all the nodes via the convective heat exchange between each node and blood. The heat balance equation and functions of controlling system are given for each node as in reference [68], and the corresponding meaning of each node number (*n*) in the model can be found in Table 3.13.

Passive system

$$\begin{cases} C_n \dfrac{dT_n}{dt} = Q_i - B_i - D_i - E_i \qquad n = 1,2 \ldots 24 \\ c_b \dfrac{dT_b}{dt} = \sum_{n=1}^{24} B_n \end{cases} \tag{3.21}$$

$$\begin{cases} \mathit{Core\ layer} : Q(N) = QB(N) \\ \mathit{Muscle\ layer} : \ Q(N+1) = QB(N+1) + WORKM(I) * (Work) + \\ \qquad\qquad\qquad\qquad CHILM(I) * CHILL \\ \mathit{Fat\ layer} : Q(N+2) = QB(N+2) \\ \mathit{Skin\ layer} : Q(N+3) = QB(N+3) \end{cases} \tag{3.22}$$

$$\begin{cases} \mathit{Core\ layer} : BF(N) = BFB(N) \\ \mathit{Muscle\ layer} : \ BF(N+1) = BFB(N+1) + Q(N+1) - BFB(N-1) \\ \mathit{Fat\ layer} : BF(N+2) = BFB(N+2) \\ \mathit{Skin\ layer} : BF(N+3) = (BFB(N+3) + SKINV(I) * DILAT) / \\ \qquad\qquad\qquad\qquad (1 + SKINC(I) * STRIC)) * 2^{(ERROR(N+3)/10)} \end{cases} \tag{3.23}$$

Controlling system

$$\begin{cases} SWEAT = CSW * ERROR(1) + SSW * (WARMS - COLDS) + PSW * WARM(1) * WARMS \\ DILAT = CDIL * ERROR(1) + SDIL * (WARMS - COLDS) + PDIL * WARM(1) * WARMS \\ CHILL = -CCHIL * ERROR(1) + SCHIL * (COLDS - WARMS) + PCHIL * COLD(1)\ COLDS \\ STRIC = -CCON\ ERROR(1) + SCON\ (COLDS - WARMS) + PCON * COLD(1) * COLDS \end{cases} \tag{3.24}$$

$$\begin{cases} ERROR(N) = T(N) - TSET(N) + RATE(N) * F(N) \\ WARM(N) = ERROR(N) \qquad ERROR(N) > 0 \\ COLD(N) = ERROR(N) \qquad ERROR(N) < 0 \\ WARMS = SKINR(1) * WARM(4) + SKINR(2) * WARM(8) + \\ \qquad SKINR(3) * WARM(12) + SKINR(4) * WARM(16) \\ \qquad + SKINR(5) * WARM(20) + SKINR(6) * WARM(24) \\ COLDS = -WARMS \end{cases} \tag{3.25}$$

The parameters involved in this model are required individually to be configured with a set of values corresponding to multi-segments or multi-nodes. The available values of these parameters were measured by Stolwijk in the development of the model principally on a man with body weight of 74.1 kg and a surface area of 1.89 m^2 [68].

When being applied to other customized persons, these parameters are better to be re-measured for more actual prediction results. Table 3.14 lists out these parameters.

Table 3.13 Node number of the body

Number	Segment	Number	Layers in each segment
k=1	Head	n=4k+1	Core
k=2	Trunk	n=4k+2	Muscle
k=3	Arm	n=4k+3	Fat
k=4	Hand	n=4k+4	Skin
k=5	Leg		
k=6	Foot		

Table 3.14 Parameters in the 25-node model

Parameters	Physical meaning	Data availability	Unit
$T_{SET}(25)$	Set point or reference point for receptors compartment N	Physiological measurement	°C
C(25)	Heat capacity of each node	Physiological measurement	Wh/°C
QB(25)	Basal metabolic heat production in N	Physiological measurement	W
EB(25)	Basal evaporative heat loss from N	Physiological measurement	W
BFB(25)	Basal effective blood flow to N	Physiological measurement	1/h
TC(25)	Thermal conductance between N and N+1	Physiological measurement	W/°C
HC(6)	Environmental convective heat transfer coefficient for segment I	Physical measurement	$W/m^2/°C$
SKINR(6)	Fraction of all skin receptors in segment I	Physiological measurement	Ratio
SKINS(6)	Fraction of sweating command applicable to skin of segment I	Physiological measurement	Ratio
SKINV(6)	Fraction of vasodilatation command applicable to skin of segment I	Physiological measurement	Ratio
SKINC(6)	Fraction of vasoconstriction command applicable to skin of segment I	Physiological measurement	Ratio
$M_{CHIL}(6)$	Fraction of total shivering occurring in muscle of segment I	Physiological measurement	Ratio

3.4 BOUNDARY AND INITIAL CONDITIONS FOR MULTI-SCALE MODELS

In order to solve these developed multi-scale models, the boundary and initial conditions are required to be further specified to define the solution domain and the initial status of the solution. Through the boundary conditions, the dynamic interactions and communications between the clothing, human body and environment are realized with the real-time output values from the simulation models of clothing and human body.

The clothing is usually constructed with one or several layers of fabrics, and even several suits of clothing are worn on the body in the real wearing situations. In the computational scheme of such condition, the simulation of clothing is realized with the simultaneous computation for each fabric layer with the fabrics' dynamic heat and moisture transfer model. The mathematical model executed for each fabric layer should have specified boundary conditions with accordant to individual practical situations. For each fabric which may be regarded with being next to skin/other fabric/environment, the boundary conditions at the inner side(x=0) and the outer side(x=L) are specified by considering the connective nature of the boundary fabrics, air layer and the resistance at the inner and outer sides, as follows:

At x=0, for the fabric next to skin*

$$\frac{D_a}{\tau_a}\frac{\partial(C_a\varepsilon_a)}{\partial x}\bigg|_{x=0} = \begin{cases} C^*(T_0) & \textit{(contcact = true)} \\ -\frac{\varepsilon_a}{\varepsilon}H_m(C_{sk}-C_0)-\frac{p_m}{\lambda}E_{sk} & \textit{(contcact = false)} \end{cases} \tag{3.26}$$

$$\frac{D_l}{\tau_l}\frac{\partial(\rho_l\varepsilon_l)}{\partial x}\bigg|_{x=0} = \begin{cases} 1-\varepsilon_f & \textit{(contcact = true)} \\ \frac{\varepsilon_l}{\varepsilon}h_{lg}(C^*(T_0)-C_{0B}) & \textit{(contcact = false)} \\ 0 & \textit{(with waterproof membrane)} \end{cases} \tag{3.27}$$

$$K(0,t)\frac{dT}{dx}\bigg|_{x=0} = \begin{cases} \frac{K_0}{\Delta x}(T_{sk}-T_0) & \text{(contcact = }\textit{true}\text{)} \\ -(1-p_h)H_c(T_{sk}-T_0)- & \\ \quad\lambda_{\lg}h_{\lg}(C_{sk}-C^*(T_0)) & \text{(contcact = }\textit{false}\text{)} \end{cases} \tag{3.28}$$

$$p_s|_{x=0} = p_0 \tag{3.29}$$

At x=0, for the fabric next to other fabric

$$\frac{D_a}{\tau_a}\frac{\partial(C_a\varepsilon_a)}{\partial x}\bigg|_{x=0} = -\frac{\varepsilon_a}{\varepsilon}H_m(C_{0B}-C_0) \tag{3.30}$$

$$\frac{D_l}{\tau_l}\frac{\partial(\rho_l\varepsilon_l)}{\partial x}\bigg|_{x=0} = \begin{cases} \frac{\varepsilon_l}{\varepsilon}h_{lg}(C^*(T_0)-C_{0B}) & \\ 0 & \textit{(with waterproof membrane)} \end{cases} \tag{3.31}$$

$$K_{mix}\frac{dT}{dx}\bigg|_{x=0} = -H_c(T_{0B}-T_0)-\lambda_{\lg}\frac{\varepsilon_l}{\varepsilon}h_{\lg}(C_0-C^*(T_{0B})) \tag{3.32}$$

$$p_s|_{x=0} = p_0 \tag{3.33}$$

At x=L for the fabric next to other fabric

$$\frac{D_a}{\tau_a}\frac{\partial(C_a\varepsilon_a)}{\partial x}\bigg|_{x=L} = \frac{\varepsilon_a}{\varepsilon}H_m(C_N-C_{NB}) \tag{3.34}$$

$$\frac{D_l}{\tau_l}\frac{\partial(\rho_l \varepsilon_l)}{\partial x}\bigg|_{x=L} = \begin{cases} \dfrac{\varepsilon_l}{\varepsilon} h_{lg}\left(C_N - C^*(T_{NB})\right) \\ 0 \qquad \textit{(with waterproof membrane)} \end{cases} \tag{3.35}$$

$$K(0,t)\frac{dT}{dx}\bigg|_{x=L} = \lambda \frac{\varepsilon_l}{\varepsilon} h_{\lg}\left(C_N - C^*(T_{NB})\right) + H_c\left(T_N - T_{NB}\right) \tag{3.36}$$

$$p_s|_{x=L} = p_N$$

At x=L for the fabric next to environment

$$\frac{D_a}{\tau_a}\frac{\partial(C_a \varepsilon_a)}{\partial x}\bigg|_{x=L} = \frac{\varepsilon_a}{\varepsilon} H_m\left(C_e - C_N\right) \tag{3.37}$$

$$\frac{D_l}{\tau_l}\frac{\partial(\rho_l \varepsilon_l)}{\partial x}\bigg|_{x=L} = \begin{cases} \dfrac{\varepsilon_l}{\varepsilon} h_{lg}\left(C_N - C^*(T_e)\right) \\ 0 \qquad \textit{(with waterproof membrane)} \end{cases} \tag{3.38}$$

$$K(0,t)\frac{dT}{dx}\bigg|_{x=L} = \lambda \frac{\varepsilon_l}{\varepsilon} h_{\lg}\left(C_e - C^*(T_N)\right) + H_c\left(T_e - T_N\right) \tag{3.39}$$

$$p_s|_{x=L} = p_N \tag{3.40}$$

* When the style of the clothing is designed to be tight or just fit, the inner side of the fabric next to the skin will become truly in contact with the skin; while the style of the clothing is designed to be loose, the contact status between them will be false.

When the fabric is bonded with a waterproof membrane, which works as a barrier to the moisture transfer at the fabric boundaries, the effect can be taken into account through the connective water vapor transfer coefficient (h_m) and connective heat transfer coefficient (h_t). The combined coefficients are specified with Wang's definitions [54] as follows:

$$H_m = \frac{1}{W_n + \frac{1}{h_m}} \tag{3.41}$$

$$H_{cn} = \frac{1}{R_n + \frac{1}{h_t}} \tag{3.42}$$

The parameters and coefficients involved in the boundary conditions of the clothing model can obtain their values as in Table 3.15.

Table 3.15 Parameters in the boundary conditions of clothing model

Parameters	Physical meaning	Data availability	Unit
E_{sk}	Total evaporative heat transfer from skin	Output from the body model	W/m^2
C_{sk}	Water vapor concentration of the skin surface	Output from the body model	kg/m^3
T_{sk}	Temperature of skin	Output from the body model	^{o}C
h_m	Connective water vapor transfer coefficient	User specification [47, 138]	m/s
h_t	Connective heat transfer coefficient	User specification [47, 138]	W/m^2 K
W_n	Moisture transfer resistance of waterproof membrane	Material property [53]	s/m
R_n	Heat transfer resistance of waterproof membrane	Material property [139]	m^{2}K/W
p_m	Proportion of moisture vapor from the skin at the clothing-covered area	Clothing wearing mode	Ratio
p_h	Proportion of dry heat loss at the clothing-covered area	Clothing wearing mode	Ratio
p_A	Proportion of clothing-covered area	Clothing style	Ratio

The boundary conditions of either the two-node model or the 25-node model basically involve the boundary temperature, vapor pressure and evaporative heat which may be determined by the thermal status of the adjacent fabric and environment. The detailed boundary condition of the two-node model is given as follows:

$$\begin{cases} E_{max} = (1 - p_A) a_e (P_{sk} - P_{fi}) + p_A a_e (P_{sk} - P_e) \\ E_{rsw} = h_{lg} m_{rsw} \\ E_{dif} = (1 - E_{rsw} / E_{max}) 0.06 * E_{max} \end{cases} \tag{3.43}$$

No sweat on skin　　　　　　　　　　Sweat on skin

$$\begin{cases} E_{sk} = E_{rsw} + E_{dif} \\ RH_{sk} = \dfrac{E_{sk}}{E_{max}(P_f, P_e)} \end{cases} \qquad \begin{cases} E_{sk} = K_l \dfrac{T_{sk} - T_{fi}}{l} + E_{rsw} \\ RH_{sk} = \dfrac{E_{sk}}{E_{max}(P_e)} \end{cases} \tag{3.44}$$

The value of the parameters in this boundary condition can be configured as in Table 3.16.

Table 3.16 Parameters in the boundary conditions of clothing model

Parameters	Physical meaning	Data availability	Unit
a_e	Evaporative heat transfer coefficient	User specification [67]	W/(m^2 k Pa)
P_f	Vapor pressure of the inside of the fabric next to skin	Output from the clothing model	Pa
P_e	Vapor pressure of environment	Climatic condition	Pa
l	Air space between the skin and the inner side of the fabric next the skin	Clothing fitting status	m

The boundary conditions of the 25-node model are listed as follows:

$$E_{sk,i} = \frac{P_{sk,i} - P_{f,i}}{R_e} S_i \qquad (3.45)$$

$$\begin{cases} P_{sk,i} = \dfrac{P_{sat,i} R_{e,i} + P_{f,i} R_{esk,i} + m_{rsw} h_{lg} R_{e,i} R_{esk,i}}{R_{e,i} + R_{esk,i}} & if(P_{sk,i} > P_{sat,i}) \\ P_{sk,i} = P_{sat,i} & else \end{cases} \qquad (3.46)$$

And the value of the parameters in the boundary conditions can be obtained as listed in Table 3.17.

Table 3.17 Parameters in the boundary conditions of 25-node model

Parameters	Physical meaning	Data availability	Unit
R_e	Evaporation heat resistence on the skin surface in N	Physical measurement [68]	m^2 Pa/W
R_{esk}	Evaporation resistance of the skin in N	Physical measurement [68]	m^2 Pa/W
$P_{f,i}$	Vapor pressure of the inside of the fabric next to skin in N	Output from the clothing model	Pa
S_i	Skin area of the ith segment in N	Physical measurement [68]	m^2

The initial condition for the fabric heat and moisture transfer model of fabric and the thermoregulatory model is given with the assumption that the wearing system including clothing and human body is thermally equilibrated with the initial thermal condition of the wearing situation. When specified in a wearing situation, the fabric model is initialized with its thermal values with linear distributions across the thickness according to the thermal states of the body skin and environment. The initial conditions of clothing model may be given as follows:

$$\begin{cases} C_a(x,0) = (C_{sk}, C_e)_i \\ T(x,0) = (T_{sk}, T_e)_i \\ \varepsilon_l(x,0) = S_0 \\ p_s(x,0) = p_{s0} \\ C_f(x,0) = f(T, RH)_i \end{cases} \tag{3.47}$$

The human body models are initialized with the practical data of skin temperature and relative humidity at the time point before wearing the clothing.

3.5 CONCLUSION

In this chapter, the focus is placed on the integration of the multi-scale models for clothing thermal engineering design. A set of criteria are established for the evaluation of the potential/suitability of existing models when being directly applied for engineering design or being selected as a component of the models in the engineering framework. With these criteria, critical analysis of well-known thermal models related to textile material, human body and integrated human body-clothing system are performed with regard to the assumptions in the model development, data availability of parameters/variables and model validation and application.

Based on the critical analysis, the multi-scale models for describing the clothing wearing system from molecular to body-clothing level are integrated. They consist of the components: PCM particle heat storage model (nm-scale), fiber moisture sorption/desorption model (μm-scale), fabric heat and mass transfer model (mm-scale), and human body thermoregulatory model (m-scale). At each scale level, the model is expressed with both the mathematical equation and the engineering description of involved parameters/properties in the model in terms of physical meaning, data availability and unit. The approaches of accessing to the values of involved parameters/properties in the model are provided with references. For those can not be directly measured, effective values are calculated with other measurable properties by exploring the connections in their physical meaning and definitions. Further, the boundary and initial conditions are given to define the solution domain and initial value of the solution. The dynamic interactions/communications between the human body, clothing and environment are defined through the boundary conditions. The simulation model plays a crucial role in simulating the thermal behaviors in the clothing wearing system, and is the basis to realize the simulation computation for clothing thermal engineering design.

CHAPTER 4 COMPUTATIONAL SCHEME FOR CLOTHING THERMAL ENGINEERING DESIGN

4.1 INTRODUCTION

The multi-scale models for clothing thermal engineering design have been developed and described in Chapter 3 and consist of a set of differential and algebraic governing equations. For these differential equations, it has been found difficult to obtain analytical solutions even under simplified initial and boundary conditions [116]. Presently, numerical methods have been utilized to solve differential equations in engineering applications, predominately including finite difference method, finite volume method and finite element method [140]. The finite difference method is easy to use but requires the solution domain is regular and the mesh can not be too loose. The finite element method can be applied on the irregular solution domain but is too complex and causes intensive computation load. As a balance of the advantages and disadvantages between the finite difference method and finite element method, the finite volume method, which does not require a structured mesh and is frequently applied in computational fluid dynamics package, is adopted in this chapter to discretize the partial differential equations.

In the first part of this chapter, the focus is placed on the descretization process of the partial differential equations involved in the multi-scale models, and the descrtized equation assemblies are obtained. Then, structural computational scheme is developed for the simulation of the clothing wearing system by solving the multi-scale models. The multi-scale models can be integrated with a two-node or a 25-node thermoregulatory model in order to achieve one-dimensional and multi-dimensional clothing thermal engineering design. Further, the influence of a series of coefficients on simulation results is analyzed including the physical properties of clothing, the boundary condition coefficients and, the grid number and time step.

4.2 DISCRETIZATION OF THE PARTIAL DIFFERENTIAL EQUATIONS

As a summary, the partial differential equation assemblies developed in Chapter 3 for the coupled heat and moisture transfer behaviors of textiles fabric are listed in the following:

$$\frac{\partial(\varepsilon_a C_a)}{\partial t} = \frac{D_a \varepsilon_a}{\tau_a}\frac{\partial^2 C_a}{\partial x^2} + G_a \frac{\partial^2 p_s}{\partial x^2} + \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\text{lg}} \tag{4.1}$$

$$\frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l \frac{\partial(\rho_l \varepsilon_l)}{\partial x}\right) + G_l \frac{\partial^2 p_s}{\partial x^2} + \varpi_l \frac{\partial C_f}{\partial t} - \Gamma_{\text{lg}} \tag{4.2}$$

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_t \frac{\partial T}{\partial x}\right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + (\omega_a \lambda_v + \omega_l \lambda_l)\varepsilon_f \frac{\partial C_f}{\partial t} - \lambda_{\text{lg}} h_{\text{lg}} \Gamma_{\text{lg}} + \dot{q}(x,t) + W \tag{4.3}$$

$$\frac{M_g \varepsilon_a}{RT}\frac{\partial p_s}{\partial t} - \frac{p_s \varepsilon_a M_g}{RT^2}\frac{\partial T}{\partial t} - \frac{M_g p_s}{RT}\frac{\partial \varepsilon_l}{\partial t} = \frac{\partial}{\partial x}\left[G_s \frac{\partial p_s}{\partial x}\right] - \varpi_1 \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\text{lg}} \tag{4.4}$$

$$\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(r D_f(x,t)\frac{\partial C_f(x,r,t)}{\partial r}) \tag{4.5}$$

The finite volume method is adopted to spatially discretize these partial differential equation assemblies. In this method, the volume integrals in a partial differential equation that contain a divergence term are converted to surface integrals and the equation is always kept conservative during the discretization process. In order to get the discretized form of these coupled differential equations, the fabric material is geometrically meshed on the thickness direction and a small volume surrounding each point in the mesh is chosen. The differential equations are integrated on all the small volumes and are evaluated as algebraic equations.

In the discretization process, the implicit method is utilized as the time integration method rather than the explicit method. Though the explicit method is pointwise independent and has no need for linearization, it is demanding on the stability of the scheme which must satisfy the condition $\frac{\Delta t}{\Delta x^2} \leq \frac{1}{2}$ (Δt is time step and Δx is mesh size) [141]. That condition will result in unacceptably small time step when the mesh size is very small in some practical cases, which may be greatly surpass the accuracy requirement of solution with explicit algorithm, and the calculation efficiency hence will be greatly decreased. The implicit method, though needing linear algebraic equations, has the advantage of unconditional stability, which allows the usage of large time step and has the flexibility in adapting the time step for controlling the accuracy of solution.

In the meshed domain (shown in Figure 4.1), considered a control volume Ω with space Δx ($\mu = \frac{\Delta t}{\Delta x^2}$), the differential equation assemblies can be discretized by integral values as follows:

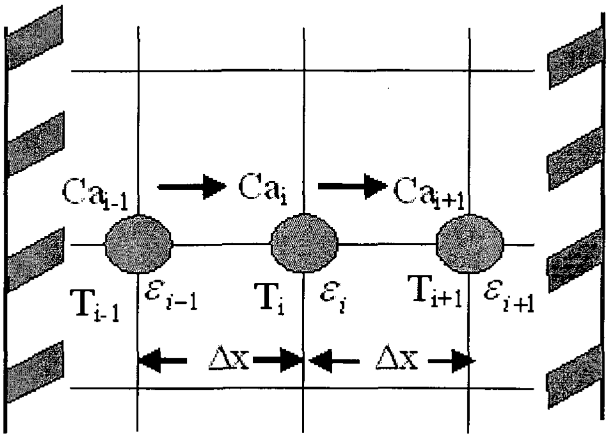


Figure 4.1 Meshed control volume for equation discretization

For Equation (4.1), it can be re-written as:

$$A_1 \frac{\partial C_a}{\partial t} + B_1 \frac{\partial \varepsilon_l}{\partial t} = \frac{\partial}{\partial x}\left(D_1 \frac{\partial C_a}{\partial x}\right) + \frac{\partial}{\partial x}\left(G_a \frac{\partial p_s}{\partial x}\right) + E_1 + F_1 \tag{4.6}$$

Where, $A_1 = \varepsilon_a, B_1 = C_a, D_1 = \frac{D_a \cdot \varepsilon_a}{\tau_a}, E_1 = \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t}, F_1 = h_{lg} S_v \left(C_a^*(T) - C_a\right)$

$$G_a = C_a \frac{3\varepsilon \sin^2 \alpha d_c^2}{80\mu_a}\left(1 - \left(\frac{\varepsilon_l}{\varepsilon}\right)^3\right)$$

Then Equation (4.6) can be expressed in the integral form:

$$\int_\Omega [A_1 \frac{\partial C_a}{\partial t} + B_1 \frac{\partial \varepsilon_l}{\partial t} - E_1 - F_1] dx = \int_\Omega [\frac{\partial}{\partial x}(D_1 \frac{\partial C_a}{\partial x}) + \frac{\partial}{\partial x}\left(G_a \frac{\partial p_s}{\partial x}\right)] dx \tag{4.7}$$

Then the integral value is discreted as:

$$\begin{aligned} &A_{1,i}^n\left(C_{a,i}^{n+1} - C_{a,i}^n\right) + B_{1,i}^n\left(\varepsilon_{l,i}^{n+1} - \varepsilon_{l,i}^n\right) - E_{1,i}^n \Delta t - F_{1,i}^n \Delta t = \mu_{i+\frac{1}{2}} D_{1,i+\frac{1}{2}}^n\left(C_{a,i+1}^{n+1} - C_{a,i}^{n+1}\right) - \\ &\mu_{i-\frac{1}{2}} D_{1,i-\frac{1}{2}}^n\left(C_{a,i}^{n+1} - C_{a,i-1}^{n+1}\right) + \mu_{i+\frac{1}{2}} G_{a,i+\frac{1}{2}}^n\left(P_{s,i+1}^{n+1} - P_{s,i}^{n+1}\right) - \mu_{i-\frac{1}{2}} G_{a,i-\frac{1}{2}}^n\left(P_{s,i}^{n+1} - P_{s,i-1}^{n+1}\right) \end{aligned} \tag{4.8}$$

The final discreted equation can be expressed as:

$$\begin{aligned}&\left(\mu_{i-\frac{1}{2}}D^{n}_{1,i-\frac{1}{2}}\right)C^{n+1}_{a,i-1}-\left(A^{n}_{1,i}+\mu_{i-\frac{1}{2}}D^{n}_{1,i-\frac{1}{2}}+\mu_{i+\frac{1}{2}}D^{n}_{1,i+\frac{1}{2}}\right)C^{n+1}_{a,i}+\left(\mu_{i+\frac{1}{2}}D^{n}_{1,i+\frac{1}{2}}\right)C^{n+1}_{a,i+1}+\\&\left(B^{n}_{1,i}\right)\varepsilon^{n+1}_{l,i}+\left(\mu_{i-\frac{1}{2}}G^{n}_{a,i-\frac{1}{2}}\right)p^{n+1}_{s,i-1}-\left(\mu_{i-\frac{1}{2}}G^{n}_{a,i-\frac{1}{2}}+\mu_{i+\frac{1}{2}}G^{n}_{a,i+\frac{1}{2}}\right)p^{n+1}_{s,i}+\left(\mu_{i+\frac{1}{2}}G^{n}_{a,i+\frac{1}{2}}\right)p^{n+1}_{s,i+1}\\&=-A^{n}_{1,i}C^{n}_{a,i}+B^{n}_{1,i}\varepsilon^{n}_{l,i}+E^{n}_{1,i}\Delta t-F^{n}_{1,i}\Delta t\end{aligned}\tag{4.9}$$

For Equation (4.2), it can be re-written as:

$$A_2\frac{\partial\varepsilon_l}{\partial t}=\frac{\partial}{\partial x}\left[D_2\frac{\partial\varepsilon_l}{\partial x}\right]+\frac{\partial}{\partial x}\left[G_l\frac{\partial p_s}{\partial x}\right]+E_2-F_2\tag{4.10}$$

Where, $A_2=\rho_l, D_2=\frac{\rho_l\cdot D_l}{\tau_l},\ G_l=\rho_l\frac{3\varepsilon\sin^2\beta d_c^2}{80\mu_l}\left(\frac{\varepsilon_l}{\varepsilon}\right)^3$

$E_2=\varpi_l\varepsilon_f\frac{\partial C_f}{\partial t}, F_2=h_{\lg}S_v\left(C_a^*(T)-C_a\right)$

Then Equation (4.10) can be expressed in the integral form:

$$\int_\Omega[A_2\frac{\partial\varepsilon_l}{\partial t}-E_2+F_2]dx=\int_\Omega[\frac{\partial}{\partial x}\left[D_2\frac{\partial\varepsilon_l}{\partial x}\right]+\frac{\partial}{\partial x}\left[G_l\frac{\partial p_s}{\partial x}\right]]dx\tag{4.11}$$

Then the integral value is discreted as:

$$\begin{aligned}&A^{n}_{2,i}\left(\varepsilon^{n+1}_{l,i}-\varepsilon^{n}_{l,i}\right)+E^{n}_{2,i}\Delta t+F^{n}_{2,i}\Delta t=\mu_{i+\frac{1}{2}}\left(D_2\right)^{n}_{i+\frac{1}{2}}\left(\varepsilon^{n+1}_{l,i+1}-\varepsilon^{n+1}_{l,i}\right)-\\&\mu_{i-\frac{1}{2}}\left(D_2\right)^{n}_{i-\frac{1}{2}}\left(\varepsilon^{n+1}_{l,i+1}-\varepsilon^{n+1}_{l,i-1}\right)+\mu_{i+\frac{1}{2}}\left(G_l\right)^{n}_{i+\frac{1}{2}}\left(p^{n+1}_{s,i+1}-p^{n+1}_{s,i}\right)-\mu_{i-\frac{1}{2}}\left(G_l\right)^{n}_{i-\frac{1}{2}}\left(p^{n+1}_{s,i}-p^{n+1}_{s,i-1}\right)\end{aligned}\tag{4.12}$$

The final discreted equation can be expressed as:

$$\begin{aligned}&\left(\mu_{i-\frac{1}{2}}\left(D_2\right)^{n}_{i-\frac{1}{2}}\right)\varepsilon^{n+1}_{l,i-1}-\left(A^{n}_{i}+\mu_{i-\frac{1}{2}}\left(D_2\right)^{n}_{i-\frac{1}{2}}+\mu_{i+\frac{1}{2}}\left(D_2\right)^{n}_{i+\frac{1}{2}}\right)\varepsilon^{n+1}_{l,i}+\left(\mu_{i+\frac{1}{2}}\left(D_2\right)^{n}_{i+\frac{1}{2}}\right)\varepsilon^{n+1}_{l,i+1}+\\&\left(\mu_{i-\frac{1}{2}}\left(G_2\right)^{n}_{i-\frac{1}{2}}\right)p^{n+1}_{s,i-1}-\left(\mu_{i-\frac{1}{2}}\left(G_l\right)^{n}_{i-\frac{1}{2}}+\mu_{i+\frac{1}{2}}\left(G_l\right)^{n}_{i+\frac{1}{2}}\right)p^{n+1}_{s,i}+\left(\mu_{i+\frac{1}{2}}\left(G_l\right)^{n}_{i+\frac{1}{2}}\right)p^{n+1}_{s,i+1}=\\&-A^{n}_{2,i}\varepsilon^{n}_{l,i}+E^{n}_{2,i}\Delta t+F^{n}_{2,i}\Delta t\end{aligned}\tag{4.13}$$

For Equation (4.3), it can be re-written as:

$$A_3\frac{\partial T}{\partial t}-B_3-C_3+D_3=\frac{\partial}{\partial x}\left[E_3\frac{\partial T}{\partial x}\right]+F_3-G_3+H_3\tag{4.14}$$

Where,

$$A_3 = c_v, B_3 = \lambda_v \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t}, C_3 = -\lambda_l \varpi_l \varepsilon_f \frac{\partial C_f}{\partial t}, D_3 = \lambda h_{lg} S_v \left(C_a^*(T) - C_a\right), E_3 = K$$

$$F_3 = \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x}, G_3 = \dot{q}(x,t), H_3 = W$$

Then Equation (4.14) can be expressed in the integral form:

$$\int_\Omega [A_3 \frac{\partial T}{\partial t} - B_3 - C_3 + D_3 - F_3 + G_3 - H_3] dx = \int_\Omega [\frac{\partial}{\partial x}\left[E_3 \frac{\partial T}{\partial x}\right]] dx \qquad (4.15)$$

Then the integral value is discreted as:

$$\begin{aligned} & A_{3,i}^n \left(T_i^{n+1} - T_i^n\right) - B_{3,i}^n \Delta t - C_{3,i}^n \Delta t + D_{3,i}^n \Delta t - F_{3,i}^n \Delta t + G_{3,i}^n \Delta t - H_{3,i}^n \Delta t = \\ & \mu_{i+\frac{1}{2}} E_{3,i+\frac{1}{2}}^n \left(T_{i+1}^{n+1} - T_i^{n+1}\right) - \mu_{i-\frac{1}{2}} E_{3,i-\frac{1}{2}}^n \left(T_i^{n+1} - T_{i-1}^{n+1}\right) \end{aligned} \qquad (4.16)$$

The final discreted equation can be expressed as:

$$\begin{aligned} & \left(\mu_{i-\frac{1}{2}} E_{3,i-\frac{1}{2}}^n\right) T_{i-1}^{n+1} - \left(A_{3,i}^n + \mu_{i-\frac{1}{2}} E_{3,i-\frac{1}{2}}^n + \mu_{i+\frac{1}{2}} E_{3,i+\frac{1}{2}}^n\right) T_i^{n+1} + \left(\mu_{i+\frac{1}{2}} E_{3,i+\frac{1}{2}}^n\right) T_{i+1}^{n+1} = -A_{3,i}^n T_i^n \\ & + B_{3,i}^n \Delta t + C_{3,i}^n \Delta t - D_{3,i}^n \Delta t + F_{3,i}^n \Delta t - G_{3,i}^n \Delta t + H_{3,i}^n \Delta t \end{aligned} \qquad (4.17)$$

The radiative heat item ($F = \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x}$) can be evaluated by a binominal approximation presented by Farnworth [17] as:

$$\begin{cases} F = \beta \sigma (T_i^4 - T_0^4) \\ T_0 = \dfrac{T(0,0) + T(n,0)}{2} \end{cases}$$

For Equation (4.4), it can be re-written as:

$$A_4 \frac{\partial p_s}{\partial t} + B_4 \frac{\partial T}{\partial t} + C_4 \frac{\partial \varepsilon_l}{\partial t} + E_4 - F_4 = \frac{\partial}{\partial x}\left[G_s \frac{\partial p_s}{\partial x}\right] \qquad (4.18)$$

Where, $A_4 = \frac{M_s \varepsilon}{RT}, B_4 = -p_s \frac{\varepsilon M_s}{RT^2}, C_4 = -\frac{M_s p_s}{RT}, E_4 = \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t}$,

$$F_4 = h_{lg} S_v \left(C_a^*(T) - C_a\right), \quad G_s = \frac{M_s p_s}{RT} \frac{3\varepsilon \sin^2 \alpha d_c^2}{80 \mu_a} \left(1 - \left(\frac{\varepsilon_l}{\varepsilon}\right)^3\right)$$

Then Equation (4.18) can be expressed in the integral form:

$$\int_{\Omega}[A_4 \frac{\partial p_s}{\partial t} + B_4 \frac{\partial T}{\partial t} + C_4 \frac{\partial \varepsilon_l}{\partial t} + E_4 - F_4]dx = \int_{\Omega}[\frac{\partial}{\partial x}\left[G_s \frac{\partial p_s}{\partial x}\right]]dx \tag{4.19}$$

Then the integral value is discreted as:

$$\begin{aligned}&A_{4,i}^n\left(p_{s,i}^{n+1} - p_{s,i}^n\right) + B_{4,i}^n\left(T_i^{n+1} - T_i^n\right) + C_{4,i}^n\left(\varepsilon_{l,i}^{n+1} - \varepsilon_{l,i}^n\right) + E_{4,i}^n\Delta t - F_{4,i}^n\Delta t = \\ &\mu_{i+\frac{1}{2}}(G_s)_{i+\frac{1}{2}}^n\left(p_{s,i+1}^{n+1} - p_{s,i}^n\right) - \mu_{i-\frac{1}{2}}(G_s)_{i-\frac{1}{2}}^n\left(p_{s,i}^{n+1} - p_{s,i-1}^n\right)\end{aligned} \tag{4.20}$$

The final discreted equation can be expressed as:

$$\begin{aligned}&-\left(B_{4,i}^n\right)T_i^{n+1} - \left(C_{4,i}^n\right)\varepsilon_{l,i}^{n+1} + \left(\mu_{i-\frac{1}{2}}(G_s)_{i-\frac{1}{2}}^n\right)p_{s,i-1}^{n+1} - \left(A_{4,i}^n + \left(\mu_{i-\frac{1}{2}}(G_s)_{i-\frac{1}{2}}^n\right) + \left(\mu_{i+\frac{1}{2}}(G_s)_{i+\frac{1}{2}}^n\right)\right)p_{s,i}^{n+1} \\ &+ \left(\mu_{i+\frac{1}{2}}(G_s)_{i+\frac{1}{2}}^n\right)p_{s,i+1}^{n+1} = -A_{4,i}^n p_{s,i}^n - B_{4,i}^n T_i^n - C_{4,i}^n \varepsilon_{l,i}^n + E_{4,i}^n\Delta t - F_{4,i}^n\Delta t\end{aligned} \tag{4.21}$$

Similar to the discretization process of the coupled heat and moisture transfer models of fabric, the fiber moisture absorption/desorption model can be discretized with the meshed volumes on the fiber radius direction. Equation 4.5 is re-written in the integral form as:

$$\int_{\Omega P}\left(r\frac{\partial C_f}{\partial t}\right)dr = \int_{\Omega P}\left(\frac{\partial}{\partial r}\left(rD_f \frac{\partial C_f}{\partial r}\right)\right)dr \tag{4.22}$$

Then the final discretized equation can be obtained as:

$$\begin{aligned}&\left(\mu\eta r_{i-\frac{1}{2}} D_{f,i-\frac{1}{2}}^n\right)C_{f,i-1}^{n+1} - \left(\mu\eta r_{i+\frac{1}{2}} D_{f,i+\frac{1}{2}}^n + \mu\eta r_{i-\frac{1}{2}} D_{f,i-\frac{1}{2}}^n + 1\right)C_{f,i}^{n+1} \\ &+ \left(\mu\eta r_{i+\frac{1}{2}} D_{f,i+\frac{1}{2}}^n\right)C_{f,i+1}^{n+1} = -C_{f,i}^n\end{aligned} \tag{4.23}$$

Where $\eta = \dfrac{2}{r_{i-\frac{1}{2}} + r_{i+\frac{1}{2}}}$

With respect to these discretized partial differential equations, their corresponding boundary condition equations can be expressed with discretized form as the following:

At x=0, for the fabric next to skin

$$\left[D^n_{1-\frac{1}{2}}\frac{C^{n+1}_{a,2}-C^{n+1}_{a,1}}{\Delta x}\right]=\begin{cases} C*\left(T_1^n\right) & (\text{contcact} = \mathit{true}) \\ -\frac{\varepsilon_a}{\varepsilon}H_m\left(C_{sk}-C^n_{a,1}\right)-\frac{p_m}{\lambda}E_{sk} & (\text{contcact} = \mathit{false}) \end{cases} \tag{4.24}$$

$$\left[(DL)^n_{1-\frac{1}{2}}\frac{\varepsilon^{n+1}_{l,2}-\varepsilon^{n+1}_{l,1}}{\Delta x}\right]=\begin{cases} 1-\varepsilon_f & (\text{contcact} = \mathit{true}) \\ \frac{\varepsilon^n_{l,1}}{\varepsilon}h_{\lg}\left(C*(T_1^n)-C_{0B}\right) & (\text{contcact} = \mathit{false}) \\ 0 & (\text{with waterproof membrane}) \end{cases} \tag{4.25}$$

$$K^n_{1-\frac{1}{2}}\frac{T_2^{n+1}-T_1^{n+1}}{\Delta x}=\begin{cases} \frac{K_1^n}{\Delta x}\left(T_{sk}-T_1^n\right) & (\text{contcact} = \mathit{true}) \\ -(1-p_h)H_c\left(T_{sk}-T_1^n\right)- & \\ \quad\lambda_{\lg}h_{\lg}\left(C_{sk}-C^*(T_1^n)\right) & (\text{contcact} = \mathit{false}) \end{cases} \tag{4.26}$$

$$p^{n+1}_{s,0}=p_{0B} \tag{4.27}$$

At x=0, for the fabric next to other fabric

$$\left[D^n_{1-\frac{1}{2}}\frac{C^{n+1}_{a,2}-C^{n+1}_{a,1}}{\Delta x}\right]=-\frac{\varepsilon_a}{\varepsilon}H_m\left(C_{0B}-C^n_{a,1}\right) \tag{4.28}$$

$$\left[(DL)^n_{1-\frac{1}{2}}\frac{\varepsilon^{n+1}_{l,2}-\varepsilon^{n+1}_{l,1}}{\Delta x}\right]=\begin{cases} \frac{\varepsilon_l}{\varepsilon}h_{\lg}\left(C*(T_0^n)-C_{0B}\right) & \\ 0 & (\text{with waterproof membrane}) \end{cases} \tag{4.29}$$

$$K^n_{1-\frac{1}{2}}\frac{T_2^{n+1}-T_1^{n+1}}{\Delta x}=-H_c\left(T_{0B}-T_0^n\right)-\lambda_{\lg}\frac{\varepsilon_l}{\varepsilon}h_{\lg}\left(C_0^n-C^*(T_{0B})\right) \tag{4.30}$$

$$p^{n+1}_{s,0}=f(v) \tag{4.31}$$

At x=L for the fabric next to other fabric

$$\left[D^n_{N-\frac{1}{2}}\frac{C^{n+1}_{a,N}-C^{n+1}_{a,N-1}}{\Delta x}\right]=\frac{\varepsilon_a}{\varepsilon}H_m\left(C^n_{a,N}-C_{NB}\right) \tag{4.32}$$

$$\left[(GL)^n_{N-\frac{1}{2}} \frac{p^{n+1}_{s,N} - p^{n+1}_{s,N-1}}{\Delta x}\right] = \begin{cases} \frac{\varepsilon_l}{\varepsilon} h_{\lg}\left(C^n_{a,N} - C*(T_{NB})\right) \\ 0 \qquad \text{(with waterproof membrane)} \end{cases} \tag{4.33}$$

$$K^n_{N-\frac{1}{2}} \frac{T^{n+1}_N - T^{n+1}_{N-1}}{\Delta x} = \lambda \frac{\varepsilon_l}{\varepsilon} h_{\lg}\left(C^{\,n}_{a,N} - C^*(T_{NB})\right) + H_c\left(T^{\,n}_N - T_{NB}\right) \tag{4.33}$$

$$p^{n+1}_{s,N} = p_{NB}$$

At x=L for the fabric next to environment

$$\left[D^n_{N-\frac{1}{2}} \frac{C^{n+1}_{a,N} - C^{n+1}_{a,N-1}}{\Delta x}\right] = \frac{\varepsilon_a}{\varepsilon} H_m\left(C_e - C^n_{a,N}\right) \tag{4.34}$$

$$\left[(GL)^n_{N-\frac{1}{2}} \frac{p^{n+1}_{s,N} - p^{n+1}_{s,N-1}}{\Delta x}\right] = \begin{cases} \frac{\varepsilon_l}{\varepsilon} h_{\lg}\left(C^n_{a,N} - C*(T_e)\right) \\ 0 \qquad \text{(with waterproof membrane)} \end{cases} \tag{4.35}$$

$$K^n_{N-\frac{1}{2}} \frac{T^{n+1}_N - T^{n+1}_{N-1}}{\Delta x} = \lambda \frac{\varepsilon_l}{\varepsilon} h_{\lg}\left(C_e - C^*(T^{\,n}_N)\right) + H_c\left(T_e - T^{\,n}_N\right) \tag{4.36}$$

$$p^{n+1}_{s,N} = p_{NB} \tag{4.37}$$

In these discretized boundary conditions, the heat and mass transfer coefficients have important influence on the simulation results, which will be discussed in detail in Chapter 4.4.

With the discretized form of the partial differential equations and the corresponding boundary condition equations, the partial differential equations in the multi-scale models can be solved by constructing the solution matrix and calculating the coefficients of the variables in the dicretized equations to fill in the matrix. The algebraic equations in the multi-scale models do not need special solution method. The solving process of the multi-scale models is essentially important to develop computational scheme for clothing thermal engineering design.

4.3 MULTI-STRUCTURAL COMPUTATIONAL SCHEME

The multi-scale models developed in Chapter 3 have shown the clear framework models of increasing scale level and expressed the physical mechanisms behind. However, the scheme of computational simulation for clothing thermal engineering design still needs to be developed on the basis of the solving process of the multi-scale models. Figure 4.2 shows the main structure of the computational scheme, which illustrates the structure information and communications between the multi-scale models of human body, clothing, fabric and fiber for simulating the thermal behaviors involved in the clothing wearing system.

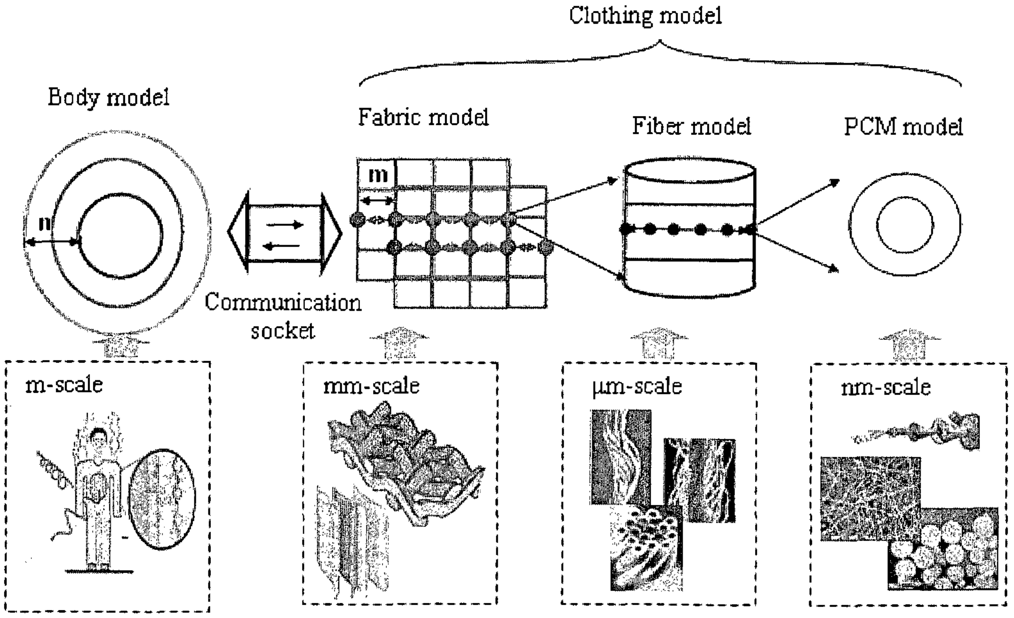


Figure 4.2 The main structure of computational scheme

Computational simulation of clothing thermal function is carried out with the hierarchical structure of garments, fabrics and fibers corresponding to the wearing sequence and design principles of clothing and textile fabrics, and is systematically based on the simultaneous computation on individually composed fabric layers of the garment. Before the computation, the discretized equations developed in the above section are individually configured with the characteristic data of each fabric layer in terms of material properties, structural features and functional treatments, and then generate solution resutls of thermal variables in the models by iterative computation. In the computational solution process of fabric model, the fiber's absorption/desorption model and PCM micro-encapsulation heating model, which have been embedded in the fabric heat and moisture transfer model, are synchronously solved to contribute their effects in real time to the heat and moisture content of the fabric.

However, considering that the functional treatments, such as PCM micro-encapsulation, membrane, moisture management treatment and self-heating fabric, are optional during the fabric functional design, the existing of individual models for these functional treatments in the fabric heat and moisture transfer model will be determined by the practical design. If any functional treatment is made on the fabric, the corresponding model to describe such treatment will be embedded into the fabric heat and moisture transfer model as a source item.

In the part of computational simulation of human body, the computation structure is dependant on the body nodes, which govern the heat balance of the clothed body and environment. Since the governing equations of the 2-node and 25-node thermoregulatory models presented in Chapter 3 are algebraic and simple first-order differential equations, which do not need special solution method, the computational flow of the thermoregulatory system of human body is comparatively facile to that of the clothing. However, the important effort is to develop communication sockets for smooth data flow between the models of clothing and human body.

In the computational simulation of the clothing wearing system, the models of clothing and human body play dominating roles in numerically representing the thermal activities of clothing and body and simulating thermal values of the clothing and body. Meanwhile, the thermal interactions between the clothing, the human body and the environment also require a numerical representation and simulation. The heat and mass exchanges take place in the thermal interactions, such as heat conduction, convection and radiation, sweat evaporation. Based on the physical mechanism analysis, the data flow representing the exchanged heat and mass in the interactions is worked out, and the communication sockets are developed, by which the data can be smoothly transferred into or out of the models through boundary conditions. The communication sockets for the data flow between the human body model and clothing model are developed as shown in Figure 4.3, which illustrates the exchanged data through the communication sockets related to the human body, clothing and environment conditions.

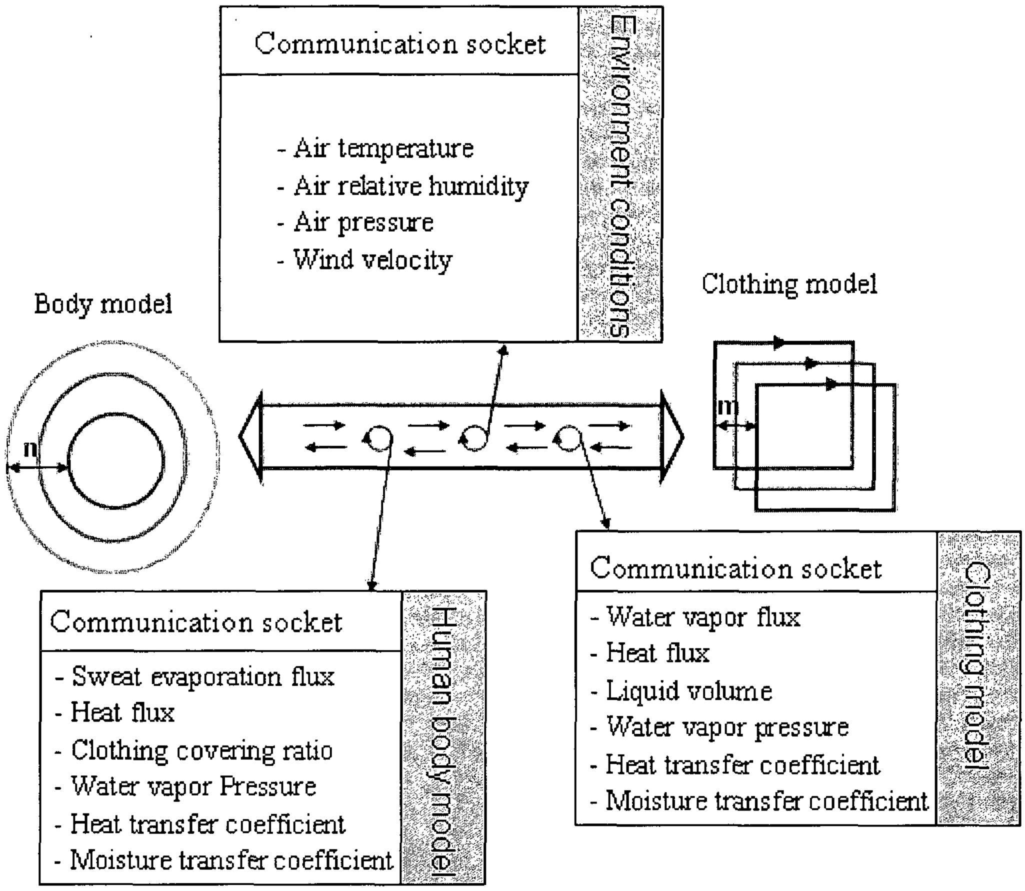


Figure 4.3 Communication sockets between the clothing and human body models

During the iterative computation, the thermal interactions between clothing, human body, and environment happen at the boundary between the body skin and the fabric layer of clothing close to the skin, and at the boundary between the environment and the fabric layer of clothing exposed to the environment, which have been demonstrated in the boundary condition equations in Chapter 3.4. The values of exchanged data in the data flow are automatically updated by the communication sockets when the thermal values of the human body and the fabric layer of clothing at the boundaries are dynamically generated by the models, or when the wearing scenario changes.

However, the thermal interactions between the clothing and human body are different when individually adopting the 2-node thermoregulatory model and 25-node thermoregulatory model in the computational scheme. The 2-node thermoregulatory model enables the thermal interactions at the whole level, and the structure of the computational scheme is one-dimension. While the 25-node thermoregulatory model enables the interactive communication pertaining to 6 parts of head, trunk, arms, hands, legs and feet, and the structure of the computational scheme is multi-dimensional.

4.3.1 One-dimensional computational scheme

In the one-dimensional computational scheme, the clothing model is incorporated with the 2-node thermoregulatory model as developed in Chapter 3.3 to numerically express the clothing wearing system and virtually simulate the thermal behaviors involved in the system. Since in the 2-node thermoregulatory model the human body is regarded as a two-node concentric shell and the thermal status of skin is predicted at the whole level, the thermal interactions between the models of clothing and human body consequently happen at the whole level. The computation of heat and moisture behaviors in clothing which covers the body skin is needed on the whole level, which generates thermal values of the clothing to interact with the thermoregulatory system of human body. The predicted thermal performance of clothing wearing system is thus viewed at the whole level.

Figure 4.4 shows the structure of the one-dimensional computational scheme, which illustrates the algorithms for simulating the clothing wearing system with a flowchart diagram and is explained as followings:

1) Initialize the clothing and human body. The clothing and human body are configured in an initial state since the initial conditions are required to be given before solving the thermal models. As listed in Chapter 3.4, the initial conditions include the temperature, water vapor concentration, liquid water volume fraction and air pressure of the clothing, and the initial temperature and relative humidity on skin of the human body. Practically, it is not easy to determine these exact initial conditions by experiments. However, the model itself can calculate the real initial conditions when the simulation results reach a stable condition after some time of the calculation. Considering this reason, the general way to obtain the initial conditions is to calculate a steady-state of wearing scenario. Unlike the initial conditions of human body, which is in some extent independent to the environment, the initial conditions of clothing are determined as linear distribution of the thermal states of body skin and environment across the thickness direction.

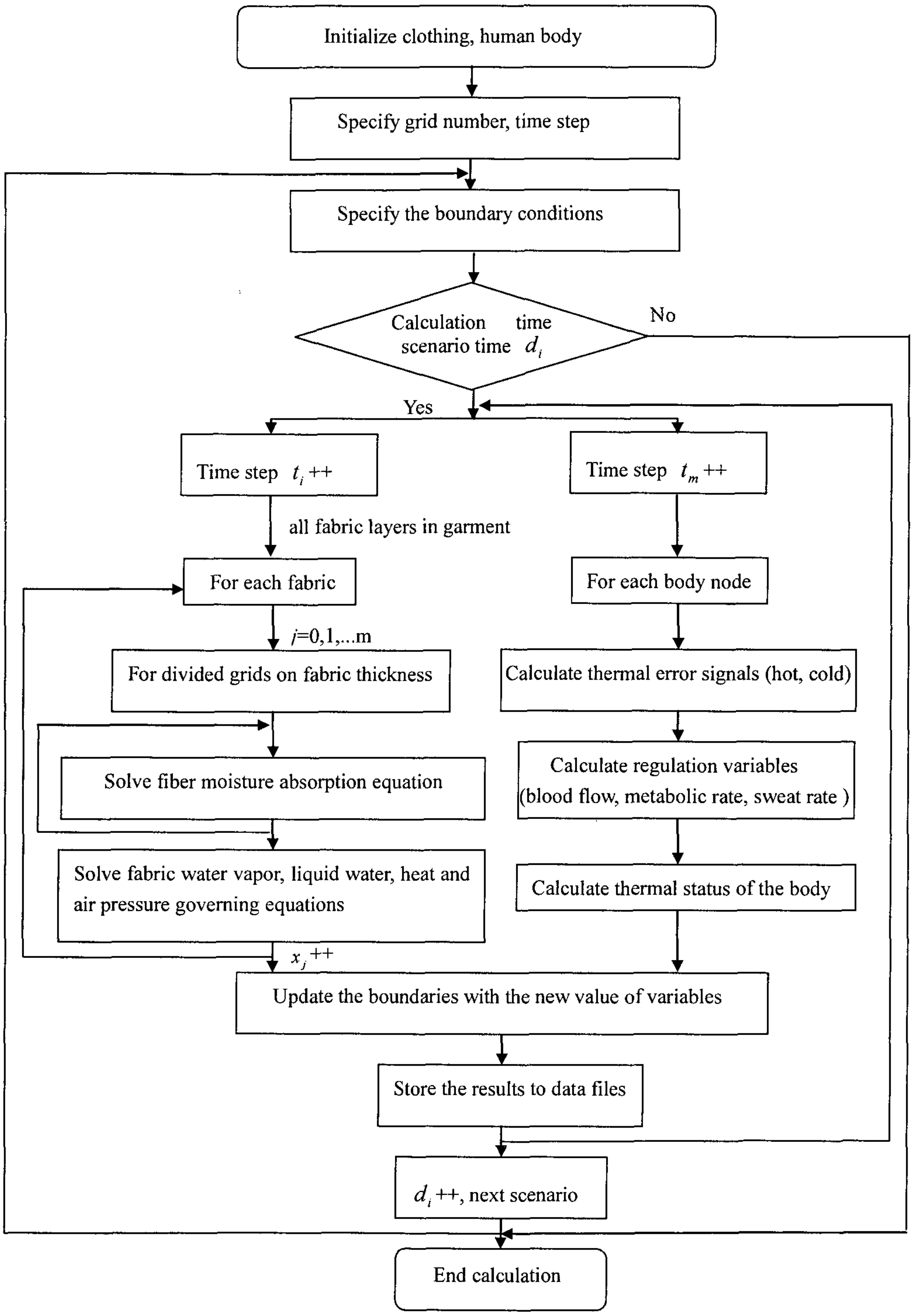


Figure 4.4 One-dimensional computational scheme

2) Specify grid number and time step. The grid number determines the density of volume points in the solution domain, and the time step determines the frequency of the iterative computation. Both of them can influence the accurate level of the

simulation results but meanwhile influence the computational intensity in the opposite direction. The grid number is individually configured for the fabric and the fiber/capsulation. The influence of mesh size and time step on the accuracy of simulation results will be detailed presented in Section 4.4.

3) Specify boundary conditions. The boundary condition is another prerequisite besides the initial conditions for solving the models. As discussed in Chapter 3.4, the boundary conditions of the fabric models refer to the thermal status of the skin, the climatic conditions of environment and the thermal status of adjacent fabrics; the boundary conditions of the thermoregulatory model refer to the thermal status of the fabric next to the skin and the climatic conditions of environment. During the computation simulation, the boundary conditions are required to be specified for each step of the calculation. Since the thermal status of clothing and human body are dynamically generated by the models, the referred thermal values of clothing and human body in the boundary conditions can be automatically refreshed with the generated results in the last time step. Furthermore, the heat and mass transfer coefficients and clothing covering ratio on the skin involved in the boundary conditions are decided by the environment and wearing mode. Considering this, the wearing period is divided into different wearing scenarios with different climatic conditions or different wearing modes, and the boundary conditions are also updated when the computation enters into a different wearing scenario.

4) Judge if the calculation enters into another wearing scenario. If the calculation time goes over the duration of a specified wearing scenario, it comes to deliberately

update the boundary conditions; otherwise, it continues the calculation at the next time step.

5) Locate the volume point (Δx) on the meshed domain of fabric for calculation. The computational simulation of clothing is on the unit of fabric so that the clothing is subdivided into joined composed fabrics. For each layer of fabric in the hierarchical iterative structure, the computation individually locates all the volume points to solve the equations and obtain a numerical solution.
6) Solve the fiber moisture absorption equation. In the located volume point of the fabric, the fiber component is meshed on the diameter direction. Similar to the fabric, the iterative computation locates each volume point (Δr) on the meshed domain of fiber for calculation and then solve the fiber moisture absorption equations. The solution of the fiber moisture absorption equation is utilized for solving the fabric equation.
7) Solve the equations in fabric heat and moisture transfer model. With the discretized equations developed in Chapter 4.2, the solution matrix can be constructed for the coupled governing equations of water vapor, liquid water, heat and air pressure. The coefficients of all the variables in the discretized equations are required to be calculated and filled in the matrix. At this step, the moisture absorbed/desorbed by fibers, the heat released/consumed by PCM, the changed phase of moisture by condensation/evaporation and the energy produced by the heat fabric are solved and utilized in the calculation of these coefficients.
8) Solve the thermoregulatory model. The solving process is carried out by calculating

the thermal error signals and regulation variables, and solving the energy governing equations on the two nodes to generate thermal status of the body. As the thermoregulatory model is not very sensitive to the time step, the calculation frequency of this step is ten times smaller than that of the fabric model.

9) Update the boundary conditions. In the fabric model, the boundary conditions are automatically updated with the generated simulation results after the calculation on each volume point at every time step. The refreshed thermal status of each volume point is new boundary conditions for its adjacent volume points. Meanwhile, at the boundary between the fabric and skin, the boundary conditions are updated when the thermoregulatory model generates new results.
10) Store the simulation results to data file. The simulation results are stored to files according to specified format and name rules to be used for analysis and visualization. The thermal data related to fiber, fabric and human body are stored respectively in different files.
11) Count the calculation time by adding the time step. If the calculation time goes over the total duration of all wearing scenarios, end the iterative calculation.

4.3.2 Multi-dimensional computational scheme

When the clothing model is incorporated with the 25-node thermoregulatory model as reported in Chapter 3.3, the computational scheme is expanded to be multi-dimensional due to the multi-part division of human body in the thermoregulatory model, which enables the thermal interactions between the clothing and human body considered separately for different body parts. To generate the thermal status of clothing for communicating with each part of the body, the clothing is regarded as subsystems individually covering the head, trunk, arms, hands, legs and feet, and the computational simulation of the clothing is executed concurrently in all the subsystems. The communication sockets for the data flow between the models of clothing and human body are applied for the thermal interaction between the fabric-skin boundaries of all the clothed body parts. Due to this multi-part expansion, the computational simulation makes it possible to design clothing with different materials, structures, styles and wearing modes for different body parts. Meanwhile, the concurrent computation of all subdivided clothing and human body subsystems increases the computational intensity. The computation process needs to take more time to obtain the numerical solution of the clothing models at all the parts and the multi-node thermoregulatory model.

Figure 4.5 shows the algorithm in the multi-dimensional computational scheme. Most steps taken in this scheme are logically similar to those of the one-dimensional computational scheme. The differences are discussed below:

1) Initialize clothing for each part and specify boundary conditions. Different from the one-dimensional computational scheme, the clothing covering on the body skin is divided into subsystems according to the body parts, and the subsystem may be different from each other according to the practical wearing situations. All the clothing subsystems are simulated in the concurrent way, which means they need to

be individually specified with initial conditions and boundary conditions before computational solution.

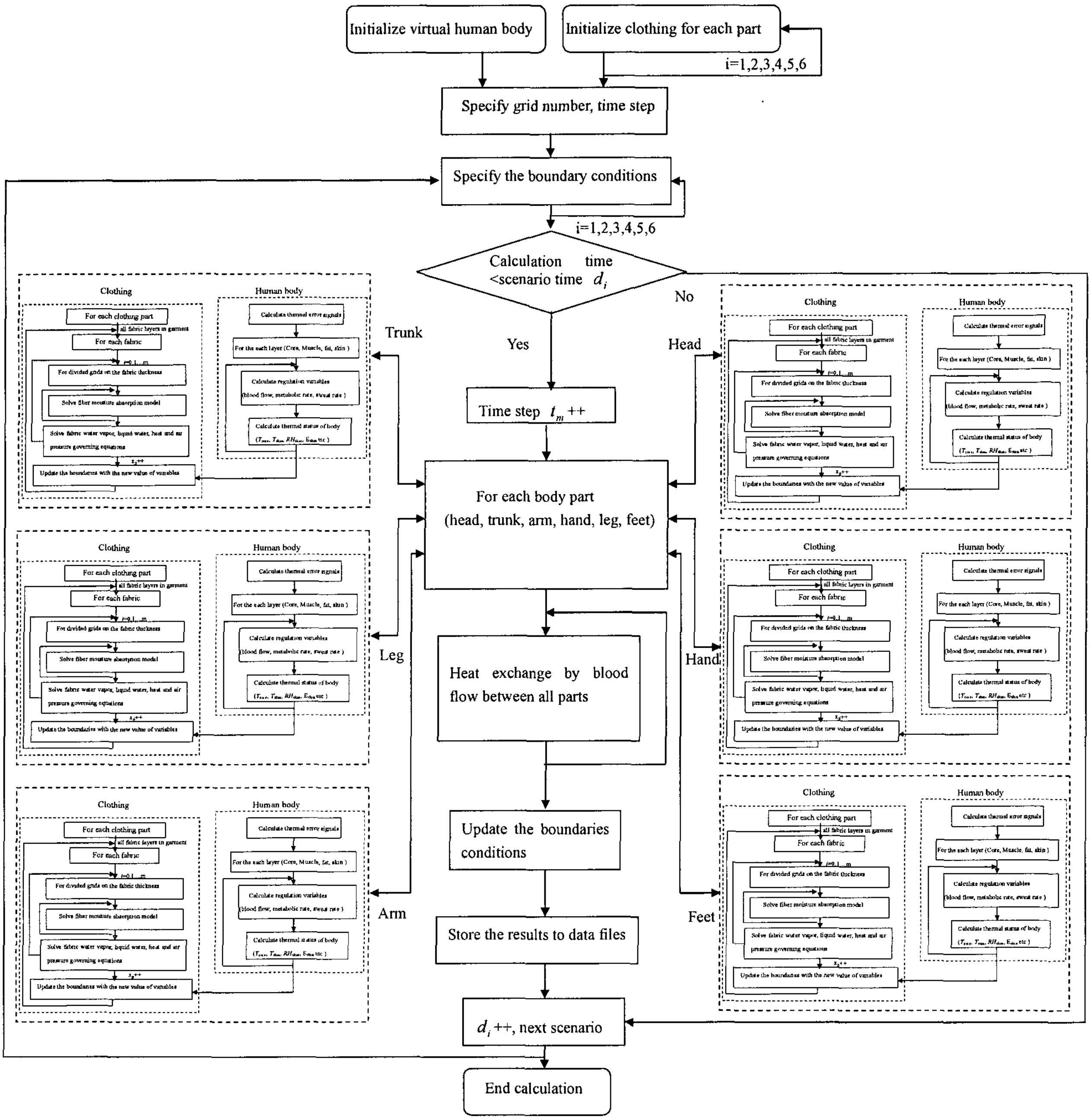


Figure 4.5 Multi-dimensional computational scheme

2) Solve the fabric heat and moisture model for all the divided clothing subsystem. From the step of locating the volume point (Δx) on the meshed domain of the fabric

to the step of solving the equations in the fabric model in the one-dimensional computational scheme, the computation iterates for all the divided clothing subsystems to obtain all the solutions and generate the thermal status of all clothing subsystems on the current time step.

3) Update the boundary conditions. The boundary conditions of the fabric model for all the clothing subsystems are automatically updated with the newly generated simulation results, like in the one-dimensional computational scheme. When the thermoregulatory model generates thermal status of body pertaining to each part, the boundary conditions between the fabric and skin are updated.

4.4 INFLUENCE OF COEFFICIENTS ON THE SIMULATION RESULTS

The accuracy of simulation results of the thermal models during the iterative computation depends on many coefficients. Basically, the simulation results are influenced by the physical properties of clothing and the physiological properties of human body. In the clothing thermal engineering design, we place the focus on the influence of physical properties of clothing on the simulation results, which are related to the textile materials and garment design, to reveal the thermal performance of clothing. Besides, the simulation results are also influenced by the boundary conditions, which give out the solution domain of computational simulation, and the mesh size and time step, which determine the accuracy of the computation. It is very important for the user to have clear concepts of these coefficients in the engineering design process.

In this section, in order to offer the reader a quantitive understanding of the influence of these properties on the thermal performance of clothing, computational experiments were carried out to show the influenced thermal values of the clothing when changing these coefficients. The clothing utilized in the computational experiments is a one-layer garment with basic physical properties, as shown in Table 4.1. The wearing protocol in the computational experiments is specified as a male person with 175 cm height, 65 kg weight wearing this garments has a slow running (2 Met) in an environment with 20 °C temperature and 60% RH for 30 minutes.

Table 4.1 Basic properties of the garment with one-layer fabric

Garment	Fiber material	Fiber radius (μm)	Fabric thickness (mm)	Fabric porosity (%)	Fabric water vapor diffusion coefficient (cm2/s)	Fabric liquid water diffusion coefficient (cm^2/s)	Fabric effective thermal conductivity (Cal/s/cm/K)
One layer fabric	Cotton	2	2.5	0.85	0.25	8.0e-9	7.8e-5

4.4.1 Influence of the physical properties of clothing

A variety of material properties of clothing are important to quantify the thermal performance of clothing for different wearing scenarios, including the water vapor diffusion coefficient (D_{fab}), effective thermal conductivity (K_t), liquid water diffusion coefficient (D_l), thickness (L) and porosity of the fabric (ε), and the radius of the fiber (R_f).

The water vapor diffusion coefficient of fabric (D_{fab}) indicates the moisture diffusion velocity and determines the water vapor concentration of the fabric. With increasing D_{fab}, the water vapor concentration is becoming higher until the saturation of moisture regain within the fibers. Since the fabric is composed by the fiber and enclosed air, D_{fab} is mainly determined by the water vapor coefficients of fiber and air.

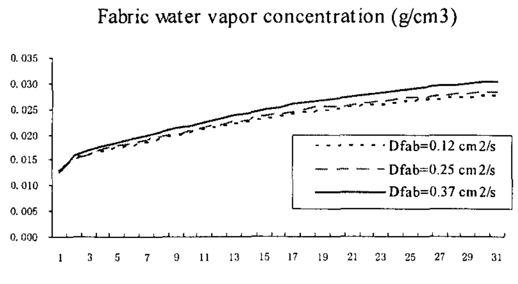
The liquid water diffusion coefficient (D_l) indicates the velocity of liquid water in diffusing through the fabric. With increasing D_l, the liquid water content will also become higher by capillary actions. As defined in Chapter 3.3.3, D_l is determined by a number of factors: surface tension (γ), contact angle (θ), effective capillary angle (α), liquid viscosity (u_l), largest effective radius of the pore in fabrics (d_c) and volume fraction of liquid water (ε_l). When the contact angle is greater than 90 °C, D_l is small and indicates that the liquid water cannot diffuse into the fabric, and the water content of fabric is very low. Furthermore, the evaporation process and the moisture sorption of fibers are further influenced by the liquid water diffusion. When the liquid water cannot diffuse into the fabric, evaporation can just occur at the fabric's lower surface and the moisture sorption of fibers is mainly determined by water vapor transport. When there is liquid diffusion in the fabric, evaporation can occur throughout the fabric and the moisture sorption of fibers is mainly determined by liquid transport [46].

The effective thermal conductivity of fabric (K_t) directly determines the transfer rate of heat flux through the fabric. With increasing K_t, the temperature of fabric is decreased to be with a smaller gradient. In the definition of K_t, as defined in Chapter 3.3.3, it is a fractional sum of the thermal conductivity of air and wetted fabrics. In order to increase the thermal insulation function of clothing, it is a common method to decrease K_t by various methods, such as increasing the porosity of fabric since the thermal conductivity of air is much lower than that of fibers.

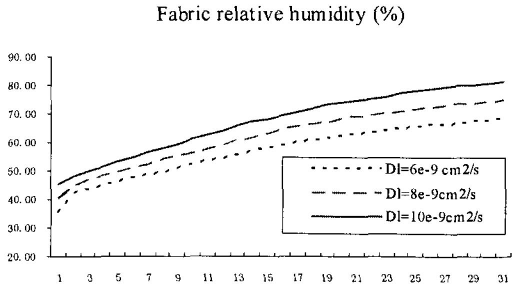
The thickness of fabric (L) has significantly influenced on the distribution of water vapor concentration, liquid water fraction volume and temperature. With greater thickness, the fabric has higher thermal and mass resistances to the heat and moisture transfer processes, and it can hence obtain obvious gradients of water vapor concentration, liquid water fraction volume and temperature through fabric thickness. The porosity of fabric (ε) has an important influence on liquid diffusion process and heat transfer process, as well as on water vapor diffusion process. Therefore, if the fabric has greater porosity, it will have more noticeable gradients of liquid water volume fraction and temperature.

The radius of fiber (R_f) can influence the process of moisture diffusion into the fibers in the fabric, and meanwhile transfer the influence to the heat equilibrium by moisture sorption/desorption. The transient period of moisture diffusion may cause an increasing pulse of water vapor concentration in the fiber with a smaller fiber diameter, and the temperature also increases during the transient moisture diffusion [46]. The influence of R_f is insignificant to the liquid diffusion process, in which the liquid water volume fraction has no obvious change. However, the liquid diffusion process can be influenced by the largest effective radius of the pore in the fabric (d_c), which indicates the pore distribution in the fabric. The smaller d_c means the smaller pore distribution and liquid permeability will decrease. The liquid water volume fraction may have greater gradient in the fabric with a smaller d_c [46].

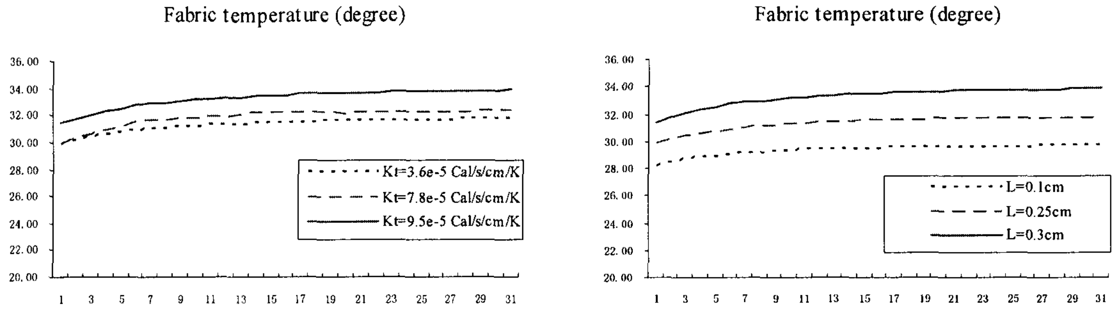
Figure 4.6 shows the influenced thermal values of the clothing in terms of the water vapor concentration (g/cm^3), relative humidity (%), temperature (degree) of the fabric by these properties (D_{fab}, D_l, K_t, L, ε and R_f) through computational experiments. In each case, the focused property is varied while others are fixed to show the influence of this property. It can be observed that the thermal values of clothing are influenced as the physical mechanisms discussed above when the property is specified with different values.



(a) Water vapor diffusion coefficient of the fabric (D_{fab})

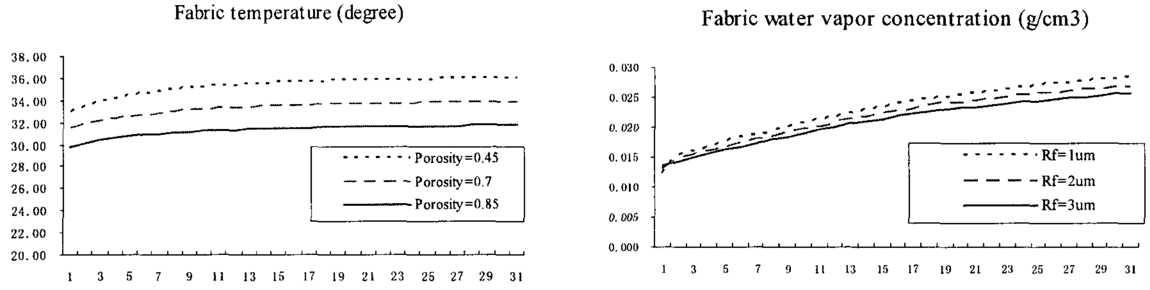


(b) Liquid water diffusion coefficient of the fabric (D_l)



(c) Effective thermal conductivity of the fabric (K_t)

(d) Thickness of the fabric (L)



(e) Porosity of the fabric (ε)

(f) Radius of the fiber (R_f)

Figure 4.6 Influence of physical properties on the thermal performance of clothing

These physical parameters may have a direct influence on one or more heat and mass transfer process. However, it should be noticed that the heat and moisture transfer processes are interactive and the effect may be transferrable due to the interactions. Also, the influence by one or more parameters at the same time is very complex and it is why the user needs to validate the thermal performance of clothing by computational experiments.

4.4.2 Influence of the boundary conditions

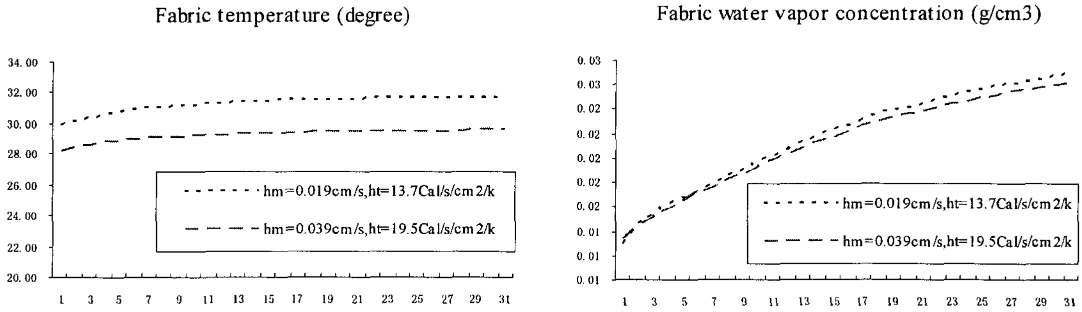
The numerical simulation requires specifications of the boundary conditions to define the interested or meaningful solution domain for practical problems. Different boundary conditions for different physical processes in boundary regions may cause quite different simulation results. Improper sets of boundary conditions may introduce errors to the simulation system, and improper value specifications of the coefficients in the boundary conditions may greatly change the simulation results.

The boundary conditions of the models of clothing and human body, which is discussed in Chapter 3.4, require specifications of thermal status of fabrics, the skin and climatic conditions, including the connective heat and mass transfer coefficients, and the wearing mode coefficients. The thermal status of fabrics and the skin including the temperature, water vapor concentration, liquid water volume fraction, air pressure and evaporative heat (T_{fi} , T_{sk} , C_a , C_{sk} , ε_l , P, E_{sk}) are automatically generated by the simulation models at each time step and their values in the boundary condition are updated in real-time. The climatic conditions refer to the temperature, water vapor concentration and air pressure of the environment (T_e, C_e, P_e) in each wearing scenario, and the connective heat and mass transfer coefficients (h_t, h_m) are specified by the user for each wearing scenario according to wearing situations. The wearing feature coefficients including the proportion of clothing-covered area ratio (p_A), the proportion of dry heat loss at the clothing-covered area (p_h), and the proportion of moisture vapor from the skin at the clothing-covered area (p_m), are determined by the clothing style, fitting status and wearing mode during the wearing time. A user should specify the values of p_h and p_m according to their estimation of the pumping effects during wear, which is related to the levels of snugness, opening at neckline, cuff and trouser, as well as the level of body motion. Attention should be paid to the specifications of connective heat and mass transfer coefficients and the wearing feature coefficients, which requires estimation from experiences and is every important in the engineering design.

Connective heat and mass transfer coefficients

The connective heat and mass transfer coefficients (h_t, h_m) in the thermal-dynamical field are empirical variables to calculate the transfer rates of heat and mass by convection from the solid to a surrounding fluid with Newton's law. Theoretically, they are functions of the system geometry and the motion and properties of the fluid, and usually are reported in dimensionless values which can be numerically expressed with empirical equations. There are many experiments for determining the connective heat and mass transfer coefficients. As discussed in Chapter 3.4, a available set of empirical values of the connective heat and mass transfer coefficients for the textile material in surrounding environment (h_t, h_m) respectively are 810 W/m^2 K and 0.137 m/s [47]. Also there are different methods for dealing with the evaluation of the heat and mass transfer coefficients, such as the calculation method reported by Yigit and Li, in which (h_t, h_m) can be calculated as: 1)for the fabric boundary exposed to the environment, $h_t = 3.43 + 5.93v$ (v is velocity in m/s) and $h_m = h_t / 1084.86$; 2) for the fabric boundary with a air layer, $h_t = k_a / t_a$ (k_a is heat conductivity of air, t_a is the thickness of the air layer) and $h_m = D_a / t_a$ (ka is moisture diffusion coefficient of air of air) [77, 139]. The velocity is regarded as the wind velocity in body-steady situations and should add the running speed in running situations. The effect of wind can be directly taken during this mathematical definition of heat and mass transfer coefficients.

The mathematical expression of the connective heat and mass transfer process, as Equations 1.3, shows that the higher convective heat and mass transfer coefficient, the greater amount of heat and mass will be taken away by convection process. Putting back the view on the boundary conditions of the models of clothing and the human body, the convective heat and mass transfer coefficients indicate the intensity of heat and mass loss from the fabrics and the human body by convection at the boundary. For the wearing situations where have intensive convection, the convective heat and mass transfer coefficients should be specified with higher values.



(a) Temperature of the fabric

(b) Water vapor concentration of the fabric

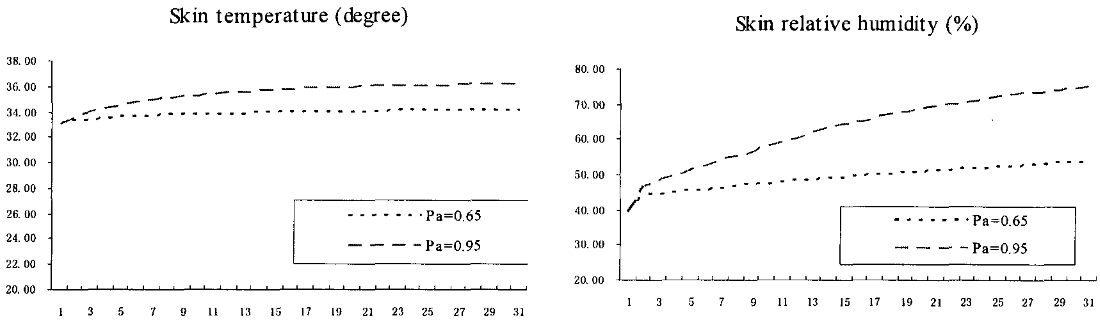
Figure 4.7 Influence of the coefficients (h_t, h_m) on the thermal performance of clothing

Through the response of boundary conditions, the temperature and water vapor concentration in the fabric, accordingly, are influenced by the values of these coefficients. Namely, the fabric whose boundaries have higher values of these coefficients will lose more heat and moisture to the surrounding micro-environment and has lower temperature and water vapor concentration. Figure 4.7 shows the influence of different specifications of h_t and h_m on the temperature and water vapor concentration of the fabric in the garment by computational experiments.

Wearing feature coefficients

The wearing feature of clothing is an important aspect to determine the coefficients in the boundary conditions, including the proportion of clothing-covered area ratio (p_A), the proportion of dry heat loss at the clothing-covered area (p_h), and the proportion of moisture vapor from the skin at the clothing-covered area (p_m). In the engineering design process, the wearing feature of clothing may vary in each wearing scenario, which mainly includes the style and fitting status and wearing mode of the clothing, as summarized in Chapter 2.3.

The style of clothing designed by the designer from the viewpoint of thermal world influences the thermal performance of clothing mostly through the coefficient of proportion of clothing-covered area ratio (p_A). For instance, garments with and without sleeves and short and long trousers have different values of the proportion of clothing-covered area ratio (p_A). The human body will directly exchange heat and mass with the environment at the area uncovered by clothing. The coefficient (p_A) with higher value may reduce heat and moisture loss from the skin, and the change rate of the temperature and relative humidity of the skin may decrease due to more area being covered by clothing. Figure 4.8 shows the influence of different specifications of the proportion of clothing-covered area ratio (p_A) on the thermal status of the human body during the wearing period by computational experiments.

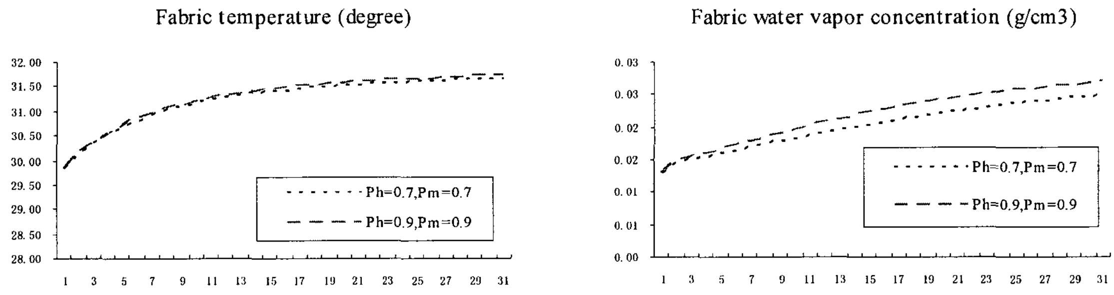


(a) Skin temperature

(b) Skin relative humidity

Figure 4.8 Influence of the coefficient (p_A) on the thermal status of the human body

The fitting status of clothing during the wearing time may be tight-fit, just-fit and loose-fit. The different fitting statuses of clothing actually have different pumping rates for the heat and mass transfer between the human body and clothing. That is, the fitting status of clothing may determine the proportion of dry heat loss at the clothing-covered area (p_h) and the proportion of moisture vapor from the skin at the clothing-covered area (p_m). The more tight-fit of clothing, the smaller pumping rate and the higher coefficient (p_h, p_m) values, which means that a greater proportion of heat and mass loss from the human body will be transferred to clothing, and the temperature and water vapor concentration of the fabric next to the skin may be increased. On the contrary, the more heat and moisture from the human body will be directly dissipated to the environment and the speed is faster without the barrier of clothing. Similarly, the wearing mode, such as the open or snugness level at neckline, cuff and trouser, and the level of body motion, such as sitting, walking and running, may influence the pumping rate and the value of these coefficients. The open wearing mode enables a higher pumping rate. That is why people will unbutton the garment when they feel hot and will button up it when they feel cold. Figure 4.9 shows the influence of different specifications of the proportion of dry heat loss at the clothing-covered area (p_h) and the proportion of moisture vapor from the skin at the clothing-covered area (p_m) on the thermal values of the garment by computational experiments.



(a) Temperature of the fabric

(b) Water vapor concentration of the fabric

Figure 4.9 Influence of the coefficients (p_h, p_m) on the thermal performance of the clothing

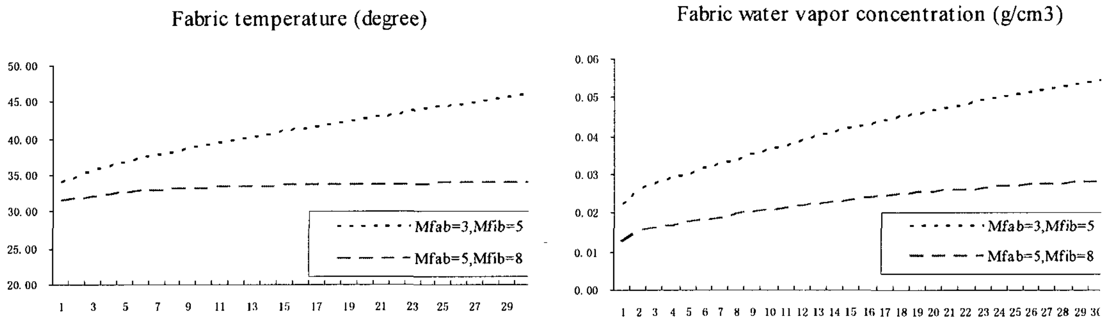
4.4.3 Influence of mesh size and time step

The grid number in meshed domain and the time step for computation have critical importance on the stability and accuracy of numerical solution of the simulation models.

The grid number decides the mesh size and the time step decides the temporal intervals between two computation steps. In the computational scheme, the clothing is meshed one-dimensionally at the fabric thickness direction and the mesh size (Δx) is calculated by $L / (m+1)$, where L is fabric thickness and m is grid number. The method of meshing the fiber is analogical at the radius direction and the mesh size of the body is decided by the body nodes concerned in the thermoregulatory model.

Due to the multi-scale features of the clothing wearing system, the mesh size of the fiber, the fabric and the human body may be different, which is also determined by the different complexity of corresponding models. In the computational scheme, the user may specify different mesh sizes respectively for the fiber, the fabric and the human body. Referring to the simulation scheme in previous studies [43, 45-47, 50], the mostly configured grid number respectively for the fabric and fiber are five and eight, which are also dealt with as default configuration for the above computational scheme. However, the user is still able to change this configuration according to the practical requirements before starting the simulation. For instance, if the thickness of fabric is thicker or the radius of fiber is bigger than that of common ones, it is wise to increase the grid number to keep an appropriate grid size to obtain an accurate solution. Furthermore, when a higher accurate level of the solution is expected or the solution gradient is out of reasonable range, it is an option to decrease the mesh size, which is helpful to decrease the error produced on each point in the domain.

In principal, with greater grid number and smaller time step, the numerical solution is more stable and accurate. However, the price to achieve this advantage is that more computational power and time has to be spent. Figure 4.10 shows the influence of different specifications of mesh sizes of fabric and fiber (M_{fab}, M_{fib}) on the thermal performance of clothing in the computational simulation. The simulation results in the case with the mesh sizes (M_{fab}=5, M_{fib}=8) are quick to converge, while in the case with the mesh sizes (M_{fab}=3, M_{fib}=5), the simulation results become divergent with the time going and the value of the results came to be far away from the reasonable range. The time step is also significant to be used to control the convergence of the simulation results. If the time step is too large, the deviation in the solution will be obvious and may leads to the abnormal stop of the simulation during the iterative computation. However, the smaller time step will meantime increase the expensed time for the simulation in times.



(a) Temperature of the fabric

(b) Water vapor concentration of the fabric

Figure 4.10 Influence of mesh size on the thermal performance of clothing

4.5 CONCLUSION

This chapter has reported the computational scheme for clothing thermal engineering design. The descretization process of the partial differential equations involved in the multi-scale models has been achieved with the implicitly finite volume method considering the flexibility in accuracy requirements of the simulation results. Based on the solving process, the one-dimensional and multi-dimensional computational schemes have been developed with explanation of the algorithms involved. The influence of physical properties, boundary condition coefficients and, mesh size and time step on the simulation results has been addressed so than the user can control the thermal performance of clothing and the accuracy of simulation results. With the computational scheme, the thermal behaviors in the clothing wearing system can be numerically simulated and the computer-aided clothing thermal engineering design is able to be realized.

CHAPTER 5 SOFTWARE ARCHITECTURE FOR CLOTHING THERMAL ENGINEERING CAD SYSTEM

5.1 INTRODUCTION

The two key parts of clothing thermal engineering design are computational simulation and computer-aided software system. In Chapter 4 and Chapter 5, the multi-scale simulation models and computational scheme have been established to enable the computational simulation in clothing thermal engineering design. Based on that capacity, the clothing thermal engineering design can be realized with the aid of computer software system, which provides the user with friendly functionalities including life-oriented design procedure, simulation management, visualized analysis, thermal performance evaluation and engineering database support. With the computer aided software system, users can finish their design and configuration of the wearing scenarios, execute computational simulation, obtain scientific and effective feedback from the visualized analysis and evaluation, and thus iteratively improve their design, and finally produce the products with desirable thermal performance.

This chapter first gives the views on the user requirements of the clothing thermal engineering CAD system (CTE-CAD), and then proposes an innovative software architecture, which addresses the functional components and their relationship in the CTE-CAD system. In the following parts, the design and realization of the system with object-oriented method is reported, and the engineering database supporting the software system is designed to facilitate clothing thermal engineering design.

5.2 USER REQUIREMENTS OF THE CTE-CAD SYSTEM

The CTE-CAD system is a specific kind of computer aided engineering software system which has become increasingly powerful, complex, useful and diverse and has a wide range of applications in using computer aided methods and/or tools in the solution of process/design engineering problems. These software systems are commonly developed by transforming the computer aided engineering methods via models to provide information/knowledge for scientific decision-making. In principle, they should be able to correctly interpret the user-specified data, integrate involved software components, solve the specific problem, generate results, and provide analysis/evaluation reports to the user. Besides that general requirement, it is necessary to identify all specific user requirements for clothing thermal engineering design in advance when developing the CTE-CAD system. These requirements are fundamental documents to develop the software architecture and consider what functionaries the software system should provide to aid the user in engineering design. Following are the description of the specific user requirements for clothing thermal engineering design in terms of functional requirements, performance requirements, input and out requirements, data management requirements.

5.2.1 Functional requirements

Functional requirements are actually the definition of communication modes between the user and computer, which addresses what can be performed by end users on the computer and meanwhile what information can be received from end users into the computer. A software system for computer aided engineering design is essential to offer functionalities, which enable end users to define and solve their problems and acquire all necessary information to trigger the numerical solution process. However, the increased complexity of functionalities will lead to more difficulty in user-operation and user-understanding. A series of scientific and user-friendly functionalities are required in the engineering design process, which need a deep understanding of the design principles and user habits, and effectively translate them into computer expression.

Based on such concerns and efforts, in order to achieve clothing thermal engineering design, the software system should provide the user with functionalities in three categories of 1) design and configuration; 2) perform simulation, and 3) analysis and evaluation with reference to the principles of define problems, solve problems and produce solution results, as shown in Figure 5.1. In the design and configuration phase, end users are able to define their problem by the functionalities including clothing design, human body definition, wearing specification, boundary condition specification and control information configuration. Then end users can solve the defined problem by performing simulation and obtain solution results. In the analysis and evaluation phase, end users need the functionalities including data visualization, data animation and performance evaluation to obtain scientific and useful feedback to achieve the solution of defined problems. The detailed description of these functionalities can be found in Table 5.1.

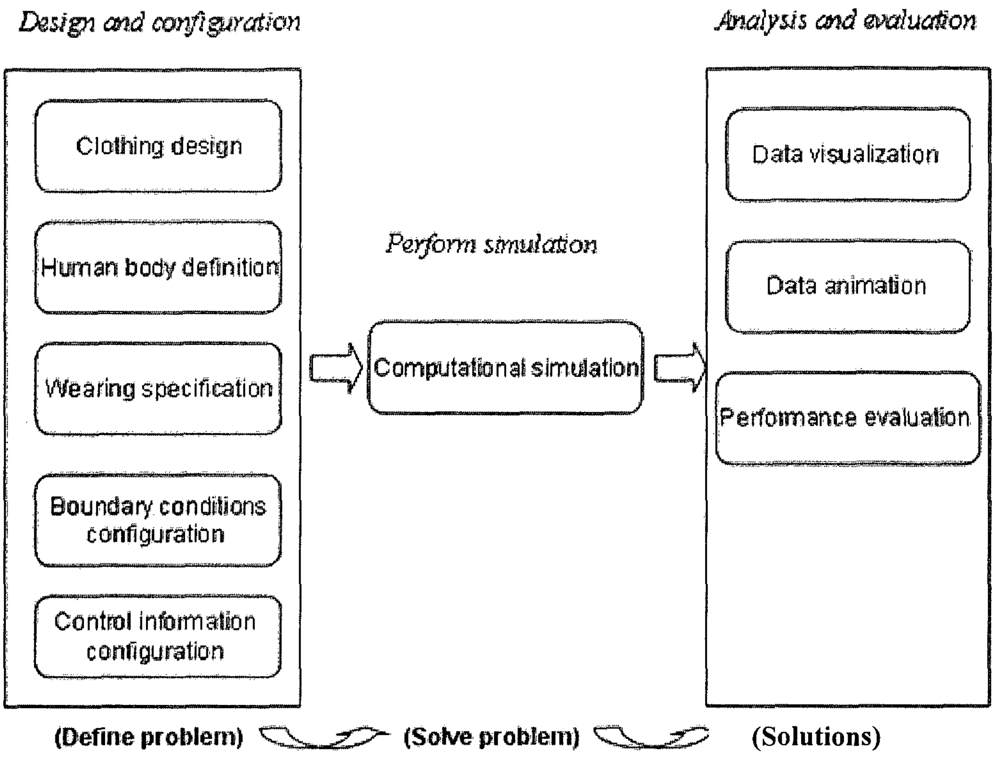


Figure 5.1 Functional requirements in clothing thermal engineering design

Table 5.1 Description of required functionalities of the CTE-CAD system

Functionalities	Description	Output
Clothing design	Clothing is designed with accordant to practical clothing design principles, including clothing style, fiber material, fabric design and functional treatment.	• clothing style; • fabric layers; • fiber material and construction method of each fabric layer; • functional treatment
Human body definition	The human body wearing the clothing is defined	• body physical data • body physiological data
Wearing specification	Specify all wearing scenarios, including the wearing environment, body activity and wearing duration	• climatic information of environment • metabolic rate

		• stage time
Boundary condition configuration	For the specialist user, he/she can adjust the coefficient's value in boundary conditions based on the default ones corresponding to specific situations	• boundary conditions of fabric-skin • boundary condition of fabric-fabric
Control information configuration	Configure the necessary control information for numerical solution	• time step • grid number • data saving frequency
Computational simulation	Computational simulation is performed to simulate the wearing system and generate solution results	• thermal values of clothing and human body in spatial and temporal direction
Data visualization	Simulation results are visualized in 2D or 3D charts for easily read and understood	• 2D charts • 3D charts
Data animation	Simulation results are animated in a virtual space to give a more direct view of simulated wearing system	• 3D virtual space • Dynamic refreshed colors with corresponding to simulation results
Performance evaluation	Evaluate the thermal comfort of human body	• Thermal sensation • Moisture sensation • Thermal comfort

From the above description, it can be observed that these required functionalities offer end users with the ability to define their design concept and validate it through simulation and visualized analysis, and these functionalities will transfer the user input information and output new information. The output information in the design and configuration phase is the input data for the model simulation. That in the perform simulation phase is solution results for analysis, and that in the analysis and performance phase is useful information from the simulation results and feedback given to end users.

5.2.2 Performance requirements

With the functionalities discussed above, the software system enables end users to finish the information input and obtain output results. However, it just concentrates on functionally accomplishing the clothing thermal engineering and design process in a computer-aided way. The quality of provided functionalities and the performance of released software system need to be further considered to produce more potential benefits to end users. The performance requirements of the software system for CTE-CAD are identified in terms of efficiency, usability, accuracy and flexibility, as shown in Figure 5.2.

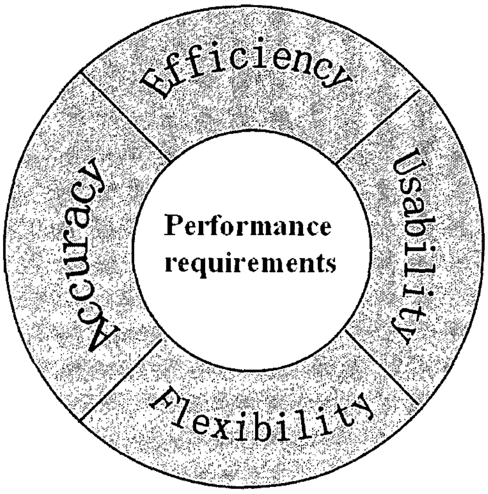


Figure 5.2 Performance requirements of the software system for CTE-CAD

Efficiency requirement

The CTE-CAD system should be able to help end users quickly finish the definition of their problems and find the solution of their problems so that the design cycle can be effectively shortened due to the fast computing speed of the computer. The efficiency of the software system can be improved through the software itself and the hardware configuration of computer. As for the software approach, it is possible to achieve higher efficiency by: 1) easily-understood design/operation procedure and intuitive user interfaces; 2) less time spent for simulation, which demands on the mesh and time step strategy and algorithm structure in the computational scheme; 3) easily stored and retrieved design data and simulation results; 4) easily read and analyzed graphical presentation of simulation results. As for the hardware approach, increased computing power by better hardware configuration, such as much more RAM, higher clock speed and a larger hard drive, can effective reduce the simulation time consumed and improve the speed of response to all functionalities.

Usability requirement

The usability of the CTE-CAD system can be regarded as the direct index of quality of the communication and interface between the end user and the computer, which can be required in terms of operation model, runtime environment, user group and user training.

1) Operation model which refers to how and what the end user can operate with the software tool directly determines its complexity level facing the end user. A user-friendly and reasonable operation model should be developed to provide good guidelines for all end users even if they have little specialized knowledge and engineering experience.
2) The runtime environment is important for the software system to show its

availability to the user with the computer, including the operation system of computer and software configuration. The developer needs to concern and decide the runtime environment of the software system before the development, which should be convenient and easily accessible for the end user.

3) In the past, the modeling tools were restricted to a very small number of engineers who had highly specialized knowledge/experience. By incorporating the sophisticated algorithms into widely available, industry standard computer aided tools, the user group of this software should be extensive to more general users with/without expertise backgrounds to make use of state-of-the-art computing and modeling tools.
4) The user interfaces are required to be intuitive and use-friendly with easily understood content and layout so that the end user can be effectively educated or trained to use the software system.

Accuracy requirement

The CTE-CAD system is a model-based and simulation-based system with scientific computation. The accuracy of the simulation results and corresponding visualization are critically required to generate useful and accurate feedback to the end user. The accuracy of the software system must be validated with the data from applications before final release to assure the fidelity in extensive applications. The accuracy requirement of the system can be met by the three main aspects of input information, solution algorithm and information storage and retrieval format.

1) As the resource of the data input into the model, the input information directly obtained from the end user need to be accurate. The strategy of avoiding wrong input data or inappropriate values is required.
2) The simulation algorithm is the essential aspect to control the accuracy of the simulation results, which is detailed to each time step and meshed point of the solution domain. It is necessary to have a scientific computational scheme and intelligent time step and mesh strategy.
3) The information generated in the simulation process needs an effective storage and retrieval mode so that the visualization is the actual presentation of actual simulation results.

Flexibility requirement

The flexibility of the software system can be mainly evaluated from the aspects of convenient update of itself and possible corporation with other software systems. In order to achieve functionality extension or update corresponding to new user requirements in future with low cost, the architecture of the software system should have the flexibility to add functionalities without influencing the previous functionalities and breaking the previous software structure. The end user can easily accept the updated or new functionalities without too many efforts. On the other hand, the software system may develop corporation with other software systems to utilize and share information so as to maximize the benefits to end users. For instance, the actual body shape and properties from other systems can be exported into this software system for the body definition and visualization, the simulation results of this software system can also be imported into other systems for virtual visualization and analysis.

5.2.3 Input and output requirement

The input and output requirements of the software define the content of communication between the end user and the computer, which address what information needs to be obtained from the end user and what results can be delivered to the end user. The input and output requirements have been mentioned as functionalities of the software system in the phase of define problem and solution results, as described in Section 5.2.1. Here they will be further discussed in detail to show what will be involved and how they are presented to the end user.

Input requirement

The CTE-CAD system requires end users to input their design scheme into the computer and generates feedback to them for validating their design scheme. The input information consists of the design information of clothing, the human body and wearing scenarios, and the configuration information for simulation. All involved information can be input by the parametric description method. And importantly, as an engineering design tool, the engineering meaning of the input information should be considered in terms of effective value range and engineering unit, which has a significant influence on the simulation results and should be offered to the end user to consciously avoid wrong input and make effective design in the process of defining problem. That requirement is also an important feature of engineering design tools which is different from that of other software tools. The input mediums for end users provided by the software are graphic user interfaces and can easily obtain input information by the mouse and keyboard.

Output requirement

In order to manage simulation and deliver the end user simulation results, the CTE-CAD system should have a series of outputs including design case, self-document, simulation results data, and data visualization and animation. The design case is to record all the design information and configuration information in a design case and to be stored in a case file. The users can load and review/re-use their previous design in future. The self-document is to document all materials and structures of clothing, the human body and wearing scenarios, as well as the configuration for simulation used in the computational simulation with their parametric description and readable explanation. This documentation is useful for the end user to directly check and ensure whether their input information is correctly obtained for computational simulation, since there are some chances to get incorrect information by users' mistake or misunderstanding. Simulation results data refers to all the thermal distribution data of clothing and human body generated from the solution of the simulation models in temporal and spatial coordinates according to the configuration of simulation. This data usually has a large volume and it is very difficult for users to read and directly obtain information from the tedious data. Hence the software system should be able to output the simulation results in visualized or animated forms.

5.2.4 Data manage ability requirement

A large amount of data is involved in the CTE-CAD system during the input and output process. It is quite important for this system to have a data manage ability for effective storage and retrieval. As discussed in the above section, during the input process end users will perform their design and input the properties of clothing material/human body/wearing scenario. The clothing design deals with a great number of raw materials, semi products and final products, and the human body has different properties across different persons. The fundamental technical specifications of clothing design and human body with engineering meanings are very important for both the user and the software system. The user should be able to easily store and retrieve these fundamental technical specifications. The software system is required to provide the user this ability by the support of an engineering database. This engineering database is developed to help the user effectively manage or utilize engineering technical specifications of clothing and human body according to the engineering design principles, for instance, the clothing is designed from fiber, fabric to garment.

5.3 SOFTWARE ARCHITECTURE

Similar to most of software systems for engineering design, the CTE-CAD system is developed in the functional module flow of pre-processing, computational simulation and post processing, and communicates with end users through user graphic interfaces. In order to offer a friendly operation model and consider the design principles in clothing making, a special functional module of life-oriented design is supplied in the pre-processing for end users to finish clothing functional design and specification of wearing scenarios. The user requirements of the CTE-CAD system identified in the above section are respectively responded in these modules, as illustrated in Figure 5.3. For instance, the functional requirements in terms of defining problems, solving problems and simulation results are directly realized in the modules of life-oriented design, computational simulation and post processing. The data management ability is required in the modules of life-oriented design, pre-processing, computational simulation and post processing.

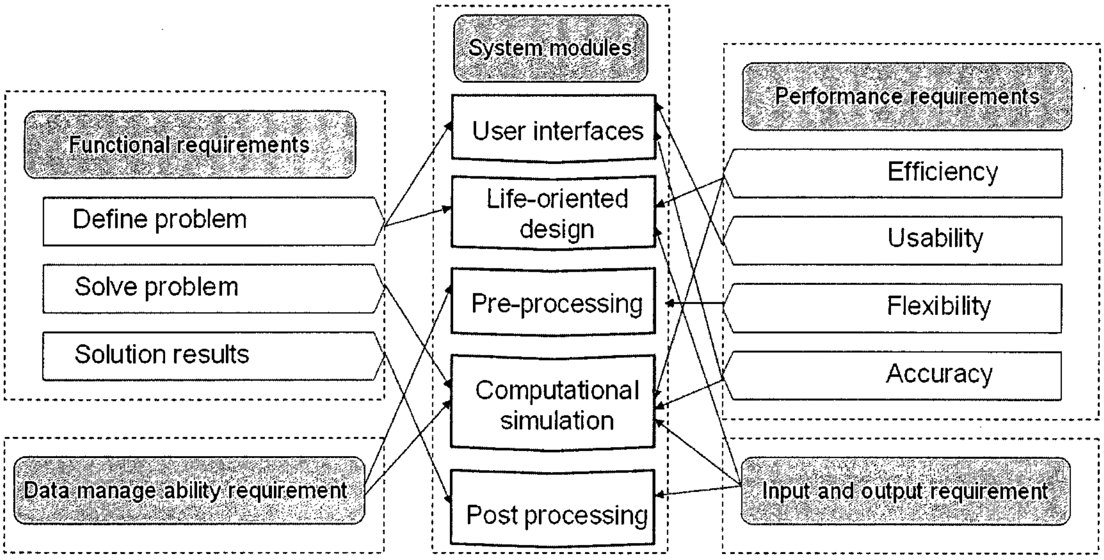


Figure 5.3 Corresponding of user requirements in system modules

The individual functional modules of the CTE-CAD system, which are also regarded as software components, are systematically collected through a defined architecture. Figure 5.4 shows the architecture of the CTE-CAD system, which illustrates the relationships and interactions between the functional modules. The software system obtains input information from users through user graphic interfaces in the life-oriented design module which is supported by an engineering database, deals with the input information in pre-processing module, executes numerical solver in computational simulation, and represents the simulation results in post processing module. Considering the software working environments of most people, this software system is designed to run on Windows OS.

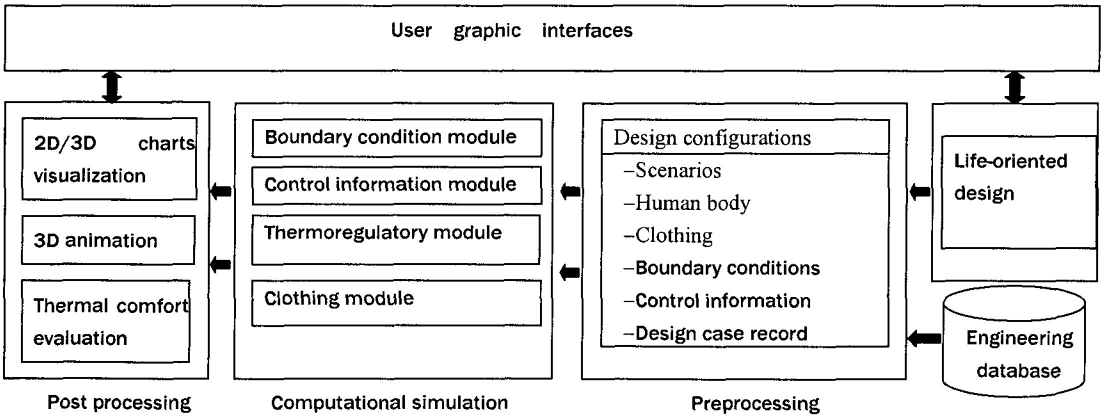


Figure 5.4 Architecture of the CTE-CAD software system

5.3.1 User graphic interfaces

User graphic interfaces, which are easily understood and operated by users, are the medium of communication between the end user and this software system. Besides being an important tool for the end users to define their problem, the content of the user graphic interfaces also influences the usability and accuracy of the software system. As shown in Figure 5.5, in the development of user graphic interfaces, the number and content of interfaces are determined by the design procedure, system functionalities, characteristic data and engineering design principles. The design procedure and system functionalities are main consideration when designing the titles of interfaces. In order to obtain engineering data with meaningful values, the input of characteristic data is provided with physical units and the input dialogue is settled with a value range to avoid ineffective input. The user graphic interfaces are mainly needed in the functional modules of life-oriented design and post processing to serve the end user.

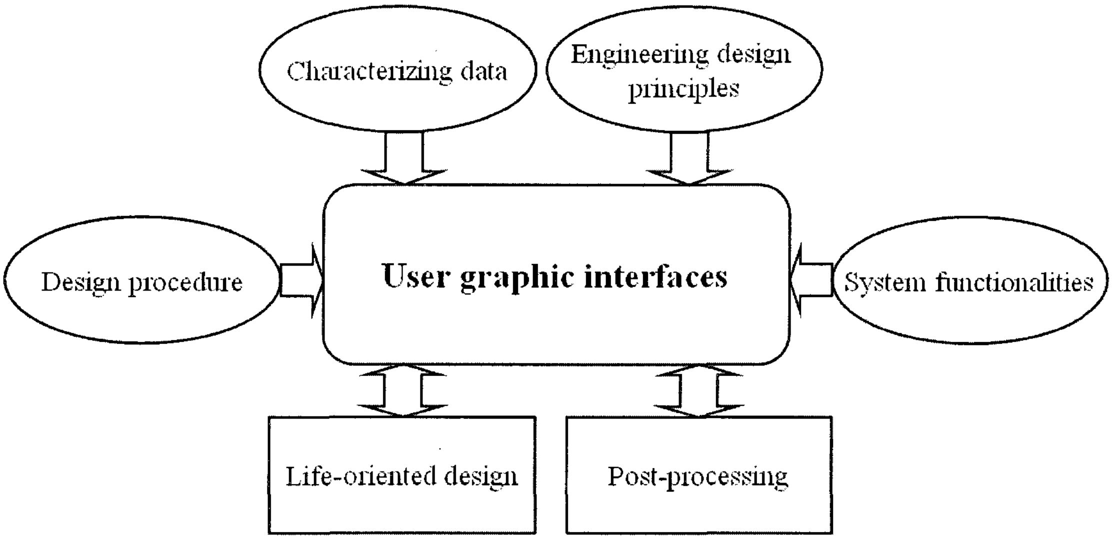


Figure 5.5 Development of user graphic interfaces

5.3.2 Life-oriented design

A friendly and effective operation model/design procedure is necessary for the functionalities of the CTE-CAD system, is also required by the consideration of its performance. This system presents a life-oriented design procedure for end users, which will guide them to finish clothing thermal design through a series of user graphic interfaces as specifying wearing situations for daily life.

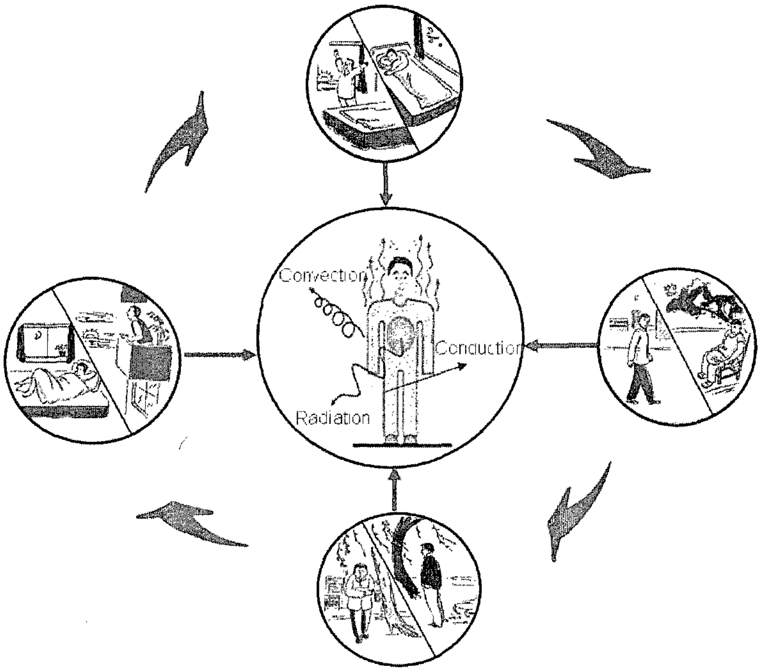


Figure 5.6 Wearing scenarios of people in daily life (revised from [142])

Assuming that when people come to wear clothing before opening the wardrobe, the expected wearing scenario will appear in their mind, including the following information (illustrated in Figure 5.6): what activities are going to attend? What are the climatic conditions for the activities? Who will wear this clothing, and what is the physical, physiological and psychological status of the wearer? These questions detect whether the thermal functions of clothing are suitable for the expected wearing scenario, and are also the issues needed to be considered in the clothing thermal functional design.

With reference to these issues, this system presents the design procedure as the sequential specification of "Activity", "Environment", "Wearer" and "Garment". The designers can follow this flow to finish their designs according to the wearing protocol. Figure 5.7 shows an example of wearing protocol, including the information of environment, wearer, activity and clothing. In the design process of clothing, the design principles are applied in the garment design process. For instance, the garment is designed with hierarchical structure of fiber→fabric→garment, a garment may be constructed by one or more fabric layers, and a fabric layer may be designed by one or more fiber materials and may have functional treatments. Meanwhile, the design process is supported by an engineering database, which will be discussed in Section 5.5. At each step during the design process, the engineering database is provided for querying, acquiring and saving the technical information of the climatic conditions, human body and clothing materials.

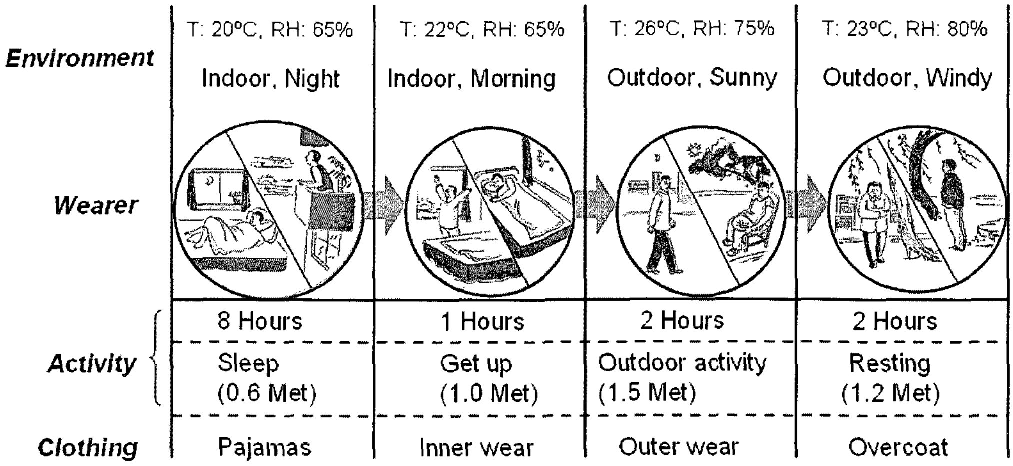


Figure 5.7 A example of wearing protocol

1) Activity

This interface specifies the activities which are going to be performed, the duration of each activity and the metabolic rate of human body when wearing the designed clothing. The human body's metabolic rate in a series of typical activities has been listed in Table 2.1. The end user can arrange an activity schedule with reference to the metabolic rate of each activity.

2) Environment

Through this interface the user is able to locate the virtual wearer in any expected place by setting the local climatic variables of temperature, relative humidity and wind velocity. If the end user is not familiar with the climatic conditions of a particular place and time, he/she can retrieve it from the engineering database with the query conditions of location, date and time. Furthermore, each activity scheduled by the user can be specified in different climatic conditions.

3) Wearer

The wearer is defined by a set of physical, physiological and psychological parameters and can be accessed from the engineering database by the categorized conditions of gender, age and race. The virtual human body can be customized for any kind of person by the definition of physical and physiological parameters. That flexibility is very helpful for the designer to design the clothing and analyze the thermal performance of the clothing for any targeted users.

4) Clothing

The clothing is designed to be worn on the virtual wearer with the order of garment by garment. In each garment design, the first step for the user is to choose the clothing style and fitting status of the desirable clothing. Then, the garment is designed by following the design principles. In this procedure, the user can either define new fibers, fabrics and garments through the interfaces by a set of parameters which describe its structural, physical and thermal features, or obtain the existing materials from the engineering database. The innovative technology/materials, such as membrane, phase change material, heating fabric and moisture management treatment, can also be applied in the garment design by giving the values of physical properties and parameters.

5.3.3 Pre-processing module

In the life-oriented design procedure, a great deal of information may be obtained by the input and operation of end users on the interfaces. This information will be used to initialize the computational simulation of specified wearing scenarios. However, the great amount of obtained information is not easy to be correctly transferred into the computational module without effective processing and management. The pre-processing module serves to deal with the obtained information from end users and classify them into different categories in terms of activity, environment, wearer and clothing, as illustrated in Figure 5.8. Each category of information consists of scientific data in the relevant areas that are essential to derive numerical solutions of the models.

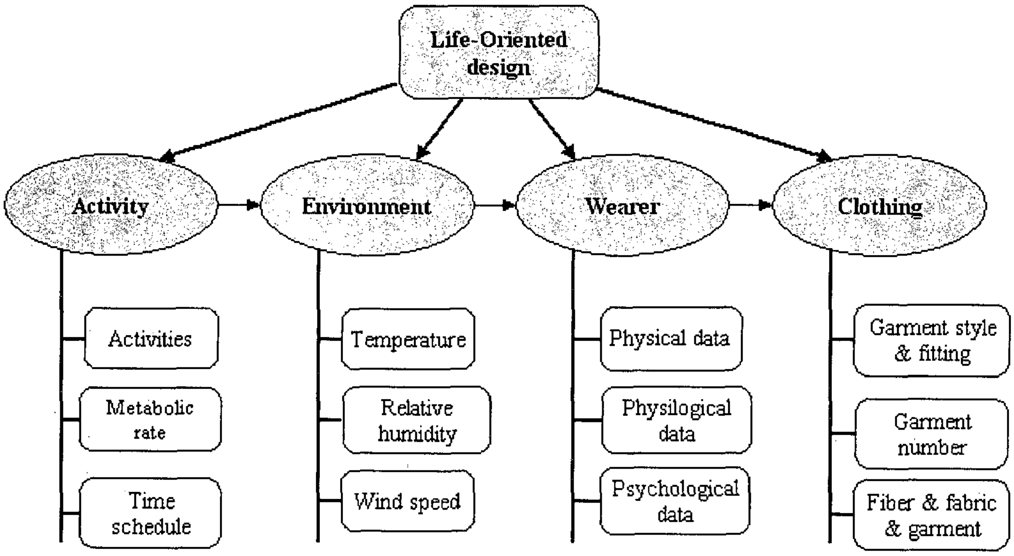


Figure 5.8 Categorized information obtained in life-oriented design procedure

In the categories of wearer and clothing, the information in an aspect may be a collection of data. For instance, the physical data, physiological data and psychological data in wearer and, the fiber, fabric, garment in clothing all are data collections. Meanwhile, all the functional treatments on each fabric are recorded and included in the information of fabric using to enable corresponding description models.

In order to achieve an open and flexible architecture of this software, the objects involved in the wearing scenarios are encapsulated into Classes, which will be discussed in detail in Section 5.3. The categorized sets of information are consequently used to initialize all the Classes after unit transformation. This pre-processing of obtained information enables the user inputs to be used effectively and correctly.

Another important role of the pre-processing module is to record the input information. The input information is recorded into two types of files which are respectively project design file and input record file. The project design file aims to record all of the design in a project including the design configuration of climatic conditions, human body and clothing materials. The detailed format description is illustrated in Table 5.2. This project design file is essential for end users to re-load the previous design cases and review/reuse previous design configurations. The input record file aims to record the input information from the end user, and this information is going to be transferred into the computational simulation, whose structure is illustrated in Table 5.3. This input record file is very useful for end users to check their input during the design procedure and verify the correctness of the data which will be used. That is an important effort to meet the accuracy requirement of the system performance.

Table 5.2 Format description of the project design file

Involved simulation model	local temperature, liquid, water vapor, pressure, membrane, PCM, self heating, radiation, human body, comfort: Boolean
Fiber list	Fiber number
	Fiber properties: float
Membrane list	Membrane number
	Membrane properties: list
PCM list	PCM number
	PCM properties: float
Heating fabric	Selected: Boolean
	Temperature control point: float
Fabric list	fabric number
	Fabric properties: float
	Fiber composition: list
	Membrane: list
	PCM: list
Garment list	Garment list
	Garment properties: float
	Fabric components: list
Human body	Physical properties: float Physiological properties: float Psychological properties: float
Wearing scenarios	Stage number
	Activity: float Wearing Garment： list Climatic conditions: float Boundary conditions: float
Control information	Time step: float Grid number: integration Initial value: float

Table 5.3 Structure of the input record file

<table>
<tr><th colspan="4">Fluid information</th></tr>
<tr><td colspan="2">Water vapor</td><td colspan="2">Liquid water</td></tr>
<tr><th colspan="4">Clothing information</th></tr>
<tr><td rowspan="4">Garment</td><td colspan="2" rowspan="4">Fabric</td><td>Fiber</td></tr>
<tr><td>Membrane</td></tr>
<tr><td>PCM</td></tr>
<tr><td>Self-heating</td></tr>
<tr><th colspan="4">Human body information</th></tr>
<tr><th colspan="4">Wearing scenario information</th></tr>
<tr><td>Environment</td><td colspan="2">Clothing</td><td>Human body</td></tr>
</table>

5.3.4 Computational simulation

With the technical specifications of the clothing, human body and wearing scenarios following the life-oriented design procedure, the computational simulation is ready to be executed with the preparation of parameters being input into the involved mathematical models. The flow of computational simulation is shown in Figure 5.9.

The technical specification from the input information is transferred into the modules of clothing, body thermoregulation, boundary condition and control information. These modules deal with the received specification by transferring them from the input units to the units used in calculation, initialize the Classes defined in Section 5.3 and assign values to the parameters of each equation in the involved models. After that, the multi-structured iterative computation starts to run according to the computational scheme, which has been reported in Chapter 4.

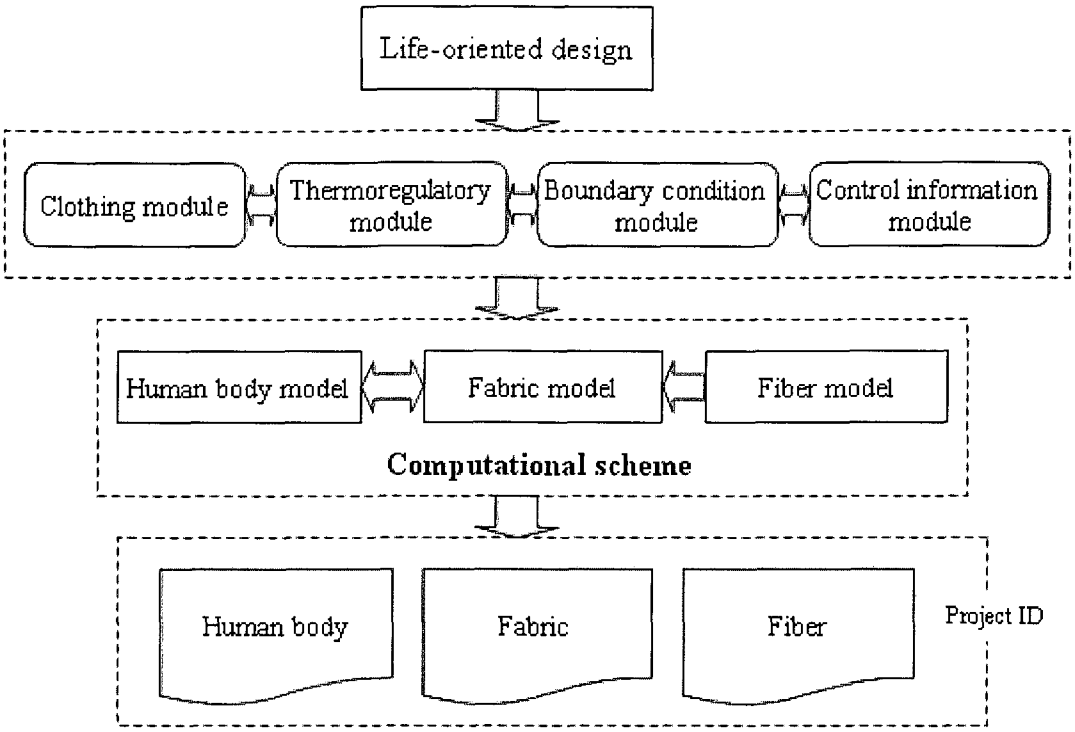


Figure 5.9 Flow of computational simulation

During the computation process, the simulation results generated from the solution of models involved are stored to data files, which are primarily important outputs to the end user. The data files mainly consist of three types of files for fiber, fabric and human body. The values of relevant thermal variables of fiber, fabric and human body is respectively stored in each file separately. The file format is that the value of each variable is stored in a volume with the temporal and spatial information. These data files are stored in a specified directory with a case ID on the storage medium in order to allow the end user to access them easily.

5.3.5 Post processing module

In the computational simulation, a large amount of simulation results has been generated and is available for the end user to retrieve. However, these numerous results are tedious and difficult to become useful information/knowledge through direct reading. In the post processing module, the simulation results are dealt in a direct and lively way by chart visualization and 3D animation to make them understandable for various users to view and evaluate the clothing thermal performance and thus obtain helpful feedback. Figure 5.10 illustrates the schematics of the graphic presentation of simulation results in the post processing module, in which the variables related to clothing thermal performance and human body thermal response can be visualized by 2D/3D charts and 3D animation.

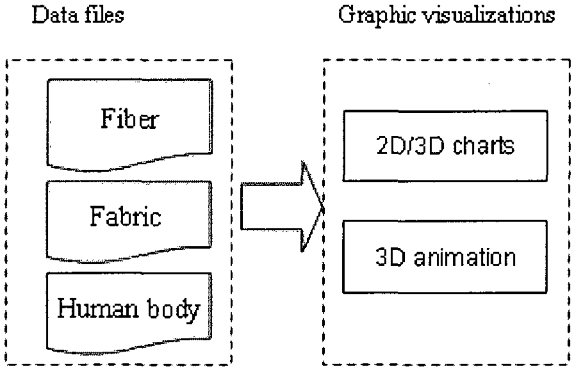


Figure 5.10 Graphic presentation of simulation results

Basically, the simulation results are interpreted by graphical presentation and deliver both 2D/3D charts to the end user. The dimension of chart is decided by the available temporal and spatial information of the results. Through the presentation with 2D/3D charts, it is easy to observe the distributions of the thermal variables of the clothing including all fabric layers and fiber materials and, all parts of the human body during the wearing scenarios. The end user is hence able to analyze the thermal performance of the clothing and thermal status of human body in a case or compare them in multiple cases to evaluate if the thermal functions of clothing are suitable for the wearing scenario and the wearer is thermal comfortable during the wearing process. If the feedback from the distribution analysis indicates the thermal performance of clothing is not desirable, the end user can further improve the design and configuration by manipulating various coefficients, as discussed in Section 4.4.

The presentation of simulation results with 3D animation also provides a virtual thermal space to animate the thermal status of clothing, human body and wearing environment. In the 3D virtual thermal space, the human body and all the fabric layers of the clothing are displayed as 3D objects separately for the body with core, or only clothing, or a body that wears the clothing. The environment is displayed as the background grids in this virtual space. The values of the thermal variables of the human body/clothing/environment such as temperature, moisture concentration and relative humidity are mapped onto the 3D objects with correspondent with special color bars. That provides a dynamic animated presentation of the thermal status of the human boy-clothing-environment system, and the end user also can preview and evaluate the thermal performance of clothing in another way.

5.4 OBJECT-ORIENTED DESIGN OF THE SOFTWARE SYSTEM

In order to make the software system open and flexible so that it can be easily maintained and updated or integrated with other system, the CTE-CAD system is designed with object-oriented technique, and is developed with C++ language, since the systems implemented with traditional languages, such as FORTRAN, COBOL or even Assembler, are very expensive to maintain. The data flow between the functional components is figured out based on the process and tasks sequence in the clothing thermal engineering design.

5.4.1 Class encapsulation and class structure

With applying the object-oriented technique to realize this software system, the related parameters and behaviors of clothing, human body and wearing scenario are encapsulated into Classes as individual objects. All the properties and relevant process methods of an object are encapsulated in a Class. There is no dependence in the data and method management between individual Class. Meanwhile, these Classes keep communication by means of calling access methods considering their relationships. The structure of encapsulated Classes in the object-oriented modeling system is shown in Figure 5.11.

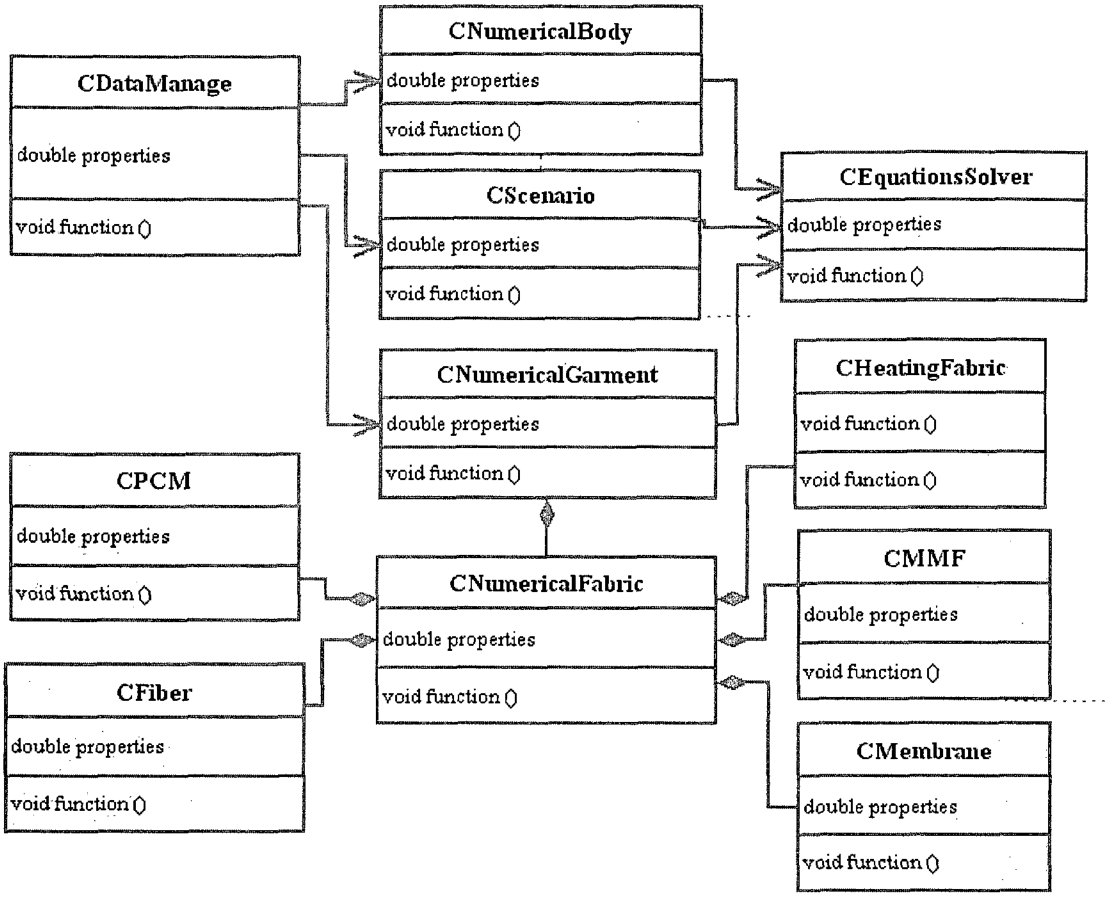


Figure 5.11 Class structure in the object-oriented modeling system

In Figure 5.11, Class CDataManage is responsible for acquiring data from the interfaces and storage media and sorting it into the particular datasets for each of the encapsulated Classes in the system, then distributing these datasets to all the objects for Class initialization before starting the computation simulation. The methods of managing data in Class CDataManage are called in all the modules in computational simulation to perform data processing and initialization of all objects.

Class CEquationsSolver acts as the public calling method, which encapsulates various numerical methods for solving the mathematical equations involved in the models of human body, clothing and scenario, such as numerical interpolation, algebraic calculation, and solving the discretized partial differential equations by building up the solution matrix.

The CNumericalGarment, CNumericalFabric and CFiber are the Class encapsulation for garment, fabric and fiber, which are the basic textile materials and products in clothing design. Class CPCM CMMF, CMembrane, and CHeatingFaric are the encapsulated objects of phase change material (PCM), Moisture management fabric (MMF), membrane and self-heating fabric, which are the materials or fabrics that can be utilized in the clothing thermal functional design. According to the design principles of clothing, there is an aggregation relationship between these Classes. CNumericalGarment is the aggregation of Class CNumericalFabric, which is the aggregation of Class CFiber, CPCM CMMF, CMembrane, and CHeatingFaric. However, the appearance of the objects of CPCM, CMMF, CMembrane, and CHeatingFaric in the object of CNumericalFabric is determined if the corresponding functional treatment has been made on the fabric. If the information of the fabric from the life-oriented design process has recorded no such functional treatment, then the corresponding Class will not be initialized.

CNumericalBody is the Class of human body encapsulating the physical, physiological and psychological properties and thermal regulating process. Class CScenario is the encapsulation of wearing scenario including the interaction information between clothing, human body and environment and the interaction methods to communication between Classes of clothing and human body.

These encapsulated Classes are greatly significant to ensure the system maintained or updated without changing the system architecture and source code structure but focusing on updating the individual Class. That is very effective in maintaining and updating the system in future and also is very economical due to reusing most of the source codes.

5.4.2 Data flow between the system components

Based on these encapsulated Classes, the system components for individual functionalities can be realized with the implementation of these Classes. Before that happens, the data flow between the system components is systematically developed to facilitate the communications between different components, which is shown in Figure 5.12 and is explained as follows:

The input data management component obtains input information from the approaches of users input, project design files and the engineering database, stores design information to data file, and export design specifications of textile material and products to the engineering database. The output data from this component flows into the components of Class initialization and Class communication. The component of computational solver receives the data flow containing the information with correct categories and units from the component of Class initialization, and the data flow with refreshed boundary interactions information from the component of Class communication. The communication with the data flow between the components of computation solver and Class communication is continuous until the end of computational simulation. The simulation results, meanwhile, are continuously stored in the data files during the process of computational simulation, and become the input information for the components of visualization and animation, and performance evaluation. The graphic files of visualized data are also saved from the component of visualization and animation. By such data input and output communications, the data flow between the system components is realized according to the relationships between the system functionalities.

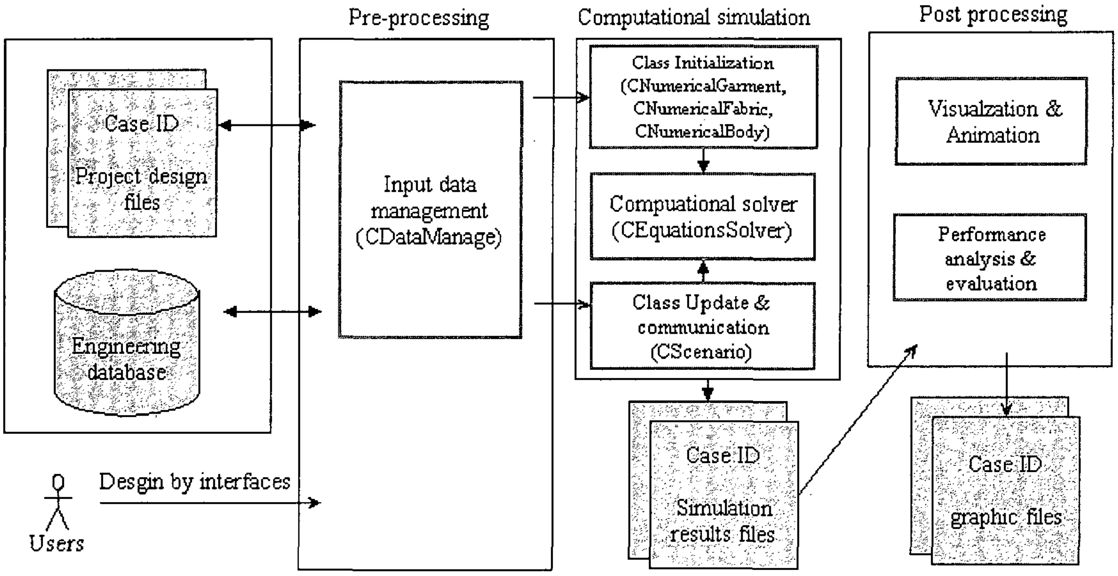


Figure 5.12 Data flow between the system components

In order to provide a better understanding of the system functionalities, the functionalities and their response sequence are illustrated in Figure 5.13. The functionality of simulation solver is performed after the implementation of the functionalities of activity schedule, wearing specification and clothing design by time order. The functionalities of visualization and analysis depend on the completion of simulation and the information from functionalities of activity schedule, wearing specification and clothing design.

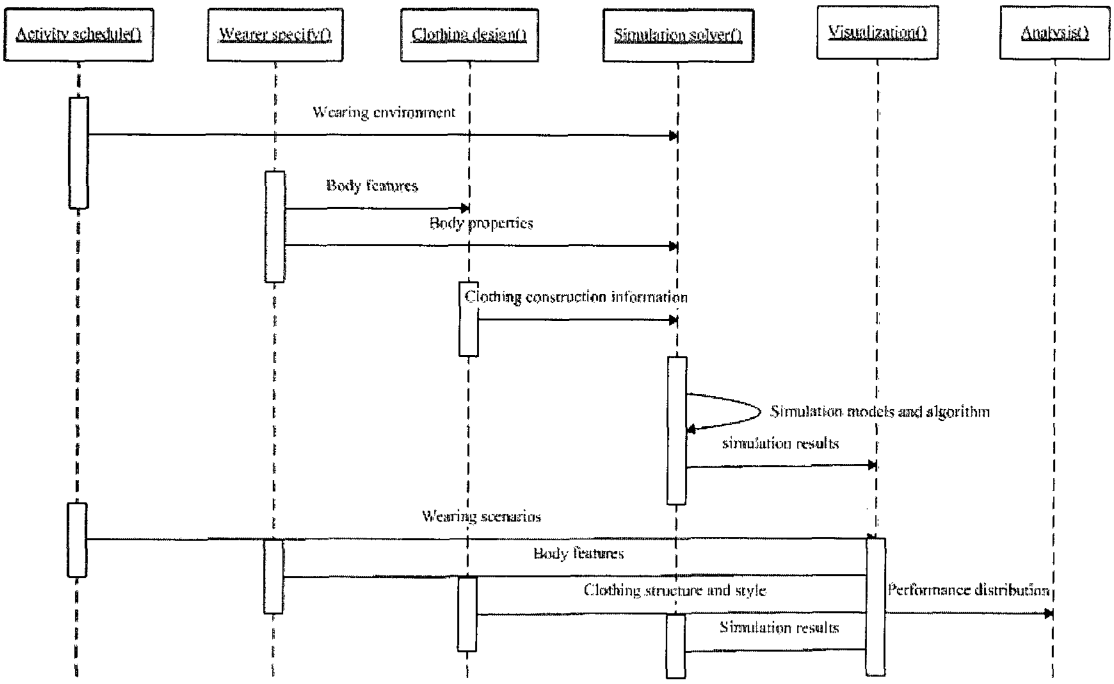


Figure 5.13 Response sequence of the functionalities

5.5 SUPPORT OF ENGINEERING DATABASE

5.5.1 Functionalities of the engineering database

During the life-oriented design process, there is a great amount of technical information including fibers, fabrics, garments and functional treatment materials (PCM, membrane), human body including physical, physiological and psychological properties, and wearing environments. It is important to support the software system with an engineering database so that the end user can effectively manage and utilize the technique information by storing and retrieving the measured or calculated properties of textile materials and human body, and acquiring the climatic conditions of a particular wearing environment in a particular place and time.

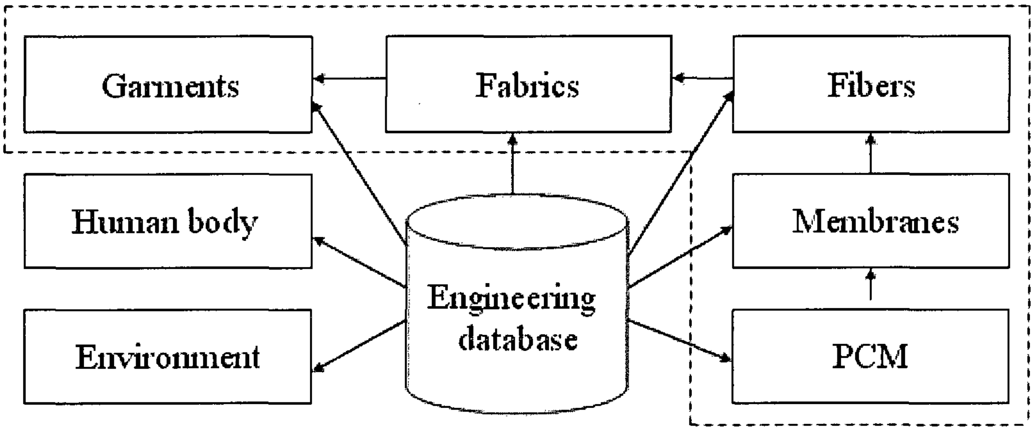


Figure 5.14 Support of the engineering database during the engineering design

The support of this engineering database is presented in all the engineering design steps of clothing, human body and wearing environment, as shown in Figure 5.14, in which the structural and properties of raw material, semi-products and final products needed in clothing design process including fiber, membrane, PCM, fabric and garment are all provided by the engineering database. This engineering database enables the end user to store, retrieve and acquire these different sets of specification and information through user graphic interfaces. Namely, each step in the engineering design process has a special database interface to store information to the database, and /or query, view and acquire information from the database. Figure 5.15 illustrates all such functionalities supported from the engineering database for the life-oriented engineering design process, in which the system component of input data management plays the role in processing the data flow between the database and user graphic interfaces.

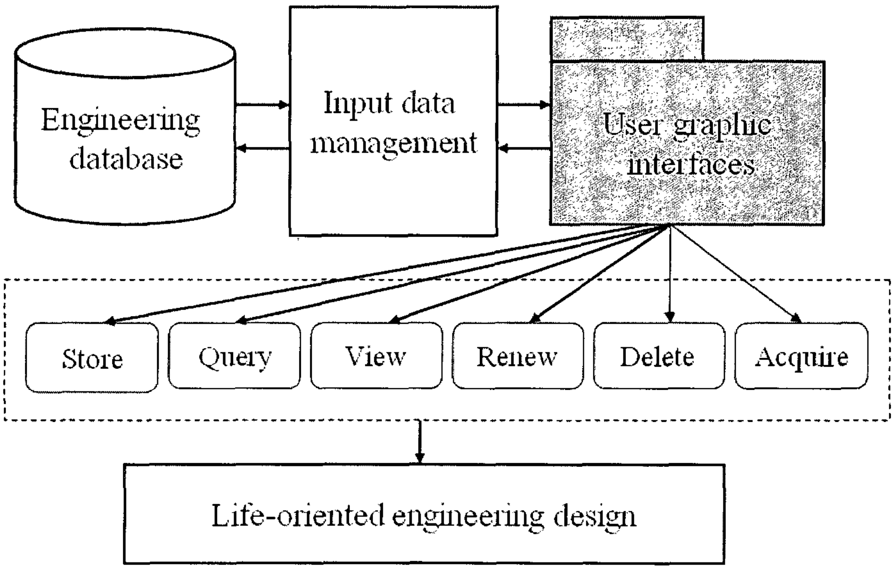


Figure 5.15 Functionalities supported from the engineering database

5.5.2 Design of the engineering database

Before the development of this engineering database, it is necessary to identify what information to be stored in the database, which is the basic requirement of a database. Table 5.4 shows all the information to be stored in the engineering database, which is related to garment, human body and wearing environment with various categories of properties. In Table 5.4, special attention needs to be paid to the structure of garment information, which includes fabric layers and each fabric layer further includes fiber, membrane, PCM and self-heating fabric. These textile materials are actually subsets of the database according to the hierarchical relationship (fiber→ fabric→garment).

Table 5.4 Information stored in the engineering database

<table>
<tr><td rowspan="4">Garment</td><td rowspan="4">• Style
• Fitting status
• Fabric layers</td><td>Fabric</td><td>Fiber</td><td>• Physical properties
• Geometrical properties
• Fluid properties</td></tr>
<tr><td rowspan="3">• Physical properties
• Structure properties
• Geometrical properties
• Fluid properties
• Functional properties
• Fiber material
• Membrane
• PCM
• Self-heating</td><td>PCM</td><td>• Physical properties
• Geometrical properties</td></tr>
<tr><td>Membrane</td><td>• Fluid properties</td></tr>
<tr><td>Self-heating fabric</td><td>• Physical properties</td></tr>
<tr><td>Human body</td><td colspan="4">• Physical properties
• Physiological properties
• Psychological properties</td></tr>
<tr><td>Wearing environment</td><td colspan="4">• Climatic conditions
• Geographical information
• Time information</td></tr>
</table>

Based on the summarization of the information stored in the engineering database and the hierarchical relationship in textile materials (garment, fabric and fiber et al.), the engineering database needs including the following components:

1) Garment DB: storing the garment information, including style, pattern and size information.

2) Human model DB: storing the physical, physiological and psychological properties of human body used in thermoregulatory models.

3) Material DB: storing the information of textile materials (fabric, fiber, membrane, PCM and self-heating fabrics) used in the garment design, including physical, structural, geometrical, fluid and functional properties.

4) Environment DB: storing the wearing environment information for the engineering design, including climatic conditions such as temperature, humidity, wind velocity and solar radiation, geographical information and time information (day-month-year).

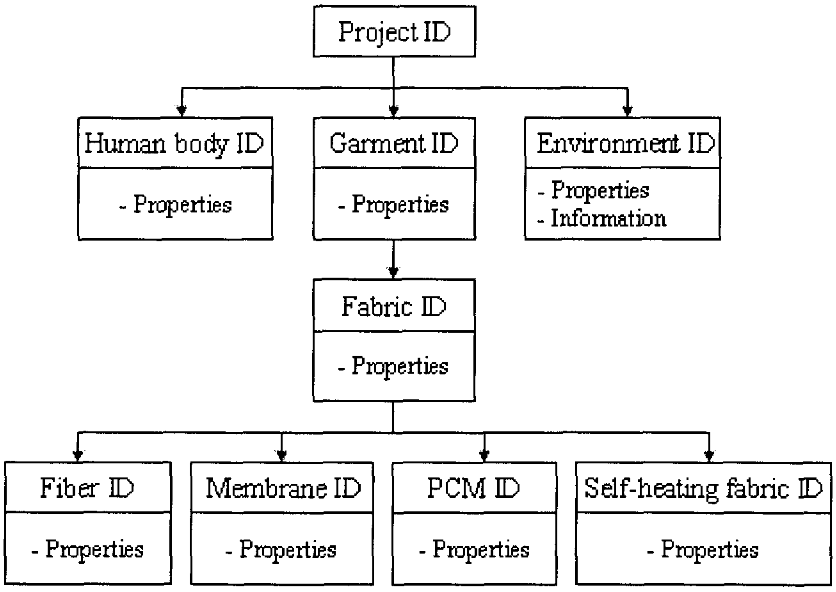
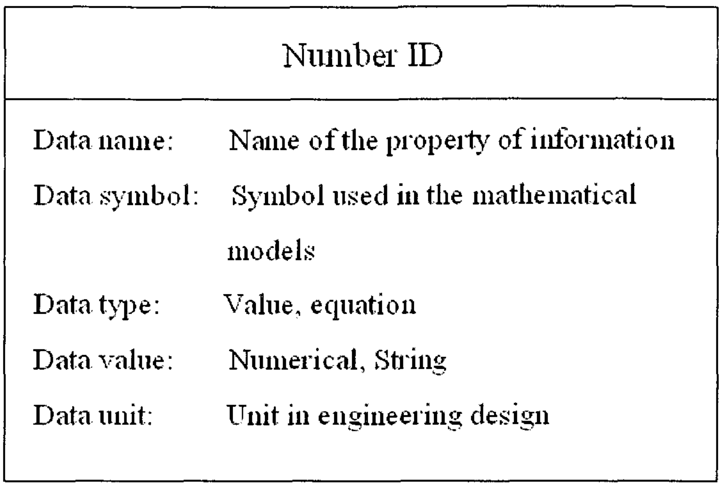


Figure 5.16 Hierarchical data model of the database system

A hierarchical data model is employed to construct the database system, as shown in Figure 5.16. In this data model, all the data subsets (Garment, fabric, fiber, membrane, PCM and self-heating fabric, human body and wearing environment) in Table 5.4 are expressed as individual entities, which consist of the relevant properties and information, and number ID for identification in the engineering database table. For the entities which are children in the hierarchical relationship of a tree, their number ID also inherit the ID of their parents to illustrate the hierarchical relationship.

In the clothing thermal engineering design process, the database needs to store various categories of information, as discussed in Table 5.4. The information in different categories may have different expression in engineering purpose. For instance, some properties are directly measured with physical units, while some properties are calculated with formulas. In such cases, the measured properties must have physical units, while the units of calculated properties must be derived using calculation formulas. Those situations often happen in the engineering design and need to be considered in the design of the engineering database. This is a unique feature of the engineering database, which is different from the traditional database.

In order to solve the difficulties in storing the information of different categories, a special data type is proposed to describe the information recorded in the engineering database, as shown in Figure 5.17, which consists of data name, data symbol, data type, data value and data unit. The data name is given by the system or the user for easily recalling the data such as fiber thickness and human body height. The data symbol is the symbol of the information/property used in the mathematical model, which is very useful for the user to identify the properties in the models. The data type can be numerical value or equation to characterize the measured or calculated properties. The data value can be expressed with numerical numbers or strings. The data unit indicates the physical units of the property used in the engineering design.



Number ID

Data name: Name of the property of information
Data symbol: Symbol used in the mathematical models
Data type: Value, equation
Data value: Numerical, String
Data unit: Unit in engineering design

Figure 5.17 Data type of the information in the engineering database

With the designed data model and data structure as above, the engineering database for clothing thermal engineering design are realized with the SQL Server tool. In order to enable the end user to share the engineering database, this engineering database is installed on a public server which can be accessed by the end user through internet, so that the CTE-CAD system can run on individual computer while share a common engineering database to utilize the information effectively.

5.6 CONCLUSION

In this chapter, the software architecture is developed and discussed for the CTE-CAD system. The requirements of the CTE-CAD system are identified, including functional requirements, performance requirements, input and output requirements and data manage ability requirements. With understanding of these identified requirements, the software architecture is constructed with the functional modules of user graphic interface, life-oriented design procedure, pre-processing module, numerical solver, and post processing modules. In order to enable the system to be open and flexible in maintenance and update, the object-oriented technique is adopted to develop the system. The structure of encapsulated Class and the data flow between the system components are designed. In the last section in this Chapter, the engineering database supporting the engineering design process is designed by identifying the functionalities of the database and constructing a hierarchical data model and a special data structure for the database. Under this software architecture, a series of CAD system with different design capacities can be developed by reusing most of the Class and modules of the system.

CHAPTER 6 A CAD SYSTEM FOR MULTI-LAYER CLOTHING THERMAL ENGINEERING DESIGN

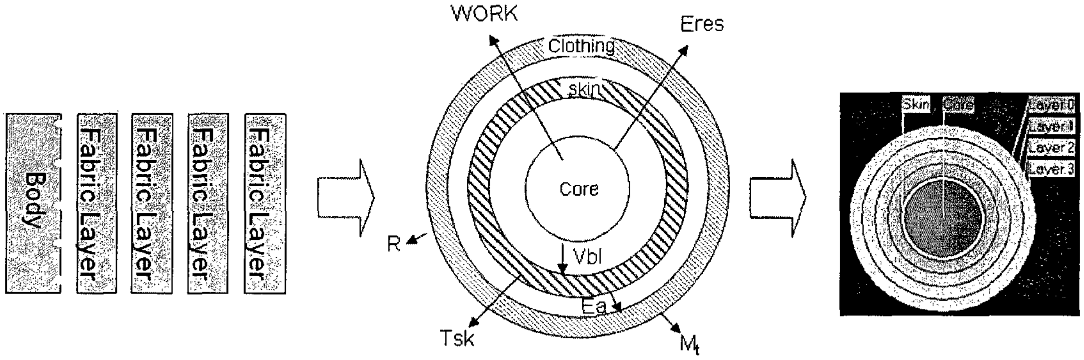
6.1 INTRODUCTION

The software architecture for computer-aided clothing thermal engineering design system has been proposed in Chapter 5. With this architecture, the software system for clothing thermal engineering design can be developed to enable the users to carry out their thermal engineering design of clothing. Furthermore, due to the open structure and flexibility of this architecture, it is possible to provide the users with a series of software systems that correspond to different application requirements under the same architecture.

In this Chapter, a CAD system for multi-layer clothing thermal engineering design is developed based on the achievements in the previous Chapters, including the simulation models in Chapter 3, the computational scheme in Chapter 4 and the software architecture in Chapter 5. This CAD system, named P-smart enables the users to perform multi-layer clothing thermal engineering design and preview the overall thermal performance of clothing and the thermal responses of the human body. This Chapter first introduces the development process and functionalities of the software system, then reports on two design cases to show the design process with this system and validate the accuracy of prediction results, finally, discusses the perspectives and features of this innovative CAD system.

6.2 DEVELOPMENT OF THE P-SMART SYSTEM

The P-smart system is developed to achieve multi-layer clothing thermal engineering design, which aims to help the designers to design clothing with multi-layer fabrics, simulate the clothing wearing system with simulation models, and preview the thermal performance of clothing and human body, as illustrated in Figure 6.1. By analyzing the thermal performance of clothing, the designers can iteratively improve their designs until achieve desirable thermal functions of clothing with this virtual tool before making any real samples.



Multi-layer design **Computational simulation** **Overall thermal performance**

Figure 6.1 Multi-layer clothing thermal engineering design

As shown in the framework of clothing thermal engineering design, which has been presented in Chapter 2, the capacity of computational simulation determined by the simulation models is the key part to develop the CAD system. The simulation models adopted in P-smart involve the PCM heating model, fiber moisture absorption/desorption model, fabric heat and moisture transfer models and a two-node thermoregulatory model of human body to numerically express the multi-scale thermal behaviors in the clothing wearing system. The main mathematical equations in the multi-scale simulation models are listed as follows [17, 20, 24, 49, 67, 117, 137]:

Heat and moisture models for the fabric

$$\frac{\partial\,(\varepsilon_a C_a)}{\partial t} = \frac{D_f \varepsilon_a}{\tau_a}\frac{\partial^2 C_a}{\partial x^2} + G\frac{\partial^2 p_s}{\partial x^2} + \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\mathrm{lg}} \tag{6.1}$$

$$\frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l \frac{\partial(\rho_l \varepsilon_l)}{\partial x}\right) + GL\frac{\partial^2 p_s}{\partial x^2} + \varpi_l \frac{\partial C_f}{\partial t} - \Gamma_{lg} \tag{6.2}$$

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + (\omega_a \lambda_v + \omega_l \lambda_l)\varepsilon_f \frac{\partial C_f}{\partial t} - \lambda h_{lg} \Gamma_{lg} + \dot{q}(x,t) + W \tag{6.3}$$

$$\frac{M_g \varepsilon_a}{RT}\frac{\partial p_s}{\partial t} - \frac{p_s \varepsilon_a M_g}{RT^2}\frac{\partial T}{\partial t} - \frac{M_g p_s}{RT}\frac{\partial \varepsilon_l}{\partial t} = \frac{\partial}{\partial x}\left[GS\frac{\partial p_s}{\partial x}\right] - \varpi_1 \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\mathrm{lg}} \tag{6.4}$$

$$\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rD_f(x,t)\frac{\partial C_f(x,r,t)}{\partial r}) \tag{6.5}$$

Human body thermoregulatory models

$$S_{cr} = M - E_{res} - C_{res} - W - (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) \tag{6.6}$$

$$S_{sk} = (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) - E_{sk} - R - C \tag{6.7}$$

The detailed descriptions of the multi-scale mathematical models from the molecular to the body-clothing level can be found in Chapter 3. The characteristic data of individual physical behaviors in the clothing wearing system is considered into these models as input parameters. The availability of the value of these parameters has also been discussed in Chapter 3. With the communication sockets developed in Chapter 4, the heat and moisture models for the fabric and the human body thermoregulatory models can be effectively integrated through the boundary conditions and numerically express the thermal behaviors of the clothing wearing system. Since the adopted human body thermoregulatory model is a two-node model, which is one-dimensional, and meanwhile the adopted heat and moisture transfer models for the fabric are also one-dimensional, the thermal behaviors in the clothing wearing system are simulated in the whole level.

With the basis of the simulation models, the CAD system can be realized with the computational scheme and software technologies. The development of P-smart, which is programmed with C++ language and runs on Windows platform, is reported in terms of system architecture and modules, computational algorithms and user interfaces.

6.2.1 System architecture and modules

In Chapter 5, the general software architecture for the CAD system of clothing thermal engineering design has been proposed and described. In this Chapter, the architecture of P-smart is realized with reference to the capacity of multi-layer design, as shown in Figure 6.2. The CAD system is developed following the flow of virtual design from pre-processing, computational simulation to post processing, and provides user graphic interfaces to communicate with the user. In the processing phase, the information obtained from the virtual design phase is preprocessed and transferred to the computational simulation phase. The simulate results generated in the computational simulation phase are provided to the post processing phase. The information from the virtual design phase related to the garment, human body and wearing scenarios is structured as data sets to transfer into the simulation models.

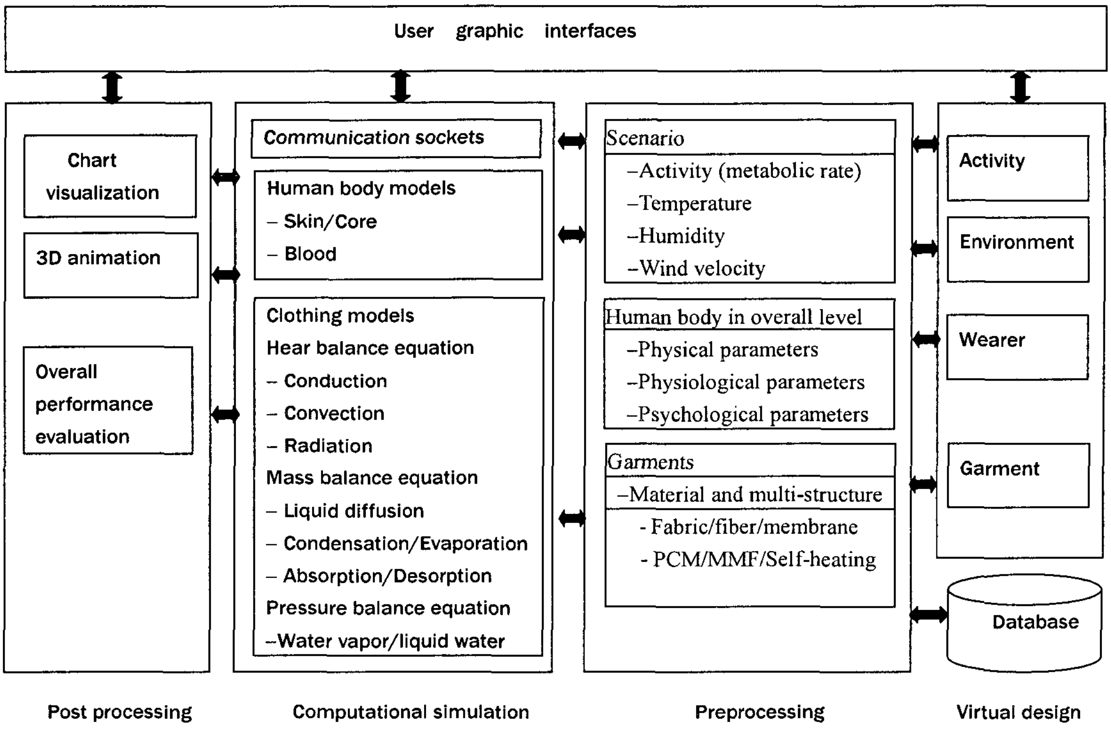


Figure 6.2 System architecture of the P-smart system

Under the elaborated software architecture, the functionalities of P-smart can be designed and are illustrated in Figure 6.3. The users start their virtual designs with the life-oriented design procedure, in which they can perform multi-layer clothing design according to the engineering principle of fiber→fabric→garment, define the human body covered by the clothing, specify the wearing scenario and control information of the simulation. In this procedure, an engineering database is provided to support the clothing design, human body definition and scenario specification. The user can save or load the specification data of textile materials and products (fiber, fabric and garment), human body and climatic conditions in a specified space and time to or from the database through a series of operations of “Store”, “Query”, “View”, “Renew”, “Delete” and “Acquire”.

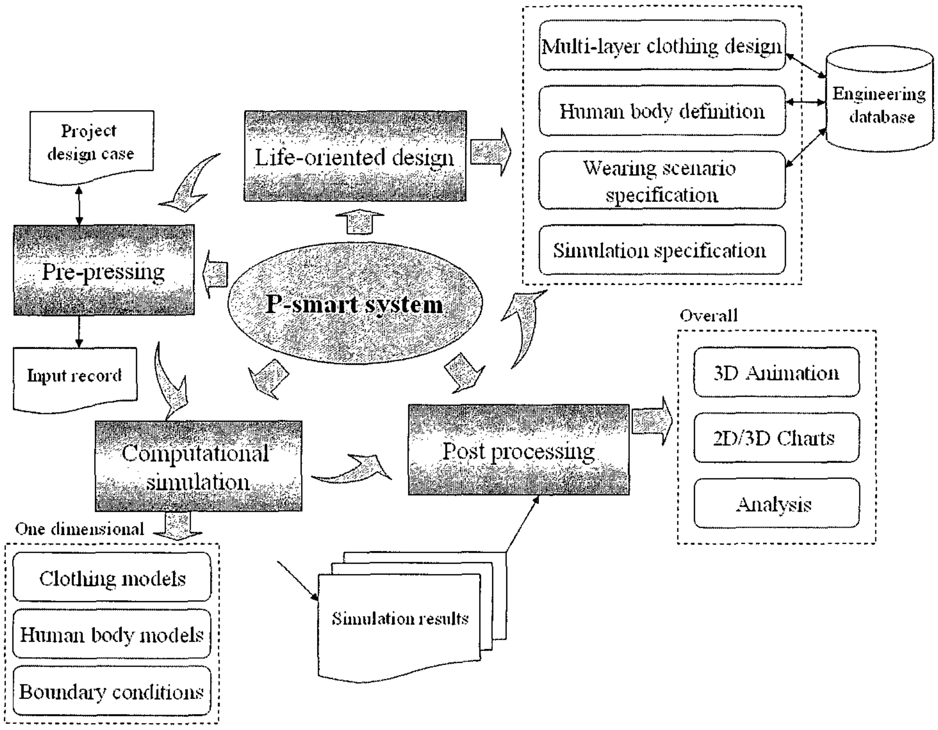


Figure 6.3 Functionalities flow of the P-smart system

After the virtual design, a pre-processing of the information obtained from the life-oriented design procedure, is executed to structure the data as data sets categorized in terms of fiber, PCM, Membrane, Self-heating fabric, MMF, fabric, garment, human body, scenario and control information, and the units of the data are converted from the input units to the ones used in calculation. These data sets are transferred to the computational solver to start the simulation. In order to have an effective management of the design specification, the obtained data is exported as design case file according to a designed format, which has been described in Section 5.3.3. Meanwhile, it can be loaded to the system to reuse. The program description of the design case file is illustrated in Table 6.1, which demonstrates the detail content and logic structure of the design case file. Additionally, an input record file is also exported for the user to quickly check the input specifications, whose format has also been given in Section 5.3.3.

Table 6.1 Program description of the design case file

```
1. whether define body: $B$ [if B=0, go to line 14]
 {
2. Cswr_max: $m$ Cswr_reg: $m$ Cshv_reg: $m$ Cswr_pow: $m$
3. Vbld_skmax: $m$ Vbld_skmin: $m$ Vbld_skneu: $m$ Cbld_dia: $m$
4. Cbld_strt: $m$ Density_bld: $m$ T_skneu: $m$ T_crneu: $m$
5. T_bmneu: $m$ cp_bld: $m$ cp_bm: $m$
6. IsMale: $B$ IsFemale: $B$ Age: $m1$ Race: $m2$
7. Weight of humanbody: $m$ Area of humanbody: $0$ Height of humanbody: $m$
8. Skin Temperature: $m$ Core Temperature: $m$ abs_sk: $m$ k_b: $ $ RH_sk: $m$
9. Warm_Skin_Ks1: $m$ Warm_Skin_Ks2: $m$ Cold_Skin_Ks1: $m$ Cold_Skin_Ks2: $m$
10.Warm_Skin_Kd1: $m$ Warm_Skin_Kd2: $m$ Cold_Skin_Kd1: $m$ Cold_Skin_Kd2: $m$"
11.Warm_Skin_C1: $m$ Warm_Skin_C2: $m$ Cold_Skin_C1: $m$ Cold_Skin_C2: $m$
12.Warm_Core_Ks1: $m$ Warm_Core_Ks2: $m$ Cold_Core_Ks1: $m$ Cold_Core_Ks2: $m$
13.Warm_Core_C1: $m$ Warm_Core_C2: $m$ Cold_Core_C1: $m$ Cold_Core_C2: $m$"
 }
14 fiber types: $m$ [if m=0 go to line ]
   for(int i=0;i<m;i++)

33  Thickness: $m$ CapAngle: $m$ TortuosLqd: $m$ ContactAngle: $m$
34   MMF Treatment: $B$ [if B=0, go to line 42]
      {
35     TopWetR:$m$ BottomWetR: $m$ TopWetTime: $m$
36      BottomWetTime: $m$ TopAngle: $m$ BottomAngle: $m$
37     TopWeightTxt: $m$ BottomWeight: $m$ ;
      }
38     SelfHeating:$B$ [if B=0, go to line 44]
      {
39     Heating Load: $m$ Min Control Temperature: $m$ Max Control Temperature: $m$
      }
40    PCM:$B$   [if B=0, go to line 49]
     {
41        PCM name: $S$"
42         Radius: $m$ Density: $m$ K_ml: $m$ K_ms: $m$
43         Ramda_m: $m$ T_p: $m$ h_T: $m$
44         PCM volume: $m$"
      }
45  Thermal Conductivity: $m$ MaxDisCapDia: $m$ MeanDiameter: $m$
46  fiber ratio points: $m$
     for(int j=0;j<m;j++)
      {
47        fiber j ratio: $m$   [S is the ratio of fiber in the fabric}
```

```
   {
15      fiber name : $S$
16      Diameter: $m$ Density: $m$ Emissivity: $m$
17      VaporDiff: $ $ LiqConAngle: $ $ TherConductivity: $ $
18      FiberRegain value point: $m1$
   }
  // membrane part
 19. Membrane types: $m$"
    for(int i=0;i<m;i++)
   {
20      Membrane name: $S$
21      Thickness: $m$
22      Membrane WVP value points: $m1$
         for(int j=0;j<m1;j++)
         {
23            $m$   if((j+1)%8==0) "\n" [8 point in a line]
          }
          if(m1%8!=0)  "\n"
24      Membrane WVP temperature points: $m2$
               for(int j=0;j<m2;j++)
               {
25    file<<"$"<<Membrane->WVPX[j]<<"$ "
           if((j+1)%8==0) "\n"
       }
        if(m2%8!=0)  "\n"
26      Membrane TR value points: $m1$
       for(int j=0;j<m1;j++)
         {
27            $m$  if((j+1)%8==0)  "\n"  [8 point in a line]
          }
if(m1%8!=0) "\n"
28     Membrane TR temperature points: $m2$
    for(int j=0;j<m2;j++)
   {
29          $m$   if((j+1)%8==0)  "\n }
               if(m2%8!=0) "\n }
 // fabric part
abric types: $m$
    for(int i=0;i<m;i++) {
31      fabric name: $S$"
32     Porosity: $m$ Emissivity: $m$ TortuosGas: $m$
         }
48       fiber count: $m$
         for(int j=0;j<m;j++)
         {
49           fiber j name: $S$ [S is the fiber name]
         }
50       Membrane count: $m$
         for(int j=0;j<m;j++)
         {
            Membrane j name: $S$ [S is the membrane name]
         }
    }
// garment part
51 Garment Number: $m$"
    for(int i=0;i<m;i++)
    {
52        Clothing Style: $m1$ Clothing Fitting: $m2$"
53          Fabric name: $S$ [S is the name of the fabric selected for the
current layer]
       }
// Stage information
59  Stage count: $m$"
    for(int i=0;i<m;i++)
    {
60   Stage Name: $S$ InnerT_a: $0$  OuterT_a: $m$ ActivityIndex: $m1$
Wind: $m$ Door: $ m2$
61   InnerG_rad: $0$ OuterG_rad: $0$  InnerRH: $0$  OuterRH: $m$
62   InnerVFL: $0$  OuterVFL: $0 $ Metabolic rate: $m $ StageTime: $m$
   }
63 TimeStep: $m$ Savefrequence: $m$ SweatAccumu: $0$
64  for(int i=0;i< Stage count;i++)
    {
65        clothingCoverRatio:   $m$   MoistureTransferRatio:   $m$
HeatTransferRatio: $m$
     }
66   fabric thickness grid : $m$
67   fabric radius: $m$
```

In the computer solver, the computational simulation is implemented with specified control information by solving the multi-scale models and updating the boundary conditions. The simulation results are saved to data files which are stored in a specified directory with a case ID on the storage medium, as shown in Figure 6.4. The values of relevant thermal variables of fiber, fabric and human body is respectively stored in a data file. The detail explanation of the structure of these files can be found in Table 6.2.

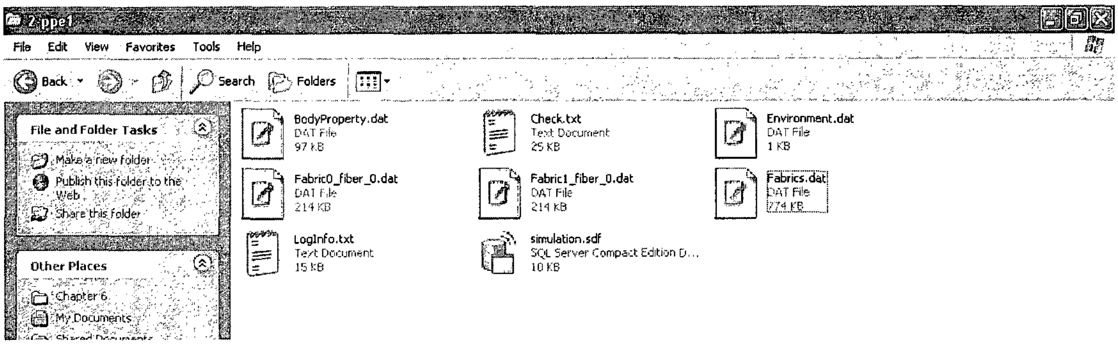


Figure 6.4 The data files of simulation results

Table 6.2 the structure of the data files saving simulation results

File name	File structure
Fabrics	Timepos, spacepos, fabric-number, Ca, Cf, FRateEC, RHF, RateSorp, TempF, VFL
	Timpos: time position at which the data will be saved. Spacepos: the delta of fabric at which the part differential formulations were dispersed. Fabric-number: the order number of the fabric in the clothing system Ca: Water vapor concentration in all the fibers of the fabric Cf: Mean Water vapor Concentration in all the fibers of the fabric FRateEC: the evaporation and condensation rate of the fabric RHF: relative humidity of the fabric RateSorp: the mean moisture sorption rate of all the fibers of the fabric TempF: temperature of the fabric VFL: the liquid volume fraction of the fabric
Fiber number in	Timepos, spacepos, MeanMoisConcentration, Rate_MoisSorp, MoisContent

fabric number	MeanMoisConcentration: the mean moisture concentration of the fiber Rate_MoisSorp: the moisture sorption rate of the fiber MoisContent: the moisture content of the fiber
Bodyproperty	Timepos ,T_sk ,T_cr, Wsk, MR, RH, Vbld_sk, SWR, Esk, DRY, E_rsw, E_dif
	Timepos: time position T_sk: temperature of skin T_cr: temperature of core W_sk: skin wetness MR: metabolism rate of human body RH: relative humidity of skin Vbld_sk: blood flow volume of skin SWR: sweating rate E_sk: the evaporative heat from skin Dry: the dry heat loss from skin, Ersw: regulative heat loss by sweating E_dif: heat loss by vaporized water diffusion through skin

* In the file, every variable is recorded as column; a tab space is used as an interval between columns.

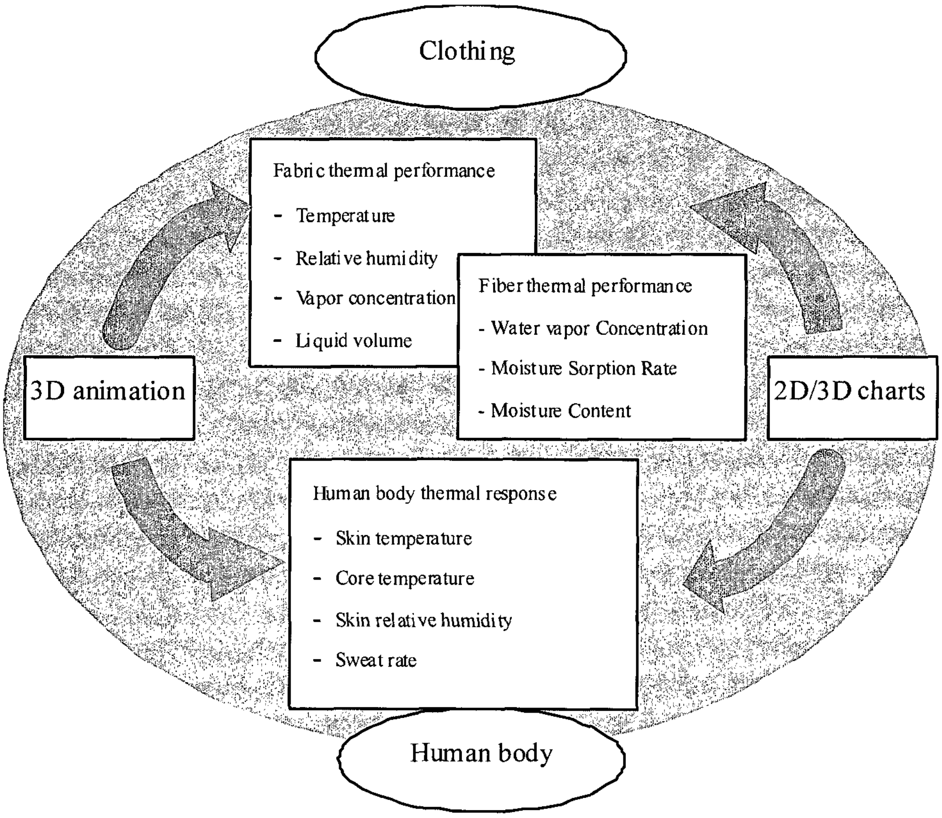


Figure 6.5 Graphic visualizations of the simulation results

In the post processing, the data files are loaded in the system and the saved simulation results are read out as data sets of fiber, PCM, Membrane, Self-heating fabric, MMF, fabric, garment, human body, scenario and control information. The thermal variables of all fibers, fabrics and the human body are visualized with 2D/3D charts or 3D animation, as illustrated in Figure 6.5.

The dimensions the charts are decided by the available temporal and spatial information of the results. In the 3D animation, the human body and clothing including all fabric layers are animated as 3D objects and mapped with the color which is calculated with the value of thermal variables according the color bar. The mapped color is dynamically updated with the value of the specified variable in real time. The background grids in the 3D space are mapped with the color according to the temperature of the wearing environment.

In order to achieve the functionalities of P-smart described above, the program is coded with an assembly of modules, which are divided with reference to the logic relationships of the functionalities and the object-oriented programming view. Figure 6.6 illustrates the module structure in the program of P-smart, which shows the necessary modules for the functionalities of pre-processing, computational solver and post-processing. The description of the function of these modules involved can be found in Table 6.3.

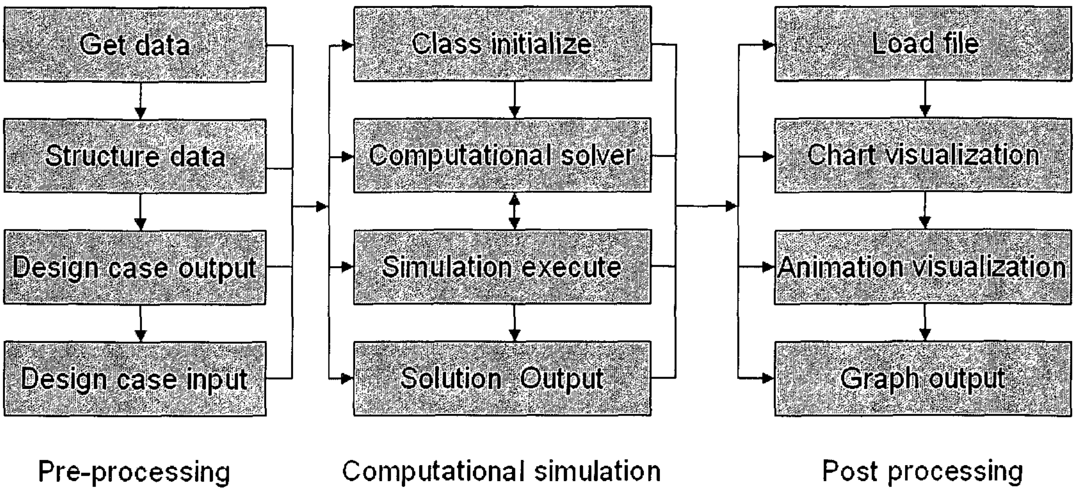


Figure 6.6 The module structure in the P-smart system

Table 6.3 the function description of the modules

Modules		Function explanation
Pre-processing	Get data	Get data from the interfaces or design case file with right value
	Structure data	Structure the data relate to fiber, PCM, self-heating fabric, MMF, fabric, garment, human body, scenario and control information as data sets for computational solver
	Design case output	Save the design specifications into a data file according to a specified format
	Design case input	Load the design case file and read out the design specifications of clothing, human body, wearing scenarios and control information
Computational simulation	Class initialize	Initialize all the Class with entities which is involved in the design and simulation
	Computational solver	Solve the mathematical models involved in the computational simulation
	Simulation execute	Execute the computational simulation of the multi-scale models according to the control information for all the wearing scenarios
	Solution output	Output the simulation results to data files and clear the data array
Post processing	Load file	Load the data file and read out the simulation results for visualization
	Chart visualization	Visualize the value of thermal variables as 2D or 3D charts to observe their distributions in temporal or and spatial coordinates
	Animation visualization	Animate the clothing and human body as 3D objects and map the color on them according the value of thermal variables in real time
	Graph output	Output the visualization to graphic files

When to realize these modules described above, the program in the unit of function is further organized to have a smooth data flow and effective management. The distribution of the main functions to program these modules can be found in Table 6.4, which lists out the input parameters and purpose of each function.

Table 6.4 Distribution of main functions to program the modules in P-smart

Modules	Functions	Input parameters	Purpose
Get data	NumberControl()	Input number	Assure the right input of number
	StringControl()	Input string	Assure the right input of number
	GetValue()	Input of a object	Get the values of all properties of a object
Structure data	FiberType()	Properties of fiber	Collect all the properties of fiber as a structure
	MembraneType()	Properties of membrane	Collect all the properties of membrane as a structure
	PCMType()	Properties of PCM	Collect all the properties of PCM as a structure
	SelfHeatingType()	Properties of self-heating fabric	Collect all the properties of self-heating fabric as a structure
	FabricType()	Properties of fabric	Collect all the properties of fabric as a structure
	GarmentType()	Properties of garment	collect all the properties of garment as a structure
	BodyType()	Properties of human body	Collect all the properties of human body as a structure
	StageType()	Properties of a scenario	Collect all the properties of a scenario as a structure
	ControlType()	Control information	Collect all the control information as a structure
Design case output	SaveBody()	Structure of the human body	Output the human body
	SaveFiber()	Structure of the fiber	Output the fiber
	SaveMembrane()	Structure of the membrane	Output the membrane
	SavePCM()	Structure of the PCM	Output the PCM
	SaveSelf-heating()	Structure of the self-heating fabric	Output the self-heating fabric

	SaveFabric()	Structure of the fabric	Output the fabric
	SaveGarment()	Structure of the garment	Output the garment
	SaveStage()	Structure of the scenario	Output the scenario
	SaveControl()	Structure of the control information	Output the control information
Design case input	LoadFiber()	Design case file	Load the fiber from the file
	LoadMembrane()	Design case file	Load the membrane from the file
	LoadPCM()	Design case file	Load the PCM from the file
	LoadSelf-heating()	Design case file	Load the self-heating fabric from the file
	LoadFabric()	Design case file	Load the fabric from the file
	LoadGarment()	Design case file	Load the garment from the file
	LoadBody()	Design case file	Load the human body from the file
	LoadStageType()	Design case file	Load a scenario from the file
	LoadSaveControl()	Design case file	Load the control information from the file
Class initialize	NumericalFiber ()	Structure of the fiber	Initialize the Class of fiber
	NumericalMembrane()	Structure of the membrane	Initialize the Class of membrane
	NumericalPCM()	Structure of the PCM	Initialize the Class of PCM
	NumericalSelfHeating()	Structure of the self-heating fabric	Initialize the Class of Self-heating fabric
	NumericalFabric()	Structure of the fabric	Initialize the Class of fabric
	NumericalGarment()	Structure of the garment	Initialize the Class of garment
	NumericalBody()	Structure of the human body	Initialize the Class of human body
	NumericalStage ()	Structure of the scenario	Initialize the Class of scenario
	NumericalControl()	Structure of the control information	Initialize the Class of control information
Computational solve	SolveLiquidSorption()	Entity of fiber Class	Solve the fiber sorption equation
	SolvePCMHeat()	Entity of PCM Class	Solve the PCM heating model
	SolveFabricEquations()	Entity of fabric Class	Solve the coupled fabric models
	BodyRegulation()	Entity of human body Class	Solve the 2-node thermoregulatory models of human body
	ScenarioUpdate()	Entity of scenario Class	Update the scenario information
	BodyFabricUpdate()	Entity of body and clothing Class	Update the boundary conditions between the skin and fabric

	InterFabricUpdate()	Entity of fabric Class	Update the boundary conditions between two adjoining fabrics
Simulation execute	SimulationRun()	Entities of all Class	Implement the simulation of the multi-scale models with the specified control information for all the wearing scenarios
Solution output	ClearBody()	Entity of human body Class	Save the solution of boy models to the data file
	ClearFabric()	Entity of fabric Class	Save the solution of fabric models to the data file
	ClearFiber()	Entity of fiber Class	Save the solution of fiber models to the data file
Load file	LoadFabricFile()	Simulation results file	Load the data of properties of fabric
	LoadFiberFile()	Simulation results file	Load the data of properties of fiber
	LoadBodyFile()	Simulation results file	Load the data of properties of human body
	LoadScenarioFile()	Simulation results file	Load the information of all scenarios
Chart visualization	ChangePanelForGL()	Index of page of interface	Change the panel to get handle of interface for OpenGL
	DrawAxis()	Dimension of the data	Draw the coordinates of the chart
	DrawPanel()	Index of the data array	Draw the value of a specified properties with all dimensions
Animation visualization	RenderModel()	.dxf file of the 3D model	Initialize the 3D objects of body and clothing with a initial color
	DrawBackground()	Information of scenarios	Draw the background of 3D space with reference to the scenario information
	CalculateColor()	Data array of fabric or hum body	Calculate the mapped color value of the data according to the color map
	ColorMap()	Color value	Map the color on the fabric or human body dynamically
Graph Output	GraphicExport()	Handle of the draw panel	Save the visualized graph into files

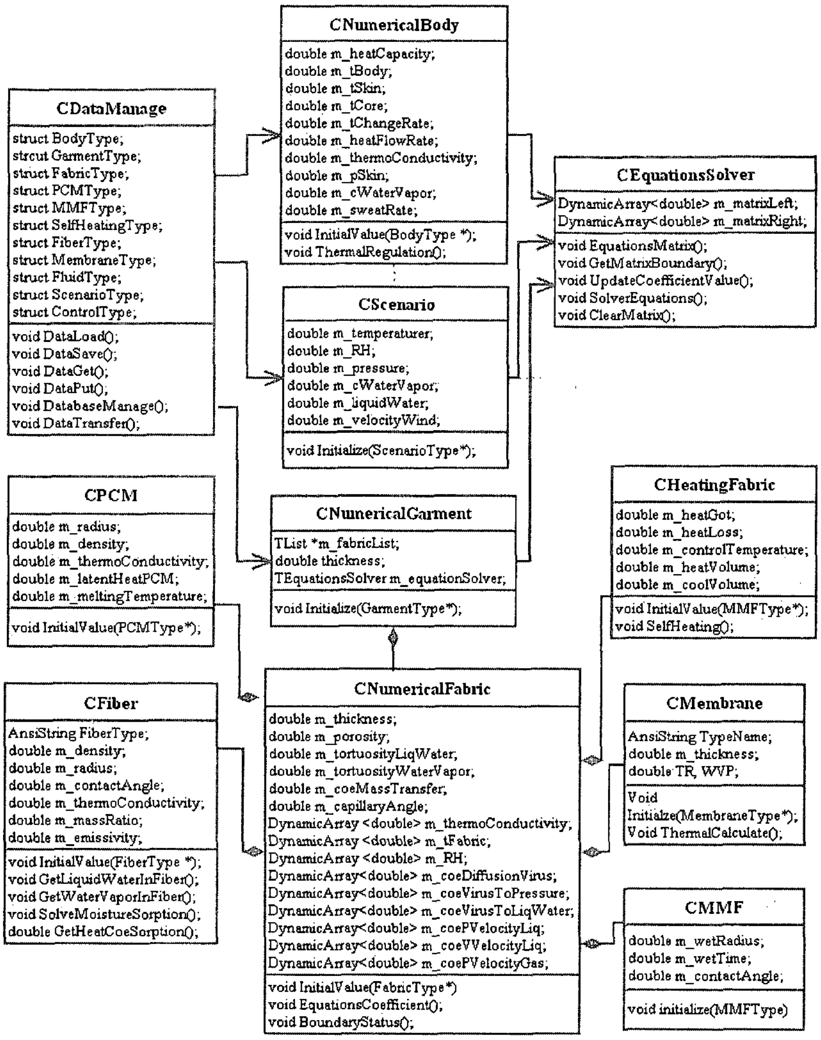


Figure 6.7 The entity-relationship in the P-smart system

Since P-smart is programmed with the object-oriented method, all the textile materials and products (fiber, PCM, MMF, self-heating fabric, membrane, fabric and garment), the human body and wearing scenario, as well as the computational solver, are encapsulated as individual object. All the properties and relevant process methods of an object are encapsulated in a Class. The general structure and functions of the Class have been discussed in Section 5.4.1. The entity-relationship of P-smart is illustrated in Figure 6.7, which shows the detail properties and functions of all the Classes involved. With these encapsulated Class, the structure of the program is clear and easy to be understood, and is open and flexible for effective and economical maintenance and update.

6.2.2 Computational algorithms

The computational algorithms, which is required to execute the computational simulation, is based on the solution of the integrated multi-scale models and constructed according to mesh structure of the clothing wearing system. The detail discretization of the multi-scale models and their boundary conditions to obtain the model's solution has been presented in Chapter 4. Due the one-dimensional feature of the adopted models, the computational scheme is hence a one-dimensional structure, which can also be referred to Chapter 4.

In the control information, which is specified by the user in the virtual design procedure, the mesh information including the grid number of fabric and the grid number of fiber and the time step information have been structured before the computational simulation. The computational simulation is iteratively performed with the interval of time step for each grid subdividing the composed fabrics along thickness directory and each grid subdividing the involved fiber along radius directory. The body skin and body core are connected by the blood flow to regulate the body thermal status. The structure of the algorithm in the computational simulation of P-smart is illustrated in Figure 6.8, which demonstrates the iteration level of the computation and the interactions between the human body, clothing and environment during the computation. The influence of the mesh grid and time step on the computational simulation has been discussed in Chapter 4.

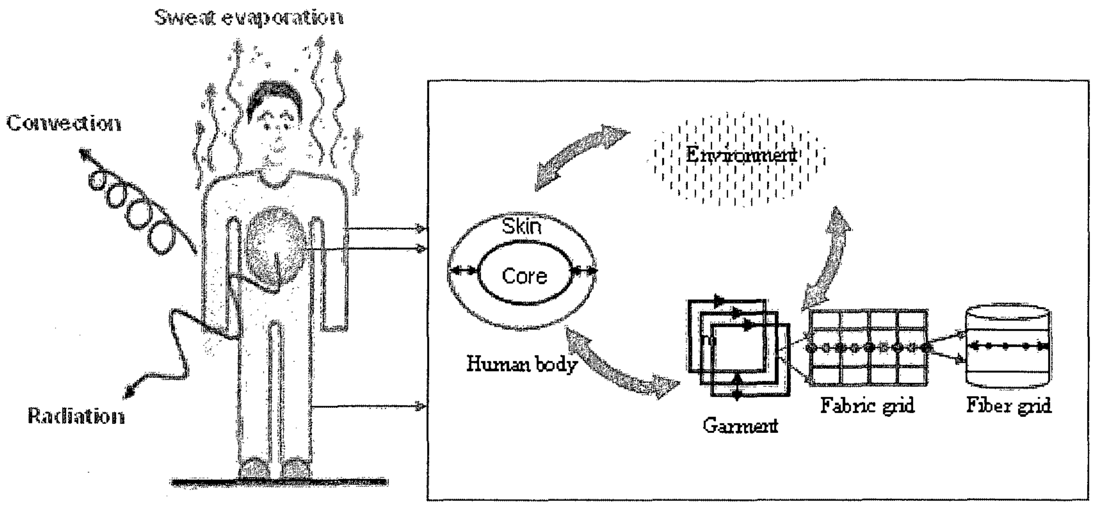


Figure 6.8 The structure of the algorithm of P-smart

Before the computational simulation starts, an important issue is to convert the units of the data obtained from the design phase to the ones used in calculation. Different from many other calculation applications (in statistics or economics), the units of the data play a significant role in the engineering computation. Generally, the variables or properties of the materials or models published in the references use the ISO standard units, which, however, have a large scale in the dimension and are easy to cause error in the results after the iterative computation. In the engineering computation, the units of the data are converted to the ones which have smaller scale in the dimension to assure the accuracy of the computational results and to reduce computational cost. Table 6.5 lists out the ISO standard units and the calculation units of the properties of the items (fiber, PCM, fabric, human body) involved in the computational simulation and their numerical relationships in the unit conversion.

Table 6.5 The unit conversion of the input data

Item	Properties	Symbol	Calculation unit	ISO standard unit	Unit conversion
Fiber	Vapor diffusivity	D_a	cm^2/s	m^2/s	1.0e+4
	Thermal conductivity	K	*Cal/s/cm/K*	*W/m/K*	2.39e-3
	Radius	r	*cm*	*m*	1.0e+2
	Density	ρ_f	*g/cm*	Kg/m^3	1.0e-3
	SurfaceVolumeRatio	S_v	*1/cm*	*1/m*	1.0e-2
PCM	Radius	r_l	cm	m	1.0e+2
	Density	ρ_l	g/cm^3	Kg/m^3	1.0e-3
	Latent Heat of PCM fusion	λ_m	*Cal/g*	*J/Kg*	2.39e-4
	Melting Point	T_p	^oC	*K*	273
	Thermal Conductivity of Liquid PCM	T_{ml}	*Cal/s/cm/K*	*W/m/K*	2.39e-3
	Thermal Conductivity of Solid PCM	T_{ms}	*Cal/s/cm/K*	*W/m/K*	2.39e-3
	Heat Transfer Coefficient	h_T	$Cal/s/cm^2/deg$	$W/m^2/K$	2.39e-5
Fabric	Thickness	L	*cm*	*m*	1.0e+2
	Max distributed capillary diameter	d_c	*cm*	*m*	1.0e+2
Human body	Maximum sweating rate	SWR_{max}	$g/cm^2/hr$	$mg/m^2/s$	3.6 e-4
	Pow sweating rate	SWR	$g/cm^2/hr$	$mg/m^2/s$	3.6 e-4
	Regulative shivering constant	SHV_{reg}	$cal/s/cm^2$	W/m^2	2.39e-5
	Maximal volume of blood flow of skin	V_{blmax}	*L/hr/cm*	$L/h/m^2$	3.6e-1
	Minimum volume of blood flow of skin	V_{blmin}	*L/hr/cm*	$L/h/m^2$	3.6e-1
	Neutral volume of blood flow of skin	V_{bl}	*L/hr/cm*	$L/h/m^2$	3.6e-1
	Dilation factor of blood vessel	Diat	*L/hr/cm*	$L/h/m^2$	3.6e-1
	Strict factor of blood vessel	Strt	*L/hr/cm*	$L/h/m^2$	3.6e-1
	Density of blood	ρ_{bl}	*g/cm3*	*Kg/m3*	1.0e-3
	Neutral temperature of skin	T_{skin}	^oC	*K*	273
	Neutral temperature of core	T_b	^oC	*K*	273
	Specific heat at constant pressure of blood	c_{pbld}	*cal/g/deg*	*J/Kg/K*	2.39e-4

	Thermal conductance of body tissue	k_b	*cal/s/cm/deg*	W/m^2	2.39e-5
	Human body weight	W_d	*g*	*kg*	1e+3
	Human body area	A_d	cm^2	m^2	1e+4
	Skin temperature	Tsk	^oC	*K*	273
	Core temperature	Tcr	^oC	*K*	273

The detail description of the main algorithms for computational simulation can be found in Table 6.6. The simulation begins with the pre-processing of the design data and the initialization of all Classes involved. To enable the corresponding simulation models for the materials or functional treatments (membrane, PCM, MMF and self-heating fabric) in the design specifications, a setting is arranged by marking the corresponding dataset as full or not to decide the further steps. If the materials or functional treatments have been used and the data of their properties is available, the corresponding Class is initialized and the corresponding models are solved during the computational simulation. The computation is iterative for all the wearing scenario, meshed fabrics and fibers, and human body nodes, and generates solutions of the models, which are obtained and stored to data files.

Table 6.6 Main algorithms for the computational simulation

```
(1) Get the data and obtain the data sets of fiber, PCM, MMF, self-heating fabric, Membrane, fabric, garment,
    human body, scenario and control information
(2) If there is no use of the textile materials or human body ,the corresponding data set is full
(3) Initialize all the class with corresponding data set which is not full
(4) For each wearing scenario
(5) For each time step $t_i$ $(i=0,1,\ldots, T)$
(6)   For every fabric layer of clothing
(7)   {  For every fabric grid $x_j$ $(j=0.2\ldots, m)$
            If (Membrane is not full )
(8)            Calculate the TR and WVP for the boundary coefficients
```

```
        If (MMF is not full )
(9)       Update the properties of fabric with MMF properties
        If ( Self-heating fabric is not full )
(10)      Calculate the power rate to as a source item for the fabric model
        If (PCM is not full)
(11)      Solve the PCM heating model
(12)    for every fiber grid $k_j$ ($j=0,1,\ldots,n$)
        {
(13)          Solve the fiber moisture sorption model for $k_j$ at $t_i$
        }
(14)    Calculate all the variables' coefficients in the equations of the fabric model discretized at $x_j$
(15)    Solve the fabric models for $x_j$ at $t_i$
(16)    Update the boundary conditions between $x_j$ and $x_{j+1}$ at $t_i$
(17)    Record the solutions to the data files
      }
(18)  Solve the human body equations
(19)  Record the solution to the data file
(20)  Update boundary conditions in terms of the thermal variables of the body
(21)  If the scenarios end, end the simulation
```

6.2.3 User interfaces

User interfaces are the medium of the software to communicate with the user. As shown in the software architecture (Figure 6.2), P-smart provides user interfaces for the user to perform the system functionalities, especially in the virtual deign and post processing phases. Figure 6.9 is the diagram of the interfaces of P-smart and is explained as follows:

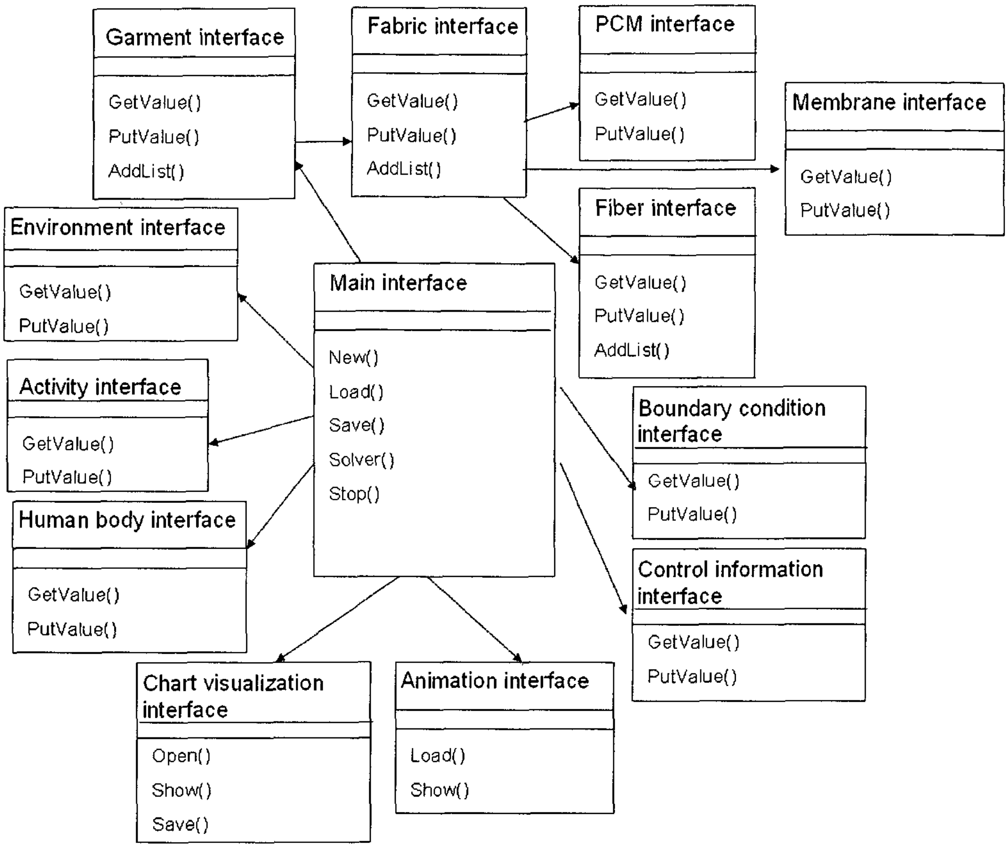


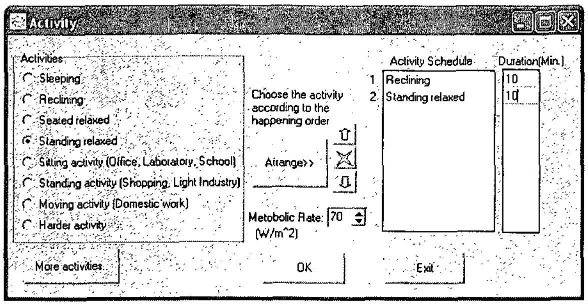
Figure 6.9 The diagram of the main user interfaces of P-smart

Through the main interface, the user can do the virtual life-oriented design through the interfaces of activity, environment, human body, garment, boundary condition and control information, and the post processing including the interfaces of chart visualization and animation. Through the interface of garment, the user can further access the interfaces of fabric, PCM, membrane and fiber according the design principle of fiber→fabric→garment. The functions of each interface are also illustrated in this diagram, such as getting the value from the input on the interface (GetValue()), showing the data to the interface (PutValue()) and adding the designed item to the material list (AddList()). Especially, for the main interface, it undertakes the functions of creating a design project (New()), loading design case file (Load()), Saving design case (Save()), starting the simulation(Solver()), and stopping the simulation (Stop()).

To provide a solid view of the software, following lists out the main user interfaces of P-smart in the phases of life-oriented design, computational simulation and post processing.

1) Life-oriented design

The interfaces in the life-oriented design phase enable the users to finish their designs by following the guide of the life-oriented procedure in terms of activity, environment, wearer and clothing. Further, the experienced users can specify the boundary conditions and control information for the simulation through the interfaces. Figure 6.10 illustrates the main user interfaces in the life-oriented design phase, which can see the interfaces for activity definition, environment definition, wearer definition, body properties definition, human body query with database, fiber design, fiber query with database, garment style definition, garment construction, PCM definition, membrane design, fiber design, fiber query with database, fabric design, fabric query with database, coefficients of human body and fabric in boundary conditions, and control information specification. During the design process, the input parameters have default values and the users just need to input the value which they want to specify. The boundary conditions are generated automatically and provided for the experienced users to adjust the involved coefficients. All the input data of the design can be stored as a project file and be loaded again for the user to change the design.


Activity

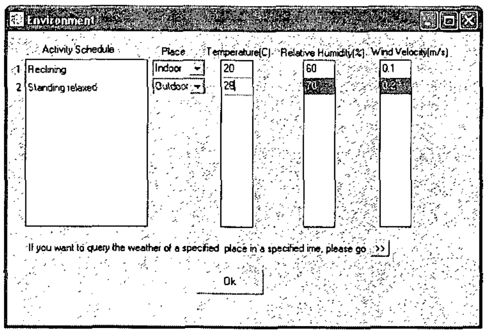
Activities
- ○ Sleeping
- ○ Reclining
- ○ Seated relaxed
- ● Standing relaxed
- ○ Sitting activity (Office, Laboratory, School)
- ○ Standing activity (Shopping, Light Industry)
- ○ Moving activity (Domestic work)
- ○ Harder activity

Choose the activity according to the happening order

Metobolic Rate: 70 (W/m^2)

	Activity Schedule	Duration(Min.)
1	Reclining	10
2	Standing relaxed	10

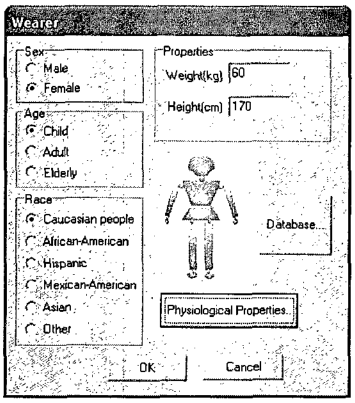
Activity definition


Environment

	Activity Schedule	Place	Temperature(C)	Relative Humidity(%)	Wind Velocity(m/s)
1	Reclining	Indoor	20	60	0.1
2	Standing relaxed	Outdoor	28	70	0.2

If you want to query the weather of a specified place in a specified ime, please go >>

Environment definition


Wearer

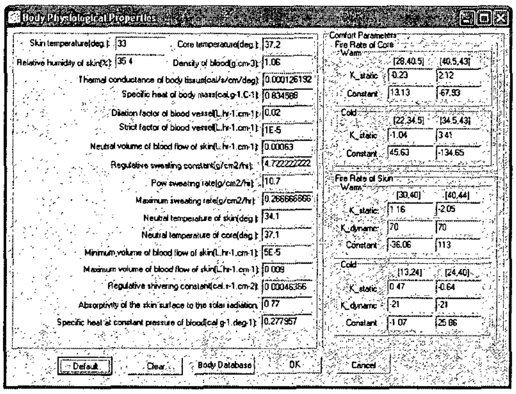
Sex
- ○ Male
- ● Female

Age
- ● Child
- ○ Adult
- ○ Elderly

Race
- ● Caucasian people
- ○ African-American
- ○ Hispanic
- ○ Mexican-American
- ○ Asian
- ○ Other

Properties
Weight(kg) 60
Height(cm) 170

Wearer definition


Body Physiological Properties

Skin temperature(deg.): 33
Core temperature(deg.): 37.2
Relative humidity of skin(%): 35.4
Density of blood(g.cm-3): 1.06
Thermal conductance of body tissue(cal/s/cm/deg): 0.000126192
Specific heat of body mass(cal.g-1.C-1): 0.834588
Dilation factor of blood vessel(L.hr-1.cm-1): 0.02
Strict factor of blood vessel(L.hr-1.cm-1): 1E-5
Neutral volume of blood flow of skin(L.hr-1.cm-1): 0.00063
Regulative sweating constant(g/cm2/hr): 4.722222222
Pow sweating rate(g/cm2/hr): 10.7
Maximum sweating rate(g/cm2/hr): 0.266666666
Neutral temperature of skin(deg.): 34.1
Neutral temperature of core(deg.): 37.1
Minimum volume of blood flow of skin(L.hr-1.cm-1): 5E-5
Maximum volume of blood flow of skin(L.hr-1.cm-1): 0.009
Regulative shivering constant(cal.s-1.cm-2): 0.00046366
Absorptivity of the skin surface to the solar radiation: 0.77
Specific heat at constant pressure of blood(cal.g-1.deg-1): 0.277957

Comfort Parameters

Fire Rate of Core

Warm

	[28,40.5]	[40.5,43]
K_static	0.23	2.12
Constant	13.13	-67.93

Cold

	[22,34.5]	[34.5,43]
K_static	-1.04	3.41
Constant	45.63	-134.65

Fire Rate of Skin

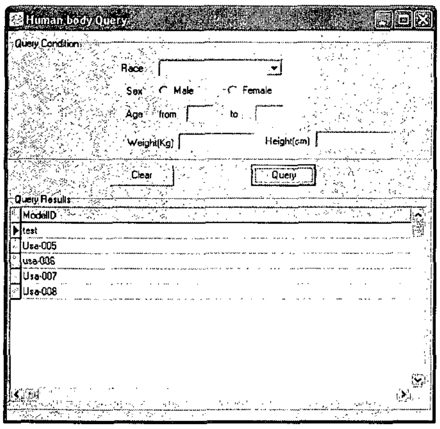
Warm

	[30,40]	[40,44]
K_static	1.16	-2.05
K_dynamic	70	70
Constant	-36.06	113

Cold

	[13,24]	[24,40]
K_static	0.47	-0.64
K_dynamic	-21	-21
Constant	-1.07	25.86

Body properties definition

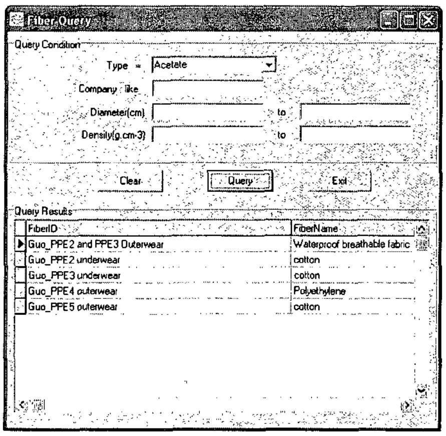

Human body Query

Query Condition
Race
Sex ○ Male ○ Female
Age from to
Weight(Kg)
Height(cm)

Query Results

ModelID
test
Usa-005
usa-006
Usa-007
Usa-008

Human body query with DB

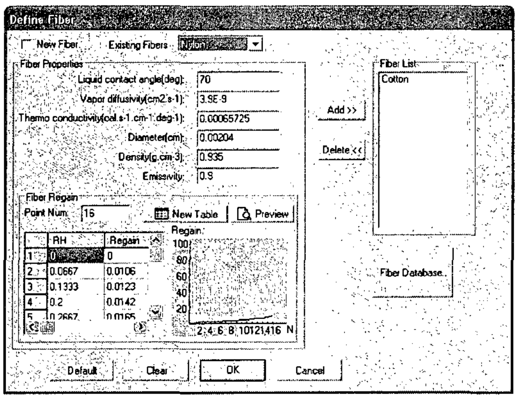

Fiber Query

Query Condition
Type = Acetate
Company like
Diameter(cm) to
Density(g.cm-3) to

Query Results

FiberID	FiberName
Guo_PPE2 and PPE3 Outerwear	Waterproof breathable fabric
Guo_PPE2 underwear	cotton
Guo_PPE3 underwear	cotton
Guo_PPE4 outerwear	Polyethylene
Guo_PPE5 outerwear	cotton

Fiber query with DB



Existing Fibers: Nylon

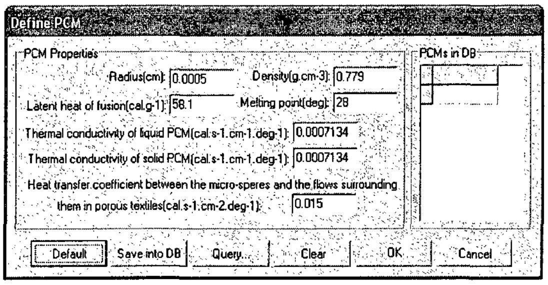
Fiber Properties
Liquid contact angle(deg): 70
Vapor diffusivity(cm2.s-1): 3.9E-9
Thermo conductivity(cal.s-1.cm-1.deg-1): 0.00065725
Diameter(cm): 0.00204
Density(g.cm-3): 0.935
Emissivity: 0.9

Fiber List: Cotton

Fiber Regain
Point Num: 16

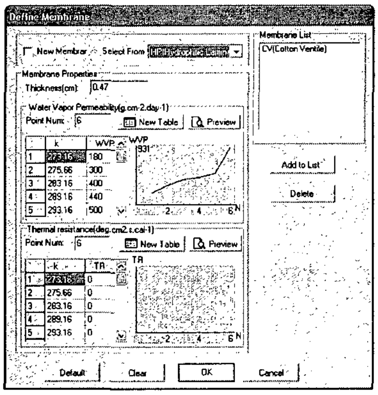
	RH	Regain
1	0	0
2	0.0667	0.0106
3	0.1333	0.0123
4	0.2	0.0142
5	0.2667	0.0165

Fiber design



PCM Properties
Radius(cm): 0.0005
Density(g.cm-3): 0.779
Latent heat of fusion(cal.g-1): 58.1
Melting point(deg): 28
Thermal conductivity of liquid PCM(cal.s-1.cm-1.deg-1): 0.0007134
Thermal conductivity of solid PCM(cal.s-1.cm-1.deg-1): 0.0007134
Heat transfer coefficient between the micro-speres and the flows surrounding them in porous textiles(cal.s-1.cm-2.deg-1): 0.015

PCM design



Select From: HP(Hydrophilic Lamin

Membrane List: CV(Cotton Ventile)

Membrane Properties
Thickness(cm): 0.47

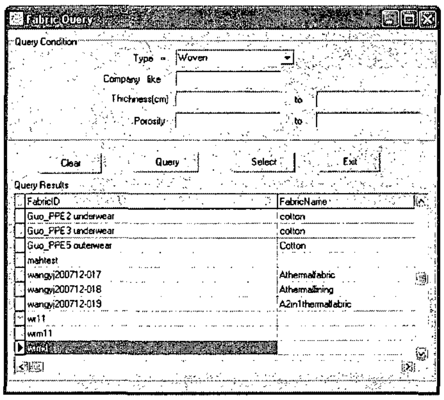
Water Vapor Permeability(g.cm-2.day-1)
Point Num: 6

	k	WVP
1	273.15	180
2	275.66	300
3	283.16	400
4	289.16	440
5	293.16	500

Thermal resistance(deg.cm2.s.cal-1)
Point Num: 6

	k	TR
1	273.16	0
2	275.66	0
3	283.16	0
4	289.16	0
5	293.16	0

Membrane design

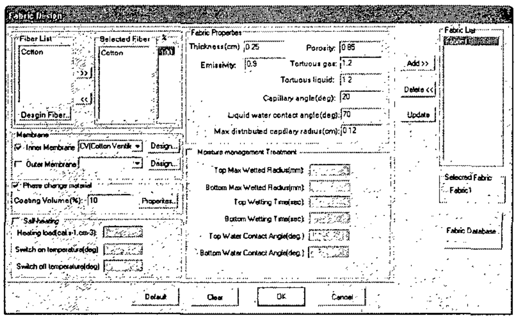


Query Condition
Type = Woven
Company like
Thichness(cm) to
Porosity to

Query Results

FabricID	FabricName
Guo_PPE2 underwear	cotton
Guo_PPE3 underwear	cotton
Guo_PPE5 outerwear	Cotton
mahtest	
wangyj200712-017	Athermalfabric
wangyj200712-018	Athermallining
wangyj200712-019	A2in1thermalfabric
wr11	
wrm11	
wrm1	

Fabric query with DB



Fiber List: Cotton
Selected Fiber: Cotton

Fabric Properties
Thickness(cm): 0.25
Porosity: 0.85
Emissivity: 0.9
Tortuous gas: 1.2
Tortuous liquid: 1.2
Capillary angle(deg): 20
Liquid water contact angle(deg): 70
Max distributed capillary radius(cm): 0.12

Membrane
☑ Inner Membrane: CV(Cotton Ventile
☐ Outer Membrane:

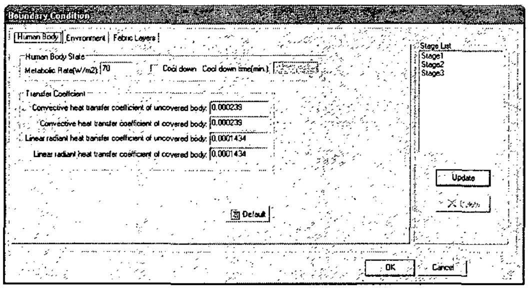
☑ Phase change material
Coating Volume(%): 10

☐ Self-heating
Heating load(cal.s-1.cm-3):
Switch on temperature(deg)
Switch off temperature(deg)

☐ Moisture management Treatment
Top Max Wetted Radius(mm):
Bottom Max Wetted Radius(mm):
Top Wetting Time(sec):
Bottom Wetting Time(sec):
Top Water Contact Angle(deg.)
Bottom Water Contact Angle(deg.)

Selected Fabric: Fabric1

Fabric design

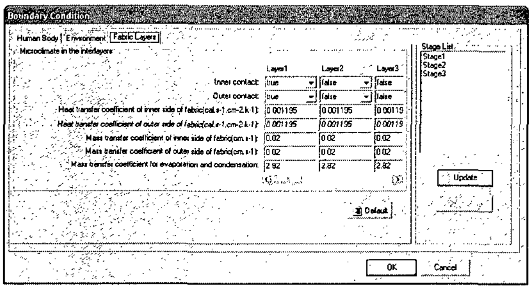


Human Body State
Metabolic Rate(W/m2): 70
☐ Cool down
Cool down time(min.):

Transfer Coefficient
Convective heat transfer coefficient of uncovered body: 0.000239
Convective heat transfer coefficient of covered body: 0.000239
Linear radiant heat transfer coefficient of uncovered body: 0.0001434
Linear radiant heat transfer coefficient of covered body: 0.0001434

Stage List
Stage1
Stage2
Stage3

Coefficients of human body in boundary conditions

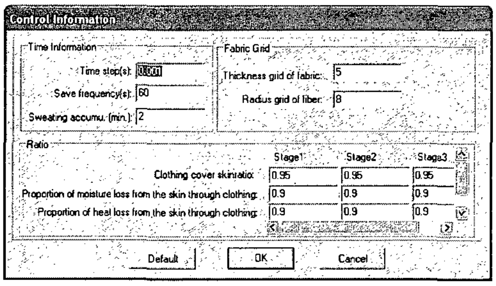


Microclimate in the interlayers

	Layer1	Layer2	Layer3
Inner contact:	true	false	false
Outer contact:	true	false	false
Heat transfer coefficient of inner side of fabric(cal.s-1.cm-2.k-1):	0.001195	0.001195	0.00119
Heat transfer coefficient of outer side of fabric(cal.s-1.cm-2.k-1):	0.001195	0.001195	0.00119
Mass transfer coefficient of inner side of fabric(cm.s-1):	0.02	0.02	0.02
Mass transfer coefficient of outer side of fabric(cm.s-1):	0.02	0.02	0.02
Mass transfer coefficient for evaporation and condensation:	2.82	2.82	2.82

Stage List
Stage1
Stage2
Stage3

Coefficients of fabric in boundary condition



Time Information
Time step(s): [illegible]
Save frequency(s): 60
Sweating accumu. (min.): 2

Fabric Grid
Thickness grid of fabric: 5
Radius grid of fiber: 8

Ratio

	Stage1	Stage2	Stage3
Clothing cover skinratio:	0.95	0.95	0.95
Proportion of moisture loss from the skin through clothing:	0.9	0.9	0.9
Proportion of heat loss from the skin through clothing:	0.9	0.9	0.9

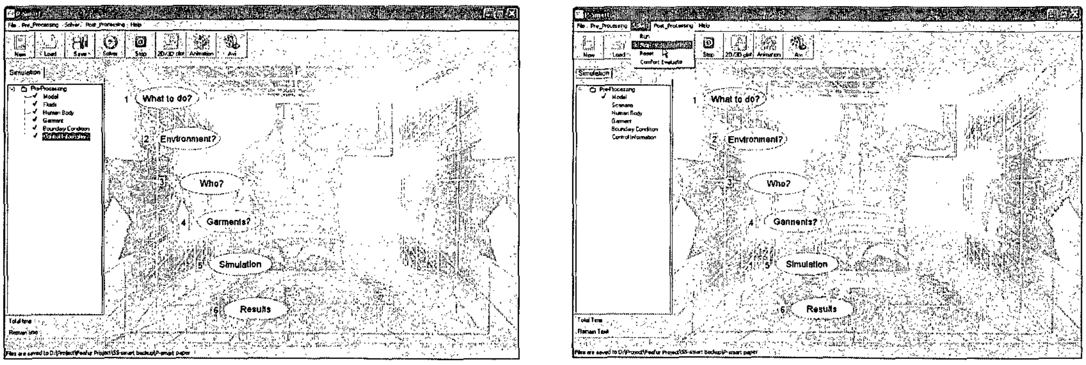
Control information specification

Figure 6.10 Main interfaces for in the P-smart system

Considering the input requirements discussed in Chapter 5, apart from the life-oriented design procedure, these user interfaces are designed with regarding a design activity (fiber design, fabric design, human body definition etc.) as a unit of interface, and the layout of these interfaces is arranged with reference to the characteristic data of the materials and design behaviors and the design principles. The engineering units of the input data on the interface have been provided and the reasonable value range of the input data has been set to assure the right input by the user.

2) Computational simulation

The computational simulation is performed with the main interface of P-smart. When the design and specification have been finished, the simulation can start or be stopped or reset by clicking the buttons on the main interface. Figure 6.11 shows the interface and operation for the computational simulation. When the simulation starts, the time spent to finish the simulation for all the specified wearing scenarios will be shown to the user.



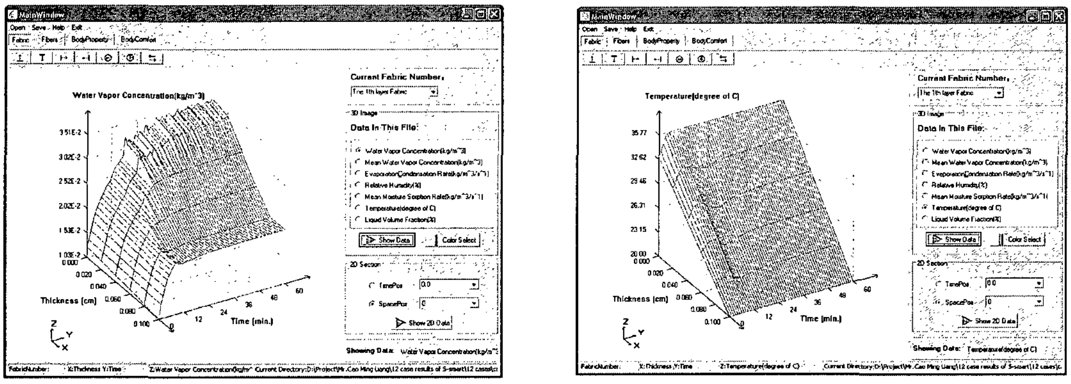
Main interface

Perform simulation on the main interface

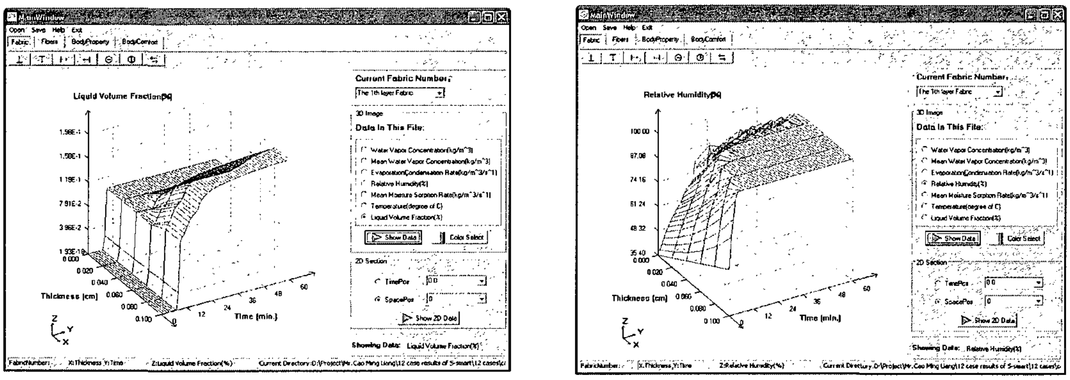
Figure 6.11 Interface and operation for computational simulation

3) Post processing

The interfaces in post processing include the chart visualization interface and 3D animations. The thermal variables of the fiber, fabric and human body are listed out on the interface for the user to choose to view their distributions. Figure 6.12 shows the chart visualization of the thermal variables of the fabric, including the water vapor concentration, temperature, liquid water volume and relative humidity. The chart visualization of the thermal variables of the fiber and the human body can be found in Figure 6.13 and Figure 6.14.

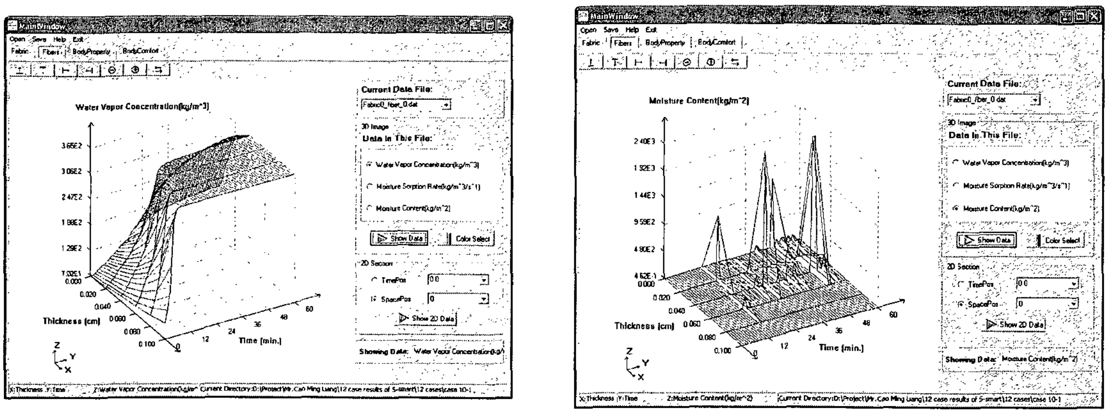


Water vapor concentration Temperature



Liquid water volume Relative humidity

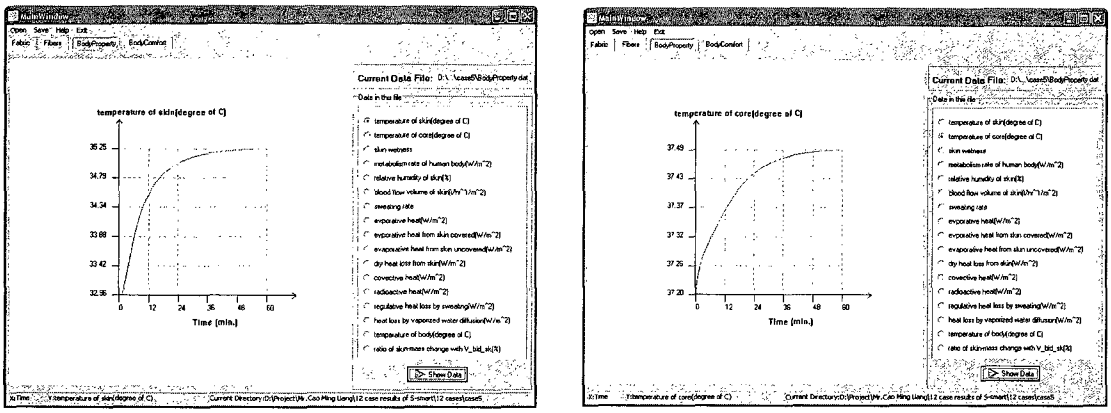
Figure 6.12 Chart visualization of the thermal variables of the fabric



Water vapor Concentration

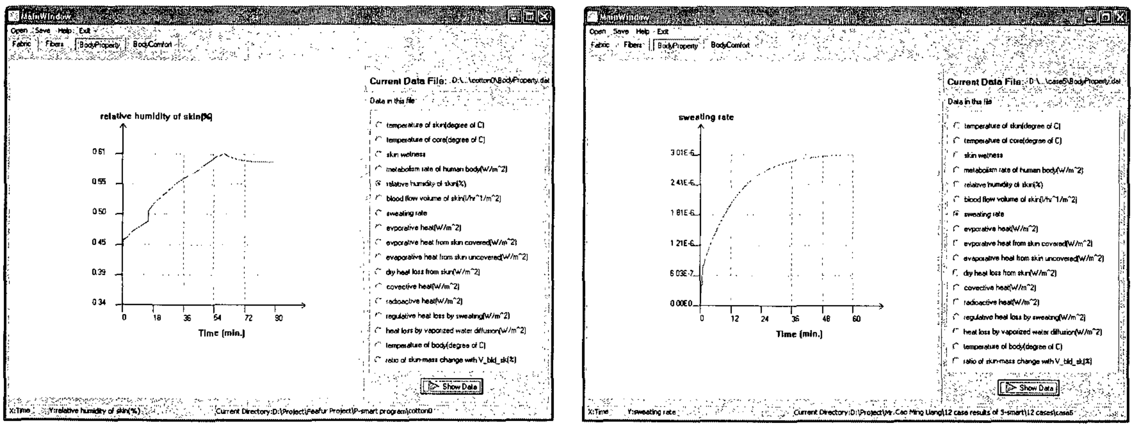
Moisture Content

Figure 6.13 Chart visualization of the thermal variables of the fiber



Skin temperature

Core temperature

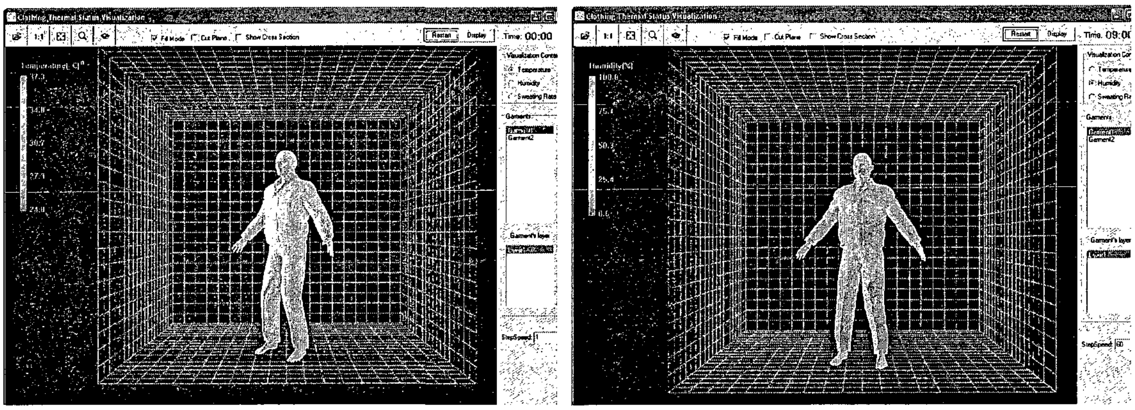


Skin relative humidity

Sweating rate

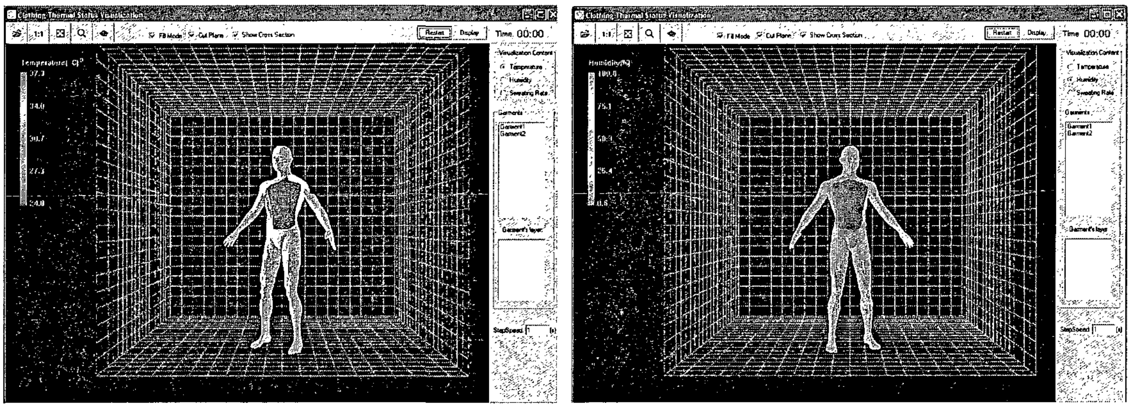
Figure 6.14 Chart visualization of the thermal variables of the human body

Figure 6.15 shows the animated clothing and human body with mapped colors according to the value of the thermal variables, including temperature, water vapor concentration and relative humidity. The mapped color is dynamically updated in time during the wearing period. Each fabric layer of clothing can be chosen to see its animated thermal performance. The animated human body can show the thermal status of the skin and core at the same time.



Animated temperature of the clothing

Animated water vapor concentration of the clothing



Animated temperature of the human body

Animated relative humidity of the human body

Figure 6.15 Animated thermal variables of the clothing and human body

6.3 TWO DESIGN CASES

In order to illustrate the functionalities and the design process of P-smart, two design cases are simulated by using this CAD system. One is a case of designing thermal functional clothing with different functional treatments for summer outdoor active sports. The other one is a case of designing personal protective clothing with multi-layer fabrics for the healthcare worker wearing in the hospital.

6.3.1 A design case with different functional treatments

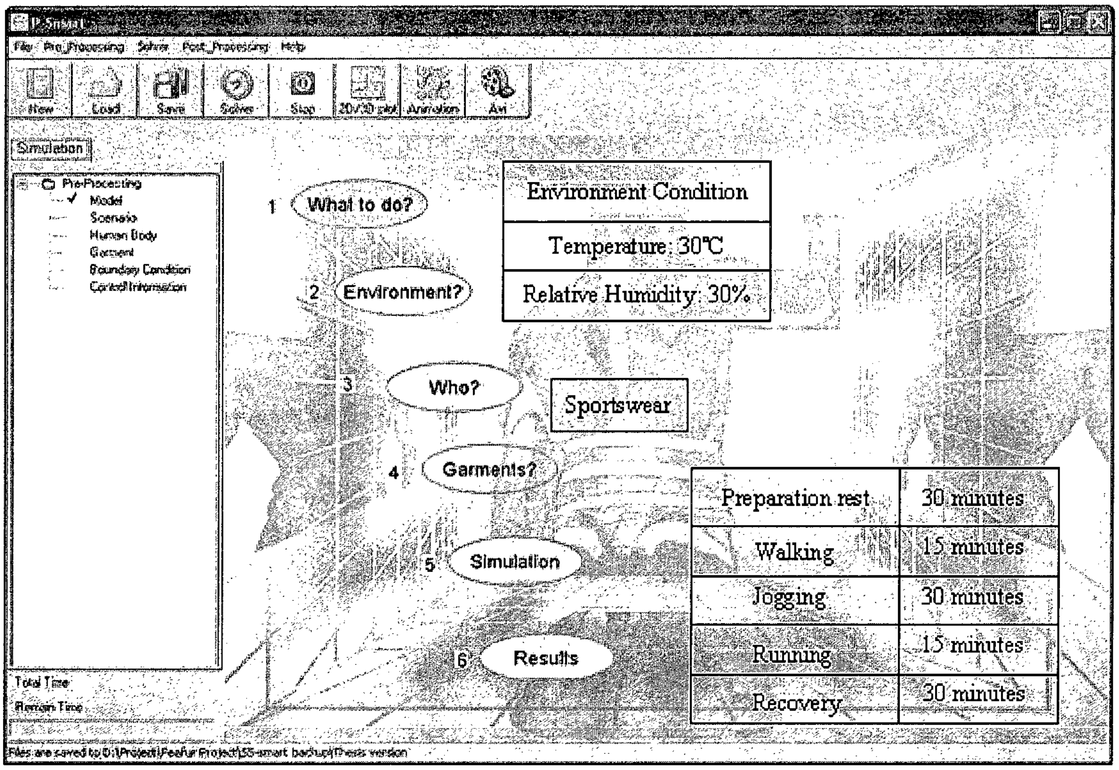
A design case of one layer sports-shirt with different functional treatments (hydrophilic and hydrophobic effects) is illustrated to show the functional design procedure and functionalities of P-smart. This sports-shirt is designed for summer outdoor active sports such as running and playing tennis. The wearer is specified as a male person with 65 Kg weight and 1.8 m^2 body surface area. The wearing scenario is assumed in an environment with 30 °C temperature, 30% relative humidity and 0.2 m/s wind velocity. The clothing is designed with cotton fabric with nano-finishing to achieve hydrophilic and hydrophobic effects, as shown in Table 6.7.

Table 6.7 Physical properties of the sports wear

Garment type	Fiber	Functional finishing	Weight (g/m^2)	Thickness (mm)	Density (g/cm^3)	Moisture regain (%)
Sports wear	Cotton	Hydrophilic/ Hydrophobic	3.4	1.6	202	7.5

And the wearing protocol is set as: rest for 30 minutes → walking for 15 minutes → slow running for 30 minutes → fast running for 15 minutes → sit down and relax for 30 minutes, as shown in Figure 6.16.

With this information, the designer can preview the thermal functional performances of the garments made from the two nano-functional fabrics by using P-smart, following the simulation flow of life-oriented procedure design→simulation→post processing.



Environment Condition
Temperature: 30℃
Relative Humidity: 30%

Sportswear

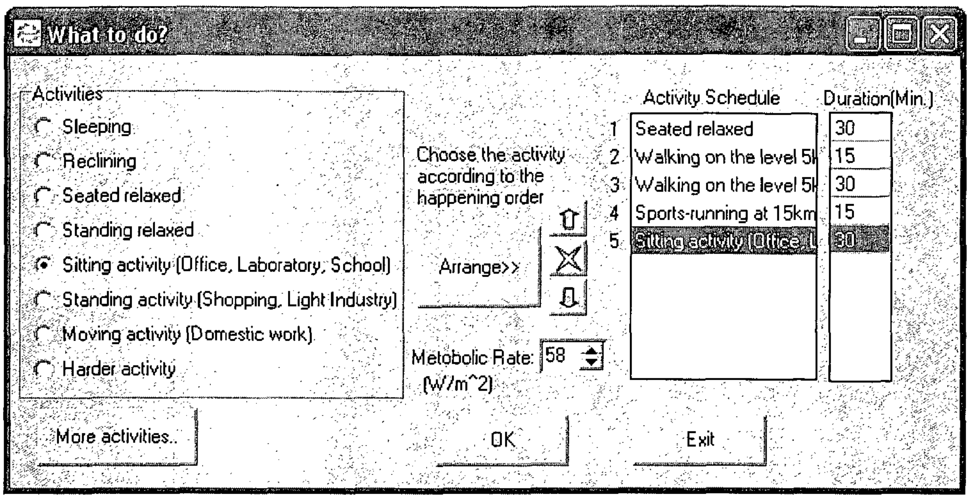
Preparation rest	30 minutes
Walking	15 minutes
Jogging	30 minutes
Running	15 minutes
Recovery	30 minutes

Figure 6.16 The wear protocol of the design case

Life-oriented design

In the design stage, the garment, thermal status of human body, environmental condition and wear protocol are all specified through the graphic interfaces in P-smart. The life-oriented design procedure provided by the software system guides the user to finish all these designs and specifications to define their design scheme.

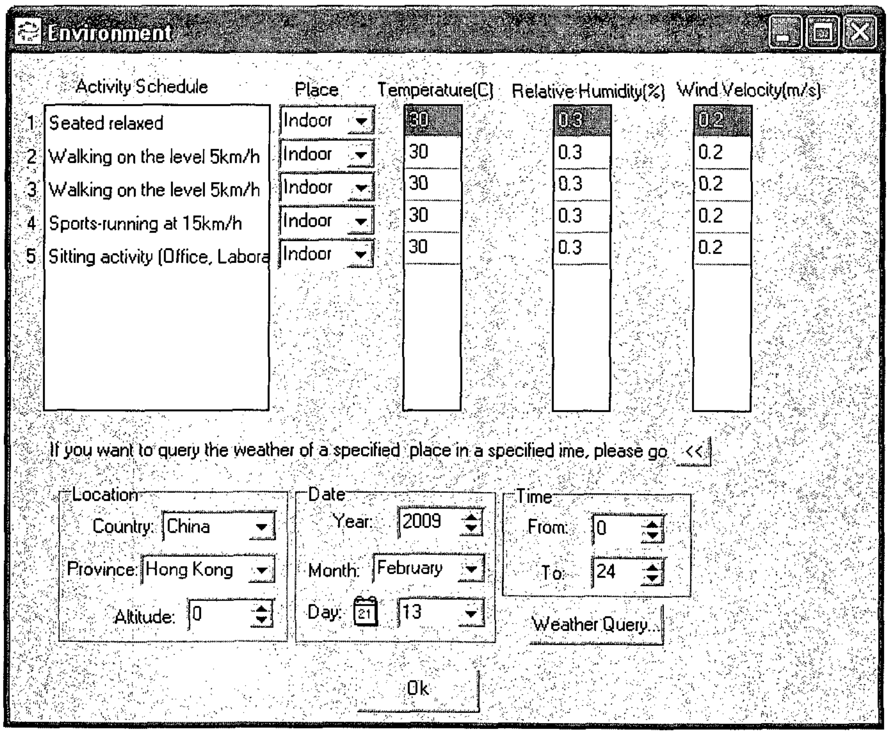
Figure 6.17 is the interface for activity specification, which provides a series of sports activities and working activities to choose and create an activity schedule for wearing the clothing and specify activity durations.



Metobolic Rate: 58 (W/m^2)

	Activity Schedule	Duration(Min.)
1	Seated relaxed	30
2	Walking on the level 5l	15
3	Walking on the level 5l	30
4	Sports-running at 15km	15
5	Sitting activity (Office, L	30

Figure 6.17 The interface for activity specification



	Activity Schedule	Place	Temperature(C)	Relative Humidity(%)	Wind Velocity(m/s)
1	Seated relaxed	Indoor	30	0.3	0.2
2	Walking on the level 5km/h	Indoor	30	0.3	0.2
3	Walking on the level 5km/h	Indoor	30	0.3	0.2
4	Sports-running at 15km/h	Indoor	30	0.3	0.2
5	Sitting activity (Office, Labora	Indoor	30	0.3	0.2

Location
Country: China
Province: Hong Kong
Altitude: 0

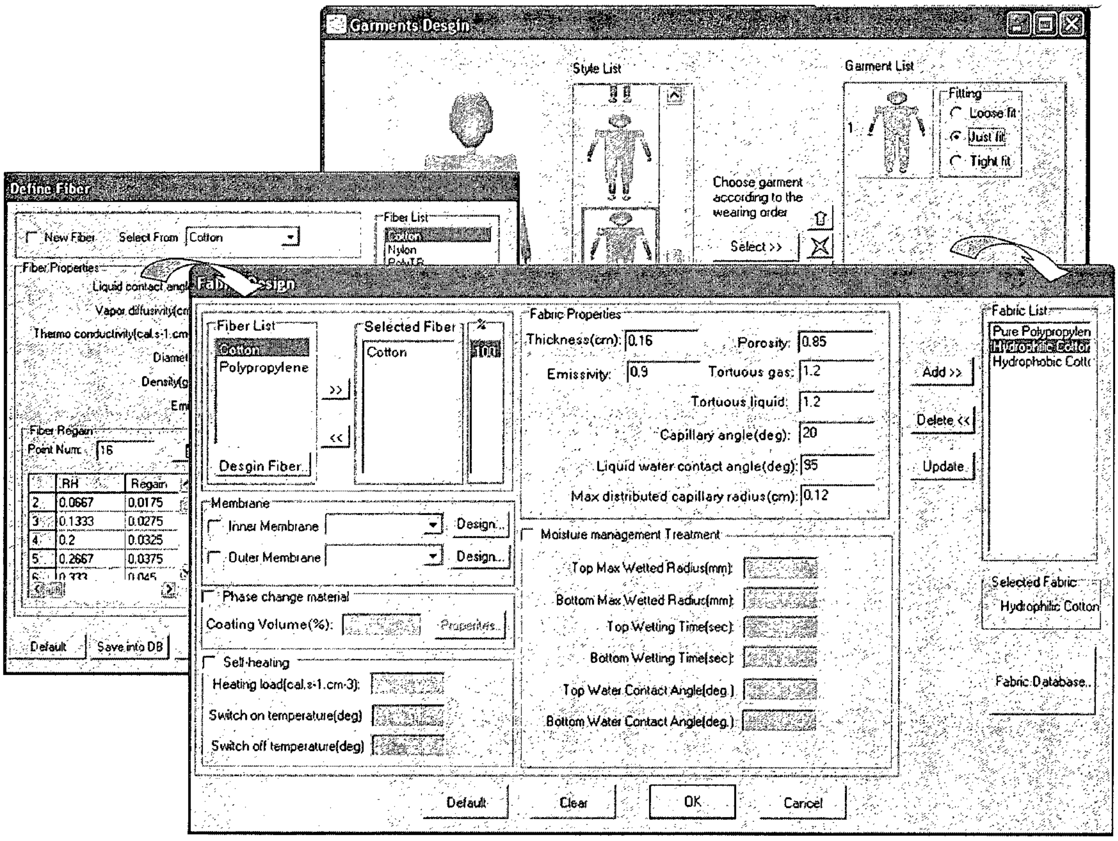
Date
Year: 2009
Month: February
Day: 13

Time
From: 0
To: 24

Figure 6.18 The interface for wearing environment specification

Figure 6.18 is the interfaces for wearing environment specification, which can specify the wearing environment of each activity, and query the climatic conditions of a specified place to set as the wearing environment.

The garment design is completed by first selecting the style and fitting status, defining the properties of adopted fiber materials, and then designing the fabric layers in the clothing, as shown in Figure 6.19. The hydrophilic and hydrophobic effects of the nano-finishing are represented by specifying the contact angles of the fabrics as 95 degree and 5 degree, respectively.



Garment List: 1

Fitting: ○ Loose fit ● Just fit ○ Tight fit

☐ New Fiber Select From: Cotton

Fiber Regain

Point Num: 16

	RH	Regain
2	0.0667	0.0175
3	0.1333	0.0275
4	0.2	0.0325
5	0.2667	0.0375

Selected Fiber: Cotton 100

☐ Inner Membrane

☐ Outer Membrane

☐ Phase change material

Coating Volume(%):

☐ Self-heating

Heating load(cal.s-1.cm-3):

Switch on temperature(deg)

Switch off temperature(deg)

Thickness(cm): 0.16

Porosity: 0.85

Emissivity: 0.9

Tortuous gas: 1.2

Tortuous liquid: 1.2

Capillary angle(deg): 20

Liquid water contact angle(deg): 95

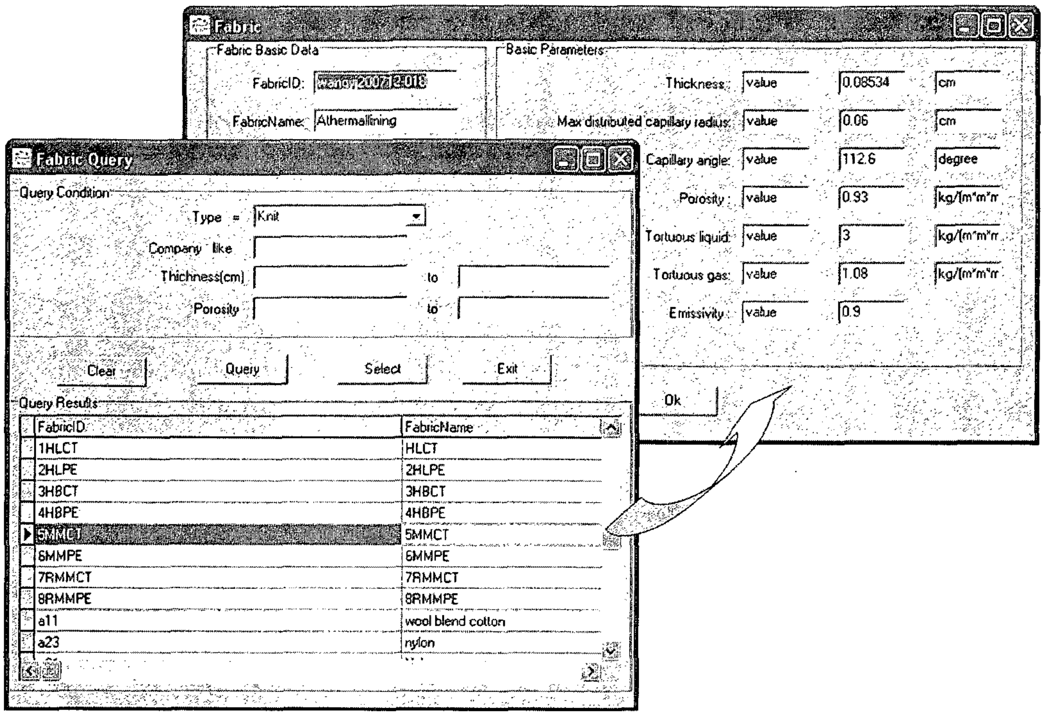
Max distributed capillary radius(cm): 0.12

☐ Moisture management Treatment

Selected Fabric: Hydrophilic Cotton

Figure 6.19 The interfaces for defining clothing materials

In the clothing design process, the engineering database is available to support the design of fabric, fiber, membrane and PCM, as shown in Figure 6.20, which is the interface of the engineering database supporting the fabric design.



FabricID: wangyi200712-018

FabricName: Athermallining

Thickness:	value	0.08534	cm
Max distributed capillary radius:	value	0.06	cm
Capillary angle:	value	112.6	degree
Porosity:	value	0.93	kg/(m*m*r
Tortuous liquid:	value	3	kg/(m*m*r
Tortuous gas:	value	1.08	kg/(m*m*r
Emissivity:	value	0.9	

Type = Knit

Company like

Thichness(cm) to

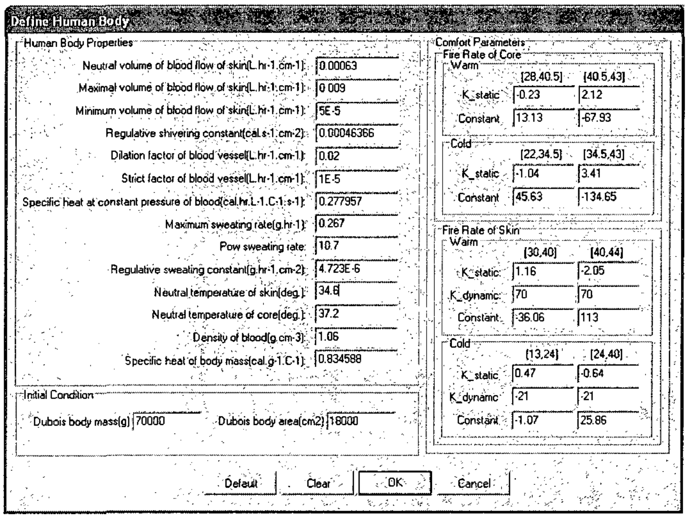
Porosity to

FabricID	FabricName
1HLCT	HLCT
2HLPE	2HLPE
3HBCT	3HBCT
4HBPE	4HBPE
5MMCT	5MMCT
6MMPE	6MMPE
7RMMCT	7RMMCT
8RMMPE	8RMMPE
a11	wool blend cotton
a23	nylon

Figure 6.20 The interfaces of the engineering database supporting for fabric design

The thermal status of the human body is defined by inputting the physical, physiological and psychological properties of a male with mass of 70 kg and skin area of 1.8 m^2. The definition interfaces are shown in Figure 6.21, which first defines the particular physical information of the body and then specifies the physiological and psychological properties. The interface of the engineering database for human body definition is shown in Figure 6.22.

The boundary conditions between the human body, external environment and clothing layers in each wearing stage are shown in Figure 6.23, which is provided to the experienced user to update the coefficients in the boundary condition, including the thermal status of the body, the climatic conditions of the wearing environment, and the connective heat and mass transfer coefficients of the fabric-skin system.



Human Body Properties

Neutral volume of blood flow of skin(L.hr-1.cm-1): 0.00063
Maximal volume of blood flow of skin(L.hr-1.cm-1): 0.009
Minimum volume of blood flow of skin(L.hr-1.cm-1): 5E-5
Regulative shivering constant(cal.s-1.cm-2): 0.00046366
Dilation factor of blood vessel(L.hr-1.cm-1): 0.02
Strict factor of blood vessel(L.hr-1.cm-1): 1E-5
Specific heat at constant pressure of blood(cal.hr.L-1.C-1.s-1): 0.277957
Maximum sweating rate(g.hr-1): 0.267
Pow sweating rate: 10.7
Regulative sweating constant(g.hr-1,cm-2): 4.723E-6
Neutral temperature of skin(deg.): 34.6
Neutral temperature of core(deg.): 37.2
Density of blood(g.cm-3): 1.06
Specific heat of body mass(cal.g-1.C-1): 0.834588

Initial Condition

Dubois body mass(g) 70000
Dubois body area(cm2) 18000

Comfort Parameters

Fire Rate of Core

Warm

	[28,40.5]	[40.5,43]
K_static	-0.23	2.12
Constant	13.13	-67.93

Cold

	[22,34.5]	[34.5,43]
K_static	-1.04	3.41
Constant	45.63	-134.65

Fire Rate of Skin

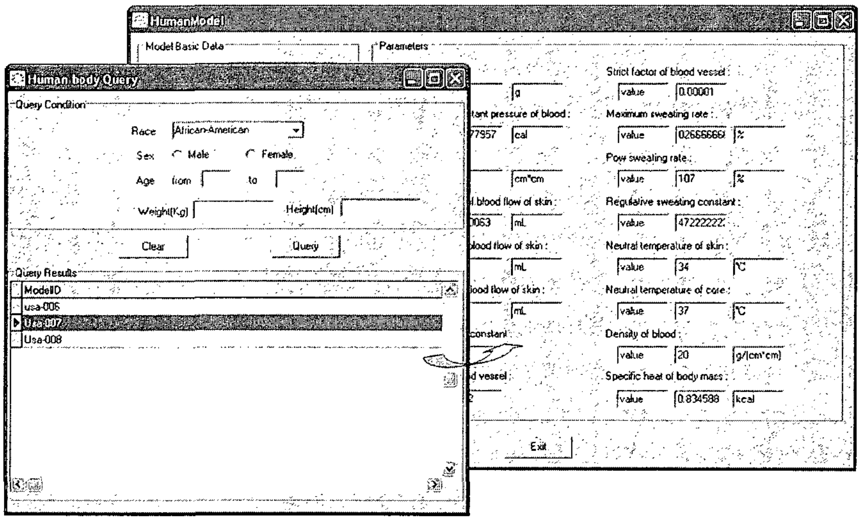
Warm

	[30,40]	[40,44]
K_static	1.16	-2.05
K_dynamc	70	70
Constant	-36.06	113

Cold

	[13,24]	[24,40]
K_static	0.47	-0.64
K_dynamc	-21	-21
Constant	-1.07	25.86

Figure 6.21 The interfaces for defining body physiological properties



Query Condition

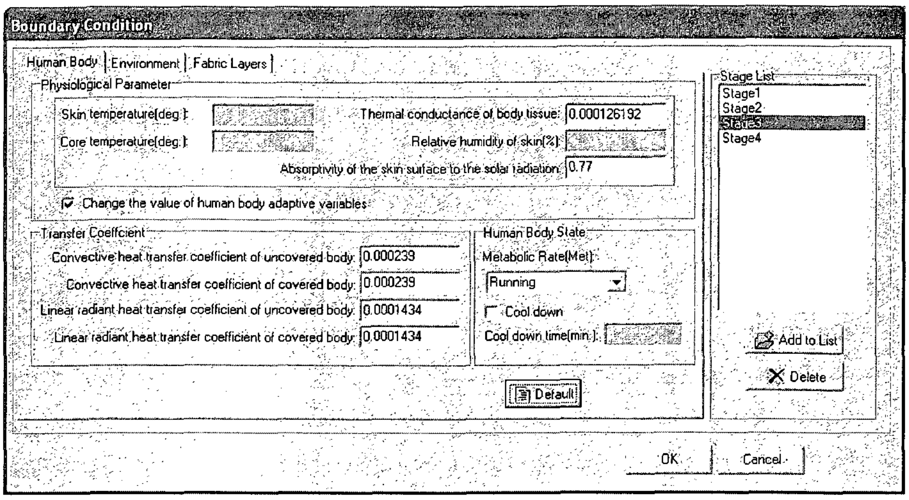
Race: African-American
Sex: ○ Male ○ Female
Age from to
Weight(Kg) Height(cm)

Query Results

ModelID
usa-006
Usa-007
Usa-008

Strict factor of blood vessel: value 0.00001
Maximum sweating rate: value 02666666 %
Pow sweating rate: value 107 %
Regulative sweating constant: value 47222222
Neutral temperature of skin: value 34 ℃
Neutral temperature of core: value 37 ℃
Density of blood: value 20 g/(cm*cm)
Specific heat of body mass: value 0.834588 kcal

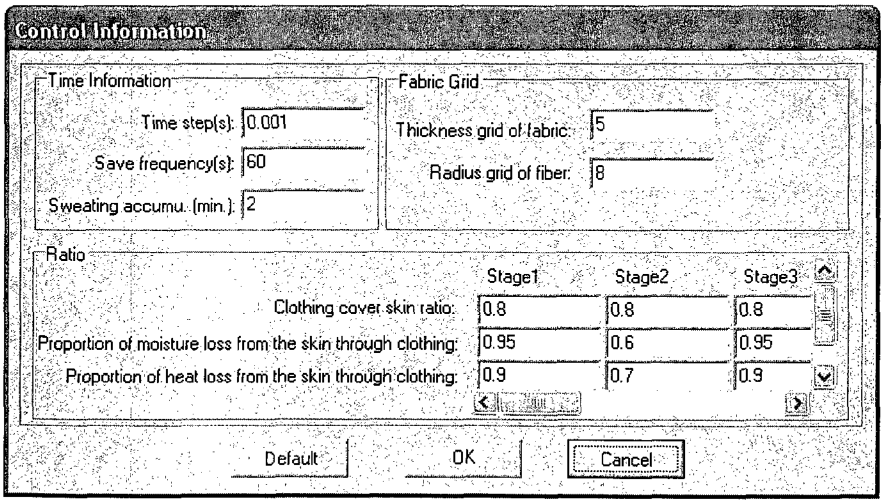
Figure 6.22 The interfaces of the engineering database for human body definition



Skin temperature(deg.):
Core temperature(deg.):
Thermal conductance of body tissue: 0.000126192
Relative humidity of skin(%):
Absorptivity of the skin surface to the solar radiation: 0.77
☑ Change the value of human body adaptive variables
Convective heat transfer coefficient of uncovered body: 0.000239
Convective heat transfer coefficient of covered body: 0.000239
Linear radiant heat transfer coefficient of uncovered body: 0.0001434
Linear radiant heat transfer coefficient of covered body: 0.0001434
Metabolic Rate(Met): Running
☐ Cool down
Cool down time(min.):
Stage List: Stage1, Stage2, Stage3, Stage4

Figure 6.23 The interface for updating the boundary conditions

The interface for specifying the controlling information of the simulation is shown in Figure 6.24, which can specify the time step, simulation results frequency, fabric grid number and the ratio of heat and mass transfer between the fabric and the skin for each wearing scenario.



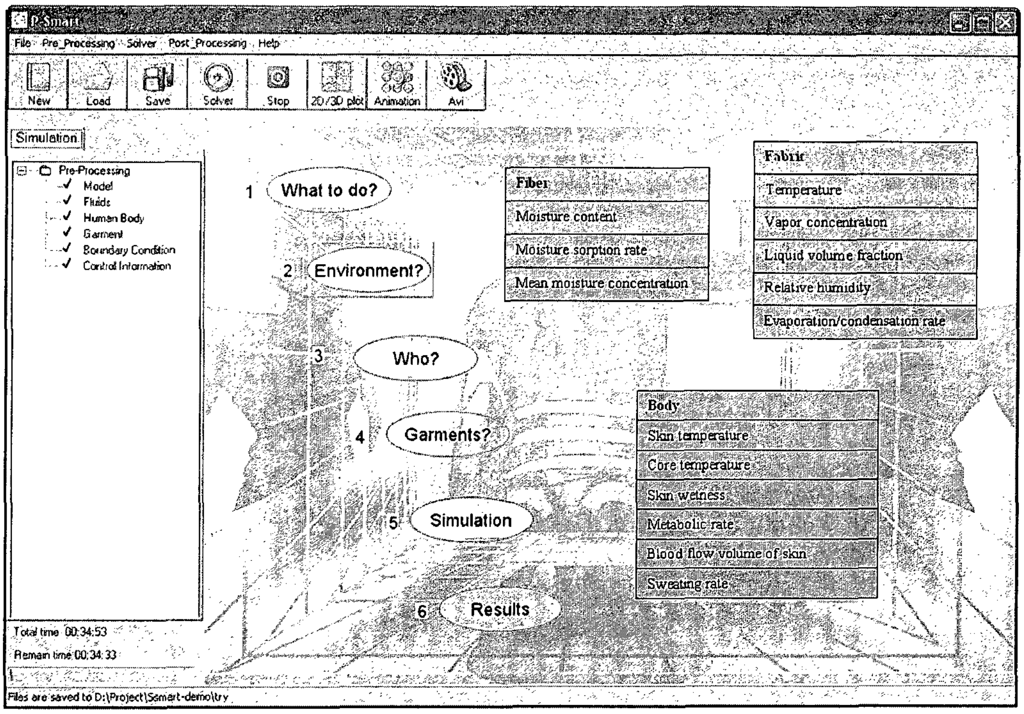
Time step(s): 0.001
Save frequency(s): 60
Sweating accumu. (min.): 2
Thickness grid of fabric: 5
Radius grid of fiber: 8

	Stage1	Stage2	Stage3
Clothing cover skin ratio:	0.8	0.8	0.8
Proportion of moisture loss from the skin through clothing:	0.95	0.6	0.95
Proportion of heat loss from the skin through clothing:	0.9	0.7	0.9

Figure 6.24 The interface for control information specifications

Computational simulation

After completing the clothing design and definition of thermal status of human body and wear protocol, the computational simulation starts to run. The time spent on the simulation depends on the duration of the activity schedule and the control specification for the simulation such as the time step and fabric grid. The key thermal variables of the fibers, clothing and human body are listed as outputs of the simulation results, as shown in Figure 6.25.



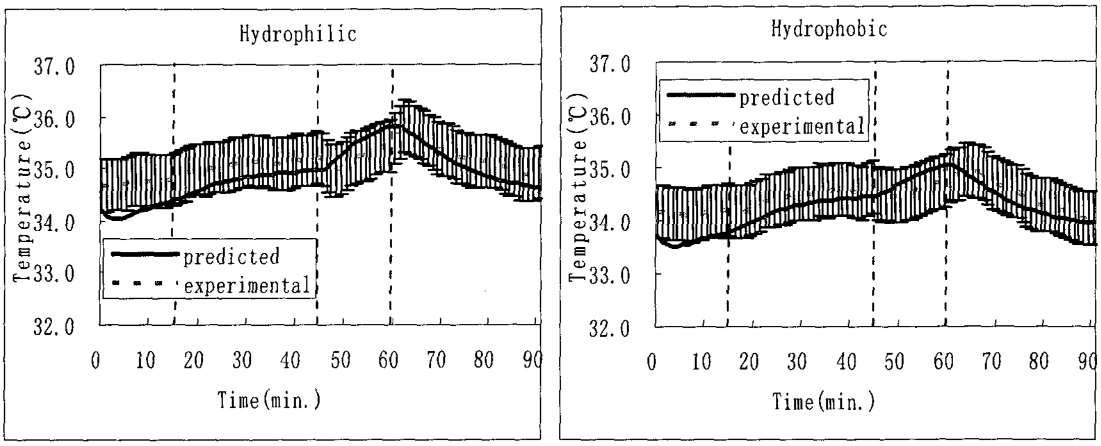
Total time 00:34:53
Remain time 00:34:33
Files are saved to D:\Project\Psmart-demo\try

Figure 6.25 The interface of computational simulation

Validation of the simulation results

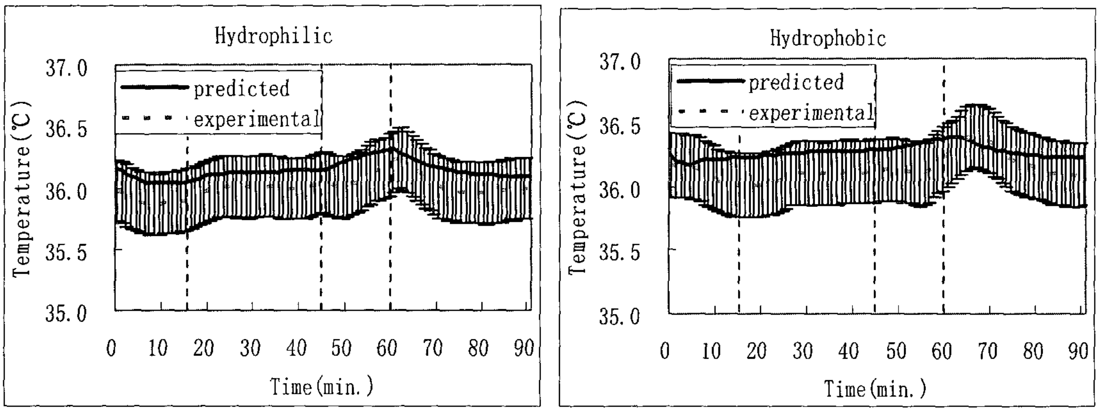
During the computational process, the simulation results of the key thermal variables are recorded and stored in the data files. In order to validate P-smart, a series of wear trials by human subjects have been carried out in a climatic chamber, which was controlled according to the same wear protocol of the design specification. There were totally 8 subjects participating in the wear trials, wearing the same style of clothing and doing the same exercises on the treadmill in the chamber according to the wear protocol [143]. Each subject performed the tests twice, the first time wearing the hydrophilic sportswear and the second time wearing the hydrophobic sportswear. The sensors placed on the skin and in the deep ear canales continuously recorded the temperature and humidity data in the experiments.

The simulation results were compared with the experimental measurements on the skin temperature and core temperature, as shown in Figure 6.26~ Figure 6.27. In these figures, the experimental data are presented with mean values (dotted line) with error bars to indicate data variations. As shown in these figures, P-smart can predict similar trends of changes in the temperatures, and the predicted values fall within the variations in the experimental measurements, which indicate P-smart is able to provide reasonably good simulation results that can fit closely with the experimental observations.



(a) Hydrophilic sportswear (b) Hydrophobic sportswear

Figure 6.26 Comparisons between the predicted and experimental skin temperature

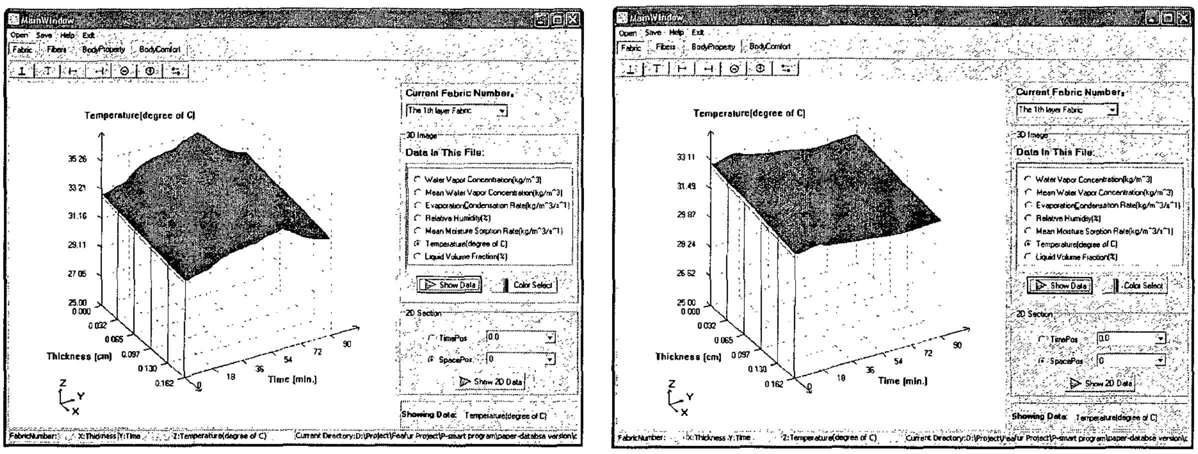


(a) Hydrophilic sportswear (b) Hydrophobic sportswear

Figure 6.27 Comparisons between the predicted and experimental core temperature

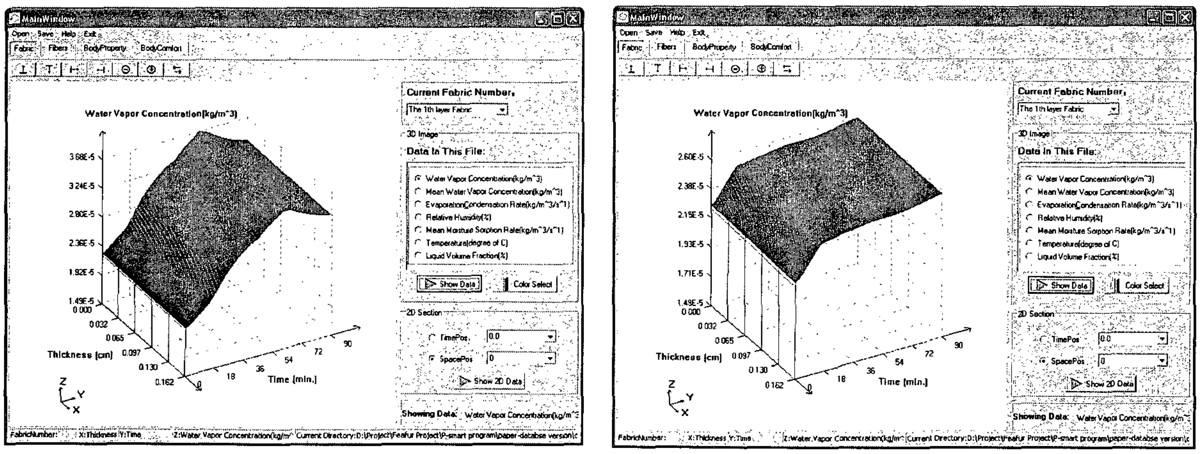
Post-processing

To present the thermal statuses of the clothing and human body, all the key thermal variables visualized are listed in the right bar in the user interface and can be chose to show their graphic distributions. The two 3D charts in Figure 6.28 respectively show the predicted temperature distributions of the hydrophilic and hydrophobic sports-shirts alone the time and thickness axes. It is observed that the temperature of the hydrophilic sports-shirt obviously increases during the activity period and then decreases during the relaxing period, while that of the hydrophilic sports-shirt has no obvious change. Furthermore, the temperature of the hydrophilic sports-shirt is great higher than that of the hydrophilic sports-shirt during the wearing period.



(a) Hydrophilic sportswear (b) Hydrophobic sportswear

Figure 6.28 Visualization of the predicted temperature distributions

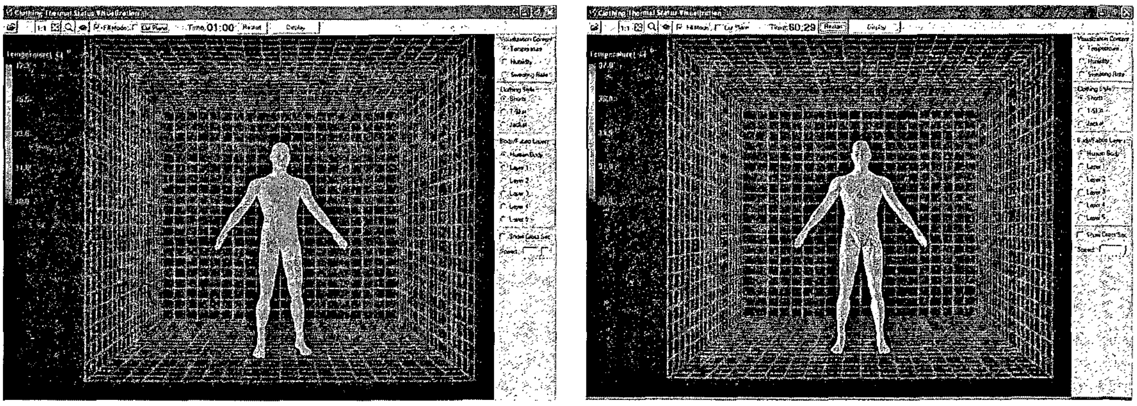


(a) Hydrophilic sportswear (b) Hydrophobic sportswear

Figure 6.29 Visualization of the predicted water vapor concentration distributions

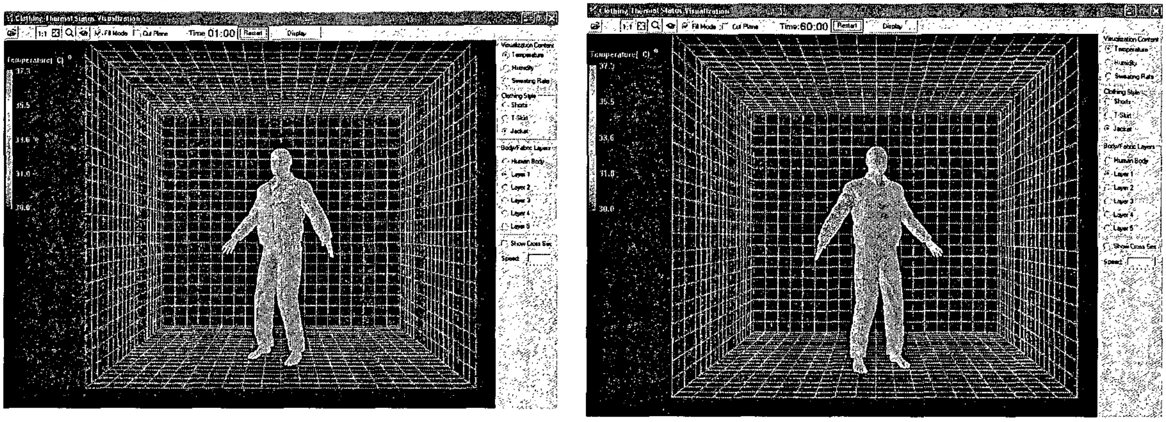
The two 3D charts in Figure 6.29 respectively show the predicted water vapor concentration distributions of the hydrophilic and hydrophobic sports-shirts. It is observed that the water vapor concentration of the hydrophilic sports-shirt increases very quickly and is great higher than that of the hydrophobic sports-shirt. The main reason for the different thermal performance of these two sports-shirts is that the sweat generated by the body during the activity period was absorbed by the hydrophilic sports-shirt but was repelled by the hydrophobic sports-shirt, and the absorption process released heat and increased the temperature of sports-shirt.

Meanwhile, the predicted distributions of the key thermal variables of the clothing and human body can also be visualized in a 3D virtual space for the users to easily understand the simulation results. Figure 6.30 illustrates 4 snapshots of the 3D animation of skin temperature and the temperature on the outer surface of the hydrophobic sportswear respectively at the time point of the 1st minute and the 60th minute in the wear protocol. In the 3D virtual space, the color of the human body, clothing and environment was mapped with the temperature value at that time point according to the color bar on the left. With the time going, the mapped color was dynamically refreshed according to the temperature value at different time points. The designer is thus able to observe the temperature distribution in a more direct and vivid way.



(a) Skin temperature at the 1st minute

(b) Skin temperature at the 60th minute



(c) Clothing outer surface temperature at the 1st minute

(d) Clothing outer surface temperature at the 60th minute.

Figure 6.30 Snapshots of 3D temperature visualization in a thermal virtual space

With these visualizations of the simulation results, even if the designers have limited theoretical knowledge behind the clothing wearing system, they can design, simulate and preview the thermal performance of the hydrophilic and hydrophobic sports-shirts, and importantly, can compare their thermal distributions in the same wearing scenarios to see the difference in their thermal performance. Through the preview and comparison, feedbacks can be obtained to help the designers to make decisions to improve their designs.

This case has illustrated the design procedure of a sports-shirt with different functional treatments (hydrophilic and hydrophobic effects) using P-smart. The designer can preview and compare the thermal performance of the clothing treated with different functional effects, and improve their functional design schemes before making the real product. This case shows the capacity of P-smart in designing thermal functional clothing achieving for superior thermal performance in an effective and economical way.

6.3.2 A design case with multi-layer fabrics

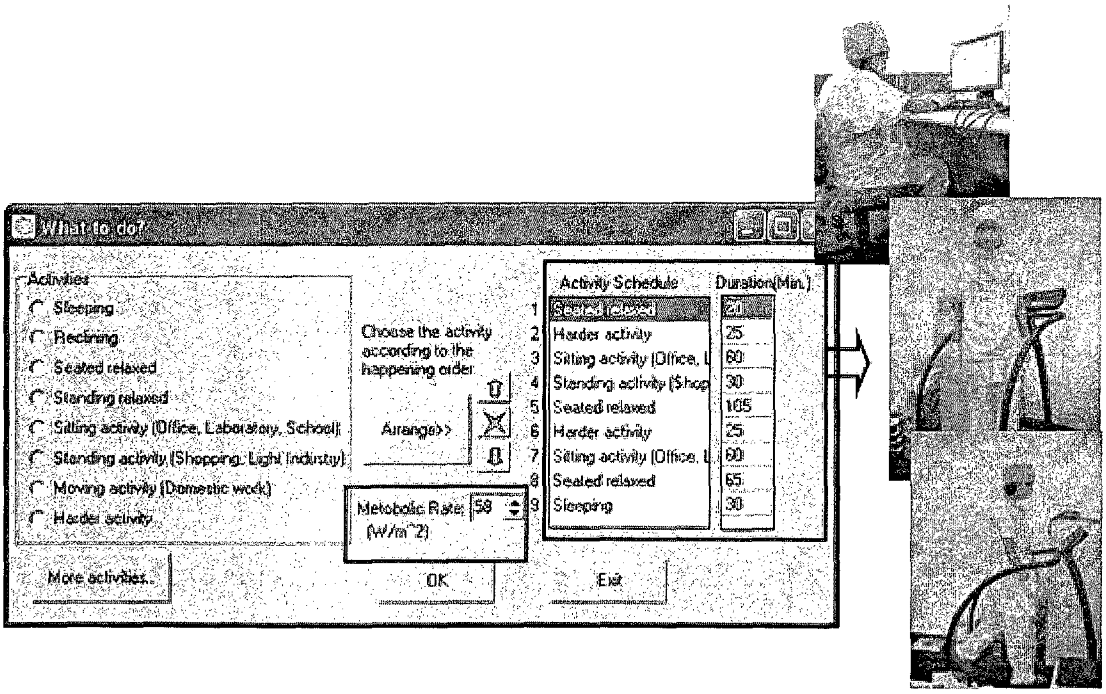
Another design case is illustrated to show the designing process of a set of multi-layer personal protective clothing for the healthcare worker wearing in the hospital using P-smart. The specification of the basic properties of the textile material used for this clothing is listed in Table 6.8.

Table 6.8 Physical properties of the protective wear

Garment type	Fiber	Weight (g/m^2)	Thickness (mm)	Thermal conductivity (W/m.K)	Water vapor permeability ($g/24hr.cm^2 \cdot mm\ Hg \cdot cm$)	Air permeability ($ml/sec/cm^2$)
Inner layer	Cotton	146.4	0.4	0.051	0.053	4.83
Outer layer	Polyethylene	29	0.29	0.035	0.053	7.89

The design process of this personal protective clothing with P-smart is similar to that of the case discussed above, namely following the procedure of life-oriented design →simulation→post processing. It has no need to repeat the descriptions of the functionalities of P-smart again. Here, we only illustrate the main interfaces in the design process and discuss the predicted results to show the capacity of thermal functional multi-layer clothing design with P-smart.

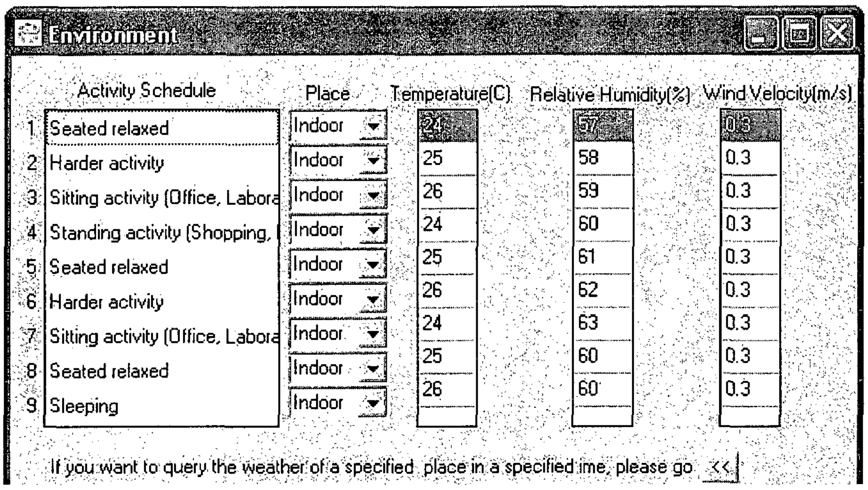
In the life-oriented design phase, the wearing protocol of this clothing is shown in Figure 6.31, which consists of a series of successive activities with the designation of their durations. The climatic conditions for each activity in the schedule are specified as in Figure 6.32, including the temperature, relative humidity of air and wind velocity. The multi-layer protective clothing is designed through the interfaces as shown in Figure 6.33.



Metabolic Rate (W/m^2): 58

	Activity Schedule	Duration(Min.)
1	Seated relaxed	20
2	Harder activity	25
3	Sitting activity (Office, L	60
4	Standing activity (Shop	30
5	Seated relaxed	105
6	Harder activity	25
7	Sitting activity (Office, L	60
8	Seated relaxed	65
9	Sleeping	30

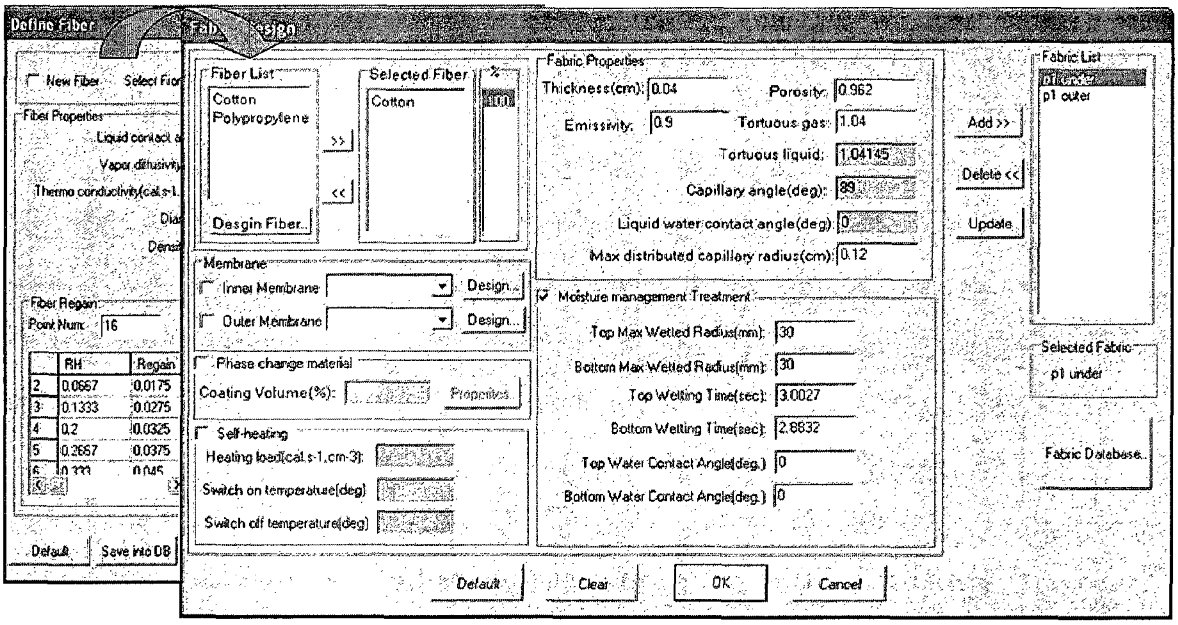
Figure 6.31 Activity schedule for wearing the clothing



	Activity Schedule	Place	Temperature(C)	Relative Humidity(%)	Wind Velocity(m/s)
1	Seated relaxed	Indoor	24	57	0.3
2	Harder activity	Indoor	25	58	0.3
3	Sitting activity (Office, Labora	Indoor	26	59	0.3
4	Standing activity (Shopping,	Indoor	24	60	0.3
5	Seated relaxed	Indoor	25	61	0.3
6	Harder activity	Indoor	26	62	0.3
7	Sitting activity (Office, Labora	Indoor	24	63	0.3
8	Seated relaxed	Indoor	25	60	0.3
9	Sleeping	Indoor	26	60	0.3

If you want to query the weather of a specified place in a specified ime, please go

Figure 6.32 Climatic conditions for the specified activities



Fiber Regain
Point Num: 16

	RH	Regain
2	0.0667	0.0175
3	0.1333	0.0275
4	0.2	0.0325
5	0.2667	0.0375

Fiber List: Cotton, Polypropylene
Selected Fiber: Cotton

Fabric Properties
Thickness(cm): 0.04
Porosity: 0.962
Emissivity: 0.9
Tortuous gas: 1.04
Tortuous liquid: 1.04145
Capillary angle(deg): 89
Liquid water contact angle(deg): 0
Max distributed capillary radius(cm): 0.12

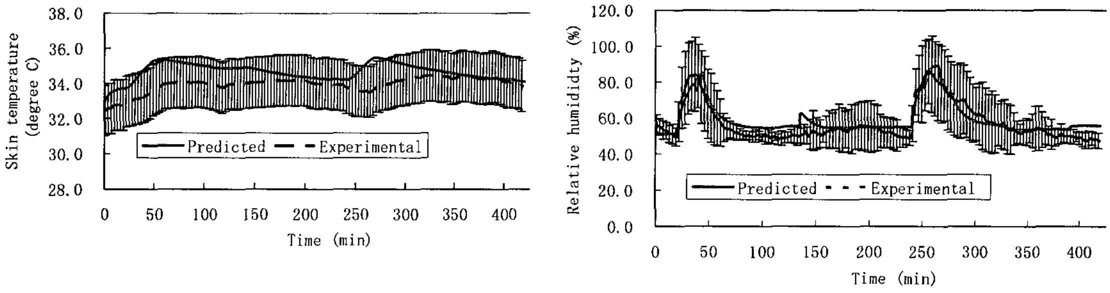
☑ Moisture management Treatment
Top Max Wetted Radius(mm): 30
Bottom Max Wetted Radius(mm): 30
Top Wetting Time(sec): 3.0027
Bottom Wetting Time(sec): 2.8832
Top Water Contact Angle(deg.) 0
Bottom Water Contact Angle(deg.) 0

Fabric List: p1 under, p1 outer
Selected Fabric: p1 under

Figure 6.33 Multi-layer design of the personal protective clothing

With the design and configuration in the life-oriented design, the computational simulation was implemented and the results can be visualized for analysis. Meanwhile, the real experiment was carried out by asking ten human subjects to wear the clothing in a climatic chamber to validate the predicted results [61]. The wearing protocol is same to that of the design specifications for the P-smart. The sensors placed on the skin and clothing continuously recorded the temperature and humidity data in the experiments.

Figure 6.34 compares the predicted results with the experimental results of skin temperature of the human body and the relative humidity of the outer layer of the clothing, which shows an acceptable agreement between them.



(a) Skin temperature distributions (b) RH distributions of the outer layer fabric

Figure 6.34 Comparison between the predicted and experimental results

Figure 6.35 and Figure 6.36 illustrate the predicted water vapor concentration distributions of the inner and outer layer of the clothing during the wearing period. The water vapor concentration of the inner layer greatly increased when the wearer performed hard activities in the morning and afternoon due to the sweating evaporation, and decreased during the sitting and resting time. Also, it is observed that the water vapor concentration of the inner fabric layer is higher than that of the outer fabric layer.

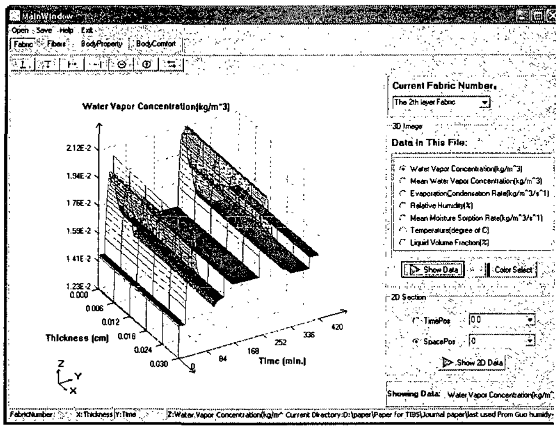


Figure 6.35 Predicted water vapor concentration distribution of the inner fabric layer

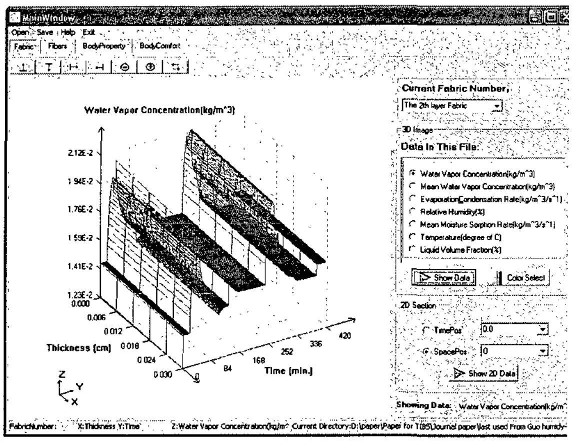


Figure 6.36 Predicted temperature distribution of the outer fabric layer

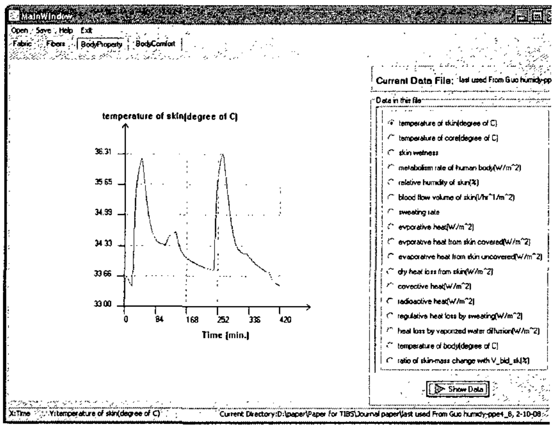


Figure 6.37 Predicted skin temperature distribution

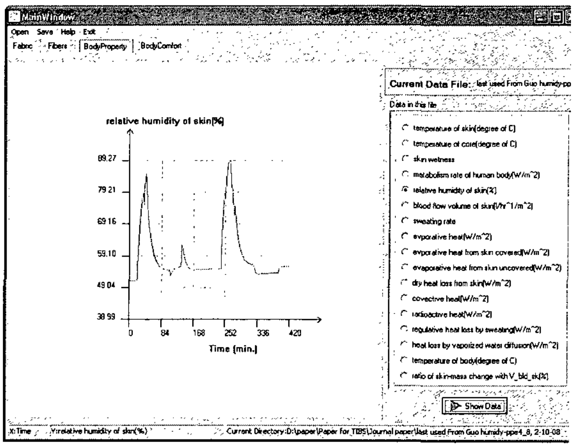


Figure 6.38 Predicted skin relative humidity distribution

Figure 6.37 and Figure 6.38 illustrate the predicted skin temperature and skin relative humidity distributions of the human body. It can be seen that the skin temperature increased in the beginning of the hard activity, but decreased when the human body started to sweat and the sweating evaporation happened. The skin relative humidity also rises during the activity period and is slight due to the sweat absorption by the clothing.

Meanwhile, the designer can preview the thermal performance of this multi-layer personal protective clothing more directly through the 3D animation in a 3D virtual space. Figure 6.39 and Figure 6.40 respectively illustrate the snapshots of the 3D temperature visualization of the inner and outer fabric layers of the clothing at 30th minutes. The mapped colors on the virtual human body and clothing are dynamically refreshed with the time going. The designer can thus directly preview the thermal performance of the clothing in a vivid and dynamic way.

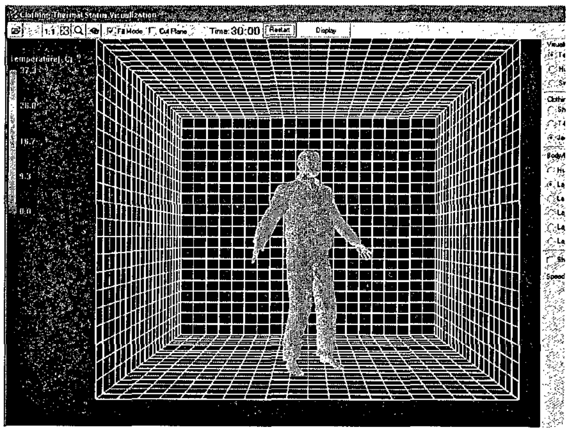


Figure 6.39 Snapshots of 3D temperature visualization of the inner fabric layer at the 30th minute

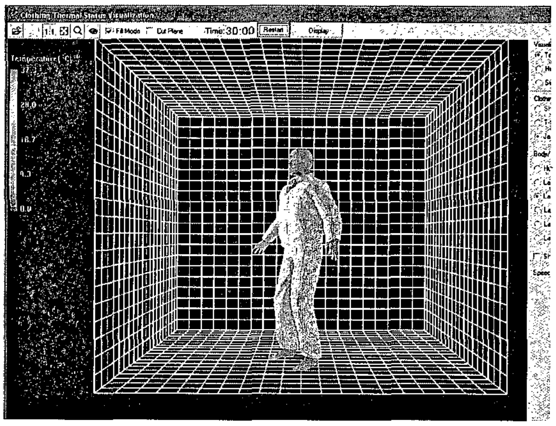


Figure 6.40 Snapshots of 3D temperature visualization of the outer fabric layer at the 30th minute

In this design case, a set of multi-layer personal protective clothing has been designed, and the thermal performance of the clothing detailed to each fabric layer and the thermal status of the human body during the specified wearing scenarios can be simulated and predicted. The designer can preview and evaluate the thermal performance of the multi-layer clothing and even improve the design with this virtual CAD system. This case shows the capacity of P-smart in multi-layer thermal functional clothing design.

6.4 PERSPECTIVES AND DISCUSSIONS

As shown in these design cases, P-smart can help the designer to preview and verify the thermal performance of clothing, which is designed for intended wearing situations. Based on the simulation results, the designer is able to identify which design is better or to look for a better configuration by improving the design without making real garments. In the traditional clothing design procedure, trial and error is the normal practice to verify the design concept, which involves sourcing or making fabrics, constructing patterns and making prototype garments and then conducting wear trial tests. Using P-smart, the design concept can be tested and optimized directly in a virtual space, which effectively speeds up the design process, saves time and money, and increases productivity.

P-smart has a number of unique features as follows:

1) P-smart system is developed on the basis of the multi-disciplinary theoretical framework and innovative software architecture of clothing thermal engineering design. It is the first software tool to provide the capacity of clothing thermal engineering design for designers or engineers with little/limited background knowledge of the technical information, complex physics, mathematics and computational techniques.
2) P-smart is an innovative CAD software tool designed and developed systematically

with user-friendly interfaces, life-oriented engineering design procedures, computational simulation and post processing modules, as well as a supporting engineering database. It is able to simulate and predict the overall thermal functional performance of clothing assemblies with reasonable accuracy in representing the practical wear situations, as demonstrated by the design cases.

3) P-smart allows the users to design multi-layer thermal functional clothing assembly with the consideration of the fundamental and measurable properties of clothing materials from fiber diameters, moisture sorption capacity, nano coating on fiber surface, yarn and fabric structural features such as density, porosity, as well as incorporating of advanced smart materials such as PCM nano/microcapsules.

4) P-smart not only presents a tool to virtually verify the thermal functional performance of clothing constructed from existing materials, but also directs its benefit to new material creation. Designers and or engineers can create new materials, such as fibers and fabrics, by parametric definition with the friendly interfaces, and carry out simulations to analyze their thermal functional performance. This provides a good facility to enable the users to decide the thermal properties of a new material to achieve an expected thermal functional performance. With the facilities of the material database, these new materials can be stored for the future utilization.

5) Additionally, P-smart offers new paths toward innovative design techniques for the

clothing industry. For instance, the effects of using smart materials such as phase change material nano/micro capsules in clothing design can be tested and previewed with the consideration of its melting point, capsule size and concentrations, as well as distributions in a clothing assembly before making any actual garments.

The comprehensive mathematical models adopted in P-smart allow us to consider the fundamental physical/chemical properties and structural features of fibers, yarns and fabrics in the computational simulation to generate solutions that are very close to practical situations. Using these models, the impact of application of nano and nano-composite materials and smart materials on the thermal functional and comfort performance of clothing can be quantified by specifying them as measurable input variables such as surface tension and contact angle.

However, due to the one-dimensional feature of the simulation models adopted in P-smart, this system can only simulate and predict the overall the heat and moisture transfer processes in clothing and thermoregulation process of the body, which limits the design of clothing system in the one-dimensional multi-layered assembly. When coming to the case where the designer needs to consider the effect of different clothing styles, such as short, medium and long sleeves, and short, medium and long trousers/skirts, the P-Smart system can not help. For instance, in the case of sportswear design, it needs to consider using different fabric materials to cover different parts of the body according to the sweating rates of individual body parts.

6.5 CONCLUSION

This chapter has reported on a CAD system (P-smart) for multi-layer clothing thermal engineering design, which is developed on the basic of the work in previous Chapters. The one-dimensional simulation models of clothing and human body are employed in this system, and the one-dimensional computational scheme is adopted to solve the employed models and carry out the computational algorithm. A series of functionalities of the system have been developed for the user including life-oriented design, computational simulation and post processing. Two design cases have been reported to show the functional design capacity of this system and validate the accuracy of prediction.

Based on the multi-disciplinary framework of clothing thermal engineering design and the innovative software architecture for the CAD system involved, P-smart is the first software tool in the world to provide the users the capacity of clothing thermal engineering design. With this CAD system, the users can perform multi-layer clothing thermal functional design from textile materials and functional treatments, simulate and preview the thermal performance of the clothing wearing system at the whole level, identify and improve their designs before making any real garments. The benefits of this system are further directed to create and verify new materials and innovative design techniques for the clothing industry. As a virtual tool for the user to access the strategy of clothing thermal engineering design, P-smart has many advantages compared to the traditional trial and error design method, such as speeding up the design process, saving time and money, and increasing productivity. The potential users of this CAD system may include the designers, engineers, or even consumers with little/limited background knowledge and technical information. The strategy of clothing thermal engineering design can thus be directly applied by the users in their cases with this CAD system. The limitation of this system is that it is good enough for designing multi-layer clothing systems but can not design clothing with different styles.

CHAPTER 7 A CAD SYSTEM FOR MULTI-STYLE CLOTHING THERMAL ENGINEERING DESIGN

7.1 INTRODUCTION

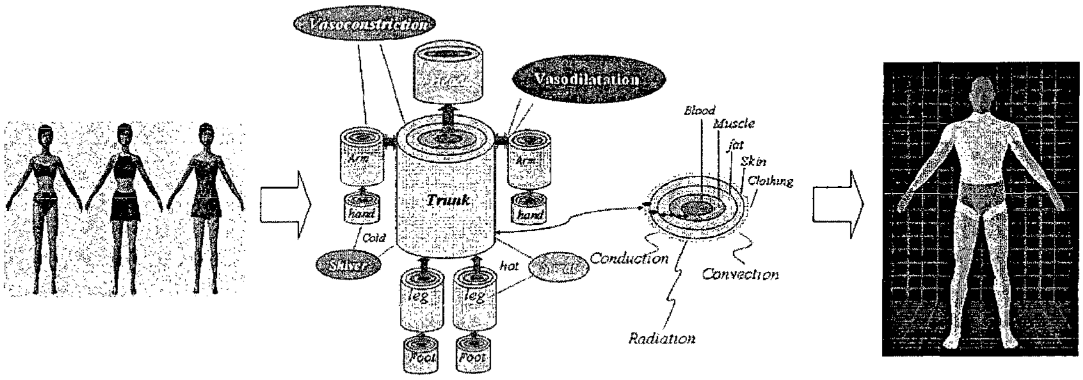
With the open and flexible software architecture proposed in Chapter 5, it is possible to develop a series of software systems for clothing thermal engineering design to satisfy different application requirements. In Chapter 6, a CAD system (P-smart) for multi-layer clothing thermal engineering design has been developed and demonstrated with design cases. As the world's first system providing the designer with a special CAD tool, P-smart can be used to perform clothing thermal functional design, simulate and visualize the overall thermal performance of the clothing and the thermal responses of the human body. It is good for designing multi-layer clothing systems, but it can not hand the case of clothing design with different styles. It is essential for the CAD software to have the capacity to simulate and preview the thermal performance of the clothing with different styles covering on different body parts and the thermal status of individual body parts.

This Chapter presents a CAD system (T-smart) that allows the designer to carry out thermal functional design considering the effect of different clothing styles. Using this new system, the designer can investigate the effects of using different materials and styles for different body parts (i.e. hats, underwear, jackets, trousers, gloves, socks etc.) by simulating and previewing the thermal performance of clothing during the wearing period.

This chapter firstly introduces the development process of the system, including the adopted simulation models, computational algorithms and developed user interfaces; secondly, illustrates two design cases to show the design process with this CAD system and validate its prediction accuracy; finally, discusses the new features and advantages of this CAD system.

7.2 DEVELOPMENT OF THE T-SMART SYSTEM

T-smart is developed for designing and engineering garments with different styles. The key improvement of this system is that the thermal performance of the garments can be designed pertaining to six body parts (head, trunk, arm, hand, leg and feet). With this system, the designers can perform multi-style clothing thermal functional design by changing the design for the individual body parts, including 1) different clothing fitness, 2) different coverage of clothing on the skin, 3) different clothing material and 4) different composed fabric layers. The schematic diagram of T-smart system is demonstrated in Figure 7.1, which illustrates that the multi-style design of clothing is achieved by the multi-dimensional computational simulation detailed to six body parts. The thermal performance of clothing is able to be simulated and previewed in all the body parts. Therefore, it is easy to observe and compare the distributions of the thermal values of clothing and human body at different body parts during the wearing period. The designers can thus obtain more detail and useful information to iteratively improve their designs without traditional trial-and-error method.



Multi-style design **Computational simulation** **Multi-dimensional thermal performance**

Figure 7.1 Multi-style clothing thermal engineering design

Since the multi-dimensional models adopted in this system plays an important role in the realization of the clothing multi-style thermal engineering design, the integrated multi-dimensional models in T-smart involve the PCM heating model, fiber moisture absorption/desorption model, fabric heat and moisture transfer models and a 25-node thermoregulatory model of human body. The main mathematical equations in these multi-scale models are listed as follows [17, 20, 24, 49, 67, 117, 137]:

Heat and moisture models for the fabric

$$\frac{\partial(\varepsilon_a C_a)}{\partial t} = \frac{D_f \varepsilon_a}{\tau_a}\frac{\partial^2 C_a}{\partial x^2} + G\frac{\partial^2 p_s}{\partial x^2} + \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{lg} \tag{7.1}$$

$$\frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l \frac{\partial(\rho_l \varepsilon_l)}{\partial x}\right) + GL\frac{\partial^2 p_s}{\partial x^2} + \varpi_l \frac{\partial C_f}{\partial t} - \Gamma_{lg} \tag{7.2}$$

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x} \right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + (\omega_a \lambda_v + \omega_l \lambda_l)\varepsilon_f \frac{\partial C_f}{\partial t} - \lambda h_{lg} \Gamma_{lg} + \dot{q}(x,t) + W \tag{7.3}$$

$$\frac{M_g \varepsilon_a}{RT} \frac{\partial p_s}{\partial t} - \frac{p_s \varepsilon_a M_g}{RT^2} \frac{\partial T}{\partial t} - \frac{M_g p_s}{RT} \frac{\partial \varepsilon_l}{\partial t} = \frac{\partial}{\partial x}\left[GS \frac{\partial p_s}{\partial x} \right] - \varpi_1 \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\mathrm{lg}} \tag{7.4}$$

$$\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}(r D_f(x,t) \frac{\partial C_f(x,r,t)}{\partial r}) \tag{7.5}$$

Human body thermoregulatory models

$$\begin{cases} C_n \dfrac{dT_n}{dt} = Q_i - B_i - D_i - E_i \quad n = 1,2...24 \\ c_b \dfrac{dT_b}{dt} = \sum_{n=1}^{24} B_n \end{cases} \tag{7.6}$$

The heat and moisture models for the fabric consist of a series of partial differential equations, and the human body thermoregulatory model divides the entire body into six parts comprising head, trunk, arms, hands, legs and feet. The detailed report of these multi-scale models can be found in Chapter 3. The specifications of the parameters in these models with the characteristic data of the physical behaviors in the clothing wearing system have also been addressed in Chapter 3. These multi-scale models are integrated through boundary conditions and the interactions between the clothing, human body and environment are performed through the communication sockets at the six body parts, as discussed in Chapter 4.

Due to this feasibility of the interactions between the clothing and human body considered at multi-part, the simulation of the thermal behaviors in the clothing wearing system is expanded to different body parts, and the multi-style clothing thermal functional design is thus achieved.

Based on these models, T-smart is developed with the multi-dimensional computational scheme reported Chapter 4 and the software technique reported in Chapter 5. The development of T-smart is reported in terms of system architecture and modules, computational algorithms and user interfaces.

7.2.1 System architecture and modules

Based on the general software architecture reported in Chapter 5, the architecture of T-smart is developed to achieve the capacity of clothing multi-style design and simulation. Figure 7.2 shows the software architecture of T-smart, which is also developed following the flow of virtual design, pre-processing, computational simulation and post processing to provide user graphic interfaces to perform the system functionalities. The description of the responsibilities of these phases can be referred to Section 6.2.1. The garment information from the virtual design phase include the physical properties of materials (fabric, fiber, PCM, membrane), and the human body information is detailed to head, trunk, arms, hands, legs and feet. All the obtained information is structured with data sets and transferred into the multi-dimensional simulation models, as listed above. Through the chart visualization and 3D animation of the simulation results, the multi-dimensional thermal performance of clothing and human body can be analyzed.

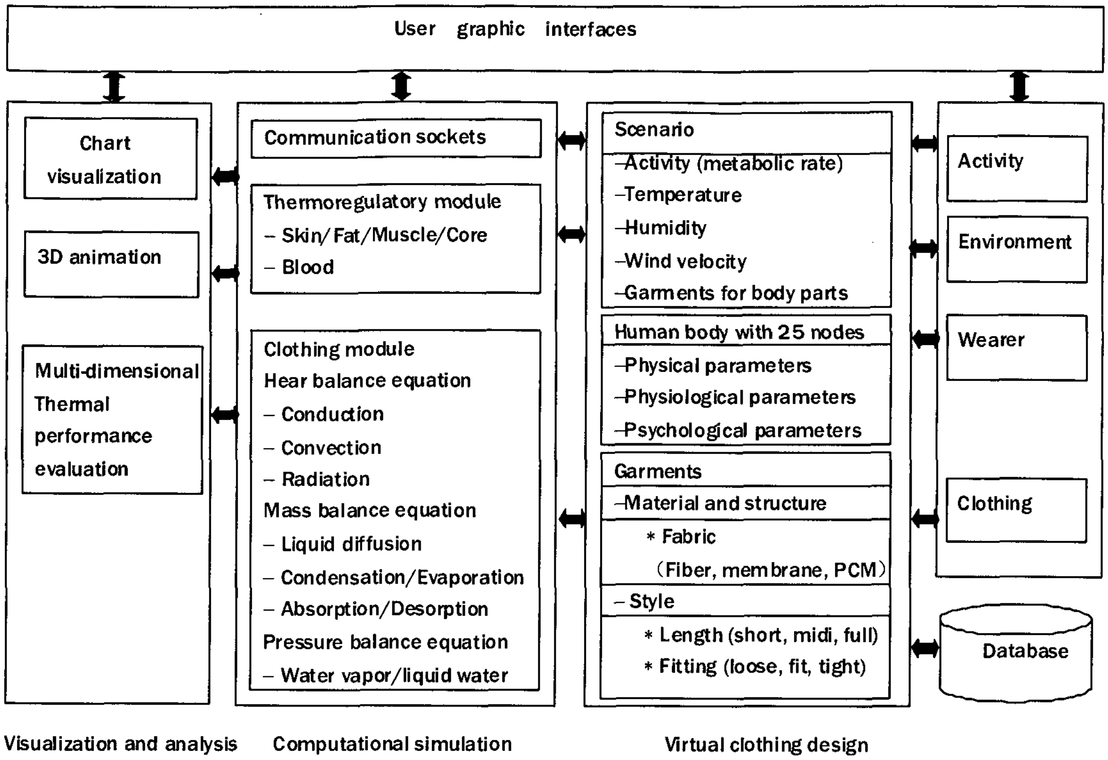


Figure 7.2 System architecture of the T-smart system

The functionalities of T-smart are designed under this elaborated software architecture, as illustrated in Figure 7.3. In the life-oriented design procedure, the user can design garments with different styles by selecting different fabrics for the six segments of body (head, trunk, arms, hands, legs and feet), and specify the coverage and fitness for individual body parts. An engineering database is developed to support the clothing design, human body definition and scenario specification, which is similar to that of P-smart. However, the data structure of the database is renewed to manage the information of clothing with multi-style and the human body with six segments.

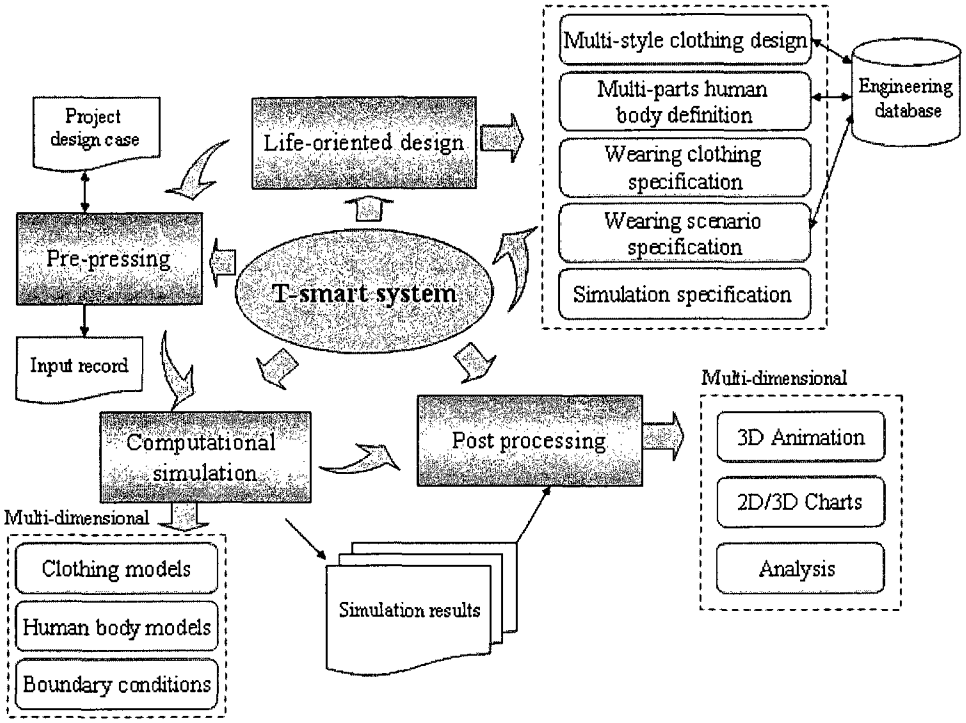
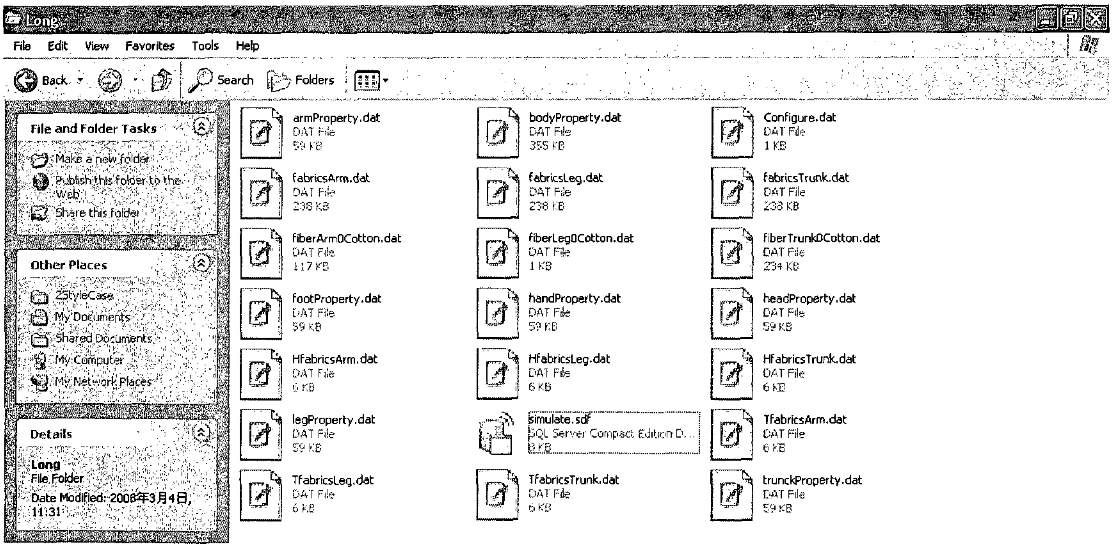


Figure 7.3 Functionalities flow of the T-smart system

The pre-processing phase deals with the information obtained from the life-oriented design procedure and structures the data as data sets (fiber, PCM, Membrane, Self-heating fabric, MMF, fabric, garment, human body, clothing worn, scenario and control information), which are transferred to the computational simulation. The design specification of a design case is exported as design case file for further processing. The program description of the design case file is similar to that of P-smart, but is restructured for the multi-style design.

In the computer solver, the computational simulation starts to solve the multi-scale models according to the control information and iterates the computation with regarding to six divided subsystems (head, trunk, arms, hands, legs and feet). The computational simulation of the clothing is executed concurrently in all the subsystems to generate the thermal status of clothing for communicating with each part of the body. The computation process thus needs more time to obtain the numerical solution of the models at all the parts. The simulation results are saved to data files put in a specified directory with a case ID on the storage medium, as shown in Figure 7.4. The values of relevant thermal variables of fiber, fabric and human body is stored in a data file separately. However, in order to easily manage the simulation results of the garments covering different body parts, the number of the files of fiber and fabric is expanded according to different garment and body parts. The structure of these files is shown in detail in Table 7.1.



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bodyProperty.dat DAT File 355 KB
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fabricsLeg.dat DAT File 238 KB
fabricsTrunk.dat DAT File 238 KB
fiberArm0Cotton.dat DAT File 117 KB
fiberLeg0Cotton.dat DAT File 1 KB
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headProperty.dat DAT File 59 KB
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legProperty.dat DAT File 59 KB
simulate.sdf SQL Server Compact Edition D... 8 KB
TfabricsArm.dat DAT File 6 KB
TfabricsLeg.dat DAT File 6 KB
TfabricsTrunk.dat DAT File 6 KB
trunckProperty.dat DAT File 59 KB

Figure7.4 The data files of simulation results

Table 7.1 The structure of the data files saving simulation results

File name	File structure
Configure	stageNum, Temperature, RH, Velocity, Head, Trunk, Arm, Hand, Leg, Foot, Time
	stageNum----the number of the stage

	Temperature-----the temperature of environment RH----the RH of environment Velocity---the velocity of environment Head-----0 means not covered by clothing, 1 means covered by clothing Trunk-----0 means not covered by clothing, 1 means covered by clothing Arm -----0 means not covered by clothing, 1 means covered by clothing Hand -----0 means not covered by clothing, 1 means covered by clothing Leg -----0 means not covered by clothing, 1 means covered by clothing Foot -----0 means not covered by clothing, 1 means covered by clothing Time-----the time of the stage
FabricsX.dat (X means the part of body. (head; trunk; arm; hand; leg; foot)	Timepos, spacepos, fabric-number, Cg, Cfm, FRateEC, RHF, RateSorp, TempF, VFL
	Timpos: time position at which the data will be saved. Spacepos: the delta of fabric at which the part differential formulations were dispersed. Fabric-numb: the order number of the fabric in the clothing system Cg: Water vapor concentration in all the fibers of the fabric Cfm: Mean Water vapor Concentration in all the fibers of the fabric FRateEC: the evaporation and condensation rate of the fabric RHF: relative humidity of the fabric RateSorp: the mean moisture sorption rate of all the fibers of the fabric TempF: temperature of the fabric VFL: the liquid volume fraction of the fabric
FiberXYZ(X is the body part, Y is the fabric number, Z is the fiber name)	Timepos, spacepos, MeanMoisConcentration, Rate_MoisSorp, MoisContent
	MeanMoisConcentration: the mean moisture concentration of the fiber Rate_MoisSorp: the moisture sorption rate of the fiber MoisContent: the moisture content of the fiber
Bodyproperty	Timepos, Segment, T_sk ,T_cr, Wsk, MR, RH, Vbld_sk, SWR, Esk, DRY, E_rsw, E_dif
	Timepos: time position Segment-----the part of body: 0-head;1-trunck; 2-arm; 3-hand; 4-leg; 6-foot T_sk: temperature of skin T_cr: temperature of core W_sk: skin wetness MR: metabolism rate of human body RH: relative humidity of skin Vbld_sk: blood flow volume of skin SWR: sweating rate E_sk: the evaporative heat from skin *Dry: the dry heat loss from skin* Ersw: regulative heat loss by sweating E_dif: heat loss by vaporized water diffusion through skin

* In the file, every variable is recorded as column; a tab space is used as an interval between columns.

In the post processing, the simulation results stored in the data files are visualized with 2D/3D charts or 3D animation to help the user to analyze and understand the data information. The process of data loading and visualization has been reported in Section 6.2.1. The thermal variables of all fibers, fabrics in the garments and the human body, visualized in the post-processing, are illustrated in Figure 7.5.

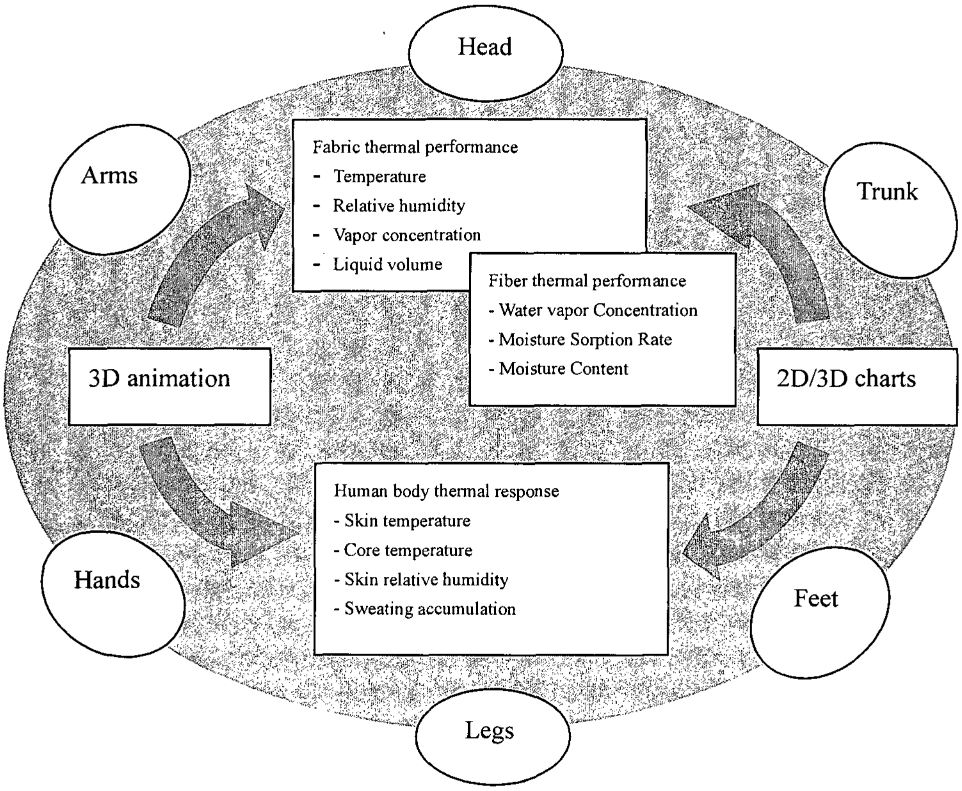


Figure 7.5 Graphic visualizations of the simulation results

The visualization in terms of 2D/3D charts and 3D animation are detailed to individual body parts of head, trunk, arms, hands, legs and feet. In the chart visualization, the user can choose the garment corresponding to the individual body part to view their thermal status. In the 3D animation, the style of the clothing and the shape of the human body are consistent with those in the design specifications. The user can observe the temperature, humidity and sweating rate of the clothing and human body by the mapped colors detailed to all the parts simultaneously.

The functionalities of T-smart are realized by coding with object-oriented programming method. Benefitting from the open and flexible structure of the software architecture reported in Chapter 5, the modules on pre-processing, computational simulation and post processing in P-smart can be reused. The detail modules and their functional descriptions can be found in Section 6.2.1. When to realize these modules involved in the program, most of the main functions distributed in these modules, as listed in Table 6.4, can also be reused. The revised or new functions to achieve the multi-style design and simulation capacity in related modules are listed in Table 7.2.

Table 7.2 New or revised functions in the modules of the T-smart system

Modules	Functions	Input parameters	Purpose
Structure data	GarmentType()	Properties and style information of a garment	collect all the properties and style information of garment as a structure
	BodyType()	Properties of six segments of the human body	Collect all the properties of six segments of the human body as a structure
	ClothingWornType()	Wearing specification of the garments on each body segments	Collect the wearing specification of multi-style clothing as a structure
Design case output	SaveBody()	Structure of the human body	Output the six segments of the human body
	SaveGarment()	Structure of the garment	Output the garments with style information
	SaveClothingWorn()	Structure of the wearing specification of the clothing	Output the wearing specification of garments on each body part
Design case input	LoadGarment()	Design case file	Load the garment from the file

			with style information
	LoadBody()	Design case file	Load the six segments of the human body from the file
	LoadClothingWorn()	Design case file	Load the specification of the garments covering the human body from the file
Class initialize	NumericalGarment()	Structure of the garment	Initialize the Class of garment with style information
	NumericalBody()	Structure of the human body	Initialize the Class of human body with six segments
	NumericalStage ()	Structure of the scenario	Initialize the Class of scenario with the specifications of clothing worn on the body
Computational solve	SolveLiquidSorption()	Entity of fiber Class	Solve the fiber sorption equation
	BodyRegulation()	Entity of human body Class	Solve the 25-node thermoregulatory models of the human body
	BodyFabricUpdate()	Entity of body and clothing Class	Update the boundary conditions between the skin and fabric at all the body parts
Solution output	ClearBody()	Entity of human body Class	Save the solution of boy models to the data file for all the body parts
	ClearFabric()	Entity of fabric Class	Save the solution of fabric models to the data file for all the worn garments
Load file	LoadBodyFile()	Simulation results file	Load the data of properties of the six segments of the body
	LoadScenarioFile()	Simulation results file	Load the information of all scenarios and clothing style information
Chart visualization	GroupFabricData()	Loaded data of all the fabrics	Group the fabric data according to the different garments covering different parts
	GroupBodyData()	Loaded data of all the segments of the body	Group the body data according to six segments
Animation visualization	RenderModel()	.dxf file of the 3D model	Initialize the 3D objects of body and clothing with six divided parts
	ColorMap()	Color value of the grouped data	Dynamically map the color on garment or human body with different parts

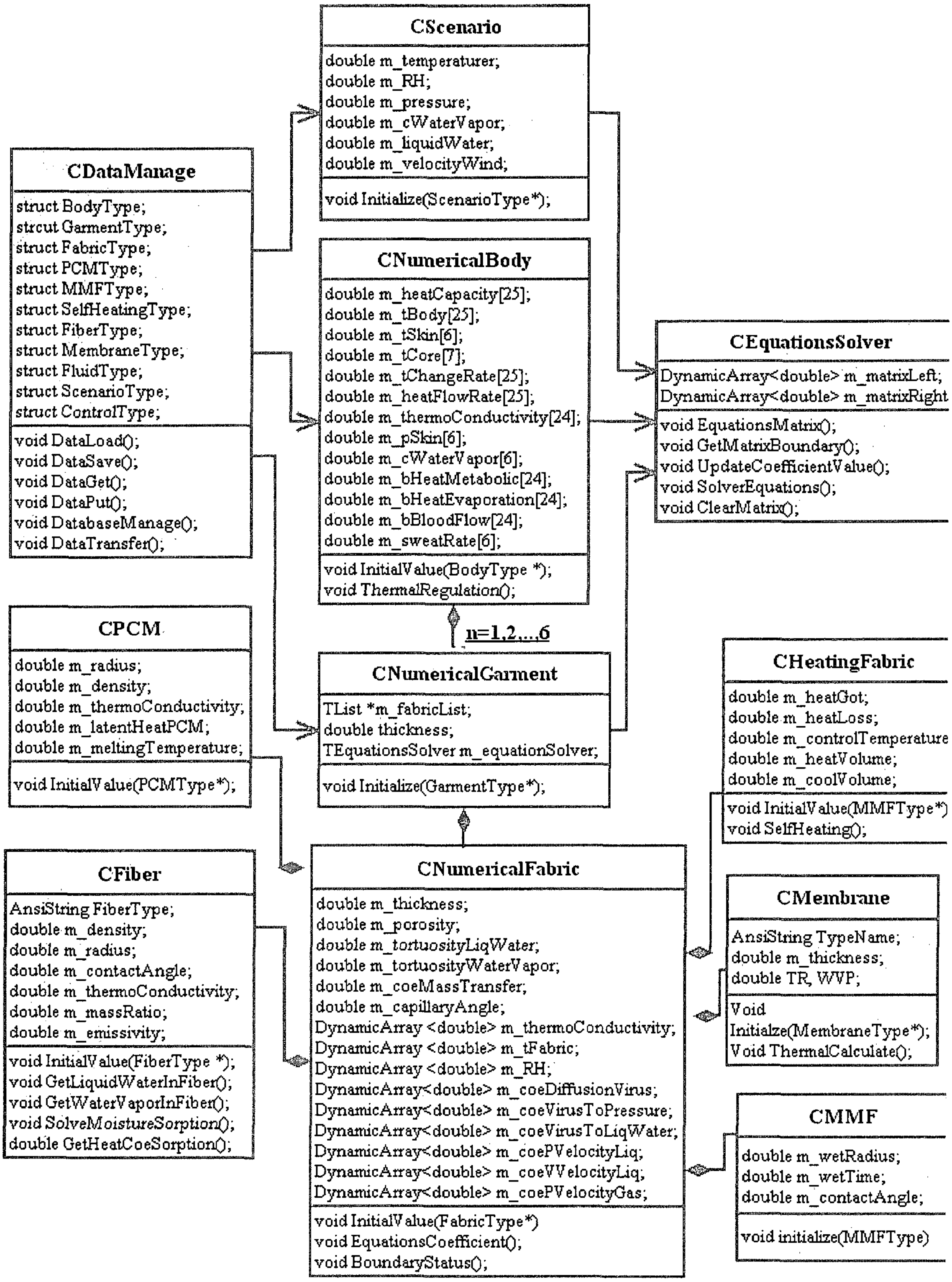


Figure 7.6 The entity-relationship in the T-smart system

Similar to the Class encapsulation of P-smart, all the textile materials and products (fiber, PCM, MMF, self-heating fabric, membrane, fabric and garment), the human body and wearing scenario, as well as the computational solver, are encapsulated as individual object in T-smart, as illustrated in Figure 7.6. The Class of human body encapsulates the properties of the human body pertaining to six segments and the new thermal regulation functions. The Class of garment iteratively creates the entity of garment for covering all the body parts.

7.2.2 Computational algorithms

When the user has finished all the specifications, the computational simulation is performed to generate the simulation results from the solution of the multi-scale models during the iterative computation process. To make this happen, the computational algorithms are developed on the basis of the solution of the adopted multi-scale models and the mesh structure of the clothing wearing system. The detail discretization of these multi-scale models and their boundary conditions can be found in Section 4.2. Due to the clothing wearing system is regarded as subsystems according to the six body parts, the computational simulation is performed for all the six parts to simulate the thermal behaviors of clothing wearing system pertaining to head, trunk, arms, hands, legs and feet. The computational scheme is hence a multi-dimensional structure, which can also be referred to Section 4.3.2.

The process of developing computational algorithms in T-smart is similar to that of

P-smart, as presented in Section 6.2.2. However, the algorithms are expanded to achieve the multi-dimensional computation. The structure of the algorithm for the computational simulation of T-smart is illustrated in Figure 7.7, which shows the interactions between the models of clothing, human body and environment are considered at multi-parts, and the iterative computation for all the clothing subsystems. The mesh information including the grid number of fabric and the grid number of fiber is also needed for the computation, and the units of the data utilized for computation are also required to be converted to the ones used in calculation, as discussed in Section 6.2.2.

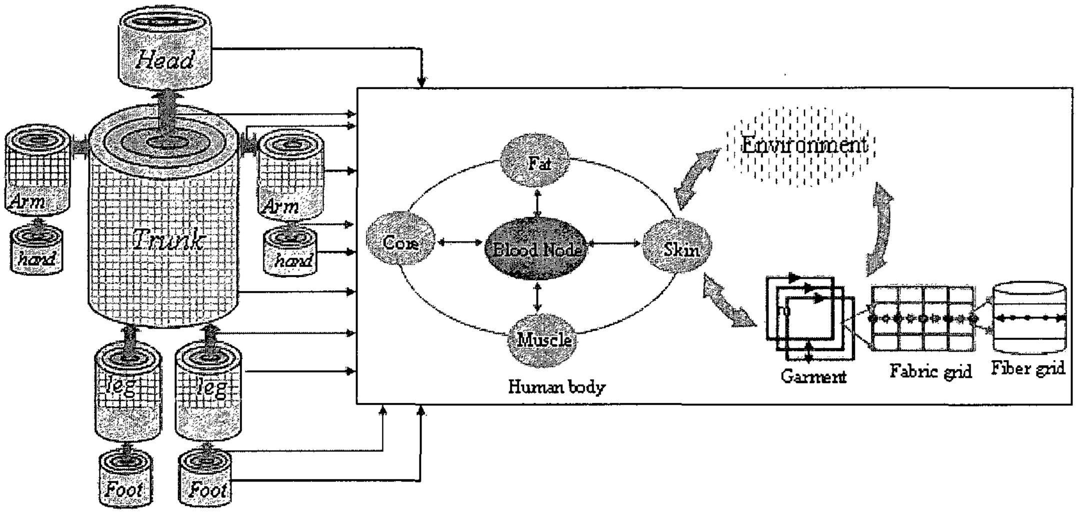


Figure 7.7 Structure of computational algorithms in T-smart

The detail description of the main algorithms for computational simulation in T-smart can be found in Table 7.3. Similar to that of P-smart, it begins with the pre-processing of the design data and the initialization of all Classes involved, and also makes detail to the garments covering each body parts according to the clothing wearing specification.

The simulation models involved for PCM, fiber, fabric and human body are automatically enabled according to the setting of corresponding design specifications. For all the wearing scenarios, the computational simulation is iteratively performed with the interval of time step for all the clothing subsystems, in which the fabric in the worn garment is meshed by the specified grid number along thickness directory and the fibers is meshed by specified the grid number along radius directory. The solutions of the models for all the clothing subsystems are generated to communicate with each part of the body, the thermal status of which is simulated pertaining to all divided body parts and is connected by the blood flow. As a matter of fact, the intensity of multi-dimensional simulation computation in T-smart is increased more six times compared to that of P-smart.

Table 7.3 Main algorithms for the computational simulation

```
(1)  Get the data and obtain the data sets of fiber, PCM, MMF, self-heating fabric, Membrane, fabric, garment,
     human body, wearing clothing specification, scenario and control information
(2)  If there is no use of the textile materials or human body ,the corresponding data set is full
(3)  If there is no garment covering on the individual body part, the corresponding data set for clothing worn is full
(4)  Initialize all the class with corresponding data set which is not full
(5)  For each wearing scenario
(6)  For each time step $t_i$ $(i=0,1,..., T)$
      For each body parts {
      For each garment worn on the body part {
(7)    For every fabric layer of clothing
(8)    {  For every fabric grid $x_j$ $(j=0.2..., m)$
             If (Membrane is not full )
(9)           Calculate the TR and WVP for the boundary coefficients
              If (MMF is not full )
(10)         Update the properties of fabric with MMF properties
              If ( Self-heating fabric is not full )
(11)          Calculate the power rate to as a source item for the fabric model
             If (PCM is not full)
```

```
            Solve the PCM heating model
            for every fiber grid $k_j$ ($j=0,1,\dots,n$)
           {
                 Solve the fiber moisture sorption model for $k_j$ at $t_i$
           }
        Calculate all the variables' coefficients in the equations of the fabric model discretized at $x_j$

        Solve the fabric models for $x_j$ at $t_i$

        Update the boundary conditions between $x_j$ and $x_{j+1}$ at $t_i$
        Record the solutions to the data files according the name rules
        }
      }
    Solve the human body equations
    Record the solution to the data file
  }
Update boundary conditions of between the human body and fabric in the subsystem with the newly
  generated values of the thermal variables
If the scenarios end, end the simulation
```

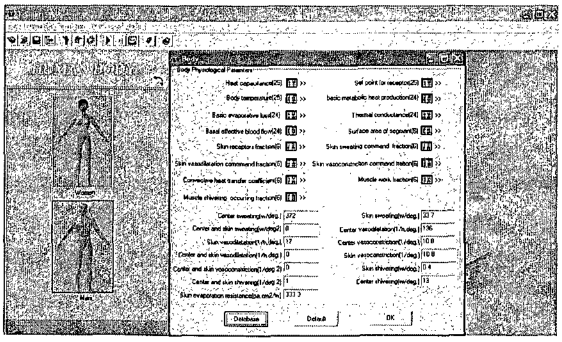
7.2.3 User interfaces

The user interfaces of T-smart are developed for the user to achieve the multi-style clothing thermal functional design with a CAD tool. The distribution of the user interfaces in the life-oriented design, computational simulation and post processing is the same to that of P-smart, as illustrated in Figure 6.9. However, the content of the user interfaces are revised in the areas of multi-style clothing design, multi-part human body definition, clothing wearing specification in the life-oriented design phase, and illustration of the multi-dimensional thermal performance of the clothing and human body in the post processing phase.

The main user interfaces of T-smart in the phases of life-oriented design, computational simulation and post processing, as shown as follows.

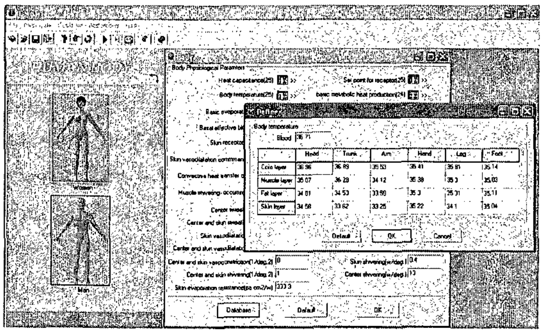
1) Life-oriented design

The user interfaces include the interfaces of activity, environment, human body, clothing, multi-style wearing scenario specification and simulation specification. The interfaces in the garment design including fabric design, fiber design, membrane design etc. are inherited from P-smart. The interfaces related to multi-style design are newly developed according to the design principles. Figure 7.8 illustrates in new interfaces in the life-oriented design with T-smart, including multi-part human body definition, properties of human body definition detailed to each node or segment, multi-style garment design, garment construction, clothing wearing specification and control information specification. In the body definition, the properties of the human body are defined pertaining to each node or segment of the body. After the clothing design, the user need to specify the designed garments to wear on each body part in the interface of clothing wearing specification.



Center sweating(w/deg.) 372
Skin sweating(w/deg.) 33.7
Center and skin sweating(w/deg2) 0
Center vasodilatation(1/h.deg.) 136
Skin vasodilatation(1/h.deg.) 17
Center vasoconstriction(1/deg.) 10.8
Center and skin vasodilatation(1/h.deg.) 0
Skin vasoconstriction(1/deg.) 10.8
Center and skin vasoconstriction(1/deg 2) 0
Skin shivering(w/deg.) 0.4
Center and skin shivering(1/deg 2) 1
Center shivering(w/deg.) 13
Skin evaporation resistance(pa.cm2/w) 333.3

Multi-part human body definition

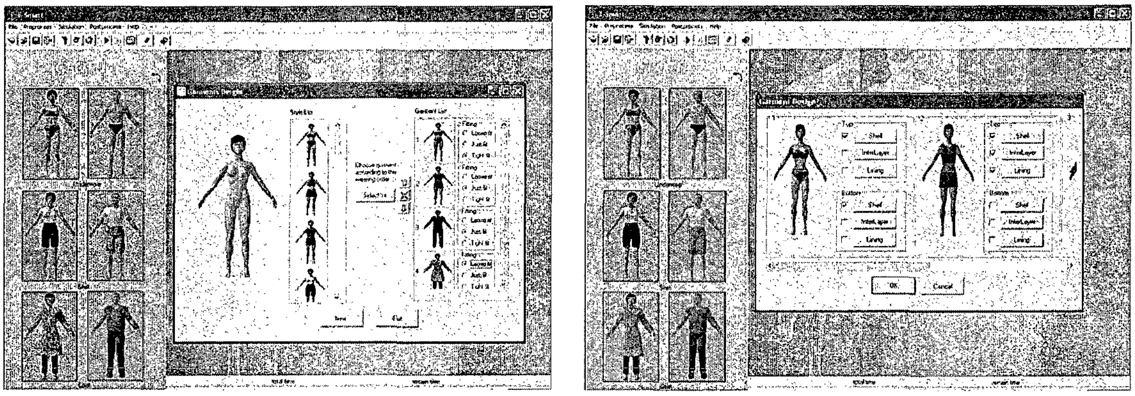


Blood 36.71

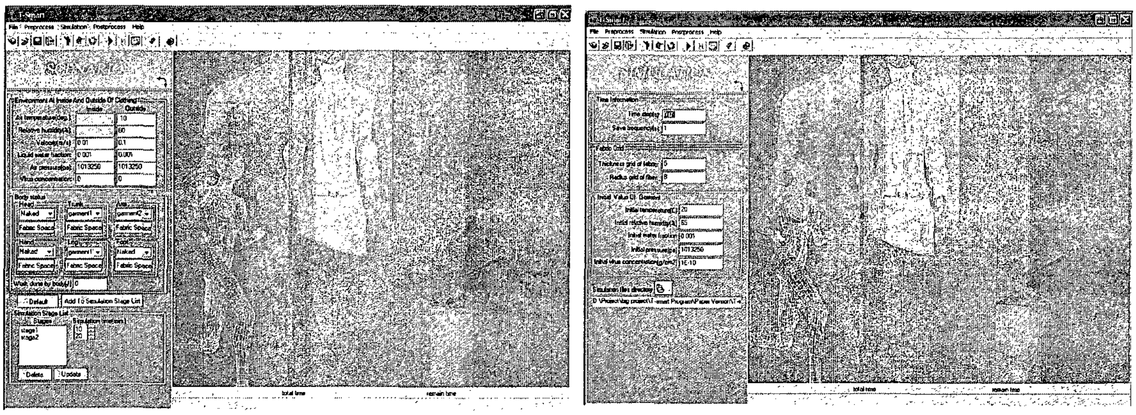
	Head	Trunk	Arm	Hand	Leg	Foot
Core layer	36.96	36.89	35.53	35.41	35.81	35.14
Muscle layer	36.07	36.28	34.12	35.38	35.3	35.03
Fat layer	34.81	34.53	33.99	35.3	35.01	35.11
Skin layer	34.58	33.62	33.25	35.22	34.1	35.04

Skin shivering(w/deg.) 0.4
Center and skin shivering(1/deg 2) 1
Center shivering(w/deg.) 13
Skin evaporation resistance(pa.cm2/w) 333.3

Properties of human body definition detailed to each node or segment



Multi-style garment design Garment construction



Clothing wearing specification Control information specification

Figure 7.8 Main interfaces for multi-style design

2) Computational algorithms

The computational simulation is performed with the main interface of T-smart. The user can start or stop or reset the simulation by clicking the buttons on the main interface, as shown in Figure 7.9. The time spent for the design case is shown on the main interface.

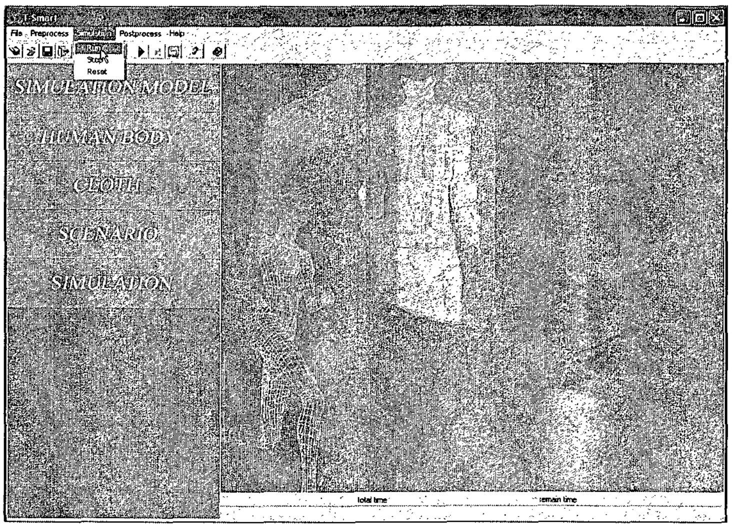
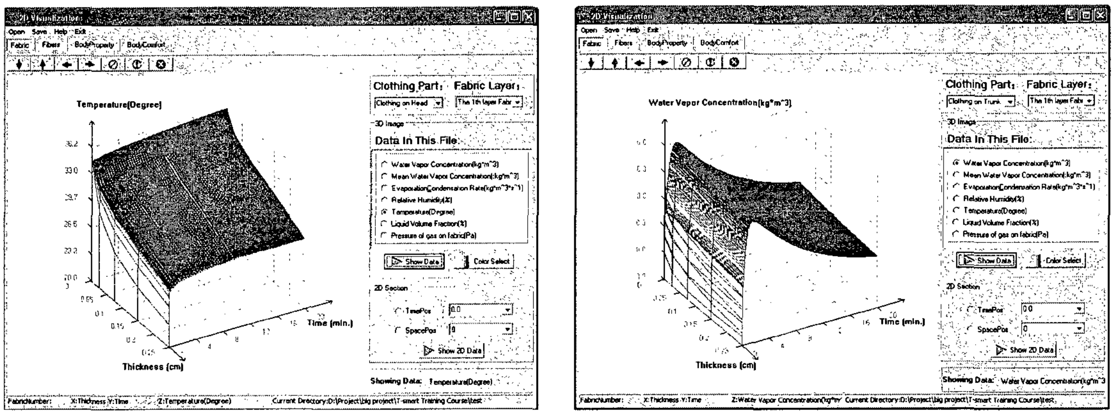


Figure 7.9 Perform computational simulation on the main interface

3) Post processing

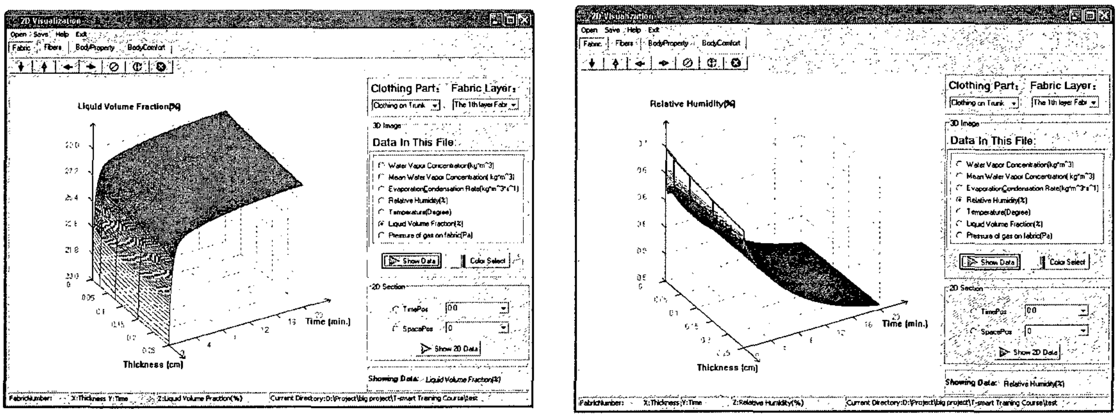
T-smart represents all the simulation results obtained in the computational simulation with both 2D/3D charts visualization and 3D animation in the post processing phase. The thermal variables of all the worn garments, all fabric layers involved and the human body pertaining to six parts (head, trunk, arms, hands, legs and feet) throughout the wearing scenarios can be viewed by means of the 2D/3D charts or animated wearing scenarios.

Figure 7.10 shows the examples of the chart visualization of the thermal variables of the fabric on the trunk part, including temperature, water vapor concentration, liquid water volume and relative humidity. Figure 7.11 shows the examples of the chart visualization of the thermal variables of the human body on the trunk part, including skin temperature, core temperature, skin relative humidity and skin evaporate heat. The thermal variables of the fabrics in the garment and human body detailed to all the parts are listed out on the interface for the user to choose to view their distributions.



Temperature of the garment on the trunk part

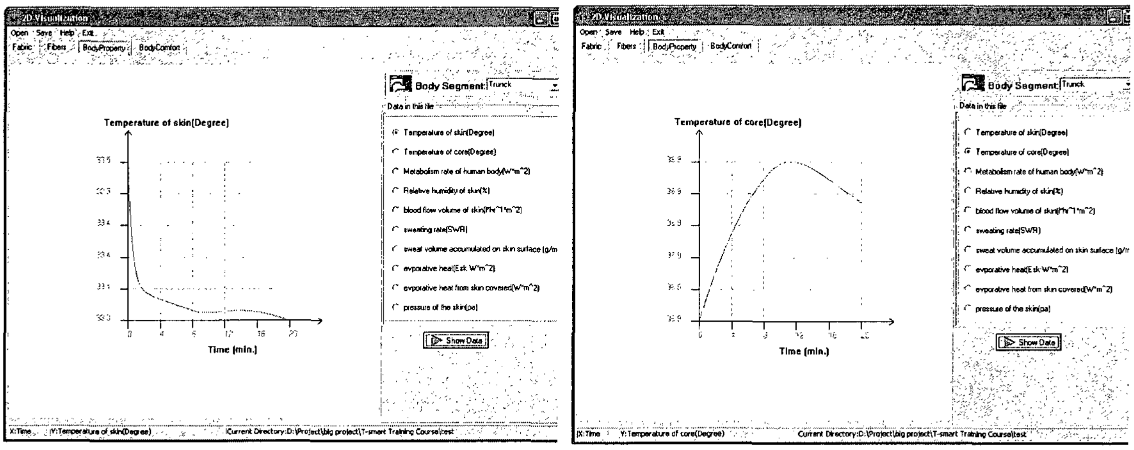
Water vapor concentration of the garment on the trunk part



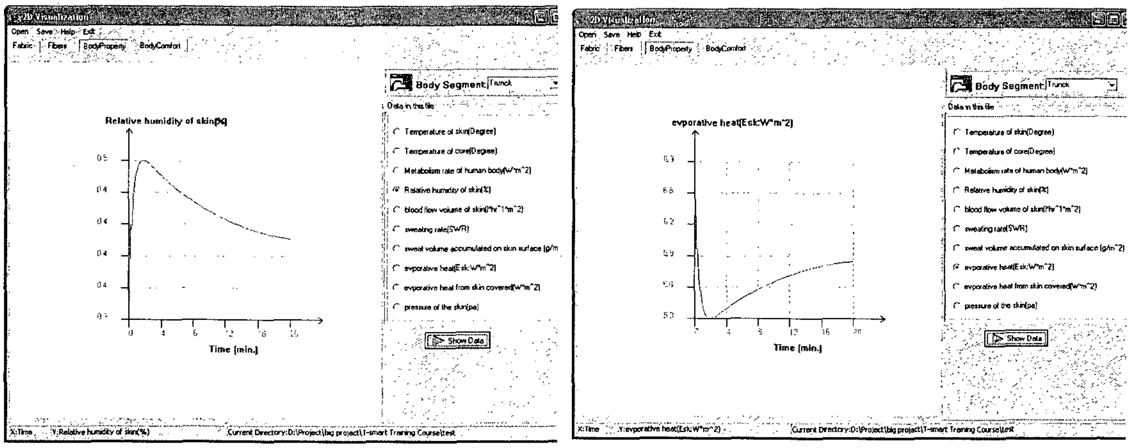
Liquid water volume of the garment on the trunk part

Relative humidity of the garment on the trunk part

Figure 7.10 Chart visualization of the thermal variables of the fabric



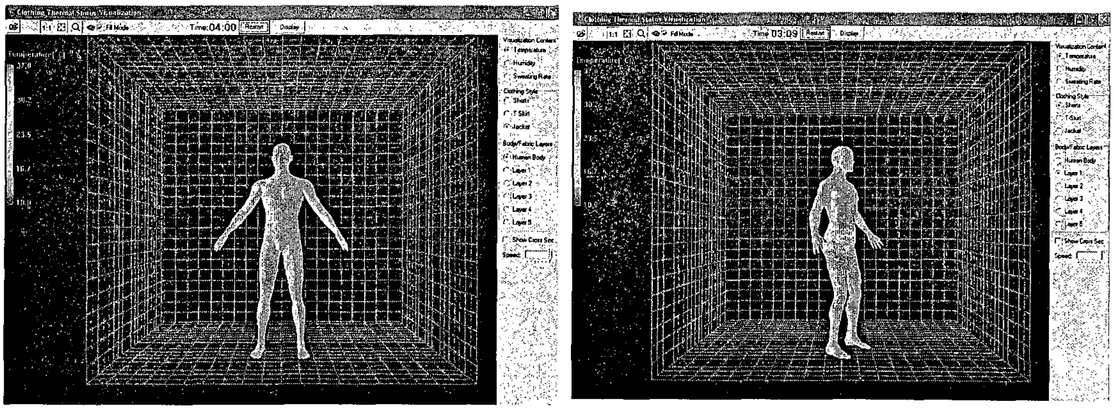
Skin temperature of the trunk Core temperature of the trunk



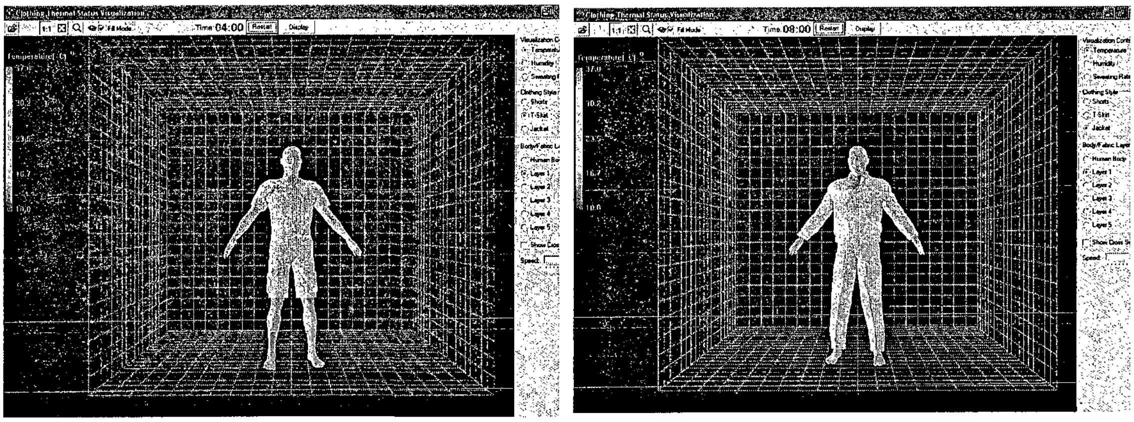
Skin relative humidity of the trunk Skin evaporate heat of trunk

Figure 7.11 Chart visualization of the thermal variables of the human body

Figure 7.12 shows the examples of animated thermal variables of the clothing and human body, including the temperature and relative humidity of the body skin, under wear, short wear and long wear. The mapped colors on the clothing system are dynamically updated in time according to the thermal values of individual parts.

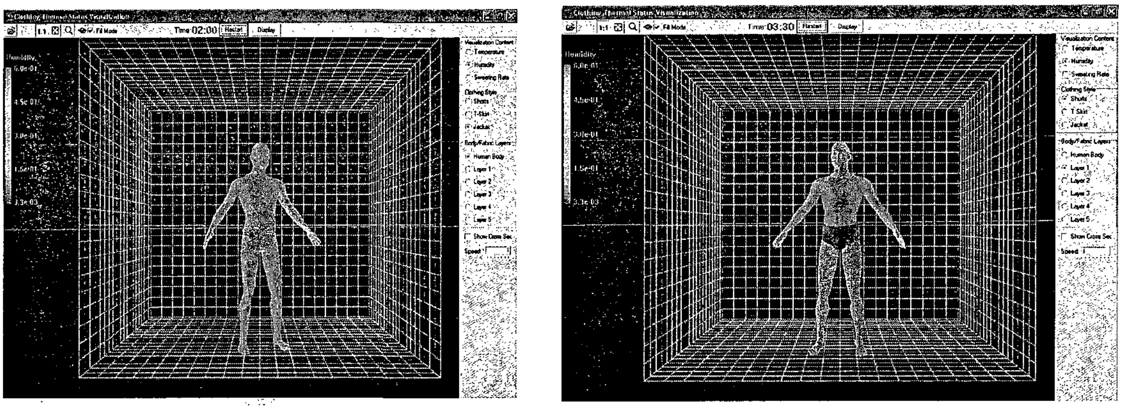


Temperature of the skin Temperature of under pants



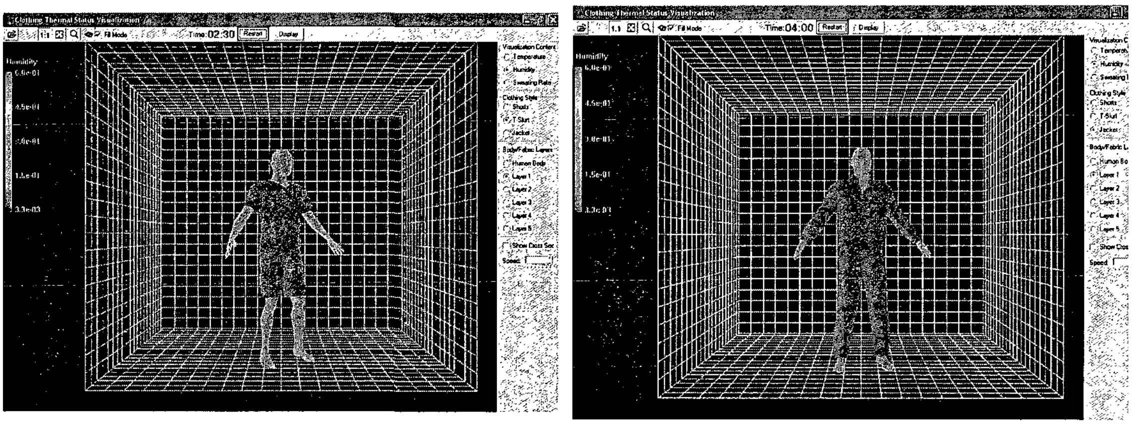
Temperature of under wear

Temperature of outer wear



Relative humidity of the skin

Relative humidity of the under pants



Relative humidity of the under wear

Relative humidity of the outer wear

Figure 7.12 Animated thermal status of the clothing and human body

The thermal status in different parts of clothing and human body with different colors can be used to view their differences. This gives the designer visual presentation of how the clothing performs thermally at different body parts in a thermal virtual world, what the thermal response of the human body wearing the clothing is, as well as the interactions and differences between different clothing and body parts to evaluate whether they are customized by the different materials or structures of the clothing covering different body parts.

7.3 DESIGN CASES

To investigate the prediction ability and multi-style design functionalities of T-smart, two design cases with different scenarios are discussed with the presentation of visualized results.

7.3.1 A design case compared with the experiment

This design case is implemented by using the virtual CAD system and then compared with the experimental results obtained in the laboratory. The design concept of this case is to tailor a set of thermal functional clothing for human beings in an extremely cold climate. The detailed material and structure of the designed clothing in this case is listed in Table 7.4 [61], in which both the vest and coat were coated with the phase change material (PCM) to obtain a smooth change of clothing temperature when the climatic temperature changes sharply. The wearing scenarios are specified as the human body in a cold environment of -15 ^{o}C temperature, 30% relative humidity and 0.1 m/s^2 wind velocity with three stages: 1) sit resting for 30 minutes; 2) running at a velocity of 6.4 km/hour for 30 minutes; 3) sit resting again for 30 minutes.

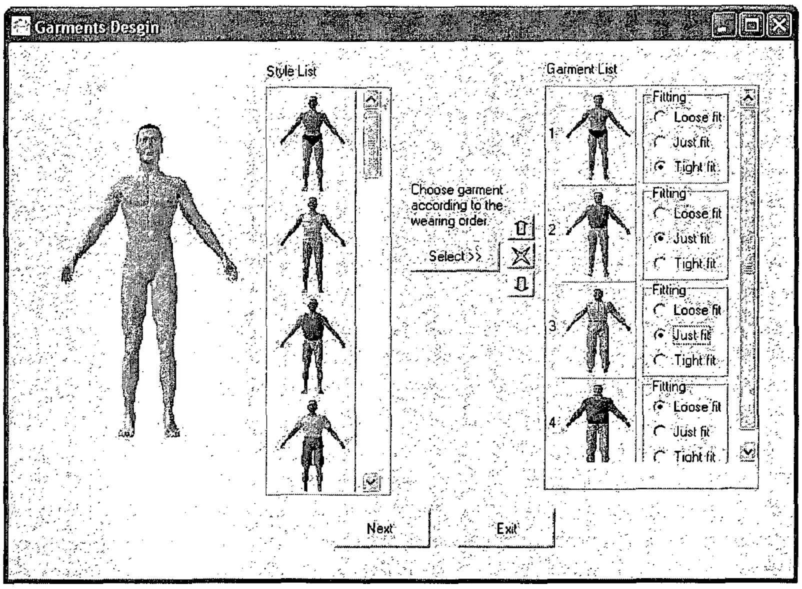
Table 7.4 Material and structure of the functional clothing assembly

	Underwear	**Vest (20%PCM1)**			**Coat (20%PCM2)**			**Outer Jacket**	
Layer	**1**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**
Material	Wool blend Cotton	Woven Nylon Fabric	Nonwoven Polyester Fabric	Woven Nylon Fabric	Woven Nylon Fabric	Nonwoven Polyester Fabric	Woven Nylon Fabric	Mesh Polyester fabric	Woven Nylon Fabric
Thickness (mm)	0.988	0.252	4.79	0.30	0.252	4.79	0.371	0.548	0.371
Thermal conductivity $Wm^{-1}k^{-1}$	0.0754	0.0929	0.0511	0.0731	0.0929	0.0511	0.0853	0.0628	0.0853
Water Vapor Permeability ($gm^{-2}Day^{-1}$)		329		347	329		1107	1275	1107

* PCM1: Freeze point: 15 °C, Melt point: 28 °C
PCM2: Freeze point: 5 °C, Melt point: 15 °C

In T-smart, the virtual design of this clothing was achieved with the provided life-oriented design procedure. Figure 7.13 shows the interfaces for the design procedure of virtual clothing, in which the user firstly chose the clothing style and size, garment by garment, to be worn on the virtual human body, then designed each garment by making the fabrics of shell, inter-layer and lining, and the innovated materials/technologies were applied in the fabric deign.

The human body was defined by the interfaces as shown in Figure 7.14, in which the physiological properties were defined detail to each part and layer. The specification of wearing scenarios was performed including the specification of the wearing environment, the garments covering on individual body parts, and the air space between the layers of each garment worn on the body.



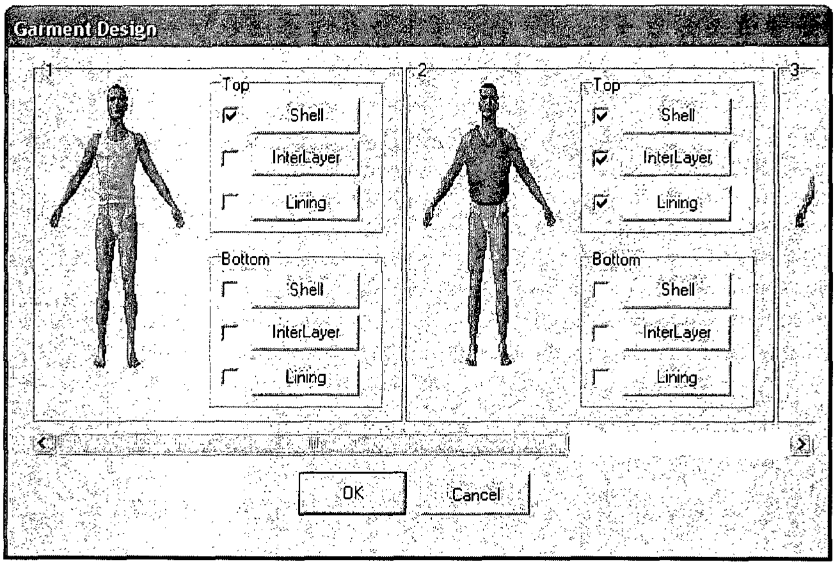
1 Fitting: ○ Loose fit ○ Just fit ● Tight fit

2 Fitting: ○ Loose fit ● Just fit ○ Tight fit

3 Fitting: ○ Loose fit ● Just fit ○ Tight fit

4 Fitting: ● Loose fit ○ Just fit ○ Tight fit

(a) Selecting garment style and fitting status



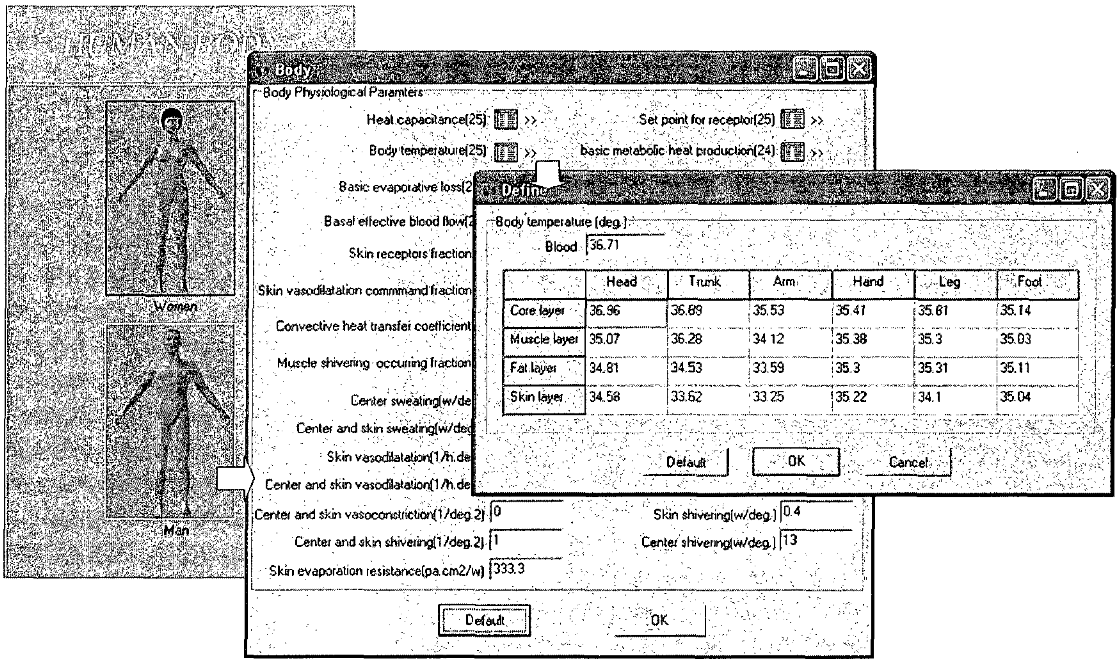
1
Top: ☑ Shell ☐ InterLayer ☐ Lining
Bottom: ☐ Shell ☐ InterLayer ☐ Lining

2
Top: ☑ Shell ☑ InterLayer ☑ Lining
Bottom: ☐ Shell ☐ InterLayer ☐ Lining

3

(b) Garment design through three fabric layers

Figure 7.13 Interfaces for garment design



Body temperature (deg.)

Blood 36.71

	Head	Trunk	Arm	Hand	Leg	Foot
Core layer	36.96	36.89	35.53	35.41	35.61	35.14
Muscle layer	35.07	36.28	34.12	35.38	35.3	35.03
Fat layer	34.81	34.53	33.59	35.3	35.31	35.11
Skin layer	34.58	33.62	33.25	35.22	34.1	35.04

Center and skin vasoconstriction(1/deg.2) 0

Skin shivering(w/deg.) 0.4

Center and skin shivering(1/deg.2) 1

Center shivering(w/deg.) 13

Skin evaporation resistance(pa.cm2/w) 333.3

Figure 7.14 Interface for defining the human body

After the computational simulation, the data files recording the simulation results related to individual body parts and the corresponding garments were generated and available for the user to analyze the thermal performance of clothing and the thermal response of the human body during the wearing scenarios with chart visualization and 3D animation.

On the other hand, the real samples of this set of clothing were worn by a group of human subjects in the laboratory, who performed a series of activities according to the specified wearing scenarios. During the experimental period, a set of thermal sensors attached on the skin and different layers of the clothing were used to record the thermal data, such as temperature and relative humidity. The thermal data at these points were continuously recorded until the experiment ended.

To validate the prediction accuracy of T-smart, the results recorded from the experiment are compared with the simulation results simulated from T-smart at four points: a) temperature of underwear; b) temperature of the vest shell; c) skin temperature of trunk; and d) skin temperature of arm, as shown in Figure 7.15. The patterns of the simulated and experimental temperature distributions at these four points are similar throughout the wearing period and the deviation between them is acceptable, indicating that T-smart system is able to predict the thermal functional performance of the garments.

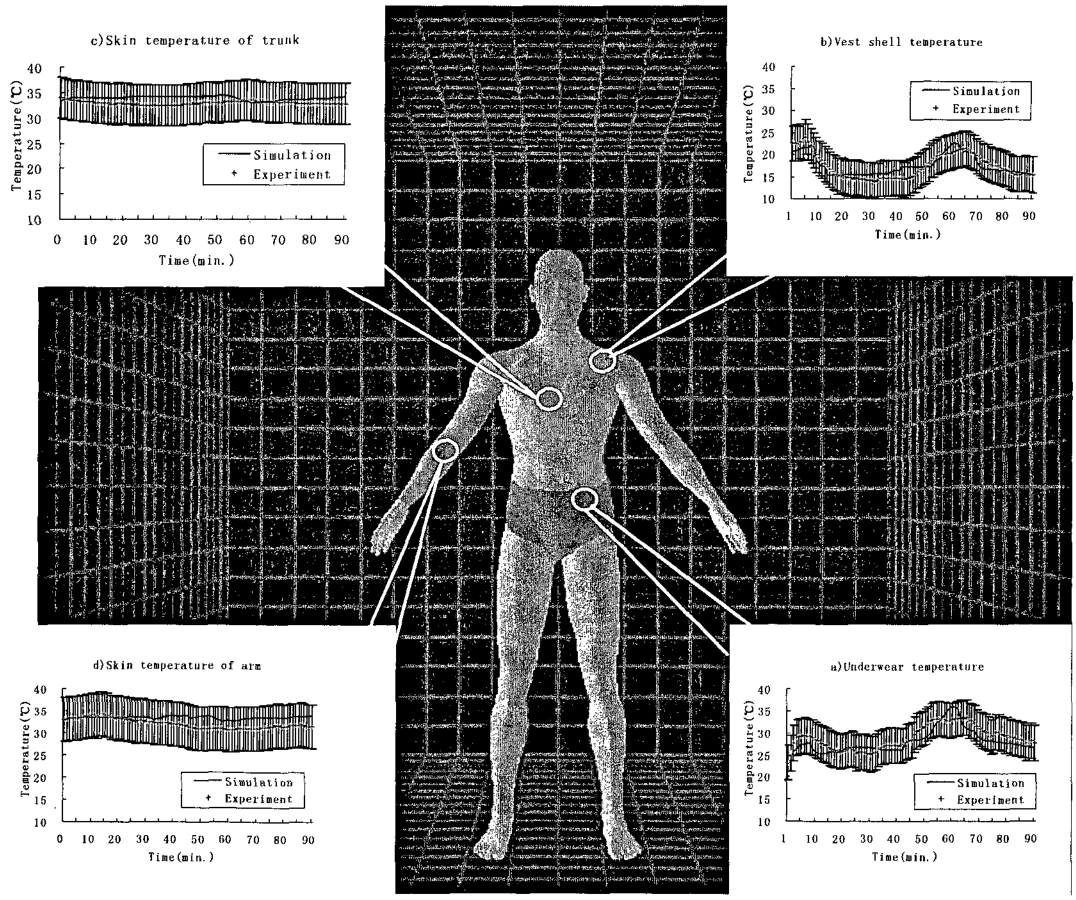
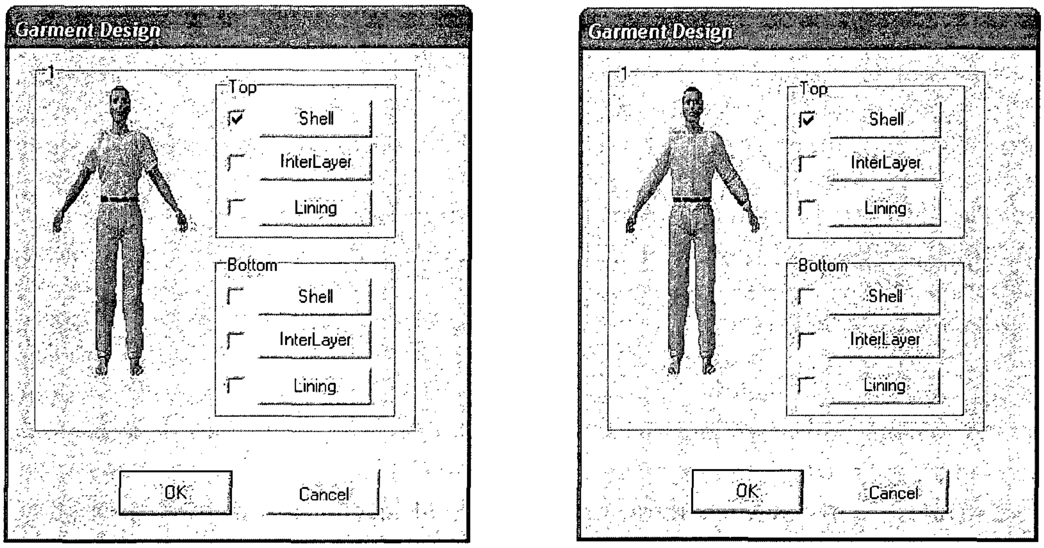


Figure 7.15 Comparison between the experimental and predicted results.

7.3.2 A multi-style design case

To show the multi-style design functionality of the T-smart system, a design case was performed with the same clothing material and structure but different styles. In this case, two sports T-shirts, one with short sleeves and the other with long sleeves were designed and worn on the virtual human body to predict the thermal performance of clothing and the body thermal response during the wearing scenarios.


Garment Design
1
Top
☑ Shell
☐ InterLayer
☐ Lining
Bottom
☐ Shell
☐ InterLayer
☐ Lining

Garment Design
1
Top
☑ Shell
☐ InterLayer
☐ Lining
Bottom
☐ Shell
☐ InterLayer
☐ Lining

(a) Sportswear with short sleeves (b) Sportswear with long sleeves

Figure 7.16 Design interfaces of the sports T-shirts

The material and structure of the sports T-shirt can be found in Table 7.5 and the design interface can be seen from Figure 7.16. With the purpose to examine the thermal performance of this sportswear, the wearing scenarios are designed with reference to different climatic conditions and activities. The detailed protocol is illustrated in Table 7.6, including three stages: 1) Sitting in the room with 25°C temperature, 40% RH, 0.3

m/s wind velocity for 15 minutes; 2) Running in the room with 32°C temperature, 60% RH, 0.1 m/s wind velocity for 20 minutes; and 3) Resting in the room with 25°C temperature, 40% RH, 0.3 m/s wind velocity for 40 minutes.

Table 7.5 Material and structure of the sports wear

Garment type	Fiber	Thickness (mm)	Density (g.cm-3)	Moisture regain (%)
Sports T-shirt A,B	Cotton	1.6	202	7.5

* A-- Sports T-shirt with short sleeves; B--Sports T-shirt with long sleeves

Table 7.6 wearing scenarios for the sports T-shirt

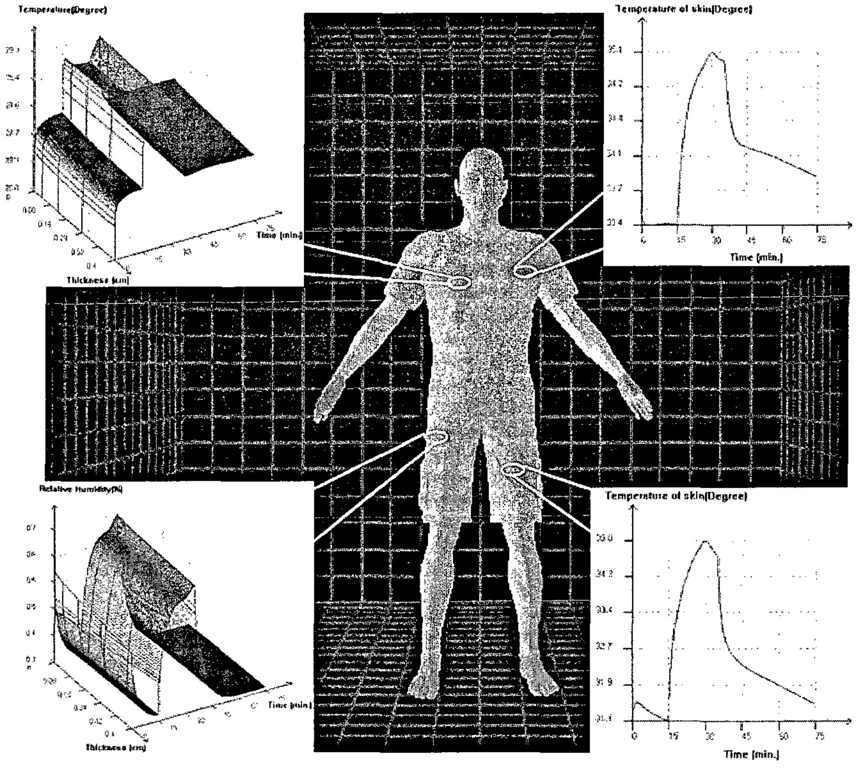
Scenario	Body activity	Room temperature (°C)	Room relative humidity (%)	Wind velocity (m/s)	Duration (Min.)
Stage1	Sitting (1Met)	25	40	0.3	15
Stage2	Running (3Met)	32	60	0.1	20
Stage3	Resting (1Met)	25	40	0.3	40

After the virtual design and computational simulation, the results are visualized with 2D/3D charts and 3D animation to predict the temperature and relative humidity distribution of clothing and human body at different parts during the wearing scenarios, as illustrated in Figure 7.17 and Figure 7.18. From these two figures, the following results can be observed:

a) Temperature distribution of the T-shirt at the trunk. The temperature of T-shirt B is higher than that of T-shirt A throughout the whole wearing scenario in stage 1, and when the human body steps into stage 3 from stage 2 of running status, the temperature of T-shirt B deceases more slowly than that of T-shirt A.

(a) Temperature distribution of the T-shirt on trunk part

(c) Skin temperature distribution on trunk part



(b) Relative humidity distribution of the T-shirt on trunk part

(d) Skin temperature distribution on leg part

Figure 7.17 Predicted results of sports T-shirt A (with short sleeves)

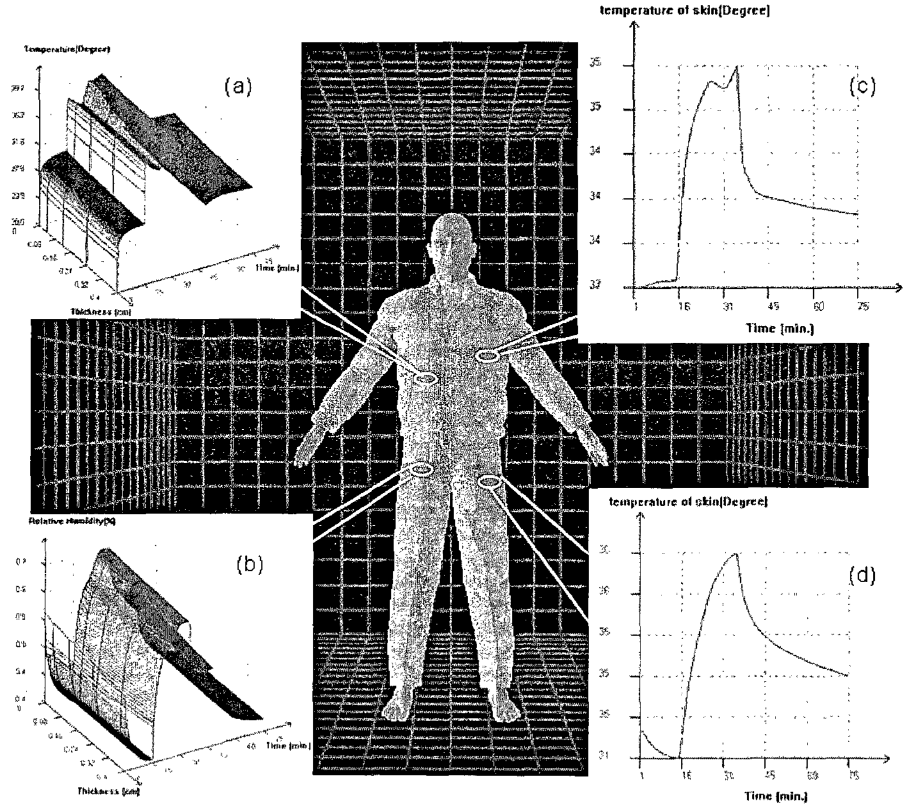
b) Relative humidity distribution of at T-shirt in the trunk. Given the high dependence between the thermal variables of temperature and relative humidity, the analysis of the relative humidity distribution of the T-shirts is similar to that of the temperature distribution.

c) Skin temperature distribution at the trunk. The reason that the short sleeves have better ability to emit heat also results in the skin temperature of the trunk part being lower in case A than in case B in stage 3. In stage 2, the skin temperature in case A decreases earlier than in case B because it evaporates sweat more easily, and thus taking away the heat. Consequently, the skin temperature in case B changes more sharply than in case A when the human body stops running at the end of stage 2. However, in stage 3, the skin temperature in case B still cools more slowly than in case A.

d) Skin temperature distribution at the leg. The analysis of the skin temperature on the leg is similar to that at the trunk. The difference is that the leg part in case B is covered by the clothing while it is exposed directly to the environment in case A. Therefore, the skin temperature in case A cools more quickly than that in case B, and the differences between these two cases is clearer than that of the temperature at the trunk.

(a) Temperature distribution of the T-shirt on trunk part

(c) Skin temperature distribution on trunk part



(b) Relative humidity distribution of the T-shirt on trunk part

(d) Skin temperature distribution on leg part

Figure 7.18 Predicted results of sports T-shirt B (with long sleeves).

In order to have a more direct observation of the different thermal performance of clothing in this multi-style design case, the core temperature and skin temperature of the trunk and leg in case A and case B are compared by with the chart visualization, as shown in Figure 7.19, in which the distributions of the skin temperature of trunk and leg have been discussed above. The core temperature distributions of these parts are different due to the influence of the clothing with different styles.

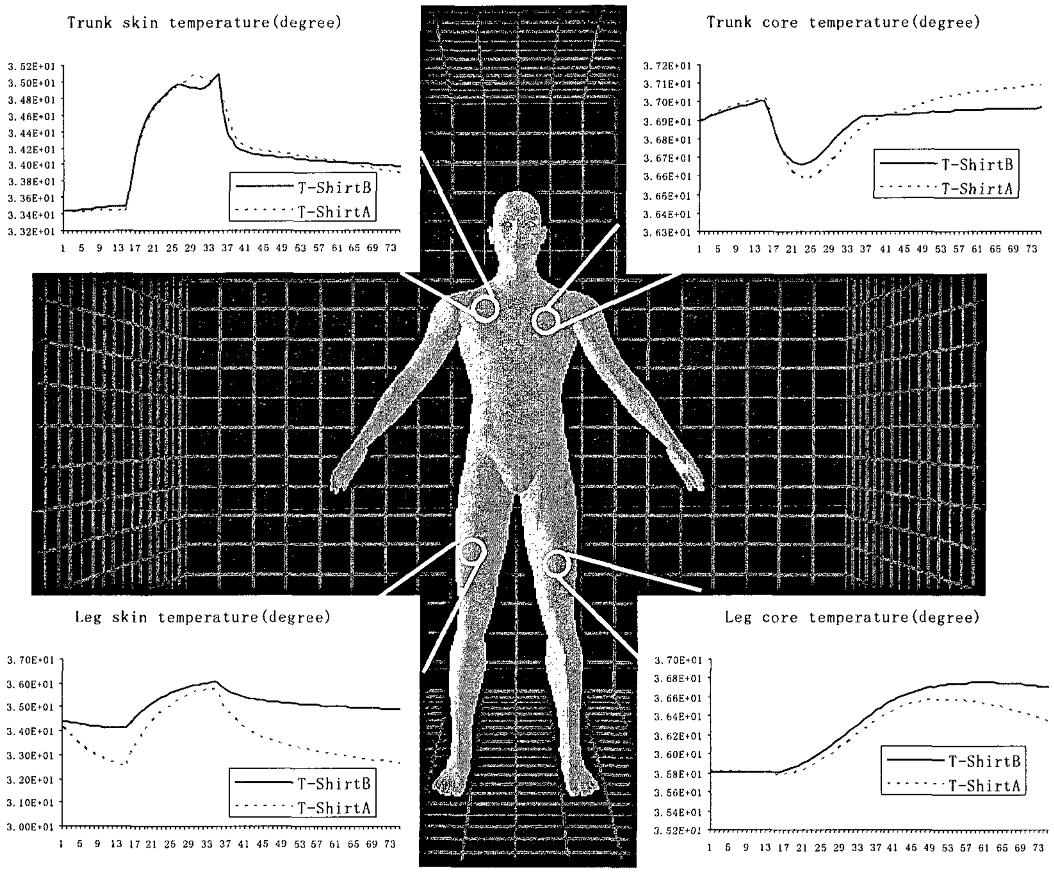


Figure 7.19 Comparison of the thermal status of the body in case A and case B

In this case, the design of two sports swears with multi-styles (long sleeve and short sleeve) using T-smart has been demonstrated. The designer can design, simulate, preview and compare the thermal performance of these two sports wears to see their difference. Even more, with this system the user can perform clothing multi-style design that utilizing different textile materials or functional treatments for different parts instead of the same material for different parts as in this case.

7.4 DISCUSSION

By adopting the simulation models with multi-part division of the human body, the simulation of the thermal behaviors in the clothing wearing system can be accomplished in six parts: head, trunk, arms, hands, legs and feet. The designer is thus able to perform clothing multi-style thermal design in this virtual CAD system, which is an important advance in terms of considering detailed design with different styles and materials in different parts, and is more applicable to the practical design cases for different applications. With this virtual system, the designer can avoid making real samples in the initial design stage and view the thermal performance of clothing and the thermal status of the human body in different parts in the specified wearing scenarios. As illustrated in the design cases, the visual presentation of the simulation results helps the designer to view directly the thermal distributions of the clothing and human body at different points, and analyze whether the thermal performance of the clothing conforms to the design concept, then go back to improve and optimize the design. With the ability of multi-style design, T-smart has the following new characteristics:

1) In the design process, the designer is able to consider the clothing style, including various lengths and fitting status, and distinguish the clothing for

different body parts, such as hats, vests, gloves, socks, instead of the overall design as in the P-smart system. Therefore, a detailed design concept can be achieved at the design process, such as different clothing material for different parts of the body, and different clothing thickness in different parts to take account of the difference of thermal sensitivity and activity flexibility in different body parts.

2) With the support of the engineering database, the designer is able to view the thermal performance of the clothing on different people with different gender, age and race, and even for an individual person by giving the values of the person's physical and physiological parameters. The user can also specify the wearing scenarios in any expected place and time by querying the climatic information from the database. This extends the ability of the designers to tailor their designs for different people and different environments. For instance, some people may have more sweating accumulation on the back or armpit skin, where the clothing needs more special considerations, such as setting a slide fastener or using breathable materials to help the body to breathe.

3) T-smart offers more support for the application of innovative technology on clothing thermal functional design, such as the moisture management treatment, self-heating fabric, and phase change material (PCM) nano/microcapsules coating. In particular, the PCM coating volume on different clothing parts can be adjusted according to the distribution of thermal sensors in the human body, and more

volume can be considered at the thermally sensitive part of the body to effectively regulate the thermal microenvironment between the clothing and body.

To sum up, T-smart enables multi-style clothing thermal design with expected wearing scenarios and predicts the thermal performance of the clothing and thermal response of the human body during the simulated wearing period. However, the computational load is increased due to the simultaneous simulation of the thermal behaviors of the multi-parts of clothing and human body.

7.5 CONCLUSION

This Chapter has reported a virtual CAD system named T-smart for multi-style clothing thermal engineering design under the software architecture proposed in Chapter 5, which enables the designer to realize the design of various styles and clothing materials for different body parts. To achieve the multi-style design capability, the models for simulating the thermal behaviors in the clothing wearing system adopts the clothing model and a 25-node human body model, whose detailed description has been presented in Chapter 3. The computational scheme with multi-dimensional structure reported in Chapter 4 is used to execute the computational algorithms. The main functionalities of T-smart include life-oriented design, computational simulation, and post processing. In the final part, two design cases have been presented to validate the simulation results and show the multi-style design of T-smart.

T-smart expands the capacity of clothing thermal functional design from the overall level of P-smart reported in Chapter 6 to the multi-style level, which is limited in P-smart but needed frequently in the practical design cases for different applications. T-smart is an important advance in clothing thermal functional design to allow the designer to consider different clothing styles and materials in different body parts, simulate, preview and analyze the thermal performance of the clothing and human body at these parts. With this virtual CAD system, it is possible for the user to carry out thermal functional design of clothing with different styles (hats, vests, gloves, socks, jacket, and pants etc.), tailor thermal functional clothing for different people and different environments and explore more innovative use of smart and functional materials on clothing thermal functional design.

CHAPTER 8 CONCLUSIONS AND FUTURE WORK

8.1 CONCLUSIONS

In order to design clothing to achieve desirable thermal functions meeting for thermal biological requirements of the human body, a systematical and scientific strategy of computer-aided clothing thermal engineering design is presented and realized in this thesis. Development of CTE-CAD involves multi-disciplinary knowledge in physical, physiological, mathematical, computational and software sciences. The CTE-CAD system can be applied to design, simulate, preview, analyze and evaluate the thermal performance of clothing before making any real garment.

The five objectives of this study have been achieved, including: 1) development of systematic description and theoretical framework of clothing thermal engineering design; 2) selection and integration of simulation models; 3) development of computational schemes for engineering application purposes; 4) design and development of software architecture of the computer-aided systems and 5) realization and development of the computer-aided systems for clothing thermal engineering design. The achievements of these objectives have been reported in Chapters 2~7 respectively. Specifically, the results of this study are summarized as follows.

Chapter 1 presents an extensive literature review to reveal the knowledge gaps and derive the objectives of this study. The available knowledge in relevant disciplinary areas was surveyed through literature review, including physical mechanisms and description models of the thermal behaviors in textiles, biological mechanisms and description models of the thermoregulatory system of human body, simulation of the integrated human body and clothing system, and the state of the art of the computer tools in clothing thermal functional design. In order to achieve the strategy of computer-aided clothing thermal engineering design, the knowledge gaps have been identified and the objectives of this study have been derived to fill these gaps.

Chapter 2 presents a systematic definition and a multi-disciplinary framework of clothing thermal engineering design. First, the requirements of clothing with thermal functions have been discussed and analyzed to reveal the relationships between the thermal physiology of human body and physical mechanisms governing the heat and moisture transfer in clothing, and to illustrate the necessity of clothing thermal engineering design. Due to the reason that the thermal functions of clothing are quite difficult to be achieved in the traditional way, a strategy of clothing thermal engineering design was hence introduced as the application of a systematic and quantitative way of designing and engineering clothing with the application and integration of knowledge in physical, physiological, mathematical, computational and software sciences. The multi-disciplinary framework of clothing thermal engineering design was developed to work out the relationship/communication between them. The computational simulation and computer-aided system were identified as the two central components of the multi-disciplinary framework.

In Chapter 3, an assembly of multi-scale models for clothing thermal engineering design was presented. In order to assess the potential/suitability of existing models for engineering design purposes, a set of criteria was established, with which published thermal models related to textile material, human body and integrated human body-clothing system were critically analyzed. Based on this analysis, an assembly of multi-scale models was selected and integrated to model the thermal behaviors involved in the clothing wearing system from the molecular to body-clothing level, which consist of the following components: PCM nano/micro-capsulation heat storage model (nm-scale), fiber moisture sorption/desorption model (μm-scale), fabric heat and mass transfer model (mm-scale), and human body thermoregulatory model (m-scale). The parameters/properties in the models in terms of physical meaning, data availability and unit were then investigated for effective engineering applications. The boundary and initial conditions of these models were given to define the solution domain and initial values of the solution.

In Chapter 4, the computational scheme was developed for clothing thermal engineering design. To generate the numerical solutions of the multi-scale simulation models presented in Chapter 3, the descretization process of the partial differential equations involved was carried out with the implicitly finite volume method. Based on the numerical solutions, a one-dimensional scheme and a two-dimensional computational scheme were developed to implement the numerical algorithms of computational simulation for the purpose of clothing thermal engineering design. The influence of physical properties and boundary condition coefficients on the simulation results was studied.

In Chapter 5, an innovative software architecture was designed for the CTE-CAD system. The user requirements on clothing thermal engineering design CAD system were identified before the development of the architecture. With reference to the user requirements, the software architecture was developed and described, which consists of the functional components of the user graphic interface, life-oriented design procedure, pre-processing module, numerical solver, and post processing modules. The object-oriented technique was adopted to design the CAD system in order to make it open and flexible for future maintenance and update. The engineering database supporting the engineering design process was designed with a hierarchical data model and a special data structure to manage and utilize the garment design and material data.

Under the proposed software architecture, two computer-aided systems for multi-layer and multi-style clothing thermal engineering design were developed and described respectively in Chapter 6 and Chapter 7.

In Chapter 6, the development of a CAD system (P-smart) was reported for multi-layer clothing thermal engineering design, which is the first software tool in the world to provide the users the capacity of clothing thermal engineering design. This CAD system employed the one-dimensional simulation models of clothing and human body to simulate the thermal behaviors in the clothing wearing system, and adopted the one-dimensional computational scheme to implement the computational algorithms. A series of functionalities of the system, including life-oriented design, computational simulation and post processing were developed for the users to design, simulate and preview the overall thermal performance of clothing and thermal status of the body during the wearing period. Two design cases were presented to show the functional design capacity of this system and validate the accuracy of prediction.

In Chapter 7, the development of a CAD system (T-smart) was reported for multi-style clothing thermal engineering design, which enables the designer to carry out the design of various styles and use of different clothing materials for different body parts. To achieve the multi-style design capability, this system employed the clothing models and a 25-node human body model to simulate the thermal behaviors in the clothing wearing system and the multi-dimensional computational scheme to implement the simulation algorithms. The functionalities of this system in terms of life-oriented design, computational simulation and post processing were developed to facilitate the user to perform multi-style clothing thermal functional design. Two design cases were presented to validate the simulation results and show the multi-style design capacity of this CAD system.

8.2 DIRECTIONS FOR FUTURE WORK

The objectives of this study have been achieved as summarized above. Future work can be continued to improve the performance of this strategy of computer-aided clothing thermal engineering design and to present the strategy to the user as a more user-friendly and powerful tool. The future work can be developed in the following areas:

1) To expand the simulation models. Currently, the simulation models ulitized to numerically express the thermal behaviros in the clothing wearing system in this study are a assembly of multi-scale model, The models for the textile materias are one-dimesnional and incoporated with a one-node and 25-node thermoregulatory models of the huma body. The simulation models thus can not simulate the thermal behaivors in the clothing wearing system in a 3D. With the increasing capability of computing power, it is feasible to employ a 3D thermoregulatory model of human body), to expand the dimension of the integrated model assembly to 3D. Meanwhile, it is also possible to develop more comprehensive 3D mathematical models to simulate the heat and moisture transfer processes in the textile material.
2) To improve the computational scheme. In the development of the computational scheme, there should always be a balance between the accuracy and efficiency of the computation. It is easy for the solutions of the simulation models which consist of partial differential equations to be divergent due to various reasons, such as rough mesh for solution domain, long time step, and wrong input configuration. More sophisticated algorithms or strategy can be developed and applied to control or improve the accuracy of the simulation results while having a slightly influence

on the computational efficiency.

3) To strengthen the functionalities of the CAD system. In order to provide the user with a more user-friendly and powferful tool for clothing thermal engineering design, the functioanlities can be strenghtened by improving the design capacity, such as 3D clothing thermal functioanl design, the input user interfaces and the visiulization capability (The visualziation of the simulation results can be consistent with the configurations of the input engineering design so that the user has a more direct observation).

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