# PERFORMANCE OF COOLING AND HEATING PANELS USED IN BUILDING AIR CONDITIONING SYSTEMS IN BOTH CEILING AND FLOOR POSITIONS

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## COMMITTEE DECISION

**This Thesis/Dissertation (Performance Of Cooling and Heating Panels Used In Building Air Conditioning Systems In Both Ceiling And Floor Positions) was Successfully Defended and Approved on 30/7/2009**

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تعتمد كلية الدراسات العليا
هذه النسخة من الرسالــة
التوقيع.......التاريخ٩/٨/٩

# DEDICATION

**To my great father**

**To my kind mother**

**My brothers and sisters**

**My family**

**My friends**

**&**

**All those lovely people who encouraged me**

**I dedicate this work**

**Hazem Maher Alassaf**

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# NOMENCLATURE

| | |
|---|---|
| A | Radiant panel area. |
| $A_{p}$, $A_r$ | area of panel surface and factious surface, respectively. |
| $A_j$ | Area of surfaces other than panel. |
| C | Equation constant. |
| $C_p$ | Water specific heat (kJ/kg.K). |
| $F_r$ | radiation exchange factor (dimensionless) |
| $F_{p-r}$ | Radiation angle factor from panel to factious surface. |
| h | the Convection heat transfer coefficient ($W/m^2$ K). |
| $h_{cc}$ | the Convection heat transfer coefficient for ceiling cooling ($W/m^2$ K). |
| $h_{cf}$ | the Convection heat transfer coefficient for floor heating ($W/m^2$ K). |
| k | Thermal conductivity of air (W/m K). |
| L | The length of Radiant panel. |
| m | The mass flow rate of water (kg/s). |
| n, m | Equation index. |
| Q | The total heat transfer flux. |
| T | Tempereture in ($^{o}$C). |
| $T_a$ | The ambient temperature. |
| $T_b$ | The bulk tempereture. |
| $T_c$ | Ceiling tempereture. |
| $T_i$ | Water inlet temperature ($^{o}$C). |
| $T_P$ | effective temperature of panel surface. |
| $T_o$ | temperature of factious surface (unheated or uncooled) K. |
| $T_r$ | water outlet temperature ($^{o}$C). |
| $T_w$ | Wall tempereture. |

| | |
|---|---|
| V | The volume flow rate of water. |
| $\varepsilon_j$ | thermal emittance other than panel. |
| $\sigma$ | Stefan-Boltzman constant = 5.67*10^-8 $W/m^2.K^4$. |
| $\varepsilon_{r}$, $\varepsilon_p$ | Thermal emittance of panel surface and factious surface, respectively. |
| $\rho$ | The air density in ($kg/m^3$) at atmospheric conditions. |
| $\mu$ | The air dynamic viscosity. |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| Nu | Nusselt number. |
| Gr | Grashof number. |
| Pr | Prandtl number. |
| CFD | Computational fluid dynamics. |
| HVAC | Heating, ventilating, and air conditioning. |
| CRCP | Ceiling radiant cooling panel. |

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## APPENDIX A

1- Tests temperature tables with different water flow rate and figures show the behavior of system at heating and cooling.

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# PERFORMANCE OF COOLING AND HEATING PANELS USED IN BUILDING AIR CONDITIONING SYSTEMS IN BOTH CEILING AND FLOOR POSITIONS

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## ABSTRACT

This research is an experimental study of the performance of cooling and heating panels used in building air conditioning systems in both ceiling and floor positions. Two panels of 0.6 x 0.6 m were located inside a highly insulated box, one at floor level for heating purposes and the other for cooling purposes at ceiling level.

The experiments were done in both cooling and heating modes at water mass flow rate ranged from 0.2 to 2 L/min to achieve different natural convection heat transfer coefficients. The outside ambient temperatures were changing at the same mode as inside the box trying to improve the experiments for an adiabatic system.

The effects of the basic experimental parameters such as temperatures and mass flow rate on the natural convection heat transfer coefficient were studied. The temperatures in the test box at different levels were measured and recorded at steady state conditions over a period of time for each test.

The values of Nusselt, Grashof, and Prandtl numbers were observed experimentally and their effect on the system equations was determined.

Experimental analysis was carried out, and two new empirical correlations were developed to calculate the average natural convection heat transfer coefficient during cooling and heating modes for the used panels. The predicted values of Nusselt No. for natural convection heat transfer for heating and cooling was proved to be highly accurate with Bias error = 0.41 and 0.32 % , and with Absolute Average Deviation (AAD) = 4.3 and 3.75% respectively.
The temperature ranges for air were between 20$^{o}$C and 32 $^{o}$C for heating and between 20$^{o}$C and 28 $^{o}$C for cooling.
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# CHAPTER 1

# INTRODUCTION

## 1.0 Overview

Radiant panel systems has been refined and used successfully for the air conditioning purposes in Europe for more than 24 years, especially in the form of radiant floors and ceilings. But it should be mentioned that the idea of radiant panel cooling system was used in the Roman Era.The ancient Romans were known to circulate water through the walls of certain houses to cool them. There are three main types of panels: Ceiling panels, Floor panels, and Wall panels.

In this thesis, the ceiling and floor panels were examined only.

## 1.1 Natural convection heat transfer

Convective heat transfer occurs when a liquid or gas (fluids) comes in contact with a material of a different temperature. Natural convection occurs when the flow of a liquid or gas is primarily due to density differences within the fluid due to heating or cooling of that fluid.

The movement of the fluid in natural convection results from the buoyancy forces imposed on the fluid when its density is changed. The buoyancy forces are present because the fluid is acted upon by gravity.

# CHAPTER 2

# LITERATURE SURVEY

Radiant Cooling and Heating panels are new suggested methods that are still under engineering studies and investigations to check its ability to compensate for traditional Air Conditioning systems, since it requires special materials for construction.

Many published papers discuss the theory of radiant cooling and heating panels: such as the work of Min et al, (1956) which conducted experimental studies for a 3-dimensional room conditions. Analysis work developed the following two equations:

$h_{cc} = 2.13\ (T_a - T_p)^{0.31}$ (for cooled ceiling or heated floor) (2.1)

$h_{cc} = 0.134\ (T_a - T_p)^{0.25}$ (for cooled floor or heated ceiling) (2.2)

Kilkis et al, (1994) developed an analytical heat diffusion model which is applicable to heating and cooling. Sample design indicated that this model has some accuracy comparable to that of a finite element model and can be used easily by the engineering design for practical purposes.

Ho et al, (1994) developed a two-dimensional numerical model for a hydronic heating panel. The model couples the heating panel to an enclosure, which in turn is losing heat to the surroundings, and is capable of predicting both steady state temperature profiles and transient responses. Both the finite difference method and the finite element method were used to solve the numerical model. Of the two, the finite difference method gave slightly higher temperature values and required more execution time. Model predictions are compared with the experimental data from a bungalow style house equipped with hydronic heating system. Steady state results of the simulation compared well with the experimental results, while the model predicted a faster response time for the room air temperature than was observed experimentally. Incorporation of an extra term in the dynamic model to account for heat retention in the walls of the structure resulted in good agreement between the experimental and simulated responses.

Imanari et al, (1999) investigated the various characteristics of a radiant ceiling panel systems and their practical application to office buildings. The radiant ceiling panel system and conventional air-conditioning system were compared in terms of thermal comfort, energy consumption, and cost. Results showed lower cost, energy consumption and thermal comfort for the radiant ceiling panel systems.

Roulet et al (1999) studied the usage of large panels to control the indoor temperature, by cooling as well as by heating, in several types of buildings. The panels were made out of two corrugated stainless steel foils, seam welded on the perimeter and spot welded at many places on the area. Water at controlled temperature circulated in this cushion. These panels were either installed as conditioning ceilings or walls. In well-insulated buildings, the power required to control indoor temperature is rather low, and a small temperature difference between the panel and the indoor environment sufficient to deliver or absorb the required heat. The paper presented the panel itself and its use in residential and non-residential buildings, as well as some industrial and research implementations.

Awbi and Hatton , (2000) studied the capability of cooling radiant panels. The following correlations for an office room with dimensions of 2.78 × 2.78 × 2.3 m:

$h_{cc} = 2.175/L^{0.076} (T_a - T_p)^{0.308}$ (for cooled ceiling and heated floor) (2.3)

$h_{cc} = 0.704/L^{0.601} (T_a - T_p)^{0.133}$ (for cooled floor) (2.4)

Miriel et al, (2002) investigated experimentally the thermal performance of a ceiling panel system considering copper tubes with aluminum fin. They developed a model for that system. They noted that the rate of radiative heat transfer to total heat transfer was 2/3 for the case of ceiling cooling and 4/5 for the case of ceiling heating.

Jeong and Mumma (2003) estimated the impact of the mixed convection effect on the cooling capacity of a ceiling radiant panel in mechanically ventilated spaces. To estimate panel cooling capacity enhancement caused by mixed convection, a verified analytical panel model was used. The simplified correlation for mixed convection heat transfer coefficient which can be easily adopted in panel cooling capacity estimation was derived from established mixed convection and natural convection correlations. It was found that the total cooling capacity of radiant panels can be enhanced in mixed convection situations by 5–35% under normal operating panel surface temperatures.

Ardehali et al, (2004) presented a proof-of-concept formulation and procedure for modeling the heat transfer mechanisms of radiant conditioning panels with considerations for the occupant in a thermal zone. A literature review was conducted to identify the key parameters that affect the performance of the conditioning panels. This resulted in a proof of concept model developed and the performance of the conditioning panels was analyzed.

Jeong and Mumma, (2004) developed a simplified cooling capacity estimating correlation for a top insulated metal ceiling radiant cooling panel (CRCP). By statistically analyzing the impact of various panel design parameters on the panel cooling capacity was experimented, a linear regression equation was derived. A validated analytical CRCP model was used to collect panel performance data for the various combinations of design parameters. In this analysis, it was found that eight single design parameters and eleven two-factor interactions significantly affect the panel cooling capacity.

ASHRAE book of systems and equipment (2004) included a chapter about ceiling panel cooling systems in which empirical formulae were listed. For small plates, laminar range, the following empirical formulae was suggested:

$h = 0.27\ (\Delta t/L)^{0.25}$

And for Large plates, turbulent range the following empirical formulae was suggested:

$h = 0.22\ (\Delta t)^{0.33}$. (2.5)

Nasr et al. (2005) investigated heat transfer numerically for laminar convection conditions and for Rayleigh number ranges of $10^2$–$10^6$ in a two dimensioned enclosure of which walls are insulated and of which ceiling was cooled. They gave the following correlation for cooling panels installed on walls:

$Nu = 0.553\ Ra^{0.2}$ (2.6)

Refet Karadag (2008) simulated numerically the convective heat transfer coefficient of cooling panels of walls and ceilings for different room dimensions of 3 x 3 x 3, 4 x 3 x 4 and 6 x 3 x 4 m. Thermal conditions of ceiling temperature were $T_c$ = 0–25 $^{o}$C and wall temperature were $T_w$ = 28–36 $^{o}$C. Radiative heat transfer was calculated theoretically for different surface emissivities of ($\varepsilon_w = \varepsilon_c$ = 0.7, 0.8 and 0.9). Finally he gave the following correlation for cooled ceiling panels:

$h_{cc} = 2.6\ (Ti - Tc)^{0.27}$ (2.7)

Where $T_i$ is the ambient air temperature.

In this literature survey, it is clear that all researchers studied these panels within non adiabatic, special cases, and ignoring the effect of Grashof on the natural convection heat transfer systems.

The majority of these researchers depended on a numerical solution to get their correlations, and in general, most the correlations used the simplified form of

h = function ($\Delta T$) only.

The present work will be different from the previous studies in the following features:

1- The present work deals with two cases; one for heating at floor level and the other for cooling at ceiling level, in another meaning this work will lead to two different correlations representing the effect of Grashof number and Prandtl number in the form Nu = function (Gr, Pr).

2- This work presents experimentally a study of a single panel in a highly insulated system to improve an adiabatic process and reach more accurate results.

3- Ranges of main parameters such as temperatures, water mass flow rates, Grashof and Prandtl numbers used in the correlations will be stated in this work.

# CHAPTER 3

# EXPERIMENTAL SET-UP AND INSTRUMENTATIONS

## 3.0 Introduction

The main aim of this research is to study and investigate the performance of heating and cooling panels systems experimentally. Three different water flow rate for both modes were conducted.

Locally constructed experimental setup was used to measure experimentally different parameters to get the empirical correlation for natural convection heat transfer.

## 3.1 Experiment set-up

The schematic diagram of the test apparatus and its main components is shown in Fig.1, A general photograph of the actual experimental set-up is shown in figure 2.

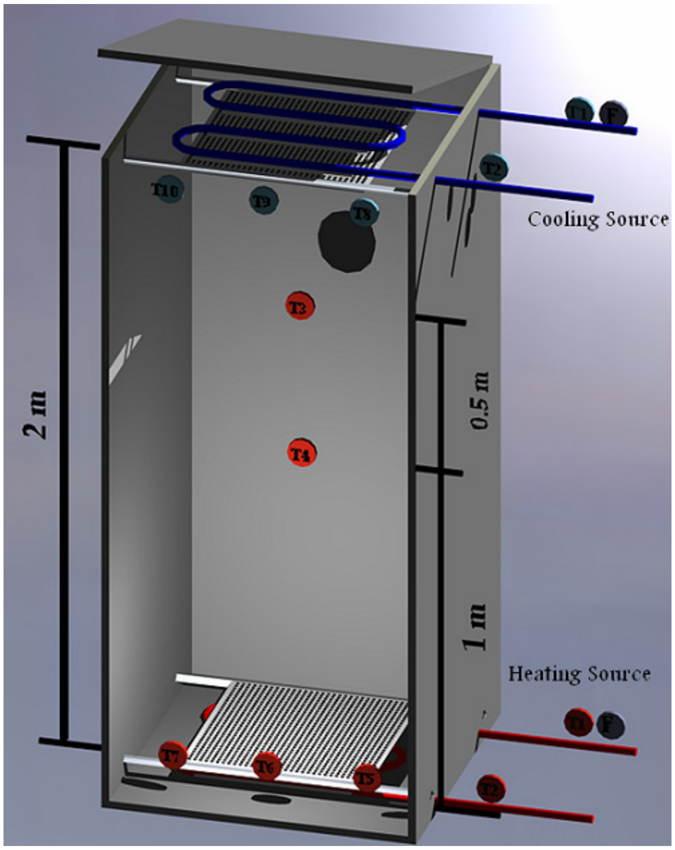

**Fig.1**: Schematic of the Experiment setup

The experimental set-up consists basically of an insulated box. Radiant Cooling and Heating panels are installed in the box which is 0.8m x 0.8m x (2 m height). The box was made of 2.5 cm Foam and Aluminum P3 Sandwich Sheets. The panels in the box were insulated at upper side and lower side of the box.

One panel was installed in the top of the box for the cooling tests and the other was installed at the bottom for the heating tests, the panel pipes were made from Thermo pipe with aluminum fins. The system was equipped with a water flow meter and a flow regulator so the amount of heat transferred to the panel was controlled.

Temperature readings were taken for both inlet and outlet water and for the box space at different locations and different times, see figure 1. Readings were taken at different flow rates.

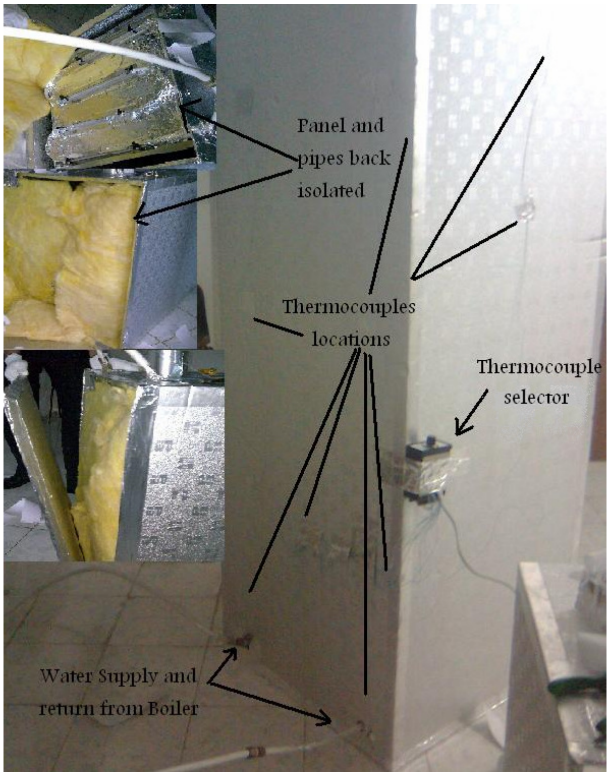

**Fig. 2:** The actual experimental set-up

The detailed description and the function of each component of the experimental apparatus are given below.

The experiments were set to measure water mass flow rates and temperatures at different points to investigate the behavior and the main parameters for the heating and cooling processes.

### 3.1.1 Radiant panels

Two aluminum 60 x 60 cm panels were installed in the center of the lower side and upper side of the box.

The bottom of the box was closed with foam and aluminum layer so that it was sealed against air flow to insure a natural heat transfer.

These panels exchanged heat between the air in the insulated box and the heated or cooled water.

However, the other side of the panel will also make a heat exchange with the gap of air in the box and this will affect on the stability and steady state conditions of the system; to overcome that, the back of the panels were closed by a rock wool layer as shown in Figure 3.

**Fig. 3:** The Radiant panel and Rock wool layer

### 3.1.2 Insulated Box

In order to localize air that its temperature changed due to the used Radiant panel, a 0.8m x 0.8m x (2 m height) box was installed the box was made of 2.5 cm Foam and Aluminum P3 Sandwich Sheets.

After installing the box and closing all gaps, a layer of 5 cm insulation Rock wool was used to cover the foam-Aluminum box, this insured adiabatic condition. Some tests were done at the box and assumed adiabatic conditions.

### 3.1.3 Water regulating valve

A globe valve was used to regulate water flow in the thermo pipes; this lead to a change in the amount of heat transfer between water and the box.

### 3.1.4 Thermo pipe with aluminum fins

A single 16 mm thermo pipe was connected between the supply and the return collectors, and became a part of the lab cooling and heating system, this pipe creates a loop at the location of the radiant panel as shown in Figure 4, the pipe is connected to the panel by four aluminum fins, making sure that no gap between the fins and the panel.

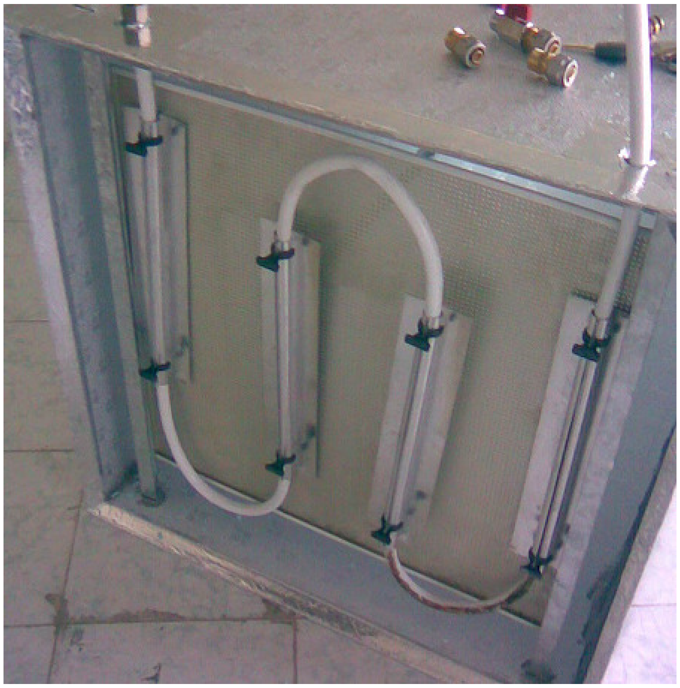

**Fig. 4:** Thermo pipe with aluminum fins

### 3.1.5 Cooling and Heating Sources (Chiller and boiler)

For the experimental work the same boiler and chiller used to cool or heat the lab space were used. This will decrease the difference of temperature between the inner space of the box and the ambient, thus adiabatic conditions can be approved.

## 3.2 Instrumentations

Different temperature locations in the experimental box, outside wall surface temperature, water inlet and outlet temperatures, ambient temperature and the volumetric flow rate of water for heating and cooling processes are the main variables that were measured during the experiments.

### 3.2.1 Temperature Measurement

K-type thermocouples were used during the experimental tests to measure different temperature locations. This type of thermocouples is recommended for low temperature measurements. Thermocouples are standardized against a reference temperature of 0 degrees Celsius.

The two wires of the thermocouple were welded together to form the thermal junction by means of an electrical welding machine which is already available in the laboratories of the Mechanical Engineering Department at the University of Jordan.

The heating and the cooling experiments were instrumented with 14 thermocouples at different locations. These locations and distributions can be shown in Table 1.

**Table 1**: Thermocouples distribution

| Heating and cooling process | |
|---|---|
| Thermocouple number | Location |
| 1 | Supply water from boiler or chiller |
| 2 | Return water to boiler or chiller |
| 3 | Center of radiant panel |
| 4 | half the distance between center and edge at the panel |
| 5 | Edge of the radiant panel |
| 6 | 50 cm from the radiant panel in the box at the right. |
| 7 | 50 cm from the radiant panel in the box at the left. |
| 8 | 100 cm from the radiant panel in the box at the right. |
| 9 | 100 cm from the radiant panel in the box at the left. |
| 10 | 150 cm from the radiant panel in the box at the right. |
| 11 | 150 cm from the radiant panel in the box at the left. |
| 12 | 200 cm from the radiant panel in the box at the center. |
| 13 | At outside wall of the box |
| 14 | Ambient space |

Thermocouples 13 and 14 were used once for calculations to insure adiabatic conditions.

And for a sample state where ΔT between thermocouples 13 and 14 to be =0.8 °C, calculating U=0.373 W/m$^2$K , area of conduction = 7.68 m$^2$ then q $_{conduction}$ = 2.3 Watt and this value is negligible and assuming adiabatic system.

### 3.2.2 Water flow rate

The water flow rate was measured by a Rotameter liquid flow meter calibrated for water as shown in figure 5. The Rotameter is made by Dwyer Company and flow range of measurements was 0-6 l/min with 0.2 l/min divisions. The flow meter is connected on the supply collector.

**Fig. 5:** Water flow meter(Rotameter)

# CHAPTER 4

# HEATING EXPERIMENTAL WORK

## 4.0 Introduction

This chapter contains the test procedure, sample calculation, analysis for radiation, natural convection heat transfer and some correlation parameters for heating mode.

## 4.1 Test procedure

The radiant panel was heated to an average temperature of 33-40 $^{o}$C by connecting the thermo pipe tubes to the boiler water collector, and thus increasing the temperature of air space inside the test box.

Since the need to change the amount of heat added to the test box in time periods, varying the mass water flow rate was necessary using the regulating valve, thus making different experiments at different water flow rates 0.2,1 and 2 liter/min.

The values of the main independent variables such as water temperature drop, the water mass flow rate and the dependent variables represented in a list of temperatures,(1-12 points), were tabulated experimentally as shown in table 1, while the Grashof, Prandtl and Nusselt were calculated.

## 4.2 Calculations of Natural convection heat transfer during heating process

### 4.2.1 Sample calculation

In order to clarify the procedure of calculations of Natural convection heat transfer during heating process, sample test of water flow rate = 1 l/min at 20 min was selected. The radiation from the panel was calculated and subtracted from the total value of heat transferred.

Tests of 1 l/min were done and the measured temperatures are located in Table 2

**Table 2**: Experimental data for heating process at 1 l/min

| Heating process at 1 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^{o}$C) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 53.0 | 54.8 | 56.2 | 57.2 | 58.2 | 59.4 | 61.4 | 61.8 | 62.2 |
| 2 | 49.7 | 51.3 | 52.8 | 53.7 | 54.8 | 55.7 | 57.6 | 58.0 | 58.4 |
| 3 | 26.6 | 27.0 | 29.5 | 30.0 | 30.3 | 31.3 | 33.0 | 33.9 | 34.8 |
| 4 | 25.9 | 27.5 | 30.0 | 30.0 | 31.0 | 31.8 | 33.3 | 33.9 | 34.7 |
| 5 | 31.6 | 33.2 | 35.0 | 36.2 | 36.9 | 38.0 | 39.5 | 40.1 | 40.8 |
| 6 | 19.1 | 19.5 | 20.7 | 21.5 | 22.4 | 23.2 | 24.8 | 25.3 | 25.8 |
| 7 | 18.2 | 19.5 | 20.8 | 21.6 | 22.3 | 23.3 | 24.8 | 25.4 | 25.8 |
| 8 | 18.3 | 19.8 | 20.8 | 21.6 | 22.4 | 23.2 | 24.8 | 25.4 | 25.8 |
| 9 | 18.5 | 19.5 | 20.8 | 21.7 | 22.5 | 23.3 | 24.9 | 25.3 | 25.9 |
| 10 | 18.7 | 19.6 | 20.9 | 21.7 | 22.6 | 23.4 | 24.9 | 25.4 | 25.8 |
| 11 | 18.4 | 19.3 | 20.8 | 21.5 | 22.5 | 23.3 | 24.8 | 25.5 | 25.9 |
| 12 | 19.0 | 19.9 | 21.2 | 22.3 | 23.3 | 24.1 | 26.6 | 26.1 | 26.5 |

All points inside the box have a regular rate of $\frac{dT}{dt}$, and that can be shown from the beginning of the experiment at the first 5 min since we have a good adiabatic system.

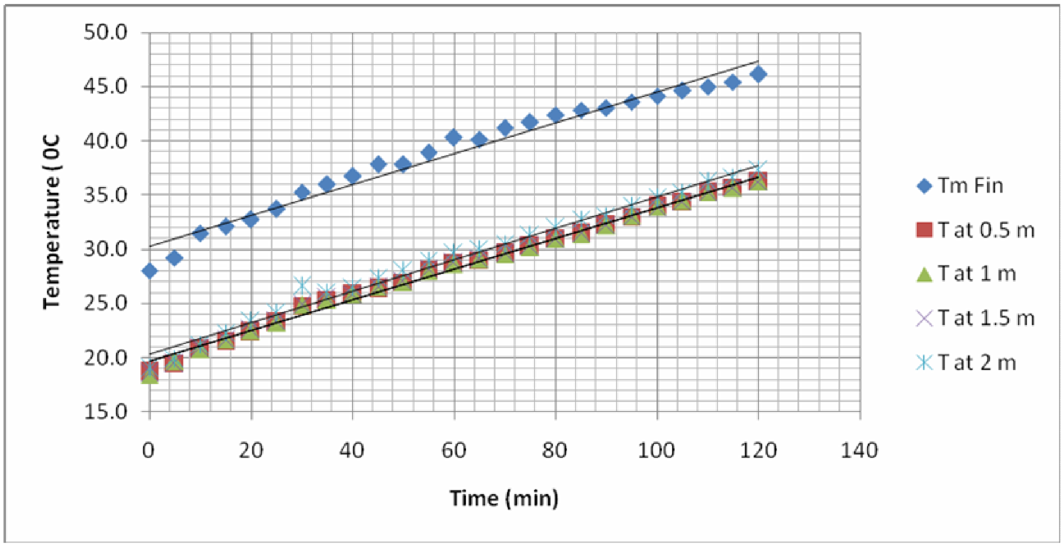

**Fig. 6:** behavior of system temperatures at heating process for 1 l/min.

### 4.2.2 Properties

The properties of air are taken at the air bulk temperature. Table 3 shows the needed air properties for calculations.

**Table 3**: properties of air

| Temperature -T- ($^0$C) | Density -ρ- (kg/m$^3$) | Specific heat capacity -$c_p$- (kJ/kg K) | Thermal conductivity -k- (W/m k) | Kinematic viscosity -v- (m$^2$/s)x10$^6$ | Expansion coefficient -β- (1/K) x 10$^{-3}$ |
|---|---|---|---|---|---|
| 20 | 1.205 | 1.005 | 0.0257 | 15.11 | 3.43 |
| 40 | 1.127 | 1.005 | 0.0271 | 16.97 | 3.20 |

The range of temperature between 20 $^o$C and 40 $^o$C was used; Appendix B shows the calculated properties at each temperature at the experiments.

## 4.2.3 Analysis

Mathematical analysis was carried out for the both modes of heat transfer from the radiant panel, (radiation and convection). The amount of heat transfer by radiation was calculated and subtracted from the total heat transfer value.

### A. Radiation Heat Transfer

Using Stefan Boltzman Equation for calculating radiation heat transfer as follows:

$$q_r = \sigma\, F_r\, (T_p^4 - T_r^4)\ .\ A_P \qquad (4.1)$$

Where:

$\sigma$= Stefan-Boltzman constant = 5.67*10^-8 W/m$^2$.K$^4$.

$F_r$= radiation exchange factor (dimensionless)

$T_P$= effective temperature of heated (cooled) panel surface.

$T_r$= temperature of factious surface (unheated or uncooled) K, that is given by

$$T_r = \frac{\sum_{j \neq P}^{n} A_j \varepsilon_j T_j}{\sum_{j \neq P}^{n} A_j \varepsilon_j} \qquad (4.2)$$

$A_j$= area of surfaces other than panel.

$\varepsilon_j$= thermal emittance other than panel.

But it can be generalized, when the emittances of an enclosure are nearly equals and the surfaces exposed to the panel are marginally unheated or uncooled ($T_r$ =AUST=average unheated (uncooled) surface temperature).

$$F_r = \frac{1}{\frac{1}{F_{P-r}} + \left(\frac{1}{\varepsilon_P - 1}\right) + \frac{A_P}{A_r}\left(\frac{1}{\varepsilon_r} - 1\right)} \qquad (4.3)$$

Where:

$F_{p\text{-}r}$ = radiation angle factor from panel to factious surface (1.0 for flat surface)

$A_p$, $A_r$= area of panel surface and factious surface, respectively.

$\varepsilon_r$, $\varepsilon_p$ = thermal emittance of panel surface and factious surface, respectively.

Assuming $F_r$=1 for the test box because an enclosure volume was used, then

$$q_r = 5.67 \times 10^{-8} \left[ (T_P + 273)^4 - (AUST + 273)^4 \right] A_p \tag{4.4}$$

Values apply for ceiling, floor and wall panel output.

$T_P$ = effective panel surface temperature (°C).

AUST = area weighted uncooled surface temperature, to be taken at the middle of the box at 1 m height.

Starting sample calculations with equation (4.4) and from Table 2 at 20 min, the mean effective panel surface temperature can be calculated from the 3 thermocouples temperature readings, to get $T_P$ = 32.7 °C.

The area weighted uncooled surface temperature AUST = 22.5 °C.

Substituting in the equation we get

$$q_r = 5.67 \times 10^{-8} \left[ (32.7 + 273)^4 - (22.5 + 273)^4 \right] *0.36/1000$$

The area of the panel is 0.36 $m^2$.

Then $q_r$ = 0.02281 kW

This value will be subtracted from the total heat transferred.

## B. Natural Convection Heat Transfer

To calculate the natural convection heat transfer, it is necessary to calculate the total heat transfer from the radiant panel. This can be done by measuring the difference between supply and return water temperatures and using the equation below

$$Q = m\ C_p\ (T_o - T_i) \tag{4.5}$$

Where:

Q: total heat transfer (kW).

m:  water mass flow rate (kg/s).

$C_p$: water specific heat (kJ/kg.K).

$T_o$: water outlet temperature (°C).

$T_i$: water inlet temperature (°C).

Substituting values at the sample state in the equation we get $T_o - T_i = 3.4\ ^{o}C$, m= 0.01667 kg/s and for water $C_p$= 4.18 kJ/kg.K, we get:

Q = 0.23687 kW

Since $Q = q_r + q_c$, removing the value of radiation heat from the total heat will present the natural convection heat value.

$q_c$ = 0.23687-0.02281 = 0.21406 kW.

## C. Correlation Parameters

In the natural convection situation, the main equations must have the form of Nu = function (Gr, Pr). In this research the assumed correlation will have the form of:

$$Nu = c\ (Gr)^{n}\ (Pr)^{m} \tag{4.6}$$

Where:

Nu: Nusselt number.

Gr: Grashof number.

Pr: Prandtl number.

c: equation constant , n, m: are exponents .

To solve this equation, we use the experiment results. Three different values of water mass flow rate were used to get three different experiments.

Then we have equation 4.6 in the logarithmic form as

$$\ln(Nu) = \ln(c) + n \ln(Gr) + m \ln(Pr) \tag{4.7}$$

With three values for Nu, Gr and Pr the equation can be solved for c, m and n.

Starting calculations with Nusselt No. from equation below:

$$Nu = \frac{hL}{k} \tag{4.8}$$

Where:

h: the convection heat transfer coefficient (W/$m^2$ K)

L: panel length (m).

k: thermal conductivity of air (W/m K).

And making use of convection heat transfer equation

$$h = q_c / (L^2 (T_p - T_a)) \tag{4.9}$$

Where: $T_a$ is the ambient temperature to be taken at the middle at 1 m height temperature. To get

$$Nu = \frac{q_c}{L(T_p - T_a)k} \tag{4.10}$$

Substituting all values in equation 4.10, and making sure that all air properties were taken at bulk temperature, and k=0.02623 W/m K and finally

$$Nu = \frac{0.21406 * 1000}{0.6.(32.7 - 22.5).0.02623} = 1333.3$$

Now for Grashof calculations and using the equation below:

$$Gr = \frac{L^3 \rho^2 \beta g \Delta T}{\mu^2} \tag{4.11}$$

$$= \frac{0.6^3 (1.1754)^2 (0.003327)(9.81)(32.7 - 22.5)}{(1.175393 * 1.5816\text{E} - 05)^2} \quad = \quad 290598386.6$$

Finally, calculating Prandtl using the following equation:

$$\Pr = \frac{\mu . c_p}{k} \tag{4.12}$$

With $c_p$ for air to be constant at experiments temperature ranges, $c_p = 1.005$kJ/kg K

Substituting for

$$\Pr = \frac{(1.5816\text{E} - 05 * 1.175393).(1.005) * 1000}{0.026231} = 0.7121$$

For the case air temperature domain changes in Pr were negligible, the equation will change to another form as in equation below:

$$\text{Nu} = \text{k Gr}^{\text{n}} \tag{4.13}$$

Where $\text{k} = \text{c Pr}^{\text{m}}$, and in the logarithmic form

$$\ln(\text{Nu}) = \text{n} \ln(\text{Gr}) + \ln(\text{k}) \tag{4.14}$$

# CHAPTER 5

# COOLING EXPERIMENTAL WORK

## 5.0 Introduction

This chapter contains the test procedure, sample calculation, analysis for radiation, natural convection heat transfer and some correlation parameters for cooling mode.

## 5.1 Test procedure

The radiant panel was cooled to an average temperature of 17-23 $^{o}$C by connecting the thermo pipe tubes to the chiller water collector, and thus decreasing the temperature of air space inside the test box.

Since the need to change the amount of heat removed from the test box in time periods, varying the mass water flow rate was necessary using the regulating valve, thus making different experiments at different water flow rates 0.2,1 and 2 litter/min.

## 5.2 Calculations of Natural convection heat transfer during cooling process

### 5.2.1 Sample calculation

In order to clarify the procedure of calculations of Natural convection heat transfer during cooling process, sample test of water flow rate = 1 l/min at 20 min was selected. The radiation from the panel was calculated and subtracted from the total value of heat transferred.

Tests of 1 l/min were done and the measured temperatures are located in Table 4

**Table 4**: Experimental data for cooling process at 1 l/min

| Cooling process at 1 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^o$C) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 22.9 | 21.8 | 20.9 | 20.0 | 18.9 | 18.2 | 17.1 | 15.9 | 15.0 |
| 2 | 26.7 | 25.4 | 24.7 | 23.6 | 22.5 | 21.9 | 20.8 | 19.7 | 18.8 |
| 3 | 27.1 | 26.2 | 24.9 | 23.9 | 23.1 | 21.8 | 21.0 | 20.5 | 19.4 |
| 4 | 27.0 | 26.1 | 25.1 | 24.0 | 23.2 | 21.9 | 21.1 | 20.0 | 18.9 |
| 5 | 24.3 | 23.0 | 21.9 | 21.1 | 20.2 | 19.0 | 17.9 | 16.9 | 16.0 |
| 6 | 28.0 | 27.6 | 26.9 | 26.1 | 25.3 | 24.8 | 23.9 | 22.6 | 21.5 |
| 7 | 28.0 | 27.7 | 26.8 | 26.2 | 25.4 | 24.8 | 24.0 | 22.7 | 21.6 |
| 8 | 27.9 | 27.6 | 26.8 | 26.2 | 25.4 | 24.8 | 24.0 | 22.7 | 21.6 |
| 9 | 28.0 | 27.6 | 26.9 | 26.1 | 25.3 | 24.9 | 23.9 | 22.6 | 21.7 |
| 10 | 28.1 | 27.6 | 26.8 | 26.1 | 25.4 | 24.9 | 24.0 | 22.6 | 21.7 |
| 11 | 28.1 | 27.7 | 26.8 | 26.1 | 25.5 | 24.8 | 24.0 | 22.5 | 21.5 |
| 12 | 27.7 | 27.2 | 26.2 | 25.3 | 24.6 | 24.1 | 23.3 | 21.9 | 20.8 |

All points inside the box have a regular rate of $\frac{dT}{dt}$, and that can be shown from the beginning of the experiment at the first 5 min since we have a good adiabatic system.

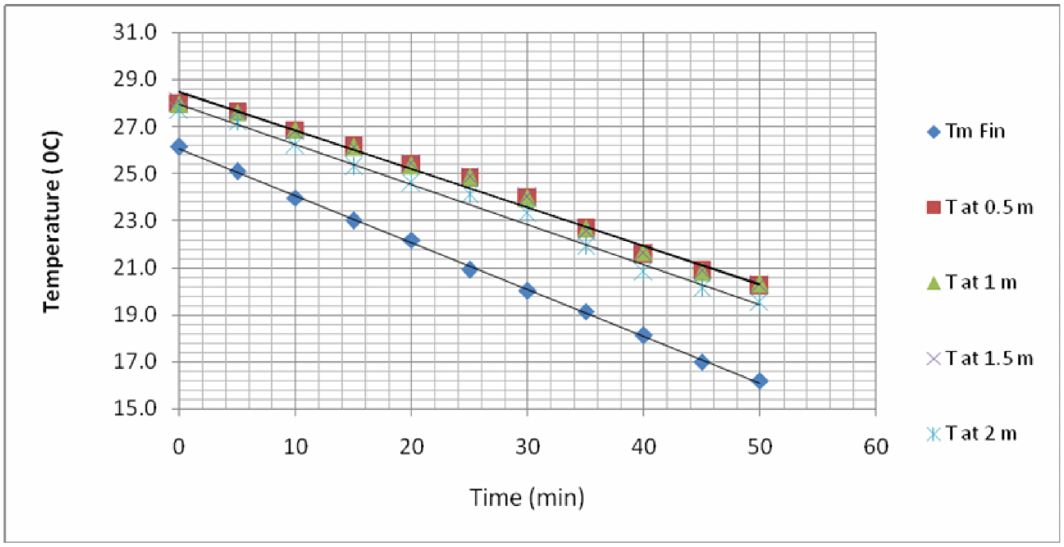

**Fig. 7:** behavior of system temperatures for cooling process at 1 l/min.

### 5.2.2 Properties

The properties of air are taken at the air bulk temperature. Table 3 shows the needed air properties for calculations. The range of temperature between 20 $^{o}$C and 40 $^{o}$C will be used; Appendix B shows the calculated properties at each temperature at the experiments.

### 5.2.3 Analysis

Mathematical analysis was carried out for the both modes of heat transfer from the radiant panel, (radiation and convection). The amount of heat transfer by radiation was calculated and subtracted from the total heat transfer value.

### A. Radiation Heat Transfer

Using Stefan Boltzman Equation for calculating radiation heat transfer as in heating mode and from Table 4 at 20 min, the mean effective panel surface temperature can be calculated from the 3 thermocouples temperature readings, to get $T_P = 22.2\,^{o}C$.

The area weighted uncooled surface temperature AUST = $25.4\,^{o}C$.

Substituting in the equation we get

$$q_r = 5.67\times10^{-8}\left[(22.2+273)^4-(25.4+273)^4\right]*0.36/1000$$

The area of the panel is 0.36 $m^2$.

Then $q_r = 0.0068$ kW

This value will be subtracted from the total heat transferred.

### B. Natural Convection Heat Transfer

To calculate the natural convection heat transfer, it is necessary to calculate the total heat transfer from the radiant panel. This can be done by measuring the difference between supply and return water temperatures and using equation below:

$$Q = m\,C_p\,(T_o - T_i) \qquad (5.5)$$

Where:

Q: total heat transfer (kW).

m: water mass flow rate (kg/s).

$C_p$: water specific heat (kJ/kg.K).

$T_o$: water outlet temperature ($^{o}C$).

$T_i$: water inlet temperature ($^{o}C$).

Substituting values at the sample state in the equation we get $T_o - T_i = 3.6\,^{o}C$, m= 0.01667 kg/s and for water $C_p$= 4.18 kJ/kg.K, we get:

Q = 0.251302 kW

Since Q = $q_{r}$ + $q_c$ , removing the value of radiation heat from the total heat will present the natural convection heat value.

$q_c$ = 0.251302-0.0068 = 0.2445 kW.

### C. Correlation Parameters

The same form used in heating mode will be used in cooling mode**.** Starting calculations with Nusselt from equation below:

Substituting all values in equation 4.10, and making sure that all air properties were taken at bulk temperature, then k=0.025963 W/m K and finally

$$Nu = \frac{0.2445 * 1000}{0.6.(25.4 - 22.2).0.025963} = 4930$$

Now for Grashof calculations and using the equation 4.11:

$$\text{Gr} = \frac{0.6^3 (1.200343)^2 (0.00337)(9.81)(25.4 - 22.2)}{(1.200343 * 1.55095\text{E} - 05)^2} \quad = \quad 94494157.6$$

Finally, calculating Prandtl using the following equation 4.12, with $c_p$ for air to be constant at experiments temperature ranges, $c_p$ = 1.005 kJ/kg K

Substituting for

$$\text{Pr} = \frac{(1.5816\text{E} - 05 * 1.175393).(1.005) * 1000}{0.026231} = 0.7121$$

# CHAPTER 6

# RESULTS AND DISCUSSION

## 6.0 Introduction

This chapter contains the experimental results for both modes (heating and cooling), the final results of this research with new correlations and the uncertainty analysis.

## 6.1 Heating mode results

Three experiments were conducted with different water flow rates (0.2, 1.0 and 2 l/min). All tests data and calculated parameters are tabulated and shown in Appendix B. All parameters are calculated at different experiments, the experimental relation between Nu and Gr can be shown in figures 8, 9 and 10.

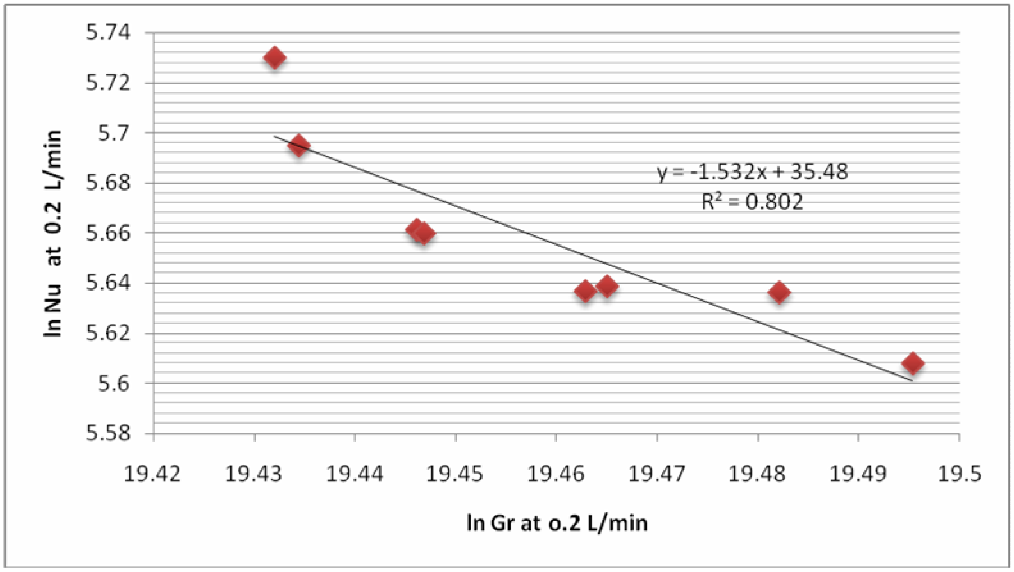

**Fig. 8:** Experimental relation between Nu and Gr at 0.2 l/min water flow rate and constant Pr=0.7121 for heating.

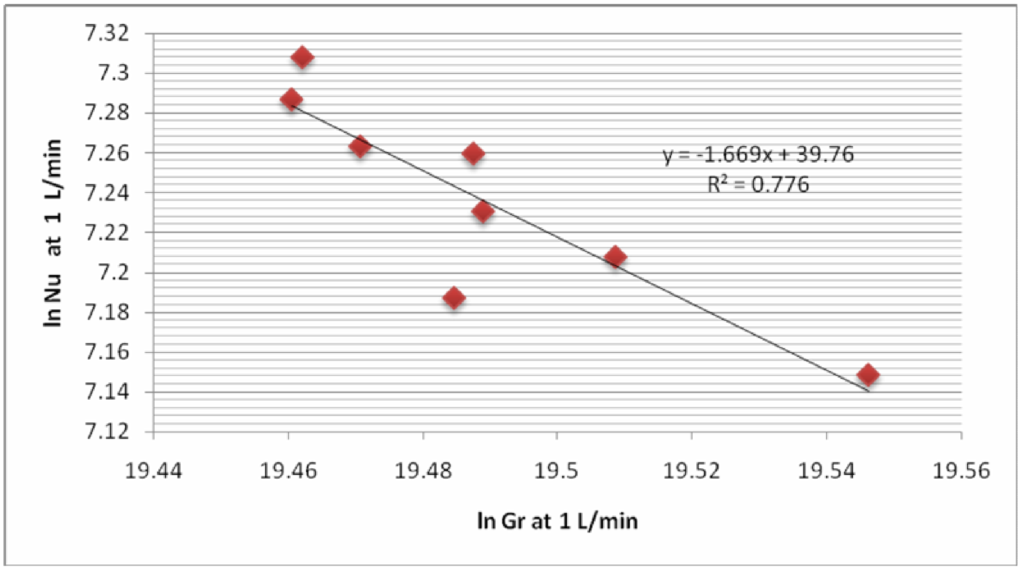

**Fig. 9:** Experimental relation between Nu and Gr at 1 l/min water flow rate and constant Pr=0.7121 for heating.

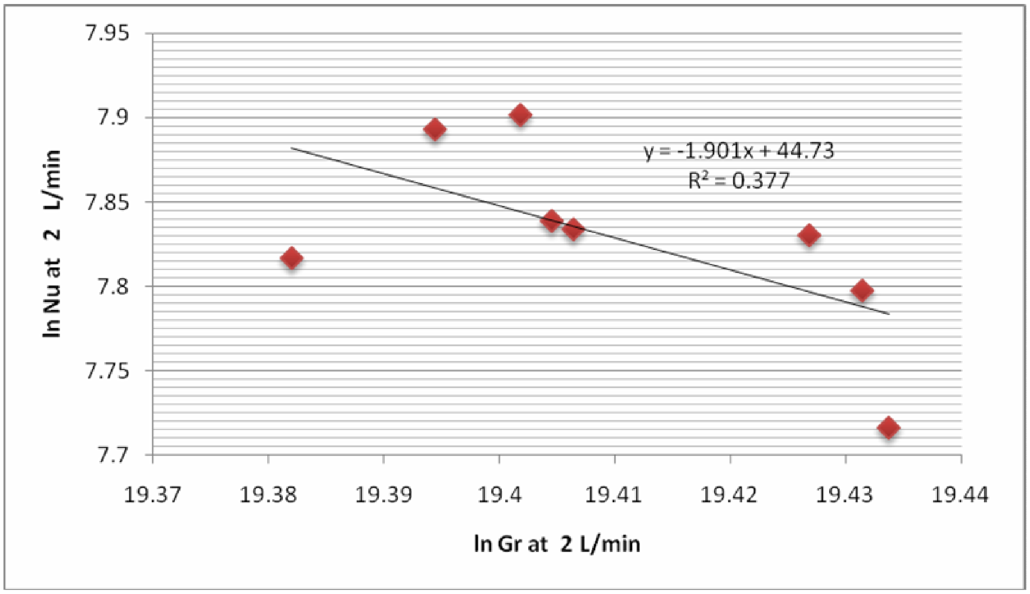

**Fig. 10:** Experimental relation between Nu and Gr at 2 l/min water flow rate and constant Pr=0.7121 for heating.

### 6.1.1 Correlation constants

Having the equations of best fit line for experimental parameters, we can solve the equations for k and n to get:

$$n = \frac{^{-}1.9 + ^{-}1.669 + ^{-}1.53}{3} \quad = -1.7$$

$$\ln k = \frac{44.73+39.76+35.48}{3} \quad = 40$$

$$k = 2.3 \text{ x } 10^{17}$$

Finally, the equation for a single heating radiant panel at floor position within temperature ranges for air between 20°C and 32 °C will be:

$$Nu = \mathbf{2.3\ x10^{+17}}\ (Gr)^{\mathbf{-1.7}} \qquad (6.1)$$

## 6.2 Cooling mode results

Three test experiments were done with different water flow rates (0.2, 1.0 and 2 l/min), all tests data and calculated parameters were tabulated as shown in Appendix B.

All parameters are calculated at different experiments, the experimental relation between Nu and Gr can be shown in figures 12, 13 and 14.

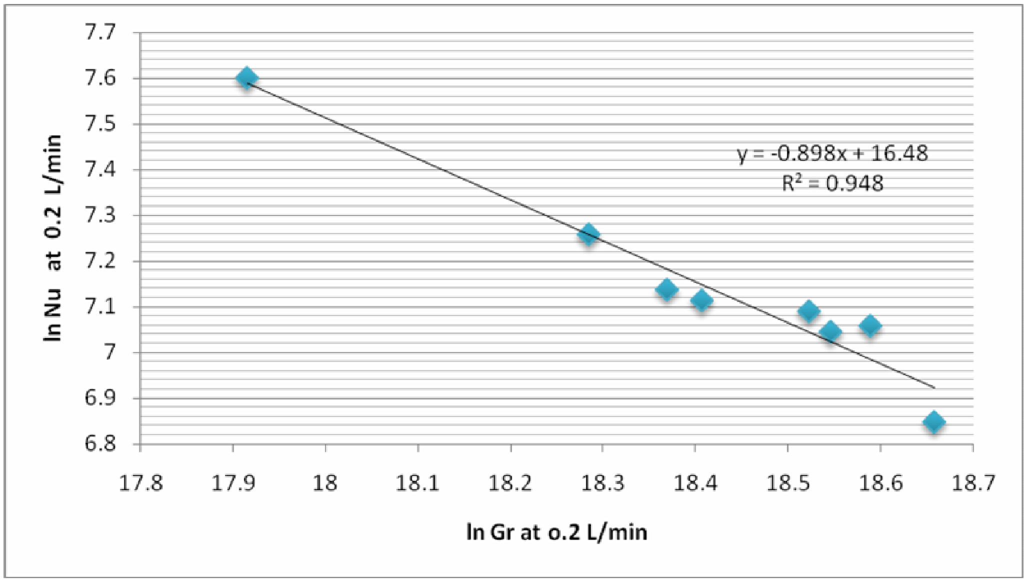

**Fig. 12:** Experimental relation between Nu and Gr at 0.2 l/min water flow rate and constant Pr=0.7121 for cooling.

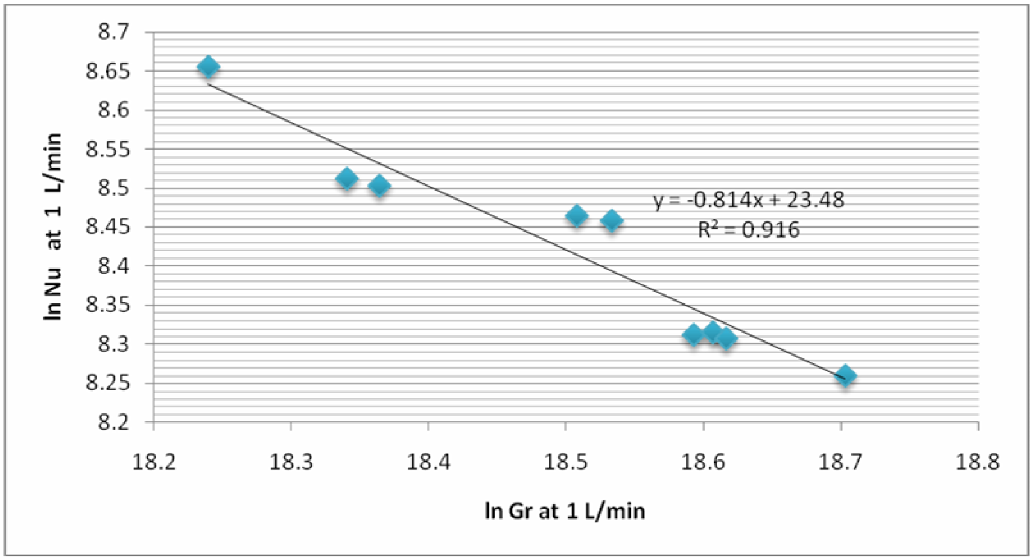

**Fig. 13:** Experimental relation between Nu and Gr at 1 l/min water flow rate and constant Pr=0.7121 for cooling.

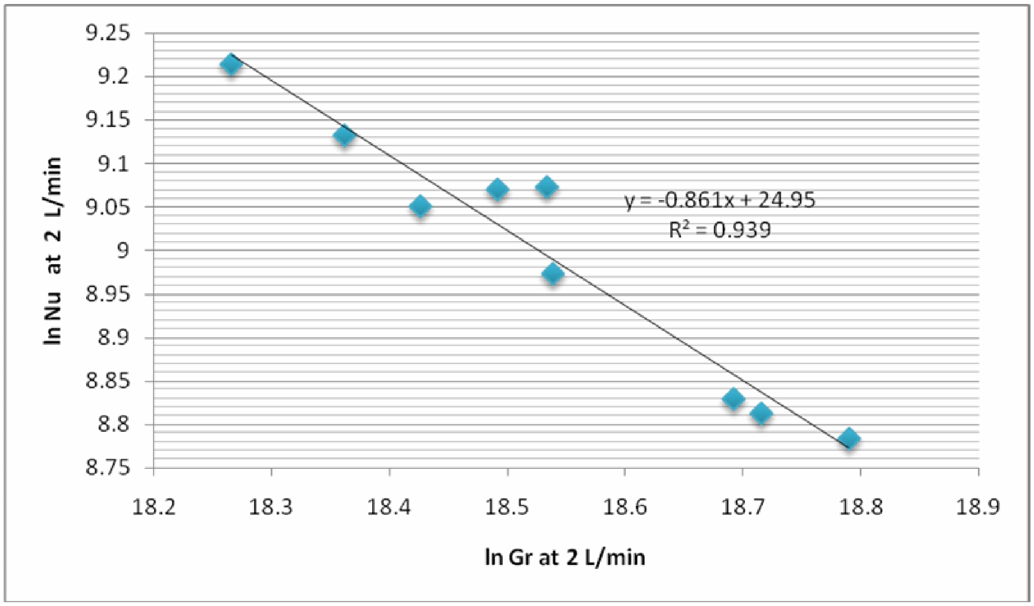

**Fig. 14:** Experimental relation between Nu and Gr at 2 l/min water flow rate and constant Pr=0.7121 for cooling.

### 6.2.1 Correlation constants

Having the equations of best fit line for experimental parameters, we can solve the equations for k and n to get:

$$n = \frac{{}^{-}0.861 + {}^{-}0.814 + {}^{-}0.898}{3} = -0.86$$

$$\ln k = \frac{24.95+23.48+16.48}{3} = 21.6$$

$k = 2.5 \times 10^{9}$

Finally, the equation for a single cooling radiant panel at ceiling position within temperature ranges for air between 20°C and 28 °C will be:

$$Nu = \mathbf{2.5 \times 10^{9}}\,(Gr)^{\mathbf{-0.86}} \tag{6.2}$$

## 6.3 Correlation Validation

In this part, the relation of Nusselt number with Grashof number is calculated using the evolved correlation and compared with those calculated using the experimental data.

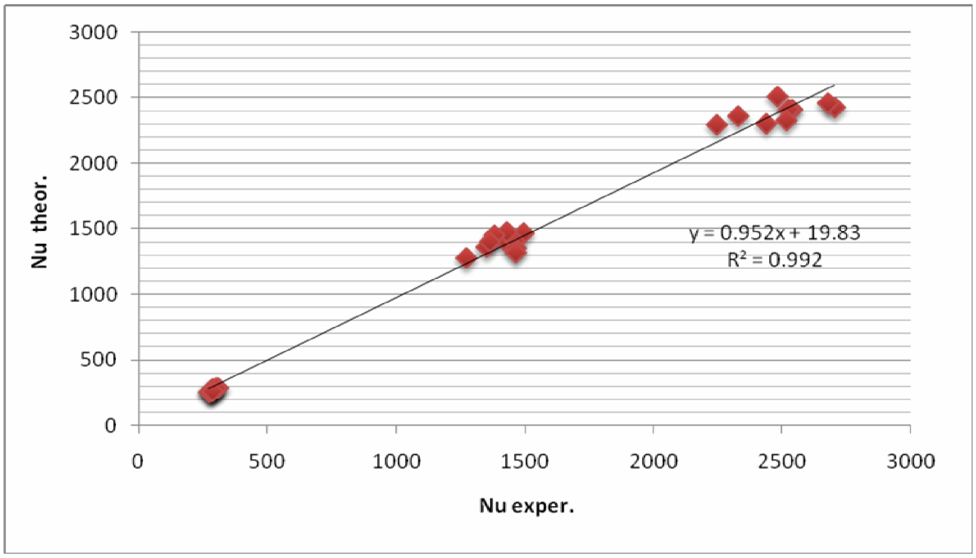

**Fig. 16:** Nu analytical vs. Nu experimental for heating validating equation.

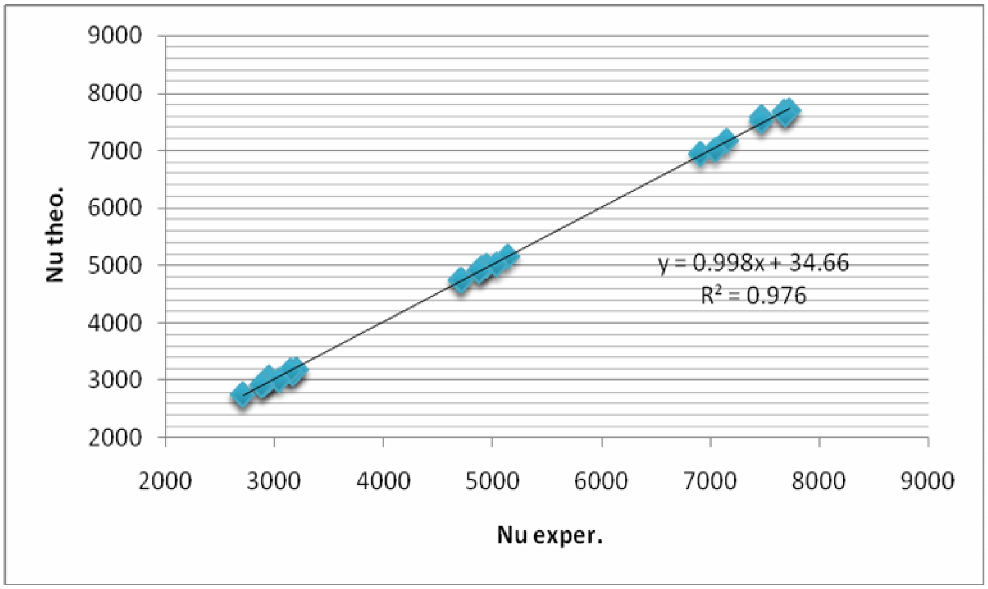

**Fig. 17:** Nu analytical vs. Nu experimental for cooling validating equation.

There is a close similarity in Nu between experimentally calculated values and those calculated using the empirical formulae.

As seen from figure 16 and 17, for fitting it is clear that $R^2$ = 0.976 and 0.992 which indicates that 97.6 and 99.2 percent of the original uncertainty for cooling and heating respectively has been explained by the linear model.

The accuracy refers to how closely a computed value agrees with the measured value. The inaccuracy (also called bias) of our measured and calculated values can be calculated as follows:

$$\text{Bias error } (\%) = [\Sigma \, ((Nu_{\text{analytical}} - Nu_{\text{exp}}) / Nu_{\text{exp}}) * 100] / N \qquad (6.3)$$

Where N is the number of data points.

The Bias error (%) = 0.32 % for cooling.

And the Bias error (%) = 0.41 % for heating.

While the Absolute Average Deviation (AAD);

$$\text{AAD} = [\Sigma \, | \, ((Nu_{\text{analytical}} - Nu_{\text{exp}}) / Nu_{\text{exp}}) | * 100] / N \qquad (6.4)$$

AAD = 3.75 % for cooling.

And AAD = 4.3 % for heating

Obviously, form the above mentioned three criteria's it can be seen that the correlation for finding Nusselt number during heating and cooling reveals a good fit with those values that were determined experimentally.

## 6.4 Comparison of this work results with other works

Works in literature used different formulae validation to calculate the heat transfer coefficient and the Nusselt number. These results were compared with the results as sown in figure 18, 19.

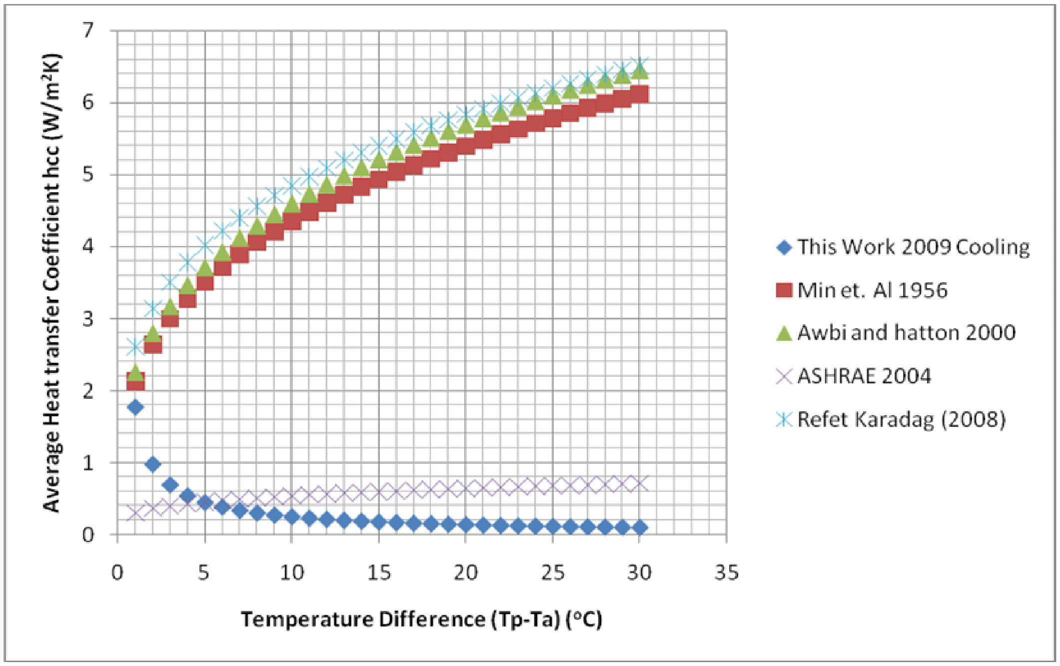

**Fig. 18:** average heat transfer coefficient vs. temperature difference for cooling comparison.

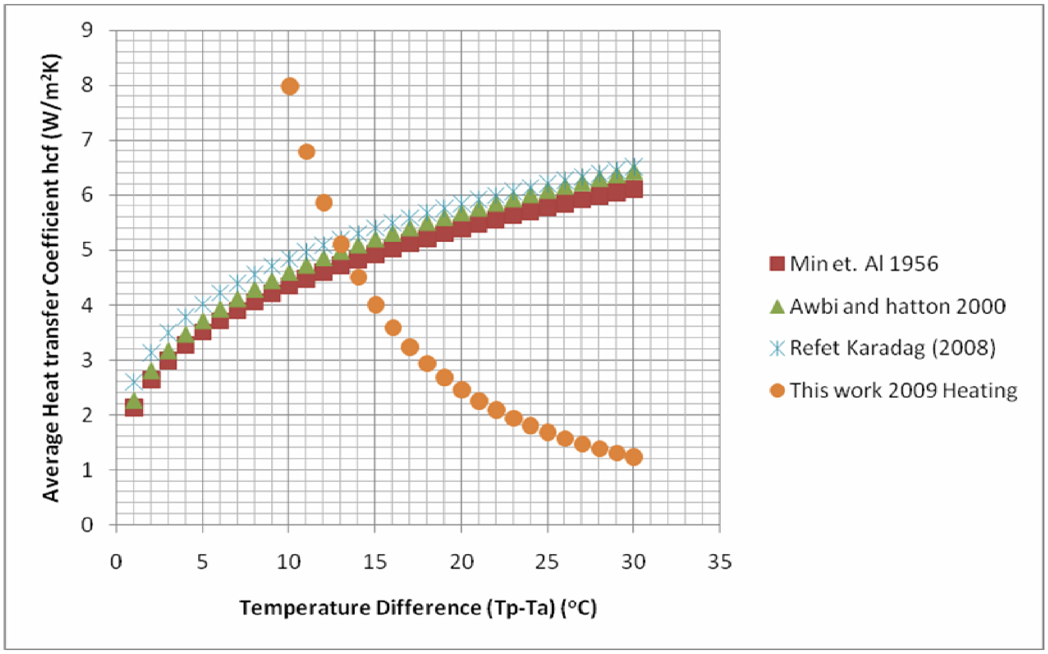

**Fig. 19:** average heat transfer coefficient vs. temperature difference for heating comparison.

This work correlation values as shown in figure 18 gives results closely compared to those of ASHRAE results, and they are far away from those published by Min el al, (1956), Awbi and Hatton, (2000) and Karadag, (2008), this indicates that results of this work is accurate. ASHRAE used only ΔT as a variable, while this work used both ΔT and Gr as variables.

Figure 19 shows more accurate values than those published by those published by Min el al, (1956), Awbi and Hatton, (2000) and Karadag, (2008), because of the use of ΔT and Gr as variables.

## 6.5 Uncertainty analysis

### 6.5.1 Experimental errors

Experimental tests are used for engineering analysis and design and carried out using different apparatus and laboratory instrumentation tools. The validity of the experimental data is very necessary and can be achieved by the trust in the accuracy of used apparatus, the measuring procedure or the trust in the experiments.

However, measurement of the physical quantity has a meaning and two main informations should be established: the numerical value (magnitude) of required quantity and the amount of uncertainty. The amounts of these uncertainties are called the experimental errors.

### 6.5.2 The main causes of experimental errors

The real errors in experimental data are those factors that always carry some amount of uncertainty, so it is better to mention experimental uncertainty instead of experimental error because the magnitude of error is always uncertain. Among these causes we have:

1- The resolution uncertainty which gives a simple approximation of the error by assuming that the uncertainty in the measurement of any physical quantity measured by any measuring device equal to the half of the smallest scale on this device. In this research there is two measuring devices to measure water flow rate and half the smallest scale is equal to 0.1 l/min, the other device is to measure temperatures and half the smallest scale is equal to 0.05 °C.

2- Reading uncertainty: knowing the uncertainty in final results due to uncertainty in primary measurements can be done by the logic and a common sense analysis.

3- Calibration uncertainty: calibration should be carried out for the measuring devices and instrumentation in advance with a standard instrument which has high accuracy. A calibration allows decomposition of the total error of a measurement process into two Parts, the bias and the imprecision. Once the instrument has been calibrated, the bias error (also called the systematic error) can be removed, and the only remaining error is that due to imprecision (also called random error or non repeatability). In this work the K-type thermocouples were calibrated.

The uncertainty in the result is computed according to the relation presented by Kline and McClintock to the first order using a root-sum-square of the product of the uncertainties in the measured variables and the sensitivities of the result to change in that variable:

$$W_r = [(\frac{\partial R}{\partial X_1} W_{X1})^2 + (\frac{\partial R}{\partial X_2} W_{X2})^2 + \ldots\ldots.. + (\frac{\partial R}{\partial X_j} W_{Xj})^2]^{1/2} \qquad (6.5)$$

Where;

$W_r$ is the uncertainty in the result

$W_j$ is the uncertainty in each basic measurement

And the Partial derivatives $\frac{\partial R}{\partial X_j}$ are the sensitivity coefficients which determined the sensitivities of the calculated Parameters to small changes in each of the input Parameters.

Thus, this method gives a straight forward procedure to determine the fidelity of the systems computations.

In order to apply the general uncertainty analysis approach as described on the average convective heat transfer coefficient, the relationship of this coefficient in terms of the process variables are stated as follows:

$$\text{Nu} = \text{Nu}\,(\text{T}, \dot{V}) \qquad (6.6)$$

The error depends on the accuracy of previously mentioned measuring variables, so the uncertainty of Nusselt number can be calculated as follows:

$$\text{W}_{\text{Nu}} = [(\frac{\partial Nu}{\partial T} W_T)^2 + (\frac{\partial Nu}{\partial V} W_V)^2]^{1/2} \qquad (6.7)$$

In order to calculate the uncertainty of the extracted results, one sample point will be considered as a testing point of uncertainty,

T=25 ±0.05 $^{\text{o}}$C

V= 0.0167 ± 0.00167 L/s

Then the uncertainty according to equation mentioned above will be

$$\text{dNu}=[(\frac{0.05}{25})^2 + (\frac{0.00167}{0.0167})^2]^{1/2} = \pm 0.1$$

Nusselt number uncertainty is written in the following order:

Nu= Nu ± 0.1

This gives an error of around average value of 0.01%.

# CHAPTER 7

# CONCLUSIONS

1- Radiant cooling and heating panels can be used in air conditioning building sector with more accurate design calculations and Energy savings.

2- The Nusselt number decreases when increasing the Grashof number in both heating and cooling modes.

3- The Nusselt number is highly sensitive for small changes of ambient temperature and water flow rate.

4- Grashof number in cooling operating mode ranged from $0.5 \times 10^8$ to $1.5 \times 10^8$, while in heating operating mode ranged from $1.5 \times 10^8$ to $3 \times 10^8$.

5- Changing the operating system temperatures and water flow rate will view highly changes in the equation parameters, so these correlations are for the operating parameters in reality uses, and out of these ranges the natural convection profile will have other different correlations.

6- For heating processes, an empirical correlation was developed for the natural convective heat transfer, as shown in equation (6.1). This correlation was proved to be highly accurate with the bias error = 0.41 % and AAD = 4.3 %.

7- For cooling processes, an empirical correlation was developed for the natural convective heat transfer, as shown in equation (6.2). This correlation was proved to be also highly accurate with the bias error = 0.32 % and AAD = 3.75 %.

8- The Nusselt number increased with increasing of the heat flux, while decreased with increasing the Grashof number.

9- The effect of radiation heat transfer in heating process was more than that in cooling process.

10- Exhibiting the new correlations in one figure as shown in figure 20. It can be shown that both modes are different in profiles, and each process has its own equation.

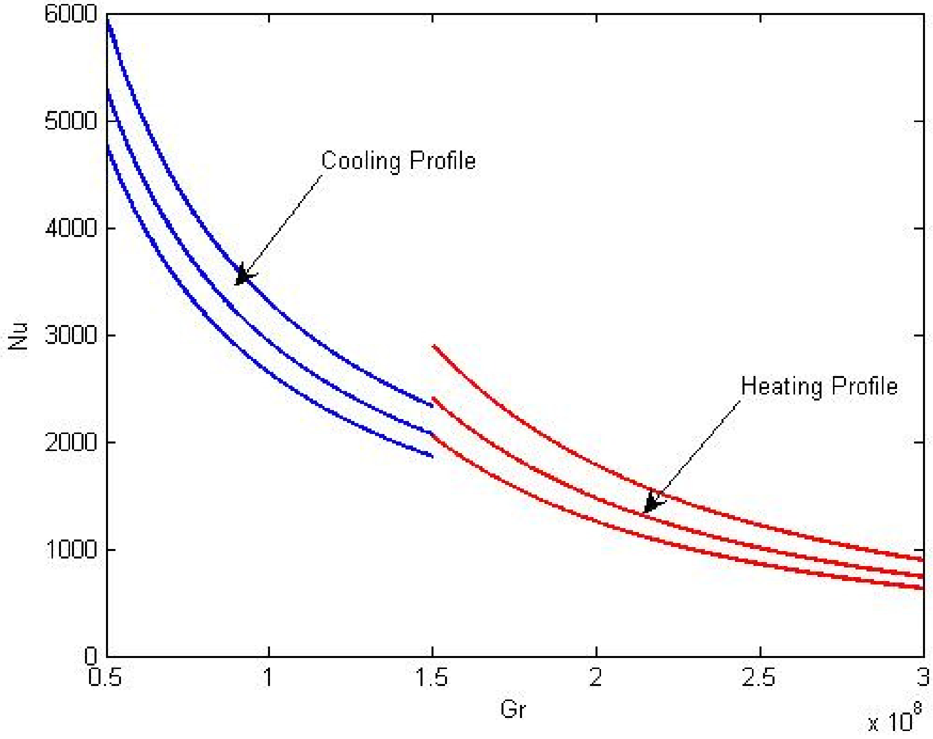

**Fig. 20:** heating and cooling new correlation profiles.

# CHAPTER 8

# RECOMMENDATIONS

Based on the results of this study, the following recommendations for future works may be stated:

1- Intensive study may be conducted and focused on introducing radiation effect in the colorations.

2- Advanced study can use the experimental correlations of this research and solving for other ranges using numerical techniques.

3- Study of combined (forced and natural) convection heat transfer. Using the recent correlations,

4- Study of the effect of water mass flow rate and varying with different ranges of temperatures.

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## APPENDIX A

1- Tests temperature tables with different water flow rate and figures show the behavior of system at heating and cooling.

**Table 5**: Experimental data for heating process at 0.2 l/min

| Heating process at 0.2 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^o$C) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 52.9 | 54.1 | 55.3 | 56.3 | 57.8 | 58.5 | 59.3 | 60.1 | 60.8 |
| 2 | 48.1 | 49.5 | 50.7 | 51.6 | 52.8 | 53.6 | 54.3 | 55.0 | 55.6 |
| 3 | 26.1 | 27.5 | 27.5 | 28.6 | 30.1 | 30.6 | 32.0 | 32.2 | 33.5 |
| 4 | 28.2 | 29.0 | 29.5 | 30.7 | 32.0 | 33.1 | 33.8 | 34.5 | 35.1 |
| 5 | 32.4 | 33.3 | 34.2 | 35.4 | 37.0 | 37.8 | 38.4 | 39.1 | 39.7 |
| 6 | 19.5 | 20.0 | 20.8 | 21.6 | 23.3 | 23.6 | 24.2 | 25.1 | 25.4 |
| 7 | 19.3 | 20.0 | 20.6 | 21.7 | 23.3 | 23.6 | 24.2 | 25.2 | 25.4 |
| 8 | 19.4 | 20.0 | 20.8 | 21.9 | 23.2 | 23.5 | 24.4 | 25.0 | 25.4 |
| 9 | 19.3 | 19.9 | 20.8 | 21.7 | 23.2 | 23.7 | 24.3 | 25.2 | 25.3 |
| 10 | 19.4 | 20.4 | 20.7 | 21.7 | 23.3 | 23.6 | 24.4 | 25.2 | 25.3 |
| 11 | 19.3 | 19.9 | 20.8 | 21.6 | 23.2 | 23.7 | 24.3 | 25.0 | 25.3 |
| 12 | 19.8 | 20.6 | 21.5 | 22.3 | 23.9 | 24.5 | 24.9 | 25.6 | 26.0 |

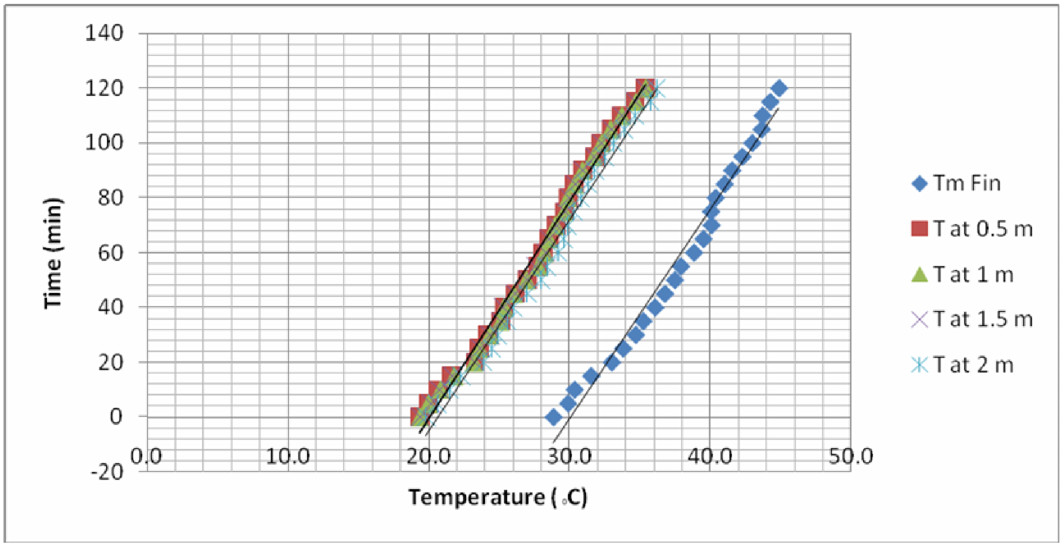

**Fig. 21:** Behavior of system temperatures at heating process for 0.2 l/min.

**Table 6**: Experimental data for heating process at 1 l/min

| Heating process at 1 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^oC$) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 53.0 | 54.8 | 56.2 | 57.2 | 58.2 | 59.4 | 61.4 | 61.8 | 62.2 |
| 2 | 49.7 | 51.3 | 52.8 | 53.7 | 54.8 | 55.7 | 57.6 | 58.0 | 58.4 |
| 3 | 26.6 | 27.0 | 29.5 | 30.0 | 30.3 | 31.3 | 33.0 | 33.9 | 34.8 |
| 4 | 25.9 | 27.5 | 30.0 | 30.0 | 31.0 | 31.8 | 33.3 | 33.9 | 34.7 |
| 5 | 31.6 | 33.2 | 35.0 | 36.2 | 36.9 | 38.0 | 39.5 | 40.1 | 40.8 |
| 6 | 19.1 | 19.5 | 20.7 | 21.5 | 22.4 | 23.2 | 24.8 | 25.3 | 25.8 |
| 7 | 18.2 | 19.5 | 20.8 | 21.6 | 22.3 | 23.3 | 24.8 | 25.4 | 25.8 |
| 8 | 18.3 | 19.8 | 20.8 | 21.6 | 22.4 | 23.2 | 24.8 | 25.4 | 25.8 |
| 9 | 18.5 | 19.5 | 20.8 | 21.7 | 22.5 | 23.3 | 24.9 | 25.3 | 25.9 |
| 10 | 18.7 | 19.6 | 20.9 | 21.7 | 22.6 | 23.4 | 24.9 | 25.4 | 25.8 |
| 11 | 18.4 | 19.3 | 20.8 | 21.5 | 22.5 | 23.3 | 24.8 | 25.5 | 25.9 |
| 12 | 19.0 | 19.9 | 21.2 | 22.3 | 23.3 | 24.1 | 26.6 | 26.1 | 26.5 |

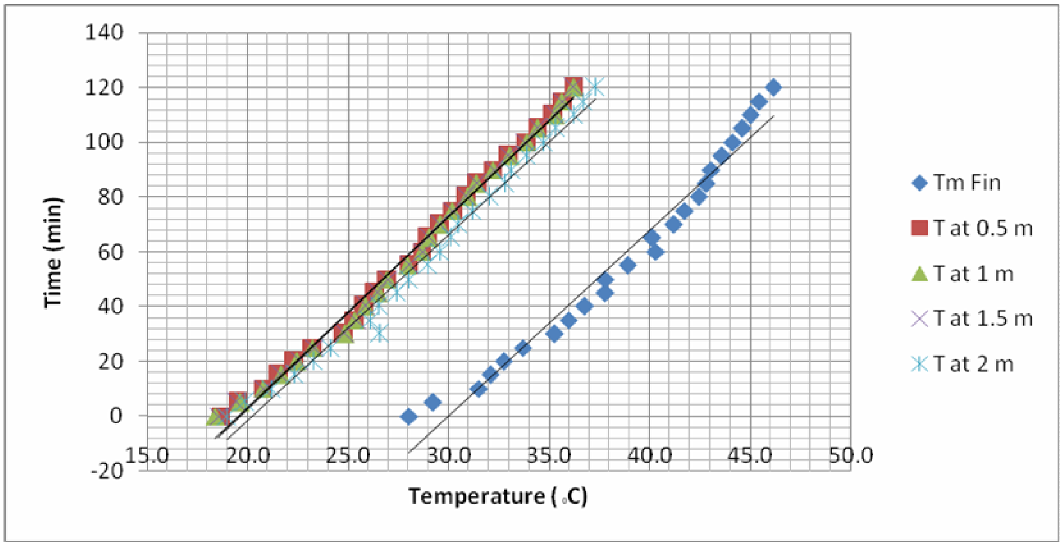

**Fig. 22:** Behavior of system temperatures at heating process for 1 l/min.

**Table 7**: Experimental data for heating process at 2 l/min

| Heating process at 2 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature (°C) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 52.4 | 56.7 | 60.5 | 63.0 | 65.2 | 67.1 | 68.8 | 70.0 | 71.0 |
| 2 | 49.5 | 54.0 | 57.6 | 59.7 | 62.0 | 63.7 | 65.5 | 66.6 | 67.5 |
| 3 | 27.8 | 30.0 | 34.0 | 35.7 | 36.9 | 38.8 | 40.0 | 41.0 | 41.9 |
| 4 | 27.6 | 30.0 | 33.5 | 35.2 | 36.7 | 38.6 | 39.8 | 40.7 | 42.0 |
| 5 | 30.7 | 34.4 | 38.7 | 40.8 | 42.9 | 44.5 | 46.2 | 47.5 | 48.2 |
| 6 | 24.0 | 25.6 | 26.0 | 27.0 | 28.4 | 29.6 | 30.5 | 31.5 | 32.3 |
| 7 | 24.0 | 24.5 | 26.0 | 27.0 | 28.5 | 29.5 | 30.4 | 31.9 | 32.3 |
| 8 | 24.0 | 24.5 | 26.0 | 27.1 | 28.4 | 29.5 | 30.5 | 31.8 | 32.3 |
| 9 | 24.0 | 24.4 | 25.4 | 27.1 | 28.5 | 29.6 | 30.6 | 31.8 | 32.3 |
| 10 | 24.0 | 24.6 | 26.0 | 27.1 | 28.4 | 29.5 | 30.4 | 31.8 | 32.3 |
| 11 | 24.0 | 24.4 | 26.0 | 27.0 | 28.4 | 29.4 | 30.5 | 31.9 | 32.3 |
| 12 | 24.2 | 25.0 | 26.5 | 27.9 | 29.2 | 30.3 | 31.3 | 32.5 | 33.3 |

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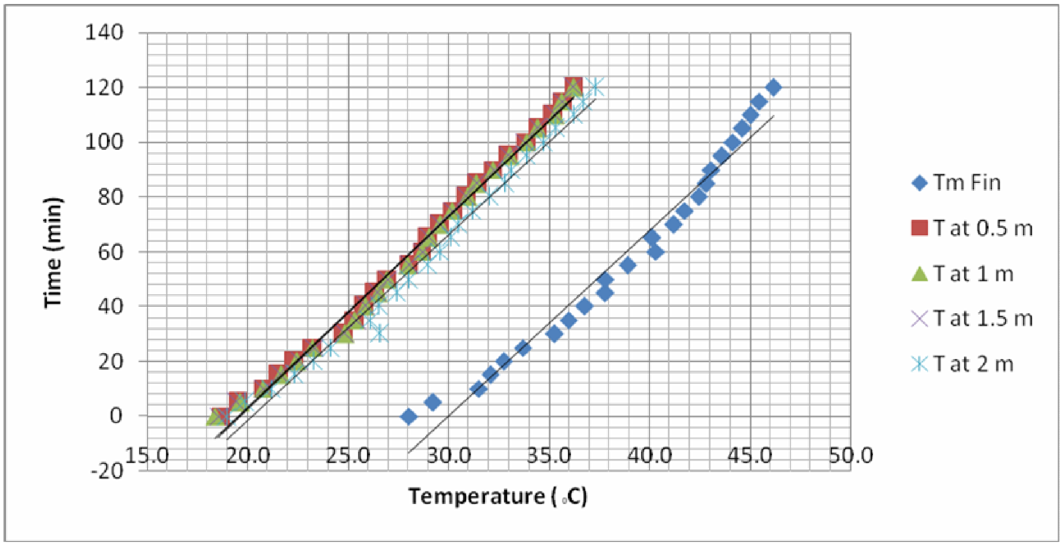

**Fig. 23:** Behavior of system temperatures at heating process for 2 l/min.

**Table 8**: Experimental data for cooling process at 0.2 l/min

| Cooling process at 0.2 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^oC$) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 21.1 | 20.0 | 19.1 | 18.2 | 17.1 | 16.5 | 15.2 | 14.1 | 13.1 |
| 2 | 26.2 | 24.9 | 24.2 | 23.1 | 22.0 | 21.4 | 20.3 | 19.2 | 18.3 |
| 3 | 25.3 | 24.4 | 23.1 | 22.1 | 21.3 | 20.0 | 19.2 | 18.7 | 17.6 |
| 4 | 25.2 | 24.3 | 23.3 | 22.2 | 21.4 | 20.1 | 19.3 | 18.2 | 17.1 |
| 5 | 22.5 | 21.2 | 20.1 | 19.3 | 18.4 | 17.2 | 16.1 | 15.1 | 14.2 |
| 6 | 26.2 | 25.4 | 25.1 | 24.2 | 23.6 | 23.3 | 21.6 | 20.8 | 20.0 |
| 7 | 26.1 | 25.4 | 25.2 | 24.2 | 23.6 | 23.3 | 21.7 | 20.6 | 20.0 |
| 8 | 26.1 | 25.4 | 25.0 | 24.4 | 23.5 | 23.2 | 21.9 | 20.8 | 20.0 |
| 9 | 26.0 | 25.3 | 25.2 | 24.3 | 23.7 | 23.2 | 21.7 | 20.8 | 19.9 |
| 10 | 26.2 | 25.3 | 25.2 | 24.4 | 23.6 | 23.3 | 21.7 | 20.7 | 20.4 |
| 11 | 26.1 | 25.3 | 25.0 | 24.3 | 23.7 | 23.2 | 21.6 | 20.8 | 19.9 |
| 12 | 25.0 | 24.0 | 24.6 | 23.9 | 22.5 | 21.9 | 20.3 | 19.6 | 18.8 |

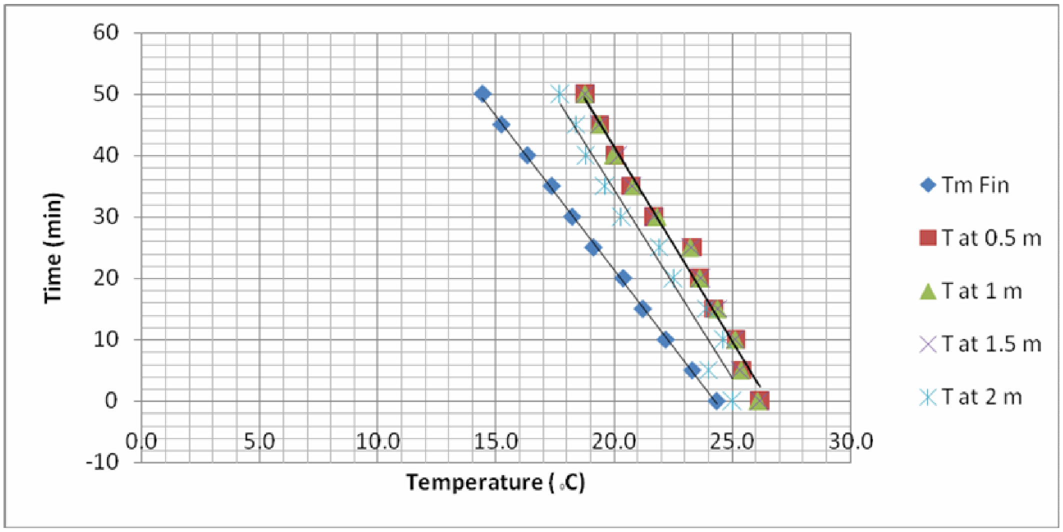

**Fig. 24:** Behavior of system temperatures at cooling process for 0.2 l/min.

**Table 9**: Experimental data for cooling process at 1 l/min

| Cooling process at 1 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^o$C) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 22.9 | 21.8 | 20.9 | 20.0 | 18.9 | 18.2 | 17.1 | 15.9 | 15.0 |
| 2 | 26.7 | 25.4 | 24.7 | 23.6 | 22.5 | 21.9 | 20.8 | 19.7 | 18.8 |
| 3 | 27.1 | 26.2 | 24.9 | 23.9 | 23.1 | 21.8 | 21.0 | 20.5 | 19.4 |
| 4 | 27.0 | 26.1 | 25.1 | 24.0 | 23.2 | 21.9 | 21.1 | 20.0 | 18.9 |
| 5 | 24.3 | 23.0 | 21.9 | 21.1 | 20.2 | 19.0 | 17.9 | 16.9 | 16.0 |
| 6 | 28.0 | 27.6 | 26.9 | 26.1 | 25.3 | 24.8 | 23.9 | 22.6 | 21.5 |
| 7 | 28.0 | 27.7 | 26.8 | 26.2 | 25.4 | 24.8 | 24.0 | 22.7 | 21.6 |
| 8 | 27.9 | 27.6 | 26.8 | 26.2 | 25.4 | 24.8 | 24.0 | 22.7 | 21.6 |
| 9 | 28.0 | 27.6 | 26.9 | 26.1 | 25.3 | 24.9 | 23.9 | 22.6 | 21.7 |
| 10 | 28.1 | 27.6 | 26.8 | 26.1 | 25.4 | 24.9 | 24.0 | 22.6 | 21.7 |
| 11 | 28.1 | 27.7 | 26.8 | 26.1 | 25.5 | 24.8 | 24.0 | 22.5 | 21.5 |
| 12 | 27.7 | 27.2 | 26.2 | 25.3 | 24.6 | 24.1 | 23.3 | 21.9 | 20.8 |

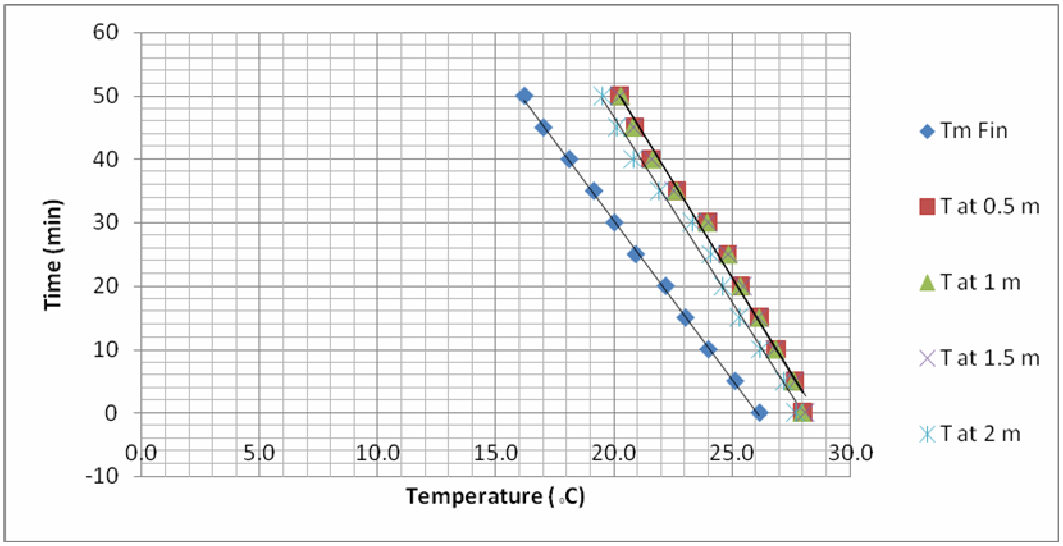

**Fig. 25:** Behavior of system temperatures at cooling process for 1 l/min.

**Table 10**: Experimental data for cooling process at 2 l/min

| Heating process at 2 l/min | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Thermocouple number | Temperature ($^{o}$C) at time (min) | | | | | | | | |
| | 0min | 5min | 10min | 15min | 20min | 25min | 30min | 35min | 40min |
| 1 | 22.5 | 21.4 | 20.4 | 19.5 | 18.5 | 17.9 | 16.6 | 15.4 | 14.3 |
| 2 | 25.8 | 24.6 | 23.7 | 22.8 | 21.7 | 21.2 | 19.8 | 18.7 | 17.7 |
| 3 | 25.9 | 24.7 | 23.5 | 22.5 | 21.7 | 20.3 | 19.6 | 19.4 | 18.2 |
| 4 | 25.9 | 24.4 | 23.5 | 22.7 | 21.6 | 20.4 | 19.5 | 18.4 | 17.6 |
| 5 | 22.8 | 21.3 | 20.8 | 19.6 | 18.9 | 17.3 | 16.7 | 15.5 | 14.8 |
| 6 | 26.5 | 25.9 | 25.5 | 24.7 | 24.0 | 23.7 | 22.0 | 21.2 | 20.4 |
| 7 | 26.5 | 25.8 | 25.6 | 24.7 | 24.0 | 23.7 | 22.1 | 21.0 | 20.4 |
| 8 | 26.5 | 25.9 | 25.4 | 24.8 | 24.0 | 23.6 | 22.3 | 21.1 | 20.4 |
| 9 | 26.4 | 25.8 | 25.6 | 24.7 | 24.1 | 23.6 | 22.1 | 21.2 | 20.3 |
| 10 | 26.6 | 25.9 | 25.6 | 24.8 | 24.1 | 23.7 | 22.1 | 21.1 | 20.4 |
| 11 | 26.5 | 25.9 | 25.4 | 24.7 | 24.1 | 23.6 | 22.2 | 21.2 | 20.3 |
| 12 | 25.4 | 24.4 | 24.9 | 24.4 | 22.8 | 22.3 | 20.7 | 20.1 | 19.2 |

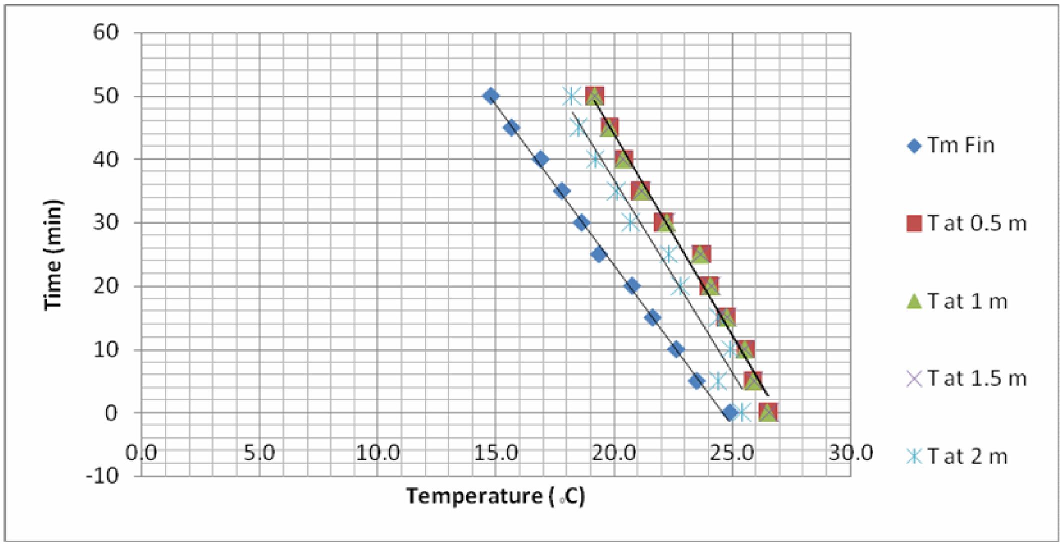

**Fig. 26:** Behavior of system temperatures at cooling process for 2 l/min.

# APPENDIX B

1. Tables of calculated parameters and air properties.

**Table 11**: Calculated parameters for heating process at 0.2 l/min

| Time (minute) | ΔT water | Tm Fin | T at 0.5 m | T at 1 m | T at 1.5 m | T at 2 m | T bulk | Q water(kW) | Qr (kW) | Qc (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 4.6 | 29.9 | 20.0 | 20.0 | 20.2 | 20.6 | 24.9 | 0.06409269 | 0.021564 | 0.042528 |
| 10 | 4.6 | 30.4 | 20.7 | 20.8 | 20.8 | 21.5 | 25.6 | 0.06409269 | 0.020874 | 0.043219 |
| 15 | 4.7 | 31.6 | 21.7 | 21.8 | 21.7 | 22.3 | 26.7 | 0.06548601 | 0.021468 | 0.044018 |
| 20 | 5.0 | 33.0 | 23.3 | 23.2 | 23.3 | 23.9 | 28.1 | 0.06966597 | 0.021926 | 0.04774 |
| 25 | 4.9 | 33.8 | 23.6 | 23.6 | 23.7 | 24.5 | 28.7 | 0.06827265 | 0.022955 | 0.045317 |
| 30 | 5.0 | 34.7 | 24.2 | 24.4 | 24.4 | 24.9 | 29.5 | 0.06966597 | 0.023484 | 0.046182 |
| 35 | 5.1 | 35.3 | 25.2 | 25.1 | 25.1 | 25.6 | 30.2 | 0.07105929 | 0.02314 | 0.047919 |
| 40 | 5.2 | 36.1 | 25.4 | 25.4 | 25.3 | 26.0 | 30.7 | 0.07245261 | 0.0246 | 0.047853 |
| 45 | 5.3 | 36.8 | 26.2 | 26.1 | 26.2 | 27.0 | 31.4 | 0.07384593 | 0.02477 | 0.049076 |
| 50 | 5.6 | 37.5 | 27.0 | 27.0 | 27.0 | 28.0 | 32.2 | 0.07802589 | 0.024501 | 0.053525 |
| 55 | 5.5 | 37.9 | 27.8 | 27.8 | 27.6 | 28.4 | 32.9 | 0.07663257 | 0.023682 | 0.052951 |
| 60 | 5.7 | 38.9 | 28.1 | 28.3 | 28.3 | 29.2 | 33.6 | 0.07941921 | 0.024981 | 0.054439 |
| 65 | 5.7 | 39.5 | 28.6 | 28.6 | 28.6 | 29.6 | 34.0 | 0.07941921 | 0.025966 | 0.053453 |
| 70 | 5.7 | 40.1 | 29.1 | 29.0 | 29.1 | 29.9 | 34.6 | 0.07941921 | 0.026373 | 0.053046 |
| 75 | 4.5 | 40.1 | 29.7 | 29.7 | 29.7 | 30.3 | 34.9 | 0.06269937 | 0.024823 | 0.037877 |
| 80 | 5.2 | 40.4 | 29.9 | 29.9 | 30.0 | 30.8 | 35.2 | 0.07245261 | 0.025093 | 0.04736 |
| 85 | 5.2 | 41.0 | 30.4 | 30.4 | 30.4 | 31.3 | 35.7 | 0.07245261 | 0.025552 | 0.046901 |
| 90 | 5.3 | 41.6 | 31.0 | 31.0 | 31.0 | 31.8 | 36.3 | 0.07384593 | 0.025646 | 0.0482 |
| 95 | 5.1 | 42.3 | 31.8 | 31.8 | 31.8 | 32.5 | 37.0 | 0.07105929 | 0.025675 | 0.045384 |
| 100 | 5.2 | 43.0 | 32.3 | 32.3 | 32.3 | 33.1 | 37.7 | 0.07245261 | 0.026198 | 0.046254 |
| 105 | 4.8 | 43.7 | 33.0 | 33.0 | 33.0 | 33.9 | 38.3 | 0.06687933 | 0.026406 | 0.040473 |
| 110 | 5.3 | 43.7 | 33.7 | 33.8 | 33.7 | 34.7 | 38.7 | 0.07384593 | 0.024701 | 0.049145 |
| 115 | 5.4 | 44.3 | 34.7 | 34.8 | 34.7 | 35.8 | 39.5 | 0.07523925 | 0.02372 | 0.051519 |
| 120 | 5.0 | 44.9 | 35.4 | 35.5 | 35.4 | 36.2 | 40.2 | 0.06966597 | 0.023705 | 0.045961 |

**Table 12**: Calculated air properties, ln Gr and ln Nu for heating process at 0.2 l/min

| Time (minute) | ρ at 1m | v at 1m | k  at 1m | B  at 1m | Ln Gr | Ln Nu |
|---|---|---|---|---|---|---|
| 5 | 1.185728 | 1.55696E-05 | 0.026046 | 0.003356 | 19.44611808 | 5.66147 |
| 10 | 1.18316 | 1.56308E-05 | 0.026092 | 0.003349 | 19.44685888 | 5.65967 |
| 15 | 1.178935 | 1.57316E-05 | 0.026168 | 0.003337 | 19.43201477 | 5.730207 |
| 20 | 1.173345 | 1.58649E-05 | 0.026268 | 0.003321 | 19.46287448 | 5.636662 |
| 25 | 1.171005 | 1.59207E-05 | 0.02631 | 0.003314 | 19.46508017 | 5.638828 |
| 30 | 1.167788 | 1.59974E-05 | 0.026368 | 0.003305 | 19.43442722 | 5.695136 |
| 35 | 1.165285 | 1.60571E-05 | 0.026413 | 0.003298 | 19.48216889 | 5.63652 |
| 40 | 1.163173 | 1.61074E-05 | 0.026451 | 0.003292 | 19.47179989 | 5.659903 |
| 45 | 1.160443 | 1.61725E-05 | 0.0265 | 0.003285 | 19.44121585 | 5.763351 |
| 50 | 1.157323 | 1.62469E-05 | 0.026556 | 0.003276 | 19.39148769 | 5.791178 |
| 55 | 1.15482 | 1.63066E-05 | 0.026601 | 0.003269 | 19.42794976 | 5.770474 |
| 60 | 1.152123 | 1.63709E-05 | 0.026649 | 0.003262 | 19.45484432 | 5.716979 |
| 65 | 1.150238 | 1.64159E-05 | 0.026683 | 0.003257 | 19.45800485 | 5.697446 |
| 70 | 1.148255 | 1.64632E-05 | 0.026719 | 0.003252 | 19.38998428 | 5.423342 |
| 75 | 1.147053 | 1.64918E-05 | 0.02674 | 0.003248 | 19.39371868 | 5.638055 |
| 80 | 1.145915 | 1.6519E-05 | 0.026761 | 0.003245 | 19.39812951 | 5.614211 |
| 85 | 1.143705 | 1.65717E-05 | 0.0268 | 0.003239 | 19.38873741 | 5.641684 |
| 90 | 1.141593 | 1.6622E-05 | 0.026838 | 0.003234 | 19.37140156 | 5.585797 |
| 95 | 1.138603 | 1.66933E-05 | 0.026892 | 0.003226 | 19.37655374 | 5.589048 |
| 100 | 1.136165 | 1.67515E-05 | 0.026936 | 0.003219 | 19.3686967 | 5.452264 |
| 105 | 1.133598 | 1.68127E-05 | 0.026982 | 0.003212 | 19.2916343 | 5.716157 |
| 110 | 1.131908 | 1.6853E-05 | 0.027012 | 0.003208 | 19.23286207 | 5.809228 |
| 115 | 1.128918 | 1.69243E-05 | 0.027066 | 0.0032 | 19.21638779 | 5.700376 |
| 120 | 1.126318 | 1.69863E-05 | 0.027112 | 0.003193 | 19.49532846 | 5.607973 |

**Table 13**: Calculated parameters for heating process at 1 l/min

| Time (minute) | ΔT water | Tm Fin | T at 0.5 m | T at 1 m | T at 1.5 m | T at 2 m | T bulk | Q water(kW) | Qr (kW) | Qc (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 3.5 | 29.2 | 19.5 | 19.7 | 19.5 | 19.9 | 24.4 | 0.243834 | 0.020596 | 0.22324 |
| 10 | 3.4 | 31.5 | 20.8 | 20.8 | 20.9 | 21.2 | 26.2 | 0.236867 | 0.023396 | 0.21347 |
| 15 | 3.5 | 32.1 | 21.6 | 21.7 | 21.6 | 22.3 | 26.9 | 0.243834 | 0.022938 | 0.2209 |
| 20 | 3.4 | 32.7 | 22.4 | 22.5 | 22.6 | 23.3 | 27.6 | 0.236867 | 0.022811 | 0.21406 |
| 25 | 3.7 | 33.7 | 23.3 | 23.3 | 23.4 | 24.1 | 28.5 | 0.257767 | 0.023385 | 0.23438 |
| 30 | 3.8 | 35.3 | 24.8 | 24.9 | 24.9 | 26.6 | 30.1 | 0.264734 | 0.02368 | 0.24105 |
| 35 | 3.8 | 36.0 | 25.4 | 25.4 | 25.5 | 26.1 | 30.7 | 0.264734 | 0.024279 | 0.24046 |
| 40 | 3.8 | 36.8 | 25.8 | 25.9 | 25.9 | 26.5 | 31.3 | 0.264734 | 0.025126 | 0.23961 |
| 45 | 3.9 | 37.8 | 26.4 | 26.5 | 26.5 | 27.4 | 32.2 | 0.271701 | 0.026225 | 0.24548 |
| 50 | 4.0 | 37.8 | 27.0 | 27.0 | 27.0 | 28.0 | 32.4 | 0.278667 | 0.025236 | 0.25343 |
| 55 | 4.2 | 38.9 | 28.0 | 28.0 | 28.1 | 29.0 | 33.4 | 0.292601 | 0.025732 | 0.26687 |
| 60 | 4.3 | 40.3 | 28.7 | 28.7 | 28.8 | 29.6 | 34.5 | 0.299567 | 0.02766 | 0.27191 |
| 65 | 4.3 | 40.1 | 29.0 | 29.1 | 29.1 | 30.1 | 34.6 | 0.299567 | 0.026344 | 0.27322 |
| 70 | 3.8 | 41.2 | 29.6 | 29.6 | 29.6 | 30.5 | 35.4 | 0.264734 | 0.027904 | 0.23683 |
| 75 | 3.8 | 41.7 | 30.3 | 30.2 | 30.3 | 31.2 | 36.0 | 0.264734 | 0.027783 | 0.23695 |
| 80 | 3.6 | 42.4 | 30.9 | 31.0 | 30.9 | 32.0 | 36.7 | 0.250801 | 0.027858 | 0.22294 |
| 85 | 3.9 | 42.8 | 31.5 | 31.4 | 31.5 | 32.8 | 37.1 | 0.271701 | 0.027851 | 0.24385 |
| 90 | 3.9 | 43.1 | 32.2 | 32.2 | 32.3 | 33.1 | 37.6 | 0.271701 | 0.026602 | 0.2451 |
| 95 | 4.0 | 43.6 | 33.0 | 33.1 | 33.0 | 33.9 | 38.3 | 0.278667 | 0.025999 | 0.25267 |
| 100 | 3.8 | 44.1 | 33.9 | 33.9 | 33.9 | 34.7 | 39.0 | 0.264734 | 0.025387 | 0.23935 |
| 105 | 3.9 | 44.6 | 34.4 | 34.5 | 34.4 | 35.3 | 39.5 | 0.271701 | 0.025391 | 0.24631 |
| 110 | 3.8 | 45.0 | 35.2 | 35.3 | 35.3 | 36.2 | 40.2 | 0.264734 | 0.024326 | 0.24041 |
| 115 | 3.7 | 45.5 | 35.7 | 35.7 | 35.7 | 36.7 | 40.6 | 0.257767 | 0.024716 | 0.23305 |
| 120 | 3.8 | 46.1 | 36.2 | 36.3 | 36.3 | 37.3 | 41.2 | 0.264734 | 0.025035 | 0.2397 |

**Table 14**: Calculated air properties, ln Gr and ln Nu for heating process at 1 l/min

| Time (minute) | ρ at 1m | v at 1m | k at 1m | B at 1m | Ln Gr | Ln Nu |
|---|---|---|---|---|---|---|
| 5 | 1.187678 | 1.55231E-05 | 0.026011 | 0.003362 | 19.5462244 | 7.148737 |
| 10 | 1.181015 | 1.5682E-05 | 0.026131 | 0.003343 | 19.50863894 | 7.207867 |
| 15 | 1.178253 | 1.57478E-05 | 0.02618 | 0.003335 | 19.48467089 | 7.187339 |
| 20 | 1.175393 | 1.5816E-05 | 0.026231 | 0.003327 | 19.48745276 | 7.259618 |
| 25 | 1.171948 | 1.58982E-05 | 0.026293 | 0.003317 | 19.46058078 | 7.286676 |
| 30 | 1.165773 | 1.60454E-05 | 0.026404 | 0.0033 | 19.47067773 | 7.263582 |
| 35 | 1.163433 | 1.61012E-05 | 0.026446 | 0.003293 | 19.48891035 | 7.230468 |
| 40 | 1.160898 | 1.61617E-05 | 0.026492 | 0.003286 | 19.51099727 | 7.217928 |
| 45 | 1.157615 | 1.624E-05 | 0.026551 | 0.003277 | 19.46704724 | 7.289868 |
| 50 | 1.156738 | 1.62609E-05 | 0.026566 | 0.003275 | 19.46081461 | 7.329594 |
| 55 | 1.152643 | 1.63585E-05 | 0.02664 | 0.003263 | 19.50745734 | 7.283575 |
| 60 | 1.148548 | 1.64562E-05 | 0.026713 | 0.003252 | 19.45589606 | 7.337963 |
| 65 | 1.148093 | 1.6467E-05 | 0.026721 | 0.003251 | 19.49438786 | 7.143102 |
| 70 | 1.145038 | 1.65399E-05 | 0.026776 | 0.003243 | 19.47576368 | 7.152129 |
| 75 | 1.14273 | 1.65949E-05 | 0.026818 | 0.003237 | 19.46096568 | 7.093646 |
| 80 | 1.139903 | 1.66623E-05 | 0.026868 | 0.003229 | 19.45049203 | 7.186541 |
| 85 | 1.138245 | 1.67019E-05 | 0.026898 | 0.003225 | 19.39224872 | 7.241138 |
| 90 | 1.13623 | 1.67499E-05 | 0.026934 | 0.003219 | 19.35278449 | 7.299333 |
| 95 | 1.133533 | 1.68142E-05 | 0.026983 | 0.003212 | 19.31245311 | 7.273853 |
| 100 | 1.130835 | 1.68786E-05 | 0.027031 | 0.003205 | 19.30009685 | 7.30607 |
| 105 | 1.128788 | 1.69274E-05 | 0.027068 | 0.0032 | 19.24285253 | 7.328869 |
| 110 | 1.126415 | 1.6984E-05 | 0.027111 | 0.003193 | 19.24903829 | 7.284784 |
| 115 | 1.124823 | 1.70219E-05 | 0.027139 | 0.003189 | 19.24688017 | 7.304509 |
| 120 | 1.122353 | 1.70808E-05 | 0.027183 | 0.003183 | 19.46209862 | 7.308277 |

**Table 15**: Calculated parameters for heating process at 2 l/min

| Time (minute) | ΔT water | Tm Fin | T at 0.5 m | T at 1 m | T at 1.5 m | T at 2 m | T bulk | Q water(kW) | Qr (kW) | Qc (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 2.7 | 31.5 | 25.1 | 24.5 | 24.5 | 25.0 | 28.0 | 0.376196 | 0.015619 | 0.36058 |
| 10 | 2.9 | 35.4 | 26.0 | 25.7 | 26.0 | 26.5 | 30.6 | 0.404063 | 0.022157 | 0.38191 |
| 15 | 3.3 | 37.2 | 27.0 | 27.1 | 27.1 | 27.9 | 32.2 | 0.459795 | 0.02352 | 0.43628 |
| 20 | 3.2 | 38.8 | 28.5 | 28.5 | 28.4 | 29.2 | 33.6 | 0.445862 | 0.024451 | 0.42141 |
| 25 | 3.4 | 40.0 | 29.6 | 29.6 | 29.5 | 30.3 | 34.8 | 0.473729 | 0.024882 | 0.44885 |
| 30 | 3.3 | 41.6 | 30.5 | 30.6 | 30.5 | 31.3 | 36.1 | 0.459795 | 0.026646 | 0.43315 |
| 35 | 3.4 | 42.8 | 31.7 | 31.8 | 31.9 | 32.5 | 37.3 | 0.473729 | 0.026757 | 0.44697 |
| 40 | 3.5 | 43.6 | 32.3 | 32.3 | 32.3 | 33.3 | 38.0 | 0.487662 | 0.027748 | 0.45991 |
| 45 | 3.2 | 44.3 | 32.9 | 32.9 | 32.9 | 33.8 | 38.6 | 0.445862 | 0.028374 | 0.41749 |
| 50 | 3.3 | 45.0 | 33.6 | 33.6 | 33.6 | 34.4 | 39.3 | 0.459795 | 0.02839 | 0.4314 |
| 55 | 3.3 | 44.5 | 34.3 | 34.3 | 34.3 | 35.1 | 39.4 | 0.459795 | 0.025311 | 0.43448 |
| 60 | 3.1 | 45.7 | 35.1 | 35.1 | 35.1 | 36.0 | 40.4 | 0.431929 | 0.02656 | 0.40537 |
| 65 | 3.0 | 47.1 | 35.9 | 35.9 | 35.9 | 37.0 | 41.5 | 0.417996 | 0.028455 | 0.38954 |
| 70 | 3.1 | 46.3 | 36.4 | 36.4 | 36.4 | 37.3 | 41.3 | 0.431929 | 0.025236 | 0.40669 |
| 75 | 3.4 | 46.6 | 37.0 | 37.0 | 37.0 | 37.8 | 41.8 | 0.473729 | 0.024369 | 0.44936 |
| 80 | 3.2 | 46.6 | 37.6 | 37.6 | 37.6 | 38.4 | 42.1 | 0.445862 | 0.023206 | 0.42266 |
| 85 | 3.2 | 47.0 | 38.2 | 38.2 | 38.2 | 39.1 | 42.6 | 0.445862 | 0.022624 | 0.42324 |
| 90 | 3.3 | 47.4 | 38.8 | 38.8 | 38.8 | 39.7 | 43.1 | 0.459795 | 0.022182 | 0.43761 |
| 95 | 3.1 | 47.8 | 39.4 | 39.4 | 39.4 | 40.2 | 43.6 | 0.431929 | 0.021769 | 0.41016 |
| 100 | 3.3 | 47.9 | 39.9 | 39.9 | 39.9 | 40.8 | 43.9 | 0.459795 | 0.020791 | 0.439 |
| 105 | 3.2 | 48.2 | 40.2 | 40.2 | 40.2 | 41.1 | 44.2 | 0.445862 | 0.020885 | 0.42498 |
| 110 | 3.1 | 48.7 | 40.7 | 40.7 | 40.7 | 41.5 | 44.7 | 0.431929 | 0.021075 | 0.41085 |
| 115 | 3.2 | 47.7 | 40.9 | 40.9 | 40.9 | 41.9 | 44.3 | 0.445862 | 0.017865 | 0.428 |
| 120 | 3.1 | 47.7 | 41.2 | 41.0 | 41.2 | 42.1 | 44.4 | 0.431929 | 0.017576 | 0.41435 |

**Table 16**: Calculated air properties, ln Gr and ln Nu for heating process at 2 l/min

| Time (minute) | ρ at 1m | v at 1m | k at 1m | B at 1m | Ln Gr | Ln Nu |
|---|---|---|---|---|---|---|
| 5 | 1.173963 | 1.58501E-05 | 0.026257 | 0.003323 | 19.3819872 | 7.816806 |
| 10 | 1.163855 | 1.60912E-05 | 0.026439 | 0.003294 | 19.40177937 | 7.901933 |
| 15 | 1.15755 | 1.62415E-05 | 0.026552 | 0.003277 | 19.40450825 | 7.839014 |
| 20 | 1.151798 | 1.63787E-05 | 0.026655 | 0.003261 | 19.39438997 | 7.892714 |
| 25 | 1.147378 | 1.64841E-05 | 0.026734 | 0.003249 | 19.43138828 | 7.797889 |
| 30 | 1.142308 | 1.6605E-05 | 0.026825 | 0.003235 | 19.40642682 | 7.833725 |
| 35 | 1.137595 | 1.67174E-05 | 0.02691 | 0.003223 | 19.42681919 | 7.830592 |
| 40 | 1.134995 | 1.67794E-05 | 0.026957 | 0.003216 | 19.43375144 | 7.716051 |
| 45 | 1.132493 | 1.6839E-05 | 0.027001 | 0.003209 | 19.41844142 | 7.752938 |
| 50 | 1.129893 | 1.6901E-05 | 0.027048 | 0.003202 | 19.30070612 | 7.875688 |
| 55 | 1.129405 | 1.69127E-05 | 0.027057 | 0.003201 | 19.32513248 | 7.76515 |
| 60 | 1.125505 | 1.70057E-05 | 0.027127 | 0.003191 | 19.36760849 | 7.664234 |
| 65 | 1.12115 | 1.71095E-05 | 0.027205 | 0.00318 | 19.25172721 | 7.826117 |
| 70 | 1.121833 | 1.70932E-05 | 0.027193 | 0.003181 | 19.20600126 | 7.963989 |
| 75 | 1.120045 | 1.71359E-05 | 0.027225 | 0.003177 | 19.14983464 | 7.953778 |
| 80 | 1.118843 | 1.71645E-05 | 0.027246 | 0.003174 | 19.11350676 | 7.983751 |
| 85 | 1.117023 | 1.72079E-05 | 0.027279 | 0.003169 | 19.08106373 | 8.040646 |
| 90 | 1.11491 | 1.72583E-05 | 0.027317 | 0.003164 | 19.05057124 | 7.998107 |
| 95 | 1.11296 | 1.73048E-05 | 0.027352 | 0.003159 | 18.99761201 | 8.114092 |
| 100 | 1.11179 | 1.73327E-05 | 0.027373 | 0.003156 | 18.99610802 | 8.078876 |
| 105 | 1.110783 | 1.73567E-05 | 0.027391 | 0.003153 | 18.99310057 | 8.039611 |
| 110 | 1.108768 | 1.74048E-05 | 0.027427 | 0.003148 | 18.83721634 | 8.242934 |
| 115 | 1.110328 | 1.73676E-05 | 0.027399 | 0.003152 | 18.81876765 | 8.22748 |
| 120 | 1.10997 | 1.73761E-05 | 0.027406 | 0.003151 | 19.09690819 | 8.090063 |

**Table 17**: Calculated parameters for cooling process at 0.2 l/min

| Time (minute) | ΔT water | Tm Fin | T at 0.5 m | T at 1 m | T at 1.5 m | T at 2 m | T bulk | Q water(kW) | Qr (kW) | Qc (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 4.9 | 23.3 | 25.4 | 25.4 | 25.3 | 25.9 | 24.3 | 0.0682727 | 0.004399 | 0.063873 |
| 10 | 5.1 | 22.2 | 25.2 | 25.1 | 25.1 | 25.8 | 23.6 | 0.0710593 | 0.006251 | 0.064808 |
| 15 | 4.9 | 21.2 | 24.2 | 24.4 | 24.4 | 25.6 | 22.8 | 0.0682727 | 0.006655 | 0.061618 |
| 20 | 4.9 | 20.4 | 23.6 | 23.6 | 23.7 | 25.4 | 22.0 | 0.0682727 | 0.006776 | 0.061496 |
| 25 | 4.9 | 19.1 | 23.3 | 23.2 | 23.3 | 25.2 | 21.2 | 0.0682727 | 0.00852 | 0.059752 |
| 30 | 5.1 | 18.2 | 21.7 | 21.8 | 21.7 | 25.1 | 20.0 | 0.0710593 | 0.007394 | 0.063665 |
| 35 | 5.1 | 17.3 | 20.7 | 20.8 | 20.8 | 25.0 | 19.1 | 0.0710593 | 0.007052 | 0.064007 |
| 40 | 5.2 | 16.3 | 20.0 | 20.0 | 20.2 | 24.8 | 18.1 | 0.0724526 | 0.007353 | 0.065099 |
| 45 | 4.9 | 15.2 | 19.4 | 19.4 | 19.4 | 24.6 | 17.3 | 0.0682727 | 0.008288 | 0.059985 |
| 50 | 4.9 | 14.4 | 18.8 | 18.8 | 18.8 | 24.3 | 16.6 | 0.0682727 | 0.008625 | 0.059648 |

**Table 18**: Calculated air properties, ln Gr and ln Nu for cooling process at 0.2 l/min

| Time (minute) | ρ at 1m | ν at 1m | k at 1m | B at 1m | Ln Gr | Ln Nu |
|---|---|---|---|---|---|---|
| 5 | 1.198133 | 1.55622E-05 | 0.026003 | 0.003363 | 18.28418008 | 7.25753 |
| 10 | 1.20083 | 1.54979E-05 | 0.025954 | 0.003371 | 18.3686689 | 7.138105 |
| 15 | 1.204178 | 1.54181E-05 | 0.025894 | 0.003381 | 18.40703357 | 7.112164 |
| 20 | 1.207265 | 1.53445E-05 | 0.025839 | 0.00339 | 18.65746293 | 6.848183 |
| 25 | 1.210515 | 1.5267E-05 | 0.025781 | 0.0034 | 18.54538699 | 7.044799 |
| 30 | 1.215 | 0.00001516 | 0.0257 | 0.003413 | 18.52232128 | 7.090437 |
| 35 | 1.21864 | 1.50732E-05 | 0.025635 | 0.003424 | 18.58873814 | 7.058394 |
| 40 | 1.222313 | 1.49856E-05 | 0.025569 | 0.003435 | 18.73062132 | 6.850522 |
| 45 | 1.225628 | 1.49066E-05 | 0.025509 | 0.003445 | 18.78885678 | 6.799747 |
| 50 | 1.228358 | 1.48415E-05 | 0.02546 | 0.003453 | 17.91526749 | 7.599439 |

**Table 19**: Calculated parameters for cooling process at 1 l/min

| Time (minute) | ΔT water | Tm Fin | T at 0.5 m | T at 1 m | T at 1.5 m | T at 2 m | T bulk | Q water(kW) | Qr (kW) | Qc (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 3.6 | 25.1 | 27.7 | 27.6 | 27.7 | 27.2 | 26.4 | 0.251302 | 0.005476 | 0.245826 |
| 10 | 3.8 | 24.0 | 26.9 | 26.9 | 26.8 | 26.2 | 25.4 | 0.265263 | 0.006256 | 0.259007 |
| 15 | 3.6 | 23.0 | 26.2 | 26.2 | 26.1 | 25.3 | 24.6 | 0.251302 | 0.006777 | 0.244524 |
| 20 | 3.6 | 22.2 | 25.4 | 25.4 | 25.5 | 24.6 | 23.8 | 0.251302 | 0.006793 | 0.244509 |
| 25 | 3.7 | 20.9 | 24.8 | 24.9 | 24.9 | 24.1 | 22.9 | 0.258282 | 0.008354 | 0.249928 |
| 30 | 3.7 | 20.0 | 24.0 | 24.0 | 24.0 | 23.3 | 22.0 | 0.258282 | 0.008278 | 0.250004 |
| 35 | 3.8 | 19.1 | 22.7 | 22.7 | 22.6 | 21.9 | 20.9 | 0.265263 | 0.007289 | 0.257974 |
| 40 | 3.8 | 18.1 | 21.6 | 21.7 | 21.6 | 20.8 | 19.9 | 0.265263 | 0.007282 | 0.257981 |
| 45 | 3.5 | 17.0 | 20.9 | 20.8 | 20.9 | 20.1 | 18.9 | 0.244321 | 0.007717 | 0.236604 |
| 50 | 3.6 | 16.2 | 20.2 | 20.3 | 20.3 | 19.5 | 18.3 | 0.251302 | 0.008271 | 0.243031 |

**Table 20**: Calculated air properties, ln Gr and ln Nu for cooling process at 1 l/min

| Time (minute) | ρ at 1m | ν at 1m | k at 1m | Β at 1m | Ln Gr | Ln Nu |
|---|---|---|---|---|---|---|
| 5 | 1.190235 | 1.57506E-05 | 0.026145 | 0.003341 | 18.08287322 | 8.743275 |
| 10 | 1.193908 | 1.5663E-05 | 0.026079 | 0.003351 | 18.23983146 | 8.655375 |
| 15 | 1.197158 | 1.55855E-05 | 0.02602 | 0.00336 | 18.3410039 | 8.511618 |
| 20 | 1.200343 | 1.55095E-05 | 0.025963 | 0.00337 | 18.36404857 | 8.503228 |
| 25 | 1.203788 | 1.54274E-05 | 0.025901 | 0.00338 | 18.59343797 | 8.311748 |
| 30 | 1.207298 | 1.53437E-05 | 0.025838 | 0.00339 | 18.60736482 | 8.314488 |
| 35 | 1.211523 | 1.52429E-05 | 0.025762 | 0.003403 | 18.50801795 | 8.46501 |
| 40 | 1.215488 | 1.51484E-05 | 0.025691 | 0.003414 | 18.53336169 | 8.458369 |
| 45 | 1.21929 | 1.50577E-05 | 0.025623 | 0.003426 | 18.61675733 | 8.306477 |
| 50 | 1.221825 | 1.49973E-05 | 0.025578 | 0.003433 | 18.70301779 | 8.259069 |

**Table 21**: Calculated parameters for cooling process at 2 l/min

| Time (minute) | ΔT water | Tm Fin | T at 0.5 m | T at 1 m | T at 1.5 m | T at 2 m | T bulk | Q water(kW) | Qr (kW) | Qc (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 3.2 | 23.5 | 25.9 | 25.9 | 25.9 | 24.4 | 24.7 | 0.4458622 | 0.005132 | 0.44073 |
| 10 | 3.3 | 22.6 | 25.6 | 25.5 | 25.5 | 24.9 | 24.1 | 0.4597954 | 0.006206 | 0.453589 |
| 15 | 3.3 | 21.6 | 24.7 | 24.8 | 24.8 | 24.4 | 23.2 | 0.4597954 | 0.006682 | 0.453113 |
| 20 | 3.2 | 20.7 | 24.0 | 24.1 | 24.1 | 22.8 | 22.4 | 0.4458622 | 0.00698 | 0.438882 |
| 25 | 3.3 | 19.3 | 23.7 | 23.6 | 23.7 | 22.3 | 21.5 | 0.4597954 | 0.008895 | 0.4509 |
| 30 | 3.2 | 18.6 | 22.1 | 22.2 | 22.2 | 20.7 | 20.4 | 0.4458622 | 0.007424 | 0.438438 |
| 35 | 3.3 | 17.8 | 21.1 | 21.2 | 21.2 | 20.1 | 19.5 | 0.4597954 | 0.00691 | 0.452885 |
| 40 | 3.4 | 16.9 | 20.4 | 20.4 | 20.4 | 19.2 | 18.6 | 0.4737286 | 0.007053 | 0.466676 |
| 45 | 3.1 | 15.6 | 19.8 | 19.8 | 19.8 | 18.5 | 17.7 | 0.431929 | 0.008257 | 0.423672 |
| 50 | 3.2 | 14.8 | 19.2 | 19.2 | 19.2 | 18.2 | 17.0 | 0.4458622 | 0.008725 | 0.437137 |

**Table 22**: Calculated air properties, ln Gr and ln Nu for cooling process at 2 l/min

| Time (minute) | ρ at 1m | v at 1m | k at 1m | B at 1m | Ln Gr | Ln Nu |
|---|---|---|---|---|---|---|
| 5 | 1.196833 | 1.55932E-05 | 0.026026 | 0.00336 | 18.06082724 | 9.2136 |
| 10 | 1.199205 | 1.55367E-05 | 0.025984 | 0.003366 | 18.26635328 | 9.132219 |
| 15 | 1.202618 | 1.54553E-05 | 0.025922 | 0.003376 | 18.36249774 | 9.050868 |
| 20 | 1.205673 | 1.53824E-05 | 0.025867 | 0.003385 | 18.42615337 | 8.828516 |
| 25 | 1.20928 | 1.52964E-05 | 0.025803 | 0.003396 | 18.69237858 | 8.973286 |
| 30 | 1.21344 | 1.51972E-05 | 0.025728 | 0.003408 | 18.5391211 | 9.070343 |
| 35 | 1.217113 | 1.51096E-05 | 0.025662 | 0.003419 | 18.49182181 | 9.073533 |
| 40 | 1.220428 | 1.50306E-05 | 0.025603 | 0.003429 | 18.53435171 | 8.812313 |
| 45 | 1.224003 | 1.49453E-05 | 0.025538 | 0.00344 | 18.71593007 | 8.782846 |
| 50 | 1.226863 | 1.48771E-05 | 0.025487 | 0.003449 | 18.79036916 | 9.2136 |

# دراسة اداء الواح التبريد و التسخين المستخدمة في انظمة التكييف للابنية في وضعي السقوف والارضيات

إعداد
**حازم ماهر العساف**

المشرف
**الأستاذ الدكتور محمود حماد**

## ملخص

يهدف هذا البحث إلى دراسة اداء الواح التبريد و التسخين المستخدمة في انظمة التكييف للابنية في وضعي السقوف والارضيات بالتجارب العملية.

لوحين بقياس ٦٠ x ٦٠ سم تم وضعهما بداخل صندوق معزولاً عزلاً حراريا تاماً، أحدهما بمستوى الأرض لدراسة أداء التسخين و الاخر بمستوى السقف لدراسة أداء التبريد.

تم عمل تجارب التبريد و التسخين بتدفق للماء يتراوح بين ٠,٢ الى ٢ لتر في الدقيقة للحصول على قيم مختلفة لمعامل انتقال الحرارة بالحمل. درجات الحرارة خارج الصندوق كانت تتغير بنفس نظام تغير الحرارة بداخله للحصول على نظام معزول مثالي.

تم دراسة تأثير المعاملات الأساسية العملية مثل درجات الحرارة و كمية تدفق الماء على معامل انتقال الحرارة بالحمل، و تم قياس و تسجيل درجات الحرارة داخل الصندوق و على ارتفاعات مختلفة في حالات الثبوت و الاستقرار خلال فترات زمنية مختلفة لكل التجارب.

بيان تأثير قيم (ناسلت) ، (غراشوف) و (برانتل) على النظام و المعادلات، و احتساب هذه القيم عمليا.

دراسة نتائج التجارب و التوصل الى معادلتين جديدتين لحساب معدل معامل انتقال الحرارة بالحمل لعمليتي التسخين و التبريد للالواح المستخدمة. هذه المعادلات بقيم (ناسلت) والتي توصلنا لحساب معامل انتقال الحرارة بالحمل للتبريد و التسخين بنسبة خطأ تبلغ ٠،٤١ % و ٣,٢% و معدل انحراف مطلق يبلغ ٣,٧٥% و ٤,٣% على الترتيب.

هذه الدراسة كانت لدرجات حرارة للهواء تتراوح من ٢٠ الى ٣٢ درجة مئوية للتسخين و ٢٠ الى ٢٨ درجة مئوية للتبريد. دلت نتائج هذا البحث على إمكانية استخدام هذه الانظمة بدقة أفضل و توفير أكبر للطاقة في قطاع الابنية.