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A Thesis
Presented to
the Academic Faculty

by

Mohammed S. Al-Johani

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in Nuclear Engineering

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I would also like to thank my father, Subian, for the selfless purpose which he instilled in me and to my mother, Luhiah, my deep appreciation for her constant prayers and continued encouragement in those dark moments. My parents showered me with favors to the extent that no words will ever explain my appreciation and gratitude.

Special thanks to my wife, Ebtisam, for without here this task would never have reached completion, also for here love and understanding and much needed humor. Furthermore she deserves most of the credit for my obtainment of this degree because of here constant sacrifice and patience and Here understanding of Arabic poetry and literature made the darkness lighter. Here standing beside me during my physical illness which forced me to quit my studies for several quarters and here taking care of almost every thing will never be forgotten.

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To the ladies who make my life a joy

My mother Luhiah Al-suraisiry

and

My wife Ebtisam Al-anbari

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NOMENCLATURE

a speed of sound (m/s)
c_p specific heat at constant pressure (J/kgK)
c_v specific heat at constant volume (J/kgK)
D_{12} vapor-noncondensable mass diffusivity (m^2/s)
D_i inner diameter (m)
D_O outer diameter (m)
d particle diameter
e total internal energy per unit volume (J/m^3)
F_x x-porous medium frictional force
F_y y-porous medium frictional force
F_z z-porous medium frictional force
Gr Grashof number
g gravitational acceleration (m/s^2)
h heat transfer coefficient (w/m^2K)
h_{fg} latent heat of condensation (J/kg)
$\overline{h}$ average heat transfer coefficient (w/m^2K)
$\dot{h}_g$ heat transfer coefficient in the presence of mass transfer (w/m^2K)
I Identity matrix
Ja Jakob Number
k thermal conductivity (w/mK)
K_g gas side mass transfer coefficient (kg/m^2s)
m condensation rate per unit fluid volume (kg/m^3s)
$\dot{m}''$ condensation rate per unit area (kg/m^2s)
m vapor mass fraction; parameter defined as ρu (kg/m^2s)
M_G molecular weight of noncondensable gas $(kg/kmole)$
M_v molecular weight of vapor $(kg/kmole)$
N number of tubes
N_u Nusselt number

n vapor mass fraction; parameter defined as ρv (kg/m^2s)

p pressure (N/m^2)

P tube pitch (m)

P_r Prandtl number

q'' local heat flux (w/m^2)

q vapor mass fraction; parameter defined as ρw (kg/m^2s)

R ideal gas constant (J/kgK); overall thermal resistance (m^2K/w)

Re Reynolds number

s specific interphase surface area m^{-1}

t time (s)

T temperature (K)

T_G secondary system bulk temperature (K)

T_p primary system bulk temperature (K)

T_s interphase temperature (K)

u velocity in the x-direction (m/s)

U overall heat transfer transfer coefficient (w/m^2K)

$\vec{U}$ conservative variables vector

U_p absolute value of velocity $(u^2 + v^2 + w^2)^{1/2}$

v velocity in the y-direction (m/s)

V volume (m^3)

$\vec{v}$ velocity vector (m/s)

w velocity in the z-direction (m/s)

x,y,z Cartesian cordinates

GREEK SYMBOLS

α stretching parameter eqn. (2.27)

β local volume porosity

β_t porosity of the tube bundle region

γ specific heat ratio; parameter in Roberts' transformaton eqn. (2.27)

δ parameter specifying nature of conservation equations

$$= \begin{cases} 0 & \text{Navier-Stokes} \\ 1 & \text{porous media with condensation} \end{cases}$$

λ second coefficient of viscosity (kg/ms)

ϵ internal energy (J/kg)

$\varepsilon_e, \varepsilon_i$ coefficients in explicit and implicit artificial dissipation terms

μ viscosity (kg/ms)

ξ_x, ξ_y, ξ_z pressure loss coefficients in x,y, and y directions respectively (m^{-1})

ξ, η, ζ transformed cordinates

ρ density (kg/m^3)

ρ_f density of condensate

ϕ gas mass fraction

SUBSCRIPTS

c condensate

f liquid

i, j, k nodal indices in x,y and z directions respectively

l last node in the x direction

G gas side noncondensable gas

p primary system; particle in porous media

s interphase

sat saturation

w wall

x, y, z Cartesian coordinate directions

SUPERSCRIPTS

$n-1$ $(n-1)$th time steps

n nth time steps

$n+1$ $(n+1)$th time steps

$*, **$ first and second-stage itermediate-time variables

w wall

SUMMARY

Condensers are essential components in power plants, process plants, air-conditioning, refrigeration, etc. Inadequate design of a condenser may lead to poor power plant efficiency; hence, condensers must be optimized to maximize the power plant output.

The presence of noncondensable gases in condensers is one of the major causes for the deterioration of the condenser efficiency. Since avoiding non-condensables is impossible in most practical applications, a reliable method is needed to establish the effect of the non-condensable gas concentration in condensers so that they can be designed to minimize the accumulation of such gases in specific areas.

In this work, a new and general model that is applicable to various types of condensers, is presented. The developed model has two separate components, referred to in this thesis as macroscopic- and microscopic-level models. The macroscopic-level model is concerned with the numerical solution of vapor-noncondensable conservation equations. The microscopic-level models address the heat and mass transfer processes at the interface between the condensate liquid and the vapor-noncondensable mixture. The macroscopic and microscopic models are coupled, and are solved iteratively. To avoid limiting the application of the model to specific configuration, it is assumed that the condensing vapor flows through a porous medium.

The macroscopic model is based on the numerical solution of the steam mass continuity, steam-noncondensable mixture momentum and energy and the noncondensable mass species conservation equations inside the hot region of a

condenser. These conservation equations are three-dimensional, and account for the compressibility of the vapor-gas mixture. The pressure, velocity, density and the gas mass fraction obtained from the macroscopic system solution are then used in the microscopic modeling scheme, based on the stagnant film model. This microscopic solution assumes that the condenser can be divided into geometrically identical unit cells. A unit cell includes the outer surface and the vicinity of a tube in the case of a shell and tube condenser, a plate in the case of a plate condenser, a sphere in the case of packed bed condensers and a similarly defined space in any irregular shape.

The numerical solution of the macroscopic-level equations was performed using an implicit factored finite difference numerical scheme (IFS). The scheme was modified in two ways, however. One modification made it possible to include the porous media and condensation terms. The second modification allows one to include as many mass continuity equations as the situation needs. This modification is implemented through a simple and innovation method, whereby the inclusion of the additional conservation equations increases the computational coast only slightly. The latter modification makes it possible to model mixture of noncondensables when necessary.

The developed model was applied to a large number of one, two, and three dimensional problems, involving open channel, porous media, packed bed and shell and tube condensers. The model predictions were compared with results obtained from analytical solutions wherever such solutions were available, and solutions obtained from well-proven numerical schemes when analytical solutions were unavailable. Excellent agreement was found everywhere, confirming the correctness of the developed model.

CHAPTER 1

INTRODUCTION

1.1. General Remarks

Condensation occurs when a wet, saturated, or slightly super-heated vapor contacts a surface which has a temperature below the saturation temperature corresponding to the vapor partial pressure. Condensation also occurs when vapor comes into direct contact with subcooled liquid. Although homogeneous condensation can also occur in highly subcooled metastable vapor, practical applications generally involve heterogeneous condensation. Heterogeneous condensation itself may be divided into two types: film-wise and drop-wise.

In film-wise condensation, the condensate forms a liquid film on the cooling surface, and it occurs when the cooling surface is easily wetted. However, in drop-wise condensation, the vapor condenses in the form of drops which grow and detach because of the effect of gravity and/or the effect of high shear forces after they grow large enough to overcome the interfacial forces between the drops and the cooling surface. New drops would take the position of the detached ones. Drop-wise condensation occurs on non-wetted cooling surfaces; therefore, because of its lower heat transfer resistance, the heat transfer coefficients are about four times larger than those of film-wise condensation [1]. When drop-wise condensation takes place on a surface, the heat transfer coefficients increase with the increase of $(T_{sat} - T_w)$ to a point and then decrease, because further increase of the degree of sub-cooling makes the cooling surface wetted and film-wise condensation begins [1]. Because of the high heat transfer coefficient, it is advantageous to have drop wise condensation. Drop-wise condensation, however, is difficult to maintain and the process will eventually change to film-wise condensation. However, if appropriate care is taken, such as coating the cooling surface or adding a detergent to prevent the surface from being wetted, drop-wise condensation can be maintained. Because of the above stated reasons, most surface condensers are designed to operate on film-wise condensation.

A major difficulty encountered in condensers is the presence of non-condensable gases. These gases, which are difficult to avoid in practice, reduce the heat transfer coefficient of condensers by introducing an additional gas film resistance for heat and mass transfer.

1.2. Condensation of Pure Vapors

Condensation of a saturated vapor in the absence of noncondensables is, in principle, a liquid-side controlled process and is relatively simple to model, in particular in regular geometries. Classical condensation models dealt with this situation. In what follows, some of the important classical models are reviewed.

In film-wise condensation, a continuous film of liquid coats the cooling surface and is driven downward by the effect of gravity. The condensate film behavior on the cooling surface of the condenser is an important factor in determining the heat transfer rate. The first analytical work to determine the heat transfer coefficient was proposed in 1916 by Nusselt [2] with the following assumptions:

1. Steady state, laminar flow, and no rippling on the condensate film.
2. Within the liquid film, heat is transferred slowly by conduction.
3. Properties of the fluid are constant.

4. Vapor does not exert any force on the liquid film.
5. Acceleration of the liquid is negligible compared to gravitational and viscous forces.
6. Wall and interface temperatures are constant.
7. Energy deffect associated with sub-cooling of liquid film is neglected.
8. The vapor is pure.

By implementing the above assumptions with the appropriate boundary conditions on the Navier Stokes equations, Nusselt derived the following well-known relationship:

$$\bar{h}_{Nu} = 0.943\left[\frac{\rho_f^2 g_x h_{fg} k_f^3}{L\mu_f \Delta T_f}\right]^{1/4} \tag{1.1}$$

where $\Delta T_f = (T_{sat} - T_w)$, and g_x is the component of the gravitational acceleration vector along the inclined surface.

The above equation describes the liquid-side heat transfer coefficient over an inclined plate of length L. Because pure film condensation is rarely found without the presence of drop wise condensation, and because the condensate has ripples that help the liquid to mix with the film, condensation heat transfer coefficients are usually higher than those predicted by Equation (1.1).

Rohsenow [3] solved the filmwise condensation problem, accounting for the correct nonlinear temperature distribution. He assumed that the wall temperature is constant, vapor is saturated, no vapor shear stress on the liquid film, and the physical properties of the liquid are constant. Rohsenow also suggested that, h_{fg} in Equation (1.1) should be replaced by $h_{fg} + 0.68c_{pf}(T_{sat} - T_w)$ where c_{pf} is the specific heat of the liquid.

Chen [4]; and Koh, Sparrow, and Hartnett [5] have taken into account the effect of the drag which the vapor exerts on the liquid. Chen [4] has suggested the following approximate Equation that includes momentum and interfacial shear effects.

$$\frac{\bar{h}_{Nu}}{h_{Nu}} = \left[\frac{1 + 0.68A + 0.02AB}{1 + 0.85b - 0.15AB}\right]^{1/4} \tag{1.2}$$

where $A = \frac{c_{pf}\Delta T_f}{h_{fg}}$ and $B = \frac{k_f \Delta T_f}{\mu_f h_{fg}}$.

Equation (1.2) is only valid for $A < 2$, $B < 20$ and $Pr_f < 0.05$, or $Pr_f > 1$.

In the case of turbulent film flow, the Nusselt assumptions are evidently not valid. Turbulent flow might occur at the lower end of the inclined plate. In this case, heat can no longer be assumed to be transferred through the condensate film by conduction, due to the significance of eddy diffusivity, which greatly increases the heat transfer rate. Unlike the laminar case, the heat transfer coefficient increases with the distance along the plate ,x, because the turbulence increases as the film thickness gets larger. The following correlation[1] gives the average heat transfer coefficient for turbulent film condensation:

$$\bar{h} = 0.0076\left[\frac{\rho_f(\rho_f - \rho_s)g_x k_f^3}{\mu_f^2}\right]^{1/3} Re_L^{0.4} \tag{1.3}$$

where Re_L is the Reynolds number at $x = L$.

Nusselt also derived the following correlation for the heat transfer coefficient for film condensation on a horizontal tube using assumptions similar to those he had made for the plate geometry:

$$\frac{\bar{h}_{Nu} D_0}{k_f} = 0.728\left[\frac{\rho_f(\rho_f - \rho_s)g h_{fg} D_0^3}{\mu_f(T_{sat} - T_w)k_f}\right]^{1/4} \tag{1.4}$$

Equation (1.4) was derived with the assumption that the condensation thickness is much smaller than the radius of the tube.

In the case of forced convection, the shear forces between the condensate and the vapor are important. In order to solve this problem correctly, it is necessary to solve the continuity and momentum conservation equations for the vapor and the condensate.

Shekriladze and Gomelauri [6] extended the analytical work of Nusselt for an isothermal cylinder without separation by assuming that the change in momentum across the condensate-liquid interface is the main factor which causes the surface shear stress. The following result was obtained:

$$\bar{h} = 0.9\frac{k_f}{D_0}\bar{Re}^{1/2} \tag{1.5}$$

where $\bar{Re} = \frac{\rho_f u_g D_0}{\mu_f}$ and u_g is the steam velocity. When gravity and velocity are involved, they recommended the following equation:

$$\bar{N}_u = 0.64\bar{Re}\left[1 + \left(1 + 1.69\frac{gD_0\mu_f h_{fg}}{u_g^2 k_f \Delta T}\right)\right]^{1/2} \tag{1.6}$$

A great deal of analytical work for pure vapor condensation on flat plates and cylinders is available in the literature. An excellent review of laminar film condensation is given by Rose [7,8].

1.3. Condensation in the Presence of Noncondensables

In the previous section, condensation of pure vapor was discussed, where the major heat transfer resistance was due to the condensate layer which accumulates on the cooling surface. The assumption of pure vapor condensation is not valid in most practical cases, because a small amount of noncondensable gases can easily find its way into a condenser. Collier [9] and Minkowycz [10] reported that even 0.5% mass of air may decrease the heat transfer rate by more than 50%.

It has been noted that a small amount of noncondensable gases present in steam reduces the overall heat transfer coefficient, which, in turn, degrades the performance of the condenser. As steam condenses on the cooling surface, the noncondensables accumulate and form a noncondensable-rich layer between the condensate and the steam. This gas film reduces the rate of steam that reaches the cooling surface by introducing an additional mass transfer resistance. Figure 1.1 is a schematic of the vapor and noncondensable concentration profiles near the vapor-condensate interphase. The flow of condensing vapor towards the interphase results in the accumulation of noncondensable gas near the liquid surface. The vapor pressure at the interphase is reduced significantly, even when the concentration of noncondensables in the bulk vapor is quite small.

Othmer [11] in 1929 studied the effect of a small quantity of air on the temperature drop and on the condensation rate of steam, along an isothermal surface. He carried out experiments using a shell with a tube partially filled with liquid. The steam was allowed to pass through the shell and the liquid to pass through the tube. He suggested an empirical correlation which relates the heat transfer coefficient to the steam temperature drop, and the air concentration:

$$\begin{aligned} \log(h) &= \log(\Delta T)[1.213 - 0.0024T] \\ &+ \left[\frac{\log(\Delta T)}{3.439} - 1\right]\left[\log(C + 0.505) - 1.551 - 0.009T\right] \end{aligned} \tag{1.7}$$

where h is in $Btu/(hr - ft^2 - F), C$ is the percent volume of air, T is the temperature of steam in degree Fahrenheit, and ΔT is the temperature difference between the bulk vapor and the cooling surface. In deriving his empirical correlation, Othmer assumed that the temperature of the tube wall remained constant, and the air-stream mixture was stagnant. Othmer's work was followed by a myriad of analytical, experimental, and numerical studies in the area of condensation. Some of these investigations are discussed below.

Meisenburg, Boarts, and Badger [12] studied condensation in the presence of noncondensables, in a vertical tube and correlated the ratio of the actual

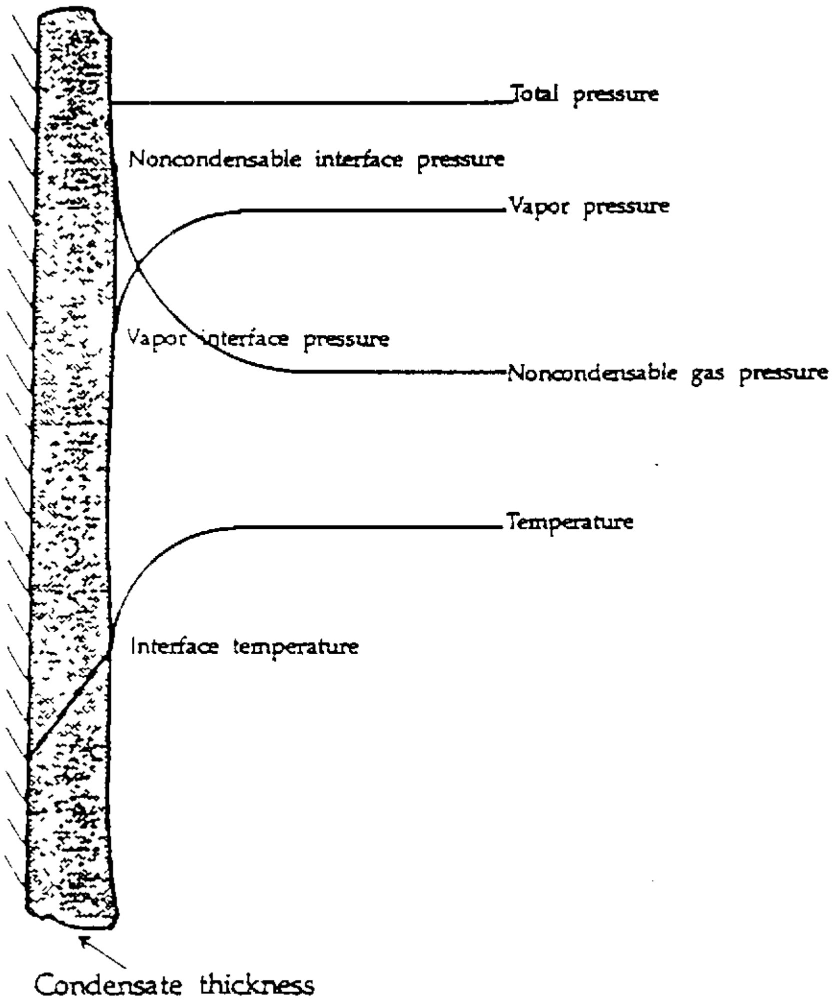

Figure 1.1. Temperature and Partial Pressure Profiles at the Condensate-Gas Interphase.

SUMMARY

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APPENDIX A-1

SOME THERMODYNAMIC AND PHYSICAL PROPERTIES OF WATER AND STEAM

The following equation is the density of water in kg/m^3 as a function of temperature

$$\rho = 598.8134 + 2.828807T - 3.784399 \times 10^{-3}T^2 - 7.474704 \times 10^{-6}T^3 + 1.129865 \times 10^{-8}T^4 \quad 275k \leq T \leq 580k. \qquad \text{(A-1.1)}$$

The specific heat at constant pressure in J/kgk for water as a function of temperature is given by

$$C_p = 10146.91 - 62.78324T + 2.500216 \times 10^{-1}T^2 - 4.520721 \times 10^{-4}T^3 + 3.17923 \times 10^{-7}T^4 \quad 275k \leq T \leq 580k \qquad \text{(A-1.2)}$$

and C_p is in J/kgk.

$$k = -1.561273 + 1.564598 \times 10^{-2}T - 3.970037 \times 10^{-5}T^2 + 4.560812 \times 10^{-8}T^3 - 2.247724 \times 10^{-11}T^4 \quad 275k \leq T \leq 580k \qquad \text{(A-1.3)}$$

where k is thermal conductivity of water (W/mk).

$$\nu \times 10^6 = 61.79776 - 2.5 \times 10^{-1}T - 1.79165 \times 10^{-4}T^2 - 4.969477 \times 10^{-7}T^3 + 5.225 \times 10^{-9}T^4 + 1.457343 \times 10^{-11}T^5 - 4.675553 \times 10^{-14}T^6 \quad 275k \leq T \leq 330k$$

and

$$\nu \times 10^6 = 10.31275 - 6.536036 \times 10^{-2}T + 1.488566 \times 10^{-4}T^2$$
$$- 1.666241 \times 10^{-7}T^3 + 2.34858 \times 10^{-10}T^4 - 4.176862 \times 10^{-13}T^5$$
$$+ 2.884012 \times 10^{-16}T^6 \quad 330k \leq T \leq 580k \qquad \text{(A-1.4)}$$

When ν is kinematic viscosity of water (m^2/sec)

$$p_{sat} \times 10^{-5} = 5.56268 \times 10^{-1} - 2.069575 \times 10^{-3}T_{sat}$$
$$- 4.339096 \times 10^{-6}T_{sat}^2 + 1.306466 \times 10^{-8}T_{sat}^3$$
$$- 5.830305 \times 10^{-12}T_{sat}^4 - 1.735039 \times 10^{16}T_{sat}^5$$
$$+ 2.540331 \times 10^{-16}T_{sat}^6 \quad 273.25k \leq T_{sat} \leq 305k$$
$$p_{sat} \times 10^{-5} = 2.267565 \times 10^{-1} + 1.537165 \times 10^{-3}T_{sat}$$
$$+ 7.357538 \times 10^{-6}T_{sat}^2 - 2.980122 \times 10^{-8}T_{sat}^3$$
$$- 3.012597 \times 10^{-10}T_{sat}^4 + 3.864352 \times 10^{-13}T_{sat}^5$$
$$+ 1.369178 \times 10^{-15}T_{sat}^6 \quad 305 < T_{sat} \leq 350$$
$$p_{sat} \times 10^{-5} = -16.98454 + 1.154695 \times 10^{-1}T_{sat}$$
$$- 1.492 \times 10^{-4}T_{sat}^2 - 1.866152 \times 10^{-7}T_{sat}^3$$
$$+ 4.152246 \times 10^{-10}T_{sat}^4 - 3.366653 \times 10^{-12}T_{sat}^5$$
$$+ 8.03126 \times 10^{-15}T_{sat}^6 \quad 350 < T_{sat} \leq 550 \qquad \text{(A-1.5)}$$

where p_{sat} is the saturation pressure as a function of the saturation temperature (N/m^2).

The saturation temperature as a function of pressure [59]

$$T_{sat} = a_1 + a_2 p_{sat} + a_3 p_{sat}^2 + a_4 p_{sat}^3$$
$$+ \frac{a_5}{p_{sat}} + \frac{a_6}{p_{sat}^2} + \frac{a_7}{p_{sat}^3} + a_8 p_{sat}^{1/2} + \frac{a_9}{p_{sat}^{1/2}} \qquad \text{(A-1.6)}$$

where

$$a_1 = 3.5653 \times 10^2$$

$$a_2 = -2.0611$$

$$a_3 = 5.7064 \times 10^{-3}$$

$$a_4 = -1.0110 \times 10^{-5}$$

$$a_5 = 2.1841$$

$$a_6 = -9.9885 \times 10^{-3}$$

$$a_7 = 2.5304 \times 10^{-5}$$

$$a_8 = 3.8845 \times 10^1$$

$$a_9 = -2.2420 \times 10^1$$

when T_{sat} is in k and p_{sat} in bars.

The saturated liquid and vapor enthalpies in $Btu/1bm$ as a function of saturated pressure in psia are given by the following relations [60]

$$h_f = \begin{cases} \Sigma_{i=0}^{8} a2_i \big(\ln(p_{sat})\big)^i & 0.1 \le p_{sat} \le 950 \\ \Sigma_{i=0}^{8} a2_i \big(\ln(p_{sat})\big)^i & 850 \le p_{sat} \le 2250 \\ \Sigma_{i=0}^{8} a3_i \big((p_{crit} - p_{sat})^{0.41}\big)^i & 2250 \le p_{sat} \le p_{crit} \end{cases} \qquad \text{(A-1.7)}$$

and

$$h_g = \begin{cases} \Sigma_{i=0}^{11} b1_i \big(\ln(p_{sat})\big)^I & 0.1 \le p_{sat} \le 1500 \\ \Sigma_{i=0}^{8} b2_i \big(\ln(p_{sat})\big)^i & 1100 \le p_{sat} \le 2650 \\ \Sigma_{i=0}^{6} b3_i \big((p_{crit} - p_{sat})^{0.41}\big)^i & 2550 \le p_{sat} \le p_{crit} \end{cases} \qquad \text{(A-1.8)}$$

where the coefficients $a1_i, a2_i, a3_i, b1_i, b2_i,$ and $b3_i$ are given by the following table:

Table A-1.1. Coefficient Used in Equations (A.7) and (A.8).

i	$a1_i$	$a2_i$	$a3_i$
0	$.6970887859 \times 10^{2}$	$.8408618802 \times 10^{6}$	9060030436×10^{3}
1	$.333752994 \times 10^{2}$	$.3637413208 \times 10^{6}$	$-.1426813520 \times 10^{2}$
2	$.2318240735 \times 10^{1}$	$-.4634506669 \times 10^{6}$	$.1522233257 \times 10^{1}$
3	$.1840599513 \times 10^{0}$	$.1130306339 \times 10^{6}$	$-.6973992961 \times 10^{0}$
4	$-.5245502284 \times 10^{-2}$	$-.4350217298 \times 10^{3}$	$.1743091663 \times 10^{0}$
5	$.2878007027 \times 10^{-2}$	$-.3898988188 \times 10^{4}$	$-.2319717696 \times 10^{-1}$
6	$.1753652324 \times 10^{-2}$	$.6697399434 \times 10^{3}$	$.1694019149 \times 10^{-2}$
7	$-.4334859620 \times 10^{-3}$	$-.4730726377 \times 10^{2}$	$-.6454771710 \times 10^{-4}$
8	$.3325699282 \times 10^{-4}$	$.1265125057 \times 10^{1}$	$.1003003098 \times 10^{-5}$
i	$b1_i$	$b2_i$	$b3_i$
0	$.1105836875 \times 10^{4}$	$-.2234264997 \times 10^{7}$	$.9059978254 \times 10^{3}$
1	$.1436943768 \times 10^{2}$	$.1231247634 \times 10^{7}$	$.5561957539 \times 10^{1}$
2	$.8018288621 \times 10^{0}$	$-.1978847871 \times 10^{6}$	$.3434189609 \times 10^{1}$
3	$.1617232913 \times 10^{-1}$	$.1859988044 \times 10^{2}$	$-.6406390628 \times 10^{0}$
4	$-.1501147505 \times 10^{-2}$	$-.2765701318 \times 10^{1}$	$.5918579484 \times 10^{-1}$
5	$.0000000000 \times 10^{0}$	$.1036033878 \times 10^{4}$	$-.2725378570 \times 10^{-2}$
6	$.0000000000 \times 10^{0}$	$-.2143423131 \times 10^{3}$	$.5006336938 \times 10^{-4}$
7	$.0000000000 \times 10^{0}$	$.1690507762 \times 10^{2}$	
8	$.0000000000 \times 10^{0}$	$-.4864322134 \times 10^{2}$	
9	$-.1237675562 \times 10^{-5}$		
10	$.3004773304 \times 10^{-5}$		
11	$-.2062390734 \times 10^{-6}$		

APPENDIX A-2

PROGRAM LISTING

```
C       A THREE DIMENSIONAL COMPRESSIBLE FLUID FLOW USING POROUS
C       MEDIUM IN    THE PRESENCE OF NONCONDENSABLE.
C       A PROGRAM WRITTEN BY MOHAMMED ALJOHANI
C       THE SUBROUTINES NBTRIP AND PBTRIP ARE TAKEN FROM
C       (COMPUTATIONAL FLUID
C       MECHANICS AND HEAT TRANSFER) BY ANDERSON, TANNEHILL AND
C       PLETCHER
C       THESE SUBROUTINES
C       WERE WRITTEN BY AUKUMAR R. CHAKRAVARTHY,
        PROGRAM MAIN
        PARAMETER(L=11,M=11,N=11,IS=6)
        REAL*8 UX(L,M,N),VY(L,M,N),WZ(L,M,N),RHO(L,M,N),TE(L,M,N)
        REAL*8 RHO1(L,M,N),RHO2(L,M,N)
        REAL*8 ASMI(IS,IS),ASPI(IS,IS),RSMI(IS,IS),RSPI(IS,IS)
        REAL*8 RSI(IS,IS),ATMI(IS,IS,L),ATPI(IS,IS,L),ATI(IS,IS,L)
        REAL*8 CTMI(IS,IS,N),CTPI(IS,IS,N),CTI(IS,IS,N)
        REAL*8 PFX(IS),PV1X(IS),PV2X(IS),PV3X(IS),PV2X2(IS,L,M,N)
        REAL*8 PV3X2(IS,L,M,N),PV1X2(IS,L,M,N),PGY(IS)
        REAL*8 PR(L,M,N),EN(L,M,N),PW1Y2(IS,L,M,N)
        REAL*8 PW2Y2(IS,L,M,N),PW3Y2(IS,L,M,N),PW1Y(IS)
        REAL*8 PW2Y(IS),PW3Y(IS),PXDV1(IS),PXDV2(IS),PXDV3(IS),DELU(IS)
        REAL*8 BMAINX(IS,L),BMAINY(IS,M),BMAINZ(IS,N),UCON(IS)
        REAL*8 UCONX(IS,L),UCONY(IS,M),UCONZ(IS,N)
        REAL*8 PYDW1(IS),PYDW2(IS),PYDW3(IS),DUCON(IS,L,M,N)
        REAL*8 UOLD(IS,L,M,N),BTMI(IS,IS,M),UNEW(IS,L,M,N)
        REAL*8 BTPI(IS,IS,M),BTI(IS,IS,M),PHZ(IS),PE1Z(IS),PE2Z(IS)
        REAL*8 PE3Z(IS),PZDE1(IS),PE1Z2(IS,L,M,N),PZDE2(IS),PZDE3(IS)
        REAL*8 PE2Z2(IS,L,M,N),PE3Z2(IS,L,M,N),BETA(L,M,N),ERGUN(IS)
        REAL*8 SOURC(IS,IS),ERGUNS(IS),SOURCS(IS,IS)
        REAL*8 AMDD(L,M,N),QOA(L,M,N),SPECSA(L,M,N),CONCS(IS)
        REAL*8 CONN(IS,IS),CONNEW(IS,L,M,N),CONOLD(IS,L,M,N)
        REAL*8 FISE(L,M,N),UE(L,M,N),PS(L,M,N),TC(L,M,N),HSA(L,M,N)
        REAL*8 HEAS(L,M,N),FIS(L,M,N),HFG(L,M,N),HCA(L,M,N)
        REAL*8 XX(L,M,N),YY(L,M,N),ZZ(L,M,N),AJM(L,M,N),ITMM
```

```
 REAL*8 DX1,DX,DY1,DY,DZ1,DZ,FRAC1,FRAC2,FRAC,PIN,POUT,DT
 REAL*8 RPI,RMI,RIJ,R1PI,R1MI,R1IJ,R2PI,R2MI,R2IJ,UPI,UMI,UIJ
 REAL*8 VPI,VMI,VIJ,WPI,WMI,WIJ,EPI,EMI,EIJ,PPI,PMI,PIJ,TPI,TMI
 REAL*8 TIJ,BPI,BMI,BIJ,RPJ,RMJ,R1PJ,R1MJ,R2PJ,R2MJ,UPJ,UMJ,VPJ
 REAL*8 VMJ,WPJ,WMJ,EPJ,EMJ,PPJ,PMJ,TPJ,TMJ,BPJ,BMJ,RPK,RMK,R1PK
 REAL*8     R1MK,R2PK,R2MK,UPK,UMK,VPK,VMK,WPK,WMK,EPK,
/EMK,PPK,PMK,TPK
 REAL*8 TMK,BPK,BMK,RPIPJ,RMIPJ,R1PIPJ,R1MIPJ,R2PIPJ,R2MIPJ,UPIPJ
 REAL*8 UMIPJ,VPIPJ,VMIPJ,WPIPJ,WMIPJ,EPIPJ,EMIPJ,RPIMJ,RMIMJ
 REAL*8 R1PIMJ,R1MIMJ,R2PIMJ,R2MIMJ,UPIMJ,UMIMJ,
/VPIMJ,VMIMJ,WPIMJ
 REAL*8 WMIMJ,EPIMJ,EMIMJ,RPIPK,RMIPK,R1PIPK,
/R1MIPK,R2PIPK,R2MIPK
 REAL*8 UPIPK,UMIPK,VPIPK,VMIPK,WPIPK,WMIPK,EPIPK,EMIPK,RPIMK
 REAL*8 RMIMK,R1PIMK,R1MIMK,R2PIMK,R2MIMK,UPIMK,UMIMK,
/VPIMK,VMIMK
 REAL*8 WPIMK,WMIMK,EPIMK,EMIMK,RPJPK,RMJPK,R1PJPK,
/R1MJPK,R2PJPK
 REAL*8 R2MJPK,UPJPK,UMJPK,VPJPK,VMJPK,WPJPK,
/WMJPK,EPJPK,EMJPK
 REAL*8 RPJMK,RMJMK,R1PJMK,R1MJMK,R2PJMK,R2MJMK,
/UPJMK,UMJMK,VPJMK
 REAL*8 VMJMK,WPJMK,WMJMK,EPJMK,EMJMK
 REAL*8 UPIH,UMIH,UPJH,UMJH,UPKH,UMKH,VPIH,VMIH,
/VPJH,VMJH,VPKH,VMKH
 REAL*8 WPIH,WMIH,WPJH,WMJH,WPKH,WMKH,RPIH,RMIH,RPJH,
/RMJH,RPKH,RMKH
 REAL*8 BPIH,BMIH,BPJH,BMJH,BPKH,BMKH
 REAL*8 AA,BB,CC,DD
 OPEN(UNIT=12,FILE='TRANS',STATUS='UNKNOWN')
 OPEN(UNIT=101,FILE='C0401',STATUS='UNKNOWN')
```

```
 OPEN(UNIT=102,FILE='C0402',STATUS='UNKNOWN')
 OPEN(UNIT=103,FILE='C0403',STATUS='UNKNOWN')
 OPEN(UNIT=104,FILE='C0404',STATUS='UNKNOWN')
 OPEN(UNIT=105,FILE='C0405',STATUS='UNKNOWN')
 OPEN(UNIT=106,FILE='C0406',STATUS='UNKNOWN')
 OPEN(UNIT=107,FILE='C0407',STATUS='UNKNOWN')
 OPEN(UNIT=108,FILE='C0408',STATUS='UNKNOWN')
 OPEN(UNIT=109,FILE='C0409',STATUS='UNKNOWN')
 OPEN(UNIT=110,FILE='C0410',STATUS='UNKNOWN')
 OPEN(UNIT=111,FILE='C0411',STATUS='UNKNOWN')
 OPEN(UNIT=112,FILE='C0412',STATUS='UNKNOWN')
```

```
 PRINT *, 'FOR CONSTANT INLET PRSR, PRES 1,
/FOR CONS INLT VELCY PRES ANY NMBR'
 READ(*,*) PRESUR
 PRINT *, 'TIME STEP-DT-'
 READ(*,*) DT
 PRINT *, 'STEAM INLET FRACTION'
 READ(*,*) FRAC1
 PRINT *, 'GAS INLET FRACTION'
 READ(*,*) FRAC2
 PRINT *, 'FOR PACKED BED ENTER 1, ELSE ENTER ZERO'
 READ(*,*) PORNTP
 PRINT *, 'FOR SHELL AND TUBE ENTER 1, ELSE ENTER ZERO'
 READ(*,*) PORNTS
 IF(PRESUR.EQ.1.) THEN
 PRINT *, 'ENTER INLET PRESSURE'
 READ(*,*) PIN
 ELSE
 PRINT *, 'ENTER INLET X-VELOCITY'
 READ(*,*) UIN
 PRINT *, 'FOR SHELL AND TUBE CONDENSATION
/ENTER 1, ELSE ENTER ANY NUMBER'
```

```
      READ(*,*) SHNON
      PRINT *, 'ENTER INLET X-VELOCITY'
      PRINT *, 'FOR PACKED BED CONDENSATION
     /ENTER 1, ELSE ENTER ANY NUMBER'
      READ(*,*) PANON
      ENDIF

      PRINT *, 'ENTER OUTLET PRESSURE'
      READ(*,*) POUT
      PRINT *, 'ENTER X-DISSIPATION COEFFIETIENT'
      READ(*,*) EPSX
      PRINT *, 'ENTER Y-DISSIPATION COEFFIETIENT'
      READ(*,*) EPSY
      PRINT *, 'ENTER Z-DISSIPATION COEFFIETIENT'
      READ(*,*) EPSZ
C      DT=.02

      DO 2003 I=1,L
      DO 2003 J=1,M
      DO 2003 K=1,N
C   READ THE TRANSFORMATION COORDINATE SYSTEM FROM THE FILE
C  TRANS
C   THE FILE TRANS IS GENERATED BY THE PROGRAM TRANS.F
C   XX, YY, ZZ ARE THE GREEK LETTERS XI, ETA, AND ZETA, RESP.
C   AJM IS THE TRANSFORMATION JACOBIAN.
C      READ(12,*) XX(I,J,K),YY(I,J,K),ZZ(I,J,K),AJM(I,J,K)
C   FOR NO TRANSFORMATION REMOVE THE FOUR COMMENTED LINES
C  AND DO NOT RUN TRANS.F


       XX(I,J,K)=1.
       YY(I,J,K)=1.
       ZZ(I,J,K)=1.
       AJM(I,J,K)=1.
 2003 CONTINUE


C     READ THE METRICS FORM FILE XYZ.GRD
```

```
C     THESE ARE THE CORNORS OF THE BOUNDARIES
C       DELHX=.9999

C     THESE ARE THE DIMENSTIONS IN WHICH THE BOUNDARIES ARE
C     DEFINED.

      LX1=1
      LX2=1
      LX3=L
      LX4=L
      NY1=1
      NY2=6
      NY3=6
      NY4=M




      diff=0.

C    THESE ARE THE INCREMENTS IN ALL DIRECTIONS
      DX1=.1
      DX=2.*DX1

C       DELHY=.9999
      DY1=.1
      DY=2.*DY1

      DZ1=.1
      DZ=2.*DZ1
```

```
      PI=3.1415927

      THK=0.0035


      GAM=1.4
C      AVIS=.896
      ALAM=-2./3.*AVIS

C     DP IS THE PARTICaL DIAMETER IN THE POROUS MEDIUM
C    FORMULATION

      DP=5./1000.

      TH=1.

      SW=.5

C     THIS IS THE INITIAL TEMPERATURE.
      TIN=300.


      THD=TH

      ALV=ALAM+2.*AVIS



C    THE FOLLOWING ARE THE IMPLICIT DISSIPATION COEFFICEINTS.
C    PUT PROPER VALUES WHEN NEEDED AS AFUNCTION OF EPSX,EPSY
C    AND EPSX

      EPSIX=0.
      EPSIY=0.
      EPSIZ=0.


C    THIS IS THA MAXIMUM TIME LIMIT
```

```
      ITMAX=5000
00
      WX=(1.+2.*SW)/2.
C      WX=0.
      WY=WX
      WWZ=WX
      RIN=1.

      VINF=1.
      RINF=1.

      AMINF=1.
      TINF=VINF*VINF
      ALINF=1.
      RGAS=287.
C      8.314E3/18.
      CVOL=RGAS/(GAM-1.)


      CP=GAM*RGAS/(GAM-1.)

      AMCINF=VINF/SQRT(GAM*RGAS*TINF)



C


      PRNUM=0.72
C      AVIS*AMINF*CP/THK


      REINF=RINF*VINF*ALINF/AMINF



C     DSO IS THE TUBE DIAMETER
      DSO=19/1000.
C     PIT IS THE PITCH SIZE
```

```
      PIT=26/1000.

C     THIS IS THE CONVERGANCE RELATIVE LIMIT

      EPPS=1.E-5


C     THIS THE POROSITY FOR PACKED BED AND SHELL AND TUBE

      DO 50 I=1,L

      DO 50 J=1,M
      DO 50 K=1,N
      IF(PORNTP.EQ.0.AND.PORNTS.EQ.0.) THEN
      BETA(I,J,K)=1.

      ELSEIF(PORNTS.EQ.1) THEN

      BETA(I,J,K)=1.-PI/4.*(DSO/PIT)**2.

C     THESE ARE INITIAL CONDITIONS FOR CONDENSATION PART OF SHELL
C     AND TUBE

      AMDD(I,J,K)=0.
      QOA(I,J,K)=0.


C     THIS IS THE SPECIFIC AREA OF THE SHELL AND TUBE CONDNESER

      SPECSA(I,J,K)=4.*(1.-BETA(I,J,K))/DSO


ELSEIF(PORNTP.EQ.1) THEN
```

```
      BETA(I,J,K)=.39
C     THESE ARE INITIAL CONDITIONS FOR CONDENSATION PART OF
C     PACKED BED CONDENSOR
      AMDD(I,J,K)=0.
      QOA(I,J,K)=0.

C     THIS IS THE SPECIFIC AREA OF THE PACKED BED CONDNESER
      SPECSA(I,J,K)=6.*(1.-BETA(I,J,K))/DP

      ELSE
      ENDIF

   50 CONTINUE
C     THIS IS THE VALUE OF BT
      BETAT=1.-PI/4.*(DSO/PIT)**2.

C     THIS IS THE COEFFICEINT OF THE MASS EQUATIONS INCLUDING THE
C     NONDIMINSIONALIZED TERM.
C     DIFF IS THYE DIFFUSION COEFFICIENT.
C      DIFF=1.
      GEE=DIFF/(VINF*ALINF)
```

```
C     THIS IS THE INITIAL CON. ALL OVER THE NUMERICAL DOMAIN

      DO 120 I=2,L-1
      DO 120 J=2,M-1
      DO 120 K=2,N-1
      IF((I.LE.LX2.AND.J.LE.NY2).OR.(I.GE.LX3.AND.J.GE.NY3)) THEN
      UX(I,J,K)=0.
      VY(I,J,K)=0.
      WZ(I,J,K)=0.
      PR(I,J,K)=0.
      RHO1(I,J,K)=0.
      RHO2(I,J,K)=0.
      RHO(I,J,K)=0.
      EN(I,J,K)=0.
      TE(I,J,K)=0.
      ELSE
      UX(I,J,K)=0.
      VY(I,J,K)=0.
      WZ(I,J,K)=0.
      PR(I,J,K)=POUT
      RHO1(I,J,K)=FRAC1*RIN
      RHO2(I,J,K)=FRAC2*RIN
      RHO(I,J,K)=RHO1(I,J,K)+RHO2(I,J,K)

      EN(I,J,K)=PR(I,J,K)/(GAM-1.)
      TE(I,J,K)=1./(RHO(I,J,K)*CVOL)*EN(I,J,K)
      ENDIF
```

```
 120  CONTINUE
C     TO BE USED FOR WRITE STATEMENT AT FIXED Z

      NY=(M-1)/2+1
      NZ=(N-1)/2+1

C     THE FOLL. IS THE TIME LOOP

      DO 130 ITIME=1,ITMAX

C     ITMM IS AN INDEX TO PRINT DATA AT CERTAIN INTERVALS
C     THE INTERVAL HERE IS 100

      FFITM=(FLOAT(ITIME)+49.)/50.
      ITMM=INT((ITIME+49)/50)
      RRITM=FFITM-ITMM

      IF(ITIME.EQ.150.OR.ITIME.EQ.400.OR.ITIME.EQ.600.OR.ITIME
     / .EQ.800.OR.ITIME.EQ.1400) THEN
      DO  988 KK=1,N
      WRITE(*,*)
     /UX(2,NY,KK),RHO(2,NY,KK),UX(L,NY,KK),RHO(L,NY,KK),ITIME
 988  CONTINUE
      ELSE
      ENDIF
```

```
C     THE FOLLOWING STATEMENET ARE TO BE USED AT THE END OF THE
C     PROGRAM TO INITIALIZE THE
C     CONVERGANCE CRITERION

      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
      SUM6=0.


      IF(ITIME.EQ.1) THEN
      SWSW=0.

      THDSW=0.
      ELSE

      SWSW=SW/(1.+SW)

      THDSW=THD*DT/(1.+SW)
      ENDIF


      DTSW=DT/(1.+SW)
      THSW=TH*DT/(1.+SW)
C     INLET AND EXIT B.C'S



      DO 132 KK=2,N-1
      DO 132 JJ=2,M-1
C     THIS IS THE OPEN INLET BOUNDARY CONDITIONS

      IF(JJ.GT.NY2) THEN


      IF(PRESUR.EQ.1.) THEN
```

```
      UX(1,JJ,KK)=UX(2,JJ,KK)
      PR(1,JJ,KK)=PIN
      ELSE
      UX(1,JJ,KK)=UIN
      PR(1,JJ,KK)=PR(2,JJ,KK)
      ENDIF

      VY(1,JJ,KK)=0.

      WZ(1,JJ,KK)=0.


      RHO1(1,JJ,KK)=FRAC1*RIN

      RHO2(1,JJ,KK)=FRAC2*RIN

      RHO(1,JJ,KK)=RHO1(1,JJ,KK)+RHO2(1,JJ,KK)



                  EN(1,JJ,KK)=PR(1,JJ,KK)/(GAM-1.)+
     /0.5*RHO(1,JJ,KK)*UX(1,JJ,KK)**2.

      TE(1,JJ,KK)=1./(RHO(1,JJ,KK)*CVOL)*(EN(1,JJ,KK)-
     /0.5*RHO(1,JJ,KK)*UX(1,JJ,KK)**2.)
      ELSE
      ENDIF

C     THIS IS THE NONSLIP INLET ( 1ST. X SURFACE)
      IF(JJ.LE.NY2) THEN
      UX(LX2,JJ,KK)=0.
      PR(LX2,JJ,KK)=4./3.*PR(LX2+1,JJ,KK)-1./3.*PR(LX2+2,JJ,KK)

      VY(LX2,JJ,KK)=0.
      WZ(LX2,JJ,KK)=0.
      TE(LX2,JJ,KK)=1./3.*(4.*TE(LX2+1,JJ,KK)-TE(LX2+2,JJ,KK))
      EN(LX2,JJ,KK)=1./3.*(4.*EN(LX2+1,JJ,KK)-EN(LX2+2,JJ,KK))
      RHO1(LX2,JJ,KK)=1./3.*(4.*RHO1(LX2+1,JJ,KK)-RHO1(LX2+2,JJ,KK))
```

```
      RHO2(LX2,JJ,KK)=1./3.*(4.*RHO2(LX2+1,JJ,KK)-RHO2(LX2+2,JJ,KK))
      RHO(LX2,JJ,KK)=RHO1(LX2,JJ,KK)+RHO2(LX2,JJ,KK)
      ELSE
      ENDIF


C     THE FOLL. ARE THE OUTLET B.C'S
      IF(JJ.LT.NY3) THEN
      UX(L,JJ,KK)=UX(L-1,JJ,KK)

      VY(L,JJ,KK)=VY(L-1,JJ,KK)

      WZ(L,JJ,KK)=WZ(L-1,JJ,KK)

      RHO1(L,JJ,KK)=RHO1(L-1,JJ,KK)
      RHO2(L,JJ,KK)=RHO2(L-1,JJ,KK)
      RHO(L,JJ,KK)=RHO1(L,JJ,KK)+RHO2(L,JJ,KK)



      PR(L,JJ,KK)=POUT

            EN(L,JJ,KK)=PR(L,JJ,KK)/(GAM-1.)+
     /0.5*RHO(L,JJ,KK)*(UX(L,JJ,KK)**2.
     /+VY(L,JJ,KK)**2.+WZ(L,JJ,KK)**2.)

      TE(L,JJ,KK)=1./(RHO(L,JJ,KK)*CVOL)*(EN(L,JJ,KK)-
     /0.5*RHO(L,JJ,KK)*(UX(L,JJ,KK)**2.+VY(L,JJ,KK)**2.+
     /WZ(L,JJ,KK)**2.))
      ELSE
      ENDIF
C     THIS IS THE NON-SLIP OUTLET B.C'S ( 2ND X SURFACE)
      IF(JJ.GE.NY3) THEN
      UX(LX3,JJ,KK)=0.
      VY(LX3,JJ,KK)=0.
      WZ(LX3,JJ,KK)=0.
      PR(LX3,JJ,KK)=4./3.*PR(LX3-1,JJ,KK)-1./3.*PR(LX3-2,JJ,KK)

      TE(LX3,JJ,KK)=1./3.*(4.*TE(LX3-1,JJ,KK)-TE(LX3-2,JJ,KK))
```

```
      EN(LX3,JJ,KK)=1./3.*(4.*EN(LX3-1,JJ,KK)-EN(LX3-2,JJ,KK))
      RHO1(LX3,JJ,KK)=1./3.*(4.*RHO1(LX3-1,JJ,KK)-RHO1(LX3-2,JJ,KK))
      RHO2(LX3,JJ,KK)=1./3.*(4.*RHO2(LX3-1,JJ,KK)-RHO2(LX3-2,JJ,KK))
      RHO(LX3,JJ,KK)=RHO1(LX3,JJ,KK)+RHO2(LX3,JJ,KK)
      ELSE
      ENDIF


  132 CONTINUE

C     NOW, START THE WALL B.C'S, NORMAL TO THE Y-AXIS
C     FIRST, THE LOWER B.C,S

      DO 134 II=1,L
      DO 134 KK=1,N
C     1ST Y SURFACE FROM BOTTOM

      IF(II.GT.LX2) THEN
      UX(II,1,KK)=0.
      PR(II,1,KK)=PR(II,2,KK)
C      4./3.*PR(II,2,KK)-1./3.*PR(II,3,KK)

      VY(II,1,KK)=0.
      WZ(II,1,KK)=0.
      TE(II,1,KK)=TE(II,2,KK)
C      1./3.*(4.*TE(II,2,KK)-TE(II,3,KK))
      EN(II,1,KK)=EN(II,2,KK)
C      1./3.*(4.*EN(II,2,KK)-EN(II,3,KK))
      RHO1(II,1,KK)=RHO1(II,2,KK)
C      1./3.*(4.*RHO1(II,2,KK)-RHO1(II,3,KK))
      RHO2(II,1,KK)=RHO2(II,2,KK)
C      1./3.*(4.*RHO2(II,2,KK)-RHO2(II,3,KK))
      RHO(II,1,KK)=RHO1(II,1,KK)+RHO2(II,1,KK)

      ELSE
      ENDIF
C     THE 2ND Y SURFACE FROM BOTTOM
```

```
      IF(II.LE.LX2) THEN

      UX(II,NY2,KK)=0.
      PR(II,NY2,KK)=PR(II,NY2+1,KK)
C      4./3.*PR(II,NY2+1,KK)-1./3.*PR(II,NY2+2,KK)

      VY(II,NY2,KK)=0.
      WZ(II,NY2,KK)=0.
      TE(II,NY2,KK)=TE(II,NY2+1,KK)
C      1./3.*(4.*TE(II,NY2+1,KK)-TE(II,NY2+2,KK))
      EN(II,NY2,KK)=EN(II,NY2+1,KK)
C      1./3.*(4.*EN(II,NY2+1,KK)-EN(II,NY2+2,KK))
      RHO1(II,NY2,KK)=RHO1(II,NY2+1,KK)
C      1./3.*(4.*RHO1(II,NY2+1,KK)-RHO1(II,NY2+2,KK))
      RHO2(II,NY2,KK)=RHO2(II,NY2+1,KK)
C      1./3.*(4.*RHO2(II,NY2+1,KK)-RHO2(II,NY2+2,KK))
      RHO(II,NY2,KK)=RHO1(II,NY2,KK)+RHO2(II,NY2,KK)

      ELSE
      ENDIF

C     THE 3RD. Y SYRFACE

      IF(II.GE.LX3) THEN

      UX(II,NY3,KK)=0.
      PR(II,NY3,KK)=PR(II,NY3-1,KK)
C      4./3.*PR(II,NY3-1,KK)-1./3.*PR(II,NY3-2,KK)

      VY(II,NY3,KK)=0.
      WZ(II,NY3,KK)=0.
      TE(II,NY3,KK)=TE(II,NY3-1,KK)
C      1./3.*(4.*TE(II,NY3-1,KK)-TE(II,NY3-2,KK))
      EN(II,NY3,KK)=EN(II,NY3-1,KK)
C      1./3.*(4.*EN(II,NY3-1,KK)-EN(II,NY3-2,KK))
      RHO1(II,NY3,KK)=RHO1(II,NY3-1,KK)
C      1./3.*(4.*RHO1(II,NY3-1,KK)-RHO1(II,NY3-2,KK))
      RHO2(II,NY3,KK)=RHO2(II,NY3-1,KK)
```

```
C        1./3.*(4.*RHO2(II,NY3-1,KK)-RHO2(II,NY3-2,KK))
      RHO(II,NY3,KK)=RHO1(II,NY3,KK)+RHO2(II,NY3,KK)

      ELSE
      ENDIF


C     NOW DO THE UPPER B.C'S
      IF(II.LT.LX3) THEN
      UX(II,M,KK)=0.
      VY(II,M,KK)=0.
      WZ(II,M,KK)=0.
      PR(II,M,KK)=PR(II,M-1,KK)
C        4./3.*PR(II,M-1,KK)-1./3.*PR(II,M-2,KK)

      TE(II,M,KK)=TE(II,M-1,KK)
C        1./3.*(4.*TE(II,M-1,KK)-TE(II,M-2,KK))
      EN(II,M,KK)=EN(II,M-1,KK)
C        1./3.*(4.*EN(II,M-1,KK)-EN(II,M-2,KK))
      RHO1(II,M,KK)=RHO1(II,M-1,KK)
C        1./3.*(4.*RHO1(II,M-1,KK)-RHO1(II,M-2,KK))
      RHO2(II,M,KK)=RHO2(II,M-1,KK)
C        1./3.*(4.*RHO2(II,M-1,KK)-RHO2(II,M-2,KK))

      RHO(II,M,KK)=RHO1(II,M,KK)+RHO2(II,M,KK)

      ELSE
      ENDIF

  134 CONTINUE



C     NOW, START THE WALL B.C'S, NORMAL TO THE Z-AXIS
```

```
C     FIRST, THE LEFT B.C,S

      DO 135 II=1,L
      DO 135 JJ=1,M
      UX(II,JJ,1)=UX(II,JJ,2)
C     0.
      PR(II,JJ,1)=PR(II,JJ,2)
C      4./3.*PR(II,JJ,2)-1./3.*PR(II,JJ,3)

      VY(II,JJ,1)=VY(II,JJ,2)
C      0.
      WZ(II,JJ,1)=WZ(II,JJ,2)
C      0.
      TE(II,JJ,1)=TE(II,JJ,2)
C      1./3.*(4.*TE(II,JJ,2)-TE(II,JJ,3))
      EN(II,JJ,1)=EN(II,JJ,2)
C      1./3.*(4.*EN(II,JJ,2)-EN(II,JJ,3))
      RHO1(II,JJ,1)=RHO1(II,JJ,2)
      RHO2(II,JJ,1)=RHO2(II,JJ,2)
      RHO(II,JJ,1)=RHO1(II,JJ,1)+RHO2(II,JJ,1)
C      1./3.*(4.*RHO(II,JJ,2)-RHO(II,JJ,3))



C     NOW DO THE UPPER B.C'S

      UX(II,JJ,N)=UX(II,JJ,N-1)
C      0.
      VY(II,JJ,N)=VY(II,JJ,N-1)
C      0.
      WZ(II,JJ,N)=WZ(II,JJ,N-1)
C      0.
      PR(II,JJ,N)=PR(II,JJ,N-1)
C      4./3.*PR(II,JJ,N-1)-1./3.*PR(II,JJ,N-2)

      TE(II,JJ,N)=TE(II,JJ,N-1)
C      1./3.*(4.*TE(II,JJ,N-1)-TE(II,JJ,N-2))
      EN(II,JJ,N)=EN(II,JJ,N-1)
```

```
C        1./3.*(4.*EN(II,JJ,N-1)-EN(II,JJ,N-2))
      RHO1(II,JJ,N)=RHO1(II,JJ,N-1)
      RHO2(II,JJ,N)=RHO2(II,JJ,N-1)

      RHO(II,JJ,N)=RHO1(II,JJ,N)+RHO2(II,JJ,N)
C        1./3.*(4.*RHO(II,JJ,N-1)-RHO(II,JJ,N-2))


 135  CONTINUE



C     THE FOLL. IS THE X-SWEEP

C     THE Y-DO-LOOP OF THE X-SWEEP

      DO 140 K=2,N-1


      DO 140 J=2,M-1


C     HERE WE UPDATE THE UCONX, THE X-DISSIPATIVE TERMS

      DO 136 I=1,L
      UCONX(1,I)=RHO1(I,J,K)
      UCONX(2,I)=RHO(I,J,K)*UX(I,J,K)
      UCONX(3,I)=RHO(I,J,K)*VY(I,J,K)
      UCONX(4,I)=RHO(I,J,K)*WZ(I,J,K)
      UCONX(5,I)=EN(I,J,K)
      UCONX(6,I)=RHO2(I,J,K)
 136  CONTINUE
```

```
C     THE X-SWEEP DO-LOOP STRATS

      DO 150 I=2,L-1

C     THIS IF STATEMENT IS TO EXCLUDE THE DOMAIN THAT HAS NO FLOW


C     NOW START THE EXCIPLIST PORTION "THE RHS OF THE X-SWEEP'

C     PFX=PARTIAL DERIVATIVE OF F WRT X
C     PV1X= ===================V1=====
C     PV2X= ===================V2=====

C     PGY======================G ====Y
C     PW1Y= ===================W1 ===Y
C     PW2Y= ===================W2 ===Y
C     DEFINE THE PREMITIVE VARIABLES AS FOLLOWS

C     THIS IS THE SUTHERLAND VISCOSITY RELATIONSHIP.

C     VISCOSITY OF STEAM
      CST=861.1
      TSR=416.1
      AVSR=.1706E-6
      AVS=AVSR*((TSR+CST)/(TE(I,J,K)+CST))*(TE(I,J,K)/TSR)**1.5


C     VISCOSITY FOR AIR
      CGT=110.6
      TGR=273.1
      AVGR=.1716E-6
```

```
      AVG=AVGR*((TGR+CGT)/(TE(I,J,K)+CGT))*(TE(I,J,K)/TGR)**1.5

C     MIXTURE VISCOSITY

      AVSGU=(1.+
((AVS/AVR)**.5)*(AMOG/AMOS)**.25)**2.
      AVSGD=SQRT(8.)*(1.+AMOS/AMOG)**.5
      PHISG=AVSGU/AVSGD
      AMOS=18.
C     ASSUMING OXYGAN ONLY.
      AMOG=29.
      AVGSU=(1.+
((AVR/AVS)**.5)*(AMOS/AMOG)**.25)**2.
      AVGSD=SQRT(8.)*(1.+AMOG/AMOS)**.5
      PHIGS=AVGSU/AVGSD

      SFRAC=RHO1(I,J,K)/(RHO1(I,J,K)+RHO2(I,J,K))
      GFRAC=RHO2(I,J,K)/(RHO1(I,J,K)+RHO2(I,J,K))
      AVIS=(SFRAC*AVS)/(SFRAC+PHISG*GFRAC)+
     /(GFRAC*AVG)/(GFRAC+PHIGS*SFRAC)


C     THK IS NOT NEEDED IN THIS PROGRAM BECAUSE IT IS INCLUDED IN
C     THE PRNUM
      THK=CP*AVIS/0.72
      ALAM=-2./3.*AVIS


C     PRREM IS A COEFFICIENT.
      PRREM=AVIS/((GAM-1.)*AMCINF*AMCINF*REINF*PRNUM)
C     NONDIMENSIONALIZE AVIS AND ALAM.

C      AVIS=AVIS/AMINF
C      ALAM=ALAM/AMINF
```

```
RPI=RHO(I+1,J,K)
RMI=RHO(I-1,J,K)
RIJ=RHO(I,J,K)

R1PI=RHO1(I+1,J,K)
R1MI=RHO1(I-1,J,K)
R1IJ=RHO1(I,J,K)

R2PI=RHO2(I+1,J,K)
R2MI=RHO2(I-1,J,K)
R2IJ=RHO2(I,J,K)

UPI=UX(I+1,J,K)
UMI=UX(I-1,J,K)
UIJ=UX(I,J,K)
VPI=VY(I+1,J,K)
VMI=VY(I-1,J,K)
VIJ=VY(I,J,K)
WPI=WZ(I+1,J,K)
WMI=WZ(I-1,J,K)
WIJ=WZ(I,J,K)
EPI=EN(I+1,J,K)
EMI=EN(I-1,J,K)
EIJ=EN(I,J,K)
PPI=PR(I+1,J,K)
PMI=PR(I-1,J,K)
PIJ=PR(I,J,K)
TPI=TE(I+1,J,K)
TMI=TE(I-1,J,K)
TIJ=TE(I,J,K)
BPI=BETA(I+1,J,K)
BMI=BETA(I-1,J,K)
BIJ=BETA(I,J,K)

RPJ=RHO(I,J+1,K)
RMJ=RHO(I,J-1,K)

R1PJ=RHO1(I,J+1,K)
```

```
R1MJ=RHO1(I,J-1,K)

R2PJ=RHO2(I,J+1,K)
R2MJ=RHO2(I,J-1,K)

UPJ=UX(I,J+1,K)
UMJ=UX(I,J-1,K)
VPJ=VY(I,J+1,K)
VMJ=VY(I,J-1,K)
WPJ=WZ(I,J+1,K)
WMJ=WZ(I,J-1,K)
EPJ=EN(I,J+1,K)
EMJ=EN(I,J-1,K)
PPJ=PR(I,J+1,K)
PMJ=PR(I,J-1,K)
TPJ=TE(I,J+1,K)
TMJ=TE(I,J-1,K)
BPJ=BETA(I,J+1,K)
BMJ=BETA(I,J-1,K)

RPK=RHO(I,J,K+1)
RMK=RHO(I,J,K-1)

R1PK=RHO1(I,J,K+1)
R1MK=RHO1(I,J,K-1)

R2PK=RHO2(I,J,K+1)
R2MK=RHO2(I,J,K-1)

UPK=UX(I,J,K+1)
UMK=UX(I,J,K-1)
VPK=VY(I,J,K+1)
VMK=VY(I,J,K-1)
WPK=WZ(I,J,K+1)
WMK=WZ(I,J,K-1)
EPK=EN(I,J,K+1)
EMK=EN(I,J,K-1)
PPK=PR(I,J,K+1)
PMK=PR(I,J,K-1)
```

```
TPK=TE(I,J,K+1)
TMK=TE(I,J,K-1)
BPK=BETA(I,J,K+1)
BMK=BETA(I,J,K-1)



RPIPJ=RHO(I+1,J+1,K)
RMIPJ=RHO(I-1,J+1,K)

R1PIPJ=RHO1(I+1,J+1,K)
R1MIPJ=RHO1(I-1,J+1,K)

R2PIPJ=RHO2(I+1,J+1,K)
R2MIPJ=RHO2(I-1,J+1,K)


UPIPJ=UX(I+1,J+1,K)
UMIPJ=UX(I-1,J+1,K)
VPIPJ=VY(I+1,J+1,K)
VMIPJ=VY(I-1,J+1,K)
WPIPJ=WZ(I+1,J+1,K)
WMIPJ=WZ(I-1,J+1,K)
EPIPJ=EN(I+1,J+1,K)
EMIPJ=EN(I-1,J+1,K)



RPIMJ=RHO(I+1,J-1,K)
RMIMJ=RHO(I-1,J-1,K)

R1PIMJ=RHO1(I+1,J-1,K)
R1MIMJ=RHO1(I-1,J-1,K)

R2PIMJ=RHO2(I+1,J-1,K)
R2MIMJ=RHO2(I-1,J-1,K)
```

```
UPIMJ=UX(I+1,J-1,K)
UMIMJ=UX(I-1,J-1,K)
VPIMJ=VY(I+1,J-1,K)
VMIMJ=VY(I-1,J-1,K)
WPIMJ=WZ(I+1,J-1,K)
WMIMJ=WZ(I-1,J-1,K)
EPIMJ=EN(I+1,J-1,K)
EMIMJ=EN(I-1,J-1,K)


RPIPK=RHO(I+1,J,K+1)
RMIPK=RHO(I-1,J,K+1)

R1PIPK=RHO1(I+1,J,K+1)
R1MIPK=RHO1(I-1,J,K+1)

R2PIPK=RHO2(I+1,J,K+1)
R2MIPK=RHO2(I-1,J,K+1)

UPIPK=UX(I+1,J,K+1)
UMIPK=UX(I-1,J,K+1)
VPIPK=VY(I+1,J,K+1)
VMIPK=VY(I-1,J,K+1)
WPIPK=WZ(I+1,J,K+1)
WMIPK=WZ(I-1,J,K+1)
EPIPK=EN(I+1,J,K+1)
EMIPK=EN(I-1,J,K+1)



RPIMK=RHO(I+1,J,K-1)
RMIMK=RHO(I-1,J,K-1)

R1PIMK=RHO1(I+1,J,K-1)
R1MIMK=RHO1(I-1,J,K-1)

R2PIMK=RHO2(I+1,J,K-1)
R2MIMK=RHO2(I-1,J,K-1)
```

```
      UPIMK=UX(I+1,J,K-1)
      UMIMK=UX(I-1,J,K-1)
      VPIMK=VY(I+1,J,K-1)
      VMIMK=VY(I-1,J,K-1)
      WPIMK=WZ(I+1,J,K-1)
      WMIMK=WZ(I-1,J,K-1)
      EPIMK=EN(I+1,J,K-1)
      EMIMK=EN(I-1,J,K-1)



      RPJPK=RHO(I,J+1,K+1)
      RMJPK=RHO(I,J-1,K+1)

      R1PJPK=RHO1(I,J+1,K+1)
      R1MJPK=RHO1(I,J-1,K+1)

      R2PJPK=RHO2(I,J+1,K+1)
      R2MJPK=RHO2(I,J-1,K+1)

      UPJPK=UX(I,J+1,K+1)
      UMJPK=UX(I,J-1,K+1)
      VPJPK=VY(I,J+1,K+1)
      VMJPK=VY(I,J-1,K+1)
      WPJPK=WZ(I,J+1,K+1)
      WMJPK=WZ(I,J-1,K+1)
      EPJPK=EN(I,J+1,K+1)
      EMJPK=EN(I,J-1,K+1)



      RPJMK=RHO(I,J+1,K-1)
      RMJMK=RHO(I,J-1,K-1)

      R1PJMK=RHO1(I,J+1,K-1)
      R1MJMK=RHO1(I,J-1,K-1)
```

```
      R2PJMK=RHO2(I,J+1,K-1)
      R2MJMK=RHO2(I,J-1,K-1)

      UPJMK=UX(I,J+1,K-1)
      UMJMK=UX(I,J-1,K-1)
      VPJMK=VY(I,J+1,K-1)
      VMJMK=VY(I,J-1,K-1)
      WPJMK=WZ(I,J+1,K-1)
      WMJMK=WZ(I,J-1,K-1)
      EPJMK=EN(I,J+1,K-1)
      EMJMK=EN(I,J-1,K-1)

C     THE FOLOWING STEPS ARE THE VELOCITIES EVALUATED HALF WAY
C     BETWEEN
C     CONSECUTIVE NODES

      UPIH=(UPI+UIJ)/2.
      UMIH=(UIJ+UMI)/2.
      UPJH=(UPJ+UIJ)/2.
      UMJH=(UIJ+UMJ)/2.
      UPKH=(UPK+UIJ)/2.
      UMKH=(UIJ+UMK)/2.

      VPIH=(VPI+VIJ)/2.
      VMIH=(VIJ+VMI)/2.
      VPJH=(VPJ+VIJ)/2.
      VMJH=(VIJ+VMJ)/2.
      VPKH=(VPK+VIJ)/2.
      VMKH=(VIJ+VMK)/2.

      WPIH=(WPI+WIJ)/2.
      WMIH=(WIJ+WMI)/2.
      WPJH=(WPJ+WIJ)/2.
      WMJH=(WIJ+WMJ)/2.
      WPKH=(WPK+WIJ)/2.
```

```
      WMKH=(WIJ+WMK)/2.

      RPIH=(RPI+RIJ)/2.
      RMIH=(RIJ+RMI)/2.
      RPJH=(RPJ+RIJ)/2.
      RMJH=(RIJ+RMJ)/2.
      RPKH=(RPK+RIJ)/2.
      RMKH=(RIJ+RMK)/2.


      BPIH=(BPI+BIJ)/2.
      BMIH=(BIJ+BMI)/2.
      BPJH=(BPJ+BIJ)/2.
      BMJH=(BIJ+BMJ)/2.
      BPKH=(BPK+BIJ)/2.
      BMKH=(BIJ+BMK)/2.

C     THIS IS THE MASS FRACTION FOR CONTINUITY EQUATIONS

      FR1PI=RHO1(I+1,J,K)/RHO(I+1,J,K)
      FR1PJ=RHO1(I,J+1,K)/RHO(I,J+1,K)
      FR1PK=RHO1(I,J,K+1)/RHO(I,J,K+1)

      FR1IJ=RHO1(I,J,K)/RHO(I,J,K)

      FR1MI=RHO1(I-1,J,K)/RHO(I-1,J,K)
      FR1MJ=RHO1(I,J-1,K)/RHO(I,J-1,K)
      FR1MK=RHO1(I,J,K-1)/RHO(I,J,K-1)

      FR2PI=RHO2(I+1,J,K)/RHO(I+1,J,K)
      FR2PJ=RHO2(I,J+1,K)/RHO(I,J+1,K)
      FR2PK=RHO2(I,J,K+1)/RHO(I,J,K+1)

      FR2IJ=RHO2(I,J,K)/RHO(I,J,K)

      FR2MI=RHO2(I-1,J,K)/RHO(I-1,J,K)
      FR2MJ=RHO2(I,J-1,K)/RHO(I,J-1,K)
      FR2MK=RHO2(I,J,K-1)/RHO(I,J,K-1)
```

```
C     THESE ARE THE COEFFICIENT OF TRANSFORMATION
      XXIJ=XX(I,J,K)*XX(I,J,K)*AJM(I,J,K)*BETA(I,J,K)
      YYIJ=YY(I,J,K)*YY(I,J,K)*AJM(I,J,K)*BETA(I,J,K)
      ZZIJ=ZZ(I,J,K)*ZZ(I,J,K)*AJM(I,J,K)*BETA(I,J,K)

      XPI=XX(I+1,J,K)*AJM(I+1,J,K)*BETA(I+1,J,K)
      XMI=XX(I-1,J,K)*AJM(I-1,J,K)*BETA(I-1,J,K)

      YPJ=YY(I,J+1,K)*AJM(I,J+1,K)*BETA(I,J+1,K)
      YMJ=YY(I,J-1,K)*AJM(I,J-1,K)*BETA(I,J-1,K)

      ZPK=ZZ(I,J,K+1)*AJM(I,J,K+1)*BETA(I,J,K+1)
      ZMK=ZZ(I,J,K-1)*AJM(I,J,K-1)*BETA(I,J,K-1)


      XXPI=XX(I+1,J,K)*XX(I+1,J,K)*AJM(I+1,J,K)*BETA(I+1,J,K)
      XXMI=XX(I-1,J,K)*XX(I-1,J,K)*AJM(I-1,J,K)*BETA(I-1,J,K)

      YYPJ=YY(I,J+1,K)*YY(I,J+1,K)*AJM(I,J+1,K)*BETA(I,J+1,K)
      YYMJ=YY(I,J-1,K)*YY(I,J-1,K)*AJM(I,J-1,K)*BETA(I,J-1,K)

      ZZPK=ZZ(I,J,K+1)*ZZ(I,J,K+1)*AJM(I,J,K+1)*BETA(I,J,K+1)
      ZZMK=ZZ(I,J,K-1)*ZZ(I,J,K-1)*AJM(I,J,K-1)*BETA(I,J,K-1)

      XYPI=XX(I+1,J,K)*YY(I+1,J,K)*AJM(I+1,J,K)*BETA(I+1,J,K)
      XYMI=XX(I-1,J,K)*YY(I-1,J,K)*AJM(I-1,J,K)*BETA(I-1,J,K)
      XYPJ=XX(I,J+1,K)*YY(I,J+1,K)*AJM(I,J+1,K)*BETA(I,J+1,K)
      XYMJ=XX(I,J-1,K)*YY(I,J-1,K)*AJM(I,J-1,K)*BETA(I,J-1,K)


      XZPI=XX(I+1,J,K)*ZZ(I+1,J,K)*AJM(I+1,J,K)*BETA(I+1,J,K)
      XZMI=XX(I-1,J,K)*ZZ(I-1,J,K)*AJM(I-1,J,K)*BETA(I-1,J,K)
      XZPK=XX(I,J,K+1)*ZZ(I,J,K+1)*AJM(I,J,K+1)*BETA(I,J,K+1)
      XZMK=XX(I,J,K-1)*ZZ(I,J,K-1)*AJM(I,J,K-1)*BETA(I,J,K-1)

      YZPJ=YY(I,J+1,K)*ZZ(I,J+1,K)*AJM(I,J+1,K)*BETA(I,J+1,K)
      YZMJ=YY(I,J-1,K)*ZZ(I,J-1,K)*AJM(I,J-1,K)*BETA(I,J-1,K)
      YZPK=YY(I,J,K+1)*ZZ(I,J,K+1)*AJM(I,J,K+1)*BETA(I,J,K+1)
```

```
      YZMK=YY(I,J,K-1)*ZZ(I,J,K-1)*AJM(I,J,K-1)*BETA(I,J,K-1)

C      COEFIICIENTS EVALUALUATED HALF WAY

      XXPIH=(XXPI+XXIJ)/2.
      XXMIH=(XXMI+XXIJ)/2.

      YYPJH=(YYPJ+YYIJ)/2.
      YYMJH=(YYMJ+YYIJ)/2.

      ZZPKH=(ZZPK+ZZIJ)/2.
      ZZMKH=(ZZMK+ZZIJ)/2.

C     NEW CONSERVITIVE VARIABLES UPDATE
      UNEW(1,I,J,K)=RHO1(I,J,K)
      UNEW(2,I,J,K)=RHO(I,J,K)*UX(I,J,K)
      UNEW(3,I,J,K)=RHO(I,J,K)*VY(I,J,K)
      UNEW(4,I,J,K)=RHO(I,J,K)*WZ(I,J,K)
      UNEW(5,I,J,K)=EN(I,J,K)
      UNEW(6,I,J,K)=RHO2(I,J,K)

C     START PFX

      PFX(1)=(1./DX)*(XPI*R1PI*UPI-XMI*R1MI*UMI)/BIJ
```

```
      PFX(2)=(1./DX)*(XPI*RPI*UPI*UPI-XMI*RMI*UMI*UMI)/BIJ+
     /1./DX*(XPI*PPI-XMI*PMI)/BIJ
      PFX(3)=(1./DX)*(XPI*RPI*UPI*VPI-XMI*RMI*UMI*VMI)/BIJ
      PFX(4)=(1./DX)*(XPI*RPI*UPI*WPI-XMI*RMI*UMI*WMI)/BIJ
      PFX(5)=(1./DX)*(XPI*(EPI+PPI)*UPI-XMI*(EMI+PMI)*UMI)/BIJ
      PFX(6)=(1./DX)*(XPI*R2PI*UPI-XMI*R2MI*UMI)/BIJ

C     START THE POROSITY TERM PORDRV

C     THIS IS FOR POROUS MEDIUM

      IF(PORNTP.EQ.0.) THEN
C     PER IS THE PERMIABILITY

      PER=1.
C     PORNTP =0. WHEN NONPOROUS MEDIA IS USED

C     CER IS ERGUN FACTOR IN THE ERGUN EQUATION

      CER=0.
      ELSE

C     THE FAR STREAM VALUES AR INCLUDED HERE WHICH BELONG TO
C     THE POROUS MEDIUM SOURCE
C     ALSO REMEMBER THAT THIS FACTOR IS INVERSED WHEN INCLUDED
C     WITHE THE PER BECAUSE IT
C     IT IS PUT IN THE DENOMINATOR.
```

```
      PER=DP*DP*BIJ*BIJ*BIJ/(150.*(1.-BIJ)**2.)*
     /RINF*VINF/(ALINF*AMINF)
      CER=1.75*(1.-BIJ)/(DP*BIJ*BIJ*BIJ)*ALINF*VINF

      ENDIF

C     THIS IS FOR SHELL AND TUBE POROUS MEDIUM

      IF(PORNTS.NE.0.) THEN

C      THIS IS THE SOURCE TERM OF SHELL AND TUBE.

      REX=RIJ*RINF*UIJ*VINF*DSO/(AVIS*AMINF)

      REY=RIJ*RINF*VIJ*VINF*DSO/(AVIS*AMINF)

      REZ=RIJ*RINF*WIJ*VINF*DSO/(AVIS*AMINF)

      IF(REX.LT.8000.) THEN
      ARX=.619
      BRX=.198
      ELSE
      ARX=1.156
      BRX=.2647
      ENDIF

      IF(REY.LT.8000.) THEN
      ARY=.619
      BRY=.198
      ELSE
      ARY=1.156
      BRY=.2647
```

```
      ENDIF


      IF(REZ.LT.8000.) THEN
      ARZ=.619
      BRZ=.198
      ELSE
      ARZ=1.156
      BRZ=.2647
      ENDIF

C      IF(REX.GT.2.E5.OR.REY.GT.2.E5.OR.REZ.GT.2.E5) WRITE(*,*)
C     /"REYNOLD'S NUMBER OUT OF RANGE"


      GG1=(RINF*VINF/AMINF)
      GG2=2.*ALINF/(PIT*RINF)
      GG3=(1.-BIJ)/(1.-BETAT)
      GG4=((PIT*BIJ)/(PIT-DSO))**2.
      GG5=(DSO/AVIS)
      GGX=GG1**(-BRX)*GG2*ARX*GG3*GG4*GG5**(-BRX)

      GGY=GG1**(-BRY)*GG2*ARY*GG3*GG4*GG5**(-BRY)

      GGZ=GG1**(-BRZ)*GG2*ARZ*GG3*GG4*GG5**(-BRZ)
      ELSE

      ENDIF
```

```
C     THIS IS THE ERGUN FACTOR
      ERGUN(1)=0.
      ERGUN(2)=-AVIS*BIJ*UIJ/PER-
     /RIJ*CER*BIJ*BIJ*(UIJ*UIJ+VIJ*VIJ+WIJ*WIJ)*UIJ

      ERGUN(3)=-AVIS*BIJ*VIJ/PER-
     /RIJ*CER*BIJ*BIJ*(UIJ*UIJ+VIJ*VIJ+WIJ*WIJ)*VIJ

      ERGUN(4)=-AVIS*BIJ*WIJ/PER-
     /RIJ*CER*BIJ*BIJ*(UIJ*UIJ+VIJ*VIJ+WIJ*WIJ)*WIJ

      ERGUN(5)=0.
      ERGUN(6)=0.

C     DEFINITION OF TERMS


      AMM=RIJ*UIJ
      ANN=RIJ*VIJ
      AQQ=RIJ*WIJ
      TERMP=(AMM**2.+ANN**2.+AQQ**2.)**(.5)
      IF(UIJ.EQ.0.AND.VIJ.EQ.0.AND.WIJ.EQ.0.) THEN
      TERMM=0.
      ELSE
      TERMM=(AMM**2.+ANN**2.+AQQ**2.)**(-.5)
      ENDIF
      ABSM=ABS(AMM)
      ABSN=ABS(ANN)
      ABSQ=ABS(AQQ)
C     THIS IF STATMENTS IS PUT TO GUARANTEE THAT WE DO NOT HAVE
C     OVER FLOW WHEN HAVING ZERO VELOCITY
C     BECAUSE OF THE NEGATIVE EXPONENT
C      WRITE(*,*) UIJ,VIJ,BRX,BRY


      ERGUNS(1)=0.

      IF(UIJ.EQ.0.) THEN
```

```
      ERGUNS(2)=0.
      ELSE
      ERGUNS(2)=-GGX/(RIJ**2.)*ABSM**(-BRX)*AMM*TERMP
      ENDIF

      IF(VIJ.EQ.0.) THEN
      ERGUNS(3)=0.
      ELSE
      ERGUNS(3)=-GGY/(RIJ**2.)*ABSN**(-BRY)*ANN*TERMP
      ENDIF

      IF(WIJ.EQ.0) THEN
      ERGUNS(4)=0.
      ELSE
      ERGUNS(4)=-GGZ/(RIJ**2.)*ABSQ**(-BRZ)*AQQ*TERMP
      ENDIF

      ERGUNS(5)=0.
      ERGUNS(6)=0.
C      WRITE(*,*) ERGUNS(2),ERGUNS(3),ERGUNS(4),ITIME


C     START PV1X




      PV1X(1)=GEE/(DX1*DX1*BIJ)*(XXPIH*RPIH*(FR1PI-FR1IJ)-
     /XXMIH*RMIH*(FR1IJ-FR1MI))

      PV1X(2)=1./(BIJ*REINF*DX1**2.)*(XXPIH*ALV*(UPI-UIJ)-
     /XXMIH*ALV*(UIJ-UMI))

      PV1X(3)=1./(BIJ*REINF*DX1**2.)*(XXPIH*AVIS*(VPI-VIJ)-
     /XXMIH*AVIS*(VIJ-VMI))
```

```
      PV1X(4)=1./(BIJ*REINF*DX1**2.)*(XXPIH*AVIS*(WPI-WIJ)-
     /XXMIH*AVIS*(WIJ-WMI))

      PV1X(5)=1./(BIJ*REINF*DX1**2.)*(XXPIH*ALV*UPIH*(UPI-UIJ)-
     /XXMIH*ALV*UMIH*(UIJ-UMI))
     /+1./(BIJ*REINF*DX1**2.)*(XXPIH*AVIS*VPIH*(VPI-VIJ)-
     /XXMIH*AVIS*VMIH*(VIJ-VMI))
     /+1./(BIJ*REINF*DX1**2.)*(XXPIH*AVIS*WPIH*(WPI-WIJ)-
     /XXMIH*AVIS*WMIH*(WIJ-WMI))
     /+PRREM/(BIJ*DX1**2.)*(XXPIH*(TPI-TIJ)-
     /XXMIH*(TIJ-TMI))

      PV1X(6)=GEE/(DX1*DX1*BIJ)*(XXPIH*RPIH*(FR2PI-FR2IJ)-
     /XXMIH*RMIH*(FR2IJ-FR2MI))


C     NOW DO PV2X

      PV2X(1)=0.
      PV2X(2)=1./(BIJ*DX*DY)*(ALAM*XYPI*(VPIPJ-VPIMJ)-
     /ALAM*XYMI*(VMIPJ-VMIMJ))*1./REINF

      PV2X(3)=1./(BIJ*DX*DY)*(AVIS*XYPI*(UPIPJ-UPIMJ)-
     /AVIS*XYMI*(UMIPJ-UMIMJ))*
     /1./REINF

      PV2X(4)=0.

      PV2X(5)=1./(BIJ*DX*DY)*(ALAM*UPI*XYPI*(VPIPJ-VPIMJ)-
     /ALAM*UMI*XYMI*(VMIPJ-VMIMJ))*
     /1./REINF
     /+1./(BIJ*DX*DY)*(AVIS*VPI*XYPI*(UPIPJ-UPIMJ)-
     /AVIS*VMI*XYMI*(UMIPJ-UMIMJ))*
     /1./REINF

      PV2X(6)=0.

C     START THE PV3X
```

```
      PV3X(1)=0.

      PV3X(2)=1./(BIJ*DX*DZ)*(ALAM*XZPI*(WPIPK-WPIMK)-
     /ALAM*XZMI*(WMIPK-WMIMK))*
     /1./REINF

      PV3X(3)=0.

      PV3X(4)=1./(BIJ*DX*DZ)*(AVIS*XZPI*(UPIPK-UPIMK)-
     /AVIS*XZMI*(UMIPK-UMIMK))*
     /1./REINF

      PV3X(5)=1./(BIJ*DX*DZ)*(ALAM*UPI*XZPI*(WPIPK-WPIMK)-
     /ALAM*UMI*XZMI*(WMIPK-WMIMK))*
     /1./REINF
     /+1./(BIJ*DX*DZ)*(AVIS*XZPI*WPI*(UPIPK-UPIMK)-
     /AVIS*XZMI*WMI*(UMIPK-UMIMK))*
     /1./REINF

      PV3X(6)=0.

C     START THE PGY


      PGY(1)=1./(DY)*(YPJ*R1PJ*VPJ-YMJ*R1MJ*VMJ)/BIJ

      PGY(2)=1./(DY)*(YPJ*RPJ*UPJ*VPJ-YMJ*RMJ*UMJ*VMJ)/BIJ

      PGY(3)=1./(DY)*(YPJ*RPJ*VPJ*VPJ-YMJ*RMJ*VMJ*VMJ)/BIJ
     /+1./(DY)*(YPJ*PPJ-YMJ*PMJ)/BIJ

      PGY(4)=1./(DY)*(YPJ*RPJ*VPJ*WPJ-YMJ*RMJ*VMJ*WMJ)/BIJ

      PGY(5)=1./(DY)*(YPJ*(EPJ+PPJ)*VPJ-YMJ*(EMJ+PMJ)*VMJ)/BIJ

      PGY(6)=1./(DY)*(YPJ*R2PJ*VPJ-YMJ*R2MJ*VMJ)/BIJ
```

```
C     NOW START PW1Y

      PW1Y(1)=0.

      PW1Y(2)=1./(BIJ*DY*DX)*(AVIS*XYPJ*(VPIPJ-VMIPJ)-
     /AVIS*XYMJ*(VPIMJ-VMIMJ))*
     /1./REINF

      PW1Y(3)=1./(BIJ*DY*DX)*(ALAM*XYPJ*(UPIPJ-UMIPJ)-
     /ALAM*XYMJ*(UPIMJ-UMIMJ))*
     /1./REINF

      PW1Y(4)=0.

      PW1Y(5)=1./(BIJ*DY*DX)*(AVIS*XYPJ*UPJ*(VPIPJ-VMIPJ)-
     /AVIS*XYMJ*UMJ*(VPIMJ-VMIMJ))*
     /1./REINF+
     /1./(BIJ*DY*DX)*(ALAM*VPJ*XYPJ*(UPIPJ-UMIPJ)-
     /ALAM*XYMJ*VMJ*(UPIMJ-UMIMJ))*
     /1./REINF

      PW1Y(6)=0.


C     THIS IS PW2Y


      PW2Y(1)=GEE/(DY1*DY1*BIJ)*(BPJH*YYPJH*(FR1PJ-FR1IJ)-
     /YYMJH*RMJH*(FR1IJ-FR1MJ))

      PW2Y(2)=1./(BIJ*DY1**2.)*(AVIS*YYPJH*(UPJ-UIJ)-
     /AVIS*YYMJH*(UIJ-UMJ))*
     /1./REINF

      PW2Y(3)=1./(BIJ*DY1**2.)*(ALV*YYPJH*(VPJ-VIJ)
     /-ALV*YYMJH*(VIJ-VMJ))*
```

```
     /1./REINF

      PW2Y(4)=1./(BIJ*DY1**2.)*(AVIS*YYPJH*(WPJ-WIJ)-
     /AVIS*YYMJH*(WIJ-WMJ))*
     /1./REINF

      PW2Y(5)=1./(BIJ*DY1**2.)*(AVIS*YYPJH*UPJH*(UPJ-UIJ)-
     /AVIS*YYMJH*UMJH*(UIJ-UMJ))*1./REINF
     /+1./(BIJ*DY1**2.)*(ALV*YYPJH*VPJH*(VPJ-VIJ)-
     /ALV*YYMJH*VMJH*(VIJ-VMJ))*
     /1./REINF
     /+1./(BIJ*DY1**2.)*(AVIS*YYPJH*WPJH*(WPJ-WIJ)-
     /AVIS*YYMJH*WMJH*(WIJ-WMJ))*
     /1./REINF
     /+1./(BIJ*DY1**2.)*(YYPJH*(TPJ-TIJ)-
     /YYMJH*(TIJ-TMJ))*PRREM

      PW2Y(6)=GEE/(DY1*DY1*BIJ)*(YYPJH*RPJH*(FR2PJ-FR2IJ)-
     /YYMJH*RMJH*(FR2IJ-FR2MJ))


C     START THE PW3Y

      PW3Y(1)=0.

      PW3Y(2)=0.

      PW3Y(3)=1./(BIJ*DY*DZ)*(ALAM*YZPJ*(WPJPK-WPJMK)-
     /ALAM*YZMJ*(WMJPK-WMJMK))*
     /1./REINF

      PW3Y(4)=1./(BIJ*DY*DZ)*(AVIS*YZPJ*(VPJPK-VPJMK)-
     /AVIS*YZMJ*(VMJPK-VMJMK))*
     /1./REINF

      PW3Y(5)=1./(BIJ*DY*DZ)*(ALAM*YZPJ*VPJ*(WPJPK-WPJMK)-
     /ALAM*YZMJ*VMJ*
     /(WMJPK-WMJMK))*1./REINF
     /+1./(BIJ*DY*DZ)*(AVIS*WPJ*YZPJ*(VPJPK-VPJMK)-
```

```
     /AVIS*WMJ*YZMJ*(VMJPK-VMJMK))*
     /1./REINF

      PW3Y(6)=0.

C     START THE PHZ

      PHZ(1)=1./DZ*(ZPK*R1PK*WPK-ZMK*R1MK*WMK)/BIJ

      PHZ(2)=1./DZ*(ZPK*RPK*UPK*WPK-ZMK*RMK*UMK*WMK)/BIJ

      PHZ(3)=1./DZ*(ZPK*RPK*VPK*WPK-ZMK*RMK*VMK*WMK)/BIJ

      PHZ(4)=1./DZ*(ZPK*RPK*WPK*WPK-ZMK*RMK*WMK*WMK)/BIJ
     /+1./DZ*(ZPK*PPK-ZMK*PMK)/BIJ

      PHZ(5)=1./DZ*(ZPK*(EPK+PPK)*WPK-ZMK*(EMK+PMK)*WMK)/BIJ

      PHZ(6)=1./DZ*(ZPK*R2PK*WPK-ZMK*R2MK*WMK)/BIJ

C     START THE PE1Z

      PE1Z(1)=0.

      PE1Z(2)=1./(BIJ*DZ*DX)*(AVIS*XZPK*(WPIPK-WMIPK)-
     /AVIS*XZMK*(WPIMK-WMIMK))*
     /1./REINF

      PE1Z(3)=0.
```

```
      PE1Z(4)=1./(BIJ*DZ*DX)*(ALAM*XZPK*(UPIPK-UMIPK)-
     / ALAM*XZMK*(UPIMK-UMIMK))*
     /1./REINF

      PE1Z(5)=1./(BIJ*DZ*DX)*(AVIS*XZPK*UPK*(WPIPK-WMIPK)-
     /AVIS*XZMK*UMK*
     /(WPIMK-WMIMK))*1./REINF
     /+1./(BIJ*DZ*DX)*(ALAM*XZPK*WPK*(UPIPK-UMIPK)-
     /ALAM*XZMK*WMK*(UPIMK-UMIMK))*
     /1./REINF

      PE1Z(6)=0.


C     NOW START THE PE2Z


      PE2Z(1)=0.

      PE2Z(2)=0.

      PE2Z(3)=1./(BIJ*DZ*DY)*(AVIS*YZPK*(WPJPK-WMJPK)-
     /AVIS*YZMK*(WPJMK-WMJMK))*
     /1./REINF

      PE2Z(4)=1./(BIJ*DZ*DY)*(ALAM*YZPK*(VPJPK-VMJPK)-
     /ALAM*YZMK*(VPJMK-VMJMK))*
     /1./REINF

      PE2Z(5)=1./(BIJ*DZ*DY)*(AVIS*YZPK*VPK*(WPJPK-WMJPK)-
     /AVIS*YZMK*VMK*
     /(WPJMK-WMJMK))*1./REINF
     /+1./(BIJ*DZ*DY)*(ALAM*YZPK*WPK*(VPJPK-VMJPK)-
     /ALAM*YZMK*WMK*(VPJMK-VMJMK))*
     /1./REINF

      PE2Z(6)=0.
```

```
C     START THE PE3Z

      PE3Z(1)=GEE/(DZ1*DZ1*BIJ)*(ZZPKH*RPKH*(FR1PK-FR1IJ)-
     /ZZMKH*RMKH*(FR1IJ-FR1MK))

      PE3Z(2)=1./(BIJ*DZ1*DZ1)*(AVIS*ZZPKH*(UPK-UIJ)-
     /AVIS*ZZMKH*(UIJ-UMK))*1./REINF

      PE3Z(3)=1./(BIJ*DZ1*DZ1)*(AVIS**ZZPKH*(VPK-VIJ)-
     /AVIS*ZZMKH*(VIJ-VMK))*1./REINF

      PE3Z(4)=1./(BIJ*DZ1*DZ1)*(ALV*ZZPKH*(WPK-WIJ)-
     /ALV*ZZMKH*(WIJ-WMK))*1./REINF

      PE3Z(5)=1./(BIJ*DZ1*DZ1)*(AVIS*ZZPKH*UPKH*(UPK-UIJ)-
     /AVIS*ZZMKH*UMKH*(UIJ-UMK))*1./REINF
     /+1./(BIJ*DZ1*DZ1)*(AVIS*ZZPKH*VPKH*(VPK-VIJ)-
     /AVIS*ZZMKH*VMKH*(VIJ-VMK))*
     /1./REINF
     /+1./(BIJ*DZ1*DZ1)*(ALV*ZZPKH*WPKH*(WPK-WIJ)-
     /ALV*ZZMKH*WMKH*(WIJ-WMK))*
     /1./REINF
     /+1./(BIJ*DZ1*DZ1)*(ZZPKH*(TPK-TIJ)-
     /ZZMKH*(TIJ-TMK))*PRREM

      PE3Z(6)=GEE/(DZ1*DZ1*BIJ)*(ZZPKH*RPKH*(FR2PK-FR2IJ)-
     /ZZMKH*RMKH*(FR2IJ-FR2MK))


C     NOW START THE N-1 TERMS
C     PXDV2= THE PARTIAL DERIVATIVE OF DV2 AT N-1 WRT X
C     PYDW1= ======================== DW1 ========== Y
C
      IF(ITIME.EQ.1) THEN
      PXDV2(1)=0.
      PXDV2(2)=0.
      PXDV2(3)=0.
      PXDV2(4)=0.
```

```
PXDV2(5)=0.
PXDV2(6)=0.

PXDV3(1)=0.
PXDV3(2)=0.
PXDV3(3)=0.
PXDV3(4)=0.
PXDV3(5)=0.
PXDV3(6)=0.


PYDW1(1)=0.
PYDW1(2)=0.
PYDW1(3)=0.
PYDW1(4)=0.
PYDW1(5)=0.
PYDW1(6)=0.

PYDW3(1)=0.
PYDW3(2)=0.
PYDW3(3)=0.
PYDW3(4)=0.
PYDW3(5)=0.
PYDW3(6)=0.



PZDE1(1)=0.
PZDE1(2)=0.
PZDE1(3)=0.
PZDE1(4)=0.
PZDE1(5)=0.
PZDE1(6)=0.

PZDE2(1)=0.
PZDE2(2)=0.
PZDE2(3)=0.
PZDE2(4)=0.
```

```
PZDE2(5)=0.
PZDE2(6)=0.

ELSE

PXDV1(1)=PV1X(1)-PV1X2(1,I,J,K)
PXDV1(2)=PV1X(2)-PV1X2(2,I,J,K)
PXDV1(3)=PV1X(3)-PV1X2(3,I,J,K)
PXDV1(4)=PV1X(4)-PV1X2(4,I,J,K)
PXDV1(5)=PV1X(5)-PV1X2(5,I,J,K)
PXDV1(6)=PV1X(6)-PV1X2(6,I,J,K)

PXDV2(1)=PV2X(1)-PV2X2(1,I,J,K)
PXDV2(2)=PV2X(2)-PV2X2(2,I,J,K)
PXDV2(3)=PV2X(3)-PV2X2(3,I,J,K)
PXDV2(4)=PV2X(4)-PV2X2(4,I,J,K)
PXDV2(5)=PV2X(5)-PV2X2(5,I,J,K)
PXDV2(6)=PV2X(6)-PV2X2(6,I,J,K)

PXDV3(1)=PV3X(1)-PV3X2(1,I,J,K)
PXDV3(2)=PV3X(2)-PV3X2(2,I,J,K)
PXDV3(3)=PV3X(3)-PV3X2(3,I,J,K)
PXDV3(4)=PV3X(4)-PV3X2(4,I,J,K)
PXDV3(5)=PV3X(5)-PV3X2(5,I,J,K)
PXDV3(6)=PV3X(6)-PV3X2(6,I,J,K)

PYDW1(1)=PW1Y(1)-PW1Y2(1,I,J,K)
PYDW1(2)=PW1Y(2)-PW1Y2(2,I,J,K)
```

```
PYDW1(3)=PW1Y(3)-PW1Y2(3,I,J,K)
PYDW1(4)=PW1Y(4)-PW1Y2(4,I,J,K)
PYDW1(5)=PW1Y(5)-PW1Y2(5,I,J,K)
PYDW1(6)=PW1Y(6)-PW1Y2(6,I,J,K)

PYDW2(1)=PW2Y(1)-PW2Y2(1,I,J,K)
PYDW2(2)=PW2Y(2)-PW2Y2(2,I,J,K)
PYDW2(3)=PW2Y(3)-PW2Y2(3,I,J,K)
PYDW2(4)=PW2Y(4)-PW2Y2(4,I,J,K)
PYDW2(5)=PW2Y(5)-PW2Y2(5,I,J,K)
PYDW2(6)=PW2Y(6)-PW2Y2(6,I,J,K)

PYDW3(1)=PW3Y(1)-PW3Y2(1,I,J,K)
PYDW3(2)=PW3Y(2)-PW3Y2(2,I,J,K)
PYDW3(3)=PW3Y(3)-PW3Y2(3,I,J,K)
PYDW3(4)=PW3Y(4)-PW3Y2(4,I,J,K)
PYDW3(5)=PW3Y(5)-PW3Y2(5,I,J,K)
PYDW3(6)=PW3Y(6)-PW3Y2(6,I,J,K)


PZDE1(1)=PE1Z(1)-PE1Z2(1,I,J,K)
PZDE1(2)=PE1Z(2)-PE1Z2(2,I,J,K)
PZDE1(3)=PE1Z(3)-PE1Z2(3,I,J,K)
PZDE1(4)=PE1Z(4)-PE1Z2(4,I,J,K)
PZDE1(5)=PE1Z(5)-PE1Z2(5,I,J,K)
PZDE1(6)=PE1Z(6)-PE1Z2(6,I,J,K)


PZDE2(1)=PE2Z(1)-PE2Z2(1,I,J,K)
PZDE2(2)=PE2Z(2)-PE2Z2(2,I,J,K)
PZDE2(3)=PE2Z(3)-PE2Z2(3,I,J,K)
PZDE2(4)=PE2Z(4)-PE2Z2(4,I,J,K)
PZDE2(5)=PE2Z(5)-PE2Z2(5,I,J,K)
PZDE2(6)=PE2Z(6)-PE2Z2(6,I,J,K)


PZDE3(1)=PE3Z(1)-PE3Z2(1,I,J,K)
PZDE3(2)=PE3Z(2)-PE3Z2(2,I,J,K)
PZDE3(3)=PE3Z(3)-PE3Z2(3,I,J,K)
```

```
      PZDE3(4)=PE3Z(4)-PE3Z2(4,I,J,K)
      PZDE3(5)=PE3Z(5)-PE3Z2(5,I,J,K)
      PZDE3(6)=PE3Z(6)-PE3Z2(6,I,J,K)
C     THIS IS FOR POROUS MEDIUM

      ENDIF

C     DEPOSIT THE V2 AND W1 AT N-1 INTO PV2X2 AND PW1Y2 RESP.

      DO 160 KK=1,IS
      PV1X2(KK,I,J,K)=PV1X(KK)
      PV2X2(KK,I,J,K)=PV2X(KK)
      PV3X2(KK,I,J,K)=PV3X(KK)

      PW1Y2(KK,I,J,K)=PW1Y(KK)
      PW2Y2(KK,I,J,K)=PW2Y(KK)
      PW3Y2(KK,I,J,K)=PW3Y(KK)

      PE1Z2(KK,I,J,K)=PE1Z(KK)
      PE2Z2(KK,I,J,K)=PE2Z(KK)
      PE3Z2(KK,I,J,K)=PE3Z(KK)

  160 CONTINUE
```

```
      COURNT=1.
C       ABS(UX(I,J,K))+SQRT(GAM*PR(I,J,K)/RHO(I,J,K))*DT/DX1

      IF(I.EQ.2.AND.J.GT.NY2) THEN

      UCON(1)=0.
      UCON(2)=0.
      UCON(3)=0.
      UCON(4)=0.
      UCON(5)=0.
      UCON(6)=0.
      ELSEIF(I.EQ.(L-1).AND.J.LT.NY3) THEN

      UCON(1)=0.
      UCON(2)=0.
      UCON(3)=0.
      UCON(4)=0.
      UCON(5)=0.
      UCON(6)=0.

      ELSEIF(I.EQ.2.AND.J.LE.NY2) THEN

      UC01M1=RHO1(I,J,K)
      UC02M1=-UX(I,J,K)*RHO(I,J,K)
      UC03M1=-VY(I,J,K)*RHO(I,J,K)
      UC04M1=-WZ(I,J,K)*RHO(I,J,K)
      UC05M1=EN(I,J,K)
      UC06M1=RHO2(I,J,K)

      UCON(1)=AJM(I,J,K)*EPSX*COURNT*(UCONX(1,I+2)-
     /4.*UCONX(1,I+1)+6.*UCONX(1,I)-
     /4.*UCONX(1,I-1)+UC01M1)
```

```
 UCON(2)=AJM(I,J,K)*EPSX*COURNT*(UCONX(2,I+2)-
/4.*UCONX(2,I+1)+6.*UCONX(2,I)-
/4.*UCONX(2,I-1)+UCO2M1)

 UCON(3)=AJM(I,J,K)*EPSX*COURNT*(UCONX(3,I+2)-
/4.*UCONX(3,I+1)+6.*UCONX(3,I)-
/4.*UCONX(3,I-1)+UCO3M1)

 UCON(4)=AJM(I,J,K)*EPSX*COURNT*(UCONX(4,I+2)-
/4.*UCONX(4,I+1)+6.*UCONX(4,I)-
/4.*UCONX(4,I-1)+UCO4M1)

 UCON(5)=AJM(I,J,K)*EPSX*COURNT*(UCONX(5,I+2)-
/4.*UCONX(5,I+1)+6.*UCONX(5,I)-
/4.*UCONX(5,I-1)+UCO5M1)

 UCON(6)=AJM(I,J,K)*EPSX*COURNT*(UCONX(6,I+2)-
/4.*UCONX(6,I+1)+6.*UCONX(6,I)-
/4.*UCONX(6,I-1)+UCO6M1)


 ELSEIF(I.EQ.(L-1).AND.J.GE.NY3) THEN

 UCO1P1=RHO1(I,J,K)
 UCO2P1=-UX(I,J,K)*RHO(I,J,K)
 UCO3P1=-VY(I,J,K)*RHO(I,J,K)
 UCO4P1=-WZ(I,J,K)*RHO(I,J,K)
 UCO5P1=EN(I,J,K)
 UCO6P1=RHO2(I,J,K)

 UCON(1)=AJM(I,J,K)*EPSX*COURNT*(UCO1P1-
/4.*UCONX(1,I+1)+6.*UCONX(1,I)-
/4.*UCONX(1,I-1)+UCONX(1,I-2))


 UCON(2)=AJM(I,J,K)*EPSX*COURNT*(UCO2P1-
```

```
/4.*UCONX(2,I+1)+6.*UCONX(2,I)-
/4.*UCONX(2,I-1)+UCONX(2,I-2))

 UCON(3)=AJM(I,J,K)*EPSX*COURNT*(UC03P1-
/4.*UCONX(3,I+1)+6.*UCONX(3,I)-
/4.*UCONX(3,I-1)+UCONX(3,I-2))

 UCON(4)=AJM(I,J,K)*EPSX*COURNT*(UC04P1-
/4.*UCONX(4,I+1)+6.*UCONX(4,I)-
/4.*UCONX(4,I-1)+UCONX(4,I-2))

 UCON(5)=AJM(I,J,K)*EPSX*COURNT*(UC05P1-
/4.*UCONX(5,I+1)+6.*UCONX(5,I)-
/4.*UCONX(5,I-1)+UCONX(5,I-2))

 UCON(6)=AJM(I,J,K)*EPSX*COURNT*(UC06P1-
/4.*UCONX(6,I+1)+6.*UCONX(6,I)-
/4.*UCONX(6,I-1)+UCONX(6,I-2))


 ELSE

 UCON(1)=AJM(I,J,K)*EPSX*COURNT*(UCONX(1,I+2)-
/4.*UCONX(1,I+1)+6.*UCONX(1,I)-
/4.*UCONX(1,I-1)+UCONX(1,I-2))


 UCON(2)=AJM(I,J,K)*EPSX*COURNT*(UCONX(2,I+2)-
/4.*UCONX(2,I+1)+6.*UCONX(2,I)-
/4.*UCONX(2,I-1)+UCONX(2,I-2))

 UCON(3)=AJM(I,J,K)*EPSX*COURNT*(UCONX(3,I+2)-
/4.*UCONX(3,I+1)+6.*UCONX(3,I)-
/4.*UCONX(3,I-1)+UCONX(3,I-2))

 UCON(4)=AJM(I,J,K)*EPSX*COURNT*(UCONX(4,I+2)-
/4.*UCONX(4,I+1)+6.*UCONX(4,I)-
/4.*UCONX(4,I-1)+UCONX(4,I-2))
```

```
      UCON(5)=AJM(I,J,K)*EPSX*COURNT*(UCONX(5,I+2)-
     /4.*UCONX(5,I+1)+6.*UCONX(5,I)-
     /4.*UCONX(5,I-1)+UCONX(5,I-2))

      UCON(6)=AJM(I,J,K)*EPSX*COURNT*(UCONX(6,I+2)-
     /4.*UCONX(6,I+1)+6.*UCONX(6,I)-
     /4.*UCONX(6,I-1)+UCONX(6,I-2))

      ENDIF

C     NOW DO DU(N-1)

      IF(ITIME.EQ.1) THEN

      DELU(1)=0.
```

```
      DELU(2)=0.
      DELU(3)=0.
      DELU(4)=0.
      DELU(5)=0.
      DELU(6)=0.
      ELSE

      DO 170 KK=1,IS
      DELU(KK)=DUCON(KK,I,J,K)
C      UNEW(KK,I,J,K)-UOLD(KK,I,J,K)
 170  CONTINUE

      ENDIF

C     OLD CONSERIVATIVE VARIABLES UPDATE

      DO 175 KK=1,IS
      UOLD(KK,I,J,K)=UNEW(KK,I,J,K)
 175  CONTINUE
C     THIS IS THE MAGNITUDE OF THE VELOCITY TO BE USED IN THE
C     MICROSCOPIC SYSTEM

      UE(I,J,K)=(UX(I,J,K)**2.+VY(I,J,K)**2.+WZ(I,J,K)**2.)**.5

C     THESE ARE THE OLD VLAUES OF CONCS'S

      CONOLD(1,I,J,K)=CONCS(1)
      CONOLD(2,I,J,K)=CONCS(2)
      CONOLD(3,I,J,K)=CONCS(3)
      CONOLD(4,I,J,K)=CONCS(4)
      CONOLD(5,I,J,K)=CONCS(5)
      CONOLD(6,I,J,K)=CONCS(6)
      IF(ITIME.GE.100000) THEN
C      THESE ARE THE CONDENSATION WITH AND WITHOUT
C      NONCONDENSABLES CALLS

      FISE(I,J,K)=RHO1(I,J,K)/RHO(I,J,K)
C      THIS IS FOR SHELL AND TUBE
       IF(PORNTS.EQ.1.AND.SHNON.EQ.1) THEN
```

```
      CALL NONS(TS,AMDD,PS,TC,HSA,QOA,HEAS,FIS,UE,DX1,PR,
     /TE,L,M,N,FISE,HFG,VINF,ALINF,RINF,RHO1,SENSH,RGAS,I,J,K,HCA)
       ELSE
       ENDIF
       IF(PORNTP.EQ.1.AND.PANON.EQ.1) THEN
      CALL NONP(TS,AMDD,PS,TC,HSA,QOA,HEAS,FIS,UE,DX1,PR,
     /TE,L,M,N,FISE,HFG,VINF,ALINF,RINF,RHO1,SENSH,RGAS,I,J,K)
       ELSE
       ENDIF

      ELSE
      AMDD(I,J,K)=0.
      ENDIF

       IF(SHNON.EQ.1.OR.PANON.EQ.1) THEN

C     1. FOR THE CONTINUITY EQUATION.
      CONCS(1)=-SPECSA(I,J,K)*ALINF/(RINF*VINF)
C     2. X-MOM. EQUATION.
      CONCS(2)=-SPECSA(I,J,K)*
     /AMDD(I,J,K)*UX(I,J,K)*ALINF/(RINF*VINF)
C     3. Y-MOM. EQUATION.
      CONCS(3)=-SPECSA(I,J,K)*
     /AMDD(I,J,K)*VY(I,J,K)*ALINF/(RINF*VINF)
C     4. Z-MOM. EQUATION.
      CONCS(4)=-SPECSA(I,J,K)*
     /AMDD(I,J,K)*WZ(I,J,K)*ALINF/(RINF*VINF)
C     5. ENERGY EQUATION.
      CONCS(5)=-SPECSA(I,J,K)*AMDD(I,J,K)/RHO(I,J,K)*GAM*
     /(EN(I,J,K)-.5*RHO(I,J,K)*
     /(UX(I,J,K)**2.+VY(I,J,K)**2.+WZ(I,J,K)**2.))*ALINF/(RINF*VINF)
C      MASS FRACTION EQUATION
      CONCS(6)=-SPECSA(I,J,K)*ALINF/(RINF*VINF)
C      WRITE(*,*) CONCS(5),EN(I,J,K)/RHO(I,J,K)*AMDD(I,J,K)
C      -SPECSA(I,J,K)*QOA(I,J,K)*
C     /ALINF/(RINF*VINF**3.)
C      -SPECSA(I,J,K)*SENSH(I,J,K)
```

```
C     THESE ARE THE NEW VLAUESOF CONCS'S

      CONNEW(1,I,J,K)=CONCS(1)
      CONNEW(2,I,J,K)=CONCS(2)
      CONNEW(3,I,J,K)=CONCS(3)
      CONNEW(4,I,J,K)=CONCS(4)
      CONNEW(5,I,J,K)=CONCS(5)
      CONNEW(6,I,J,K)=CONCS(6)
C     CONN IS THE JACOBIAN OF THE CONDENSATION TERMS WHIS IS
C     SOLVED NUMARICALLY
      IF(ITIME.GE 3) THEN
      CONN(1,1)=(CONNEW(1,I,J,K)-CONOLD(1,I,J,K))
C      /DUCON(1,I,J,K)
C      CONN(1,2)=(CONNEW(1,I,J,K)-CONOLD(1,I,J,K))/DUCON(2,I,J,K)
C      CONN(1,3)=(CONNEW(1,I,J,K)-CONOLD(1,I,J,K))/DUCON(3,I,J,K)
C      CONN(1,4)=(CONNEW(1,I,J,K)-CONOLD(1,I,J,K))/DUCON(4,I,J,K)
C      CONN(1,5)=(CONNEW(1,I,J,K)-CONOLD(1,I,J,K))/DUCON(5,I,J,K)

C      CONN(2,1)=(CONNEW(2,I,J,K)-CONOLD(2,I,J,K))/DUCON(1,I,J,K)

      CONN(2,2)=(CONNEW(2,I,J,K)-CONOLD(2,I,J,K))
C      /DUCON(2,I,J,K)
C      CONN(2,3)=(CONNEW(2,I,J,K)-CONOLD(2,I,J,K))/DUCON(3,I,J,K)
C      CONN(2,4)=(CONNEW(2,I,J,K)-CONOLD(2,I,J,K))/DUCON(4,I,J,K)
C      CONN(2,5)=(CONNEW(2,I,J,K)-CONOLD(2,I,J,K))/DUCON(5,I,J,K)

C      CONN(3,1)=(CONNEW(3,I,J,K)-CONOLD(3,I,J,K))
C      /DUCON(1,I,J,K)
C      CONN(3,2)=(CONNEW(3,I,J,K)-CONOLD(3,I,J,K))/DUCON(2,I,J,K)
      CONN(3,3)=(CONNEW(3,I,J,K)-CONOLD(3,I,J,K))
C      /DUCON(3,I,J,K)
C      CONN(3,4)=(CONNEW(3,I,J,K)-CONOLD(3,I,J,K))/DUCON(4,I,J,K)
C      CONN(3,5)=(CONNEW(3,I,J,K)-CONOLD(3,I,J,K))/DUCON(5,I,J,K)

C      CONN(4,1)=(CONNEW(4,I,J,K)-CONOLD(4,I,J,K))/DUCON(1,I,J,K)
C      CONN(4,2)=(CONNEW(4,I,J,K)-CONOLD(4,I,J,K))/DUCON(2,I,J,K)
C      CONN(4,3)=(CONNEW(4,I,J,K)-CONOLD(4,I,J,K))/DUCON(3,I,J,K)
      CONN(4,4)=(CONNEW(4,I,J,K)-CONOLD(4,I,J,K))
C      /DUCON(4,I,J,K)
```

```
C       CONN(4,5)=(CONNEW(4,I,J,K)-CONOLD(4,I,J,K))/DUCON(5,I,J,K)

C       CONN(5,1)=(CONNEW(5,I,J,K)-CONOLD(5,I,J,K))/DUCON(1,I,J,K)
C       CONN(5,2)=(CONNEW(5,I,J,K)-CONOLD(5,I,J,K))/DUCON(2,I,J,K)
C       CONN(5,3)=(CONNEW(5,I,J,K)-CONOLD(5,I,J,K))/DUCON(3,I,J,K)
C       CONN(5,4)=(CONNEW(5,I,J,K)-CONOLD(5,I,J,K))/DUCON(4,I,J,K)
      CONN(5,5)=(CONNEW(5,I,J,K)-CONOLD(5,I,J,K))
C       /DUCON(5,I,J,K)


      CONN(6,6)=(CONNEW(6,I,J,K)-CONOLD(6,I,J,K))
C       DO 279 II=1,IS
C       DO 279 JJ=1,IS
C  279    WRITE(*,*) CONN(II,JJ),II,JJ

      ELSE
      ENDIF
      ELSE
      ENDIF
C     DEPOSIT PFX,PV1X,PV2X,PGY,PW1Y,PW2Y,PXDV2, PYDW1,DELU, AND
C     UCON

      DO 178 KK=1,IS
      BMAINX(KK,I)=DTSW*(-PFX(KK)+PV1X(KK)+PV2X(KK)+PV3X(KK)
     /-PGY(KK)+PW1Y(KK)+PW2Y(KK)+PW3Y(KK)
     /-PHZ(KK)+PE1Z(KK)+PE2Z(KK)+PE3Z(KK)+PORNTP*ERGUN(KK)+
     /PORNTS*ERGUNS(KK)+PORNTS*CONCS(KK))
     /+THDSW*(PXDV2(KK)+PXDV3(KK)+PYDW1(KK)+PYDW3(KK)
     /+PZDE1(KK)+PZDE2(KK)+PORNTS*CONN(KK,KK))
     /+SWSW*DELU(KK)-UCON(KK)

 178  CONTINUE


C     NOW START THE LHS OF THE X-SWEEP
C     ASMI=A SMALL"4*4 MATRIX" MINUS I
C     ASPI================== PLUS I

C     THIS IS THE IMPLICIT ERGUN TERM
```

```
 SOURC(1,1)=0.
 SOURC(1,2)=0.
 SOURC(1,3)=0.
 SOURC(1,4)=0.
 SOURC(1,5)=0.
 SOURC(1,6)=0.

 SOURC(2,1)=-AVIS*BIJ*R1IJ*UIJ/(RIJ*RIJ*PER)-
/2.*BIJ*BIJ*CER*(UIJ**3.+UIJ*VIJ*VIJ+UIJ*WIJ*WIJ)-
/AVIS*BIJ*R2IJ*UIJ/(RIJ*RIJ*PER)

 SOURC(2,2)=AVIS*BIJ/(RIJ*PER)+BIJ*BIJ*CER*(3.*UIJ*UIJ+VIJ*VIJ+
/WIJ*WIJ)

 SOURC(2,3)=BIJ*BIJ*CER*(2.*VIJ*UIJ)

 SOURC(2,4)=BIJ*BIJ*CER*(2.*UIJ*WIJ)

 SOURC(2,5)=0.

 SOURC(2,6)=-AVIS*BIJ*R2IJ*UIJ/(RIJ*RIJ*PER)-
/2.*BIJ*BIJ*CER*(UIJ**3.+UIJ*VIJ*VIJ+UIJ*WIJ*WIJ)-
/AVIS*BIJ*R1IJ*UIJ/(RIJ*RIJ*PER)

 SOURC(3,1)=-AVIS*BIJ*R1IJ*VIJ/(RIJ*RIJ*PER)-
/2.*BIJ*BIJ*CER*(VIJ*UIJ**2.+VIJ**3.+VIJ*WIJ*WIJ)-
/AVIS*BIJ*R2IJ*VIJ/(RIJ*RIJ*PER)

 SOURC(3,2)=BIJ*BIJ*CER*(2.*UIJ*VIJ)

 SOURC(3,3)=AVIS*BIJ/(RIJ*PER)+BIJ*BIJ*CER*(UIJ*UIJ+3.*VIJ*VIJ+
/WIJ*WIJ)

 SOURC(3,4)=BIJ*BIJ*CER*(2.*VIJ*WIJ)

 SOURC(3,5)=0.

 SOURC(3,6)=-AVIS*BIJ*R2IJ*VIJ/(RIJ*RIJ*PER)-
```

```
     /2.*BIJ*BIJ*CER*(VIJ*UIJ**2.+VIJ**3.+VIJ*WIJ*WIJ)-
     /AVIS*BIJ*R1IJ*VIJ/(RIJ*RIJ*PER)

      SOURC(4,1)=-AVIS*BIJ*R1IJ*WIJ/(RIJ*RIJ*PER)-
     /2.*BIJ*BIJ*CER*(WIJ*UIJ**2.+WIJ*VIJ**2.+WIJ**3.)-
     /AVIS*BIJ*R2IJ*WIJ/(RIJ*RIJ*PER)

      SOURC(4,2)=BIJ*BIJ*CER*(2.*UIJ*WIJ)

      SOURC(4,3)=BIJ*BIJ*CER*(2.*VIJ*WIJ)

      SOURC(4,4)=AVIS*BIJ/(RIJ*PER)+BIJ*BIJ*CER*(UIJ*UIJ+VIJ*VIJ+
     /3.*WIJ*WIJ)

      SOURC(4,5)=0.

      SOURC(4,6)=-AVIS*BIJ*R2IJ*WIJ/(RIJ*RIJ*PER)-
     /2.*BIJ*BIJ*CER*(WIJ*UIJ**2.+WIJ*VIJ**2.+WIJ**3.)-
     /AVIS*BIJ*R1IJ*WIJ/(RIJ*RIJ*PER)

      SOURC(5,1)=0.
      SOURC(5,2)=0.
      SOURC(5,3)=0.
      SOURC(5,4)=0.
      SOURC(5,5)=0.
      SOURC(5,6)=0.

      SOURC(6,1)=0.
      SOURC(6,2)=0.
      SOURC(6,3)=0.
      SOURC(6,4)=0.
      SOURC(6,5)=0.
      SOURC(6,6)=0.

C     THIS IS THE SOURCE TERM OF THE SHELL AND TUBE
```

```
SOURCS(1,1)=0.
SOURCS(1,2)=0.
SOURCS(1,3)=0.
SOURCS(1,4)=0.
SOURCS(1,5)=0.
SOURCS(1,6)=0.

IF(UIJ.EQ.0.) THEN
SOURCS(2,1)=0.
SOURCS(2,2)=0.
SOURCS(2,3)=0.
SOURCS(2,4)=0.
SOURCS(2,5)=0.
SOURCS(2,6)=0.
ELSE
SOURCS(2,1)=-2.*GGX/(RIJ**3.)*ABSM**(-BRX)*AMM*TERMP

SOURCS(2,2)=-BRX*GGX/(RIJ**2.)*ABSM**(-BRX-1.)*AMM*TERMP+
/GGX/(RIJ**2.)*ABSM**(-BRX)*TERMP+
/GGX/(RIJ**2.)*ABSM**(-BRX)*AMM*TERMM*AMM

SOURCS(2,3)=GGX/(RIJ**2.)*ABSM**(-BRX)*AMM*TERMM*ANN



SOURCS(2,4)=GGX/(RIJ**2.)*ABSM**(-BRX)*AMM*TERMM*AQQ


SOURCS(2,5)=0.

SOURCS(2,6)=-2.*GGX/(RIJ**3.)*ABSM**(-BRX)*AMM*TERMP

ENDIF

IF(VIJ.EQ.0.) THEN

SOURCS(3,1)=0.
SOURCS(3,2)=0.
```

```
 SOURCS(3,3)=0.
 SOURCS(3,4)=0.
 SOURCS(3,5)=0.
 SOURCS(3,6)=0.
 ELSE

 SOURCS(3,1)=-2.*GGY/(RIJ**3.)*ABSN**(-BRY)*ANN*TERMP

 SOURCS(3,2)=GGY/(RIJ**2.)*ABSN**(-BRY)*ANN*TERMM*AMM

 SOURCS(3,3)=-BRY*GGY/(RIJ**2.)*ABSN**(-BRY-1.)*ANN*TERMP+
/GGY/(RIJ**2.)*ABSN**(-BRY)*TERMP+
/GGY/(RIJ**2.)*ABSN**(-BRY)*ANN*TERMM*ANN

 SOURCS(3,4)=GGY/(RIJ**2.)*ABSN**(-BRY)*ANN*TERMM*AQQ

 SOURCS(3,5)=0.

 SOURCS(3,6)=-2.*GGY/(RIJ**3.)*ABSN**(-BRY)*ANN*TERMP

 ENDIF

 IF(WIJ.EQ.0.) THEN

 SOURCS(4,1)=0.
 SOURCS(4,2)=0.
 SOURCS(4,3)=0.
 SOURCS(4,4)=0.
 SOURCS(4,5)=0.
 SOURCS(4,6)=0.
 ELSE
 SOURCS(4,1)=-2.*GGZ/(RIJ**3.)*ABSQ**(-BRZ)*AQQ*TERMP
```

```
      SOURCS(4,1)=-2.*GGZ/(RIJ**3.)*ABSQ**(-BRZ)*AQQ*TERMP

      SOURCS(4,2)=GGZ/(RIJ**2.)*ABSQ**(-BRZ)*AQQ*TERMM*AMM

      SOURCS(4,3)=GGZ/(RIJ**2.)*ABSQ**(-BRZ)*AQQ*TERMM*ANN

      SOURCS(4,4)=-BRZ*GGZ/(RIJ**2.)*ABSQ**(-BRZ-1.)*AQQ*TERMP+
     /GGZ/(RIJ**2.)*ABSQ**(-BRZ)*TERMP+
     /GGZ/(RIJ**2.)*ABSQ**(-BRZ)*AQQ*TERMM*AQQ

      SOURCS(4,5)=0.

      SOURCS(4,6)=-2.*GGZ/(RIJ**3.)*ABSQ**(-BRZ)*AQQ*TERMP

      ENDIF
      SOURCS(5,1)=0.
      SOURCS(5,2)=0.
      SOURCS(5,3)=0.
      SOURCS(5,4)=0.
      SOURCS(5,5)=0.
      SOURCS(5,6)=0.

      SOURCS(6,1)=0.
      SOURCS(6,2)=0.
      SOURCS(6,3)=0.
      SOURCS(6,4)=0.
      SOURCS(6,5)=0.
      SOURCS(6,6)=0.


      TSDXM=THSW/DX*XMI/BIJ

      IF(I.NE.2) THEN
      ASMI(1,1)=-TSDXM*R2MI/RMI*UMI
      ASMI(1,2)=-TSDXM*R1MI/RMI
C      *R1MI/RIJ
      ASMI(1,3)=0.
      ASMI(1,4)=0.
```

```
      ASMI(1,5)=0.
      ASMI(1,6)=TSDXM*R1MI/RMI*UMI
      ASMI(2,1)=TSDXM*((3.-GAM)/2.*UMI*UMI+(1.-GAM)/2.*
     /(VMI*VMI+WMI*WMI))
      ASMI(2,2)=TSDXM*((GAM-3.)*UMI)
      ASMI(2,3)=TSDXM*((GAM-1.)*VMI)
      ASMI(2,4)=TSDXM*(GAM-1.)*WMI
      ASMI(2,5)=TSDXM*((1.-GAM))
      ASMI(2,6)=TSDXM*((3.-GAM)/2.*UMI*UMI+(1.-GAM)/2.*
     /(VMI*VMI+WMI*WMI))

      ASMI(3,1)=TSDXM*(UMI*VMI)
      ASMI(3,2)=-TSDXM*VMI
      ASMI(3,3)=-TSDXM*UMI
      ASMI(3,4)=0.
      ASMI(3,5)=0.
      ASMI(3,6)=TSDXM*(UMI*VMI)

      ASMI(4,1)=TSDXM*UMI*WMI
      ASMI(4,2)=-TSDXM*WMI
      ASMI(4,3)=0.
      ASMI(4,4)=-TSDXM*UMI
      ASMI(4,5)=0.
      ASMI(4,6)=TSDXM*UMI*WMI

      ASMI(5,1)=TSDXM*(GAM*EMI*UMI/RMI+(1.-
     / GAM)*UMI*(UMI*UMI+VMI*VMI+
     /WMI*WMI))
      ASMI(5,2)=TSDXM*(-GAM*EMI/RMI+(GAM-1.)/2.*(3.*UMI*UMI+VMI*VMI+
     /WMI*WMI))
      ASMI(5,3)=TSDXM*((GAM-1.)*UMI*VMI)
      ASMI(5,4)=TSDXM*(GAM-1.)*UMI*WMI
      ASMI(5,5)=-TSDXM*(GAM*UMI)
      ASMI(5,6)=TSDXM*(GAM*EMI*UMI/RMI+(1.-GAM)*UMI*(UMI*UMI+VMI*VMI+
     /WMI*WMI))


      ASMI(6,1)=TSDXM*R2MI/RMI*UMI
      ASMI(6,2)=-TSDXM
```

```
*R2MI/RMI
C        *R2MI/RIJ
      ASMI(6,3)=0.
      ASMI(6,4)=0.
      ASMI(6,5)=0.
      ASMI(6,6)=-TSDXM*R1MI/RMI*UMI


      ELSE
      ENDIF

      TSDXP=THSW/DX*XPI/BIJ
C     NOW DO THE I+1 "ASPI=A SMALL "4*4 MATRIX PLUS I""
      IF(I.NE.L-1) THEN
      ASPI(1,1)=TSDXP*R2PI/RPI*UPI
      ASPI(1,2)=TSDXP
*R1PI/RPI
C        *R1PI/RIJ
      ASPI(1,3)=0.
      ASPI(1,4)=0.
      ASPI(1,5)=0.
      ASPI(1,6)=-TSDXP*R1PI/RPI*UPI

      ASPI(2,1)=-TSDXP*((3.-GAM)/2.*UPI*UPI+(1.-GAM)/2.*
     /(VPI*VPI+WPI*WPI))
      ASPI(2,2)=-TSDXP*((GAM-3.)*UPI)
      ASPI(2,3)=-TSDXP*((GAM-1.)*VPI)
      ASPI(2,4)=TSDXP*(1.-GAM)*WPI
      ASPI(2,5)=-TSDXP*((1.-GAM))
      ASPI(2,6)=-TSDXP*((3.-GAM)/2.*UPI*UPI+(1.-GAM)/2.*
     /(VPI*VPI+WPI*WPI))

      ASPI(3,1)=-TSDXP*(UPI*VPI)
      ASPI(3,2)=TSDXP*(VPI)
      ASPI(3,3)=TSDXP*(UPI)
      ASPI(3,4)=0.
      ASPI(3,5)=0.
      ASPI(3,6)=-TSDXP*(UPI*VPI)
```

```
      ASPI(4,1)=-TSDXP*UPI*WPI
      ASPI(4,2)=TSDXP*WPI
      ASPI(4,3)=0.
      ASPI(4,4)=TSDXP*UPI
      ASPI(4,5)=0.
      ASPI(4,6)=-TSDXP*UPI*WPI

      ASPI(5,1)=-TSDXP*(GAM*EPI*UPI/RPI+(1.-GAM)*UPI*(UPI*UPI
     /+VPI*VPI+WPI*WPI))
      ASPI(5,2)=-TSDXP*(-GAM*EPI/RPI+(GAM-1.)/2.*(3.*UPI*UPI+VPI*VPI+
     /WPI*WPI))
      ASPI(5,3)=-TSDXP*((GAM-1.)*UPI*VPI)
      ASPI(5,4)=TSDXP*(1.-GAM)*UPI*WPI
      ASPI(5,5)=TSDXP*GAM*UPI
      ASPI(5,6)=-TSDXP*(GAM*EPI*UPI/RPI+(1.-GAM)*UPI*(UPI*UPI
     /+VPI*VPI+WPI*WPI))

      ASPI(6,1)=-TSDXP*R2PI/RPI*UPI
      ASPI(6,2)=TSDXP
*R2PI/RPI
C       *R2PI/RIJ
      ASPI(6,3)=0.
      ASPI(6,4)=0.
      ASPI(6,5)=0.
      ASPI(6,6)=TSDXP*R1PI/RPI*UPI
      ELSE
      ENDIF
C     NOW START THE R MATRIX
C     RSMI= R SMALL MINUS I
C     RSPI= R SMALL PLUS I
C     RSI=  R SMALL AT I
C     START THE I-1

      RLMI=1./(DX1*DX1)*THSW*BMIH/BIJ

      ALIX=1./(DX1*DX1)*THSW*AJM(I,J,K)/AJM(I-1,J,K)*DX1*DX1

      ALTHCV=ALV*1./REINF-PRREM/CVOL
      AVTHCV=AVIS*1./REINF-PRREM/CVOL
```

```
      IF(I.NE.2) THEN
      RSMI(1,1)=-ALIX*EPSIX
C      RSMI(1,2)=0.
C      RSMI(1,3)=0.
C      RSMI(1,4)=0.
C      RSMI(1,5)=0.
C      RSMI(1,6)=0.

C      RSMI(2,1)=RLMI*ALV*UMI/RMI*1./REINF
C      RSMI(2,2)=-RLMI*(ALV/RMI)*1./REINF-ALIX*EPSI
       RSMI(2,2)=-ALIX*EPSIX
C      RSMI(2,3)=0.
C      RSMI(2,4)=0.
C      RSMI(2,5)=0.
C      RSMI(2,6)=RLMI*ALV*UMI/RMI*1./REINF

C      RSMI(3,1)=RLMI*AVIS*VMI/RMI*1./REINF
C      RSMI(3,2)=0.
C      RSMI(3,3)=-RLMI*(AVIS/RMI)*1./REINF-ALIX*EPSI
       RSMI(3,3)=-ALIX*EPSIX
C      RSMI(3,4)=0.
C      RSMI(3,5)=0.
C      RSMI(3,6)=RLMI*AVIS*VMI/RMI*1./REINF


C      RSMI(4,1)=RLMI*AVIS*WMI/RMI*1./REINF
C      RSMI(4,2)=0.
C      RSMI(4,3)=0.
C      RSMI(4,4)=-RLMI*AVIS/RMI*1./REINF-ALIX*EPSI
       RSMI(4,4)=-ALIX*EPSIX
C      RSMI(4,5)=0.
C      RSMI(4,6)=RLMI*AVIS*WMI/RMI*1./REINF

C      RSMI(5,1)=RLMI/RMI*(ALTHCV*UMI*UMI+AVTHCV*
C      (VMI*VMI+WMI*WMI)
C     /+PRREM/CVOL*EMI/RMI)
C      RSMI(5,2)=-RLMI/RMI*(ALTHCV*UMI)
C      RSMI(5,3)=-RLMI/RMI*(AVTHCV*VMI)
C      RSMI(5,4)=-RLMI*AVTHCV*WMI/RMI
```

```
C        RSMI(5,5)=-RLMI/RMI*PRREM/CVOL-ALIX*EPSI
         RSMI(5,5)=-ALIX*EPSIX
C        RSMI(5,6)=RLMI/RMI*(ALTHCV*UMI*UMI+
 C       AVTHCV*(VMI*VMI+WMI*WMI)
C       /+PRREM/CVOL*EMI/RMI)

C        RSMI(6,1)=0.
C        RSMI(6,2)=0.
C        RSMI(6,3)=0.
C        RSMI(6,4)=0.
C        RSMI(6,5)=0.
        RSMI(6,6)=-ALIX*EPSIX

        ELSE
        ENDIF

C       START THE I+1

        RLPI=1./(DX1*DX1)*THSW*BPIH/BIJ

        RLIPX=1./(DX1*DX1)*THSW*AJM(I,J,K)/AJM(I+1,J,K)*DX1*DX1

        IF(I.NE.L-1) THEN
        RSPI(1,1)=-RLIPX*EPSIX
C        RSPI(1,2)=0.
C        RSPI(1,3)=0.
C        RSPI(1,4)=0.
C        RSPI(1,5)=0.
C        RSPI(1,6)=0.

C        RSPI(2,1)=RLPI/RPI*ALV*UPI*1./REINF
C        RSPI(2,2)=-RLPI/RPI*ALV*1./REINF-RLIPX*EPSI
         RSPI(2,2)=-RLIPX*EPSIX
C        RSPI(2,3)=0.
C        RSPI(2,4)=0.
C        RSPI(2,5)=0.
C        RSPI(2,6)=RLPI/RPI*ALV*UPI*1./REINF

C        RSPI(3,1)=RLPI/RPI*AVIS*VPI*1./REINF
```

```
C       RSPI(3,2)=0.
C       RSPI(3,3)=-RLPI/RPI*AVIS*1./REINF-RLIPX*EPSI
        RSPI(3,3)=-RLIPX*EPSIX
C       RSPI(3,4)=0.
C       RSPI(3,5)=0.
C       RSPI(3,6)=RLPI/RPI*AVIS*VPI*1./REINF


C       RSPI(4,1)=RLPI*AVIS*WPI/RPI*1./REINF
C       RSPI(4,2)=0.
C       RSPI(4,3)=0.
C       RSPI(4,4)=-RLPI*AVIS/RPI*1./REINF-RLIPX*EPSI
        RSPI(4,4)=-RLIPX*EPSIX
C       RSPI(4,5)=0.
C       RSPI(4,6)=RLPI*AVIS*WPI/RPI*1./REINF


C       RSPI(5,1)=RLPI/RPI*(ALTHCV*UPI*UPI+AVTHCV*(VPI*VPI+WPI*WPI)
C      /+PRREM/CVOL*EPI/RPI)
C       RSPI(5,2)=-RLPI/RPI*(ALTHCV*UPI)
C       RSPI(5,3)=-RLPI/RPI*AVTHCV*VPI
C       RSPI(5,4)=-RLPI*AVTHCV*WPI/RPI
C       RSPI(5,5)=-RLPI/RPI*PRREM/CVOL-RLIPX*EPSI
        RSPI(5,5)=-RLIPX*EPSIX
C       RSPI(5,6)=RLPI/RPI*(ALTHCV*UPI*UPI+AVTHCV*(VPI*VPI+WPI*WPI)
C      /+PRREM/CVOL*EPI/RPI)


C       RSPI(6,1)=0.
C       RSPI(6,2)=0.
C       RSPI(6,3)=0.
C       RSPI(6,4)=0.
C       RSPI(6,5)=0.
       RSPI(6,6)=-RLIPX*EPSIX

       ELSE
       ENDIF
```

```
C     START THE I INDICES AND ADD THE IDENTITY MATRIX
      RLI=(BPIH+BMIH)/(DX1*DX1)*THSW/BIJ
      ALXI=2./(DX1*DX1)*THSW*DX1*DX1
C      RSI(1,1)=1.0+ALXI*EPSI
```

```
C     THIS STEP SUBISTITUTES THE RS(I,I) STEPS WHEN
C     TREATING THE VISCOUS TERMS EXCIPLICITLY

             RSI(1,1)=ALXI*EPSIX+1.
             RSI(2,2)=1.+ALXI*EPSIX
             RSI(3,3)=1.+ALIX*EPSIX
             RSI(4,4)=1.+ALIX*EPSIX
             RSI(5,5)=1.+ALIX*EPSIX
             RSI(6,6)=1.+ALIX*EPSIX


C      RSI(1,2)=0.
C      RSI(1,3)=0.
C      RSI(1,4)=0.
C      RSI(1,5)=0.
C      RSI(1,6)=0.

C      RSI(2,1)=-RLI/RIJ*ALV*UIJ*1./REINF
C      RSI(2,2)=RLI/RIJ*ALV*1./REINF+1.0+ALXI*EPSI
C      RSI(2,3)=0.
C      RSI(2,4)=0.
C      RSI(2,5)=0.
C      RSI(2,6)=-RLI/RIJ*ALV*UIJ*1./REINF


C      RSI(3,1)=-RLI/RIJ*AVIS*VIJ*1./REINF
C      RSI(3,2)=0.
C      RSI(3,3)=RLI/RIJ*AVIS*1./REINF+1.0+ALXI*EPSI
C      RSI(3,4)=0.
C      RSI(3,5)=0.
C      RSI(3,6)=-RLI/RIJ*AVIS*VIJ*1./REINF



C      RSI(4,1)=-RLI*AVIS*WIJ/RIJ*1./REINF
C      RSI(4,2)=0.
C      RSI(4,3)=0.
```

```
C        RSI(4,4)=RLI*AVIS/RIJ*1./REINF+1.0+ALXI*EPSI
C        RSI(4,5)=0.
C        RSI(4,6)=-RLI*AVIS*WIJ/RIJ*1./REINF


C        RSI(5,1)=-RLI/RIJ*(ALTHCV*UIJ*UIJ+AVTHCV*(VIJ*VIJ+WIJ*WIJ)
C       /+PRREM/CVOL*EIJ/RIJ)
C        RSI(5,2)=RLI/RIJ*(ALTHCV*UIJ)
C        RSI(5,3)=RLI/RIJ*(AVTHCV*VIJ)
C        RSI(5,4)=RLI*AVTHCV*WIJ/RIJ
C        RSI(5,5)=RLI/RIJ*PRREM/CVOL+1.+ALXI*EPSI
C        RSI(5,6)=-RLI/RIJ*(ALTHCV*UIJ*UIJ+AVTHCV*(VIJ*VIJ+WIJ*WIJ)
C       /+PRREM/CVOL*EIJ/RIJ)

C        RSI(6,1)=0.
C        RSI(6,2)=0.
C        RSI(6,3)=0.
C        RSI(6,4)=0.
C        RSI(6,5)=0.
C        RSI(6,6)=1.0+ALXI*EPSI

C       NOW ADD THE B.C,S TO THE ADJACWNT NODES
C       AT FIRST DO THE INLET B.C'S AND DEPOSIT THEM AT RSI



C       ADD THE A(I,J)
C       THE FOLLOWING STEPS APPLY ONLY TO SUBSONIC FLOW, WHEN
C       SUBSONIC
C       FLOW IS NEEDED THEY SHOULD BE UNCOMMECNTED.
C       IT HAS TO BE NOTED THAT SUPERSONIC FLOW DOES NOT REQUIRE
C      THESE STEPS
C       BECAUSE ALL THE CONSERVITIVE VARIABLES ARE CONSTANT AT
C      THE INLET
C       WHICH MAKES THE DELTA OF THE CONSERVITIVE VARIABLES
C       EQUAL ZERO


         go to 359
```

```
      IF(I.EQ.2) THEN

C     THIS IS FOR CONSTANT INLET VELOCITY

      IF(J.GE.LWALLI) THEN
      IF(PRESUR.NE.1.) THEN

      RSI(2,1)=RSI(2,1)-(0.5*(GAM-1.)*UX(2,J,K)**2.)*TSDXM
      RSI(2,2)=RSI(2,2)+(GAM-1.)*UX(2,J,K)*TSDXM
      RSI(2,5)=RSI(2,5)-(GAM-1.)*TSDXM
      RSI(2,6)=RSI(2,6)-(0.5*(GAM-1.)*UX(2,J,K)**2.)*TSDXM


      RSI(5,1)=RSI(5,1)-(0.5*GAM*UX(1,J,K)*UX(2,J,K)**2.)*TSDXM
      RSI(5,2)=RSI(5,2)+GAM*UX(1,J,K)*UX(2,J,K)*TSDXM
      RSI(5,5)=RSI(5,5)-GAM*UX(1,J,K)*TSDXM
      RSI(5,6)=RSI(5,6)-(0.5*GAM*UX(1,J,K)*UX(2,J,K)**2.)*TSDXM


C     ADD THE R1(I,J)

      RSI(5,1)=RSI(5,1)-(0.5*PRREM/(RHO(1,J,K)*CVOL)*UX(2,J,K)**2.)*
     /RLMI
      RSI(5,2)=RSI(5,2)+PRREM/(RHO(1,J,K)*CVOL)*
     /UX(2,J,K)*RLMI
      RSI(5,5)=RSI(5,5)-PRREM/(RHO(1,J,K)*CVOL)*RLMI
      RSI(5,6)=RSI(5,6)-(0.5*PRREM/(RHO(1,J,K)*CVOL)*UX(2,J,K)**2.)*
     /RLMI

C     THIE INLET B.C'S OF THE DISSIPATION TERM

      RSI(5,1)=RSI(5,1)-0.5*EPSI*(UX(2,J,K)**2.+VY(2,J,K)**2.+
     /WZ(2,J,K)**2.)*ALI
      RSI(5,2)=RSI(5,2)+EPSI*UX(2,J,K)*ALI
      RSI(5,3)=RSI(5,3)+EPSI*VY(2,J,K)*ALI
      RSI(5,4)=RSI(5,4)+EPSI*WZ(2,J,K)*ALI
      RSI(5,5)=RSI(5,5)-EPSI*ALI
      RSI(5,6)=RSI(5,6)-0.5*EPSI*(UX(2,J,K)**2.+VY(2,J,K)**2.+
     /WZ(2,J,K)**2.)*ALI
```

```
      ELSE
C     THIS IS FOR CONSTANT PRESSURE AT THE INLET

      RSI(1,1)=RSI(1,1)+RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*TSDXM*
     /RHO1(1,J,K)/RHO(1,J,K)
      RSI(1,2)=RSI(1,2)-RHO(1,J,K)/RHO(2,J,K)*TSDXM
      RSI(1,6)=RSI(1,6)+RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*TSDXM*
     /RHO2(1,J,K)/RHO(1,J,K)

      RSI(2,1)=RSI(2,1)+(RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*UX(2,J,K)*
     /(3.-GAM)+
     /RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*UX(2,J,K)*(GAM-1.))*TSDXM

      RSI(2,2)=RSI(2,2)-(RHO(1,J,K)/RHO(2,J,K)*(3.-GAM)*UX(2,J,K)+
     /RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*(GAM-1.))*TSDXM

      RSI(2,6)=RSI(2,6)+(RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*UX(2,J,K)*
     /(3.-GAM)+
     /RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*UX(2,J,K)*(GAM-1.))*TSDXM

      RSI(5,1)=RSI(5,1)+(RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*(GAM*EN(1,J,K)/
     /RHO(1,J,K)+3.*(1.-GAM)/2.*UX(2,J,K)*UX(2,J,K))+
     /GAM*RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)**3.)*TSDXM


      RSI(5,2)=RSI(5,2)-(RHO(1,J,K)/RHO(2,J,K)*(GAM*EN(1,J,K)/
     /RHO(1,J,K)+3.*(1.-GAM)/2.*UX(2,J,K)*UX(2,J,K))+
     /GAM*RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)**2.)*TSDXM

      RSI(5,6)=RSI(5,6)+(RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)*(GAM*EN(1,J,K)/
     /RHO(1,J,K)+3.*(1.-GAM)/2.*UX(2,J,K)*UX(2,J,K))+
     /GAM*RHO(1,J,K)/RHO(2,J,K)*UX(2,J,K)**3.)*TSDXM
C     ADD THE R1(I,J)

      RSI(2,1)=RSI(2,1)+UX(2,J,K)/RHO(2,J,K)*BETA(1,J,K)*ALV*RLMI*
     /1./REINF

      RSI(2,2)=RSI(2,2)-BETA(1,J,K)/RHO(2,J,K)*
```

```
     /ALV*RLMI*1./REINF

      RSI(2,6)=RSI(2,6)+UX(2,J,K)/RHO(2,J,K)*BETA(1,J,K)*ALV*RLMI*
     /1./REINF

      RSI(5,1)=RSI(5,1)+(UX(2,J,K)*UX(2,J,K)/RHO(2,J,K)*BETA(1,J,K)*
     /ALTHCV+UX(2,J,K)*UX(2,J,K)/
     /RHO(2,J,K)*BETA(1,J,K)*PRREM/CVOL)*RLMI

      RSI(5,2)=RSI(5,2)-(UX(2,J,K)/RHO(2,J,K)*BETA(1,J,K)*
     /ALTHCV+UX(2,J,K)/
     /RHO(2,J,K)*BETA(1,J,K)*PRREM/CVOL)*RLMI

      RSI(5,6)=RSI(5,6)+(UX(2,J,K)*UX(2,J,K)/RHO(2,J,K)*BETA(1,J,K)*
     /ALTHCV+UX(2,J,K)*UX(2,J,K)/
     /RHO(2,J,K)*BETA(1,J,K)*PRREM/CVOL)*RLMI




      ENDIF

C     START THE WALL B.C'S FOR THE
      ELSE
      RSI(2,5)=RSI(2,5)-(GAM-1.)*TSDXM
      RSI(5,1)=RSI(5,1)+(PRREM/CVOL*EN(2,J,K)/RHO(2,J,K)**2.)*
     /RLMI
      RSI(5,5)=RSI(5,5)-(PRREM/CVOL*1./RHO(2,J,K))*RLMI
      RSI(5,6)=RSI(5,6)+(PRREM/CVOL*EN(2,J,K)/RHO(2,J,K)**2.)*
     /RLMI


      ENDIF

      ELSE
      ENDIF

C     OUTLET B.C,S
```

```
      IF(I.EQ.L-1) THEN
C     THE FOLLOWING COMMENTED LINES ARE FOR CONSTANT OUTLET
C     PRESSURE
C     WHICH IS THE CASE FOR SUBSONIC FLOW


C     THIS IF IS FOR THE NON-SLIP OUTLET B.C'S

      IF(J.LT.LWALLO) THEN
      C1=0.5*(UX(L-1,J,K)**2.+VY(L-1,J,K)**2.+WZ(L-1,J,K)**2.)

      RSI(1,2)=RSI(1,2)+TSDXP*RHO1(L,J,K)/RHO(L,J,K)
      RSI(2,6)=RSI(1,6)+TSDXP*RHO2(L,J,K)/RHO(L,J,K)



      RSI(2,1)=RSI(2,1)+((GAM-3.)/2.*UX(L,J,K)**2.+(GAM-1.)/2.*
     /(VY(L,J,K)**2.+WZ(L,J,K)**2.))*TSDXP
     /-(GAM-1.)*C1*TSDXP

      RSI(2,2)=RSI(2,2)+((3.-GAM)*UX(L,J,K))*TSDXP
     /+(GAM-1.)*UX(L,J,K)*TSDXP

      RSI(2,3)=RSI(2,3)+((1.-GAM)*VY(L,J,K))*TSDXP
     /+(GAM-1.)*VY(L,J,K)*TSDXP

      RSI(2,4)=RSI(2,4)+((1.-GAM)*WZ(L,J,K))*TSDXP
     /+(GAM-1.)*WZ(L,J,K)*TSDXP

      RSI(2,6)=RSI(2,6)+((GAM-3.)/2.*UX(L,J,K)**2.+(GAM-1.)/2.*
     /(VY(L,J,K)**2.+WZ(L,J,K)**2.))*TSDXP
     /-(GAM-1.)*C1*TSDXP


      RSI(3,1)=RSI(3,1)-UX(L,J,K)*VY(L,J,K)*TSDXP

      RSI(3,2)=RSI(3,2)+VY(L,J,K)*TSDXP
```

```
      RSI(3,3)=RSI(3,3)+UX(L,J,K)*TSDXP

      RSI(3,6)=RSI(3,6)-UX(L,J,K)*VY(L,J,K)*TSDXP


      RSI(4,1)=RSI(4,1)-UX(L,J,K)*WZ(L,J,K)*TSDXP

      RSI(4,2)=RSI(4,2)+WZ(L,J,K)*TSDXP

      RSI(4,4)=RSI(4,4)+UX(L,J,K)*TSDXP

      RSI(4,6)=RSI(4,6)-UX(L,J,K)*WZ(L,J,K)*TSDXP


      RSI(5,1)=RSI(5,1)-(GAM*EN(L,J,K)*UX(L,J,K)/RHO(L,J,K)
     /+(1.-GAM)*UX(L,J,K)*(UX(L,J,K)**2.+VY(L,J,K)**2.+
     /WZ(L,J,K)**2.))*TSDXP
     /-(GAM*UX(L,J,K)*C1)*TSDXP

      RSI(5,2)=RSI(5,2)+(GAM*EN(L,J,K)/RHO(L,J,K)+(1.-GAM)/2.*
     /(3.*UX(L,J,K)**2.+VY(L,J,K)**2.+WZ(L,J,K)**2.))*TSDXP
     /+GAM*UX(L,J,K)*UX(L,J,K)*TSDXP

      RSI(5,3)=RSI(5,3)+((1.-GAM)*UX(L,J,K)*VY(L,J,K))*TSDXP
     /+GAM*UX(L,J,K)*VY(L,J,K)*TSDXP

      RSI(5,4)=RSI(5,4)+(1.-GAM)*UX(L,J,K)*WZ(L,J,K)*TSDXP
     /+GAM*UX(L,J,K)*WZ(L,J,K)*TSDXP

      RSI(5,6)=RSI(5,6)-(GAM*EN(L,J,K)*UX(L,J,K)/RHO(L,J,K)
     /+(1.-GAM)*UX(L,J,K)*(UX(L,J,K)**2.+VY(L,J,K)**2.+
     /WZ(L,J,K)**2.))*TSDXP
     /-(GAM*UX(L,J,K)*C1)*TSDXP


C     NOW ADD R1(L,J)
```

```
    RSI(2,1)=RSI(2,1)+ALV*(UX(L,J,K)/RHO(L,J,K))*
   /RLPI*1./REINF

    RSI(2,2)=RSI(2,2)-ALV/RHO(L,J,K)*RLPI*1./REINF

    RSI(2,6)=RSI(2,6)+ALV*(UX(L,J,K)/RHO(L,J,K))*
   /RLPI*1./REINF

    RSI(3,1)=RSI(3,1)+AVIS*VY(L,J,K)/RHO(L,J,K)*
   /RLPI*1./REINF

    RSI(3,3)=RSI(3,3)-AVIS/RHO(L,J,K)*RLPI*1./REINF

    RSI(3,6)=RSI(3,6)+AVIS*VY(L,J,K)/RHO(L,J,K)*
   /RLPI*1./REINF

    RSI(4,1)=RSI(4,1)+AVIS*WZ(L,J,K)/RHO(L,J,K)*RLPI*1./REINF

    RSI(4,4)=RSI(4,4)-AVIS/RHO(L,J,K)*RLPI*1./REINF

    RSI(4,6)=RSI(4,6)+AVIS*WZ(L,J,K)/RHO(L,J,K)*RLPI*1./REINF

    RSI(5,1)=RSI(5,1)+1./RHO(L,J,K)*(ALTHCV*UX(L,J,K)**2.
   /+AVTHCV*(VY(L,J,K)**2.+WZ(L,J,K)**2.)*BPIH/BIJ
   /+PRREM/CVOL*EN(L,J,K)/RHO(L,J,K))*RLPI
   /+(PRREM/(RHO(L,J,K)*CVOL)*C1)*RLPI

    RSI(5,2)=RSI(5,2)-1./RHO(L,J,K)*(ALTHCV*UX(L,J,K))*RLPI
   /-PRREM/(RHO(L,J,K)*CVOL)*UX(L,J,K)*RLPI

    RSI(5,3)=RSI(5,3)-1./RHO(L,J,K)*(AVTHCV*VY(L,J,K))*RLPI
   /-PRREM/(CVOL*RHO(L,J,K))*VY(L,J,K)*RLPI
```

```
      RSI(5,4)=RSI(5,4)-1./RHO(L,J,K)*(AVTHCV*WZ(L,J,K))*RLPI
     /-PRREM/(RHO(L,J,K)*CVOL)*WZ(L,J,K)*RLPI

      RSI(5,6)=RSI(5,6)+1./RHO(L,J,K)*(ALTHCV*UX(L,J,K)**2.
     /+AVTHCV*(VY(L,J,K)**2.+WZ(L,J,K)**2.)*BPIH/BIJ
     /+PRREM/CVOL*EN(L,J,K)/RHO(L,J,K))*RLPI
     /+(PRREM/(RHO(L,J,K)*CVOL)*C1)*RLPI

C     THE IMPLICIT DISSIPATION TERM B.C'S


         RSI(1,1)=RSI(1,1)-EPSI*ALI
      RSI(2,2)=RSI(2,2)-EPSI*ALI
      RSI(3,3)=RSI(3,3)-EPSI*ALI
      RSI(4,4)=RSI(4,4)-EPSI*ALI

      RSI(5,1)=RSI(5,1)+C1*EPSI*ALI
      RSI(5,2)=RSI(5,2)-EPSI*UX(L-1,J,J)*ALI
      RSI(5,3)=RSI(5,3)-EPSI*VY(L-1,J,K)*ALI
      RSI(5,4)=RSI(5,4)-EPSI*WZ(L-1,J,K)*ALI
      RSI(6,6)=RSI(6,6)-EPSI*ALI
C     THIS ELSE IS FOR THE NON-SLIP OUTLET B.C,S
      ELSE

      RSI(2,5)=RSI(2,5)+(GAM-1.)*TSDXP
      RSI(5,1)=RSI(5,1)+PRREM/CVOL*EN(L-1,J,K)/(RHO(L-1,J,K)**2.)*
     /RLPI
      RSI(5,5)=RSI(5,5)-PRREM/CVOL*1./RHO(L-1,J,K)*RLPI
      RSI(5,6)=RSI(5,6)+PRREM/CVOL*EN(L-1,J,K)/(RHO(L-1,J,K)**2.)*
     /RLPI

      ENDIF




      ELSE
      ENDIF
```

```
C     ADD SIMILAR INDICES TOGETHER TO FORM THE SUBMATRICES
C     OF THE MAIN MATRIX

 359     DO 180 KK=1,IS
      DO 180 LL=1,IS
      IF(I.NE.2) THEN
      ATMI(KK,LL,I)=ASMI(KK,LL)+RSMI(KK,LL)

      ELSE
      ATMI(KK,LL,I)=0.
      ENDIF
      IF(I.NE.L-1) THEN
      ATPI(KK,LL,I)=ASPI(KK,LL)+RSPI(KK,LL)

      ELSE
      ATPI(KK,LL,I)=0.
      ENDIF
      ATI(KK,LL,I)=RSI(KK,LL)+PORNTP*THSW*SOURC(KK,LL)+
     /PORNTS*THSW*SOURCS(KK,LL)


 180  CONTINUE


C     NOW CLOSE THE X-SWEEP DO-LOOPS "THE Y AND X"


 150  CONTINUE

C     THOSE IFS IS TO FIND IL AND IUX( THE LOWER AND UPPER VALUES
C     OF IWHICH MATRICES ARE DEFIND).

      IF(NY2.GE.NY3) THEN
      IF(J.GT.1.AND.J.LT.NY3) THEN
      IL=LX2+1
      IUX=LX4-1
      ELSE
```

```
ENDIF

IF(J.GE.NY3.AND.J.LE.NY2) THEN
IL=LX2+1
IUX=LX3-1
ELSE
ENDIF

IF(J.GT.NY2.AND.J.LT.NY4) THEN
IL=LX1+1
IUX=LX3-1
ELSE
ENDIF
ELSE


IF(J.GT.1.AND.J.LE.NY2) THEN
IL=LX2+1
IUX=LX4-1
ELSE
ENDIF

IF(J.GT.NY2.AND.J.LT.NY3) THEN
IL=LX1+1
IUX=LX4-1
ELSE
ENDIF

IF(J.GE.NY3.AND.J.LT.NY4) THEN
IL=LX1+1
IUX=LX3-1
ELSE
ENDIF
ENDIF

CALL NBTRIP(ATMI,ATI,ATPI,BMAINX,IL,IUX,IS)
```

```
C     NOW DEPOSIT BMAINX INTO DUCON
C     THE DUCON WILL HAVE ALL THE CONSERVITIVE VARIABLES AT ALL
C    LOCATIONS
C     AT EVERY TIME STEP

      DO 185 I=2,L-1
      DO 185 KK=1,IS
      DUCON(KK,I,J,K)=BMAINX(KK,I)
c       WRITE(*,*) BMAINX(KK,I),KK,I,J
 185  CONTINUE



 140  CONTINUE


C     CALL SOLVE SUBROUTINE SOLVE TO FIND THE UNKOWNS WHICH
C     ARE DEPOSITED
C     AT BMAINX

C


C     START THE Y-SWEEP
      DO 200 K=2,N-1
C     THIS IS THE X-DO-LOOP FOR THE Y-SWEEP

      DO 200 I=2,L-1

C     UPDATE THE Y-DISSIPATVE TERMS


      DO 205 J=1,M
      UCONY(1,J)=RHO1(I,J,K)+DUCON(1,I,J,K)/AJM(I,J,K)
      UCONY(2,J)=RHO(I,J,K)*UX(I,J,K)+DUCON(2,I,J,K)/AJM(I,J,K)
      UCONY(3,J)=RHO(I,J,K)*VY(I,J,K)+DUCON(3,I,J,K)/AJM(I,J,K)
      UCONY(4,J)=RHO(I,J,K)*WZ(I,J,K)+DUCON(4,I,J,K)/AJM(I,J,K)
```

```
      UCONY(5,J)=EN(I,J,K)+DUCON(5,I,J,K)/AJM(I,J,K)
      UCONY(6,J)=RHO2(I,J,K)+DUCON(6,I,J,K)/AJM(I,J,K)
 205  CONTINUE




C     START THE Y-LOOP OF THE Y-SWEEP

      DO 210 J=2,M-1

C     THIS IS THE SUTHERLANS VISCOSITY.
C     VISCOSITY OF STEAM
      CST=861.1
      TSR=416.1
      AVSR=.1706E-6
      AVS=AVSR*((TSR+CST)/(TE(I,J,K)+CST))*(TE(I,J,K)/TSR)**1.5


C     VISCOSITY FOR AIR
      CGT=110.6
      TGR=273.1
      AVGR=.1716E-6
      AVG=AVGR*((TGR+CGT)/(TE(I,J,K)+CGT))*(TE(I,J,K)/TGR)**1.5

C     MIXTURE VISCOSITY

      AVSGU=(1.+
((AVS/AVR)**.5)*(AMOG/AMOS)**.25)**2.
      AVSGD=SQRT(8.)*(1.+AMOS/AMOG)**.5
      PHISG=AVSGU/AVSGD
      AMOS=18.
C     ASSUMING OXYGAN ONLY.
      AMOG=29.
      AVGSU=(1.+
((AVR/AVS)**.5)*(AMOS/AMOG)**.25)**2.
```

```
      AVGSD=SQRT(8.)*(1.+AMOG/AMOS)**.5
      PHIGS=AVGSU/AVGSD

      SFRAC=RHO1(I,J,K)/(RHO1(I,J,K)+RHO2(I,J,K))
      GFRAC=RHO2(I,J,K)/(RHO1(I,J,K)+RHO2(I,J,K))
      AVIS=(SFRAC*AVS)/(SFRAC+PHISG*GFRAC)+
     /(GFRAC*AVG)/(GFRAC+PHIGS*SFRAC)


C     THK IS NOT NEEDED IN THIS PROGRAM BECAUSE IT IS INCLUDED IN
C    THE PRNUM
      THK=CP*AVIS/0.72
      ALAM=-2./3.*AVIS


       COURNT=1.


C     THIS IS THE FOURTH ORDER DISSIPATION TERM



      IF(J.EQ.2) THEN


      UCO1M1=UCONY(1,J)
      UCO2M1=-UCONY(2,J)
      UCO3M1=-UCONY(3,J)
      UCO4M1=-UCONY(4,J)
      UCO5M1=UCONY(5,J)
      UCO6M1=UCONY(6,J)

      UCON(1)=AJM(I,J,K)*EPSY*COURNT*(UCONY(1,J+2)-
     /4.*UCONY(1,J+1)+6.*UCONY(1,J)-
     /4.*UCONY(1,J-1)+UCO1M1)

      UCON(2)=AJM(I,J,K)*EPSY*COURNT*(UCONY(2,J+2)-
     /4.*UCONY(2,J+1)+6.*UCONY(2,J)-
     /4.*UCONY(2,J-1)+UCO2M1)
```

```
 UCON(3)=AJM(I,J,K)*EPSY*COURNT*(UCONY(3,J+2)-
/4.*UCONY(3,J+1)+6.*UCONY(3,J)-
/4.*UCONY(3,J-1)+UCO3M1)

 UCON(4)=AJM(I,J,K)*EPSY*COURNT*(UCONY(4,J+2)-
/4.*UCONY(4,J+1)+6.*UCONY(4,J)-
/4.*UCONY(4,J-1)+UCO4M1)

 UCON(5)=AJM(I,J,K)*EPSY*COURNT*(UCONY(5,J+2)-
/4.*UCONY(5,J+1)+6.*UCONY(5,J)-
/4.*UCONY(5,J-1)+UCO5M1)

 UCON(6)=AJM(I,J,K)*EPSY*COURNT*(UCONY(6,J+2)-
/4.*UCONY(6,J+1)+6.*UCONY(6,J)-
/4.*UCONY(6,J-1)+UCO6M1)


 ELSEIF(J.EQ.(NY4-1)) THEN


 UCO1P1=UCONY(1,J)
 UCO2P1=-UCONY(2,J)
 UCO3P1=-UCONY(3,J)
 UCO4P1=-UCONY(4,J)
 UCO5P1=UCONY(5,J)
 UCO6P1=UCONY(6,J)


 UCON(1)=AJM(I,J,K)*EPSY*COURNT*(UCO1P1-
/4.*UCONY(1,J+1)+6.*UCONY(1,J)-
```

```
     /4.*UCONY(1,J-1)+UCONY(1,J-2))


      UCON(2)=AJM(I,J,K)*EPSY*COURNT*(UCO2P1-
     /4.*UCONY(2,J+1)+6.*UCONY(2,J)-
     /4.*UCONY(2,J-1)+UCONY(2,J-2))

      UCON(3)=AJM(I,J,K)*EPSY*COURNT*(UCO3P1-
     /4.*UCONY(3,J+1)+6.*UCONY(3,J)-
     /4.*UCONY(3,J-1)+UCONY(3,J-2))

      UCON(4)=AJM(I,J,K)*EPSY*COURNT*(UCO4P1-
     /4.*UCONY(4,J+1)+6.*UCONY(4,J)-
     /4.*UCONY(4,J-1)+UCONY(4,J-2))

      UCON(5)=AJM(I,J,K)*EPSY*COURNT*(UCO5P1-
     /4.*UCONY(5,J+1)+6.*UCONY(5,J)-
     /4.*UCONY(5,J-1)+UCONY(5,J-2))

      UCON(6)=AJM(I,J,K)*EPSY*COURNT*(UCO6P1-
     /4.*UCONY(6,J+1)+6.*UCONY(6,J)-
     /4.*UCONY(6,J-1)+UCONY(6,J-2))


      ELSE

      DO 2081 KK=1,IS
      UCON(KK)=AJM(I,J,K)*EPSY*COURNT*(UCONY(KK,J+2)-
     /4.*UCONY(KK,J+1)+6.*UCONY(KK,J)-
     /4.*UCONY(KK,J-1)+
     /UCONY(KK,J-2))
 2081 CONTINUE
```

```
      ENDIF

C     THIS IS THE ASMI IS USED INSTEAD OF USING BSMI TO MINIMIZE THE
C     THE STORAGE REQUIRED BY THIS PROGRAM

C     DEFINE THE PREMITIVE VARIABLES AS FOLLOWS

      RIJ=RHO(I,J,K)
      R1IJ=RHO1(I,J,K)
      R2IJ=RHO2(I,J,K)
      UIJ=UX(I,J,K)

      VIJ=VY(I,J,K)

      WIJ=WZ(I,J,K)

      EIJ=EN(I,J,K)

      PIJ=PR(I,J,K)

      TIJ=TE(I,J,K)

      BIJ=BETA(I,J,K)

      RPJ=RHO(I,J+1,K)
      RMJ=RHO(I,J-1,K)

      R1PJ=RHO1(I,J+1,K)
      R1MJ=RHO1(I,J-1,K)
```

```
R2PJ=RHO2(I,J+1,K)
R2MJ=RHO2(I,J-1,K)

UPJ=UX(I,J+1,K)
UMJ=UX(I,J-1,K)
VPJ=VY(I,J+1,K)
VMJ=VY(I,J-1,K)
WPJ=WZ(I,J+1,K)
WMJ=WZ(I,J-1,K)
EPJ=EN(I,J+1,K)
EMJ=EN(I,J-1,K)
PPJ=PR(I,J+1,K)
PMJ=PR(I,J-1,K)
TPJ=TE(I,J+1,K)
TMJ=TE(I,J-1,K)
BPJ=BETA(I,J+1,K)
BMJ=BETA(I,J-1,K)
BPJH=(BPJ+BIJ)/2.
BMJH=(BIJ+BMJ)/2.

YPJ=YY(I,J+1,K)*AJM(I,J+1,K)*BETA(I,J+1,K)
YMJ=YY(I,J-1,K)*AJM(I,J-1,K)*BETA(I,J-1,K)




ALTHCV=ALV*1./REINF-PRREM/CVOL
AVTHCV=AVIS*1./REINF-PRREM/CVOL


IF(J.EQ.2) THEN
DO 333 II=1,IS
DO 333 JJ=1,IS

ASMI(II,JJ)=0.
RSMI(II,JJ)=0.
```

```
333  CONTINUE
     ELSE
     ENDIF

     IF(J.EQ.M-1) THEN
     DO 444 II=1,IS
     DO 444 JJ=1,IS

     ASPI(II,JJ)=0.
     RSPI(II,JJ)=0.

444  CONTINUE
     ELSE
     ENDIF

     TSDYM=THSW/DY*YMJ/BIJ

     IF(J.NE.2) THEN
     ASMI(1,1)=-TSDYM*R2MJ/RMJ*VMJ
     ASMI(1,2)=0.
     ASMI(1,3)=-TSDYM*R1MJ/RMJ

     ASMI(1,4)=0.
     ASMI(1,5)=0.
     ASMI(1,6)=TSDYM*R1MJ/RMJ*VMJ

     ASMI(2,1)=UMJ*VMJ*TSDYM
     ASMI(2,2)=-VMJ*TSDYM
     ASMI(2,3)=-UMJ*TSDYM
     ASMI(2,4)=0.
     ASMI(2,5)=0.
     ASMI(2,6)=UMJ*VMJ*TSDYM

     ASMI(3,1)=((3.-GAM)/2.*VMJ*VMJ+(1.-GAM)/2.*(UMJ*UMJ+WMJ*WMJ))*
    /TSDYM
     ASMI(3,2)=(GAM-1.)*UMJ*TSDYM
     ASMI(3,3)=(GAM-3.)*VMJ*TSDYM
     ASMI(3,4)=(GAM-1.)*WMJ*TSDYM
```

```
      ASMI(3,5)=(1.-GAM)*TSDYM
      ASMI(3,6)=((3.-GAM)/2.*VMJ*VMJ+(1.-GAM)/2.*(UMJ*UMJ+WMJ*WMJ))*
     /TSDYM

      ASMI(4,1)=VMJ*WMJ*TSDYM
      ASMI(4,2)=0.
      ASMI(4,3)=-WMJ*TSDYM
      ASMI(4,4)=-VMJ*TSDYM
      ASMI(4,5)=0.
      ASMI(4,6)=VMJ*WMJ*TSDYM

      ASMI(5,1)=(GAM*EMJ*VMJ/RMJ+(1.-GAM)*VMJ*
     /(UMJ*UMJ+VMJ*VMJ+WMJ*WMJ))*TSDYM
      ASMI(5,2)=(GAM-1.)*UMJ*VMJ*TSDYM
      ASMI(5,3)=(-GAM*EMJ/RMJ+(GAM-1.)/2.*
     /(3.*VMJ*VMJ+UMJ*UMJ+WMJ*WMJ))*TSDYM
      ASMI(5,4)=(GAM-1.)*VMJ*WMJ*TSDYM
      ASMI(5,5)=-GAM*VMJ*TSDYM
      ASMI(5,6)=(GAM*EMJ*VMJ/RMJ+(1.-GAM)*VMJ*
     /(UMJ*UMJ+VMJ*VMJ+WMJ*WMJ))*TSDYM

      ASMI(6,1)=TSDYM*R2MJ/RMJ*VMJ
      ASMI(6,2)=0.
      ASMI(6,3)=-TSDYM*R2MJ/RMJ

      ASMI(6,4)=0.
      ASMI(6,5)=0.
      ASMI(6,6)=-TSDYM*R1MJ/RMJ*VMJ



      ELSE
      ENDIF
C     THIS IS THE I+1

      TSDYP=THSW/DY*YPJ/BIJ
      IF(J.NE.M-1) THEN
      ASPI(1,1)=TSDYP*R2PJ/RPJ*VPJ
      ASPI(1,2)=0.
```

```
      ASPI(1,3)=TSDYP*R1PJ/RPJ
C      *R1PJ/RPJ
      ASPI(1,4)=0.
      ASPI(1,5)=0.
      ASPI(1,6)=-TSDYP*R1PJ/RPJ*VPJ

      ASPI(2,1)=-UPJ*VPJ*TSDYP
      ASPI(2,2)=VPJ*TSDYP
      ASPI(2,3)=UPJ*TSDYP
      ASPI(2,4)=0.
      ASPI(2,5)=0.
      ASPI(2,6)=-UPJ*VPJ*TSDYP

      ASPI(3,1)=-((3.-GAM)/2.*VPJ*VPJ+(1.-GAM)/2.*
     /(UPJ*UPJ+WPJ*WPJ))*TSDYP
      ASPI(3,2)=-(GAM-1.)*UPJ*TSDYP
      ASPI(3,3)=-(GAM-3.)*VPJ*TSDYP
      ASPI(3,4)=(1.-GAM)*WPJ*TSDYP
      ASPI(3,5)=(GAM-1.)*TSDYP
      ASPI(3,6)=-((3.-GAM)/2.*VPJ*VPJ+(1.-GAM)/2.*
     /(UPJ*UPJ+WPJ*WPJ))*TSDYP

      ASPI(4,1)=-VPJ*WPJ*TSDYP
      ASPI(4,2)=0.
      ASPI(4,3)=WPJ*TSDYP
      ASPI(4,4)=VPJ*TSDYP
      ASPI(4,5)=0.
      ASPI(4,6)=-VPJ*WPJ*TSDYP

      ASPI(5,1)=-(GAM*EPJ*VPJ/RPJ+(1.-GAM)*VPJ*
     /(UPJ*UPJ+VPJ*VPJ+WPJ*WPJ))*TSDYP
      ASPI(5,2)=-(GAM-1.)*UPJ*VPJ*TSDYP
      ASPI(5,3)=(GAM*EPJ/RPJ-(GAM-1.)/2.*
     /(3.*VPJ*VPJ+UPJ*UPJ+WPJ*WPJ))*TSDYP
      ASPI(5,4)=(1.-GAM)*VPJ*WPJ*TSDYP
      ASPI(5,5)=GAM*VPJ*TSDYP
      ASPI(5,6)=-(GAM*EPJ*VPJ/RPJ+(1.-GAM)*VPJ*
     /(UPJ*UPJ+VPJ*VPJ+WPJ*WPJ))*TSDYP
```

```
      ASPI(6,1)=-TSDYP*R2PJ/RPJ*VPJ
      ASPI(6,2)=0.
      ASPI(6,3)=TSDYP*R2PJ/RPJ
C      *R2PJ/RPJ
      ASPI(6,4)=0.
      ASPI(6,5)=0.
      ASPI(6,6)=TSDYP*R1PJ/RPJ*VPJ


      ELSE
      ENDIF



C     DO THE RSMI "I-1"


      AL1Y=1./(DY1*DY1)*THSW*BMJH/BIJ

      ALI=1./(DY1*DY1)*THSW*AJM(I,J,K)/AJM(I,J-1,K)
      IF(J.NE.2) THEN

C      THIS IS FOR THE EXCIPLICIT VISCOUS TERMS ONLY

       RSMI(1,1)=-ALI*EPSIY
       RSMI(2,2)=-ALI*EPSIY
       RSMI(3,3)=-ALI*EPSIY
       RSMI(4,4)=-ALI*EPSIY
       RSMI(5,5)=-ALI*EPSIY
       RSMI(6,6)=-ALI*EPSIY
C      RSMI(1,1)=0.-ALI*EPSI
C      RSMI(1,2)=0.
C      RSMI(1,3)=0.
C      RSMI(1,4)=0.
```

```
C       RSMI(1,5)=0.
C       RSMI(1,6)=0.

C       RSMI(2,1)=AVIS*UMJ/RMJ*AL1Y*1./REINF
C       RSMI(2,2)=-AVIS/RMJ*AL1Y*1./REINF-ALI*EPSI
C       RSMI(2,3)=0.
C       RSMI(2,4)=0.
C       RSMI(2,5)=0.
C       RSMI(2,6)=AVIS*UMJ/RMJ*AL1Y*1./REINF


C       RSMI(3,1)=ALV*VMJ/RMJ*AL1Y*1./REINF
C       RSMI(3,2)=0.
C       RSMI(3,3)=-ALV/RMJ*AL1Y*1./REINF-ALI*EPSI
C       RSMI(3,4)=0.
C       RSMI(3,5)=0.
C       RSMI(3,6)=ALV*VMJ/RMJ*AL1Y*1./REINF


C       RSMI(4,1)=AVIS*WMJ/RMJ*AL1Y*1./REINF
C       RSMI(4,2)=0.
C       RSMI(4,3)=0.
C       RSMI(4,4)=-AVIS/RMJ*AL1Y*1./REINF-ALI*EPSI
C       RSMI(4,5)=0.
C       RSMI(4,6)=AVIS*WMJ/RMJ*AL1Y*1./REINF


C       RSMI(5,1)=1./RMJ*(ALTHCV*VMJ*VMJ+AVTHCV*
         /(UMJ*UMJ+WMJ*WMJ)
C      /+PRREM/CVOL*EMJ/RMJ)*AL1Y
C       RSMI(5,2)=-1./RMJ*(AVTHCV*UMJ)*AL1Y
C       RSMI(5,3)=-1./RMJ*(ALTHCV*VMJ)*AL1Y
C       RSMI(5,4)=-1./RMJ*AVTHCV*WMJ*AL1Y
C       RSMI(5,5)=-1./RMJ*PRREM/CVOL*AL1Y-ALI*EPSI
C       RSMI(5,6)=1./RMJ*(ALTHCV*VMJ*VMJ+
        /AVTHCV*(UMJ*UMJ+WMJ*WMJ)
C      /+PRREM/CVOL*EMJ/RMJ)*AL1Y
```

```
C       RSMI(6,1)=0.
C       RSMI(6,2)=0.
C       RSMI(6,3)=0.
C       RSMI(6,4)=0.
C       RSMI(6,5)=0.
C       RSMI(6,6)=0.-ALI*EPSI



      ELSE
      ENDIF
C     THIS IS THE RSI AT I

      ALY=(BPJH+BMJH)/(DY1*DY1)*THSW/BIJ

      ALYI=2./(DY1*DY1)*THSW

C       RSI(1,1)=1.0+ALYI*EPSI
C     THIS STEP SUBISTITUTES THE RS(I,I) STEPS WHEN TREATING THE
C     VISCOUS TERMS EXCIPLICITLY


       RSI(1,1)=-ALYI*EPSIY+1.
       RSI(2,2)=-ALYI*EPSIY+1.
       RSI(3,3)=-ALYI*EPSIY+1.
       RSI(4,4)=-ALYI*EPSIY+1.
       RSI(5,5)=-ALYI*EPSIY+1.
       RSI(6,6)=-ALYI*EPSIY+1.


C       RSI(1,2)=0.
C       RSI(1,3)=0.
C       RSI(1,4)=0.
C       RSI(1,5)=0.
C       RSI(1,6)=0.

C       RSI(2,1)=-AVIS*UIJ/RIJ*ALY*1./REINF
```

```
C       RSI(2,2)=AVIS/RIJ*ALY*1./REINF+1.+ALYI*EPSI
C       RSI(2,3)=0.
C       RSI(2,4)=0.
C       RSI(2,5)=0.
C       RSI(2,6)=-AVIS*UIJ/RIJ*ALY*1./REINF


C       RSI(3,1)=-ALV*VIJ/RIJ*ALY*1./REINF
C       RSI(3,2)=0.
C       RSI(3,3)=ALV/RIJ*ALY*1./REINF+1.+ALYI*EPSI
C       RSI(3,4)=0.
C       RSI(3,5)=0.
C       RSI(3,6)=-ALV*VIJ/RIJ*ALY*1./REINF


C       RSI(4,1)=-AVIS*WIJ/RIJ*ALY*1./REINF
C       RSI(4,2)=0.
C       RSI(4,3)=0.
C       RSI(4,4)=AVIS/RIJ*ALY*1./REINF+1.+ALYI*EPSI
C       RSI(4,5)=0.
C       RSI(4,6)=-AVIS*WIJ/RIJ*ALY*1./REINF


C       RSI(5,1)=-1./RIJ*(ALTHCV*VIJ*VIJ+AVTHCV*(UIJ*UIJ+WIJ*WIJ)
C      /+PRREM/CVOL*EIJ/RIJ)*ALY
C       RSI(5,2)=1./RIJ*(AVTHCV*UIJ)*ALY
C       RSI(5,3)=1./RIJ*(ALTHCV*VIJ)*ALY
C       RSI(5,4)=1./RIJ*AVTHCV*WIJ*ALY
C       RSI(5,5)=1./RIJ*PRREM/CVOL*ALY+1.0+ALYI*EPSI
C       RSI(5,6)=-1./RIJ*(ALTHCV*VIJ*VIJ+AVTHCV*(UIJ*UIJ+WIJ*WIJ)
C      /+PRREM/CVOL*EIJ/RIJ)*ALY


C       RSI(6,1)=0.
C       RSI(6,2)=0.
C       RSI(6,3)=0.
C       RSI(6,4)=0.
```

```
C       RSI(6,5)=0.
C       RSI(6,6)=1.+ALYI*EPSI

C      NOW DO THW RSPI "I+1"
       AL1YP=1./(DY1*DY1)*THSW*BPJH/BIJ
       ALIP=1./(DY1*DY1)*THSW*AJM(I,J,K)/AJM(I,J+1,K)
       IF(J.NE.M-1) THEN

C       THIS IS FOR THE EXCIPLICIT VISCOUS TERMS ONLY

        RSPI(1,1)=-ALIP*EPSIY
        RSPI(2,2)=-ALIP*EPSIY
        RSPI(3,3)=-ALIP*EPSIY
        RSPI(4,4)=-ALIP*EPSIY
        RSPI(5,5)=-ALIP*EPSIY
        RSPI(6,6)=-ALIP*EPSIY
C       RSPI(1,1)=0.-ALIP*EPSI
C       RSPI(1,2)=0.
C       RSPI(1,3)=0.
C       RSPI(1,4)=0.
C       RSPI(1,5)=0.
C       RSPI(1,6)=0.

C       RSPI(2,1)=AVIS*UPJ/RPJ*AL1YP*1./REINF
C       RSPI(2,2)=-AVIS/RPJ*AL1YP*1./REINF-ALIP*EPSI
C       RSPI(2,3)=0.
C       RSPI(2,4)=0.
C       RSPI(2,5)=0.
C       RSPI(2,6)=AVIS*UPJ/RPJ*AL1YP*1./REINF


C       RSPI(3,1)=ALV*VPJ/RPJ*AL1YP*1./REINF
C       RSPI(3,2)=0.
C       RSPI(3,3)=-ALV/RPJ*AL1YP*1./REINF-ALIP*EPSI
C       RSPI(3,4)=0.
C       RSPI(3,5)=0.
C       RSPI(3,6)=ALV*VPJ/RPJ*AL1YP*1./REINF
```

```
C       RSPI(4,1)=AVIS*WPJ/RPJ*AL1YP*1./REINF
C       RSPI(4,2)=0.
C       RSPI(4,3)=0.
C       RSPI(4,4)=-AVIS/RPJ*AL1YP*1./REINF-ALIP*EPSI
C       RSPI(4,5)=0.
C       RSPI(4,6)=AVIS*WPJ/RPJ*AL1YP*1./REINF


C       RSPI(5,1)=1./RPJ*(ALTHCV*VPJ*VPJ+AVTHCV*
C      /(UPJ*UPJ+WPJ*WPJ)+PRREM/CVOL*EPJ/RPJ)*AL1YP
C       RSPI(5,2)=-1./RPJ*(AVTHCV*UPJ)*AL1YP
C       RSPI(5,3)=-1./RPJ*(ALTHCV*VPJ)*AL1YP
C       RSPI(5,4)=-AVTHCV*WPJ/RPJ*AL1YP
C       RSPI(5,5)=-1./RPJ*PRREM/CVOL*AL1YP-ALIP*EPSI
C       RSPI(5,6)=1./RPJ*(ALTHCV*VPJ*VPJ+AVTHCV*
C      /(UPJ*UPJ+WPJ*WPJ)+PRREM/CVOL*EPJ/RPJ)*AL1YP

C       RSPI(6,1)=0.
C       RSPI(6,2)=0.
C       RSPI(6,3)=0.
C       RSPI(6,4)=0.
C       RSPI(6,5)=0.
C       RSPI(6,6)=0.-ALIP*EPSI


       ELSE
       ENDIF


C      DEPOSIT THE Y-SWEEP B.C'S


C      THIS IS THE LOWER B.C'S
        GO TO 789
       IF(J.EQ.2) THEN
```

```
      RSI(3,5)=RSI(3,5)-(GAM-1.)*TSDYM
      RSI(5,1)=RSI(5,1)+(PRREM/CVOL*EN(I,2,K)/RHO(I,2,K)**2.)*
     /AL1Y
      RSI(5,5)=RSI(5,5)-(PRREM/CVOL*1./RHO(I,2,K))*AL1Y
      RSI(5,6)=RSI(5,6)+(PRREM/CVOL*EN(I,2,K)/RHO(I,2,K)**2.)*
     /AL1Y

C     THIS IS YHE IMPLICIT B.C'S OF THE DISSIPATION TERM

      RSI(1,1)=RSI(1,1)-EPSI*ALI
      RSI(2,2)=RSI(2,2)-EPSI*ALI
      RSI(4,4)=RSI(4,4)-EPSI*ALI
      RSI(5,5)=RSI(5,5)-EPSI*ALI
      RSI(6,6)=RSI(6,6)-EPSI*ALI

      ELSE
      ENDIF

C     START THE UPPER B.C'S

      IF(J.EQ.M-1) THEN

      RSI(3,5)=RSI(3,5)+(GAM-1.)*TSDYP
      RSI(5,1)=RSI(5,1)+PRREM/CVOL*EN(I,M-1,K)/(RHO(I,M-1,K)**2.)*
```

```
     /AL1YP
      RSI(5,5)=RSI(5,5)-PRREM/CVOL*1./RHO(I,M-1,K)*AL1YP
      RSI(5,6)=RSI(5,6)+PRREM/CVOL*EN(I,M-1,K)/(RHO(I,M-1,K)**2.)*
     /AL1YP

C     UPPER IMPLICIT DISSIPATION
      RSI(1,1)=RSI(1,1)-EPSI*ALIP
      RSI(2,2)=RSI(2,2)-EPSI*ALIP
      RSI(4,4)=RSI(4,4)-EPSI*ALIP
      RSI(5,5)=RSI(5,5)-EPSI*ALIP

      ELSE
      ENDIF

C     THIS IS A VERY SIMPLE ALTERNATIVE DISSIPATION
C      UCON(1)=EPS/(DY1**2.)*(PPJ-2.*PIJ+PMJ)
C      UCON(2)=EPS/(DY1**2.)*(PPJ-2.*PIJ+PMJ)
C      UCON(3)=EPS/(DY1**2.)*(PPJ-2.*PIJ+PMJ)
C      UCON(4)=EPS/(DY1**2.)*(PPJ-2.*PIJ+PMJ)
C      UCON(5)=EPS/(DY1**2.)*(PPJ-2.*PIJ+PMJ)
C      UCON(6)=EPS/(DY1**2.)*(PPJ-2.*PIJ+PMJ)
```

```
 789   DO 220 KK=1,IS
       BMAINY(KK,J)=DUCON(KK,I,J,K)-UCON(KK)


 220   CONTINUE

C      ADD THE SIMILAR INDICES TO FORM THE FOLL. SUBMATRICES
C      ATMI,ATPI,AND ATI

       DO 230 KK=1,IS
       DO 230 LL=1,IS
       IF(J.NE.2) THEN
       BTMI(KK,LL,J)=RSMI(KK,LL)+ASMI(KK,LL)
       ELSE
       BTMI(KK,LL,J)=0.
       ENDIF
       IF(J.NE.M-1) THEN
       BTPI(KK,LL,J)=RSPI(KK,LL)+ASPI(KK,LL)
       ELSE
       BTPI(KK,LL,J)=0.
       ENDIF

       BTI(KK,LL,J)=RSI(KK,LL)


 230   CONTINUE

C      CLOSE THE Y-SWEEP-DO-LOOPS


 210   CONTINUE
```

```
C     THOSE IFS IS TO FIND IL AND IUY( THE LOWER AND UPPER VALUES
C     OF IWHICH MATRICES ARE DEFIND).

      IF(I.GT.1.AND.I.LE.LX2) THEN
      IL=NY2+1
      IUY=NY4-1
      ELSE
      ENDIF

      IF(I.GT.LX2.AND.I.LT.LX3) THEN
      IL=NY1+1
      IUY=NY4-1
      ELSE
      ENDIF

      IF(I.GE.LX3.AND.I.LT.LX4) THEN
      IL=NY1+1
      IUY=NY3-1
      ELSE
      ENDIF

      CALL NBTRIP(BTMI,BTI,BTPI,BMAINY,IL,IUY,IS)

      DO 240 J=2,M-1
      DO 240 KK=1,IS
      DUCON(KK,I,J,K)=BMAINY(KK,J)

  240 CONTINUE
```

```
 200   CONTINUE
C      START THE Z-SWEEP
C      THIS IS THE X-DO-LOOP FOR THE Z-SWEEP
       DO 500 I=2,L-1
C      THIS IS THE Y-DO-LOOP FOR THE Z-SWEEP
       DO 500 J=2,M-1

C      THIS IF STATEMENT IS TO EXCLUDE THE DOMAIN THAT HAS NO
C      FLOW
       IF((I.LE.LX2.AND.J.LE.NY2).OR.(I.GE.LX3.AND.J.GE.NY3)) THEN
       ELSE
C      UPDATE THE Z-DISSIPATVE TERMS

       DO 510 K=2,N-1
       UCONZ(1,K)=RHO1(I,J,K)+DUCON(1,I,J,K)/AJM(I,J,K)
       UCONZ(2,K)=RHO(I,J,K)*UX(I,J,K)+DUCON(2,I,J,K)/AJM(I,J,K)
       UCONZ(3,K)=RHO(I,J,K)*VY(I,J,K)+DUCON(3,I,J,K)/AJM(I,J,K)
       UCONZ(4,K)=RHO(I,J,K)*WZ(I,J,K)+DUCON(4,I,J,K)/AJM(I,J,K)
       UCONZ(5,K)=EN(I,J,K)+DUCON(5,I,J,K)/AJM(I,J,K)
       UCONZ(6,K)=RHO2(I,J,K)+DUCON(6,I,J,K)/AJM(I,J,K)
 510   CONTINUE
```

```
C     START THE Y-LOOP OF THE Z-SWEEP

      DO 520 K=2,N-1

C     THIS IS THE SUTHERLAND VISCOSITY RELATIONSHIP.

C     VISCOSITY OF STEAM
      CST=861.1
      TSR=416.1
      AVSR=.1706E-6
      AVS=AVSR*((TSR+CST)/(TE(I,J,K)+CST))*(TE(I,J,K)/TSR)**1.5


C     VISCOSITY FOR AIR
      CGT=110.6
      TGR=273.1
      AVGR=.1716E-6
      AVG=AVGR*((TGR+CGT)/(TE(I,J,K)+CGT))*(TE(I,J,K)/TGR)**1.5

C     MIXTURE VISCOSITY

      AVSGU=(1.+
((AVS/AVR)**.5)*(AMOG/AMOS)**.25)**2.
      AVSGD=SQRT(8.)*(1.+AMOS/AMOG)**.5
      PHISG=AVSGU/AVSGD
      AMOS=18.
C     ASSUMING OXYGAN ONLY.
      AMOG=29.
      AVGSU=(1.+
((AVR/AVS)**.5)*(AMOS/AMOG)**.25)**2.
      AVGSD=SQRT(8.)*(1.+AMOG/AMOS)**.5
      PHIGS=AVGSU/AVGSD

      SFRAC=RHO1(I,J,K)/(RHO1(I,J,K)+RHO2(I,J,K))
      GFRAC=RHO2(I,J,K)/(RHO1(I,J,K)+RHO2(I,J,K))
      AVIS=(SFRAC*AVS)/(SFRAC+PHISG*GFRAC)+
     /(GFRAC*AVG)/(GFRAC+PHIGS*SFRAC)
```

```
C     THK IS NOT NEEDED IN THIS PROGRAM BECAUSE IT IS INCLUDED IN
C     THE PRNUM
      THK=CP*AVIS/0.72
      ALAM=-2./3.*AVIS


C     THIS IS THE FOURTH ORDER DISSIPATION TERM


      IF(K.EQ.2) THEN


      UCO1M1=UCONZ(1,K)
      UCO2M1=-UCONZ(2,K)
      UCO3M1=-UCONZ(3,K)
      UCO4M1=-UCONZ(4,K)
      UCO5M1=UCONZ(5,K)
      UCO6M1=UCONZ(6,K)

      UCON(1)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(1,K+2)-
     /4.*UCONZ(1,K+1)+6.*UCONZ(1,K)-
     /4.*UCONY(1,J-1)+UCO1M1)

      UCON(2)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(2,K+2)-
     /4.*UCONZ(2,K+1)+6.*UCONZ(2,K)-
     /4.*UCONZ(2,K-1)+UCO2M1)


      UCON(3)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(3,K+2)-
     /4.*UCONZ(3,K+1)+6.*UCONZ(3,K)-
     /4.*UCONZ(3,K-1)+UCO3M1)

      UCON(4)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(4,K+2)-
     /4.*UCONZ(4,K+1)+6.*UCONZ(4,K)-
     /4.*UCONZ(4,K-1)+UCO4M1)
```

```
      UCON(5)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(5,K+2)-
     /4.*UCONZ(5,K+1)+6.*UCONZ(5,K)-
     /4.*UCONZ(5,K-1)+UCO5M1)

      UCON(6)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(6,K+2)-
     /4.*UCONZ(6,K+1)+6.*UCONZ(6,K)-
     /4.*UCONZ(6,K-1)+UCO6M1)

      ELSEIF(K.EQ.N-1) THEN

UCO1P1=UCONZ(1,J)
      UCO2P1=-UCONZ(2,J)
      UCO3P1=-UCONZ(3,J)
      UCO4P1=-UCONZ(4,J)
      UCO5P1=UCONZ(5,J)
      UCO6P1=UCONZ(6,J)

      UCON(1)=AJM(I,J,K)*EPSZ*COURNT*(UCO1P1-
     /4.*UCONZ(1,K+1)+6.*UCONZ(1,K)-
     /4.*UCONZ(1,K-1)+UCONZ(1,K-2))

      UCON(2)=AJM(I,J,K)*EPSZ*COURNT*(UCO2P1-
     /4.*UCONZ(2,K+1)+6.*UCONZ(2,K)-
     /4.*UCONZ(2,K-1)+UCONZ(2,K-2))

      UCON(3)=AJM(I,J,K)*EPSZ*COURNT*(UCO3P1-
     /4.*UCONZ(3,K+1)+6.*UCONZ(3,K)-
```

```
     /4.*UCONZ(3,K-1)+UCONY(3,K-2))

      UCON(4)=AJM(I,J,K)*EPSZ*COURNT*(UCO4P1-
     /4.*UCONZ(4,K+1)+6.*UCONZ(4,K)-
     /4.*UCONZ(4,K-1)+UCONZ(4,K-2))

      UCON(5)=AJM(I,J,K)*EPSZ*COURNT*(UCO5P1-
     /4.*UCONZ(5,K+1)+6.*UCONZ(5,K)-
     /4.*UCONZ(5,K-1)+UCONY(5,K-2))

      UCON(6)=AJM(I,J,K)*EPSZ*COURNT*(UCO6P1-
     /4.*UCONZ(6,K+1)+6.*UCONY(6,K)-
     /4.*UCONZ(6,K-1)+UCONZ(6,K-2))




      ELSE

      DO 3081 KK=1,IS
      UCON(KK)=AJM(I,J,K)*EPSZ*COURNT*(UCONZ(KK,K+2)-
     /4.*UCONZ(KK,K+1)+6.*UCONZ(KK,K)-
     /4.*UCONZ(KK,K-1)+
     /UCONZ(KK,K-2))
 3081 CONTINUE
      ENDIF
```

```
C     THIS IS THE ASMI IS USED INSTEAD OF USING BSMI TO MINIMIZE THE
C     THE STORAGE REQUIRED BY THIS PROGRAM

C     DEFINE THE PREMITIVE VARIABLES AS FOLLOWS

      RIJ=RHO(I,J,K)

      R1IJ=RHO1(I,J,K)

      R2IJ=RHO2(I,J,K)

      UIJ=UX(I,J,K)

      VIJ=VY(I,J,K)

      WIJ=WZ(I,J,K)

      EIJ=EN(I,J,K)

      PIJ=PR(I,J,K)

      TIJ=TE(I,J,K)

      BIJ=BETA(I,J,K)

      RPK=RHO(I,J,K+1)
      RMK=RHO(I,J,K-1)

      R1PK=RHO1(I,J,K+1)
      R1MK=RHO1(I,J,K-1)

      R2PK=RHO2(I,J,K+1)
```

```
      R2MK=RHO2(I,J,K-1)

      UPK=UX(I,J,K+1)
      UMK=UX(I,J,K-1)
      VPK=VY(I,J,K+1)
      VMK=VY(I,J,K-1)
      WPK=WZ(I,J,K+1)
      WMK=WZ(I,J,K-1)
      EPK=EN(I,J,K+1)
      EMK=EN(I,J,K-1)
      PPK=PR(I,J,K+1)
      PMK=PR(I,J,K-1)
      TPK=TE(I,J,K+1)
      TMK=TE(I,J,K-1)
      BPK=BETA(I,J,K+1)
      BMK=BETA(I,J,K-1)

      BPKH=(BPK+BIJ)/2.
      BMKH=(BIJ+BMK)/2.



      ZPK=ZZ(I,J,K+1)*AJM(I,J,K+1)*BETA(I,J,K+1)
      ZMK=ZZ(I,J,K-1)*AJM(I,J,K-1)*BETA(I,J,K-1)

      ALTHCV=ALV*1./REINF-PRREM/CVOL
      AVTHCV=AVIS*1./REINF-PRREM/CVOL


      IF(K.EQ.2) THEN
      DO 530 II=1,IS
      DO 530 JJ=1,IS

      ASMI(II,JJ)=0.
      RSMI(II,JJ)=0.

 530  CONTINUE
      ELSE
```

```
      ENDIF

      IF(K.EQ.N-1) THEN
      DO 540 II=1,IS
      DO 540 JJ=1,IS

      ASPI(II,JJ)=0.
      RSPI(II,JJ)=0.

  540 CONTINUE
      ELSE
      ENDIF

      TSDZM=THSW/DZ*ZMK/BIJ



      IF(K.NE.2) THEN
      ASMI(1,1)=0.
      ASMI(1,2)=0.
      ASMI(1,3)=0.
      ASMI(1,4)=-TSDZM*R1MK/RMK
      ASMI(1,5)=0.
      ASMI(1,6)=0.


      ASMI(2,1)=UMK*WMK*TSDZM
      ASMI(2,2)=-WMK*TSDZM
      ASMI(2,3)=0.
      ASMI(2,4)=-UMK*TSDZM
      ASMI(2,5)=0.
      ASMI(2,6)=UMK*WMK*TSDZM


      ASMI(3,1)=VMK*WMK*TSDZM
      ASMI(3,2)=0.
      ASMI(3,3)=-WMK*TSDZM
      ASMI(3,4)=-VMK*TSDZM
```

```
 ASMI(3,5)=0.
 ASMI(3,6)=VMK*WMK*TSDZM


 ASMI(4,1)=((3.-GAM)/2.*WMK*WMK+
/(1.-GAM)/2.*(UMK*UMK+VMK*VMK))*TSDZM
 ASMI(4,2)=(GAM-1.)*UMK*TSDZM
 ASMI(4,3)=(GAM-1.)*VMK*TSDZM
 ASMI(4,4)=(GAM-3.)*WMK*TSDZM
 ASMI(4,5)=(1.-GAM)*TSDZM
 ASMI(4,6)=((3.-GAM)/2.*WMK*WMK+
/(1.-GAM)/2.*(UMK*UMK+VMK*VMK))*TSDZM


 ASMI(5,1)=(GAM*EMK*WMK/RMK+(1.-GAM)*WMK*
/(UMK*UMK+VMK*VMK+WMK*WMK))*TSDZM
 ASMI(5,2)=(GAM-1.)*UMK*WMK*TSDZM
 ASMI(5,3)=(GAM-1.)*VMK*WMK*TSDZM
 ASMI(5,4)=(-GAM*EMK/RMK+(GAM-1.)/2.*
/(3.*WMK*WMK+UMK*UMK+VMK*VMK))*TSDZM
 ASMI(5,5)=-GAM*WMK*TSDZM
 ASMI(5,6)=(GAM*EMK*WMK/RMK+(1.-GAM)*WMK*
/(UMK*UMK+VMK*VMK+WMK*WMK))*TSDZM


 ASMI(6,1)=0.
 ASMI(6,2)=0.
 ASMI(6,3)=0.
 ASMI(6,4)=-TSDZM*R2MK/RMK
 ASMI(6,5)=0.
 ASMI(6,6)=0.


 ELSE
```

```
      ENDIF
C     THIS IS THE I+1
      TSDZP=THSW/DZ*ZPK/BIJ
      IF(K.NE.N-1) THEN
      ASPI(1,1)=0.
      ASPI(1,2)=0.
      ASPI(1,3)=0.
      ASPI(1,4)=TSDZP*R1PK/RPK
      ASPI(1,5)=0.
      ASPI(1,6)=0.


      ASPI(2,1)=-UPK*WPK*TSDZP
      ASPI(2,2)=WPK*TSDZP
      ASPI(2,3)=0.
      ASPI(2,4)=UPK*TSDZP
      ASPI(2,5)=0.
      ASPI(2,6)=-UPK*WPK*TSDZP


      ASPI(3,1)=-VPK*WPK*TSDZP
      ASPI(3,2)=0.
      ASPI(3,3)=WPK*TSDZP
      ASPI(3,4)=VPK*TSDZP
      ASPI(3,5)=0.
      ASPI(3,6)=-VPK*WPK*TSDZP



      ASPI(4,1)=((GAM-3.)/2.*WPK*WPK+
     /(GAM-1.)/2.*(UPK*UPK+VPK*VPK))*TSDZP
      ASPI(4,2)=(1.-GAM)*UPK*TSDZP
      ASPI(4,3)=(1.-GAM)*VPK*TSDZP
      ASPI(4,4)=(3.-GAM)*WPK*TSDZP
      ASPI(4,5)=(GAM-1.)*TSDZP
      ASPI(4,6)=((GAM-3.)/2.*WPK*WPK+
     /(GAM-1.)/2.*(UPK*UPK+VPK*VPK))*TSDZP
```

```
      ASPI(5,1)=(-GAM*EPK*WPK/RPK+(GAM-1.)*WPK*
     /(UPK*UPK+VPK*VPK+WPK*WPK))*TSDZP
      ASPI(5,2)=(1.-GAM)*UPK*WPK*TSDZP
      ASPI(5,3)=(1.-GAM)*VPK*WPK*TSDZP
      ASPI(5,4)=(GAM*EPK/RPK+(1.-GAM)/2.*
     /(3.*WPK*WPK+UPK*UPK+VPK*VPK))*TSDZP
      ASPI(5,5)=GAM*WPK*TSDZP
      ASPI(5,6)=(-GAM*EPK*WPK/RPK+(GAM-1.)*WPK*
     /(UPK*UPK+VPK*VPK+WPK*WPK))*TSDZP


      ASPI(6,1)=0.
      ASPI(6,2)=0.
      ASPI(6,3)=0.
      ASPI(6,4)=TSDZP*R2PK/RPK
      ASPI(6,5)=0.
      ASPI(6,6)=0.


      ELSE
      ENDIF


C     DO THE RSMI "I-1"


      AL1Z=1./(DZ1*DZ1)*THSW*BMKH/BIJ
```

```
      ALI=1./(DZ1*DZ1)*THSW*AJM(I,J,K)/AJM(I,1,K-1)

C     THIS IS FOR THE IMPLICIT DISSSIPATION TERMS

      RSMI(1,1)=-ALI*EPSIZ
      RSMI(2,2)=-ALI*EPSIZ
      RSMI(3,3)=-ALI*EPSIZ
      RSMI(4,4)=-ALI*EPSIZ
      RSMI(5,5)=-ALI*EPSIZ
      RSMI(6,6)=-ALI*EPSIZ

C     IF(K.NE.2) THEN
C     RSMI(1,1)=0.-ALI*EPSI
C     RSMI(1,2)=0.
C     RSMI(1,3)=0.
C     RSMI(1,4)=0.
C     RSMI(1,5)=0.
C     RSMI(1,6)=0.


C     RSMI(2,1)=AVIS*UMK/RMK*AL1Z*1./REINF
C     RSMI(2,2)=-AVIS/RMK*AL1Z*1./REINF-ALI*EPSI
C     RSMI(2,3)=0.
C     RSMI(2,4)=0.
C     RSMI(2,5)=0.
C     RSMI(2,6)=AVIS*UMK/RMK*AL1Z*1./REINF



C     RSMI(3,1)=AVIS*VMK/RMK*AL1Z*1./REINF
C     RSMI(3,2)=0.
C     RSMI(3,3)=-AVIS/RMK*AL1Z*1./REINF-ALI*EPSI
C     RSMI(3,4)=0.
C     RSMI(3,5)=0.
C     RSMI(3,6)=AVIS*VMK/RMK*AL1Z*1./REINF
```

```
C       RSMI(4,1)=ALV*WMK/RMK*AL1Z*1./REINF
C       RSMI(4,2)=0.
C       RSMI(4,3)=0.
C       RSMI(4,4)=-ALV/RMK*AL1Z*1./REINF-ALI*EPSI
C       RSMI(4,5)=0.
C       RSMI(4,6)=ALV*WMK/RMK*AL1Z*1./REINF


C       RSMI(5,1)=1./RMK*(ALTHCV*WMK*
C       WMK+AVTHCV*(UMK*UMK+VMK*VMK)
C      /+PRREM/CVOL*EMK/RMK)*AL1Z
C       RSMI(5,2)=-1./RMK*(AVTHCV*UMK)*AL1Z
C       RSMI(5,3)=-1./RMK*AVTHCV*VMK*AL1Z
C       RSMI(5,4)=-1./RMK*(ALTHCV*WMK)*AL1Z
C       RSMI(5,5)=-1./RMK*PRREM/CVOL*AL1Z-ALI*EPSI
C       RSMI(5,6)=1./RMK*(ALTHCV*WMK*WMK+
C      AVTHCV*(UMK*UMK+VMK*VMK)
C      /+PRREM/CVOL*EMK/RMK)*AL1Z


C       RSMI(6,1)=0.
C       RSMI(6,2)=0.
C       RSMI(6,3)=0.
C       RSMI(6,4)=0.
C       RSMI(6,5)=0.
C       RSMI(6,6)=0.-ALI*EPSI


C       ELSE
```

```
C      ENDIF
C     THIS IS THE RSI AT I


      ALZ=(BPKH+BMKH)/(DZ1*DZ1)*THSW


      ALZI=2./(DZ1*DZ1)*THSW

C      RSI(1,1)=1.0+ALZI*EPSI

C     THIS STEP SUBISTITUTES THE RS(I,I) STEPS WHEN TREATING THE
C     VISCOUS TERMS EXCIPLICITLY


       ALYI=2./(DZ1*DZ1)*THSW


       RSI(1,1)=-ALYI*EPSIZ+1.
       RSI(2,2)=-ALYI*EPSIZ+1.
       RSI(3,3)=-ALYI*EPSIZ+1.
       RSI(4,4)=-ALYI*EPSIZ+1.
       RSI(5,5)=-ALYI*EPSIZ+1.
       RSI(6,6)=-ALYI*EPSIZ+1.


C      RSI(1,2)=0.
C      RSI(1,3)=0.
C      RSI(1,4)=0.
C      RSI(1,5)=0.
C      RSI(1,6)=0.
C
C      RSI(2,1)=-AVIS*UIJ/RIJ*ALZ*1./REINF
C      RSI(2,2)=AVIS/RIJ*ALZ*1./REINF+1.+ALZI*EPSI
```

```
C       RSI(2,3)=0.
C       RSI(2,4)=0.
C       RSI(2,5)=0.
C       RSI(2,6)=-AVIS*UIJ/RIJ*ALZ*1./REINF
C
C
C
C       RSI(3,1)=-AVIS*VIJ/RIJ*ALZ*1./REINF
C       RSI(3,2)=0.
C       RSI(3,3)=AVIS/RIJ*ALZ*1./REINF+1.+ALZI*EPSI
C       RSI(3,4)=0.
C       RSI(3,5)=0.
C       RSI(3,6)=-AVIS*VIJ/RIJ*ALZ*1./REINF


C       RSI(4,1)=-ALV*WIJ/RIJ*ALZ*1./REINF
C       RSI(4,2)=0.
C       RSI(4,3)=0.
C       RSI(4,4)=ALV/RIJ*ALZ*1./REINF+1.+ALZI*EPSI
C       RSI(4,5)=0.
C       RSI(4,6)=-ALV*WIJ/RIJ*ALZ*1./REINF


C       RSI(5,1)=-1./RIJ*(ALTHCV*WIJ*WIJ+AVTHCV*(UIJ*UIJ+VIJ*VIJ)
C      /+PRREM/CVOL*EIJ/RIJ)*ALZ
C       RSI(5,2)=1./RIJ*(AVTHCV*UIJ)*ALZ
C       RSI(5,3)=1./RIJ*(AVTHCV*VIJ)*ALZ
C       RSI(5,4)=1./RIJ*ALTHCV*WIJ*ALZ
C       RSI(5,5)=1./RIJ*PRREM/CVOL*ALZ+1.0+ALZI*EPSI
C       RSI(5,6)=-1./RIJ*(ALTHCV*WIJ*WIJ+AVTHCV*(UIJ*UIJ+VIJ*VIJ)
C      /+PRREM/CVOL*EIJ/RIJ)*ALZ


C       RSI(6,1)=0.
C       RSI(6,2)=0.
C       RSI(6,3)=0.
C       RSI(6,4)=0.
C       RSI(6,5)=0.
C       RSI(6,6)=1.0+ALZI*EPSI
```

```
C     NOW DO THW RSPI "I+1"

      AL2Z=1./(DZ1*DZ1)*THSW*BPKH/BIJ
C      IF(K.NE.N-1) THEN
      ALIP=1./(DZ1*DZ1)*THSW*AJM(I,J,K)/AJM(I,J,K+1)


C      THIS IS FOR THE IMPLICIT DISSIPATION

       RSPI(1,1)=-ALIP*EPSIZ
       RSPI(2,2)=-ALIP*EPSIZ
       RSPI(3,3)=-ALIP*EPSIZ
       RSPI(4,4)=-ALIP*EPSIZ
       RSPI(5,5)=-ALIP*EPSIZ
       RSPI(6,6)=-ALIP*EPSIZ




C      RSPI(1,1)=0.-ALI*EPSI
C      RSPI(1,2)=0.
C      RSPI(1,3)=0.
C      RSPI(1,4)=0.
C      RSPI(1,5)=0.
C      RSPI(1,6)=0.



C      RSPI(2,1)=AVIS*UPK/RPK*AL2Z*1./REINF
C      RSPI(2,2)=-AVIS/RPK*AL2Z*1./REINF-ALI*EPSI
C      RSPI(2,3)=0.
C      RSPI(2,4)=0.
```

```
C       RSPI(2,5)=0.
C       RSPI(2,6)=AVIS*UPK/RPK*AL2Z*1./REINF


C       RSPI(3,1)=AVIS*VPK/RPK*AL2Z*1./REINF
C       RSPI(3,2)=0.
C       RSPI(3,3)=-AVIS/RPK*AL2Z*1./REINF-ALI*EPSI
C       RSPI(3,4)=0.
C       RSPI(3,5)=0.
C       RSPI(3,6)=AVIS*VPK/RPK*AL2Z*1./REINF


C       RSPI(4,1)=ALV*WPK/RPK*AL2Z*1./REINF
C       RSPI(4,2)=0.
C       RSPI(4,3)=0.
C       RSPI(4,4)=-ALV/RPK*AL2Z*1./REINF-ALI*EPSI
C       RSPI(4,5)=0.
C       RSPI(4,6)=ALV*WPK/RPK*AL2Z*1./REINF


C       RSPI(5,1)=1./RPK*(ALTHCV*WPK*WPK+AVTHCV*(UPK*UPK+VPK*VPK)
C      /+PRREM/CVOL*EPK/RPK)*AL2Z
C       RSPI(5,2)=-1./RPK*(AVTHCV*UPK)*AL2Z
C       RSPI(5,3)=-1./RPK*AVTHCV*VPK*AL2Z
C       RSPI(5,4)=-1./RPK*(ALTHCV*WPK)*AL2Z
C       RSPI(5,5)=-1./RPK*PRREM/CVOL*AL2Z-ALI*EPSI
C       RSPI(5,6)=1./RPK*(ALTHCV*WPK*WPK+AVTHCV*(UPK*UPK+VPK*VPK)
C      /+PRREM/CVOL*EPK/RPK)*AL2Z
```

```
C       RSPI(6,1)=0.
C       RSPI(6,2)=0.
C       RSPI(6,3)=0.
C       RSPI(6,4)=0.
C       RSPI(6,5)=0.
C       RSPI(6,6)=0.-ALI*EPSI

C       ELSE
C       ENDIF

C      DEPOSIT THE Y-SWEEP B.C'S

c      the following are the implicit bounary conditions
C      THIS IS THE LOWER B.C'S

C       IF(K.EQ.2) THEN

C       RSI(4,5)=RSI(4,5)-(GAM-1.)*TSDZM
C       RSI(5,1)=RSI(5,1)+(PRREM/CVOL*EN(I,J,2)/RHO(I,J,2)**2.)*
C      /AL1Z
C       RSI(5,5)=RSI(5,5)-(PRREM/CVOL*1./RHO(I,J,2))*AL1Z
C       RSI(5,6)=RSI(5,6)+(PRREM/CVOL*EN(I,J,2)/RHO(I,J,2)**2.)*
C      /AL1Z
```

```
C        ELSE
C        ENDIF

C      START THE UPPER B.C'S

C        IF(K.EQ.N-1) THEN

C        RSI(4,5)=RSI(4,5)+(GAM-1.)*TSDZP
C        RSI(5,1)=RSI(5,1)+PRREM/CVOL*EN(I,J,N-1)/(RHO(I,J,N-1)**2.)*
C      /AL2Z
C        RSI(5,5)=RSI(5,5)-PRREM/CVOL*1./RHO(I,J,N-1)*AL2Z
C        RSI(5,6)=RSI(5,6)+PRREM/CVOL*EN(I,J,N-1)/(RHO(I,J,N-1)**2.)*
C      /AL2Z

C        ELSE
C        ENDIF

DO 620 KK=1,IS
       BMAINZ(KK,K)=DUCON(KK,I,J,K)-UCON(KK)

 620   CONTINUE

C      ADD THE SIMILAR INDICES TO FORM THE FOLL. SUBMATRICES
C      ATMI,ATPI,AND ATI
```

```
      DO 570 KK=1,IS
      DO 570 LL=1,IS
      IF(K.NE.2) THEN
      CTMI(KK,LL,K)=RSMI(KK,LL)+ASMI(KK,LL)
      ELSE
      CTMI(KK,LL,K)=0.
      ENDIF
      IF(K.NE.N-1) THEN
      CTPI(KK,LL,K)=RSPI(KK,LL)+ASPI(KK,LL)
      ELSE
      CTPI(KK,LL,K)=0.
      ENDIF

      CTI(KK,LL,K)=RSI(KK,LL)


 570  CONTINUE

C     CLOSE THE Z-SWEEP-DO-LOOPS

 520  CONTINUE


      CALL NBTRIP(CTMI,CTI,CTPI,BMAINZ,IL,IUZ,IS)

      DO 640 K=2,N-1
      DO 640 KK=1,IS
      DUCON(KK,I,J,K)=BMAINZ(KK,K)

 640  CONTINUE



C     THIS ENDIF IS TO CLOSE THE NO FLOW DOMAIN
```

```
      ENDIF

 500   CONTINUE

C     NOW UPDATE THE PREMITIVE VARIABLES

      DO 260 I=2,L-1
      DO 260 J=2,M-1
      DO 260 K=2,N-1
       IF((I.LE.LX2.AND.J.LE.NY2).OR.(I.GE.LX3.AND.J.GE.NY3)) THEN

      ELSE
      AA=RHO(I,J,K)*UX(I,J,K)
      BB=RHO(I,J,K)*VY(I,J,K)
      CC=RHO(I,J,K)*WZ(I,J,K)

      RHO1(I,J,K)=RHO1(I,J,K)+DUCON(1,I,J,K)/AJM(I,J,K)
      RHO2(I,J,K)=RHO2(I,J,K)+DUCON(6,I,J,K)/AJM(I,J,K)
      DD=RHO1(I,J,K)+RHO2(I,J,K)
      UX(I,J,K)=(AA+DUCON(2,I,J,K)/AJM(I,J,K))/DD
      VY(I,J,K)=(BB+DUCON(3,I,J,K)/AJM(I,J,K))/DD
      WZ(I,J,K)=(CC+DUCON(4,I,J,K)/AJM(I,J,K))/DD
      EN(I,J,K)=EN(I,J,K)+DUCON(5,I,J,K)/AJM(I,J,K)
      PR(I,J,K)=(GAM-1.)*(EN(I,J,K)-.5*DD*
     /(UX(I,J,K)*UX(I,J,K)+VY(I,J,K)*VY(I,J,K)))
      TE(I,J,K)=1./(DD*CVOL)*(EN(I,J,K)-.5*DD*
     /(UX(I,J,K)*UX(I,J,K)+VY(I,J,K)*VY(I,J,K)))
      ENDIF
 260  CONTINUE

      DO 263 I=1,L
      DO 263 J=1,M
```

```
      DO 263 K=1,N
      RHO(I,J,K)=RHO1(I,J,K)+RHO2(I,J,K)
  263 CONTINUE


C     THIS IS THE CONVERGANCE CRITERION

      IF(RRITM.LE.0.0001) THEN

      DO 4350 I=2,L-1
      DO 4350 J=2,M-1
      DO 4350 K=2,N-1
      SUM1=SUM1+ABS(DUCON(1,I,J,K))
      SUM2=SUM2+ABS(DUCON(2,I,J,K))
      SUM3=SUM3+ABS(DUCON(3,I,J,K))
      SUM4=SUM4+ABS(DUCON(4,I,J,K))
      SUM5=SUM5+ABS(DUCON(5,I,J,K))
      SUM6=SUM6+ABS(DUCON(6,I,J,K))
      IF(ITIME.gt.51) THEN
      EP1=EPPS*RHO1((L+1)/2,(M+1)/2,(N+1)/2)
      EP2=EPPS*RHO((L+1)/2,(M+1)/2,(N+1)/2)*UX((L+1)/2,(M+1)/2,(N+1)/2)
C      EP3=EPPS*RHO((L+1)/2,(M+1)/2,(N+1)/2)*VY((L+1)/2,(M+1)/2,(N+1)/2)
C      EP4=EPPS*RHO((L+1)/2,(M+1)/2,(N+1)/2)*WZ((L+1)/2,(M+1)/2,(N+1)/2)
      EP5=EPPS*EN((L+1)/2,(M+1)/2,(N+1)/2)
      EP6=EPPS*RHO2((L+1)/2,(M+1)/2,(N+1)/2)
      ELSE
      ENDIF
 4350 CONTINUE

      SU1=(SUM1/((L-2)*(M-2)*(N-2)))
      SU2=(SUM2/((L-2)*(M-2)*(N-2)))
C      SU3=(SUM3/((L-2)*(M-2)*(N-2)))
C      SU4=(SUM4/((L-2)*(M-2)*(N-2)))
      SU5=(SUM5/((L-2)*(M-2)*(N-2)))
      SU6=(SUM6/((L-2)*(M-2)*(N-2)))
      WRITE(110,49) ITIME,SU1,SU2,SU3,SU4,SU5,SU6

      IF(SU1.LE.EP1.AND.SU2.LE.EP2.
```

```
     /AND.SU5.LE.EP5.AND.SU6.LE.EP6) GOTO 6535
      write(*,*) ep1,su1,ep6,su6
      ELSE
      ENDIF


 130   CONTINUE


 6535 WRITE(101,39) ((RHO1(I,J,NZ),I=1,L),J=1,M)
      WRITE(102,39) ((RHO2(I,J,NZ),I=1,L),J=1,M)
      WRITE(103,39) ((RHO(I,J,NZ),I=1,L),J=1,M)
      WRITE(104,39) ((UX(I,J,NZ),I=1,L),J=1,M)
      WRITE(105,39) ((VY(I,J,NZ),I=1,L),J=1,M)
      WRITE(106,39) ((EN(I,J,NZ),I=1,L),J=1,M)
      WRITE(107,39) ((TE(I,J,NZ),I=1,L),J=1,M)
      WRITE(108,39) ((PR(I,J,NZ),I=1,L),J=1,M)
      WRITE(109,39) ((UE(I,J,NZ),I=1,L),J=1,M)

      WRITE(*,*) ITIME


 39   FORMAT (11E15.6)
 49   FORMAT (I6,3X,6E12.5)
 59   FORMAT (11F15.6)
      END


C     THIS SUBROUTINE IS TO SOLVE NON-PERIODIC BLOCK TRIDIAGONAL
C     SYSTEM OF EQUATIONS WITHOUT PIVOTING
C     THE DIMENSION N X N HAS TO BE GREATER THAN 1

      SUBROUTINE NBTRIP(A,B,C,D,IL,IU,ORDER)
      INTEGER ORDER,ORDSQ
      REAL*8 A(1),B(1),C(1),D(1)
```

```
C     A= SUB DIAGONAL MATRIX
C     B=     DIAGONAL MATRIX
C     C= SUP DIAGONAL MATRIX
C     D= RIGHT HAND SIDE VECTOR
C     IL= LOWER VALUE OF INDEX FOR WHICH MATRICES ARE DEFINED
C     IU= UPPER ==========================================
C     ONTENTS ON THE VECTOR D ARE OVERWRITTEN
C     ORDER IS THE ORDER OF THE SUB, SUPER AND DIAGONAL MATRICES

      ORDSQ=ORDER**2

C     FORWARD ELIMINATION

      I=IL
      IOMAT=1+(I-1)*ORDSQ
      IOVEC=1+(I-1)*ORDER
      CALL LUDECO(B(IOMAT),ORDER)
      CALL LUSOLV(B(IOMAT),D(IOVEC),D(IOVEC),ORDER)

      DO 100 J=1,ORDER
      IOMATJ=IOMAT+(J-1)*ORDER
      CALL LUSOLV(B(IOMAT),C(IOMATJ),C(IOMATJ),ORDER)
  100 CONTINUE
  200 CONTINUE


      I=I+1
      IOMAT=1+(I-1)*ORDSQ
      IOVEC=1+(I-1)*ORDER
      I1MAT=IOMAT-ORDSQ
      I1VEC=IOVEC-ORDER

      CALL MULPUT(A(IOMAT),D(I1VEC),D(IOVEC),ORDER)
      DO 300 J=1,ORDER
      IOMATJ=IOMAT+(J-1)*ORDER
      I1MATJ=I1MAT+(J-1)*ORDER
      CALL MULPUT(A(IOMAT),C(I1MATJ),B(IOMATJ),ORDER)
  300 CONTINUE
```

```
      CALL LUDECO(B(IOMAT),ORDER)

      CALL LUSOLV(B(IOMAT),D(IOVEC),D(IOVEC),ORDER)
      IF(I.EQ.IU) GO TO 500
      DO 400 J=1,ORDER
      IOMATJ=IOMAT+(J-1)*ORDER
      CALL LUSOLV(B(IOMAT),C(IOMATJ),C(IOMATJ),ORDER)
 400  CONTINUE

      GO TO 200
 500  CONTINUE

C     BACK SUBISTITUTION

      I=IU
 600  CONTINUE

      I=I-1
      IOMAT=1+(I-1)*ORDSQ
      IOVEC=1+(I-1)*ORDER
      I1VEC=IOVEC+ORDER
      CALL MULPUT(C(IOMAT),D(I1VEC),D(IOVEC),ORDER)

      IF(I.GT.IL) GO TO 600

      RETURN
      END




C     SUBROUTINE TO CALCULATE L-U DECOMPOSITION

      SUBROUTINE LUDECO(A,ORDER)
      INTEGER ORDER
      REAL*8 A(ORDER,1),SUM
      DO 8 JC=2,ORDER
```

```
  8   A(1,JC)=A(1,JC)/A(1,1)
      JRJC=1
 10   CONTINUE
      JRJC=JRJC+1
      JRJCM1=JRJC-1
      JRJCP1=JRJC+1

      DO 14 JR=JRJC,ORDER
      SUM=A(JR,JRJC)
      DO 12 JM=1,JRJCM1
 12   SUM=SUM-A(JR,JM)*A(JM,JRJC)
 14   A(JR,JRJC)=SUM
      IF(JRJC.EQ.ORDER) RETURN
      DO 18 JC=JRJCP1,ORDER
      SUM=A(JRJC,JC)
      DO 16 JM=1,JRJCM1
 16   SUM=SUM-A(JRJC,JM)*A(JM,JC)

 18   A(JRJC,JC)=SUM/A(JRJC,JRJC)

      GO TO 10

      END


C     SUBROUTINE TO MULTIPLY A VECTOR B BY A MATRIX A

      SUBROUTINE MULPUT(A,B,C,ORDER)
      INTEGER ORDER
      REAL*8 A(1),B(1),C(1),SUM

      DO 200 JR=1,ORDER
      SUM=0.0
      DO 100 JC=1,ORDER
      IA=JR+(JC-1)*ORDER
100   SUM=SUM+A(IA)*B(JC)
200   C(JR)=C(JR)-SUM
```

```
      RETURN
      END



C     SUBROUTINE TO SOLVE LINEAR SYSTEM OF EQUATIONS

      SUBROUTINE LUSOLV(A,B,C,ORDER)
      INTEGER ORDER
      REAL*8 A(ORDER,1),B(1),C(1),SUM

      C(1)=C(1)/A(1,1)
      DO 14 JR=2,ORDER
      JRM1=JR-1
      SUM=B(JR)
      DO 12 JM=1,JRM1
 12   SUM=SUM-A(JR,JM)*C(JM)
 14   C(JR)=SUM/A(JR,JR)

      DO 18 JRJR=2,ORDER
      JR=ORDER-JRJR+1
      JRP1=JR+1
      SUM=C(JR)
      DO 16 JMJM=JRP1,ORDER
      JM=ORDER-JMJM+JRP1
  16  SUM=SUM-A(JR,JM)*C(JM)
  18  C(JR)=SUM

      RETURN

      END



C     THIS SUBROUTINE IS FOR NON-PERIODIC SYSTEM OF EQUATIONS
```

```
      SUBROUTINE PBTRIP(A,B,C,D,IL,IU,ORDER)
      INTEGER ORDER,ORDSQ
      REAL*8 A(1),B(1),C(1),D(1)
      REAL*8 AD(36),CD(36)

      IS=IL+1
      IE=IU-1
      ORDSQ=ORDER**2
      IUMAT=1+(IU-1)*ORDSQ
      IUVEC=1+(IU-1)*ORDER
      IEMAT=1+(IE-1)*ORDSQ
      IEVEC=1+(IE-1)*ORDER

      I=IL
      IOMAT=1+(I-1)*ORDSQ
      IOVEC=1+(I-1)*ORDER

      CALL LUDECO(B(IOMAT),ORDER)
      CALL LUSOLV(B(IOMAT),D(IOVEC),D(IOVEC),ORDER)

      DO 10 J=1,ORDER
      IOMATJ=IOMAT+(J-1)*ORDER
      CALL LUSOLV(B(IOMAT),C(IOMATJ),C(IOMATJ),ORDER)
      CALL LUSOLV(B(IOMAT),A(IOMATJ),A(IOMATJ),ORDER)
10    CONTINUE

      DO 200 I=IS,IE
      IOMAT=1+(I-1)*ORDSQ
      IOVEC=1+(I-1)*ORDER
      I1MAT=IOMAT-ORDSQ
      I1VEC=IOVEC-ORDER

      DO 20 J=1,ORDSQ
      IOMATJ=J-1+IOMAT
      IUMATJ=J-1+IUMAT
      AD(J)=A(IOMATJ)
      CD(J)=C(IUMATJ)
      A(IOMATJ)=0.0
      C(IUMATJ)=0.0
```

```
20    CONTINUE

      CALL MULPUT(AD,D(I1VEC),D(IOVEC),ORDER)

      DO 22 J=1,ORDER
      IOMATJ=IOMAT+(J-1)*ORDER
      I1MATJ=I1MAT+(J-1)*ORDER

      CALL MULPUT(AD,C(I1MATJ),B(IOMATJ),ORDER)

      CALL MULPUT(AD,A(I1MATJ),A(IOMATJ),ORDER)

22    CONTINUE

      CALL LUDECO(B(IOMAT),ORDER)

      CALL LUSOLV(B(IOMAT),D(IOVEC),D(IOVEC),ORDER)

      DO 24 J=1,ORDER
      IOMATJ=IOMAT+(J-1)*ORDER

      CALL LUSOLV(B(IOMAT),C(IOMATJ),C(IOMATJ),ORDER)

      CALL LUSOLV(B(IOMAT),A(IOMATJ),A(IOMATJ),ORDER)

24    CONTINUE

      CALL MULPUT(CD,D(I1VEC),D(IUVEC),ORDER)

      DO 26 J=1,ORDER

      IUMATJ=IUMAT+(J-1)*ORDER
      I1MATJ=I1MAT+(J-1)*ORDER

      CALL MULPUT(CD,A(I1MATJ),B(IUMATJ),ORDER)

      CALL MULPUT(CD,C(I1MATJ),C(IUMATJ),ORDER)
```

```
 26   CONTINUE

200   CONTINUE

      DO 30 J=1,ORDSQ
      IUMATJ=J-1+IUMAT
      AD(J)=A(IUMATJ)+C(IUMATJ)

 30   CONTINUE

      CALL MULPUT(AD,D(IEVEC),D(IUVEC),ORDER)

      DO 32 J=1,ORDER

      IUMATJ=IUMAT+(J-1)*ORDER
      IEMATJ=IEMAT+(J-1)*ORDER

      CALL MULPUT(AD,C(IEMATJ),B(IUMATJ),ORDER)

      CALL MULPUT(AD,A(IEMATJ),B(IUMATJ),ORDER)

 32   CONTINUE

      CALL LUDECO(B(IUMAT),ORDER)

      CALL LUSOLV(B(IUMAT),D(IUVEC),D(IUVEC),ORDER)


      DO 40 IBAC=IL,IE

      I=IE-IBAC+IL
      IOMAT=1+(I-1)*ORDSQ
      IOVEC=1+(I-1)*ORDER
      I1VEC=IOVEC+ORDER

      CALL MULPUT(A(IOMAT),D(IUVEC),D(IOVEC),ORDER)

      CALL MULPUT(C(IOMAT),D(I1VEC),D(IOVEC),ORDER)
```

```
   40 CONTINUE
      RETURN
      END

C     THIS IS THE END OF THE SUBROUTINES

C     THIS SOUBROUTINE IS TO SOLVE THE HEAT AND THE MASS
C    TRANSFER
C     FOR SHELL AND TUBE CONDENSORS.
C     THE METHOD APPLIED HERE FOR THE MASS TRANSFER PART IS THE
C     FILM
C     THEORY. FOR MORE EXPLANATION OF THS METHOD REFfER TO THE
C     BOOK
C     "TRANSFER PROCESSES" BY EDWARDS, DENNY AND MILLS.
      SUBROUTINE NONS(TS,AMDD,PS,TC,HSA,QOA,HEAS,FIS,UE,DX,PE,
     /TE,L,M,N,FISE,HFG,VINF,ALINF,RINF,RHO1,SENSH,RGAS,I,J,K,HCA)
      DIMENSION TS(L,M,N),AMDD(L,M,N),PS(L,M,N),TC(L,M,N),
     /HSA(L,M,N),QOA(L,M,N),HEAS(L,M,N),FIS(L,M,N),
     /UE(L,M,N),PE(L,M,N),TE(L,M,N),FISE(L,M,N),HFG(L,M,N),RHO1(L,M,N),
     /HCA(L,M,N)
```

```
      PI=3.1415927

C     AT THIS STAGE, ALL VALUES RECEIVED FROM THE MAIN PROGRAM
C    ARE NON-DIMENSIONALIZED.
C     WE NEED TO DE-NON-DIMENSIONALIZE THEM AT THE BEGINING OF
C    THE SUBROUTINE BECAUSE ALL
C     NOTATIONS AT THIS SUBROUTINE ARE NOT NON-DIMENSIONALIZED.

      TE(I,J,K)=TE(I,J,K)*VINF*VINF
      PE(I,J,K)=PE(I,J,K)*RINF*VINF*VINF
      RRR=UE(I,J,K)
      UE(I,J,K)=ABS(UE(I,J,K)*VINF)

      DX=DX*ALINF

C     C1 AND C2 ARE CONSTANTS OF THE SOUTHERLAND VISCOSITY
C    EQUAUATION.

      C1=1.458E-6
      C2=110.

C     PREA IS THE PRANDTLE NUMBER AT BULK TEMPERATURE OF THE
C     MACROSCOPIC SUSTEM.
C     IT IS ASSUMED THAT THE STEAM IS PERFECT GAS
      PREA=0.72

C     UCA IS THE VELOCITY OF THE COOLANT IN THE TUBE WHICH
C    ASSUMED CONSTANT.

      UCA=.15
```

```
C     RU IS THE UNIVERSAL GAS CONSTANT.

      RU=8.3143E3

      GAM=1.4

C     RS IS THE SPECIFIC GAS CONSTANT.



C     G IS THE GRAVITATIONAL CONSTANT.

      G=9.80665

C     DI AND DO ARE THE INNER AND OUTER DIAMETER OF THE TUBE
C    RESP.

      DI=16.1/1000.
C      .008
      DTO=19.1/1000.
C      .01
C     CPEA IS THE HEAT CAPASITY AT CONSTANT PRESSURE AT THE BULK
C    OF THE MACRO. SYS.

      CPEA=GAM*RGAS/(GAM-1.)

C     TO AND PO ARE REFFERENCE TEMP. AND PRESSURE RES.

      TO=256.
      PO=1.0133E5


C     AKWA IS THE THERMAL COND. OF THE WALL.
C     THE WALL IS ASSUMED BRASS WITH CONSTANT THERMAL COND.

      AKWA=111.
```

```
C     INLET TEMP. OF COOLANT.

      TC(2,J,K)=283.

C     THIS DO LOOP IS X-SWEEP LOOP

      XXX=FISE(I,J,K)*(29./18.)/(1.-FISE(I,J,K)+FISE(I,J,K)*(29./18.))
C     ASSUMPTION OF TS

C     USE FITTED STEAM TABLES
      TS1=TC(I,J,K)
      TS2=TE(I,J,K)
      TS(I,J,K)=TS1+(TS2-TS1)/2.

C      TTSAT(PE(I,J,K))

      IF(TE(I,J,K).GE.TC(I,J,K)) THEN

C     THIS IS THE AVERAGE COOLANT TEMPERATURE.
```

```
C        TCA=(TC(I,J,K)+TS(I,J,K))/2.

C       NOW START ITRATING, THIS DO LOOP FOR THE CALCULATION OF
C      THE INTERPHASE TEMPERATURE.

        DO 500 IT=1,5000

C       CALCULATION OF IDEAL GAS RELATIONSHIPS.

C       AMEA IS THE BULK VISCOSITY OF THE MACRO. SYS. "USING
C       SOUTHERLAND RELATIONSHIP."

        AMEA=9.888E-6
C        C1*(TE(I,J,K)**(3./2.))/(C2+TE(I,J,K))


C        PE(I,J,K)=RHO1(I,J,K)*(RGAS*TE(I,J,K))

C       AKEA IS THE BULK THERMAL COND. OF THE MACRO.SYS. "USING
C       SUTHERLAND RELATIONSHIP."

        AKEA=(AMEA*CPEA)/PREA


C       ANEA IS THE KINEMATIC VISCOSITY AT THE BULK OF THE MACRO.
C      SYS.

        ANEA=AMEA/RHO1(I,J,K)

C       D12 IS THE DIFFUSION COEFFICIENT OF THE STEAM.
```

```
      D12=1.97E-5*(PO/PE(I,J,K))*(TE(I,J,K)/TO)**1.685

      SC=ANEA/D12

C     RE # AT THE BULK OF THE MACRO. SYS.

      REEA=RHO1(I,J,K)*UE(I,J,K)*DTO/AMEA

C     ANUEA IS THE NU # AT THE BULK OF THE MACRO. SYS.

      ANUEA=0.3+(.62*(REEA**.5)*(SC**.33333))/
     /((1.+(.4/SC)**.6667)**.25)

C     AKMEA IS THE MASS TRANSFER COEFFICIENT AT THE BULK OF THE
C     MACROSCOPIC SYS.

      AKMEA=(RHO1(I,J,K)*D12/DTO)*ANUEA


C     CALCULATION OF THE PRIMARY COLLANT HEAT TRANSFER
C     CORRELATION.
C     THE INLET TEMPERATURE AND VELOCITY ARE BOTH KNOWN.
C     THE FLOW IS ASSUMED TURBELLENT.


C     AMCA, ROCA, CPCA AND AKCA ARE VICOSITY, DENSITY, HEAT CAP.
C     AT CONSTANT PRESSURE, AND THERMAL
C     COND. RESP. AT THE AVERAGE COOLANT TEMP.

C      PS(I,J,K)=RHO1(I,J,K)*TS(I,J,K)*RU/18.
C      PSAT(TS(I,J,K))
```

```
      ROCA=ROW(TC(I,J,K))

      CPCA=CPW(TC(I,J,K))

      AKCA=THKW(TC(I,J,K))

C     ANUW(T) IS THE FITTED KINAMATIC VISCOSITY.

      AMCA=ANUW(TC(I,J,K))*ROCA

C     RECA IS THE AVERAGE RE # OF THE COOLANT

      RECA=ROCA*UCA*DI/AMCA

C     PRCA IS THE PRANDTL # OF THE COOLANT FOUND AT THE AVERAGE
C    PROPERTIES.

      PRCA=AMCA*CPCA/AKCA

C     ANUCA IS THE AVERAGE NU # OF THE COOLANT.

      ANUCA=.023*(RECA**0.8)*(PRCA**.33)

C     HCA IS THE COOLANT HEAT TRANSFER COEFF.

      HCA(I,J,K)=AKCA*ANUCA/DI

C       WRITE(*,*) AKMEA,TSMTW,ANUEA,XXX
C     HEAT TRANSFER RESISTANCE OF THE COOLANT.

      OU1=1./(HCA(I,J,K)*DI/DTO)

C     HEAT TRANSFER RESISTANCE OF THE WALL.

      OU2=1./(AKWA*(DI+DTO)/((DTO-DI)*DTO))

C     THIS IS THE CONDENSATE HEAT TRANSFER.

C     AMSA, ROSA, AKSA, CPSA, ANSA ARE VISCOSITY, DESITY, THERMAL
```

```
C    COND., HEAT CAPACITY
C     AT CONSTANT PRESSURE, AND KINEMATIC VISCOSITY EVALUATED
C    AT AN AVERAGE TEMP. OF THE
C     CONDENSATE

      PS1=RHO1(I,J,K)*XXX*(RGAS*TS1)
      PS(I,J,K)=RHO1(I,J,K)*XXX*(RGAS*TS(I,J,K))
      PS2=RHO1(I,J,K)*XXX*(RGAS*TS2)

C      PS1=PSAT(TS1)
C      PS(I,J,K)=PSAT(TS(I,J,K))

C      PS2=PSAT(TS2)
C      WRITE(*,*) PS1,PS(I,J,K),PS2,PE(I,J,K)

      ROSA=ROW(TS(I,J,K))

      AMSA=ANUW(TS(I,J,K))*ROSA

      AKSA=THKW(TS(I,J,K))

      CPSA=CPW(TS(I,J,K))

      ANSA=ANUW(TS(I,J,K))

      ROSA1=ROW(TS1)

      AMSA1=ANUW(TS1)*ROSA

      AKSA1=THKW(TS1)
```

```
      CPSA1=CPW(TS1)

      ANSA1=ANUW(TS1)


      ROSA2=ROW(TS2)


      AMSA2=ANUW(TS2)*ROSA

      AKSA2=THKW(TS2)

      CPSA2=CPW(TS2)

      ANSA2=ANUW(TS2)

C       WRITE(*,*) TC(I,J,K),TS(I,J,K),TE(I,J,K)
C     HFG IS THE LATENT HEAT OF VAPORIZATION.
C      TSAT=TS

      HFG(I,J,K)=HV(PS(I,J,K))-HF(PS(I,J,K))


C     GRSA IS THE GRASHOF # OF THE CONDENSATE.


      GRSA=(G*DTO**3.)/ANSA**2.
       GRSA1=(G*DTO**3.)/ANSA1**2.
       GRSA2=(G*DTO**3.)/ANSA2**2.
C     PRSA IS THE PRNDTL # OF THE CONDENSATE.

      PRSA=AMSA*CPSA/AKSA
      PRSA1=AMSA1*CPSA1/AKSA1
      PRSA2=AMSA2*CPSA2/AKSA2
```

```
C     FIS IS THE CONCENTRATION RATIO OF THE STEAM  AT THE
C    INTERPHASE.


      FIS(I,J,K)=PS(I,J,K)/(PS(I,J,K)+(29./18.)*
     /(PE(I,J,K)-PS(I,J,K)))


      FIS1=PS1/(PS1+(29./18.)*(PE(I,J,K)-PS1))

      FIS2=PS2/(PS2+(29./18.)*(PE(I,J,K)-PS2))

C     THIS IS THE LATENT HEAT TRANSFER FLUX

C       WRITE(*,*) FIS(I,J,K),FIS1,FIS2
        QOLD=QOA(I,J,K)
      QOA(I,J,K)=-AKMEA*LOG(1.+(FISE(I,J,K)-
     /FIS(I,J,K))/(FIS(I,J,K)-1.))*HFG(I,J,K)


      QOA1=-AKMEA*LOG(1.+(FISE(I,J,K)-
     /FIS1)/(FIS1-1 ))*HFG(I,J,K)
      IF(FIS2.GE FISE(I,J,K)) THEN
      QOA2=0.
      ELSE
      QOA2=-AKMEA*LOG(1.+(FISE(I,J,K)-
     /FIS2)/(FIS2-1.))*HFG(I,J,K)
      ENDIF
        QNEW=QOA(I,J,K)
C       WRITE(*,*) FIS1,FIS(I,J,K),FIS2,FISE(I,J,K)
C       WRITE(*,*) PS1,PS(I,J,K),PS2,PE(I,J,K)

C     CALCULATION OF THE SENSIBLE HEAT.
C     ALL PROPERTIES ARE EVALUATED AT TEA.

C     THIS IS THE RE # OF SENSIBLE HEAT TRANSFER.

      REEAS=RHO1(I,J,K)*UE(I,J,K)*DTO/AMEA
```

```
C     ANUEAS IS THE NU # AT THE BULK  HEAT TRANSFER OF THE MACRO.
C     SYS.

      ANUEAS=0.3+(.62*(REEA**.5)*(PREA**.33333))/
     /((1.+(.4/PREA)**.6667)**.25)


C     THIS IS THE CONDENSATION FLUX RATE


      AMDD(I,J,K)=QOA(I,J,K)/HFG(I,J,K)


C     HEAT TRANSFER COEFF. FOR PURE STEAM.

      HEAPS=AKEA*ANUEAS/DTO

C      THIS IS A SIMPLYFING FACTOR.

      SIMP=AMDD(I,J,K)*CPEA/HEAPS

C     THIS IS THE SENSIBLE HEAT TRANSFER COEFF.

      HEAS(I,J,K)=-SIMP/(EXP(-SIMP)-1.)*HEAPS


C     MODIFIED QOA.

      QOA(I,J,K)=QOA(I,J,K)
C      +HEAS(I,J,K)*(TE(I,J,K)-TS(I,J,K))

C     THIS PART WILL BE EXPORTED TO THE MACROSCOPIC SYSTEM
```

```
      FAC=AKSA/DTO*(GRSA*PRSA/(3.6*CPSA/HFG(I,J,K)))**.25

      FAC1=AKSA1/DTO*(GRSA1*PRSA1/(3.6*CPSA1/HFG(I,J,K)))**.25

      FAC2=AKSA2/DTO*(GRSA2*PRSA2/(3.6*CPSA2/HFG(I,J,K)))**.25

C     THIS IS Ts-Tc

      TSMTW=(QOA(I,J,K)/FAC)**(4./3.)

      TSMTW1=(QOA1/FAC1)**(4./3.)

      TSMTW2=(QOA2/FAC2)**(4./3.)
C     HSA IS THE HEAT TRANSFER COEFF. OF THE CONDENSATE.

      HSA(I,J,K)=FAC*(1./TSMTW)**(.25)

      HSA1=FAC1*(1./TSMTW1)**(.25)
       IF(TSMTW2.LE.0.) THEN
       HSA2=100000.
      ELSE
      HSA2=FAC2*(1./TSMTW2)**(.25)
      ENDIF
C     1OU3 IS THE HEAT TRANSFER RESISTANCE OF THE CONDENSATE.

      OU3=1./HSA(I,J,K)

      OU31=1./HSA1

      OU32=1./HSA2

      UU=1./(OU1+OU2+OU3)

      UU1=1./(OU1+OU2+OU31)

      UU2=1./(OU1+OU2+OU32)
C     THIS IS THE PREVIOUS TS

      TSOLD=TS(I,J,K)
```

```
      F=TS(I,J,K)-TC(I,J,K)-QOA(I,J,K)/UU

      F1=TS1-TC(I,J,K)-QOA1/UU1

      F2=TS2-TC(I,J,K)-QOA2/UU2

      IF((F1*F).GT.0.) THEN
      TS1=TS(I,J,K)
      ELSE
      TS2=TS(I,J,K)
      ENDIF
      TS(I,J,K)=TS1+(TS2-TS1)/2.
C      WRITE(*,*) F,F1,F2,TS(I,J,K)


C     THIS IS NEW TS.

      TSNEW=TS(I,J,K)

C      WRITE(*,*) QOA(I,J,K),TS(I,J,K),TC(I,J,K),IT

C     CONVERGENCE CRITERION.

      CONV=ABS(TSNEW-TSOLD)/TSNEW
C       CONV=ABS(QNEW-QOLD)
      IF(CONV.LT.1.E-4) GOTO 200

C     NOW MODIFY THE AVERAGE TEMPERATURES TCA, AND TSA

      TIWMTC=QOA(I,J,K)/HCA(I,J,K)

C      WRITE(*,*) PS(I,J,K),PE(I,J,K)
C       WRITE(*,*) TC(I,J,K),TS(I,J,K),I,J,K

C      TCA=TC(I,J,K)+TIWMTC/2.

C      TSA=TS(I,J,K)-TSMTW/2.
```

```
C       TEA=(TE(I,J,K)+TS(I,J,K))/2.

  500 CONTINUE

 200  TC(I+1,J,K)=TC(I,J,K)+4.*QOA(I,J,K)*DX/
     /(ROCA*UCA*DTO*CPCA)

      ELSE
      QOA(I,J,K)=0.
      AMDD(I,J,K)=0.
      ENDIF

C     CLOSE THE X DO LOOP.

C     NOW NON-DIMENSIONALIZE AGAIN.

      TE(I,J,K)=TE(I,J,K)/(VINF*VINF)
      PE(I,J,K)=PE(I,J,K)/(RINF*VINF*VINF)
      UE(I,J,K)=UE(I,J,K)/VINF

      DX=DX/ALINF

      RETURN

      END
```

```
C     THIS SOUBROUTINE IS TO SOLVE THE HEAT AND THE MASS
C    TRANSFER
C     FOR PACKED BED CONDENSORS.

C     THE METHOD APPLIED HERE FOR THE MASS TRANSFER PART IS THE
C     FILM
C     THEORY. FOR MORE EXPLANATION ABOUT THS METHOD REFfER TO
C    THE BOOK
C     "TRANSFER PROCESSES" BY EDWARDS, DENNY AND MILLS.

      SUBROUTINE NONP(TS,AMDD,PS,TC,HSA,QOA,HEAS,FIS,UE,DX,PE,
     /TE,L,M,N,FISE,HFG,VINF,ALINF,RINF,RHO1,SENSH,RGAS,I,J,K)

      DIMENSION TS(L,M,N),AMDD(L,M,N),PS(L,M,N),TC(L,M,N),
     /HSA(L,M,N),QOA(L,M,N),HEAS(L,M,N),FIS(L,M,N),
     /UE(L,M,N),PE(L,M,N),TE(L,M,N),FISE(L,M,N),HFG(L,M,N),RHO1(L,M,N)



      PI=3.1415927

C     AT THIS STAGE, ALL VALUES RECEIVED FROM THE MAIN PROGRAM
C    ARE NON-DIMENSIONALIZED.
C     WE NEED TO DE-NON-DIMENSIONALIZE THEM AT THE BEGINING OF
C    THE SUBROUTINE BECAUSE ALL
C     NOTATIONS AT THIS SUBROUTINE ARE NOT NON-DIMENSIONALIZED.

      TE(I,J,K)=TE(I,J,K)*VINF*VINF
```

```
      PE(I,J,K)=PE(I,J,K)*RINF*VINF*VINF
      RRR=UE(I,J,K)
      UE(I,J,K)=ABS(UE(I,J,K)*VINF)

      DX=DX*ALINF
C     C1 AND C2 ARE CONSTANTS OF THE SOUTHERLAND VISCOSITY
C    EQUAUATION.
      C1=1.458E-6
      C2=110.
C     PREA IS THE PRANDTLE NUMBER AT BULK TEMPERATURE OF THE
C    MACROSCOPIC SUSTEM.
C     IT IS ASSUMED THAT THE STEAM IS PERFECT GAS
      PREA=0.72
C     UCA IS THE VELOCITY OF THE COOLANT IN THE TUBE WHICH
C    ASSUMED CONSTANT.
      UCA=.15
C     RU IS THE UNIVERSAL GAS CONSTANT.
      RU=8.3143E3
      GAM=1.4
C     RS IS THE SPECIFIC GAS CONSTANT.

C     G IS THE GRAVITATIONAL CONSTANT.
      G=9.80665
```

```
C       DTO ARE THE INNER AND OUTER DIAMETER OF THE TUBE RESP.

      DTO=19.1/1000.

C      CPEA IS THE HEAT CAPASITY AT CONSTANT PRESSURE AT THE BULK
C     OF THE MACRO. SYS.

      CPEA=GAM*RGAS/(GAM-1.)

C      TO AND PO ARE REFFERENCE TEMP. AND PRESSURE RES.

      TO=256.
      PO=1.0133E5


C      AKWA IS THE THERMAL COND. OF THE WALL.
C      THE WALL IS ASSUMED BRASS WITH CONSTANT THERMAL COND.

      AKWA=111.






C      INLET TEMP. OF COOLANT.

      TC(2,J,K)=283.





C      THIS DO LOOP IS X-SWEEP LOOP
```

```
      XXX=FISE(I,J,K)*(29./18.)/(1.-FISE(I,J,K)+FISE(I,J,K)*(29./18.))
C     ASSUMPTION OF TS

C     USE FITTED STEAM TABLES
      TS1=TC(I,J,K)
      TS2=TE(I,J,K)
      TS(I,J,K)=TS1+(TS2-TS1)/2.

C      TTSAT(PE(I,J,K))

      IF(TE(I,J,K).GE.TC(I,J,K)) THEN

C     THIS IS THE AVERAGE COOLANT TEMPERATURE.

C      TCA=(TC(I,J,K)+TS(I,J,K))/2.

C     NOW START ITRATING, THIS DO LOOP FOR THE CALCULATION OF
C    THE INTERPHASE TEMPERATURE.

      DO 500 IT=1,5000

C     CALCULATION OF IDEAL GAS RELATIONSHIPS.

C     AMEA IS THE BULK VISCOSITY OF THE MACRO. SYS. "USING
C     SOUTHERLAND RELATIONSHIP."

      AMEA=9.888E-6
C      C1*(TE(I,J,K)**(3./2.))/(C2+TE(I,J,K))
```

```
C        PE(I,J,K)=RHO1(I,J,K)*(RGAS*TE(I,J,K))

C       AKEA IS THE BULK THERMAL COND. OF THE MACRO.SYS. "USING
C       SUTHERLAND RELATIONSHIP."

        AKEA=(AMEA*CPEA)/PREA







C       ANEA IS THE KINEMATIC VISCOSITY AT THE BULK OF THE MACRO.
C      SYS.

        ANEA=AMEA/RHO1(I,J,K)

C       D12 IS THE DIFFUSION COEFFICIENT OF THE STEAM.

        D12=1.97E-5*(PO/PE(I,J,K))*(TE(I,J,K)/TO)**1.685

        SC=ANEA/D12

C       RE # AT THE BULK OF THE MACRO. SYS.

        REEA=RHO1(I,J,K)*UE(I,J,K)*DTO/AMEA

C       ANUEA IS THE NU # AT THE BULK OF THE MACRO. SYS.
        IF(SC.GE.6) THEN
        ANUEA=2.+.3*(REEA**.6)*(SC**.3333)
        ELSE
        ANUEA=2.+.4*(REEA*SC)**.5
        ENDIF

C       AKMEA IS THE MASS TRANSFER COEFFICIENT AT THE BULK OF THE
```

```
C     MACROSCOPIC SYS.

      AKMEA=(RHO1(I,J,K)*D12/DTO)*ANUEA

C      PS(I,J,K)=RHO1(I,J,K)*TS(I,J,K)*RU/18.
C      PSAT(TS(I,J,K))

C     HEAT TRANSFER RESISTANCE OF THE WALL.

      OU2=1./(4.*AKWA/DTO)

C     THIS IS THE CONDENSATE HEAT TRANSFER.

C     AMSA, ROSA, AKSA, CPSA, ANSA ARE VISCOSITY, DESITY, THERMAL
C     COND., HEAT CAPACITY
C     AT CONSTANT PRESSURE, AND KINEMATIC VISCOSITY EVALUATED
C    AT AN AVERAGE TEMP. OF THE
C     CONDENSATE

      PS1=RHO1(I,J,K)*XXX*(RGAS*TS1)
```

```
      PS(I,J,K)=RHO1(I,J,K)*XXX*(RGAS*TS(I,J,K))
      PS2=RHO1(I,J,K)*XXX*(RGAS*TS2)
C      PS1=PSAT(TS1)
C      PS(I,J,K)=PSAT(TS(I,J,K))
C      PS2=PSAT(TS2)
C      WRITE(*,*) PS1,PS(I,J,K),PS2,PE(I,J,K)
      ROSA=ROW(TS(I,J,K))
      AMSA=ANUW(TS(I,J,K))*ROSA
      AKSA=THKW(TS(I,J,K))
      CPSA=CPW(TS(I,J,K))
      ANSA=ANUW(TS(I,J,K))
      ROSA1=ROW(TS1)
      AMSA1=ANUW(TS1)*ROSA
      AKSA1=THKW(TS1)
      CPSA1=CPW(TS1)
      ANSA1=ANUW(TS1)
      ROSA2=ROW(TS2)
      AMSA2=ANUW(TS2)*ROSA
```

```
      AKSA2=THKW(TS2)

      CPSA2=CPW(TS2)

      ANSA2=ANUW(TS2)

C       WRITE(*,*) TC(I,J,K),TS(I,J,K),TE(I,J,K)
C     HFG IS THE LATENT HEAT OF VAPORIZATION.
C      TSAT=TS

      HFG(I,J,K)=HV(PS(I,J,K))-HF(PS(I,J,K))


C     GRSA IS THE GRASHOF # OF THE CONDENSATE.


      GRSA=(G*DTO**3.)/ANSA**2.
       GRSA1=(G*DTO**3.)/ANSA1**2.
       GRSA2=(G*DTO**3.)/ANSA2**2.
C     PRSA IS THE PRNDTL # OF THE CONDENSATE.

      PRSA=AMSA*CPSA/AKSA
      PRSA1=AMSA1*CPSA1/AKSA1
      PRSA2=AMSA2*CPSA2/AKSA2
C     FIS IS THE CONCENTRATION RATIO OF THE STEAM  AT THE
C    INTERPHASE.


      FIS(I,J,K)=PS(I,J,K)/(PS(I,J,K)+(29./18.)*
     /(PE(I,J,K)-PS(I,J,K)))


      FIS1=PS1/(PS1+(29./18.)*(PE(I,J,K)-PS1))

      FIS2=PS2/(PS2+(29./18.)*(PE(I,J,K)-PS2))

C     THIS IS THE LATENT HEAT TRANSFER FLUX
```

```
C       WRITE(*,*) FIS(I,J,K),FIS1,FIS2
        QOLD=QOA(I,J,K)
      QOA(I,J,K)=-AKMEA*LOG(1.+(FISE(I,J,K)-
     /FIS(I,J,K))/(FIS(I,J,K)-1.))*HFG(I,J,K)


      QOA1=-AKMEA*LOG(1.+(FISE(I,J,K)-
     /FIS1)/(FIS1-1.))*HFG(I,J,K)
      IF(FIS2.GE.FISE(I,J,K)) THEN
      QOA2=0.
      ELSE
      QOA2=-AKMEA*LOG(1.+(FISE(I,J,K)-
     /FIS2)/(FIS2-1.))*HFG(I,J,K)
      ENDIF
        QNEW=QOA(I,J,K)
C       WRITE(*,*) FIS1,FIS(I,J,K),FIS2,FISE(I,J,K)
C       WRITE(*,*) PS1,PS(I,J,K),PS2,PE(I,J,K)

C     CALCULATION OF THE SENSIBLE HEAT.
C     ALL PROPERTIES ARE EVALUATED AT TEA.

C     THIS IS THE RE # OF SENSIBLE HEAT TRANSFER.

      REEAS=RHO1(I,J,K)*UE(I,J,K)*DTO/AMEA

C     ANUEAS IS THE NU # AT THE BULK  HEAT TRANSFER OF THE MACRO.
C     SYS.




      IF(PREA.GE.6) THEN
      ANUEAS=2.+.3*(REEA**.6)*(PREA**.3333)
      ELSE
      ANUEAS=2.+.4*(REEA*PREA)**.5
      ENDIF
```

```
C       THIS IS THE CONDENSATION FLUX RATE


        AMDD(I,J,K)=QOA(I,J,K)/HFG(I,J,K)


C       HEAT TRANSFER COEFF. FOR PURE STEAM.

        HEAPS=AKEA*ANUEAS/DTO

C        THIS IS A SIMPLYFING FACTOR.

        SIMP=AMDD(I,J,K)*CPEA/HEAPS

C       THIS IS THE SENSIBLE HEAT TRANSFER COEFF.

        HEAS(I,J,K)=-SIMP/(EXP(-SIMP)-1.)*HEAPS


C       MODIFIED QOA.

        QOA(I,J,K)=QOA(I,J,K)
C        +HEAS(I,J,K)*(TE(I,J,K)-TS(I,J,K))

C       THIS PART WILL BE EXPORTED TO THE MACROSCOPIC SYSTEM



        FAC=AKSA/DTO*(GRSA*PRSA/(3.6*CPSA/HFG(I,J,K)))**.25

        FAC1=AKSA1/DTO*(GRSA1*PRSA1/(3.6*CPSA1/HFG(I,J,K)))**.25

        FAC2=AKSA2/DTO*(GRSA2*PRSA2/(3.6*CPSA2/HFG(I,J,K)))**.25

C       THIS IS Ts-Tc
```

```
      TSMTW=(QOA(I,J,K)/FAC)**(4./3.)

      TSMTW1=(QOA1/FAC1)**(4./3.)

      TSMTW2=(QOA2/FAC2)**(4./3.)
C     HSA IS THE HEAT TRANSFER COEFF. OF THE CONDENSATE.

      HSA(I,J,K)=FAC*(1./TSMTW)**(.25)

      HSA1=FAC1*(1./TSMTW1)**(.25)
       IF(TSMTW2.LE.0.) THEN
       HSA2=100000.
      ELSE
      HSA2=FAC2*(1./TSMTW2)**(.25)
      ENDIF
C     1OU3 IS THE HEAT TRANSFER RESISTANCE OF THE CONDENSATE.

      OU3=1./HSA(I,J,K)

      OU31=1./HSA1

      OU32=1./HSA2

      UU=1./(OU2+OU3)

      UU1=1./(OU2+OU31)

      UU2=1./(OU2+OU32)
C     THIS IS THE PREVIOUS TS

      TSOLD=TS(I,J,K)

      F=TS(I,J,K)-TC(I,J,K)-QOA(I,J,K)/UU

      F1=TS1-TC(I,J,K)-QOA1/UU1

      F2=TS2-TC(I,J,K)-QOA2/UU2
```

```
      IF((F1*F).GT.0.) THEN
      TS1=TS(I,J,K)
      ELSE
      TS2=TS(I,J,K)
      ENDIF
      TS(I,J,K)=TS1+(TS2-TS1)/2.

C      WRITE(*,*) F,F1,F2,TS(I,J,K)


C     THIS IS NEW TS.

      TSNEW=TS(I,J,K)

C      WRITE(*,*) QOA(I,J,K),TS(I,J,K),TC(I,J,K),IT

C     CONVERGENCE CRITERION.

      CONV=ABS(TSNEW-TSOLD)/TSNEW
C       CONV=ABS(QNEW-QOLD)
      IF(CONV.LT.1.E-4) GOTO 200



C      WRITE(*,*) PS(I,J,K),PE(I,J,K)
C       WRITE(*,*) TC(I,J,K),TS(I,J,K),I,J,K



C      TSA=TS(I,J,K)-TSMTW/2.

C      TEA=(TE(I,J,K)+TS(I,J,K))/2.


  500 CONTINUE


C     THIS IS THE PRIMARY TEMPERATURE WHICH IS ASSUMED CONSTANT
```

```
C     FOR PACKED BEDS

 200  TC(I+1,J,K)=285.

      ELSE
      QOA(I,J,K)=0.
      AMDD(I,J,K)=0.
      ENDIF

C     CLOSE THE X DO LOOP.



C     NOW NON-DIMENSIONALIZE AGAIN.


      TE(I,J,K)=TE(I,J,K)/(VINF*VINF)
      PE(I,J,K)=PE(I,J,K)/(RINF*VINF*VINF)
      UE(I,J,K)=UE(I,J,K)/VINF



      DX=DX/ALINF


      RETURN

      END

C     ALL UNITS ARE SI UNITS(i.e T IN K, P IN N/M2, ENTHALPY IN J/KG,
C    THERMAL CON. IN W/MK,
C     DENSITY IN KG/M3, CP IN J/KG K, NU INM2/SEC )


C     THIS FUNCTION GIVES A RELATIONSHIP OF PSAT(TSAT)
      FUNCTION PSAT(TSAT)
```

```
      X1=5.56268E-1
      X2=-2.069575E-3
      X3=-4.339096E-6
      X4=1.306466E-8
      X5=-5.830305E-12
      X6=-1.735039E-16
      X7=2.540331E-16
      IF(TSAT.GE.273.15.AND.TSAT.LE.305.) THEN
      PSAT=X1+X2*TSAT+X3*TSAT**2.+X4*TSAT**3.+X5*TSAT**4.+
     /X6*TSAT**5.+X7*TSAT**6.
      ELSEIF(TSAT.GT.305.AND.TSAT.LE.350.) THEN
      X1=2.267565E-1
      X2=1.537165E-3
      X3=7.357538E-6
      X4=-2.980122E-8
      X5=-3.012597E-10
      X6=3.864352E-13
      X7=1.369178E-15
      PSAT=X1+X2*TSAT+X3*TSAT**2.+X4*TSAT**3.+X5*TSAT**4.+
     /X6*TSAT**5.+X7*TSAT**6.
      ELSEIF(TSAT.GT.350.AND.TSAT.LE.550.) THEN
      X1=-16.98454
      X2=1.154695E-1
      X3=-1.492E-4
      X4=-1.866152E-7
      X5=4.152246E-10
      X6=-3.366653E-12
      X7=8.031262E-15
      PSAT=X1+X2*TSAT+X3*TSAT**2.+X4*TSAT**3.+X5*TSAT**4.+
     /X6*TSAT**5.+X7*TSAT**6.
      ELSE
C       WRITE(*,*) "PSAT IS OUT OF RANGE"
      ENDIF
C     CONVERT PRESSURE FROM N/M2*1.E-5 TO N/M2
      PSAT=PSAT*1.E5
      END
C     THE FOLLOWING FUNCTION IS A FITTING FUNCTION OF THE
C    SATURATED WATER ENTHALPY
```

```
C     TAKEN FROM RETRAN

      FUNCTION HF(P)
      DIMENSION A(9),B(9),C(9)

C     CONVERSION OF PRESSURE FROM N/M2 TO PSI

      P=P/6895.

      A(1)=.6970887859E2
      A(2)=.3337529994E2
      A(3)=.2318240735E1
      A(4)=.1840599513E0
      A(5)=-.5245502284E-2
      A(6)=.2878007027E-2
      A(7)=.1753652324E-2
      A(8)=-.4334859620E-3
      A(9)=.3325699282E-4

      B(1)=.8408618802E6
      B(2)=.3637413208E6
      B(3)=-.4634506669E6
      B(4)=.1130306339E6
      B(5)=-.4350217298E3
      B(6)=-.3898988188E4
      B(7)=.6697399434E3
      B(8)=-.4730726377E2
      B(9)=.1265125057E1

      C(1)=.9060030436E3
      C(2)=-.1426813520E2
      C(3)=.1522233257E1
      C(4)=-.6973992961
      C(5)=.1743091663
      C(6)=-.2319717696E-1
      C(7)=.1694019149E-2
      C(8)=-.6454771710E-4
```

```
      C(9)=.1003003098E-5

      IF(P.GE..1.AND.P.LE.950.) THEN
      HF=0.
      DO 10 I=1,9
      HF=HF+A(I)*(LOG(P))**(I-1)
   10 CONTINUE
      ELSEIF(P.GE.950.AND.P.LE.2250.) THEN

      HF=0.
      DO 20 I=1,9
      HF=HF+B(I)*(LOG(P))**(I-1)
   20 CONTINUE

      ELSE
      HF=0.
      DO 30 I=1,9
      HF=HF+C(I)*((3208.2-P)**.41)**(I-1)
   30 CONTINUE

      ENDIF
C     CONVERSION OF ENTHAPY FROM BTU/LBM TO J/KG
      HF=HF/4.299E-4
       P=P*6895.
      END

C     THE FOLLOWING FUNCTION IS A FITTING FUNCTION OF THE
C     SATURATED VAPOUR ENTHALPY
C     TAKEN FROM RETRAN

      FUNCTION HV(P)
      DIMENSION A(12),B(9),C(7)
C     CONVERSION OF PRESSURE FROM N/M2 TO PSI

      P=P/6895.
      A(1)=.1105836875E4
      A(2)=.1436943768E2
      A(3)=.8018288621
      A(4)=.1617232913E-1
```

```
      A(5)=-.1501147505E-2
      A(6)=0.
      A(7)=0.
      A(8)=0.
      A(9)=0.
      A(10)=-.1237675562E-4
      A(11)=.3004773304E-5
      A(12)=-.2062390734E-6

      B(1)=-.2234264997E7
      B(2)=.1231247634E7
      B(3)=-.1978847871E6
      B(4)=.1859988044E2
      B(5)=-.2765701318E1
      B(6)=.1036033878E4
      B(7)=-.2143423131E3
      B(8)=.1690507762E2
      B(9)=-.4864322134

      C(1)=.9059978254E3
      C(2)=.5561957539E1
      C(3)=.3434189609E1
      C(4)=-.6406390628
      C(5)=.5918579484E-1
      C(6)=-.2725378570E-2
      C(7)=.5006336938E-4


      IF(P.GE..1.AND.P.LE.1500.) THEN
      HV=0.
      DO 10 I=1,12
      HV=HV+A(I)*(LOG(P))**(I-1)
   10 CONTINUE
      ELSEIF(P.GE.1500.AND.P.LE.2650.) THEN

      HV=0.
      DO 20 I=1,9
      HV=HV+B(I)*(LOG(P))**(I-1)
   20 CONTINUE
```

```
      ELSE
      HV=0.
      DO 30 I=1,7
      HV=HV+C(I)*((3208.2-P)**.41)**(I-1)
   30 CONTINUE

      ENDIF
C     CONVERSION OF ENTHAPY FROM BTU/LBM TO J/KG
      HV=HV/4.299E-4
       P=P*6895.
      END



C     THE FOLLOWING FUNCTION IS FOR THE THERMAL CONDUCTIVITY OF
C    WATER.
C     IT IS ASSUMED THAT THE THERMAL CONDUCTIVITY IS A FUNCTION
C    OF TEMPERATURE ONLY.
C     ALL DATA ARE TAKEN FROM TRANSFER PROCESES BY MILLS AND
C     OTHERS.


      FUNCTION THKW(T)
      IF(T.GE.275.AND.T.LE.580.) THEN
      THKW=-1.561273+1.564598E-2*T-3.970037E-5*T**2.+
     /4.560812E-8*T**3.-2.247724E-11*T**4.
      ELSE
C      WRITE(*,*) "THERMAL COND. IS OUT OF RANGE"
      ENDIF
      IF(T.LE.275) THEN
      T=275
      THKW=-1.561273+1.564598E-2*T-3.970037E-5*T**2.+
     /4.560812E-8*T**3.-2.247724E-11*T**4.
      ELSE
      ENDIF
      END
```

```
C     THE FOLLOWING FUNCTION IS FOR THE HEAT CAPACITY AT
C    CONSTANT PRESSURE OF WATER.
C     IT IS ASSUMED THAT THE HEAT CAPACITY IS A FUNCTION OF
C    TEMPERATURE ONLY.
C     ALL DATA ARE TAKEN FROM TRANSFER PROCESES BY MILLS AND
C     OTHERS.

      FUNCTION CPW(T)
      IF(T.GE.275.AND.T.LE.580.) THEN
      CPW=10146.91-62.78324*T+2.500216E-1*T**2.-4.52072E-4*T**3.+
     /3.17923E-7*T**4.
      ELSE
C       WRITE(*,*) "HEAT CAP. IS OUT OF RANGE"
      ENDIF

      IF(T.LE.275.) THEN
      T=275.
      CPW=10146.91-62.78324*T+2.500216E-1*T**2.-4.52072E-4*T**3.+
     /3.17923E-7*T**4.
      ELSE
C       WRITE(*,*) "HEAT CAP. IS OUT OF RANGE"
      ENDIF


      END


C     THE FOLLOWING FUNCTION IS FOR THE KINEMATIC VISCOSITY OF
C    WATER.
C     IT IS ASSUMED THAT THE KINEMATIC VISCOSITY IS A FUNCTION OF
C    TEMPERATURE ONLY.
C     ALL DATA ARE TAKEN FROM TRANSFER PROCESES BY MILLS AND
C     OTHERS.

      FUNCTION ANUW(T)
      IF(T.GE.275.AND.T.LE.330.) THEN
      ANUW=61.74776-2.5E-1*T-1.79165E-4*T**2.-4.969477E-7*T**3.+
     /5.225E-9*T**4.+1.457343E-11*T**5.-
     /4.675553E-14*T**6.
```

```
      ANUW=ANUW*1.E-6
      ELSEIF(T.GT.330.AND.T.LE.580.) THEN
      ANUW=10.31275-(6.536036E-2)*T+(1.488566E-4)*T**2.-
     /(1.666241E-7)*T**3.+(2.34858E-10)*T**4.-
     /(4.176862E-13)*T**5.+2.884012E-16*T**6.
      ANUW=ANUW*1.E-6
      ELSEIF(T.LT.275.OR.T.GT.580.) THEN
C      WRITE(*,*) "MU IS OUT OF RANGE"
      ENDIF
      IF(T.LE.275.) THEN
      T=275.
      ANUW=61.74776-2.5E-1*T-1.79165E-4*T**2.-4.969477E-7*T**3.+
     /5.225E-9*T**4.+1.457343E-11*T**5.-
     /4.675553E-14*T**6.
      ANUW=ANUW*1.E-6
      ELSE
      ENDIF
      END


C     THE FOLLOWING FUNCTION IS FOR THE DENSITY OF WATER.
C     IT IS ASSUMED THAT THE DENSITY IS A FUNCTION OF TEMPERATURE
C     ONLY.
C     ALL DATA ARE TAKEN FROM TRANSFER PROCESES BY MILLS AND
C     OTHERS.

      FUNCTION ROW(T)
      IF(T.GE.275.AND.T.LE.580.) THEN
      ROW=598.8134+2.828807*T-3.784399E-3*T**2.-7.474704E-6*T**3.+
     /1.129865E-8*T**4.
      ELSE
C      WRITE(*,*) "DENSITY IS OUT OF RANGE"
      ENDIF
      IF(T.LE.275.) THEN
      T=275.
      ROW=598.8134+2.828807*T-3.784399E-3*T**2.-7.474704E-6*T**3.+
     /1.129865E-8*T**4.
      ELSE
C      WRITE(*,*) "DENSITY IS OUT OF RANGE"
```

```
      ENDIF
      END

C     THE FOLLOWING FUNCTION IS FOR THE TEMPERATURE AT THE
C     SATURATION LINE AS A FUNCTION
C     OF PRESSURE.

      FUNCTION TTSAT(PPSAT)
C     CONVERT PRESSURE FROM N/M2 TO N/M2*1.E-5
      PPSAT=PPSAT*1E-5
      X1=3.5653E2
      X2=-2.0611
      X3=5.7064E-3
      X4=-1.0110E-5
      X5=2.1841
      X6=-9.9885E-3
      X7=2.5304E-5
      X8=3.8845E1
      X9=-2.2420E1

      TTSAT=X1+X2*PPSAT+X3*PPSAT**2.+X4*PPSAT**3.
     /+X5/PPSAT+X6/(PPSAT**2.)+X7/(PPSAT**3.)+
     /X8*PPSAT**.5+X9/(PPSAT**.5)
C     CONVERT PRESSURE BACK TO N/M2
      PPSAT=PPSAT*1.E5
      END
```

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NOMENCLATURE

a speed of sound (m/s)

c_p specific heat at constant pressure (J/kgK)

c_v specific heat at constant volume (J/kgK)

D_{12} vapor-noncondensable mass diffusivity (m^2/s)

D_i inner diameter (m)

D_O outer diameter (m)

d particle diameter

e total internal energy per unit volume (J/m^3)

F_x x-porous medium frictional force

F_y y-porous medium frictional force

F_z z-porous medium frictional force

Gr Grashof number

g gravitational acceleration (m/s^2)

h heat transfer coefficient (w/m^2K)

h_{fg} latent heat of condensation (J/kg)

$\overline{h}$ average heat transfer coefficient (w/m^2K)

$\dot{h}_g$ heat transfer coefficient in the presence of mass transfer (w/m^2K)

I Identity matrix

Ja Jakob Number

k thermal conductivity (w/mK)

K_g gas side mass transfer coefficient (kg/m^2s)

m condensation rate per unit fluid volume (kg/m^3s)

$\dot{m}''$ condensation rate per unit area (kg/m^2s)

m vapor mass fraction; parameter defined as ρu (kg/m^2s)

M_G molecular weight of noncondensable gas $(kg/kmole)$

M_v molecular weight of vapor $(kg/kmole)$

N number of tubes

N_u Nusselt number

n vapor mass fraction; parameter defined as ρv (kg/m^2s)

p pressure (N/m^2)

P tube pitch (m)

P_r Prandtl number

q'' local heat flux (w/m^2)

q vapor mass fraction; parameter defined as ρw (kg/m^2s)

R ideal gas constant (J/kgK); overall thermal resistance (m^2K/w)

Re Reynolds number

s specific interphase surface area m^{-1}

t time (s)

T temperature (K)

T_G secondary system bulk temperature (K)

T_p primary system bulk temperature (K)

T_s interphase temperature (K)

u velocity in the x-direction (m/s)

U overall heat transfer transfer coefficient (w/m^2K)

$\vec{U}$ conservative variables vector

U_p absolute value of velocity $(u^2 + v^2 + w^2)^{1/2}$

v velocity in the y-direction (m/s)

V volume (m^3)

$\vec{v}$ velocity vector (m/s)

w velocity in the z-direction (m/s)

x,y,z Cartesian cordinates

GREEK SYMBOLS

α stretching parameter eqn. (2.27)

β local volume porosity

β_t porosity of the tube bundle region

γ specific heat ratio; parameter in Roberts' transformaton eqn. (2.27)

δ parameter specifying nature of conservation equations

$$= \begin{cases} 0 & \text{Navier-Stokes} \\ 1 & \text{porous media with condensation} \end{cases}$$

λ second coefficient of viscosity (kg/ms)

ϵ internal energy (J/kg)

$\varepsilon_e, \varepsilon_i$ coefficients in explicit and implicit artificial dissipation terms

μ viscosity (kg/ms)

ξ_x, ξ_y, ξ_z pressure loss coefficients in x,y, and y directions respectively (m^{-1})

ξ, η, ζ transformed cordinates

ρ density (kg/m^3)

ρ_f density of condensate

ϕ gas mass fraction

SUBSCRIPTS

c condensate

f liquid

i, j, k nodal indices in x,y and z directions respectively

l last node in the x direction

G gas side noncondensable gas

p primary system; particle in porous media

s interphase

sat saturation

w wall

x, y, z Cartesian coordinate directions

SUPERSCRIPTS

$n-1$ $(n-1)$th time steps

n nth time steps

$n+1$ $(n+1)$th time steps

$*, **$ first and second-stage itermediate-time variables

w wall

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CHAPTER 1

INTRODUCTION

1.1. General Remarks

Condensation occurs when a wet, saturated, or slightly super-heated vapor contacts a surface which has a temperature below the saturation temperature corresponding to the vapor partial pressure. Condensation also occurs when vapor comes into direct contact with subcooled liquid. Although homogeneous condensation can also occur in highly subcooled metastable vapor, practical applications generally involve heterogeneous condensation. Heterogeneous condensation itself may be divided into two types: film-wise and drop-wise.

In film-wise condensation, the condensate forms a liquid film on the cooling surface, and it occurs when the cooling surface is easily wetted. However, in drop-wise condensation, the vapor condenses in the form of drops which grow and detach because of the effect of gravity and/or the effect of high shear forces after they grow large enough to overcome the interfacial forces between the drops and the cooling surface. New drops would take the position of the detached ones. Drop-wise condensation occurs on non-wetted cooling surfaces; therefore, because of i'ts lower heat transfer resistance, the heat transfer coefficients are about four times larger than those of film-wise condensation [1]. When drop-wise condensation takes place on a surface, the heat transfer coefficients increase with the increase of $(T_{sat} - T_w)$ to a point and then decrease, because further increase of the degree of sub-cooling makes the cooling surface wetted and film-wise condensation begins [1]. Because of the high heat transfer coefficient, it is advantageous to have drop wise condensation. Drop-wise condensation, however, is difficult to maintain and the process will eventually change to film-wise condensation. However, if appropriate care is taken, such as coating the cooling surface or adding a detergent to prevent the surface from being wetted, drop-wise condensation can be maintained. Because of the above stated reasons, most surface condensers are designed to operate on film-wise condensation.

A major difficulty encountered in condensers is the presence of non-condensable gases. These gases, which are difficult to avoid in practice, reduce the heat transfer coefficient of condensers by introducing an additional gas film resistance for heat and mass transfer.

1.2. Condensation of Pure Vapors

Condensation of a saturated vapor in the absence of noncondensables is, in principle, a liquid-side controlled process and is relatively simple to model, in particular in regular geometries. Classical condensation models dealt with this situation. In what follows, some of the important classical models are reviewed.

In film-wise condensation, a continuous film of liquid coats the cooling surface and is driven downward by the effect of gravity. The condensate film behavior on the cooling surface of the condenser is an important factor in determining the heat transfer rate. The first analytical work to determine the heat transfer coefficient was proposed in 1916 by Nusselt [2] with the following assumptions:

1. Steady state, laminar flow, and no rippling on the condensate film.
2. Within the liquid film, heat is transferred slowly by conduction.
3. Properties of the fluid are constant.

4. Vapor does not exert any force on the liquid film.
5. Acceleration of the liquid is negligible compared to gravitational and viscous forces.
6. Wall and interface temperatures are constant.
7. Energy deffect associated with sub-cooling of liquid film is neglected.
8. The vapor is pure.

By implementing the above assumptions with the appropriate boundary conditions on the Navier Stokes equations, Nusselt derived the following well-known relationship:

$$\bar{h}_{Nu} = 0.943 \left[\frac{\rho_f^2 g_x h_{fg} k_f^3}{L \mu_f \Delta T_f} \right]^{1/4} \tag{1.1}$$

where $\Delta T_f = (T_{sat} - T_w)$, and g_x is the component of the gravitational acceleration vector along the inclined surface.

The above equation describes the liquid-side heat transfer coefficient over an inclined plate of length L. Because pure film condensation is rarely found without the presence of drop wise condensation, and because the condensate has ripples that help the liquid to mix with the film, condensation heat transfer coefficients are usually higher than those predicted by Equation (1.1).

Rohsenow [3] solved the filmwise condensation problem, accounting for the correct nonlinear temperature distribution. He assumed that the wall temperature is constant, vapor is saturated, no vapor shear stress on the liquid film, and the physical properties of the liquid are constant. Rohsenow also suggested that, h_{fg} in Equation (1.1) should be replaced by $h_{fg} + 0.68 c_{pf}(T_{sat} - T_w)$ where c_{pf} is the specific heat of the liquid.

Chen [4]; and Koh, Sparrow, and Hartnett [5] have taken into account the effect of the drag which the vapor exerts on the liquid. Chen [4] has suggested the following approximate Equation that includes momentum and interfacial shear effects.

$$\frac{\bar{h}_{Nu}}{h_{Nu}} = \left[\frac{1 + 0.68A + 0.02AB}{1 + 0.85b - 0.15AB}\right]^{1/4} \quad (1.2)$$

where $A = \frac{c_{pf}\Delta T_f}{h_{fg}}$ and $B = \frac{k_f \Delta T_f}{\mu_f h_{fg}}$.

Equation (1.2) is only valid for $A < 2$, $B < 20$ and $Pr_f < 0.05$, or $Pr_f > 1$.

In the case of turbulent film flow, the Nusselt assumptions are evidently not valid. Turbulent flow might occur at the lower end of the inclined plate. In this case, heat can no longer be assumed to be transferred through the condensate film by conduction, due to the significance of eddy diffusivity, which greatly increases the heat transfer rate. Unlike the laminar case, the heat transfer coefficient increases with the distance along the plate ,x, because the turbulence increases as the film thickness gets larger. The following correlation[1] gives the average heat transfer coefficient for turbulent film condensation:

$$\bar{h} = 0.0076\left[\frac{\rho_f(\rho_f - \rho_s)g_x k_f^3}{\mu_f^2}\right]^{1/3} Re_L^{0.4} \quad (1.3)$$

where Re_L is the Reynolds number at $x = L$.

Nusselt also derived the following correlation for the heat transfer coefficient for film condensation on a horizontal tube using assumptions similar to those he had made for the plate geometry:

$$\frac{\bar{h}_{Nu} D_0}{k_f} = 0.728\left[\frac{\rho_f(\rho_f - \rho_s)g h_{fg} D_0^3}{\mu_f(T_{sat} - T_w)k_f}\right]^{1/4} \quad (1.4)$$

Equation (1.4) was derived with the assumption that the condensation thickness is much smaller than the radius of the tube.

In the case of forced convection, the shear forces between the condensate and the vapor are important. In order to solve this problem correctly, it is necessary to solve the continuity and momentum conservation equations for the vapor and the condensate.

Shekriladze and Gomelauri [6] extended the analytical work of Nusselt for an isothermal cylinder without separation by assuming that the change in momentum across the condensate-liquid interface is the main factor which causes the surface shear stress. The following result was obtained:

$$\bar{h} = 0.9\frac{k_f}{D_0}\bar{R}e^{1/2} \tag{1.5}$$

where $\bar{R}e = \frac{\rho_f u_g D_0}{\mu_f}$ and u_g is the steam velocity. When gravity and velocity are involved, they recommended the following equation:

$$\bar{N}_u = 0.64\bar{R}e\left[1 + \left(1 + 1.69\frac{gD_0\mu_f h_{fg}}{u_g^2 k_f \Delta T}\right)\right]^{1/2} \tag{1.6}$$

A great deal of analytical work for pure vapor condensation on flat plates and cylinders is available in the literature. An excellent review of laminar film condensation is given by Rose [7,8].

1.3. Condensation in the Presence of Noncondensables

In the previous section, condensation of pure vapor was discussed, where the major heat transfer resistance was due to the condensate layer which accumulates on the cooling surface. The assumption of pure vapor condensation is not valid in most practical cases, because a small amount of noncondensable gases can easily find its way into a condenser. Collier [9] and Minkowycz [10] reported that even 0.5% mass of air may decrease the heat transfer rate by more than 50%.

It has been noted that a small amount of noncondensable gases present in steam reduces the overall heat transfer coefficient, which, in turn, degrades the performance of the condenser. As steam condenses on the cooling surface, the noncondensables accumulate and form a noncondensable-rich layer between the condensate and the steam. This gas film reduces the rate of steam that reaches the cooling surface by introducing an additional mass transfer resistance. Figure 1.1 is a schematic of the vapor and noncondensable concentration profiles near the vapor-condensate interphase. The flow of condensing vapor towards the interphase results in the accumulation of noncondensable gas near the liquid surface. The vapor pressure at the interphase is reduced significantly, even when the concentration of noncondensables in the bulk vapor is quite small.

Othmer [11] in 1929 studied the effect of a small quantity of air on the temperature drop and on the condensation rate of steam, along an isothermal surface. He carried out experiments using a shell with a tube partially filled with liquid. The steam was allowed to pass through the shell and the liquid to pass through the tube. He suggested an empirical correlation which relates the heat transfer coefficient to the steam temperature drop, and the air concentration:

$$\begin{aligned}\log(h) &= \log(\Delta T)[1.213 - 0.0024T] \\ &+ \left[\frac{\log(\Delta T)}{3.439} - 1\right]\left[\log(C + 0.505) - 1.551 - 0.009T\right]\end{aligned} \tag{1.7}$$

where h is in $Btu/(hr - ft^2 - F), C$ is the percent volume of air, T is the temperature of steam in degree Fahrenheit, and ΔT is the temperature difference between the bulk vapor and the cooling surface. In deriving his empirical correlation, Othmer assumed that the temperature of the tube wall remained constant, and the air-stream mixture was stagnant. Othmer's work was followed by a myriad of analytical, experimental, and numerical studies in the area of condensation. Some of these investigations are discussed below.

Meisenburg, Boarts, and Badger [12] studied condensation in the presence of noncondensables, in a vertical tube and correlated the ratio of the actual

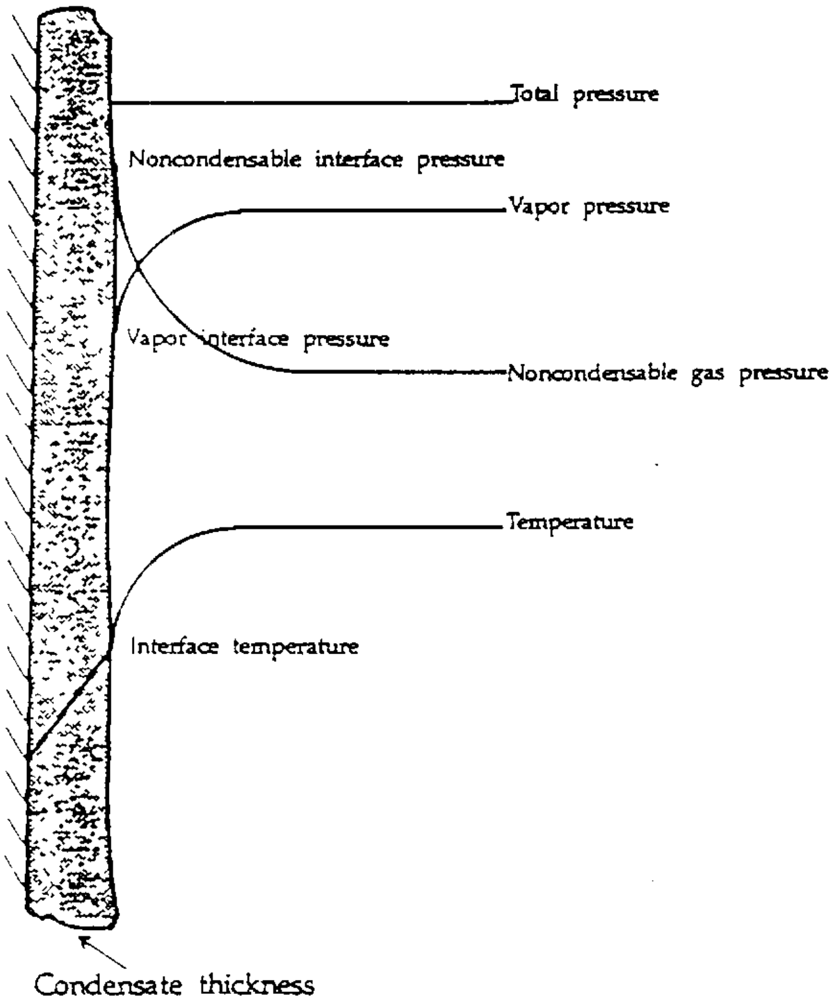

Figure 1.1. Temperature and Partial Pressure Profiles at the Condensate-Gas Interphase.

heat transfer coefficient h, (which includes the effect of noncondensables) to that of Nusselt's, h_{Nu}, (representing condensation of pure steam) as:

$$\frac{h}{h_{Nu}} = \frac{1.17}{C^{0.11}} \tag{1.8}$$

where $0 < C < 0.4$ is the air weight percent in the mixture. For a vertical plate Hampton [13] derived the following relation:

$$\frac{h}{h_{Nu}} = 1.2 - 20y \tag{1.9}$$

where $0 < y < 0.02$ is the mass fraction of noncondensables.

In 1934, Colburn and Hougen [14] suggested a design equation for condensers with noncondensables. The values of $\frac{1}{U\Delta T}$, where U is the overall heat transfer coefficient, are calculated at sufficient number of points, through trial and error, by equating the heat transferred through the condensate, the tube wall, and the cooling water film, to the sum of the sensible heat of the uncondensed gas and the latent heat of the vapor that is transferred by diffusion. After making the above calculations, the required condenser surface area can be obtained by multiplying the heat transferred per hour by the integrated average value of $\frac{1}{U\Delta T}$. The design equations of Colburn and Hougen were later modified by Smith [15] and Bras [16].

Condensation in the presence of noncondensables has also been investigated by Sparrow and Lin [17] where it has been shown that the presence of non-condensable gases can reduce the heat transfer rate significantly. A predictive theory based on the continuity, momentum, and energy conservation equations was formulated and a numerical solution was carried out.

Free convection condensation in the presence of noncondensable gases on an isothermal vertical surface under thermal equilibrium condition was studied by Mori and Hijikata [18]. The solution was carried out by the use of a liquid film and boundary layer adjoining the film and including small condensation droplets.

Rose [19] obtained approximate equations for forced convection condensation in the presence of noncondensable gas over a flat plate and horizontal tube for calculating the transfer of vapor to the condensate surface. Saprrow, Minkowycz, and Saddy [20] have studied the effect of a noncondensable gas over a flat plate in a forced laminar boundary layer flow. The problem was first carried out analytically for an arbitrary flow and was then applied to steam as the condensing vapor and air as the noncondensable gas. Also, a numerical solution of similarity differential equations was implemented. It has been found that condensation in forced convection flow is much less sensitive to the effect of noncondensables than that in free convective flow. Also, Denny, and Jusionis [21] studied the effect of noncondensable gas and forced flow on laminar film condensation. The vapor conservation equations were solved numerically using a forward marching technique.

1.4. Condensers

Condensers are very important components in power plants, chemical plants, refrigerators, air conditioners, and many other industrial systems. The function of steam condensers in closed thermodynamic cycles is to condense the steam that is exhausted from the turbine, and send the condensed steam to the feed pump. Broadly speaking, condensers may be classified into two types: steam separated condensers and direct contact condensers. In steam separated condensers, the coolant and the condensate are separated by a solid wall, while in the direct contact condensers, the coolant is allowed to mix with the steam, where mixing is maximized to ensure best exposure of the cooling water and steam.

Each of the above mentioned condensers is divided into other types. The direct contact condensers can be divided into three types:

1. The packed column condensers, where the coolant is allowed to flow down as a film on a packed material, while the vapor is allowed to flow up to mix and exchange heat with the water.
2. The pool vapor condensers, wherein the vapor is bubbled in a coolant pool.
3. The spray and tray condensers, in which the coolant is sprayed into the vapor.

The steam separated condensers commonly used in the past may also be divided into the following types:

1. Plate condensers. In this type of condensers, the coolant is separated from the vapor by corrugated metallic plates. The plates are corrugated to increase the surface area between the coolant and the vapor, thereby enhancing the heat transfer rate.
2. Shell and tube condensers. These are the most common types of condensers. They can be designed so that the vapor passes in the tubes (tube side) or passes across the tubes (shell side). Shell and tube condensers are subdivided into two types: process plant condensers and power plant condensers.

These two condenser types constitute the great majority of condensers in traditional applications. The bulk of the experimental and analytical studies reported in the past dealt with these condenser types.

Recent applications, however, demand extremely high condenser performance, which often can not be met by these traditional condenser types. Two examples of such applications are provided below.

Ocean Thermal Energy Conversion (OTEC) is an example of modern applications of condensers. The OTEC concept is based on utilizing the temperature difference between surface and deep waters in tropical oceans for power generation.

Since the available temperature difference is only about 20°C, extremely efficient condensers are needed. Research aimed at developing condenser designs capable of meeting the requirements of OTEC plants has been underway by several investigators (see e.g., [22], [23], [24]).

Recently, phase change material (PCM) condensers have attracted the attention of investigators involved in research associated with space power applications [25]. In this type of condensers, a PCM material which has a melting point lower than the condensate saturation temperature, is used as the heat sink. Condensation of the vapor results in a partial melting of the PCM material. The thermal energy stored in the PCM in this way can be disposed of later on, or it can be utilized for other applications. PCM condensers thus lack a primary coolant side, and can have various geometric configuration such as packed beds, tortuous channels, etc.

These and other new applications involve geometric and flow conditions different from simple shell-and-tube, or plate-type condensers. The available analytical and empirical design and analysis methods are generally inadequate for these new condensers.

1.5. Condenser Design Attributes

The most important applications of condensers are in power plants and the process industry. Power plant condensers and process plant condensers are similar except that the former should be designed in such a way so that they can accommodate a high heat load while maintaining low condensing temperature to increase the power plant efficiency. Shell-and-tube condensers are the most widely used design of these applications. Design attributes of power plant condensers are discussed below. Power plant condensers operate at a condensing temperature slightly below the coolant temperature. Due to the large power demand, power plant condensers have a very large tube surface area which in turn necessitates the use of a large number of tubes to increase the heat transfer between the vapor and the coolant. Condensers usually have two outlet nozzles. The first one is to remove the noncondensable gases which enter the condenser through the turbine glands and from the air dissolved in the steam. The presence of such a gas adds an additional resistance to heat transfer in the form of a gas film which reduces the performance of the condenser, hence it has to be pumped out. The other nozzle is designed for the departing condensate.

Condensation takes place due to the vapor entering the shell through an inlet nozzle where it passes across the tubes. The condensate is then collected at the condensate outlet nozzle.

Shell and tube condensers are widely used in power generation plants and they have been in use for a long time. Designs and analyses using experimental, analytical and numerical methods have been a topic of extensive research in many organizations.

The procedure for designing a condenser usually consists of the following steps [26]:

1. Process specifications.
2. Preliminary analysis of the problem.
3. Thermal hydraulic design.
4. Metallurgical design.
5. Structural design.

6. Architectural design.
7. Maintenance and economics.

The third step includes the fluid and heat transfer analysis of the condenser. To choose the optimum configuration of a condenser, the following steps are required:

1. A condenser configuration that satisfies material, structural, architectural, and cost requirements, is chosen.
2. Based on the chosen configuration, thermal analysis is performed.
3. The above two steps are repeated for different configurations until the optimum configuration is found.

In shell-and-tube condensers, baffles are used to support the tubes in the shell side and to direct the steam to flow in a zigzag manner to increase the heat transfer between the steam and the coolant. The coolant enters the tubes through the coolant inlet, loses part of its energy as it passes in the tubes, and then leaves the condenser through the coolant outlet.

Thus, because power plant efficiency depends on the condenser performance, the condenser should be thermal-hydraulically designed and optimized under a set of design conditions dictated by the overall plant design. Inadequate design of a condenser will lead to a poor power plant efficiency.

The condenser is usually selected based upon some parameters such as tube diameter, condenser pressure, cold water temperature and velocity, tube length, heat load, and tube material. In the thermal-hydraulic analysis of condensers, two important objectives have to be considered: (1) the pressure drop across the condenser must be minimized, and (2) the overall heat transfer rate between the steam side and the coolant side must be maximized. The achievement of the first objective enables the engineer to predict the power required to drive the flow through the condenser, while the achievement of the second objective allows for maximizing the efficiency of the condenser given the size and the inlet conditions.

Numerical methods for analysis of advanced condensation systems have recently been published. A finite difference numerical model was developed that studies the fluid flow and heat and mass transfer in a dual-latent packed bed system [27, 28].

Recently, a one dimensional analysis of a packed bed of encapsulated phase change material (PCM) and condensation was implemented [29]. In this work the continuity and momentum equations are solved for the steam and liquid while the energy equation is solved for the fluid and solid phase. The temporal terms in the momentum equations are not considered. Additional numerical models will be discussed in the forthcoming sections.

1.6. Flow Through Porous Media

As will be explained later, modern numerical models for condenser design and analysis, treat the secondary-sides of the condensers as porous media. Porous media formulation will be the approach in this research. Therefore, before discussing modern models, the basic principles of flow in porous media will be briefly reviewed.

The steady state bulk flow resistance through porous media was first measured by Darcy (1856), leading to the well-known Darcy's law [30]:

$$\nabla p = -\mu(\underline{\underline{\mathbf{R}}}.\vec{v}) \tag{1.10}$$

The parameter $\underline{\underline{R}}$ is a tensor of the second order rank, and is defined as:

$$\underline{\underline{R}} : \underline{\underline{K}} = \underline{\underline{I}} \tag{1.11}$$

where $\underline{\underline{K}}$ is the permeability tenser representing the porous medium, and $\underline{\underline{I}}$ is the identity tensor. In Cartesian coordinates R_{ij}, representing the (i, j) component of $\underline{\underline{R}}$, is related to the components of the permeability tensor according to:

$$R_{i,j}K_{j,i} = \delta_{ij} \tag{1.12}$$

where $\delta_{i,j}$ is the Kronecker delta, and $\underline{\underline{K}}$ is permeability of the porous medium.

Darcy's law describes laminar flow through a porous medium composed of small, irregular pore passages. It is valid only for the seepage velocity domain, which is characterized by a small Reynolds number. Experimental investigations show that Darcy's law is valid for $1 < Re < 10$,where Re is defined as.

$$Re = \frac{\rho u_{sup} d}{\mu} \tag{1.13}$$

Where d is some representative length scale of the porous matrix. However, as the superficial velocity, u_{sup}, increases to $Re \geq 10$, deviation from Darcy's law is observed due to the contribution of the inertia to the fluid momentum equation. Several models have been suggested, in which the effect of fluid inertia is considered. A second order nonlinear relationship for high velocities suggested by Forchheimer (1905) [30], is:

$$\frac{\partial p}{\partial x} = au + bu^2 \tag{1.14}$$

The most commonly used second order equation, however, was suggested by Ergun (1952) [31], which applies to flow through a bed composed of spherical particles with diameter d:

$$\frac{\partial p}{\partial x} = 150\frac{(1-\beta)\mu}{\beta^3 d^3}u + 1.75\frac{1-\beta}{\beta^3 d}u^2 \tag{1.14}$$

For multi-dimensional flow in a porous medium, Ergun's equation can be represented as [32]:

$$\nabla.(\rho'\vec{v}\vec{v}) = -\beta\nabla p - \mu\beta^2(\underline{\underline{\mathbf{R}}}.\vec{v}) - \rho' C\beta^2|\vec{v}|\vec{v} + \rho'\mathbf{g} + \nabla.(\mu\beta\nabla\vec{\mathbf{v}}) \quad (1.15)$$

where $\rho' = \beta\rho$, and $C = 1.75(1-\beta)/d\beta^3)$ is the inertial coefficient in Ergun's formulation.

Nonlinear equations of motion in many other forms have been suggested. Most of them, however, are obtained experimentally, without a strong physical basis.

1.7 Numerical Methods Applied to Power Plant Steam Condensers

Numerical methods have recently been developed for the analysis and design of condensers because of the availability of digital computers and fast algorithms. The advancement in speed and memory of computers has made reliable design and analysis of condensers possible. These numerical methods allow detailed calculations of heat transfer, mass transfer, fluid flow, temperature, pressure distributions, velocity field, and concentration of noncondensables for various complex condenser geometries.

In the past, analysis and design of condensers heavily relied on correlations and intuitive judgments to produce an optimum condenser design. An ideal design of a condenser requires that the pressure loss of steam be minimized and that gas blanketing be avoided. Gas blanketing represents conditions where noncondnesables preferentially collect in specific parts of the condenser, thus drastically deteriorating the performance of the condenser. Generally, the steps required to evaluate the performance of a condenser can be summarized as follows:

1. Evaluation of velocity and pressure fields.
1. Evaluation of concentration of noncondensables.
3. Evaluation of heat and mass transfer rates.
4. The above steps are repeated until a satisfying convergence is achieved.

Early computational studies of fluid flow and heat transfer in power plant condensers have used the network method. This method relies on experimental data and apriori knowledge of flow patterns. Brasness [33] and Chisholm, Osment, McFarlane, and Choudhury [34] developed one dimensional numerical models, and performed comparisons between theory and experiment which include the examination of the noncondensables effect. In recent years, Davidson and Rowe [35], Al-Sanea, Rhodes, Tatchell, and Wilkinson [36] and Shida, Kuragasaki and Adachi [37] have implemented two dimensional models that evaluate the performance of condensers. The fluid flow in steam condensers, however, is very complex and three dimensional because of the presence of the tube bundle and baffle plates. Due to this complexity, in more recent models the fluid is assumed to flow through a porous medium.

Butterworth was one of the early researchers, who developed analytical criteria for deriving multidimensional, porous-media transfer correlations using 1-D shell-and-tube data and correlations [38]. Caremoli [39] has described a two dimensional computational method, using a Cartesian coordinate system, that evaluates the performance of a power plant condenser using coupled heat and mass transfer and fluid flow equations. The local averaging method was used to account for the geometric complexity.

Caremoli's model appears to be one of the most comprehensive in the open literature. In view of this fact, this model will be reviewed in some detail. The gas-vapor mixture continuity and momentum, and noncondensable mass fraction conservation equations used by Caremoli [39] are as follows:

1. Continuity equation

$$\frac{\partial(\beta\rho)}{\partial t}+\frac{\partial(\beta\rho u)}{\partial x}+\frac{\partial(\beta\rho v)}{\partial y}=-\beta\dot{m} \quad (1.17)$$

2. Momentum equations

$$\frac{\partial(\beta\rho u)}{\partial t}+\frac{\partial(\beta\rho u^2)}{\partial x}+\frac{\partial(\beta\rho uv)}{\partial y}=-\beta\frac{\partial p}{\partial x}-\beta\dot{m}u+\beta F_x+\frac{\partial(\beta\tau_{xx})}{\partial x}+\frac{\partial(\beta\tau_{xy})}{\partial y} \quad (1.18)$$

$$\frac{\partial(\beta\rho uv)}{\partial t}+\frac{\partial(\beta\rho uv)}{\partial x}+\frac{\partial(\beta\rho v^2)}{\partial y}=-\beta\frac{\partial p}{\partial y}-\beta\dot{m}v+\beta F_y+\frac{\partial(\beta\tau_{xy})}{\partial x}+\frac{\partial(\beta\tau_{yy})}{\partial y} \quad (1.19)$$

3. Noncondensable (air) mass fraction equation

$$\frac{\partial(\beta\rho\phi)}{\partial t}+\frac{\partial(\beta\rho\phi u)}{\partial x}+\frac{\partial(\beta\rho\phi v)}{\partial y}=\frac{\partial}{\partial x}\left(\beta\rho D\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\beta\rho D\frac{\partial\phi}{\partial y}\right). \quad (1.20)$$

where $\dot{m}$ is the condensation mass flow rate per unit volume of the fluid mixture, and β is the porosity defined as the ratio between volume occupied by fluid and the total volume. Note that in these equations the small volume occupied by the condensate is neglected and the density of vapor is assumed constant. The parameter F is the tube friction source term which has the components,

$$F_x=-\beta\rho G_{xx}u-\beta\rho G_{xy}v \quad (1.21)$$

and

$$F_y=-\beta\rho G_{yy}u-\beta\rho G_{xy}v \quad (1.22)$$

where G's are the flow resistances and they are obtained from one dimensional single phase flow correlations. The condensation rate is related to the condensation mass flux according to

$$\dot{m}=\dot{m}''s \quad (1.23)$$

The condensation mass flux was calculated in Caremoli's model from:

$$\dot{m}''=\frac{q}{h_{fg}}=\frac{T_{sat}-T_p}{Rh_{fg}} \quad (1.24)$$

where T_{sat} is the temperature of vapor, T_p is the temperature of the primary coolant, h_{fg} is the latent heat of vaporization, the parameter R, the overall thermal resistance, is obtained using various heat transfer correlations, where the liquid-side heat transfer coefficient was obtained from Nusselt's Equation [2].

Three major shortcomings can be mentioned with respect to the above described model. Firstly, the noncondensable diffusion (represented by Equation (1.20)) is inadequate. Diffusion of mass, in particular in laminar flow conditions, occurs over very small distances. Volume-averaged equations using grid sizes large enough to allow volume averaging in condensers are way too large for adequate representation of mass diffusion. On the other hand, neglecting the mass diffusion entirely is known to be inappropriate, since it results in lack of capability for predicting gas blanketing. The second shortcoming of Caremoli's model is the inadequate representation of the effect of the noncondensables on the condensation rate. The third shortcoming is the assumption of constant vapor density.

Zhang and Sousa [40] recently reported a two dimensional numerical method that predicts the fluid flow and heat transfer in a shell-and-tube condenser. In this work, some features of previous work [35-37,39] are utilized. The continuity, momentum, and air mass species conservation equations, with diffusive terms included, are solved using a control-volume approach. However the density is assumed to be locally variable. The flow resistance forces F_x and F_y in the momentum equations were represented in terms of pressure loss coefficients, ξ_x and ξ_y, by the following relationship:

$$F_x = \xi_x u U_p \tag{1.25}$$

and

$$F_y = \xi_y v U_p. \tag{1.26}$$

The loss coefficients were calculated as suggested by Rhodes and Carlucci [41].

$$\xi_x = 2\left(\frac{f_x}{P}\right)\left(\frac{P\beta}{P - D_0}\right)^2\left(\frac{1-\beta}{1-\beta_t}\right) \tag{1.27}$$

$$\xi_y = 2\left(\frac{f_y}{P}\right)\left(\frac{P\beta}{P - D_0}\right)^2\left(\frac{1-\beta}{1-\beta_t}\right) \tag{1.28}$$

where f_x and f_y are the friction factors and β_t is the porosity in the tube bundle region only. The steam mass condensation rate per unit volume is obtained from:

$$\dot{m} = \frac{(T_{sat} - T_p)s}{Rh_{fg}} \tag{1.29}$$

where R, the overall thermal resistance for each control volume, is obtained from various empirical heat transfer correlations, and T_{sat} is the saturation temperature at the partial steam pressure.

The foregoing criticisms, with respect to the model by Caremoli [39], evidently also apply to the model by Zhang and Sousa [40].

1.8 Rationale and Objectives of this Research

In the previous sections, earlier work on the design and thermal analysis of condensers was briefly reviewed. Condensers have been in service for many decades, however, the methodology for their design was essentially empirical until quite recently. Relatively few different geometric configurations, and most frequently the shell-and-tube, were utilized. The experimental data base is quite extensive for these simple and standard geometries, making empirical methods feasible. Recent application of condensers, e.g., in space systems, Ocean Thermal

Energy Conversion (OTEC), etc., however, are based on more complex geometric configurations, rendering much of the existing empirical methods essentially inapplicable. Therefore, a numerical method which can address an arbitrary condenser geometry is needed. Treating the secondary side of a condenser as a porous medium subject to flow of a compressible gas-vapor mixture, which is the approach in this research, provides an appropriate method for such an analysis.

The concept of application of flow through porous media to the design and analysis of condensers was originally developed with the intention of better modeling the multi-dimensional flow effects in the conventional shell-and-tube heat exchangers [42], and provided an alternative to the old analytical approach where either the flow was assumed to be one-dimensional [34], or the condenser was finely nodalized such that each subchannel was treated separately [43]. The porous media approach has recently been adopted by many investigators [38, 35, 39]. Nevertheless, as was explained in the previous sections, the existing published models are inadequate, in particular with respect to their treatment of the noncondensables.

In view of the aforementioned background, the objectives of this research are:

1. To develop a numerical model for the secondary side of a condenser where the secondary side is treated as a three-dimensional, porous medium through which a compressible vapor-gas mixture flows. State-of-the-art constitutive relations will be applied for the general characterization of porous media, and the effect of noncondensables will be rigorously included in the model.
2. Study the effecs of major modeling components (e.g., viscous terms in the momentum equations) on the overall model predictions.
3. To perform parametric calculations, and thereby examine the effect of small concentrations of noncondensables on the performance of modern condensers.

CHAPTER 2

MODEL DEVELOPMENT

2.1. Introduction

This chapter develops a rigorous model that overcomes most of the major shortcomings of all previous models such as compressibility and the treatment of noncondensables. Compressibility, however, is very crucial in the design and analysis of condensers because part of the steam is lost in the process of condensation, and is compensated by a decrease in density. This change in density might be very large, depending on the condensation rate, which necessitates the solution of the compressible flow equations. The developed model is three-dimensional, compressible, and includes all the porous-media and condensation terms for shell-and-tube and packed bed systems. Moreover, the model assumes that all transport properties, such as thermal conductivity and viscosity, are space dependent. However, when solving the governing partial differential equations of the condenser secondary side, the steam is assumed to behave like a perfect gas.

The governing partial differential equations are the compressible Navier-Stokes and noncondensable species mass conservation equations, with porous-media and condensation terms added. The state-of-the-art implicit-compressible numerical solution scheme (ICS) will thus be modified to include these additional terms, and will be discussed in detail in the next chapter. Moreover, the implicit numerical scheme will be modified to include any number of species mass conservation equations.

In order to adequately model the noncondensable effect and avoid relying on purely experimental correlations, which all previous models employed, a well-proven model that relies on sound theoretical basis is needed. The stagnant film model [45], a simple engineering method for the analysis of combined heat and mass transfer that has proven to be very reliable when used in earlier calculations of steam condensers, has been used. Thus, it is expected that when this model is used in conjunction with a rigorous numerical model, the outcome will be very promising. This model will be presented at the end of this chapter.

2.2. Overview of the Model

In this model, the porous-medium vapor continuity, mixture momentum, mixture energy, and noncondensable mass species conservation equations are presented for the secondary side of the steam condenser system in their 3-D Cartesian coordinate and compressible form. The solution, however, is performed in two different and inter-related levels in order to adequately account for the effect of noncondensables. The conservation equations are first solved at the macroscopic level, using the volume-averaging concept, consistent with porous media approach. This solution provides the bulk gas mixture flow field, and makes it possible to identify areas in the condenser where advective terms are small and may result in the gas-blanketing phenomenon.

The bulk gas mixture flow field calculated in the macroscopic level solution is then utilized in calculating the heat and mass transfer through the interface between the condensate liquid and the vapor-noncondnesable mixture. These calculations, referred to hereafter as the microscopic level analysis, are based on the stagnant-film model, and represent the distributed-parameter analysis, where the flow field inside the subchannel pores is considered.

It has to be noted that the foregoing macroscopic and microscopic level analyses are coupled. The macroscopic conservation equations utilize heat transfer, condensation rates and heat fluxes provided by microscopic analysis, while the microscopic level calculations use the flow velocity, pressure, density, temperature and the bulk noncondensable concentration provided by the macroscopic level analysis. These macroscopic and the microscopic calculations are repeated iteratively until the desired convergence criterion is achieved.

2.3. Assumptions

The model involves the following assumptions. Many of these assumptions, which have been made for simplicity, can be discarded and the model can easily be modified.

1. The macroscopic level analysis assumes that the steam behaves like a perfect gas, whereas the microscopic level analysis uses polynomial fitting equations for steam and water properties.
2. The volume occupied by the condensate is assumed to be negligibly small.
3. The condensate is assumed impermeable to the noncondensable.
4. The cold solid surfaces are assumed to have constant thermal conductivities.
5. In the case of the packed bed condenser, the centerline temperature of particles is assumed constant.
6. The velocity of the primary system in the case of the shell-and-tube condenser is assumed to be constant.
7. Radiation heat transfer is neglected.
8. The steam and the noncondensable gas are in local thermal equilibrium.
9. The noncondensable gas behaves like a perfect gas.

2.4. Macroscopic Level Model

2.4.1 Conservation Equations and Constitutive Relations

The governing conservation equations can be written in conservative form as follows:

- Vapor continuity equation:

$$\frac{\partial(\beta\rho_v)}{\partial t}+\frac{\partial(\beta\rho_v u)}{\partial x}+\frac{\partial(\beta\rho_v v)}{\partial y}+\frac{\partial(\beta\rho_v w)}{\partial z}=-\beta\dot{m}\delta$$
$$+\frac{\partial}{\partial x}\left(\beta\rho D\frac{\partial\phi'}{\partial x}\right)+\frac{\partial}{\partial y}\left(\beta\rho D\frac{\partial\phi'}{\partial y}\right)$$
$$+\frac{\partial}{\partial z}\left(\beta\rho D\frac{\partial\phi'}{\partial z}\right). \tag{2.1}$$

- Mixture momentum conservation equations:

$$\frac{\partial(\beta\rho u)}{\partial t}+\frac{\partial(\beta\rho u^2)}{\partial x}+\frac{\partial(\beta\rho uv)}{\partial y}+\frac{\partial(\beta\rho uw)}{\partial z}$$
$$=-\frac{\partial(\beta p)}{\partial x}+\frac{\partial}{\partial x}\left(\beta(\lambda+2\mu)\frac{\partial u}{\partial x}+\beta\lambda\left(\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right)$$
$$+\frac{\partial}{\partial y}\left(\beta\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right)+\frac{\partial}{\partial z}\left(\beta\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right)$$
$$+(F_x-\beta\dot{m}u)\delta+\beta\rho g_x. \tag{2.2}$$

$$\frac{\partial(\beta\rho v)}{\partial t}+\frac{\partial(\beta\rho uv)}{\partial x}+\frac{\partial(\beta\rho v^2)}{\partial y}+\frac{\partial(\beta\rho vw)}{\partial z}=-\frac{\partial(\beta p)}{\partial y}$$
$$+\frac{\partial}{\partial x}\left(\beta\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right)+\frac{\partial}{\partial y}\left(\beta(\lambda+2\mu)\frac{\partial v}{\partial y}+\beta\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}\right)\right)$$
$$+\frac{\partial}{\partial z}\left(\beta\mu\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)\right)+(F_y-\beta\dot{m}v)\delta+\beta\rho g_y. \tag{2.3}$$

$$\frac{\partial(\beta\rho w)}{\partial t}+\frac{\partial(\beta\rho uw)}{\partial x}+\frac{\partial(\beta\rho vw)}{\partial y}+\frac{\partial(\beta\rho w^2)}{\partial z}=-\frac{\partial(\beta p)}{\partial z}$$
$$+\frac{\partial}{\partial x}\left(\beta\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right)+\frac{\partial}{\partial y}\left(\beta\mu\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)\right)$$
$$+\frac{\partial}{\partial z}\left(\beta(\lambda+2\mu)\frac{\partial w}{\partial z}+\beta\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right)$$
$$+(F_z-\beta\dot{m}w)\delta+\beta\rho g_z. \tag{2.4}$$

- Mixture energy conservation equation:

$$\frac{\partial(\beta e)}{\partial t}+\frac{\partial(\beta(e+p)u)}{\partial x}+\frac{\partial(\beta(e+p)v)}{\partial y}+\frac{\partial(\beta(e+p)w)}{\partial z}$$
$$=\frac{\partial}{\partial x}\left[\beta(\lambda+2\mu)u\frac{\partial u}{\partial x}+\beta\lambda\mu\left(\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+\beta\mu v\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right.$$
$$\left.+\beta\mu w\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]+\frac{\partial}{\partial x}\left(\beta k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left[\beta(\lambda+2\mu)v\frac{\partial v}{\partial y}\right.$$
$$\left.+\beta\mu u\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)+\beta\lambda v\left(\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}\right)+\beta\mu w\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)\right]$$
$$+\frac{\partial}{\partial y}\left(\beta k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial y}\left(\beta(\lambda+2\mu)w\frac{\partial w}{\partial z}+\beta\mu u\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right.$$
$$\left.+\beta\mu v\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)+\beta\lambda w\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]$$
$$+\frac{\partial}{\partial y}\left(\beta k\frac{\partial T}{\partial z}\right)-q''s\delta. \tag{2.5}$$

- Noncondensable gas mass conservation equation:

$$\frac{\partial(\beta\rho_g)}{\partial t}+\frac{\partial(\beta\rho_g u)}{\partial x}+\frac{\partial(\beta\rho_g v)}{\partial y}+\frac{\partial(\beta\rho_g w)}{\partial z}$$
$$=\frac{\partial}{\partial x}\left(\beta\rho D\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\beta\rho D\frac{\partial\phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\beta\rho D\frac{\partial\phi}{\partial z}\right) \tag{2.6}$$

Important parameters in the above equations are defined as follows. Parameter β is the local porosity, q'' is the local heat flux, and h_{fg} is the latent heat of condensation, ρ_v is the vapor partial density, ρ_g is the noncondensable partial density, and

$$\phi' = \rho_v/\rho \tag{2.7}$$

$$\phi = \rho_g/\rho \tag{2.8}$$

$$\rho = \rho_v + \rho_g \tag{2.9}$$

The parameter $\dot{m}$ is the local condensation rate, per unit volume, and is related to the local condensation mass flux by Equation (1.23). The Parameter δ in Equation (2.2) through (2.5) equals one for porous medium and condensation, and zero otherwise.

Finally, the parameters F_x, F_y and F_z are the porous medium frictional force terms and are defined as follows. For shell-and-tube porous media,

$$\begin{aligned} F_x &= -\beta\xi_x u U_p \\ F_y &= -\beta\xi_y v U_p \\ F_z &= -\beta\xi_z w U_p \end{aligned} \tag{2.10}$$

where the pressure loss coefficients ξ_x, and ξ_y, are defined in Equations (1.27) and (1.28) respectively, and ξ_z is defined as:

$$\xi_z = 2\left(\frac{f_z}{P}\right)\left(\frac{P\beta}{P-D_0}\right)^2\left(\frac{1-\beta}{1-\beta_t}\right) \tag{2.11}$$

The parameter f_x is the friction factor and is defined as [40]:

$$f_x = \begin{cases} 0.619Re_x^{-0.198}; & Re_x < 8000 \\ 1.156Re_x^{-0.2647}; & 8000 < Re_x < 2\times 10^5 \end{cases} \tag{2.14}$$

where $Re_x = \rho u D_0/\mu$. Prameters f_y, f_z, Re_y, and Re_z are defined similarly

In the above equations, P is the tube pitch, D_0 is the outer diameter of the tube, and β_t, the porosity in the tube bundle region, is found from:

$$\beta_t = 1 - \frac{\pi}{4}\left(\frac{D_0}{P}\right)^2. \tag{2.15}$$

For packed bed porous medium,

$$F_x = -\left[\mu\frac{\beta^2 u}{K} + \rho C\beta^2(u^2 + v^2 + w^2)^{1/2}u\right] \tag{2.16}$$

$$F_y = -\left[\mu\frac{\beta^2 v}{K} + \rho C\beta^2(u^2 + v^2 + w^2)^{1/2}v\right] \tag{2.17}$$

and

$$F_z = -\left[\mu\frac{\beta^2 w}{K} + \rho C\beta^2(u^2 + v^2 + w^2)^{1/2}w\right]. \tag{2.18}$$

The parameters C and K are the inertial and the permeability coefficients in Ergun's formulation, respectively [30], and are defined as:

$$C = \frac{1.75(1-\beta)}{\beta^2 d} \tag{2.19}$$

$$K = \frac{\beta^2 d^2}{(150(1-\beta)^2)}. \tag{2.20}$$

As noted, the momentum and energy conservation equations presented in the above equations assume laminar flow. Laminar flow formulation was adopted for the following reasons.

1. The flow in certain regions of the condenser is laminar.
2. The above equations can easily be modified to include turbulent effect, by adding μ_{turb} to μ and k_{turb} to k , where μ_{turb} and k_{turb} can be calculated using appropriate eddy diffusivity models.

3. In validating calculations, wherever the model is applied to open channels (i.e., when Navier-Stokes equations are addressed), only laminar flow conditions are considered, so that analytical solutions are available for comparison with the numerical model predictions.
4. As will be discussed later in Chapter 4, for porous media, and for typical condensers, the frictional and forces terms F_x, F_y, and F_z are dominant, and the effect of molecular and eddy viscosities is insignificant.

The last equation of the macroscopic system governing equation, Equation (2.6), represents the noncondensable gas continuity equation. The solution of this equation is essential in the design and analysis of steam condensers because it gives the local bulk concentration of the non-condensable gas. Once this concentration is determined in conjunction with pressure, temperature, velocity and density obtained from the solution of Equations (2.1)-(2.6), they will be used by the macroscopic system to determine the local heat flux and the local condensation rate per unit volume as will be shown later on in this chapter.

It has to be mentioned that Equations (2.1)-(2.6) are non linear coupled partial differential equations and no attempt should be allowed to uncouple Equation (2.6) from the system (2.1)-(2.5), because as the vapor condenses inside the condenser, the noncondensable partial density changes significantly.

It also has to be noted that, the Navier-Stokes equations can be obtained by setting β equal to one and δ equal to zero in equations (2.1)-(2.5).

2.4.2 Properties

It is noted also that Equations (2.1)-(2.6) are incomplete, and constitutive relations are needed for closure of these equations. Thus in order to close the system, relationships between the variables (ρ, p, e, T, and h) have to be established. Furthermore, the transport properties μ, and k have to be related to some thermodynamic variables.

Equations (2.1)-(2.6), when $\beta = 1$ and $\delta = 0$, have eight unknowns (ρ_g, ρ_v, u, v, w, p, T, e) if (μ, k) are either constants, or are related to other thermodynamic properties. Thus, two more equations are needed to close the system. These are provided by equations of state. When a perfect gas with constant specific heats is assumed, the equation of state can be written as:

$$p = (\gamma - 1)\left(e - \frac{1}{2}(\rho u^2 + \rho v^2 + \rho w^2)\right) \tag{2.21}$$

and

$$T = \frac{1}{\rho c_v}\left(e - \frac{1}{2}(\rho u^2 + \rho v^2 + \rho w^2)\right). \tag{2.22}$$

The following relations are also applicable for perfect gases:

$$c_v = \frac{R}{(\gamma - 1)}, \quad \gamma = \frac{c_p}{c_v}, \quad \text{and} \quad c_p = \frac{\gamma R}{(\gamma - 1)} \tag{2.23}$$

where c_v is the specific heat at constant volume, R is the gas constant, γ is the specific heat ratio, and c_p is the specific heat at constant pressure.

Sutherland's formula for transport property μ, which is based on the predictions made by the kinetic theory of gases, may be written as [46]:

$$\frac{\mu}{\mu_0} = (\frac{T}{T_0})^{3/2}\frac{T_0 + C}{T + C} \tag{2.24}$$

where C is a constant that takes the values 110.6^0K for air and 861.1^0K for steam.

In the parametric calculations to be presented later, the gas reference viscosity $\mu_0 = .1716X10 \times 10^{-6}\frac{kg}{ms}$ is evaluated at a reference temperature $T_0 =$

$273.1^0 K$, whereas for steam $\mu_0 = .1706X10 \times 10^{-6} \frac{kg}{ms}$ is evaluated at $T_0 = 861.1^0 K$.

The Prandtl number, Pr, is assumed constant and equal to 0.72, from which other transport property, k, can be found from the relation

$$k = \frac{c_p}{Pr}\mu. \tag{2.25}$$

The mixture viscosity is evaluated using Wilke's formula [45].

$$\mu = \sum_{i=1}^{2} \frac{x_i \mu_i}{\sum_{i=1}^{2} x_i \Phi_{ij}} \tag{2.26}$$

where x is the percent by volume and

$$\Phi_{ij} = \frac{[1 + (\frac{\mu_i}{\mu_j})^{1/2} (\frac{M_j}{M_i})^{1/2}]^2}{\sqrt{8}[1 + \frac{M_i}{M_j}]^{1/2}}. \tag{2.27}$$

Other transport properties are found similarly. It should be emphasized that the aforementioned ideal gas assumptions, and the assumptions of constant properties, are made here in order to simplify the analysis and reduce the computational time. These assumptions can easily be discarded, and properties can be obtained from appropriate tables. these, however, will render the numerical solution of the developed model considerably more computational time consuming.

Thermodynamic properties of saturated water and steam, which are used in the microscopic calculations, were calculated using empirical curvefits [59], and [60]. These curvefits are summarized in Appendix A-1

2.4.3 Manipulation of Conservation Equations

It is convenient to combine Equations (2 1)-(2.6) into the following compact conservative form:

$$\frac{\partial(\beta\vec{U})}{\partial t}+\frac{\partial(\beta\vec{F}(\vec{U}))}{\partial x}+\frac{\partial(\beta\vec{G}(\vec{U}))}{\partial y}+\frac{\partial(\beta\vec{H}(\vec{U}))}{\partial z}=\frac{\partial(\beta\vec{V_1}(\vec{U},\vec{U_x}))}{\partial x}$$
$$+\frac{\partial(\beta\vec{V_2}(\vec{U},\vec{U_y}))}{\partial x}+\frac{\partial(\beta\vec{V_3}(\vec{U},\vec{U_z}))}{\partial x}+\frac{\partial(\beta\vec{W_1}(\vec{U},\vec{U_x}))}{\partial y}$$
$$+\frac{\partial(\beta\vec{W_2}(\vec{U},\vec{U_y}))}{\partial y}+\frac{\partial(\beta\vec{W_3}(\vec{U},\vec{U_z}))}{\partial y}+\frac{\partial(\beta\vec{E_1}(\vec{U},\vec{U_x}))}{\partial z}$$
$$+\frac{\partial(\beta\vec{E_2}(\vec{U},\vec{U_y}))}{\partial z}+\frac{\partial(\beta\vec{E_3}(\vec{U},\vec{U_z}))}{\partial z}+\vec{L}\delta+\vec{Q}\delta. \tag{2.28}$$

The above equation reduces to the ordinary Navier-Stokes equations form when $\beta = 1$ and $\delta = 0$.

In the above equations $\vec{U}$, $\vec{F}(\vec{U})$, $\vec{G}(\vec{U})$, $\vec{H}(\vec{U})$, $\vec{V_1}(\vec{U},\vec{U_x})$, $\vec{v_2}(\vec{U},\vec{U_y})$, $\vec{V_3}(\vec{U},\vec{U_z})$, $\vec{W_1}(\vec{U},\vec{U_x})$, $\vec{W_2}(\vec{U},\vec{U_y})$, $\vec{W_3}(\vec{U},\vec{U_z})$, $\vec{E_1}(\vec{U},\vec{U_x})$, $\vec{E_2}(\vec{U},\vec{U_y})$, $\vec{E_3}(\vec{U},\vec{U_z})$, $\vec{L}$, and $\vec{Q}$ vectors are given by

$$\vec{U}=\begin{bmatrix}\rho_v\\ \rho u\\ \rho v\\ \rho w\\ e\\ \rho_g\end{bmatrix} \tag{2.29}$$

$$\vec{F}(\vec{U})=\begin{bmatrix}\rho_v u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (e+p)u\\ \rho_g u\end{bmatrix} \tag{2.30}$$

$$\vec{G}(\vec{U})=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (e+p)v\\ \rho_g v\end{bmatrix} \tag{2.31}$$

$$\vec{H}(\vec{U}) = \begin{bmatrix} \rho w \\ \rho u w \\ \rho v w \\ \rho w^2 + p \\ (e+p)w \\ \rho_g w \end{bmatrix} \tag{2.32}$$

$$\vec{V_1}(\vec{U}, \vec{U_x}) = \begin{bmatrix} \beta \rho D \phi'_x \\ (\lambda + 2\mu) u_x \\ \mu v_x \\ \mu w_x \\ (\lambda + 2\mu) u u_x + \mu v v_x + \mu w w_x + k T_x \\ \beta \rho D \phi_x \end{bmatrix} \tag{2.33}$$

$$\vec{V_2}(\vec{U}, \vec{U_y}) = \begin{bmatrix} 0 \\ \lambda v_y \\ \mu u_y \\ 0 \\ \lambda \mu v_y + \mu v u_y \\ 0 \end{bmatrix} \tag{2.34}$$

$$\vec{V_3}(\vec{U}, \vec{U_z}) = \begin{bmatrix} 0 \\ \lambda w_z \\ 0 \\ \mu u_z \\ \lambda \mu w_z + \mu w u_z \\ 0 \end{bmatrix} \tag{2.35}$$

$$\vec{W_1}(\vec{U}, \vec{U_x}) = \begin{bmatrix} 0 \\ \mu v_x \\ \lambda u_x \\ 0 \\ \mu u v_x + \lambda v u_x \\ 0 \end{bmatrix} \tag{2.36}$$

$$\vec{W_2}(\vec{U}, \vec{U_y}) = \begin{bmatrix} \beta \rho D \phi'_y \\ \mu u_y \\ (\lambda + 2\mu) v_u \\ \mu w_y \\ \mu u u_y + (\lambda + 2\mu) v v_y + \mu w w_y + k T_y \\ \beta \rho D \phi_y \end{bmatrix} \tag{2.37}$$

$$\vec{W_3}(\vec{U},\vec{U_z}) = \begin{bmatrix} 0 \\ 0 \\ \lambda w_z \\ \mu v_z \\ \lambda v w_z + \mu w v_z \\ 0 \end{bmatrix} \tag{2.38}$$

$$\vec{E_1}(\vec{U},\vec{U_x}) = \begin{bmatrix} 0 \\ \mu w_x \\ 0 \\ \lambda u_x \\ \mu u w_x + \lambda w u_x \\ 0 \end{bmatrix} \tag{2.39}$$

$$\vec{E_2}(\vec{U},\vec{U_y}) = \begin{bmatrix} 0 \\ 0 \\ \mu w_y \\ \lambda v_y \\ \mu v w_y + \lambda w v_y \\ 0 \end{bmatrix} \tag{2.40}$$

$$\vec{E_3}(\vec{U},\vec{U_z}) = \begin{bmatrix} \beta\rho D\phi'_z \\ \mu u_z \\ \mu v_z \\ (\lambda + 2\mu) w_z \\ \mu u u_z + \mu v v_z + (\lambda + 2\mu) w w_z + k T_z \\ \beta\rho D\phi_z \end{bmatrix}. \tag{2.41}$$

For packed bed porous medium,

$$\vec{L} = - \begin{bmatrix} 0 \\ \mu\beta^2 \frac{u}{K} + \rho C\beta^3 (u^2 + v^2 + w^2)^{1/2} u \\ \mu\beta^2 \frac{v}{K} + \rho C\beta^3 (u^2 + v^2 + w^2)^{1/2} v \\ \mu\beta^2 \frac{w}{K} + \rho C\beta^3 (u^2 + v^2 + w^2)^{1/2} w \\ 0 \\ 0 \end{bmatrix} \tag{2.42}$$

For shell-and-tube porous medium

$$\vec{L} = -\begin{bmatrix} 0 \\ \beta\eta_x u(u^2+v^2+w^2)^{1/2} \\ \beta\eta_y v(u^2+v^2+w^2)^{1/2} \\ \beta\eta_z w(u^2+v^2+w^2)^{1/2} \\ 0 \\ 0 \end{bmatrix} \tag{2.43}$$

And finally

$$\vec{Q} = \begin{bmatrix} -\beta\dot{m} \\ -\beta\dot{m}u \\ -\beta\dot{m}v \\ -\beta\dot{m}w \\ -q''s \\ 0 \end{bmatrix} \tag{2.44}$$

2.5. Microscopic-Level Model

2.5.1 The Stagnant Film Model

The objective of the microscopic level model is to find $\dot{m}$ (or equivalently $\dot{m}''$), the condensation rate per unit volume, and q'', the local heat flux. Once these two parameters are evaluated, they can be substituted into the macroscopic system equations, rendering their solution possible.

As mentioned earlier, the stagnant film model [45] will be used in the microscopic system. This classical model assumes that the gas-side heat and mass transfer resistances are associated with a thin stagnant layer at the interface between the gas and the condensate.

The coupled heat and mass transfer rates at the liquid-gas interface, in general, can be written as [45]

$$\dot{h}_G(T_G - T_i) + \dot{m}''h_{fg} = q'' \tag{2.45}$$

where T_G, the bulk gas temperature is obtained from the macroscopic system, and T_i is the vapor-condensate interface temperature. The heat transfer between primary and secondary sides of the condenser can be represented as:

$$q'' = U(T_i - T_p) \tag{2.46}$$

where T_p is the bulk temperature of the primary system, and U is the overall heat transfer coefficient, excluding the secondary-gas-side thermal resistance.

The parameters $\dot{h}_G$ and $\dot{m}''$, according to the stagnant film model, are related according to

$$\dot{h} = \frac{-\dot{m}''c_P}{\exp\left(-\frac{\dot{m}''c_P}{h_G}\right) - 1}, \tag{2.47}$$

where $C - P$ is the specific heat of the vapor-noncondensable mixture, and,

$$\dot{m}'' = -K_G \ln\left(1 + \frac{m - m_i}{m_i - 1}\right) \tag{2.48}$$

where h_G and K_G are the gas side heat and mass transfer coefficients in the limit of zero mass transfer, respectively, and m is the vapor mass fraction in the bulk mixture as obtained from the macroscopic system equations according to

$$m = 1 - \phi \tag{2.49}$$

Also, m_i, the vapor mass fraction at the interphase, is related to the local vapor partial pressure, and from there to the interphase temperature, according to:

$$m_i = \frac{p_i}{p_i + \left(\frac{M_g}{M_v}\right)(p - p_i)} \tag{2.50}$$

$$p_i = p_{sat}(T_i) \tag{2.51}$$

where p_i is the vapor partial pressure at the interphase, and p is the bulk mixture pressure obtained from the macroscopic system. Quantities M_v and M_g are the molecular masses of the vapor and the noncondensable gas, respectively.

2.5.2 Heat and Mass Transfer Correlations

As mentioned earlier that, although the basic method for representing condensers as porous media is general in nature, the shell-and-tube condensers as well as the packed bed condensers will be specifically considered in this work. Since some of the parameters in the equations presented in the previous sections strongly depend on the condenser configuration, these parameters will be presented for the above mentioned condensers. For the shell-and tube configuration:

$$U = \left[\frac{1}{h_p(D_i/D_0)} + \frac{1}{(\frac{k}{D_0 - D_i})\frac{(D_0+D_i)}{2D_0}} + \frac{1}{h_c} \right]^{-1} \tag{2.52}$$

For the packed bed, the temperature profiles inside the solid packing material should be known. this, in principle, requires the solution of transient packing energy conservation equations. To simplify the analysis, however, it is assumed that the packing is made of identical spheres, and that the temperature at the center of the sphere is constant. Thus:

$$U = \left[\frac{1}{\frac{4k}{D_0}} + \frac{1}{h_c} \right]^{-1} \tag{2.53}$$

where k is the tube wall thermal conductivity in case of shell-and-tube and the solid particle thermal conductivity in case of packed bed, D_i is the inner tube diameter (for shell-and-tube), and D_0 is the outer diameters for both shell-and-tube and packed bed, and h_c is the tube-condensate film heat transfer coefficient, and is obtained from the following correlations [45]:

$$Nu = \left[\frac{Gr_c Pr_c}{33.6 N Ja} \right]^{1/4} = \frac{h_c D_o}{k_c} \quad \text{for shell-and-tube} \tag{2.54}$$

where

$$Gr_c = \frac{(\Delta\rho/\rho_c)gD_0^3}{\gamma^2}, \tag{2.55}$$

$$\Delta\rho = \rho_c - \rho_v \tag{2.56}$$

$$Pr_c = \frac{\mu_c c_{pc}}{k_c} \tag{2.57}$$

$$Ja = \frac{c_p c(T_{sat} - T_w)}{h_{fg}} \tag{2.58}$$

In the above equations the subscript c refers to the condensate and T_w represents the wall temperature. Equation (2.54) is also used here for packed beds, for simplicity.

Finally, h_p in Equation (2.52) is the primary side heat transfer coefficient and can be evaluated using the Dittus-Boelter turbulent flow correlation [45]:

$$Nu_p = 0.023Re_p^{0.8}Pr_p^{0.33}, \quad Pr > 0.5 \tag{2.59}$$

where Nu_p, Re_p and Pr_p are the Nusselt, Reynolds, and Prandtl numbers for the primary system, respectively.
The mass transfer coefficient, K_G in Equation (2.48), can be evaluated using the relation:

$$K_G = (\rho D_{12}/D_0)Nu_m \tag{2.60}$$

where ρ is the vapor-gas mixture density and is assumed to follow ideal gas relationship. The parameter D_{12} is the vapor-noncondensable binary diffusion coefficient. For air-water vapor, in SI units [45]:

$$D_{12} = 1.97 \times 10^{-5}\left(\frac{p_0}{p}\right)\left(\frac{T}{T_0}\right)^{1.685} \tag{2.61}$$

where $p_0 = 1$ atm, $T_0 = 256$K.

For forced convection over a cylinder (i.e., shell-and-tube), using analogy between heat and mass transfer, Nu_m is found from [45]:

$$\frac{K_G D_0}{\rho D_{12}} = Nu_m = 0.3 + \frac{0.62 Re^{0.5} Sc^{0.33}}{[1. + (0.4/Sc)^{0.67}]^{0.25}}, \quad ReSc > 0.2, \quad Re < 10,000 \tag{2.62}$$

$$Nu_m = \left\{0.3 + \frac{0.62 Re^{0.5} Sc^{0.33}}{[1 + (0.4/Sc)^{0.67}]^{0.25}}\right\} \cdot \left\{1 + \left(\frac{Re}{282,000}\right)^{5/8}\right\}^{4/5}, \qquad Re > 10,000. \tag{2.63}$$

Likewise flow across a sphere (i.e., packed bed) [45]

$$\left.\begin{aligned} Nu_m &= 2. + 0.3 Re^{0.6} Sc^{0.33}, \quad && Sc \geq 0.6 \\ Nu_m &= 2. + 0.4 (Re_G Sc)^{0.5}, \quad && Sc < 0.6 \end{aligned}\right\} \quad Re < 150,000 \tag{2.64}$$

where

$$Re = \frac{\rho u D_0}{\mu}$$

$$Sc = \frac{\nu}{D_{12}}$$

Similarly, h_G in Equation (2.47) can be evaluated using

$$h_G = \left(\frac{K_G}{D_0}\right) Nu_h$$

and Nu_h for forced convection over a cylinder (i.e., shell-and-tube) [45]

$$Nu_h = 0.3 + \frac{0.62 Re^{0.5} Pr^{0.33}}{[1 + (0.4/Pr)^{0.67}]^{0.25}}, \qquad RePr > 0.2, \quad Re < 10,000 \tag{2.65}$$

$$Nu_h = \left\{0.3 + \frac{0.62 Re^{0.5} Pr^{0.33}}{[1 + (0.4/Pr)^{0.67}]^{0.25}}\right\} \cdot \left\{1 + \left(\frac{Re}{282,000}\right)^{5/8}\right\}^{4/5} \qquad Re > 10,000 \tag{2.66}$$

For flow across a sphere (i.e., packed bed) [45]

$$\left.\begin{aligned} Nu_h &= 2. + 0.3Re^{0.6}Pr^{0.33}, & Pr \geq 0.6 \\ Nu_h &= 2. + 0.4(RePr)^{0.5}, & Pr < 0.6 \end{aligned}\right\} \quad Re < 150,000 \tag{2.67}$$

It has to be noted that since perfect gas relations are used in this research, one can not include the latent heat of condensation h_{fg} in Equation 2.44. This problem can be corrected by evaluating the energy associated with the condensation rate per unit fluid area. Thus q'' in Equation 2.44 becomes:

$$q'' = \gamma\epsilon\dot{m}'' \tag{2.68}$$

Where ϵ is the internal energy per unit mass.

CHAPTER 3

DISCRETIZATION OF THE GOVERNING

3.1. Introduction

The full Navier-Stokes equations, which were presented in the previous chapter with necessary modifications for porous media, consist of a set of highly nonlinear and coupled partial differential equations. In order to solve the full Navier-Stokes equations, a numerical procedure is needed. In the present chapter, the full three dimensional Navier-Stokes equations, along with the non-condensable mass conservation equation in a Cartesian coordinate system are solved using an implicit factored scheme.

Also in the present chapter, the implicit factored scheme (IFS) is modified to include the porous medium, and heat and mass transfer terms. Moreover, a novel method is presented to fully couple any number of mass conservation equations to the full Navier-Stokes equations. The derivation of this method will be presented at the end of this chapter.

3.2. General Remarks on Numerical Solution of Compressible Flow Equations

Unlike the case of incompressible flow, the compressible flow conservation equations include variable density and are coupled to temperature variations.

Although all fluids are compressible to some extent, the flow is said to be compressible, for most practical purposes, if the change in density is 5% or more. Compressible flow is classified by the ratio of the local velocities to the speed of sound, known as the Mach number:

$$M = \frac{V_p}{a} \tag{3.1}$$

where a is the local speed of sound of the flow, which, for an ideal gas, is given by:

$$a = \sqrt{\gamma R T} \tag{3.2}$$

where γ is the ratio of specific heats and R is the specific gas constant.

The flow is subsonic if the Mach number at every point in the flow is less than unity. This type of flow regime is characterized by continuously varying properties and smooth streamlines. When the local Mach number at some points of the flow field is less than unity and at other points is greater than unity the flow is said to be transonic. The flow is classified as supersonic when the local Mach number everywhere in the flow is greater than unity. The incompressible flow equations are subsets of the compressible ones and can be derived from the compressible equations when $M \rightarrow 0$. This limit, in fact, means that the speed of sound for incompressible flow is infinitely large. There are, in fact, drastic mathematical and physical differences between supersonic and subsonic flows.

There are significant differences between the numerical solutions of compressible and incompressible flow equations. In the case of incompressible flow, the continuity equation includes a constant density which does not link with the pressure, as it does in the case of compressible flow. In addition, in the case of incompressible flow the energy equation is not coupled to the continuity and momentum equations, and can be solved if the velocity field is established by the continuity and the momentum equations; this is due to the absence of the equations of state. Also, for the same reason the pressure appears in the momentum equations as an independent variable, and this calls for a special treatment of the pressure. The unsteady compressible flow equations are, in fact a hyperbolic-parabolic set, whereas, the unsteady incompressible flow equations are an elliptic-parabolic set of equations. As a result, different numerical schemes are required for each type of these equations. Approximate incompressible solutions can of course be obtained from compressible flow schemes when using very low Mach numbers. At low Mach numbers, however, the coupling of the energy with the continuity and momentum equations becomes very weak and the convergence to the accurate solution will be more difficult [47].

Explicit and implicit finite difference schemes are both available to solve compressible Navier-Stokes equations. The choice between explicit and implicit schemes, however, depends on many considerations. Explicit schemes, compared with implicit ones, are easy to implement, but they have stability limitations which make their implementation sometimes prohibitive for certain applications. On the other hand, implicit-schemes are harder to implement and require extensive mathematical work because the implicit terms involve complex matrix manipulations; this complexity is increased when implicit boundary conditions are implemented. What makes implicit schemes attractive is that their stability conditions are not as stringent as the explicit ones. In particular when steady state solutions are needed, implicit schemes are usually recommended because their time increments can be increased close to the stability limit and the steady state solution is thus reached faster.

Because of the complexity of the governing equations discussed in the previous chapter, which is due to the presence of the extra porous-media and condensation terms obtained from the microscopic system and the repeated iterations between the macroscopic and microscopic level calculations, and because of the absence of similar experience in the open literature, it was decided to use an efficient implicit compressible scheme, and improve it to include the above mentioned extra terms. The implicit factored scheme (IFS) [48] was selected for this purpose. The IFS for the compressible Navier-Stokes equations was developed in 1978 by Beam and Warming [48]. This scheme, however, belongs to the family of the ADI schemes developed earlier by Lindemuth and Kileen [50] and McDonald and Briley [51].

Thus, in the forthcoming subsection, a modified IFS scheme is developed and discussed [48]. This scheme is based on the alternating-direction-implicit (ADI) method [49]. The main advantage of this method is its ability to reduce the multidimensional system of equations down to a one dimensional system of equations. The introduction of the ADI method is the most significant efficiency achievement for the implicit schemes [48].

3.3. Development of the Modified IFS Scheme

The three-dimensional compressible conservation Equation (2.28) is rewritten here by replacing the vapor density ρ_v with the mixture density ρ, and leaving out the noncondensable conservation equation. This is done in order to reduce the number of equations to five, for which the mathematical operations leading to the scheme development are relatively straightforward. The coupling of the noncondensable conservation equation to this system will be discussed later in this chapter.

$$
\begin{aligned}
\frac{\partial(\beta\vec{U})}{\partial t} + \frac{\partial(\beta\vec{F}(\vec{U}))}{\partial x} + \frac{\partial(\beta\vec{G}(\vec{U}))}{\partial y} + \frac{\partial(\beta\vec{H}(\vec{U}))}{\partial z} &= \frac{\partial(\beta\vec{V_1}(\vec{U},\vec{U_x}))}{\partial x} \\
&+ \frac{\partial(\beta\vec{V_2}(\vec{U},\vec{U_y}))}{\partial x} + \frac{\partial(\beta\vec{V_3}(\vec{U},\vec{U_z}))}{\partial x} + \frac{\partial(\beta\vec{W_1}(\vec{U},\vec{U_x}))}{\partial y} \\
&+ \frac{\partial(\beta\vec{W_2}(\vec{U},\vec{U_y}))}{\partial y} + \frac{\partial(\beta\vec{W_3}(\vec{U},\vec{U_z}))}{\partial y} + \frac{\partial(\beta\vec{E_1}(\vec{U},\vec{U_x}))}{\partial z} \\
&+ \frac{\partial(\beta\vec{E_2}(\vec{U},\vec{U_y}))}{\partial z} + \frac{\partial(\beta\vec{E_3}(\vec{U},\vec{U_z}))}{\partial z} + \vec{L}\delta + \vec{Q}\delta
\end{aligned} \tag{3.3}
$$

Parameters in the above equation were discussed in the previous chapter. Beam and Warming [48] used the following implicit time marching scheme

$$
\begin{aligned}
\Delta\vec{U}^n &= \frac{\theta\Delta t}{1+\tau}\frac{\partial\Delta\vec{U}^n}{\partial t} + \frac{\Delta t}{1+\tau}\frac{\partial\vec{U}^n}{\partial t} + \frac{\tau}{1+\tau}\Delta\vec{U}^{n-1} \\
&+ O\left(\left(\theta - \frac{1}{2} - \tau\right)(\Delta t)^2) + (\Delta t)^3\right).
\end{aligned} \tag{3.4}
$$

In the above scheme $\Delta\vec{U}^n = \vec{U}^{n+1} - \vec{U}^n$, and proper choice of the parameters θ and τ leads to many explicit and implicit schemes as summarized in Table 3.1. The three-point-backward implicit scheme, for which $\tau = 1$ and $\theta = \frac{1}{2}$, is selected for implementation in this thesis.

Table 3.1.Some Available Schemes for Different τ and θ.

τ	θ	Scheme	Truncation Error
0	1	Euler, implicit	$O((\Delta t)^2)$
0	0	Euler, explicit	$O((\Delta t)^2)$
0	$\frac{1}{2}$	Trapezoidal, implicit	$O((\Delta t)^3)$
$-\frac{1}{2}$	0	Leapfrog, explicit	$O((\Delta t)^3)$
1	$\frac{1}{2}$	3-point-backward, implicit	$O((\Delta t)^3)$

After expanding the time derivatives, and some simple algebraic manipulations, Equation (3.3) becomes;

$$\frac{\partial \vec{U}}{\partial t} = -\frac{1}{\beta}\frac{\partial(\beta \vec{F})}{\partial x} - \frac{1}{\beta}\frac{\partial(\beta \vec{G})}{\partial y} - \frac{1}{\beta}\frac{\partial(\beta \vec{H})}{\partial z} + \frac{1}{\beta}\frac{\partial(\beta \vec{V_1})}{\partial x}$$
$$+ \frac{1}{\beta}\frac{\partial(\beta \vec{V_2})}{\partial x} + \frac{1}{\beta}\frac{\partial(\beta \vec{V_3})}{\partial x} + \frac{1}{\beta}\frac{\partial(\beta \vec{W_1})}{\partial y} + \frac{1}{\beta}\frac{\partial(\beta \vec{W_2})}{\partial y}$$
$$+ \frac{1}{\beta}\frac{\partial(\beta \vec{W_3})}{\partial y} + \frac{1}{\beta}\frac{\partial(\beta \vec{E_1})}{\partial z} + \frac{1}{\beta}\frac{\partial(\beta \vec{E_2})}{\partial z} + \frac{1}{\beta}\frac{\partial(\beta \vec{E_3})}{\partial z}$$
$$+ \frac{1}{\beta}\vec{L}\delta + \frac{1}{\beta}\vec{Q}\delta - \frac{\vec{U}}{\beta}\frac{\partial \beta}{\partial t}. \tag{3.5}$$

Combining Equations (3.4) and (3.5) results in:

$$\Delta \vec{U}^{n+1} = \frac{\theta \Delta t}{1+\tau}\left\{\left[\frac{1}{\beta}\left(-\frac{\partial \Delta(\beta \vec{F})}{\partial x} - \frac{\partial \Delta(\beta \vec{G})}{\partial y} - \frac{\partial \Delta(\beta \vec{H})}{\partial z} + \frac{\partial \Delta(\beta \vec{V_1})}{\partial x}\right.\right.\right.$$
$$+ \frac{\partial \Delta(\beta \vec{V_2})}{\partial x} + \frac{\partial \Delta(\beta \vec{V_3})}{\partial x} + \frac{\partial \Delta(\beta \vec{W_1})}{\partial y} + \frac{\partial \Delta(\beta \vec{W_2})}{\partial y} + \frac{\partial \Delta(\beta \vec{W_3})}{\partial y}$$
$$\left.\left.\left.+ \frac{\partial \Delta(\beta \vec{E_1})}{\partial z} + \frac{\partial \Delta(\beta \vec{E_2})}{\partial z} + \frac{\partial \Delta(\beta \vec{E_3})}{\partial z} + \Delta \vec{L}\delta + \Delta \vec{Q}\delta - \Delta\left(\vec{U}\frac{\partial \beta}{\partial t}\right)\right)\right]^n\right\}$$
$$+ \frac{\Delta t}{1+\tau}\left\{\frac{1}{\beta}\left[-\frac{\partial(\beta \vec{F})}{\partial x} - \frac{\partial(\beta \vec{G})}{\partial y} - \frac{\partial(\beta \vec{H})}{\partial z} + \frac{\partial(\beta \vec{V_1})}{\partial x}\right.\right.$$
$$+ \frac{\partial(\beta \vec{V_2})}{\partial x} + \frac{\partial(\beta \vec{V_3})}{\partial x} + \frac{\partial(\beta \vec{W_1})}{\partial y} + \frac{\partial(\beta \vec{W_2})}{\partial y} + \frac{\partial(\beta \vec{W_3})}{\partial y}$$
$$\left.\left.+ \frac{\partial(\beta \vec{E_1})}{\partial z} + \frac{\partial(\beta \vec{E_2})}{\partial z} + \frac{\partial(\beta \vec{E_3})}{\partial z} + \vec{L}\delta + \vec{Q}\delta\right]\right\}^n$$
$$+ \frac{\tau}{1+\tau}\Delta \vec{U}^{n-1} + O\left[\left(\theta - \frac{1}{2} - \tau\right)(\Delta t)^2 + (\Delta t)^3\right]. \tag{3.6}$$

Dropping the error terms and assuming β is a constant, algebraic manipulation of Equation (3.6) leads to:

$$\Delta \vec{U}^{n-1} = \frac{\theta \Delta t}{1+\tau}\left\{\frac{1}{\beta}\left[\frac{\partial}{\partial x}(-\Delta \vec{F}'^n + \Delta \vec{V_1}'^n + \Delta \vec{V_2}'^n + \Delta \vec{V_3}'^n)\right.\right.$$

$$
\begin{aligned}
&+ \frac{\partial}{\partial y}(-\Delta \vec{G}'^{n} + \Delta \vec{W_1}'^{n} + \Delta \vec{W_2}'^{n} + \Delta \vec{W_3}'^{n}) \\
&+ \frac{\partial}{\partial z}(-\Delta \vec{H}'^{n} + \Delta \vec{E_1}'^{n} + \Delta \vec{E_2}'^{n} + \Delta \vec{E_3}'^{n})\Big\} \\
&+ \frac{\Delta t}{1+\tau}\Big\{\frac{1}{\beta}\left(\frac{\partial}{\partial x}(-\vec{F}'^{n} + \vec{V_1}'^{n} + \vec{V_2}'^{n} + \vec{V_3}'^{n})\right) \\
&+ \frac{\partial}{\partial y}(-\vec{G}'^{n} + \vec{W_1}'^{n} + \vec{W_2}'^{n} + \vec{W_3}'^{n}) \\
&+ \frac{\partial}{\partial z}(-\vec{H}'^{n} + \vec{E_1}'^{n} + \vec{E_2}'^{n} + \vec{E_3}'^{n})\Big\} + \frac{\tau}{1+\tau}\Delta \vec{U}^{n-1} \\
&+ \frac{\theta \Delta t}{1+\tau}\left(\frac{1}{\beta}\Delta(L^n\delta + Q^n\delta)\right) + \frac{\Delta t}{1+\tau}\left(\frac{1}{\beta}(\vec{L}^n\delta + \vec{Q}^n\delta)\right)
\end{aligned}
\tag{3.7}
$$

where $\vec{F}' = \beta\vec{F}$, $\vec{V_1}' = \beta\vec{V_1}$, $\vec{V_2}' = \beta\vec{V_2}$, $\vec{V_3}' = \beta\vec{V_3}$, $\vec{G}' = \beta\vec{G}$, $\vec{W_1}' = \beta\vec{W_1}$, $\vec{W_2}' = \beta\vec{W_2}$, $\vec{W_3}' = \beta\vec{W_3}$,

$\vec{H}' = \beta\vec{H}$, $\vec{E_1}' = \beta\vec{E_1}$, $\vec{E_2}' = \beta\vec{E_2}$, $\vec{E_3}' = \beta\vec{E_3}$.

The flux vector increments $(\Delta\vec{F}', \Delta\vec{V_1}', \Delta\vec{G}', \Delta\vec{W_2}', \Delta\vec{H}', \Delta\vec{E_3}')$ are non-linear functions of the conserved variables $\vec{U}$ and can be linearized with respect to the conserved variable $\vec{U}$ using the Taylor series expansion method. As an example:

$$
\vec{F}'^{n+1} = \vec{F}'^{n} + \left(\frac{\partial \vec{F}'}{\partial \vec{U}}\right)^n \Delta\vec{U}^n + O((\Delta t)^2) \tag{3.8}
$$

This results in:

$$
\Delta\vec{F}'^{n} = \underline{A}^n \Delta\vec{U}^n + O((\Delta t)^2) \tag{3.9}
$$

where

$$
\Delta\vec{F}'^{n} = \vec{F}'^{n+1} - \vec{F}'^{n} \tag{3.10}
$$

Also one can write:

$$\Delta \vec{V}_1{}'^{n} = \left(\frac{\partial \vec{V}_1{}'}{\partial \vec{U}}\right)^n \Delta \vec{U}^n + \left(\frac{\partial \vec{V}_1{}'}{\partial \vec{U}_x}\right)^n \Delta \vec{U}_x^n + O((\Delta t)^2)$$
$$= \underline{P}_1^n \Delta \vec{U}^n + \underline{R}_1^n \Delta \vec{U}_x + O((\Delta t)^2)$$
$$= \left(\underline{P}_1 - \underline{R}_{1x}\right)^n \Delta \vec{U}^n + \frac{\partial}{\partial x}(\underline{R}_1 \Delta \vec{U})^n + O((\Delta t)^2). \tag{3.11}$$

Similarly

$$\Delta \vec{G}'^{n} = \underline{B}^n \Delta \vec{U}^n + O((\Delta t)^2) \tag{3.12}$$

$$\Delta \vec{W}_2{}'^{n} = (\underline{P}_2 - \underline{R}_{2y})^n \Delta \vec{U}^n + \frac{\partial}{\partial y}(\underline{R}_2 \Delta \vec{U})^n + O((\Delta t)^2) \tag{3.13}$$

$$\Delta \vec{H}'^{n} = \vec{C}^n \Delta \vec{U}^n + O((\Delta t)^2) \tag{3.14}$$

and

$$\Delta \vec{E}_3{}'^{n} = (\underline{P}_3 - \underline{R}_{3z})^n \Delta \vec{U}^n + \frac{\partial}{\partial z}(\underline{R}_3 \Delta \vec{U})^n + O((\Delta t)^2) \tag{3.15}$$

The Jacobians in the above derivations are defined as follows:

$$\underline{A}^n = \left(\frac{\partial \vec{F}'}{\partial \vec{U}}\right)^n, \qquad \underline{B}^n = \left(\frac{\partial \vec{G}'}{\partial \vec{U}}\right)^n, \qquad \underline{C}^n = \left(\frac{\partial \vec{H}'}{\partial \vec{U}}\right)^n,$$

$$\underline{P}_1^n = \left(\frac{\partial \vec{V}_1{}'}{\partial \vec{U}}\right)^n, \qquad \underline{P}_2^n = \left(\frac{\partial \vec{W}_2{}'}{\partial \vec{U}}\right)^n, \qquad \underline{P}_3^n = \left(\frac{\partial \vec{E}_3{}'}{\partial \vec{U}}\right)^n,$$

$$\underline{R}_1^n = \left(\frac{\partial \vec{V}_1{}'}{\partial \vec{U}_x}\right)^n, \qquad \underline{R}_2^n = \left(\frac{\partial \vec{W}_2{}'}{\partial \vec{U}_y}\right)^n, \qquad \underline{R}_3^n = \left(\frac{\partial \vec{E}_3{}'}{\partial \vec{U}_z}\right)^n,$$

$$\underline{R}_{1x} = \frac{\partial \underline{R}_1}{\partial x}, \qquad \underline{R}_{2y} = \frac{\partial \underline{R}_2}{\partial y}, \qquad \underline{R}_{3z} = \frac{\partial \underline{R}_3}{\partial z}.$$

Note that the remaining flux vector increments ($\Delta \vec{V}_2{}'$, $\Delta \vec{V}_3{}'$, $\Delta \vec{W}_1{}'$, $\Delta \vec{W}_3{}'$, $\Delta \vec{E}_1{}'$, $\Delta E_2'$) involve cross derivative, and are to be treated explicitly. This approximation, however, does not affect the stability of the numerical schemes [48].

Also the porous increment term ΔL^n and the condensation increment term ΔQ^n can be written as:

$$\Delta \vec{L}^n = \left(\frac{\partial \vec{L}}{\partial \vec{U}}\right)^n \Delta \vec{U}^n + O((\Delta t)^2) = \underline{S}^n \Delta \vec{U}^n + O((\Delta t)^2) \qquad (3.16)$$

$$\Delta \vec{Q}^n = \left(\frac{\partial \vec{Q}}{\partial \vec{U}}\right)^n \Delta \vec{U}^n + O((\Delta t)^2) = \underline{T}^n \Delta \vec{U}^n + O((\Delta t)^2) \qquad (3.17)$$

where $\underline{S}^n$ and $\underline{T}^n$ are the Jacobian matrices $\left(\frac{\partial \vec{L}}{\partial \vec{U}}\right)^n$ and $\left(\frac{\partial \vec{Q}}{\partial \vec{U}}\right)^n$, respectively.

It has been found in this study that it is very important to solve $\Delta \vec{L}$ implicitly otherwise there will be stability problems. Analytical solutions of the Jacobian matrices $\underline{S}^n$ for packed bed and shell-and-tube porous media are presented in this chapter. On the other hand, it is very difficult to find an analytical solution of the Jacobian matrix $\underline{T}^n$. This Jacobian, however, can be solved numerically or can be solved explicitly the same way the cross derivative terms are treated. Moreover, it has been found also in this study that this term can be solved explicitly without affecting the stability of the system and can thus be replaced in Equation (3.7) with $\Delta \vec{Q}^{n-1}$

Substituting Equations (3.9), (3.10), (3.11), (3.12), (3.13), (3.14), (3.15), and (3.16) into Equation (3.7), the result may be written as:

$$\Bigg\{ I + \frac{\theta \Delta t}{\beta(1+\tau)} \Bigg[\frac{\partial}{\partial x}(\underline{A} - \underline{P}_1 \underline{+} R_{1x})^n - \frac{\partial^2 (\underline{R}_1)^n}{\partial x^2} + \frac{\partial}{\partial y}(\underline{B} - \underline{P}_2 \underline{+} R_{2y})^n$$

$$- \frac{\partial^2 (\underline{R}_2)^n}{\partial y^2} + \frac{\partial}{\partial y}(\underline{C} - \underline{P}_3 \underline{+} R_{3z})^n - \frac{\partial^2 (\underline{R}_3)^n}{\partial z^2} - \underline{S}^n \delta \Bigg] \Bigg\} \Delta \vec{U}^n$$

$$= \frac{\theta \Delta t}{\beta(1+\tau)} \Bigg[\frac{\partial}{\partial x}(\Delta \vec{V}_2{}' + \Delta \vec{V}_3{}')^{n-1} + \frac{\partial}{\partial y}(\Delta \vec{W}_1{}' + \Delta \vec{W}_3{}')^{n-1}$$

$$+ \frac{\partial}{\partial z}(\Delta \vec{E}_1' + \Delta \vec{E}_3{}')^{n-1} + (\Delta \vec{Q})^{n-1} \delta \Bigg]$$

$$+ \frac{\Delta t}{\beta(1+\tau)} \Bigg[\frac{\partial}{\partial x}(-\vec{F}' + \vec{V}_1{}' + \vec{V}_2{}' + \vec{V}_3{}')^n + \frac{\partial}{\partial y}(-\vec{G} + \vec{W}_1{}' + \vec{W}_2{}' + \vec{W}_3{}')^n$$

$$+\frac{\partial}{\partial z}(-\vec{H}' + \vec{E_1}' + \vec{E_2}' + \vec{E_3}')^n + \vec{L}^n\delta + \vec{Q}^n\delta\Big] + \frac{\tau}{1+\tau}\Delta\vec{U}^{n-1} \tag{3.19}$$

The solution of the above equation is very expensive computationally because the produced matrix that needs to be inverted at every time step is very large and involves all the three dimensions (x, y, z). Moreover, in the case of three dimensions there are five equations to be solved at every computational node and this makes the size of the matrix $(N_x \times N_y \times N_z \times 5)^2$, where N_x, N_y, and N_z are the number of the interval grid points on the x, y, and z directions, respectively. However, Equation (3.19) can be factorized to give the following approximate form

$$\left\{\underline{I} + \frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial x}(\underline{A} - \underline{P}_1 \underline{\pm} R_{1x})^n - \frac{\partial^2(\underline{R}_1)^n}{\partial x^2}\right]\right\}$$
$$\cdot\left\{\underline{I} + \frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial y}(\underline{B} - \underline{P}_2 \underline{\pm} R_{2y})^n - \frac{\partial(\underline{R}_2)^n}{\partial y^2}\right]\right\}$$
$$\cdot\left\{\underline{I} + \frac{\theta\Delta t}{\beta(1+\tau}\left[\frac{\partial}{\partial z}(\underline{C} - \underline{P}_3 \underline{\pm} R_{3z})^n - \frac{\partial(\underline{R}_3)^n}{\partial z^2}\right]\right\}\Delta\vec{U}^n$$
$$-\frac{\theta\Delta t}{\beta(1+\tau)}\underline{S}^n\Delta\vec{U}^n = RHSofEquation(3.19). \tag{3.20}$$

Comparing (3.20) and (3.19) shows that (3.20) contains the following additional terms on the LHS

$$\left(\frac{\theta\Delta t}{\beta(1+\tau)}\right)^2\left(\frac{\partial}{\partial x}(\underline{A} - \underline{P}_1 + \underline{R}_{1x})^n - \frac{\partial^2(\underline{R}_1)^n}{\partial x^2}\right)$$
$$\cdot\left(\frac{\partial}{\partial y}(\underline{B} - \underline{P}_2 + \underline{R}_{2y})^n - \frac{\partial^2(\underline{R}_2)^n}{\partial y^2} - \mathrm{L}^n\delta\right)$$
$$+\left(\frac{\theta\Delta t}{\beta(1+\tau)}\right)^2\left(\frac{\partial}{\partial x}(\underline{A} - \underline{P}_1 + \underline{R}_{1x})^n - \frac{\partial^2(yR_1)^n}{\partial x^2}\right)$$
$$\cdot\left(\frac{\partial}{\partial z}(C - P_3 + R_{3z})^n - \frac{\partial^2(R_3)^n}{\partial z^2} - \mathrm{L}^n\delta\right)$$

$$+\left(\frac{\theta\Delta t}{\beta(1+\tau)}\right)^2\left(\frac{\partial}{\partial y}(\underline{B}-\underline{P}_2+\underline{R}_{2y})^n-\frac{\partial^2(\underline{R}_2)^n}{\partial y^2}\right)$$
$$\cdot\left(\frac{\partial}{\partial z}(\underline{C}-\underline{P}_3+\underline{R}_{3z})^n-\frac{\partial^2(\underline{R}_3)^n}{\partial z^2}-\mathrm{L}^n\delta\right)$$
$$+\left(\frac{\theta\Delta t}{\beta(1+\tau)}\right)^3\left(\frac{\partial}{\partial x}(\underline{A}-\underline{P}_1+\underline{R}_{1x})^n-\frac{\partial^2(\underline{R}_1)^n}{\partial x^2}\right)$$
$$\cdot\left(\frac{\partial}{\partial y}(\beta-\underline{P}_2+\underline{R}_{2y})^n-\frac{\partial^2(\underline{R}_2)^n}{\partial y^2}\right)$$
$$\cdot\left(\frac{\partial}{\partial z}(\underline{C}-\underline{P}_3+\underline{R}_{3z})^n-\frac{\partial^2(\underline{R}_3)^n}{\partial z^2}\right). \tag{3.21}$$

It is obvious that these additional terms are of the order $(\Delta t)^2$ and have no effect on the accuracy of the solution because Equation (3.19) is also of order $(\Delta t)^2$.

Equation (3.20) can be implemented as a three-stage scheme at each time step

$$\left\{I+\frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial x}(\underline{A}-\underline{P}_1+\underline{R}_{1x})^n-\frac{\partial^2(\underline{R}_1)^n}{\partial x^2}-\underline{S}^n\delta\right]\right\}\Delta\vec{U}^*$$
$$=\frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial x}(\Delta\vec{V}_2'+\Delta\vec{V}_3')^{n-1}+\frac{\partial}{\partial y}(\Delta\vec{W}_1'+\Delta\vec{W}_3')^{n-1}\right.$$
$$\left.+\frac{\partial}{\partial z}(\Delta\vec{E}_1'+\Delta\vec{E}_2')^{n-1}+(\Delta\vec{Q})^{n-1}\delta\right]$$
$$+\frac{\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial x}(-\vec{F}'+\vec{V}_1'+\vec{V}_2'+\vec{V}_3')^n\right.$$
$$\left.+\frac{\partial}{\partial y}(-\vec{G}'+\vec{W}_1'+\vec{W}_2'+\vec{W}_3')^n+\frac{\partial}{\partial z}(-\vec{H}'+\vec{E}_1'+\vec{E}_2'+\vec{E}_3')^n+\vec{L}^n\delta+\vec{Q}^n\delta\right]$$
$$+\frac{\tau}{(1+\tau)}\Delta\vec{U}^{n-1} \tag{3.22}$$

$$\left\{I+\frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial y}(\underline{B}-\underline{P}_2+\underline{R}_{2y})^n-\frac{\partial^2(\underline{R}_2)^n}{\partial y^2}\right]\right\}\Delta\vec{U}^{**}=\Delta\vec{U}^* \tag{3.23}$$

$$\left\{ I + \frac{\theta \Delta t}{\beta(1+\tau)} \left[\frac{\partial}{\partial z} (\underline{C} - \underline{P}_3 + \underline{R}_{3z})^n - \frac{\partial^2 (\underline{R}_3)^n}{\partial z} \right] \right\} \Delta \vec{U}^n = \Delta \vec{U}^{**} \tag{3.24}$$

$$\vec{U}^{n+1} = \vec{U}^n + \Delta \vec{U}^n. \tag{3.25}$$

It can be seen from Equations (3.22), (3.23), and (3.24) that the size of the matrix to be inverted in each direction has decreased to $5N_x^2, 5N_y^2$, and $5N_z^2$ in the x, y , and z directions, respectively. The procedure to solve the above equations, however, is to solve first Equation (3.22) by sweeping in the x-direction. Once the x-direction is covered totally and the increment $\Delta\vec{U}^*$ is evaluated, equation (3.23) is solved by sweeping in the y-direction; the same procedure is subsequently done for the z-direction. The same procedure is repeated again until the steady state solution is reached.

It has to be mentioned once again that in this study the term $\frac{\partial \beta}{\partial t}$ is neglected because β is assumed to be a function of space only. However, when time dependent two-phase flow analysis is required with the condensate porosity varying with time, this term can easily be considered. Also, β can be assumed to be a function of time when the particles in the domain of interest are in motion, or undergo volume change.

When second order central differences are implemented on the implicit terms of Equations (3.22), (3.23), and (3.24), the produced system is a block tridiagonal system which can be solved using an economical way such as the block tridiagonal Thomas algorithm.

3.4. Artificial Dissipation

The addition of artificial dissipation terms to central difference schemes is very important for the stability of central differencing numerical schemes. They are added to eliminate the high frequencies generated by odd-even uncoupling grid points typical of central differencing and nonlinear effects such as shocks. The Navier-Stokes equations provide an inherent dissipation due to the presence of viscous terms in them but this dissipation, unfortunately, is not enough to ensure stability at high Reynolds number.

In order to extend the stability range of the used scheme, two numerical dissipation terms are added. A second order implicit dissipation $\vec{D}_i$ [52] is implemented according to

$$\vec{D}_i = -\varepsilon_i(\Delta x)^2 \frac{\partial^2 \Delta \vec{U}}{\partial x^2}. \tag{3.26}$$

A fourth-order explicit dissipative term [48] is also implemented:

$$\vec{D}_e = -\varepsilon_e(\Delta x)^4 \frac{\partial^4 \vec{U}}{\partial x^4} \tag{3.27}$$

Similar dissipation terms apply to the other coordinates.

According to a linear Von Neumann stability analysis, ε_e and ε_i should be in the following range [52]:

$$0 \leq \varepsilon_e \leq \frac{1}{8} \qquad \text{when } \tau = 0 \tag{3.28}$$

$$0 \leq \varepsilon_e \leq \frac{1+2\tau}{8} \qquad \text{when } \tau \neq 0 \tag{3.29}$$

The stability limit when the implicit dissipation term is included is:

$$0 \leq 8\varepsilon_e \leq 1 + 4\varepsilon_i \tag{3.30}$$

After the insertion of the dissipation terms, Equations (3.22), (3.23), and (3.24) can be written as

$$\left\{ \underline{I} + \frac{\theta \Delta t}{\beta(1+\tau)} \left[\frac{\partial}{\partial x}(\underline{A} - \underline{P}_1 + \underline{R}_{1x})^n - \frac{\partial^2 (\underline{R}_1)^n}{\partial x^2} - \underline{S}^n \delta - \varepsilon_i (\Delta x)^2 \frac{\partial^2}{\partial x^2} \right] \right\} \Delta \vec{U}^*$$
$$= RHS(3.22) - \varepsilon_e (\Delta x)^4 \frac{\partial^4 \vec{U}^n}{\partial x^4} \tag{3.31}$$

$$\left\{\underline{I} + \frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial y}(\underline{B} - \underline{P}_2 \pm R_{2y})^n - \frac{\partial^2(\underline{R}_2)^n}{\partial y^2} - \varepsilon_i(\Delta y)^2\frac{\partial^2}{\partial y^2}\right]\right\}\Delta\vec{U}^{**}$$

$$= \Delta U^* - \varepsilon_e(\Delta y)^4\frac{\partial^4(\vec{U}^n + \Delta\vec{U}^*)}{\partial y^4} \tag{3.32}$$

$$\left\{I + \frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial z}(\underline{C} - \underline{P}_3 + \underline{R}_{3z})^n - \frac{\partial^2(\underline{R}_3)^n}{\partial z^2} - \varepsilon_i(\Delta z)^2\frac{\partial^2}{\partial z^2}\right]\right\}\Delta\vec{U}^n$$

$$= \Delta\vec{U}^{**} - \varepsilon_e(\Delta z)^4\frac{\partial^4}{\partial z^4}(\vec{U}^n + \Delta\vec{U}^{**}). \tag{3.33}$$

The Jacobian matrices in the above equations, when assuming perfect gas relations (see section 2.4.2); become:

$$\underline{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ (\gamma-3)u^2 + \frac{(\gamma-1)}{2} \times (v^2+w^2) & (3-\gamma)u & (1-\gamma)v & (1-\gamma)w & (\gamma-1) \\ -uv & -v & u & 0 & 0 \\ -uw & w & 0 & u & 0 \\ -\gamma e u + (\gamma-1) \cdot u(u^2+v^2+w^2) & \frac{e\gamma}{\rho} + \frac{(1-\gamma)}{2} \cdot (3u^2+v^2+w^2) & (1-\gamma)uv & (1-\gamma)uw & \gamma u \end{bmatrix} \tag{3.34}$$

$$\underline{B} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ -uv & v & u & 0 & 0 \\ (\gamma-3)v^2 + \frac{(\gamma-1)}{2} \cdot (u^2+w^2) & (1-\gamma)u & (3-\gamma)v & (1-\gamma)w & (\gamma-1) \\ -vw & 0 & w & v & 0 \\ -\frac{\gamma e v}{\rho} + (\gamma-1)v \cdot (u^2+v^2+w^2) & (1-\gamma)uv & \frac{\gamma e}{\rho} + \frac{(1-\gamma)}{2} \cdot (3v^2+u^2+w^2) & (1-\gamma)vw & \gamma v \end{bmatrix} \tag{3.35}$$

$$\underline{C} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ -uw & w & 0 & u & 0 \\ -vw & 0 & w & v & 0 \\ (\gamma-3)w^2 + \frac{(\gamma-1)}{2} \cdot (u^2+v^2) & (1-\gamma)u & (1-\gamma)v & (3-\gamma) & (\gamma-1) \\ \frac{\gamma e w}{\rho} + (\gamma-1)w\,(u^2+v^2+w^2) & (1-\gamma)uw & (1-\gamma)vw & \frac{\gamma e}{\rho} + \frac{(1-\gamma)}{2} \cdot (3w^2+u^2+v^2) & \gamma w \end{bmatrix} \tag{3.36}$$

$$\underline{R}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \frac{(\lambda+2\mu)u}{\rho} & \frac{(\lambda+2\mu)}{\rho} & 0 & 0 & 0 \\ -\frac{\mu v}{\rho} & 0 & \frac{\mu}{\rho} & 0 & 0 \\ -\frac{\mu w}{\rho} & 0 & 0 & \frac{\mu}{\rho} & 0 \\ -\left(\lambda+2\mu-\frac{k}{C_v}\right)\frac{u^2}{\rho} - \frac{1}{\rho}\left(\mu-\frac{k}{C_v}\right)(v^2+w^2) - \frac{k}{C_v}\frac{e}{\rho^2} & \left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{u}{\rho} & \left(\mu-\frac{k}{C_v}\right)\frac{v}{\rho} & \left(\mu-\frac{k}{C_v}\right)\frac{w}{\rho} & \frac{k}{\rho C_v} \end{bmatrix} \tag{3.37}$$

$$\underline{R}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -\frac{\mu u}{\rho} & \frac{\mu}{\rho} & 0 & 0 & 0 \\ -(\lambda+2\mu)\frac{v}{\rho} & 0 & \frac{(\lambda+2\mu)}{\rho} & 0 & 0 \\ -\mu\frac{w}{\rho} & 0 & 0 & \frac{\mu}{\rho} & 0 \\ -\left(\lambda+2\mu-\frac{k}{C_v}\right)\frac{v^2}{\rho} - \left(\mu-\frac{k}{C_v}\right)\frac{(u^2+v^2)}{\rho} - \frac{k}{C_v}\frac{e}{\rho^2} & \left(\mu-\frac{k}{C_v}\right)\frac{u}{\rho} & \left(\lambda+2\mu-\frac{k}{C_v}\right)\frac{v}{\rho} & \left(\mu-\frac{k}{C_v}\right)\frac{w}{\rho} & \frac{k}{\rho C_v} \end{bmatrix} \tag{3.38}$$

$$
\underline{R}_3 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-\frac{\mu u}{\rho} & \frac{\mu}{\rho} & 0 & 0 & 0 \\
-\frac{\mu v}{\rho} & 0 & \frac{\mu}{\rho} & 0 & 0 \\
-(\lambda + 2\mu)\frac{w}{\rho} & 0 & 0 & \frac{(\lambda+2\mu)}{\rho} & 0 \\
\begin{array}{c} -\left(\lambda + 2\mu - \frac{k}{C_v}\right)\frac{w^2}{\rho} \\ -\left(\mu - \frac{k}{C_v}\right)\frac{(u^2+v^2)}{\rho} \\ -\frac{k}{C_v}\frac{e}{\rho} \end{array} & \left(\mu - \frac{k}{C_v}\right)\frac{u}{\rho} & \left(\mu - \frac{k}{C_v}\right)\frac{v}{\rho} & \left(\lambda + 2\mu - \frac{k}{C_v}\right)\frac{w}{\rho} & \frac{k}{\rho C_v}
\end{bmatrix} \tag{3.39}
$$

$$
-\underline{P}_1 + \underline{R}_{1x} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-(\lambda + 2\mu)_x\frac{u}{\rho} & \frac{(\lambda+2\mu)_x}{\rho} & 0 & 0 & 0 \\
-\mu_x\frac{v}{\rho} & 0 & \frac{\mu_x}{\rho} & 0 & 0 \\
-\mu_x\frac{w}{\rho} & 0 & 0 & \frac{\mu_x}{\rho} & 0 \\
\begin{array}{c} -\left(\lambda + 2\mu - \frac{k}{C_v}\right)_x\frac{u^2}{\rho} \\ -\left(\mu - \frac{k}{C_v}\right)_x \\ \frac{(v^2+w^2)}{\rho} \\ -\left(\frac{k}{C_v}\right)_x\frac{e}{\rho^2} \end{array} & \left(\lambda + 2\mu - \frac{k}{C_v}\right)_x\frac{u}{\rho} & \left(\mu - \frac{k}{C_v}\right)_x\frac{v}{\rho} & \left(\mu - \frac{k}{C_v}\right)_x\frac{w}{\rho} & \left(\frac{k}{C_v}\right)_x\frac{1}{\rho}
\end{bmatrix} \tag{3.40}
$$

$$
-\underline{P}_2 + \underline{R}_{2y} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-\mu_y\frac{u}{\rho} & -\frac{\mu_y}{\rho} & 0 & 0 & 0 \\
-(\lambda + 2\mu)_y\frac{v}{\rho} & 0 & (\lambda + 2\mu)_y\frac{1}{\rho} & 0 & 0 \\
-\mu_y\frac{w}{\rho} & 0 & 0 & -\frac{\mu_y}{\rho} & 0 \\
\begin{array}{c} -\left(\lambda + 2\mu - \frac{k}{C_v}\right)_y\frac{v^2}{\rho} \\ -\left(\mu - \frac{k}{C_v}\right)_y \\ \frac{(u^2+w^2)}{\rho} \\ -\left(\frac{k}{C_v}\right)_y\frac{e}{\rho^2} \end{array} & \left(\mu - \frac{k}{C_v}\right)_y\frac{u}{\rho} & \left(\lambda + 2\mu - \frac{k}{C_v}\right)_y\frac{v}{\rho} & \left(\mu - \frac{k}{C_v}\right)_y\frac{w}{\rho} & \left(\frac{k}{C_v}\right)_y\frac{1}{\rho}
\end{bmatrix} \tag{3.41}
$$

$$-\underline{P}_3+\underline{R}_{3z}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -\mu_z\frac{u}{\rho} & \frac{\mu_z}{\rho} & 0 & 0 & 0 \\ -\mu_z\frac{v}{\rho} & 0 & \frac{\mu_z}{\rho} & 0 & 0 \\ (\lambda+2\mu)_z\frac{w}{\rho} & 0 & 0 & (\lambda+2\mu)_z & 0 \\ -\left(\lambda+2\mu-\frac{k}{C_v}\right)_z\frac{w^2}{\rho} -\left(\mu-\frac{k}{C_v}\right)_z\frac{(u^2+v^2)}{\rho} -\left(\frac{k}{C_v}\right)_z\frac{e}{\rho^2} & \left(\mu-\frac{k}{C_v}\right)_z\frac{u}{\rho} & \left(\mu-\frac{k}{C_v}\right)_z\frac{v}{\rho} & \left(\lambda+2\mu-\frac{k}{C_v}\right)_z\frac{w}{\rho} & \left(\frac{k}{C_v}\right)_z\frac{1}{\rho} \end{bmatrix} \tag{3.42}$$

In the case of packed beds the Jacobian $\underline{S}$ becomes

$$\underline{S}=-\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -\frac{\mu\beta u}{\rho k}-C\beta^2 u(u^2+v^2+w^2)^{1/2} & \frac{\mu\beta}{\rho k}+C\beta^2(2u^2+v^2+w^2)\cdot(u^2+v^2+w^2)^{-1/2} & C\beta^2uv(u^2+v^2+w^2)^{-1/2} & C\beta^2uw(u^2+v^2+w^2)^{-1/2} & 0 \\ -\frac{\mu\beta v}{\rho k}-C\beta^2 v(u^2+v^2+w^2)^{1/2} & C\beta^2uv(u^2+v^2+w^2)^{-1/2} & \frac{\mu\beta}{\rho k}+C\beta^2(u^2+2v^2+w^2)\cdot(u^2+v^2+w^2)^{-1/2} & C\beta^2vw(u^2+v^2+w^2)^{-1/2} & 0 \\ -\frac{\mu\beta w}{\rho k}-C\beta^2 w(u^2+v^2+w^2)^{1/2} & C\beta^2uw(u^2+v^2+w^2)^{-1/2} & C\beta^2vw(u^2+v^2+w^2)^{-1/2} & \frac{\mu\beta}{\rho k}+C\beta^2(u^2+v^2+2w^2)\times(u^2+v^2+w^2)^{-1/2} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.43}$$

Whereas in the case of shell-and-tube condenser the Jacobian $\underline{S}$ becomes

$$
\underline{S} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-\frac{2g|m|^{-b}}{\rho^3} \times (m^4 + m^2n^2 + m^2q^2)^{1/2} & \frac{g|m|^{-b}}{2\rho^2} (m^4 + m^2n^2 + m^2q^2)^{-1/2} \times (4m^3 + 2mn^2 + 2mq^2) - \frac{bg|m|^{-b-1}}{\rho^2} (m^4 + m^2n^2 + m^2q^2)^{1/2} & \frac{g|m|^{-b}}{\rho^2} (m^4 + m^2n^2 + m^2q^2)^{-1/2} \times m^2n & \frac{g|m|^{-b}}{\rho^2} (m^4 + m^2n^2 + m^2q^2)^{-1/2} \times m^2q & 0 \\
-\frac{2g|n|^{-b}}{\rho^3} \times (m^2n^2 + n^4 + n^2q^2)^{1/2} & g|n|^{-b} (m^2n^2 + n^4 + n^2q^2)^{-1/2} \times mn^2 & \frac{g|n|^{-b}}{2\rho^2} (m^2n^2 + n^4 + n^2q^2)^{-1/2} \times (2m^2n + 4n^3 + 2nq^2) - \frac{bg|n|^{-b-1}}{\rho^2} (m^2n^2 + n^4 + n^2q^2) & g|n|^{-b} (m^2n^2 + n^4 + n^2q^2)^{-1/2} \times n^2q & 0 \\
-\frac{2g|q|^{-b}}{\rho^3} \times (m^2q^2 + n^2q^2 + q^4)^{1/2} & \frac{g|q|^{-b}}{\rho^2} (m^2q^2 + n^2q^2 q^4)^{-1/2} \times mq^2 & g|q|^{-b} (m^2q^2 + n^2q^2 + q^4)^{-1/2} \times nq^2 & g|q|^{-b} (m^2q^2 + n^2q^2 + q^4)^{-1/2} \times (2m^2q + 2n^2q + 4q^3) - \frac{bg}{\rho^2}|q|^{-b-1} (m^2q^2 + n^2q^2 + q^4)^{1/2} & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\tag{3.44}
$$

In the shell-and-tube Jacobian, $\underline{S}$, the parameters m, n, q, b, and g are defined as

$$m = \rho u, n = \rho v, q = \rho w$$

and

$$g = \frac{2a\rho D_0}{\mu P}\left(\frac{P\beta}{P - D_0}\right)^2\left(\frac{1-\beta}{1-\beta_t}\right) \tag{3.45}$$

Parameter a takes the values 0.619 or 1.156 and b takes the values 0.198 or 0.2647 depending on the Reynolds number (see Equation (2.14)).

3.5. Boundary Conditions

Finite difference schemes are usually developed to calculate the interior grid points in the domain of interest. However, exterior grid points are linked to interior grid points via boundary conditions and special relations. It is, however, very important to specify proper boundary conditions and to provide proper special relations to develop a well posed system. When the solution is sought through the finite difference method, information is carried from one point to the neighboring points and the boundary conditions influence their neighboring points until the whole domain is affected. In fact, in principle there exist infinite numbers of solutions, each one defined by a set of initial and boundary conditions; any change in these conditions will produce a new solution. The global accuracy and stability can, also, be influenced by the choice of boundary conditions.

Explicit schemes generally use explicit boundary conditions, on the other hand, implicit schemes can use explicit as well as implicit boundary conditions. Explicit boundary conditions are easy to implement and can be readily changed when needed. However, when explicit boundary conditions are used with implicit schemes, the stability of the scheme can be adversely affected. In this study implicit boundary conditions are implemented.

A great number of boundary condition models have been suggested in the open literature during the past two decades. Nonreflecting boundary conditions were developed by many researchers to prevent spurious, nonphysical reflections at inflow and outflow boundaries. This method can increase the accuracy and the computational efficiency because the computational domain can be made much smaller, as indicated by (Giles [54], Engquist and Majda [55] and Saxer [56]). This method is developed, however, by linearizing the steady and unsteady equations about the far-field conditions; the resulting system is then solved assuming a generalized wave form as suggested by Verhoff and Stookesberry [57] and Verhoff, Stookesberry, and Agrawal [58].

Correct implementation of necessary boundary conditions depends on the nature of the flow. In this study, however, the flow is assumed subsonic, and two types of boundary conditions are used.

- Boundary condition 1

The inlet density and velocity are specified, while the pressure is extrapolated from the interior. However, at the outlet the pressure is specified and all other variables are extrapolated from the interior.

- Boundary condition 2

At the inlet, the pressure and density are specified and the velocity is extrapolated from the interior, while at the outlet the pressure is specified and other variables are extrapolated from the interior. The outlet boundary condition 2 is thus the same as the outlet boundary condition 1. Both boundary conditions are implemented implicitly and successful results are obtained. When the central difference approximation is applied on Equations (3.31), (3.32), and (3.33), it can be seen that the Jacobians $\underline{A}$, $-\underline{P}_1 + \underline{R}_{1x}$, and $\underline{R}_1$ in the x-sweep direction, $\underline{B} - \underline{P}_2 + \underline{R}_{2x}$, and $\underline{R}_{2y}$ in the y-sweep direction and $\underline{C}, -\underline{P}_3 + \underline{R}_{3z}$, and $\underline{R}_{3z}$ in the z-sweep are not defined at the boundaries. In order to solve this scheme using implicit boundary conditions, these Jacobians must be defined at the boundaries.

In this research, it is also assumed that the flow enters and leaves the system through certain portions of the z-y plane at $x = 0$ and $x = H_x$ respectively, where H_x is the system length. It is, thus necessary when solving Equation (3.31) to find the Jacobians $\underline{A}, -\underline{P}_1 + \underline{R}_{1x}$, and $\underline{R}_1$ at $i = 1$ and $i = \ell$, where i is the grid point number in the x-direction. Inlet boundary condition 1 is implemented as follows:

At the inlet

$$
\begin{aligned}
\rho &= \text{constant} && \Longrightarrow && \Delta\rho = 0. \\
u &= \text{constant} && \Longrightarrow && \Delta(\rho u) = 0 \\
v &= 0 && \Longrightarrow && \Delta(\rho v) = 0 \\
w &= 0 && \Longrightarrow && \Delta(\rho w) = 0.
\end{aligned}
\tag{3.46}
$$

The pressure is extrapolated from the interior, therefore

$$p_{1,j,k} = p_{2,j,k} \tag{3.47}$$

where, consistent with the assumption of ideal gas with constant specific heats:

$$p = (\gamma - 1)\left(e - \frac{1}{2}(\rho u^2 + \rho v^2 + \rho w^2)\right). \tag{3.48}$$

Combining Equations (3.47) and (3.48), there results:

$$\Delta e_{1,j,k} = \left(\Delta e_{2,j,k} - \frac{1}{2}\Delta(\rho u^2 + \rho v^2 + \rho w^2)_{2,j,k}\right).$$

It can be easily shown that

$$\Delta(\rho u^2 + \rho v^2 + \rho w^2)_{2,j,k} = 2(u\Delta(\rho u) + v\Delta(\rho v) + w\Delta(\rho w))_{2,j,k} - (u^2 + v^2 + w^2)_{2,j,k}\Delta\rho_{2,j,k}$$

therfore:

$$\Delta e_{1,j,k} = \Delta e_{2,j,k} - \big(u\Delta(\rho u) + v\Delta(\rho v) + w\Delta(\rho w)\big)_{2,j,k} + \frac{1}{2}(u^2 + v^2 + w^2)_{2,j,k}\Delta\rho_{2,j,k}. \tag{3.49}$$

When applying Equations (3.46) and (3.49) at the inlet the inlet Jacobians A_1 and R_{11}, may be written, when the j and k indices for simplicity are suppressed, as:

$$\underline{A}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2}(\gamma-1)(u^2+v^2+w^2)_2 & -(\gamma-1)u_2 & -(\gamma-1)v_2 & -(\gamma-1)w_2^2 & (\gamma-1) \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2}\gamma u_1 (u^2+v^2+w^2)_2 & -\gamma u_1 u_2 & -\gamma u_1 v_2 & -\gamma u_1 w_2 & \gamma u_1 \end{bmatrix} \tag{3.50}$$

$$\underline{R}_{11} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2}\frac{k}{\rho_1 C_v}(u^2+v^2+w^2)_2 & -\frac{1}{2}\frac{k}{\rho_1 C_v}u_2 & -\frac{1}{2}\frac{k}{\rho_1 C_v}v_2 & -\frac{1}{2}\frac{k}{\rho_1 C_v}w_2 & \frac{k}{\rho_1 C_v} \end{bmatrix} \tag{3.51}$$

The outlet boundary conditions 1 and 2 are identical and are developed as follows. At the outlet

$$
\begin{aligned}
p_{\ell,j,k} &= \text{constant} \\
\rho_{\ell,j,k} &= \rho_{\ell-1,j,k} \\
u_{\ell,j,k} &= u_{\ell-1,j,k} \quad \Longrightarrow \quad (\rho u)_{\ell,j,k} = (\rho u)_{\ell-1,j,k} \\
v_{\ell,j,k} &= v_{\ell-1,j,k} \quad \Longrightarrow \quad (\rho v)_{\ell,j,k} = (\rho v)_{\ell-1,j,k} \\
w_{\ell,j,k} &= w_{\ell-1,j,k} \quad \Longrightarrow \quad (\rho w)_{\ell,j,k} = (\rho w)_{\ell-1,j,k}.
\end{aligned} \tag{3.52}
$$

where ℓ is the last grid point in the x-direction. Using ideal gas assumption and dropping indecis j and k for simplicity, one can write:

$$p_\ell = (\gamma - 1)(e_\ell - \frac{1}{2}(\rho u^2 + \rho v^2 + \rho w^2)_\ell) = \text{constant}$$

Now, since $\Delta p_\ell = 0.$, one gets:

$$\Delta e_\ell = \frac{1}{2}\Delta(\rho u^2 + \rho v^2 + \rho w^2)_\ell.$$

Using this equation, after some simple algebraic manipulations, it can be shown that:

$$
\begin{aligned}
\Delta e_\ell + (u\Delta(\rho u) + v\Delta(\rho v) + w\Delta(\rho w))_{\ell-1} \\
-\frac{1}{2}(u^2 + v^2 + w^2)_{\ell-1}\Delta\rho_{\ell-1}.
\end{aligned} \tag{3.53}
$$

When applying Equations (3.52) and (3.53) at the outlet, the Jacobians $\underline{A}_\ell$ and $\underline{R}_{1\ell}$ for the outlet grids becomes:

$$
\underline{A}_\ell = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 \\
\begin{array}{c}(\gamma-3)u^2_{\ell-1} + \frac{(\gamma-1)}{2} \\ (v^2+w^2)_{\ell-1} - \frac{(\gamma-1)}{2} \\ (u^2+v^2+w^2)_{\ell-1}\end{array} & \begin{array}{c}(3-\gamma)u_{\ell-1} \\ +(\gamma-1)u_{\ell-1} \\ \ \end{array} & 0 & 0 & 0 \\
-u_{\ell-1}v_{\ell-1} & -v_{\ell-1} & u_{\ell-1} & 0 & 0 \\
-u_{\ell-1}w_{\ell-1} & w_{\ell-1} & 0 & u_{\ell-1} & 0 \\
\begin{array}{c}-\gamma e_\ell u_{\ell-1} \\ +(\gamma-1)u_{\ell-1} \\ (u^2+v^2+w^2)_{\ell-1} \\ -\frac{\gamma}{2}u_{\ell-1} \\ (u^2+v^2+w^2)_{\ell-1}\end{array} & \begin{array}{c}\frac{\gamma e_\ell}{\rho_{\ell-1}} + \frac{(1-\gamma)}{2} \\ (3u^2+v^2+w^2)_{\ell-1} \\ +\gamma u^2_{\ell-1} \\ \ \\ \ \end{array} & u_{\ell-1}v_{\ell-1} & u_{\ell-1}w_{\ell-1} & 0
\end{bmatrix}
\tag{3.54}
$$

$$
\underline{R}_{1_\ell} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
\frac{(\lambda+2\mu)u_{\ell-1}}{\rho_{\ell-1}} & \frac{(\lambda+2\mu)}{\rho_{\ell-1}} & 0 & 0 & 0 \\
-\frac{\mu v_{\ell-1}}{\rho_{\ell-1}} & 0 & \frac{\mu}{\rho_{\ell-1}} & 0 & 0 \\
-\frac{\mu w_{\ell-1}}{\rho_{\ell-1}} & 0 & 0 & \frac{\mu}{\rho_{\ell-1}} & 0 \\
\begin{array}{c}-(\lambda+2\mu-\frac{k}{C_v}) \\ \frac{u^2_{\ell-1}}{\rho_{\ell-1}} - \frac{1}{\rho_{\ell-1}} \\ (\mu-\frac{k}{C_v}) \\ (v^2+w^2)_{\ell-1} \\ -\frac{k}{\rho_{\ell-1}C_v}\frac{e_\ell}{\rho^2_{\ell-1}} \\ -\frac{k}{2\rho_{\ell-1}C_v} \\ (u^2+v^2+w^2)_{\ell-1}\end{array} & \begin{array}{c}(\lambda+2\mu-\frac{k}{C_v}) \\ \frac{u_{\ell-1}}{\rho_{\ell-1}} \\ +\frac{k}{\rho_{\ell-1}C_v}u_{\ell-1} \\ \ \\ \ \\ \ \\ \ \end{array} & \begin{array}{c}(\mu-\frac{k}{C_v})\frac{v_{\ell-1}}{\rho_{\ell-1}} \\ +\frac{k}{\rho_{\ell-1}C_v}v_{\ell-1} \\ \ \\ \ \\ \ \\ \ \\ \ \end{array} & \begin{array}{c}(\mu-\frac{k}{C_v})\frac{w_{\ell-1}}{\rho_{\ell-1}} \\ +\frac{k}{\rho_{\ell-1}C_v}w_{\ell-1} \\ \ \\ \ \\ \ \\ \ \\ \ \end{array} & 0
\end{bmatrix}
\tag{3.55}
$$

The inlet boundary condition 2 can be treated in a similar way and will not be discussed here. Also, the boundary conditions of the explicit portion of the scheme are straightforward and will not be presented.

Non-slip boundary conditions are assumed at the wall, and the velocities are set to zero. The wall is also assumed to be adiabatic; the pressure and density are extrapolated from the interior assuming that

$$\frac{\partial p}{\partial n} = 0, \qquad \frac{\partial \rho}{\partial n} = 0,$$

and the adiabatic wall condition requires that $\frac{\partial T}{\partial n} = 0$, where n is a vector normal to the wall.

The implicit wall boundary conditions implementation is straightforward and will not be discussed here.

3.6. Coupling of the Noncondensable Mass Conservation Equation to the Implicit Factored Scheme

In the previous sections, an implicit factored scheme was modified to include the porous medium and heat and mass transfer source terms. The developed scheme, however, applies only for one species. This study as mentioned earlier deals with vapor and noncondensable gases assuming that the mixture is compressible. Due to the condensation, the partial density of the noncondensable varies in the condenser. The change in the density of noncondensable might be very large depending on the condensation process, and necessitates the coupling of the noncondensable mass conservation equation to the system of conservation equations.

Recall that when the implicit factored scheme was developed for one species was considered, the conservative variables were

$$\vec{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \end{bmatrix}$$

where ρ is the mixture density.

Initially, the following two methods were considered for coupling the noncondensable conservation equation to the equations for the above five variables.

1. Solve the mixture equations to evaluate the mixture variables, and then solve the noncondensable equations separately and advance the time to the next step to evaluate new variables.
2. Try to couple the noncondensable equation with the implicit factor scheme by having the conservative variables

$$\vec{U} = \begin{bmatrix} \rho_v \\ \rho u \\ \rho v \\ \rho w \\ e \\ \rho_g \end{bmatrix}$$

where, in this case, ρ_v is the vapor density, ρ is the mixture density, e is the mixture energy and ρ_g is the noncondensable density.

After implementing the first method, however, it was found that the time step became very stringent and the convergence to steady state solution took a long time. With respect to the second approach, unfortunately it does not seem possible to evaluate the Jacobians, presented earlier in this chapter, using direct differentiation when the species equation of the noncondensable is included in the compact conservative form.

In view of the above mentioned problem, a novel method was explored in which the noncondensable mass conservation equation is included in the implicit factored scheme. Once the latter method was implemented it was found that the time step was much less stringent than that of the aforementioned first method. This novel method is now presented.

Although the following derivation is applicable to any number of species equations, however, only one species equation is considered here for convenience.

Consider having continuity, momentum, and energy equations for the steam and the noncondensable separately. Then the conservative variables become

$$\vec{U}_v = \begin{bmatrix} \rho_v \\ \rho_v u \\ \rho_v v \\ \rho_v w \\ e_v \end{bmatrix} \tag{3.56}$$

and

$$\vec{U}_g = \begin{bmatrix} \rho_g \\ \rho_g u \\ \rho_g v \\ \rho_g w \\ e_g \end{bmatrix} \tag{3.57}$$

where $\vec{U}_v$ and $\vec{U}_g$ are the conservative vectors for the vapor and the noncondensable gas, respectively.

If the same procedure that was discussed in the previous sections to derive the implicit factored scheme is followed separately for each species, one will have equations similar to Equations (3.31), (3.32) and (3.33). Thus, from Equation (3.31):

- Steam

$$\begin{aligned} \Big\{ \underline{I} + \frac{\theta \Delta t}{\beta(1+\tau)} \Big[\frac{\partial}{\partial x} \big(\underline{A}_v - \underline{P}_{v_1} + \underline{R}_{v_{1_x}} \big) \\ - \frac{\partial^2 (\underline{R}_{v_1})^n}{\partial x^2} - S_v^n \delta - \epsilon_i (\Delta x)^2 \frac{\partial^2}{\partial x^2} \Big] \Big\} \Delta \vec{U}_v^* \\ = \text{RHS (3.22)} - \varepsilon_e (\Delta x)^4 \frac{\partial^4 \vec{U}_v^n}{\partial x^4} \end{aligned} \tag{3.58}$$

• Noncondensable

$$\Big\{\underline{I} + \frac{\theta\Delta t}{\beta(1+\tau)}\Big[\frac{\partial}{\partial x}(\underline{A}_g - \underline{P}_{g_1} + \underline{R}_{g_1 x}) - \frac{\partial^2(\underline{R}_{g_1})^n}{\partial x^2}$$

$$- \underline{S}_g^n\delta - \epsilon_i(\Delta x)^2\frac{\partial^2}{\partial x^2}\Big]\Big\}\Delta\vec{U}_g^*$$

$$= \text{RHS } (3.22) - \varepsilon_e(\Delta x)^4\frac{\partial^4\vec{U}_g}{\partial x^4} - \frac{\theta\Delta t}{\beta(1+\tau)}\Big[(\Delta\vec{Q})^{n-1}\delta - \vec{Q}^n\delta\Big] \tag{3.59}$$

$$\Delta\vec{U}_v = \begin{bmatrix} \Delta\rho_v \\ \Delta(\rho_v u) \\ \Delta(\rho_v v) \\ \Delta(\rho_v w) \\ \Delta e_v \end{bmatrix} = \begin{bmatrix} \Delta\rho_v \\ \Delta m_v \\ \Delta n_v \\ \Delta q_v \\ \Delta e_v \end{bmatrix} \tag{3.60}$$

and

$$\Delta\vec{U}_g = \begin{bmatrix} \Delta\rho_g \\ \Delta(\rho_g u) \\ \Delta(\rho_g v) \\ \Delta(\rho_g w) \\ \Delta e_g \end{bmatrix} = \begin{bmatrix} \Delta\rho_g \\ \Delta m_g \\ \Delta n_g \\ \Delta q_g \\ \Delta e_g \end{bmatrix} \tag{3.61}$$

Note that the last term has been included in the right hand side of Equation (3.59) because the noncondensable does not condense. The Jacobians for steam (Equation (3.58)) are given below.

$$\underline{A}_v = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -u^2 + \frac{\partial p_v}{\partial \rho_v} & 2u + \frac{\partial p_v}{\partial m_v} & \frac{\partial p_v}{\partial n_v} & \frac{\partial p_v}{\partial q_v} & \frac{\partial p_v}{\partial e_v} \\ -uv & v & u & 0 & 0 \\ -uw & w & 0 & u & 0 \\ -\frac{u}{\rho_v}(e_v + p_v) + u\frac{\partial p_v}{\partial \rho_v} & \frac{1}{\rho_v}(e_v + p_v) + u\frac{\partial p_v}{\partial m_v} & u\frac{\partial p_v}{\partial n_v} & u\frac{\partial p_v}{\partial q_v} & u + u\frac{\partial p_v}{\partial e_v} \end{bmatrix} \tag{3.62}$$

$$\underline{B}_v = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ -uv & v & u & 0 & 0 \\ -v^2 + \frac{\partial p_v}{\partial \rho_v} & \frac{\partial p_v}{\partial m_v} & 2v + \frac{\partial p_v}{\partial n_v} & \frac{\partial p_v}{\partial q_v} & \frac{\partial p_v}{\partial e_v} \\ -vw & 0 & w & v & 0 \\ -\frac{v}{\rho_v}(e_v + p_v) + v\frac{\partial p_v}{\partial \rho_v} & v\frac{\partial p_v}{\partial m_v} & \frac{1}{\rho_v}(e_v + p_v) + v\frac{\partial p_v}{\partial n_v} & v\frac{\partial p_v}{\partial q_v} & v + v\frac{\partial p_v}{\partial e_v} \end{bmatrix} \tag{3.63}$$

$$\underline{C}_v = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ -uw & w & 0 & u & 0 \\ -vw & 0 & w & v & 0 \\ -w^2 + \frac{\partial p_v}{\partial \rho_v} & \frac{\partial p_v}{\partial m_v} & \frac{\partial p_v}{\partial n_v} & 2w + \frac{\partial p_v}{\partial q_v} & \frac{\partial p_v}{\partial e_v} \\ \frac{w}{\rho_v}(e_v + p_v) + w\frac{\partial p_v}{\partial \rho_v} & w\frac{\partial p_v}{\partial m_v} & w\frac{\partial p_v}{\partial n_v} & \frac{1}{\rho_v}(e_v + p_v) + w\frac{\partial p_v}{\partial q_v} & w + w\frac{\partial p_v}{\partial e_v} \end{bmatrix} \tag{3.64}$$

$$
\underline{R}_{v1} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-\frac{(\lambda+2\mu)_v u}{\rho_v} & \frac{(\lambda+2\mu)_v}{\rho_v} & 0 & 0 & 0 \\
-\frac{\mu_v v}{\rho_v} & 0 & \frac{\mu_v}{\rho_v} & 0 & 0 \\
-\frac{\mu_v w}{\rho_v} & 0 & 0 & \frac{\mu}{\rho_v} & 0 \\
\begin{array}{c} -\frac{(\lambda+2\mu)_v u^2}{\rho_v} \\ -\frac{\mu_v v^2}{\rho_v} - \frac{\mu_v w^2}{\rho_v} \\ +k_v \frac{\partial T_{v_x}}{\partial \rho_{v_x}} \end{array} & \begin{array}{c} \frac{(\lambda+2\mu)_v u}{\rho_v} \\ +k_v \frac{\partial T_{v_x}}{\partial m_{v_x}} \end{array} & \begin{array}{c} \frac{\mu_v v}{\rho_v} \\ +k_v \frac{\partial T_{v_x}}{\partial n_{v_x}} \end{array} & \begin{array}{c} \frac{\mu_v w}{\rho_v} \\ +k_v \frac{\partial T_{v_x}}{\partial q_{v_x}} \end{array} & k_v \frac{\partial T_{v_x}}{\partial e_{v_x}}
\end{bmatrix} \tag{3.65}
$$

where $\mu_v = \frac{\rho_v}{\rho}\mu$, $\lambda_v = \frac{\rho_v}{\rho}\lambda$ and $k_v = \frac{\rho_v}{\rho}k$.

$$
\underline{R}_{v2} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-\frac{\mu_v u}{\rho_v} & \frac{\mu_v}{\rho_v} & 0 & 0 & 0 \\
-\frac{v}{\rho_v}(\lambda + 2\mu)_v & 0 & \frac{(\lambda+2\mu)_v}{\rho_v} & 0 & 0 \\
-\frac{\mu_v w}{\rho_v} & 0 & 0 & \frac{\mu_v}{\rho_v} & 0 \\
\begin{array}{c} -\frac{(\lambda+2\mu)_v v^2}{\rho_v} \\ -\frac{\mu_v}{\rho_v}u^2 - \frac{\mu_v}{\rho_v}w^2 \\ +k_v \frac{\partial T_{v_y}}{\partial \rho_y} \end{array} & \begin{array}{c} \frac{\mu_v u}{\rho_v u} \\ +k_v \frac{T_{v_y}}{\partial m_{v_y}} \end{array} & \begin{array}{c} \frac{(\lambda+2u)_v v}{\rho_v} \\ +k_v \frac{\partial T_{v_y}}{\partial n_{v_y}} \end{array} & \begin{array}{c} \frac{\mu_v w}{\rho_v} \\ +k_v \frac{\partial T_{v_y}}{\partial q_{v_y}} \end{array} & k_v \frac{\partial T_{v_y}}{\partial e_{v_y}}
\end{bmatrix} \tag{3.66}
$$

$$\underline{R}_{v3} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -\frac{\mu_v}{\rho_v}u & \frac{\mu_v}{\rho_v} & 0 & 0 & 0 \\ 0 & \frac{\mu_v}{\rho_v} & 0 & 0 & 0 \\ -\frac{w}{\rho_v}(\lambda+2u)_v & 0 & 0 & \frac{(\lambda+2u)_v}{\rho_v} & 0 \\ -\frac{\mu_v u^2}{\rho_v} - \frac{\mu_v v^2}{\rho_v} & \frac{\mu_v u}{\rho_v} & \frac{\mu_v v}{\rho_v} & \frac{(\lambda+2\mu)_v w}{\rho_v} & \lambda_v\frac{\partial T}{\partial e_v} \\ -\frac{(\lambda+2u)_v w^2}{\rho_v} & +k_v\frac{\partial T_{v_z}}{\partial m_{v_z}} & +k_v\frac{\partial T_{v_z}}{\partial n_{v_z}} & +k_v\frac{\partial T_{v_z}}{\partial q_{v_z}} & \\ +k_v\frac{\partial T_{v_z}}{\partial \rho_{v_z}} & & & & \end{bmatrix} \quad (3.67)$$

The noncondensable Jacobians $\underline{A}_g$, $\underline{B}_g$, $\underline{C}_g$, $\underline{R}_{g1}$, $\underline{R}_{g2}$, and $\underline{R}_{g3}$ are similar to $\underline{A}_v$, $\underline{B}_v$, $\underline{C}_v$, $\underline{R}_{v1}$, $\underline{R}_{v2}$, and $\underline{R}_{v3}$, respectively except that the subscript v is replaced by g everywhere. The Jacobians $(-\underline{P}_{v1}+\underline{R}_{v1x})$, $(-\underline{P}_{v2}+\underline{R}_{v2y})$, $(-\underline{P}_{v3}+\underline{R}_{v3z})$, $(-\underline{P}_{g1}+\underline{R}_{g1x})$, $(-\underline{P}_{g2}+\underline{R}_{g2y})$, $(-\underline{P}_{g3}+\underline{R}_{g3z})$ can be derived similarly.

The above Jacobians are valid for any arbitrary equation of state of the form

$$p = p(\rho, \epsilon).$$

In this work, however, it is assumed that the steam and the noncondensable gas are perfect gases. The equations of state for the steam and the noncondensable gas are as follows.

- Steam

$$p_v = (\gamma_v - 1)\left(e_v - \frac{1}{2\rho_v}(m_v^2 + n_v^2 + q_v^2)\right)$$

$$T_v = (\frac{1}{\rho_v C_{vv}})\left(e_v - \frac{1}{2\rho_v}(m_v^2 + n_v^2 + q_v^2)\right)$$

• Gas

$$p_g = (\gamma_g - 1)\left(e_g - \frac{1}{2\rho_g}(m_g^2 + n_g^2 + q_g^2)\right)$$

and

$$T_g = (\frac{1}{\rho_g C_{vg}})\left(e_g - \frac{1}{2\rho_g}(m_g^2 + n_g^2 + q_g^2)\right).$$

Also, the partial derivatives in the above Jacobians are as follows:

$$\frac{\partial p_v}{\partial \rho_v} = \frac{(\gamma - 1)}{2}(u^2 + v^2 + w^2)$$

$$\frac{\partial p_v}{\partial m_v} = -(\gamma - 1)u$$

$$\frac{\partial p_v}{\partial n_v} = -(\gamma - 1)v$$

$$\frac{\partial p_v}{\partial q_v} = -(\gamma - 1)w$$

$$\frac{\partial p_v}{\partial e_v} = (\gamma - 1)$$

$$\frac{\partial T_{v_x}}{\partial \rho_{v_x}} = -\frac{e_v}{\rho_v^2 C_{vv}} + \frac{1}{C_{vv}\rho_v}(u^2 + v^2 + w^2)$$

$$\frac{\partial T_{v_x}}{\partial m_{v_x}} = -\frac{u}{C_{vv}\rho_v}$$

$$\frac{\partial T_{v_x}}{\partial n_{v_x}} = -\frac{v}{C_{vv}\rho_v}$$

$$\frac{\partial T_{v_x}}{\partial q_{v_x}} = -\frac{v}{C_{vv}\rho_v}$$

$$\frac{\partial T_{v_x}}{\partial e_{v_x}} = \frac{1}{C_{vv}\rho_v}$$

Similar expressions can be derived for the noncondensable gas

Now, let us redefine $\Delta m_v, \Delta n_v$, Δq_v, Δe_v, $\Delta m_g, \Delta n_g$, Δq_g, and Δe_g in terms of Δm, Δn, and Δq.

$$\Delta m_v = \Delta(\frac{\rho_v}{\rho} m)$$

$$\Delta m_v = \frac{\rho_v}{\rho}\Delta m + \frac{m}{\rho}\Delta\rho_v + \rho_v m \Delta(\frac{1}{\rho}). \tag{3.68}$$

But

$$\Delta(\frac{\rho}{\rho}) = \rho\Delta(\frac{1}{\rho}) + \frac{1}{\rho}\Delta\rho = 0$$

As a result: $$\Delta(\frac{1}{\rho}) = -\frac{1}{\rho^2}\Delta\rho. \tag{3.69}$$

Substitute Equation (3.69) into Equation (3.68), after some algebraic manipulation

$$\Delta m_v = \frac{\rho_g}{\rho}u\Delta\rho_v + \frac{\rho_v}{\rho}\Delta m - \frac{\rho_v}{\rho}u\Delta\rho_g. \tag{3.70}$$

Similarly, it can be shown that:

$$\Delta n_v = \frac{\rho_g}{\rho}v\Delta\rho_v + \frac{\rho_v}{\rho}\Delta n - \frac{\rho_v}{\rho}v\Delta\rho_g. \tag{3.71}$$

$$\Delta q_v = \frac{\rho_g}{\rho}w\Delta\rho_v + \frac{\rho_v}{\rho}\Delta q_v - \frac{\rho_v}{\rho}w\Delta\rho_g \tag{3.72}$$

$$\Delta e_v = \frac{\rho_g}{\rho^2}e\Delta\rho_v + \frac{\rho_v}{\rho}\Delta e - \frac{\rho_v}{\rho^2}e\Delta\rho_g \tag{3.73}$$

where $e_v = \frac{\rho_v}{\rho}e$. Similarly:

$$\Delta m_g = \frac{\rho_v}{\rho}u\Delta\rho_g + \frac{\rho_g}{\rho}\Delta m - \frac{\rho_g}{\rho}u\Delta\rho_v \tag{3.74}$$

$$\Delta n_g = \frac{\rho_v}{\rho}v\Delta\rho_g + \frac{\rho_g}{\rho}\Delta n - \frac{\rho_g}{\rho}v\Delta\rho_v \tag{3.75}$$

$$\Delta q_g = \frac{\rho_v}{\rho}w\Delta\rho_g + \frac{\rho_g}{\rho}\Delta q - \frac{\rho_g}{\rho}w\Delta\rho_v \tag{3.76}$$

$$\Delta e_g = \frac{\rho_v}{\rho^2} e \Delta \rho_g + \frac{\rho_g}{\rho} \Delta e - \frac{\rho_g}{\rho^2} e \Delta \rho_g \tag{3.77}$$

Equations (3.58) and (3.59) are in fact representing continuity, x momentum, y momentum, z momentum, and energy equations for the steam and the noncondensable which makes a system of ten equations. The aim is to reduce this system to six equations representing continuity equation for the steam, mixture x-momentum, mixture y-momentum, mixture z-momentum, mixture energy and noncondensable continuity equations.

When Equations (3.70), (3.71), (3.72) and (3.73) are substituted into Equation (3.58), and Equations (3.74), (3.75), (3.76) and (3.77) are substituted into Equation (3.59), one will have a system of ten equations, and six unknowns assuming that the equations of state are available. These unknowns are ρ_v m, n, q, e and ρ_g. However, the number of equations can be reduced to six by adding the x-momentum equation of the steam to that of the gas, y-momentum equation of the steam to that of the gas, z-momentum equation of the steam to that of the gas and the energy equation of the steam to that of the gas. Finally one will get the following system:

- Continuity equation for the steam
- Mixture x-momentum
- Mixture y-momentum
- Mixture z-momentum
- Mixture energy equation
- Continuity equation of the gas.

After tedious algebraic manipulations, the Jacobian A may be written as:

$$
\underline{A} = \begin{bmatrix}
\frac{\rho_g}{\rho}u & \frac{\rho_v}{\rho} & 0 & 0 & 0 & -\frac{\rho_v}{\rho}u \\
\begin{array}{l} a21_v + \frac{\rho_g}{\rho} \\ [(a22_v - a22_g)u \\ +(a23_v - a23_g)v \\ +(a24_v - a24_g)w \\ +(a25_v - a25_g)\frac{e}{\rho}] \end{array} &
\begin{array}{l} a22_v\frac{\rho_v}{\rho} \\ +a22_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a23_v\frac{\rho_v}{\rho} \\ +a23_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a24_v\frac{\rho_v}{\rho} \\ +a24_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a25_v\frac{\rho_v}{\rho} \\ +a25_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a21_g + \frac{\rho_v}{\rho} \\ [(a22_g - a22_v)u \\ +(a23_g - a23_v)v \\ +(a24_g - a24_v)w \\ +(a25_g - a25_v)\frac{e}{\rho}] \end{array} \\
\begin{array}{l} a31_v + \frac{\rho_g}{\rho} \\ [(a32_v - a32_g)u \\ +(a33_v - a33_g)v \\ +(a34_v - a34_g)w \\ +(a35_v - a35_g)\frac{e}{\rho}] \end{array} &
\begin{array}{l} a32_v\frac{\rho_v}{\rho} \\ +a32_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a33_v\frac{\rho_v}{\rho} \\ +a33_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a34_v\frac{\rho_v}{\rho} \\ +a34_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a35_v\frac{\rho_v}{\rho} \\ +a35_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a31_g\frac{\rho_v}{\rho} \\ [(a32_g - a32_v)u \\ +(a33_g - a33_v)v \\ +(a34_g - a34_v)w \\ +(a35_g - a35_v)\frac{e}{\rho}] \end{array} \\
\begin{array}{l} a41_v + \frac{\rho_g}{\rho} \\ [(a42_v - a42_g)u \\ +(a43_v - a43_g)v \\ +(a44_v - a44_g)w \\ +(a45_v - a45_g)\frac{e}{\rho}] \end{array} &
\begin{array}{l} a42_v\frac{\rho_v}{\rho} \\ +a42_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a43_v\frac{\rho_v}{\rho} \\ +a43_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a44_v\frac{\rho_v}{\rho} \\ +a44_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a45_v\frac{\rho_v}{\rho} \\ +a45_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a41_g + \frac{\rho_v}{\rho} \\ [(a42_g - a42_v)u \\ +(a43_g - a43_v)v \\ +(a44_g - a44_v)w \\ +(a45_g - a45_v)\frac{e}{\rho}] \end{array} \\
\begin{array}{l} a51_v + \frac{\rho_g}{\rho} \\ [(a52_v - a52_g)u \\ +(a53_v - a53_g)v \\ +(a54_v - a54_g)w \\ +(a55_v - a55_g)\frac{e}{\rho}] \end{array} &
\begin{array}{l} a52_v\frac{\rho_v}{\rho} \\ +a52_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a53_v\frac{\rho_v}{\rho} \\ +a53_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a54_v\frac{\rho_v}{\rho} \\ +a54_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a55_v\frac{\rho_v}{\rho} \\ +a55_g\frac{\rho_g}{\rho} \end{array} &
\begin{array}{l} a51_g\frac{\rho_v}{\rho} \\ [(a52_g - a52_v)u \\ +(a53_g - a53_v)v \\ +(a54_g - a54_v)w \\ +(a55_g - a55_v)\frac{e}{\rho}] \end{array} \\
-\frac{\rho_g}{\rho}u & \frac{\rho_g}{\rho} & 0 & 0 & 0 & \frac{\rho_v}{\rho}u
\end{bmatrix} \tag{3.78}
$$

Similar procedure can be followed to evaluate the Jacobians $\underline{R}_{1x}$, $\underline{P}_1$, and $\underline{S}$. Keeping in mind that $\mu_v = \frac{\rho_v}{\rho}\mu$, $k_v = \frac{\rho_v}{\rho}k$, $\mu_g = \frac{\rho_g}{\rho}\mu$, and $k_g = \frac{\rho_g}{\rho}k$.

Repeating the same procedure for Equations (3.32) and (3.33), the Jacobians $\underline{B}$, $\underline{P}_2$, $\underline{R}_{2y}$, $\underline{C}_3$, $\underline{P}_3$ and $\underline{R}_{3z}$ can be derived.

In the Jacobian $\underline{A}$, the aij_v's and aij_g are the elements of the 5×5 Jacobians $\underline{A}_v$ and $\underline{A}_g$ respectively. The above Jacobians are, however, simplified when assuming perfect gas relations. For the sake of completeness the Jacobians when assuming perfect gas relations for the steam and the gas are presented below.

$$\underline{A} = \begin{bmatrix} \frac{\rho_g}{\rho}u & \frac{\rho_v}{\rho} & 0 & 0 & 0 & -\frac{\rho_v}{\rho}u \\ \frac{(\gamma-3)}{2}u^2 + \frac{(\gamma-1)}{2} \times (v^2+w^2) & (3-\gamma)u & (1-\gamma)v & (1-\gamma)w & (\gamma-1) & \frac{(\gamma-3)}{2}u^2 + \frac{(\gamma-1)}{2} \times (v^2+w^2) \\ -uv & v & u & 0 & 0 & -uv \\ -uw & w & 0 & u & 0 & -uw \\ -\frac{\gamma e u}{\rho'} + (\gamma-1) \times u(u^2+v^2+w^2) & \frac{e'\gamma}{\rho'} + \frac{(1-\gamma)}{2} \times (3u^2+v^2+w^2) & (1-\gamma)uv & (1-\gamma)uw & \gamma u & -\frac{\gamma e u}{\rho} + (\gamma-1) \times u(u^2+v^2+w^2) \\ \frac{\rho_g}{\rho}u & \frac{\rho_g}{\rho} & 0 & 0 & 0 & \frac{\rho_v}{\rho}u \end{bmatrix} \tag{3.79}$$

$$\underline{B} = \begin{bmatrix} \frac{\rho_g}{\rho}v & 0 & \frac{\rho_v}{\rho} & 0 & 0 & -\frac{\rho_v}{\rho}u \\ -uv & v & u & 0 & 0 & -uv \\ \begin{array}{c}\frac{(\gamma-3)}{2}v^2 \\ +\frac{(\gamma-1)}{2} \\ \times(u^2+w^2)\end{array} & (1-\gamma)u & (3-\gamma)v & (1-\gamma)w & (\gamma-1) & \begin{array}{c}(\gamma-3v^2 \\ +\frac{(\gamma-1)}{2} \\ \times(u^2+w^2)\end{array} \\ -vw & 0 & w & v & 0 & -vw \\ \begin{array}{c}-\frac{\gamma ev}{\rho'} \\ +(\gamma-1)v \\ \times(u^2 \\ +v^2+w^2)\end{array} & (1-\gamma)uv & \begin{array}{c}\frac{\gamma e}{\rho} \\ +\frac{(1-\gamma)}{2} \\ \times(3v^2 \\ +u^2+w^2)\end{array} & (1-\gamma)vw & \gamma v & \begin{array}{c}-\frac{\gamma ev}{\rho'} \\ +(\gamma-1)v \\ \times(u^2 \\ +v^2+w^2)\end{array} \\ \frac{\rho_g}{\rho}v & 0 & \frac{\rho_g}{\rho} & 0 & 0 & \frac{\rho_v}{\rho}v \end{bmatrix} \tag{3.80}$$

$$\underline{C} = \begin{bmatrix} \frac{\rho_g}{\rho}w & 0 & 0 & \frac{\rho_v}{\rho} & 0 & -\frac{\rho_v}{\rho}w \\ -uw & w & 0 & u & 0 & -uw \\ -vw & 0 & w & v & 0 & -vw \\ \begin{array}{c}\frac{(\gamma-3)}{2}w^2 \\ +\frac{(\gamma-1)}{2} \\ \times(u^2+v^2)\end{array} & (1-\gamma)u & (1-\gamma)v & (3-\gamma)w & (\gamma-1) & \begin{array}{c}(\gamma-3)w^2 \\ +\frac{(\gamma-1)}{2} \\ \times(u^2+v^2)\end{array} \\ \begin{array}{c}-\frac{\gamma e'w}{\rho'} \\ +(\gamma-1)w \\ \times(u^2 \\ +v^2+w^2)\end{array} & (1-\gamma)uw & \begin{array}{c}(1-\gamma)vw \\ +\frac{(1-\gamma)}{2} \\ \times(3w^2 \\ +u^2+v^2)\end{array} & \frac{\gamma e}{\rho} & \gamma w & \begin{array}{c}-\frac{\gamma e'w}{\rho'} \\ +(\gamma-1)w \\ \times(u^2 \\ +v^2+w^2)\end{array} \\ -\frac{\rho g}{\rho}w & 0 & 0 & \frac{\rho_g}{\rho} & 0 & \frac{\rho_v}{\rho}w \end{bmatrix} \tag{3.81}$$

$$
\underline{R}_1 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{(\lambda+2\mu)u}{\rho} & \frac{(\lambda+2\mu)}{\rho} & 0 & 0 & 0 & \frac{(\lambda+2\mu)u}{\rho} \\
-\frac{\mu v}{\rho} & 0 & \frac{\mu}{\rho} & 0 & 0 & -\frac{\mu v}{\rho} \\
-\frac{\mu w}{\rho} & 0 & 0 & \frac{\mu}{\rho} & 0 & -\frac{\mu w}{\rho} \\
-\left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{u^2}{\rho} - \left(\mu - \frac{k}{C_v}\right)\frac{(v^2+w^2)}{\rho} - \frac{k}{C_v}\frac{e}{\rho^2} & \left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{u}{\rho} & \left(\mu - \frac{k}{C_v}\right)\frac{v}{\rho} & \left(\mu - \frac{k}{C_v}\right)\frac{w}{\rho} & \frac{k}{\rho C_v} & -\left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{u^2}{\rho} - \left(\mu - \frac{k}{C_v}\right)\frac{(v^2+w^2)}{\rho} - \frac{k}{C_v}\frac{e}{\rho^2} \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{3.82}
$$

$$
\underline{R}_2 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
-\mu\frac{u}{\rho} & \frac{\mu}{\rho} & 0 & 0 & 0 & -\mu\frac{u}{\rho} \\
-(\lambda+2\mu)\frac{v}{\rho} & 0 & \frac{(\lambda+2\mu)}{\rho} & 0 & 0 & -(\lambda+2\mu)\frac{v}{\rho} \\
-\mu\frac{w}{\rho} & 0 & 0 & \frac{\mu}{\rho} & 0 & -\mu\frac{w}{\rho} \\
-\left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{v^2}{\rho} - \left(\mu - \frac{k}{C_v}\right)\frac{(u^2+v^2)}{\rho} - \frac{k}{C_v}\frac{e}{\rho^2} & \left(\mu - \frac{k}{C_v}\right)\frac{u}{\rho} & \left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{v}{\rho} & (\lambda+2\mu)\frac{w}{\rho} & \frac{k}{\rho C_v} & -\left(\lambda+2\mu - \frac{k}{C_v}\right)\frac{v^2}{\rho} - \left(\mu - \frac{k}{C_v}\right)\frac{(u^2+v^2)}{\rho} - \frac{k}{C_v}\frac{e}{\rho^2} \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{3.83}
$$

$$\underline{R}_3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ -\mu\frac{u}{\rho} & \frac{\mu}{\rho} & 0 & 0 & 0 & -\mu\frac{u}{\rho} \\ -\mu\frac{v}{\rho} & 0 & \frac{\mu}{\rho} & 0 & 0 & -\mu\frac{v}{\rho} \\ -(\lambda+2\mu)\frac{w}{\rho} & 0 & 0 & \frac{(\lambda+2\mu)}{\rho} & 0 & -(\lambda+2\mu)\frac{w}{\rho} \\ \begin{matrix} -\left(\lambda+2\mu\right. \\ \left.-\frac{k}{C_v}\right)\frac{w^2}{\rho} \\ -\left(\mu-\frac{k}{C_v}\right) \\ \frac{(u^2+v^2)}{\rho} \\ -\frac{k}{C_v}\frac{e}{\rho} \end{matrix} & \left(\mu-\frac{k}{C_v}\right)\frac{u}{\rho} & \left(\mu-\frac{k}{C_v}\right)\frac{v}{\rho} & \begin{matrix} \left(\lambda+2\mu\right. \\ \left.-\frac{k}{C_v}\right)\frac{w}{\rho} \end{matrix} & \frac{k}{\rho C_v} & \begin{matrix} -\left(\lambda+2\mu\right. \\ \left.-\frac{k}{C_v}\right)\frac{w^2}{\rho} \\ -\left(\mu-\frac{k}{C_v}\right) \\ \frac{(u^2+v^2)}{\rho} \\ -\frac{k}{C_v}\frac{e}{\rho^2} \end{matrix} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.84}$$

For a packed bed:

$$
\underline{S} = - \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{\mu\beta u}{\rho k} - C\beta^2 u(u^2 + v^2 + w^2)^{1/2} & \frac{\mu\beta}{\rho k} + C\beta^2(2u^2 + v^2 + w^2) \cdot (u^2 + v^2 + w^2)^{-1/2} & C\beta^2 uv(u^2 + v^2 + w^2)^{-1/2} & C\beta^2 uw(u^2 + v^2 + w^2)^{-1/2} & 0 & -\frac{\mu\beta u}{\rho k} \; C\beta^2 u(u^2 + v^2 + w^2)^{1/2} \\
-\frac{\mu\beta v}{\rho k} - C\beta^2 v(u^2 + v^2 + w^2)^{1/2} & C\beta^2 uv (u^2 + v^2 + w^2)^{-1/2} & \frac{\mu\beta}{\rho k} + C\beta^2(u^2 + 2v^2 + w^2) & C\beta^2 vw (u^2 + v^2 + w^2)^{-1/2} & 0 & -\frac{\mu\beta v}{\rho k} - C\beta^2 v(u^2 + v^2 + w^2)^{1/2} \\
-\frac{\mu\beta w}{\rho k} - C\beta^2 w(u^2 + v^2 + w^2)^{1/2} & C\beta^2 uw (u^2 + v^2 + v^2 + w^2)^{-1/2} & C\beta^2 vw + (u^2 + v^2 + v^2 + w^2)^{-1/2} & \frac{\mu\beta}{\rho k} + C\beta^2(u^2 + v^2 + w^2)^{-1/2} & 0 & -\frac{\mu\beta w}{\rho k} + C\beta^2 w(u^2 + v^2 + w^2)^{1/2} \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{3.85}
$$

For a shell-and-tube:

$$
\underline{S} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{2g|m|^{-b}}{\rho^3}\times(m^4+m^2n^2+m^2q^2)^{1/2} & \frac{g|m|^{-b}}{2\rho^2}(m^4+m^2n^2+m^2q^2)^{-1/2}\times(4m^3+2mn^2+2mq^2)-\frac{bg|m|^{-b-1}}{\rho^2}(m^4+m^2n^2+m^2q^2)^{1/2} & \frac{g|m|^{-b}}{\rho^2}(m^4+m^2n^2+m^2q^2)^{-1/2}\times m^2n & \frac{g|m|^{-b}}{\rho^2}(m^4+m^2n^2+m^2q^2)^{-1/2}\times m^2q & 0 & -\frac{2g|m|^{-b}}{\rho^3}\times(m^4+m^2n^2+m^2q^2)^{1/2} \\
-\frac{2g|n|^{-b}}{\rho^3}\times(m^2n^2+n^4+n^2q^2)^{1/2} & g|n|^{-b}(m^2n^2+n^4+n^2q^2)^{-1/2}\times mn^2 & \frac{g|n|^{-b}}{2\rho^2}(m^2n^2+n^4+n^2q^2)^{-1/2}\times(2m^2n+4n^3+2nq^2)-\frac{bg|n|^{-b-1}}{\rho^2}(m^2n^2+n^4+n^2q^2) & g|n|^{-b}(m^2n^2+n^4+n^2q^2)^{-1/2}\times n^2q & 0 & -\frac{2g|n|^{-b}}{\rho^3}\times(m^2n^2+n^4+n^2q^2)^{1/2} \\
-\frac{2g|q|^{-b}}{\rho^3}\times(m^2q^2+n^2q^2+q^4)^{1/2} & \frac{g|q|^{-b}}{\rho^2}(m^2q^2+n^2q^2\;q^4)^{-1/2}\times mq^2 & g|q|^{-b}(m^2q^2+n^2q^2+q^4)^{-1/2}\times nq^2 & g|q|^{-b}(m^2q^2+n^2q^2+q^4)^{-1/2}\times(2m^2q+2n^2q+4q^3)-\frac{bg}{\rho^2}|q|^{-b-1}(m^2q^2+n^2q^2+q^4)^{1/2} & 0 & -\frac{2g|q|^{-b}}{\rho^3}\times(m^2q^2+n^2q^2+q^4)^{1/2} \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{3.86}
$$

3.7. Transformation of the Governing Macroscopic Equations

In numerical modeling flow through open channels, fine mesh points are required near the walls, where the important details of the boundary layers will be lost with a coarse mesh system. In this work, in order to have grid points clustered near the wall where mesh refinement is sometimes necessary, the transformation due to Roberts [53] is used. This transformation is formally represented here as $(x, y, z) \longrightarrow (\xi, \eta, \zeta)$. As an example, in a one dimensional transformation, the y-direction transformation becomes

$$\eta = \gamma + (1-\gamma)\frac{\ln\{[\alpha + (y(2\gamma+1)/h) - 2\gamma] - 2\gamma/(\alpha - (y(2\gamma+1)/h) + 2\gamma]\}}{\ln[(\alpha+1)/(\alpha-1)]} \tag{3.87}$$

$$\eta_y = \frac{2\alpha(1-\gamma)(2\gamma+1)}{h(\alpha^2 - (y(2\gamma+1)/h - 2\gamma)^2)\ln((\alpha+1)/(\alpha-1))} \tag{3.88}$$

Where h is the channel width in y direction, and subscript y represents derivative with respect to y. When $\gamma = 0$ the mesh is refined near $y = h$, where h is the condenser width, and when $\gamma = 1/2$ the mesh refined equally near $y = 0$ and $y = h$. The stretching parameter α is, however, related to the non-dimensional boundary layer thickness by

$$\alpha = \left(1 - \frac{\delta}{h}\right)^{-1/2} \qquad 0 < \frac{\delta}{h} < 1 \qquad ()$$

Similar expressions for ξ, ζ, ξ_x and ζ_z are used, where δ is the boundary layer thickness.

Viviand [63] and Vinokur [65] have shown that in the Navier Stokes equations can be put into the following strong conservation form. Equation (2.26), after the transformation becomes:

$$(\frac{\beta\vec{U}}{J})_t + \left(\frac{\beta\vec{F}\xi_x + \beta\vec{G}\xi_y + \beta\vec{H}\xi_z}{J}\right)_\xi$$

$$+\left(\frac{\beta\vec{F}\eta_x+\beta\vec{G}\eta_y+\beta\vec{H}\eta_z}{J}\right)_\eta+\left(\frac{\beta\vec{F}\xi_x+\beta\vec{G}\zeta_y+\beta\vec{H}\zeta_z}{J}\right)_\zeta$$

$$=\left(\frac{\beta(\vec{V}_1+\vec{V}_2+\vec{V}_3)\xi_x+\beta(\vec{W}_1+\vec{W}_2+\vec{W}_3)\xi_y+\beta(\vec{E}_1+\vec{E}_2+\vec{E}_3)\xi_z}{J}\right)_\xi$$

$$+\left(\frac{\beta(\vec{V}_1+\vec{V}_2+\vec{V}_3)\eta_x+\beta(\vec{W}_1+\vec{W}_2+\vec{W}3)\eta_y+\beta(\vec{E}_2+\vec{E}_3)\eta_z}{J}\right)_\eta$$

$$+\left(\frac{\beta(\vec{V}_1+\vec{V}_2+\vec{V}_3)\zeta_x+\beta(\vec{W}_1+\vec{W}_2+\vec{W}_3)\zeta_y+\beta(\vec{E}_1+\vec{E}_2+\vec{E}_3)\zeta_z}{J}\right)_\zeta$$

$$+\frac{\vec{L}\delta+\vec{Q}\delta}{J} \tag{3.90}$$

Where J is the Jacobian of the transformation

$$J=\frac{\partial(\xi,\eta,\zeta)}{\partial(x,y,z)}=\begin{vmatrix}\xi_x & \xi_y & \xi_z\\ \eta_x & \eta_y & \eta_z\\ \zeta_x & \zeta_y & \zeta_z\end{vmatrix} \tag{3.91}$$

In this work since one dimensional stretching functions are used the above Jacobian reduces to

$$J=\begin{vmatrix}\xi_x & 0 & 0\\ 0 & \eta_y & 0\\ 0 & 0 & \zeta_z\end{vmatrix} \tag{3.92}$$

Equation (3.90) can be written as

$$\begin{aligned}\hat{U}_t+\hat{F}_x i+\hat{G}_\eta+\hat{H}_\zeta &= (\hat{V}_1+\hat{W}_1+\hat{E}_1)_\xi\\ &+(\hat{V}_2+\hat{W}_2+\hat{E}_2)_\eta+(\hat{V}_3+\hat{W}_3+\hat{E}_3)_\zeta\\ &+(\hat{L}+\hat{Q})\delta\end{aligned} \tag{3.93}$$

Where

$$\hat{U} = \frac{\beta\vec{U}}{J}, \hat{F} = \frac{\beta\xi\vec{F}}{J}, \hat{G} = \frac{\beta\eta\vec{G}}{J}, \hat{H} = \frac{\beta\zeta\vec{H}}{J},$$
$$\hat{V}_1 = \frac{\beta\xi\vec{V}_1}{J}, \hat{W}_1 = \frac{\beta\xi\vec{W}_1}{J}, \hat{E}_1 = \frac{\beta\xi\vec{E}_1}{J}, \hat{V}_2 = \frac{\beta\eta\vec{V}_2}{J},$$
$$\hat{W}_2 = \frac{\beta\eta\vec{W}_2}{J}, \hat{E}_2 = \frac{\beta\eta\vec{E}_2}{J}, \hat{V}_3 = \frac{\beta\zeta\vec{V}_3}{J}, \hat{W}_3 = \frac{\beta\zeta\vec{W}_3}{J},$$
$$\hat{E}_3 = \frac{\beta\zeta\vec{E}_3}{J}, \hat{L} = \frac{\vec{L}}{J}, \quad \text{and} \quad \hat{Q} = \frac{\vec{Q}}{J} \tag{3.94}$$

$\vec{U}$, $\vec{F}$, $\vec{G}$, $\vec{H}$, and $\vec{L}$ are the same as defined before, however, the remaining vectors are defined as follows:

$$\vec{V}_1 = \xi_x \begin{bmatrix} \rho D\phi'_\xi \\ (\lambda + 2\mu)u_\xi \\ \mu v_\xi \\ \mu w_\xi \\ (\lambda + 2\mu)uu_\xi + \mu v v_x + \mu w w_\xi + kT_\xi \\ \rho D\phi_\xi \end{bmatrix} \tag{3.95}$$

$$\vec{V}_2 = \eta_y \begin{bmatrix} 0 \\ \lambda v_\eta \\ \mu u_\eta \\ 0 \\ \lambda\mu v_\eta + \mu v u_\eta \\ 0 \end{bmatrix} \tag{3.96}$$

$$\vec{V}_3 = \zeta_z \begin{bmatrix} 0 \\ \lambda w_\zeta \\ 0 \\ \mu u_\zeta \\ \lambda\mu w_\zeta + \mu w u_\zeta \\ 0 \end{bmatrix} \tag{3.97}$$

$$\vec{W}_1 = \xi_x \begin{bmatrix} 0 \\ \mu v_\xi \\ \lambda u_\xi \\ 0 \\ \mu u v_\xi + \lambda v u_\xi \\ 0 \end{bmatrix} \tag{3.98}$$

$$\vec{W}_2 = \eta_y \begin{bmatrix} \rho D\phi'_\eta \\ \mu u_\eta \\ (\lambda + 2\mu)v_\eta \\ \mu w_\eta \\ \mu u u_\eta + (\lambda + 2\mu)v v_\eta + \mu w w_\eta + k\underline{T}_\eta \\ \rho D\phi_\eta \end{bmatrix} \tag{3.99}$$

$$\vec{W}_3 = \zeta_z \begin{bmatrix} 0 \\ 0 \\ \lambda w_\zeta \\ \mu v_\zeta \\ \lambda v w_\zeta + \mu w v_\zeta \\ 0 \end{bmatrix} \tag{3.100}$$

$$\vec{E}_1 = \xi_x \begin{bmatrix} 0 \\ \mu w_\xi \\ 0 \\ \lambda u_\xi \\ \mu u w_\xi + \lambda w u_\xi \\ 0 \end{bmatrix} \tag{3.101}$$

$$\vec{E}_2 = \eta_y \begin{bmatrix} 0 \\ 0 \\ \mu w_\eta \\ \lambda v_\eta \\ \mu v w_\eta + \lambda w v_\eta \\ 0 \end{bmatrix} \tag{3.102}$$

$$\vec{E}_3 = \zeta_z \begin{bmatrix} \rho D\phi'_\zeta \\ \mu u_\zeta \\ \mu v_\zeta \\ (\lambda + 2\mu)w_\zeta \\ \mu u u_\zeta + \mu v v_\zeta + (\lambda + 2\mu)w w_\zeta + k\underline{T}_\zeta \\ \rho D\phi_\zeta \end{bmatrix}. \tag{3.103}$$

After the transformation, Equations (3.31), (3.32), and (3.33), become:

$$\left\{\underline{I} + \frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial\xi}(\underline{A} - \underline{P}_1\underline{R}_{1x})^n - \frac{\partial^2(\hat{R}_1)^n}{\partial\xi^2} - \underline{S}^n\delta - \frac{\varepsilon_i(\Delta\xi)^2}{J}\frac{\partial^2 J}{\partial\xi^2}\right]\right\}\Delta\hat{U}^*$$

$$= \frac{\theta\Delta t}{\beta(1+\tau)}\left[\frac{\partial}{\partial\xi}(\Delta\hat{V}_2 + \Delta\hat{V}_3)^{n-1} + \frac{\partial}{\partial\eta}(\Delta\hat{W}_1 + \Delta\hat{W}_3)^{n-1}\right.$$

$$+ \frac{\partial}{\partial \zeta}(\Delta \hat{E}_1 + \Delta \hat{E}_2)^{n-1} + (\Delta \hat{Q})^{n-1}\delta \Bigg]$$

$$+ \frac{\Delta t}{\beta(1+\tau)} \left[\frac{\partial}{\partial \xi}(-\hat{F} + \hat{V}_1 + \hat{V}_2 + \hat{V}_3)^n \right.$$

$$\left. + \frac{\partial}{\partial \eta}(-\hat{G} + \hat{W}_1 + \hat{W}_2 + \hat{W}_3)^n + \frac{\partial}{\partial \zeta}(-\hat{H} + \hat{E}_1 + \hat{E}_2 + \hat{E}_3)^n + \hat{L}^n\delta + \hat{Q}^n\delta \right]$$

$$+ \frac{\xi}{(1+\tau)}\Delta \hat{U}^{n-1} - \frac{\varepsilon_e(\Delta\xi)^4}{J}\frac{\partial^4(J\hat{U}^n)}{\partial \xi^4} \tag{3.104}$$

$$\left\{ \underline{I} + \frac{\theta \Delta t}{\beta(1+\tau)} \left[\frac{\partial}{\partial \eta}(\underline{B} - \underline{P}_2 + \underline{R}_{2\eta})^n - \frac{\partial^2(\hat{R}_2)^n}{\partial \eta^2} - \frac{\varepsilon_i(\Delta\eta)^2}{J}\frac{\partial^2 J}{\partial \eta^2} \right] \right\} \Delta \hat{U}^{**}$$

$$= \Delta \hat{U}^{*} - \frac{\varepsilon_e(\Delta\eta)^4}{J}\frac{\partial^4(J\hat{U}^n)}{\partial \eta^4} \tag{3.105}$$

$$\left\{ \underline{I} + \frac{\theta \Delta t}{\beta(1+\tau)} \left[\frac{\partial}{\partial \zeta}(\underline{C} - \underline{P}_3 + \underline{R}_{3\zeta})^n - \frac{\partial^2(\underline{R}_3)^n}{\partial \zeta^2} - \frac{\varepsilon_i(\Delta\zeta)^2}{J}\frac{\partial^2 J}{\partial \zeta^2} \right] \right\} \Delta \hat{U}^{n}$$

$$= \Delta \hat{U}^{**} - \frac{\varepsilon_e(\Delta\zeta)^4}{J}\frac{\partial^4(J\hat{U}^n)}{\partial \zeta^4} \tag{3.106}$$

$$\hat{U}^{n+1} = \hat{U}^n + \Delta \hat{U}^n. \tag{3.107}$$

Where $\underline{A} = \xi_x \underline{A}$, $\hat{R}_1 = \xi_x \xi_x \underline{R}_1$, and $-\underline{P}_1 + \underline{R}_{1\xi} =$

$$\beta \xi_x \xi_x \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -(\lambda+2\mu)_\xi \frac{u}{\rho} & \frac{(\lambda+2\mu)_\xi}{\rho} & 0 & 0 & 0 \\ -\mu_\xi \frac{v}{\rho} & 0 & \frac{\mu_\xi}{\rho} & 0 & 0 \\ -\mu_\xi \frac{w}{\rho} & 0 & 0 & \frac{\mu_\xi}{\rho} & 0 \\ -\big(\lambda + 2\mu & \big(\lambda + 2\mu & \big(\mu - \frac{k}{\underline{C}_v}\big)_\xi \frac{v}{\rho} & \big(\mu - \frac{k}{\underline{C}_v}\big)_\xi \frac{w}{\rho} & \big(\frac{k}{\underline{C}_v}\big)_\xi \frac{1}{\rho} \\ -\frac{k}{\underline{C}_v}\big)_\xi \frac{u^2}{\rho} & -\frac{k}{\underline{C}_v}\big)_\xi \frac{u}{\rho} & & & \\ -\big(\mu - \frac{k}{\underline{C}_v}\big)_\xi & & & & \\ \frac{(v^2+w^2)}{\rho} & & & & \\ -\big(\frac{k}{\underline{C}_v}\big)_\xi \frac{e}{\rho^2} & & & & \end{bmatrix} \tag{3.108}$$

Jacobians $-\underline{P}_2 + \underline{R}_{2\eta}$, and $-\underline{P}_3 + \underline{R}_{3\zeta}$ are found similarly.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Introductory Remarks

In order to implement the numerical scheme presented in the previous chapter, a computer program was developed. The computer program (Appendix A-2) was written in FORTRAN 77, and was run on an IBM/RS-6000 model 243P computer. Three groups of model calculations will be presented and discussed. In the first group, addressed in section 4.2, the porous-media flow terms are left out, and the Navier-Stokes equations are numerically solved for several one and two dimensional laminar flow problems, and compared with analytical and numerical solutions. This is done in order to demonstrate the correctness of the basic numerical scheme developed in this thesis.

In the second group of model calculations, presented in section 4.3, flow in porous media is addressed. Once again, to demonstrate the correctness of the developed model, simple systems are simulated, and the generated numerical results are compared with analytical and numerical solutions.

Finally, in the third group of calculations, presented in section 4.4, the numerical model is applied to shell-and-tube and packed-bed condensers with simple geometries.

Due to the complexity of the problem and to the absence of similar experiences in the open literature, a well-known explicit numerical scheme was implemented in this research in order to validate some the results of this work. This explicit, predictor-corrector scheme is known as the explicit MacCormack scheme [61] and is implemented when two dimensional flow is considered as follows:

Predictor:

$$\vec{U}_{i,j}^{\overline{n+1}} = \vec{U}_{i,j}^{n} - \frac{\Delta t}{\Delta x}\left[\left(\vec{F}_{i-1,j}^{n} - \vec{F}_{i,j}^{n}\right) - \left(\vec{V}_{1_{i+1,j}}^{n} - \vec{V}_{1_{i,j}}^{n}\right) - \left(\vec{V}_{2_{i-1,j}}^{n} - \vec{V}_{2_{i,j}}^{n}\right)\right] - \frac{\Delta t}{\Delta y}\left[\left(\vec{G}_{i,j+1}^{n} - \vec{G}_{i,j}^{n}\right) - \left(\vec{W}_{1_{i,j+1}}^{n} - \vec{W}_{1_{i,j}}^{n}\right) - \left(\vec{W}_{2_{i,j+1}}^{n} - \vec{W}_{2_{i,j}}^{n}\right)\right] \tag{4.1}$$

Corrector:

$$\vec{U}_{i,j}^{n+1} = \frac{1}{2}\left\{\vec{U}_{i,j}^{n} + \vec{U}_{i,j}^{\overline{n+1}} - \frac{\Delta t}{\Delta x}\left[\left(\vec{F}_{i,j}^{\overline{n+1}} - \vec{F}_{i-1,j}^{\overline{n+1}}\right) - \left(\vec{V}_{1_{i,j}}^{\overline{n+1}} - \vec{V}_{1_{i-1,j}}^{\overline{n1}}\right) - \left(\vec{V}_{2_{i,j}}^{\overline{n+1}} - \vec{V}_{2_{i,j-1}}^{\overline{n+1}}\right)\right] - \frac{\Delta t}{\Delta y}\left[\left(\vec{G}_{i,j}^{\overline{n+1}} - \vec{G}_{i,j-1}^{\overline{n+1}}\right) - \left(W_{1_{i,j}}^{\overline{n+1}} - W_{1_{i,j-1}}^{\overline{n+1}}\right) - \left(W_{2_{i,j}}^{\overline{n+1}} - W_{2_{i,j-1}}^{\overline{n+1}}\right)\right]\right\} \tag{4.2}$$

where $\vec{U}$, $\vec{F}$, $\vec{V}_1$, $\vec{V}_2$, $\vec{G}$, $\vec{W}_1$, and $\vec{W}_2$ are defined by Equations (2.33), (2.34), (2.37), (2.38), (2.35), (2.40), and (2.41), respectively, with the exception that w, the z-velocity, is set equal to zero. The intermediate time-level parameters $\vec{F}_{i,j}^{\overline{n+1}}$, $\vec{V}_{2_{i,j}}^{\overline{n+1}}$, etc., are calculated after calculating the premitive variables from the conservative variables vector $\vec{U}_{i,j}^{\overline{n+1}}$.

The above scheme is simple to implement, however, it has very stringent time step restrictions, especially when a high Reynolds number flow is involved. Furthermore, when the porous media terms were included in this scheme, it was found to be very unstable. This problem might be related to improper boundary conditions imposition which needs to be investigated separately.

Different inlet and outlet boundary conditions were implemented for the MacCormack scheme when porous media terms are present, unfortunately, without success. The first inlet boundary condition implemented for the McCormack scheme is done by prescribing the inlet pressure and the density and extrapolating the velocity from the interior whereas the second inlet boundary condition is implemented by prescribing the velocity and the density at the inlet and extrapolating the pressure from the interior. The pressure was, however, prescribed at the outlet and the other variables were extrapolated from the interior.

The above scheme was implemented in two dimensions for the cases in which no porous media terms were included and the results were found identical to those results generated from the implicit factored scheme as will be shown later.

However, due to the above mentioned difficulty, the porous media numerical results are only compared with simple one dimensional analytical solutions and a simple 3-D numerical model.

Beside the comparison with the two dimensional explicit scheme discussed above, the results of implicit factored scheme developed in this research were also compared with some one dimensional analytical solutions.

Boundary conditions implementation, as discussed in section 3.5, is one of the most difficult aspects of compressible fluid flow modeling, and it is customary to start with very simple boundary conditions to make sure that the computer code is running without any problems. This approach will be followed in the forthcoming calculations.

4.2. Numerical Tests for Navier-Stokes Equations

One of the basic tests that is performed in this research is the calculation of the unsteady flow between two infinite adiabatic walls. This run will be referred to as Case 1. The objective is to check the temporal as well as the spatial accuracy of the numerical scheme and its boundary conditions.

Periodic boundary conditions are used in the x-direction in which the flow variables at $i = 1$ are set to be equal to the flow variables at $i = \ell - 1$ at every time step and the flow variables at $i = \ell$ are set to be equal to the flow variables at $i = 2$ where $i = 1$ and $i = \ell$ are the first and the last grid points in the x-direction, respectively. As can be seen, the above boundary conditions are very simple to implement explicitly and implicitly and do not require any additional specification of inlet or outlet boundary conditions.

In the calculations, the lower boundary (representing the lower plate) was assumed to be fixed, the flow was assumed initially at rest, while the upper boundary (upper plate) had an initial velocity u_0 in its own plane. An 11×11 uniform grid was used in this calculation with the following parameters:

$\Delta x = 0.00001$ m

$\Delta y = 0.00001$ m

$\Delta t = 1 \times 10^{-9}$ s

$\mu = 1.85 \times 10^{-5}\ kg/ms$

ρ_v = density of gas 1 = $0.016\ kg/m^3$

ρ_g = density of gas 2 = $0.016\ kg/m^3$

$T = 300$ K

$u_0 = 100$ m/s

The results of this Couette flow, figure 4.1, and predictions of the analytical solutions [62] are in good agreement. The steady state solution is achieved after approximately 300 iteration.

The above calculation was also repeated in such a way that x was made the moving dimension and y was made the periodic spatial boundary. The same procedure was also repeated for the x-z and y-z-dimensions. This was done to ensure that the same results are obtained in all directions. The results were similar to Figure 4.1, and confirmed correctness of the solution scheme.

The next test referred to hereafter as Case 2, is the flow behavior near an oscillating flat plate. This test was chosen to also check the temporal as well as the spatial accuracy of the computer code. Periodic boundary conditions similar to those described for the previous test were chosen in the x-direction. The lower boundary was assumed at rest, and the upper boundary was oscillating with a period of 500 s^{-1}. The same grid and calculation parameters of the previous example were chosen for this example except that, here:

$$\Delta t = 1 \times 10^{-8} s$$

and

$$u_0 = 100 \sin\left(\frac{2\pi N \Delta t}{500 \Delta t}\right)$$

where u_0 is the oscillating velocity of the upper plate, and N is the number of time steps. The same test was repeated for all directions.

The computed results are compared with the exact solutions [62] in Figure 4.2, indicating excellent agreement.

Case 3, Figure 4.3, is a straight duct flow in which the Mach number is maintained very low inside the duct to simulate incompressible flow. In this example the inlet velocity is maintained constant and the outlet pressure is

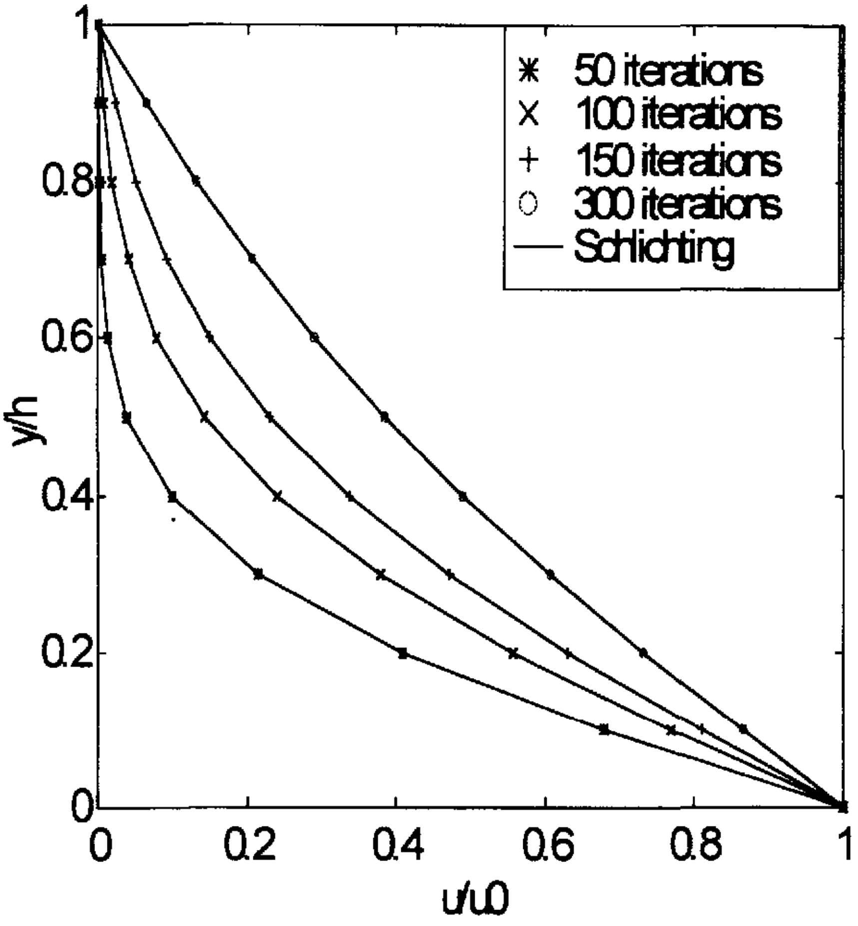

Figure 4.1. Flow Formation in Couette Motion (Case 1).

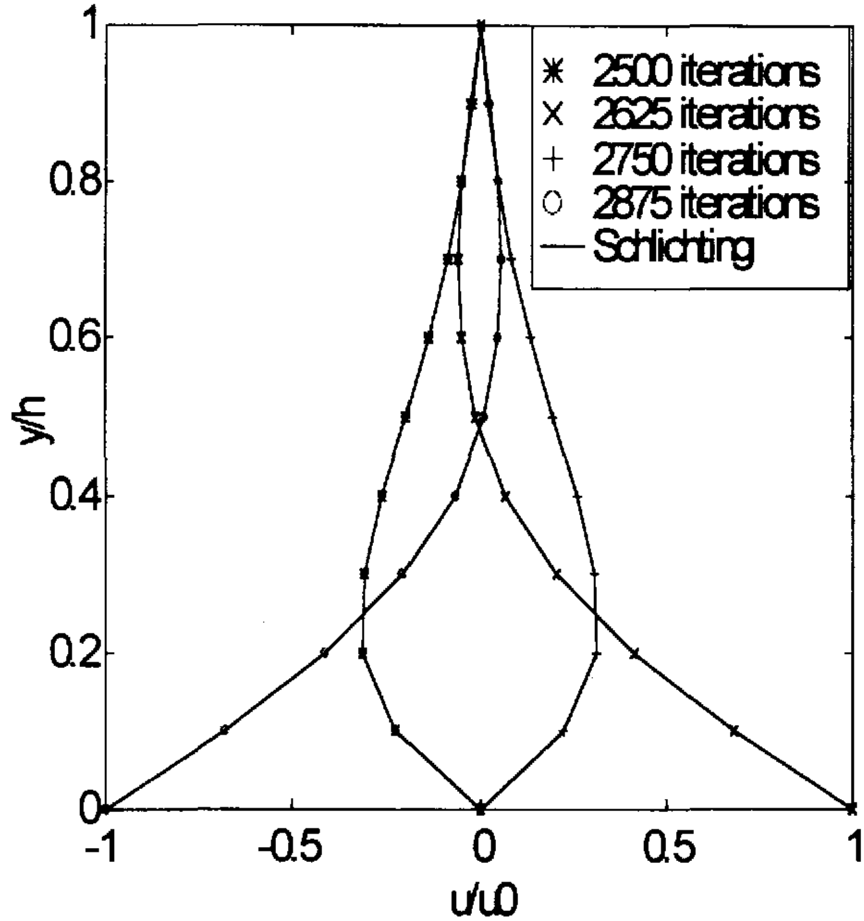

Figure 4.2. Velocity Distribution in the Neighborhood of an Oscillating Wall (Case 2).

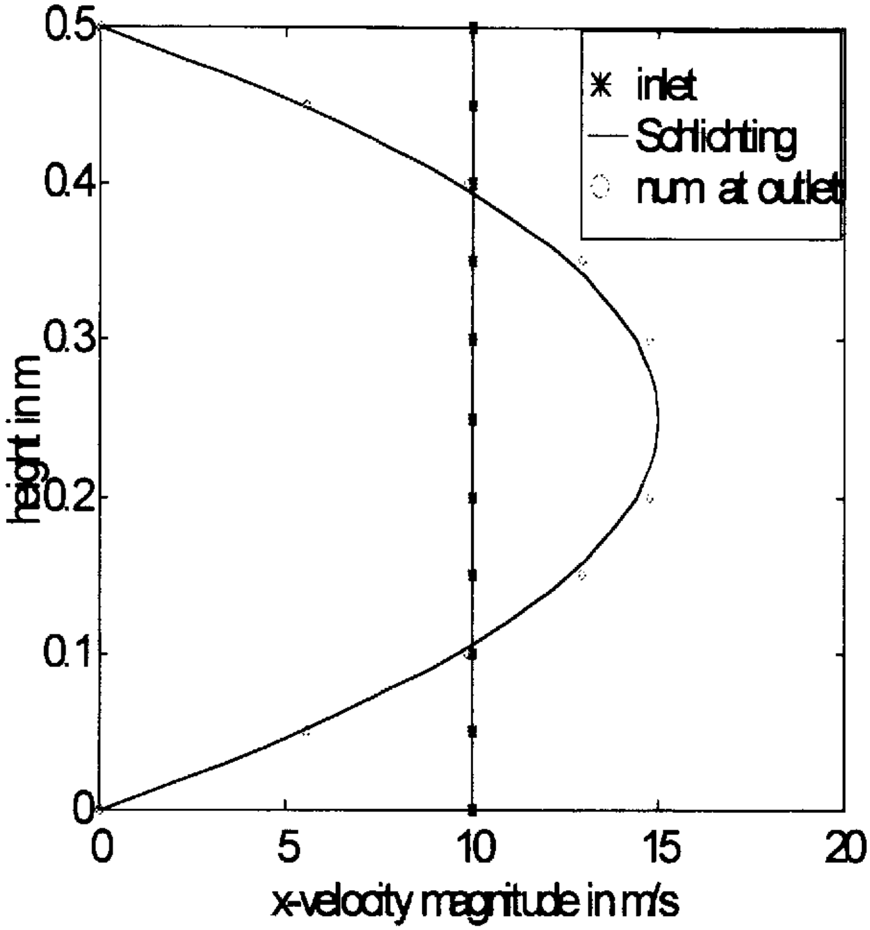

Figure 4.3. Straight Duct Velocity Distribution at Inlet and outlet (Case 3).

specified. The outlet pressure is maintained relatively high to maintain low Mach number. The x-velocity magnitude is presented and found in good agreememt with the analytical solution [62], the parabolic shape is recovered at the outlet. The relatively small difference between the numerical and the analytical results is due to the fact that in order to simulate exact incompressible flow using compressible numerical schemes one has to set the Mach number equal to zero. This condition, however, requires imposing infinite pressure values at the outlet which is impossible to do numerically.

The explicit methods for solving the compressible Navier-Stokes equations as well as some implicit ones are limited to time steps usually less than the Courant-Friedrichs-Lewy (CFL) condition:

$$\Delta t \leq \frac{1}{\left(\frac{(u)}{\Delta x} + \frac{(v)}{\Delta y} + \frac{(w)}{\Delta z} + a\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}\right)} \tag{4.3}$$

This condition shows that $\Delta t \to 0$ as $a \to \infty$ where a is the speed of sound. However a approaches infinity for incompressible flows. This is the reason why it is not possible to simulate exact incompressible flows using compressible numerical schemes. The parameters for Figure 4.3, and 4.4 are

$\Delta x = 0.05\ m$

$\Delta y = 0.025\ m$

$\rho = 0.28\ kg/m^3$

$\mu = 0.056\ kg/ms$

21×21 uniform grid

Inlet velocity $= 10\ m/s$

Outlet pressure $= 2000\ N/m^2$

Figure 4.4 shows the relative errors of the conservative variables (i.e., ρ_v, ρu, ρv, ρw, e, ρ_g) versus the iteration number. It can be seen that the relative errors of

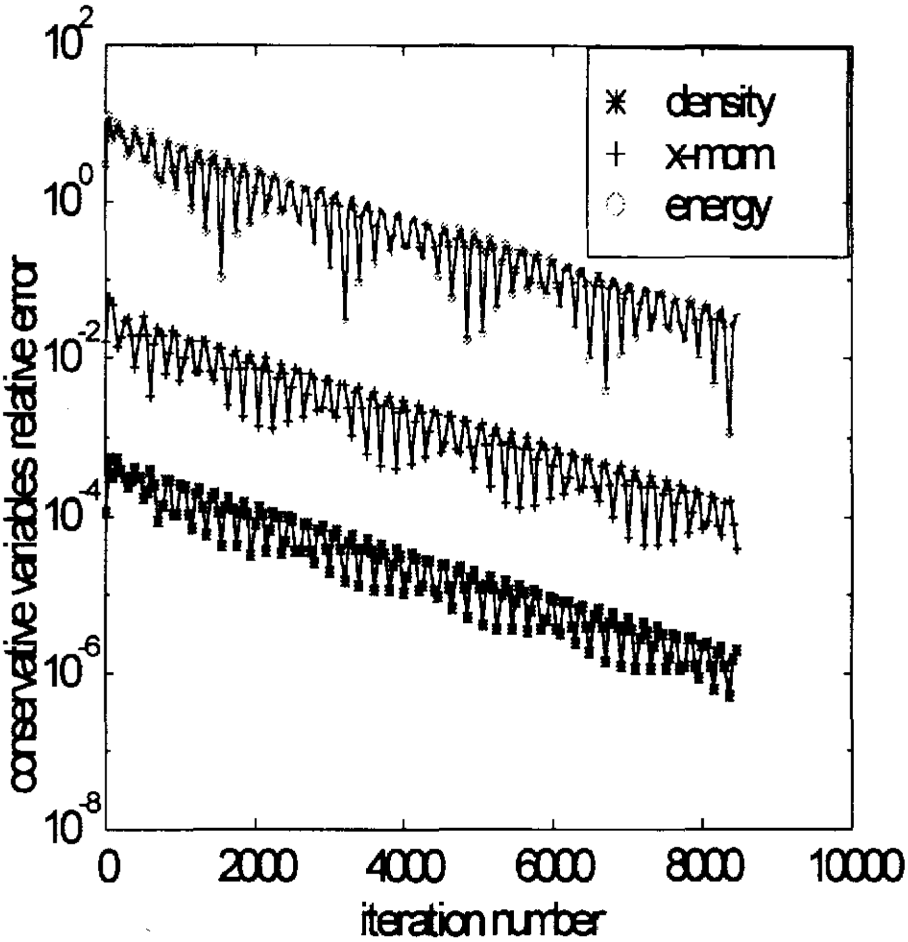

Figure 4.4. Conservative Variables Relative Errors (Case 4).

the conservative variables decrease as the iteration number increases until the convergence criterion is achieved.

The next example Case 4, the results of which are depicted in Figures 4.5, 4.6, and 4.7, is similar to the previous one except that the pressure is specified both at the inlet and the outlet, as:

Inlet pressure = 2020 N/m^2

Outlet pressure = 2000 N/m^2

The pressure is maintained relatively large to maintain small Mach number in order to simulate incompressible flow. The velocity distribution (Figure 4.5) as well as the pressure drop (Figure 4.6) are in good agreement with the analytical solution. Figure 4.7 shows the relative error of the conservative variables. This error as expected decreases with more iterations, until convergence is achieved.

The tests that were discussed before dealt with incompressible flow only, because the Mach number was maintained very low. However, in order to test the computer code for compressible flows the Mach number has to be increased. Two one dimensional, compressible cases referred to as Cases 5 and 6 in the following, are discussed here. The parameters for these cases are:

Parameters for Case 5:

$\Delta x = 0.05\ m$

$\Delta y = 0.025\ m$

$\mu = 0.504\ kg/ms$

Inlet density of gas 1 = 2.52 kg/m^3

Inlet density of gas 2 = 0.0000252 kg/m^3

Inlet velocity = 10 m/s

Outlet pressure = 2000 N/m^2

(21 × 21) grid points

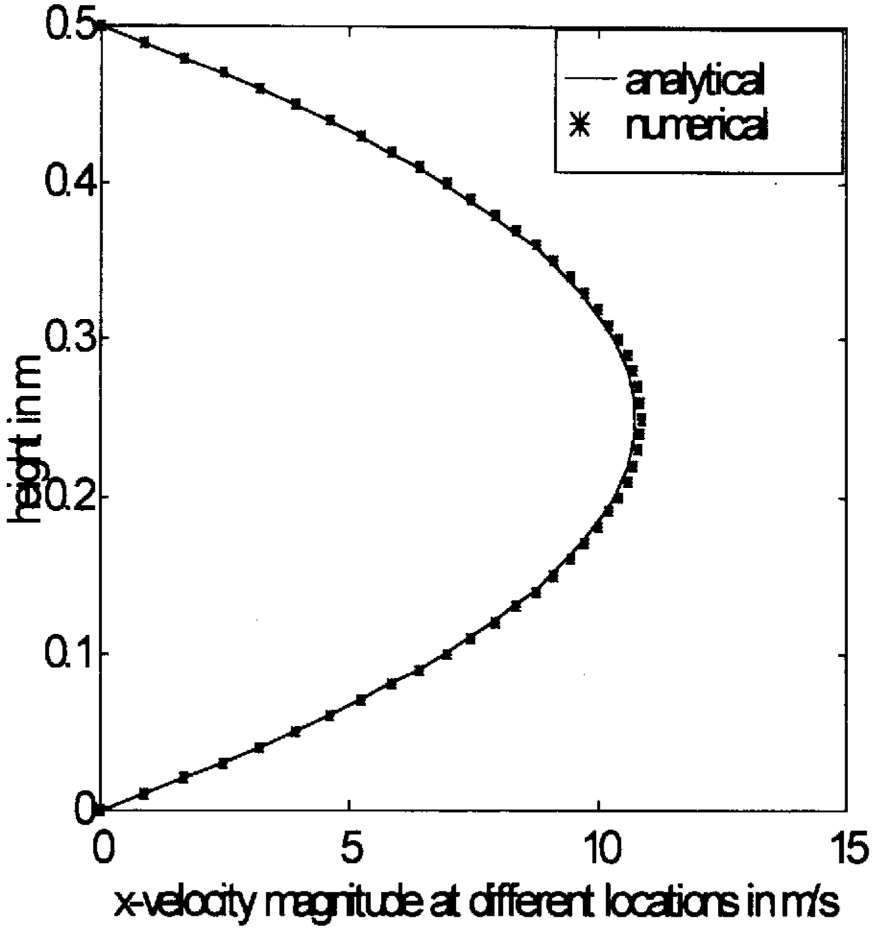

Figure 4.5. Straight Duct Velocity Distribution at Constant Inlet Pressure (Case 4).

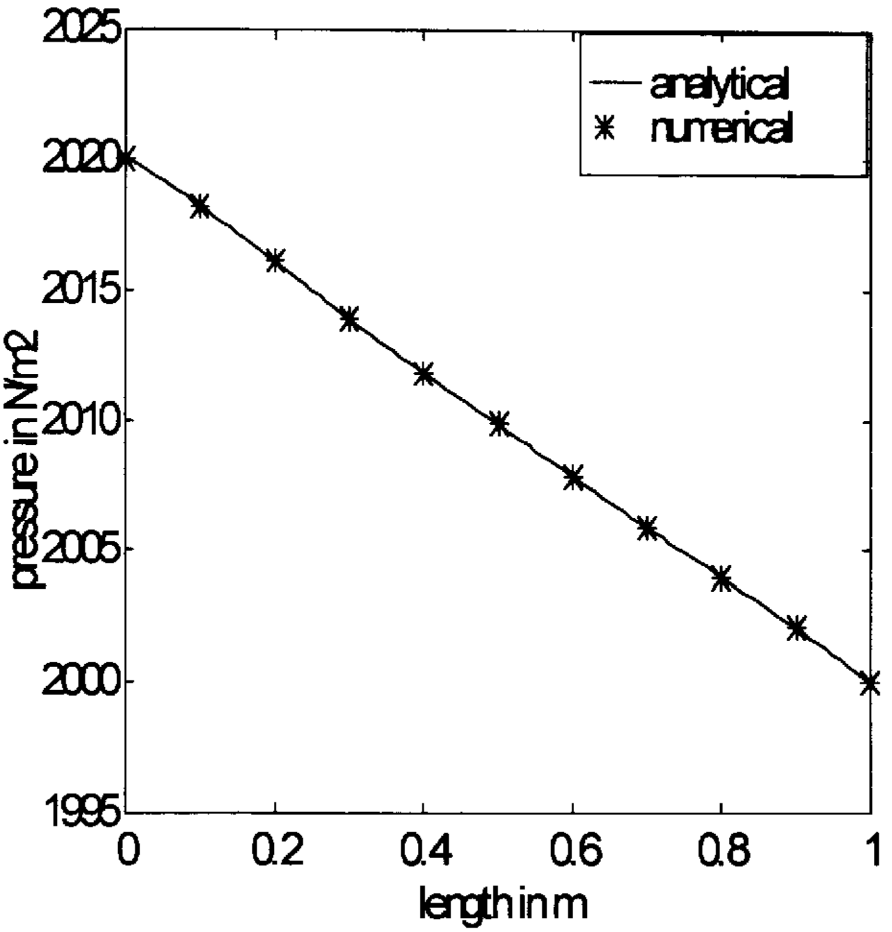

Figure 4.6. Straight Duct Pressure Distribution at Constant Inlet Pressure (Case 4).

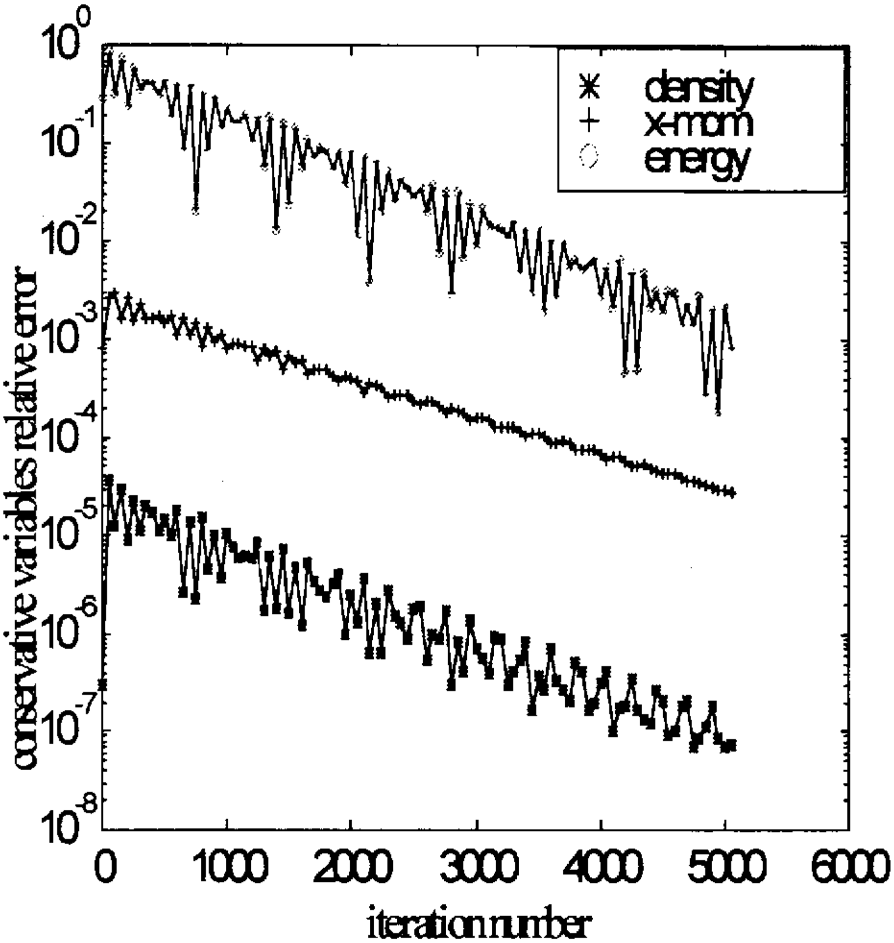

Figure 4.7. Conservative variables Relative Errors (Case 4).

Parameters for Case 6:

$\Delta x = 0.05\ m$

$\Delta y = 0.025\ m$

$\mu = 0.504\ kg/ms$

Inlet density of gas 1 $= 2.52\ kg/m^3$

Inlet density of gas 2 $= 0.0000252\ kg/m^3$

Inlet pressure $= 2300\ N/m^3$

Outlet pressure $= 2000\ N/m^3$

(21×21) grid points

Figures 4.8, 4.9, 4.10, 4.11, and 4.12 represent Case 5. Figure 4.8 shows the velocity distribution, Figure 4.9 shows the pressure distribution, Figure 4.10 shows the density variation of gas 1, Figure 4.11 shows the density variation of gas 2 and, finally, Figure 4.12 shows the conservative variables error as a function of iteration number. Using simple calculations, it can be shown that in this computation mass is always conserved at any cross-section along the duct.

Figures 4.13, 4.14, 4.15, and 4.16 are similar to those discussed above except that they were generated for the aforementioned Case 6, namely, at fixed inlet and outlet pressures. As noted, the above two compressible cases are found to be in good agreement with those generated from the explicit scheme.

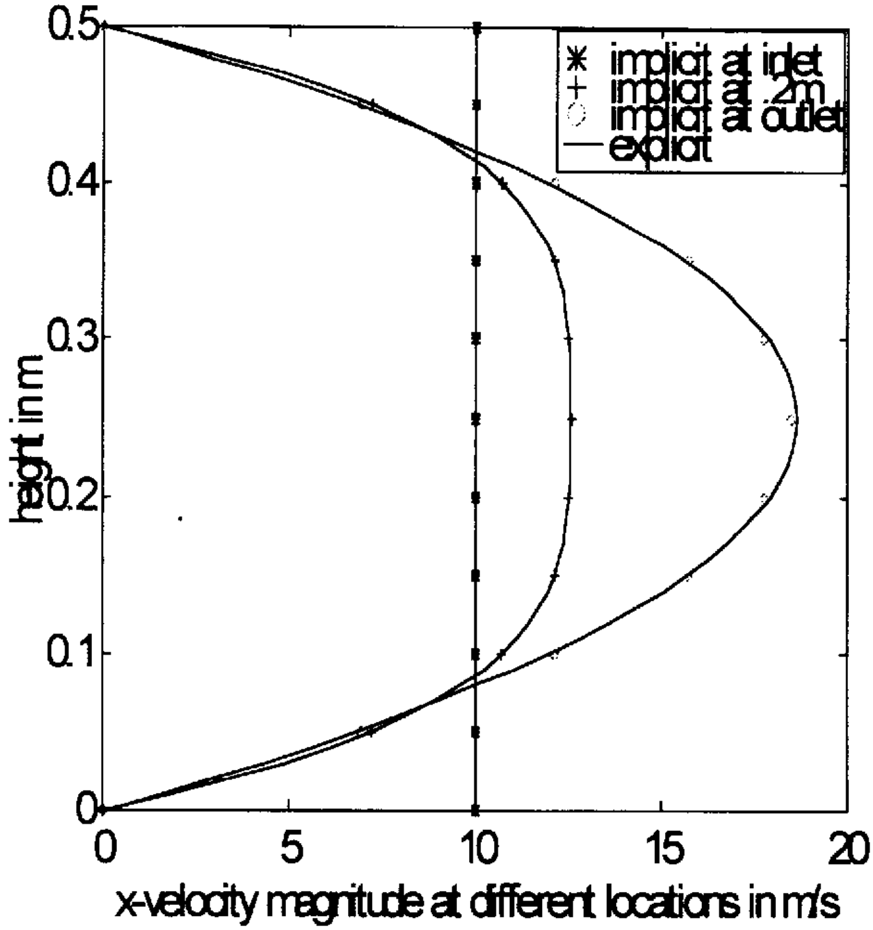

Figure 4.8. Velocity Distribution at High Mach Number and Constant Inlet Velocity (Case 5).

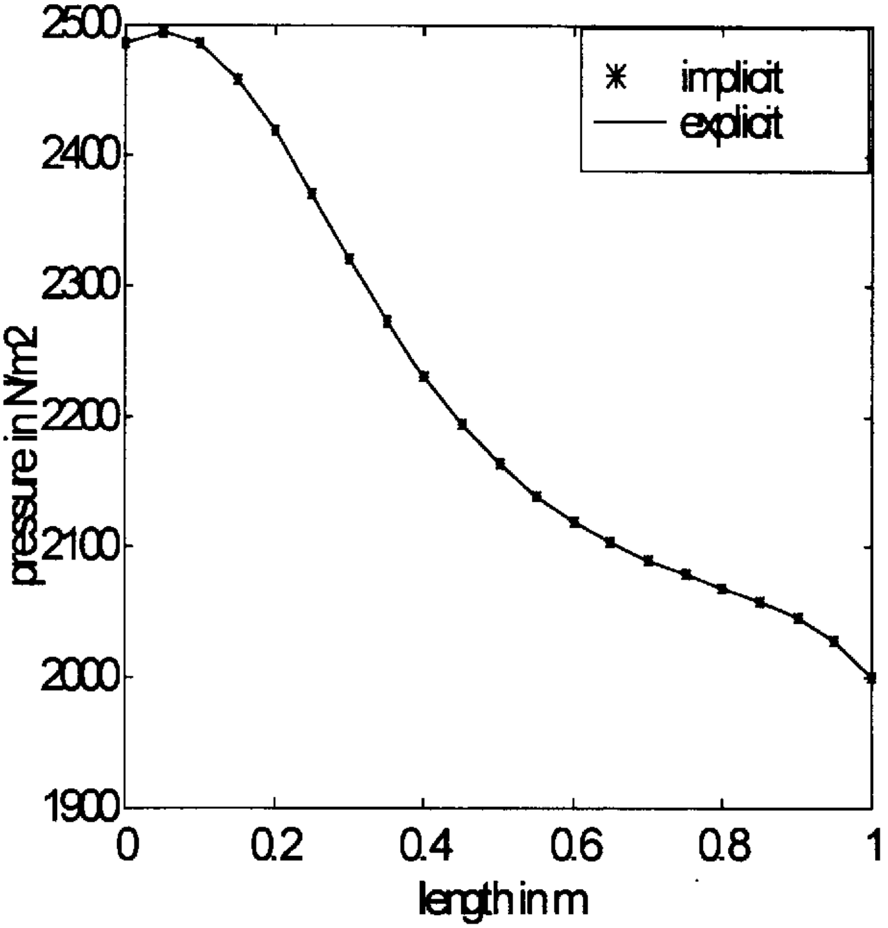

Figure 4.9. Pressure Distribution at High Mach Number and Constant Inlet Velocity (Case 5).

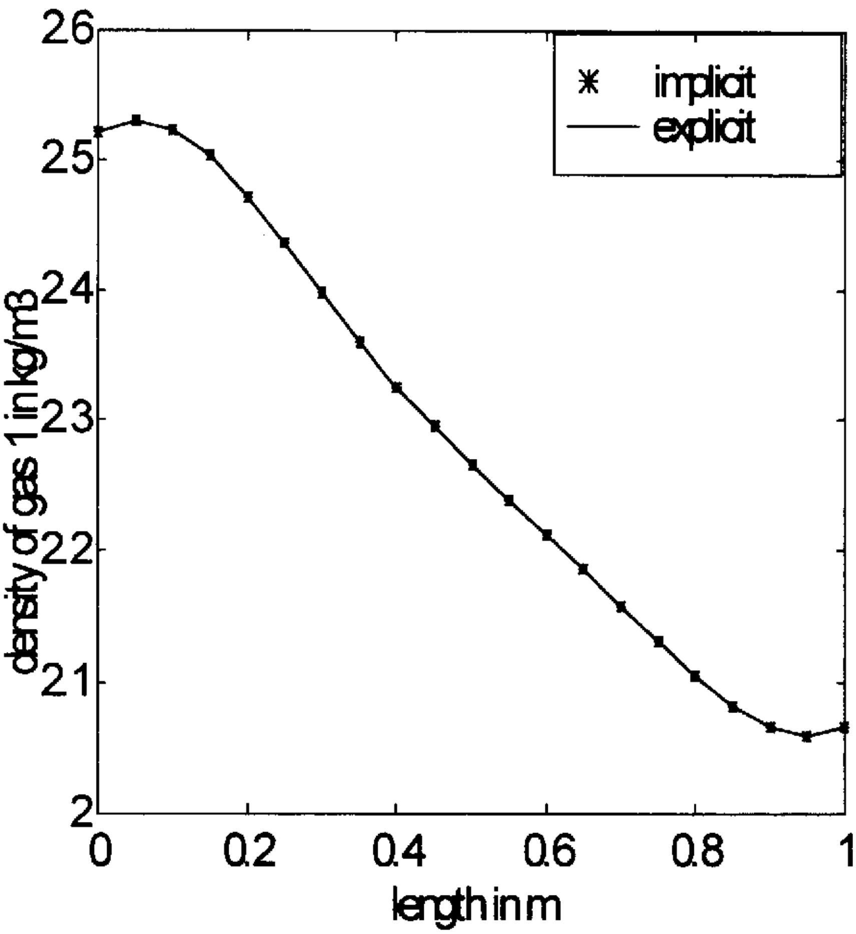

Figure 4.10. Density of Gas 1 at High Mach Number and Constant Inlet Velocity (Case 5).

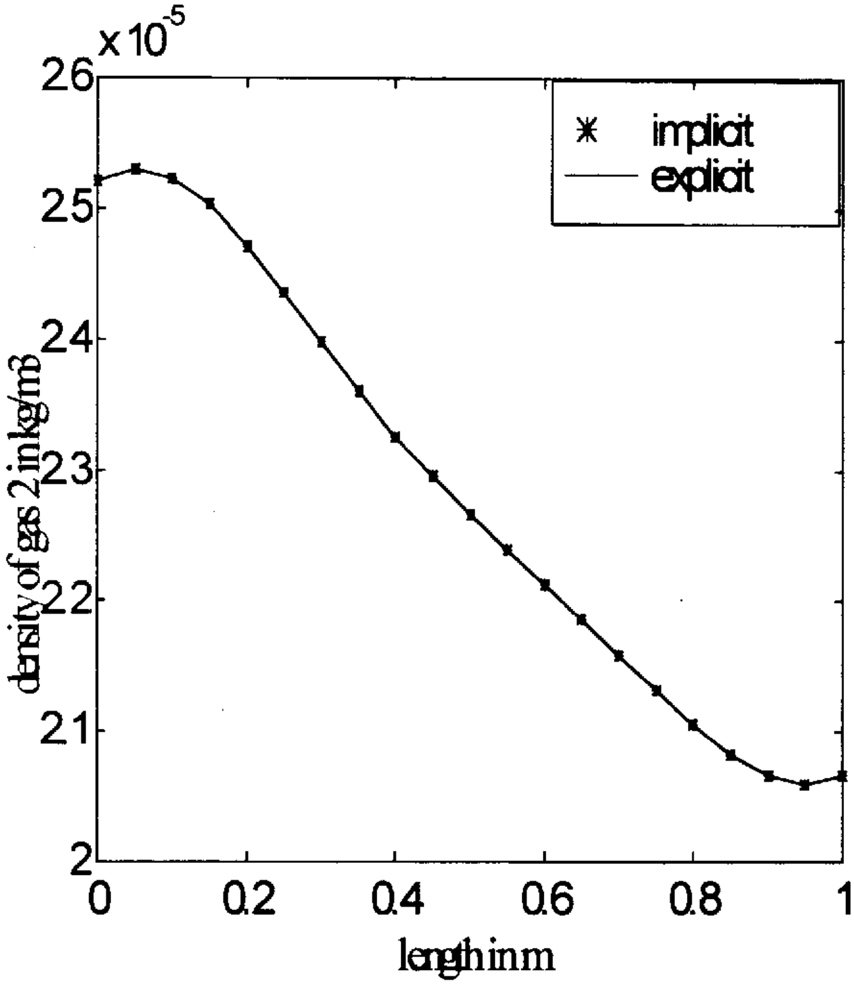

Figure 4.11. Density of Gas 2 at High Mach Number and Constant Inlet Velocity (Case 5).

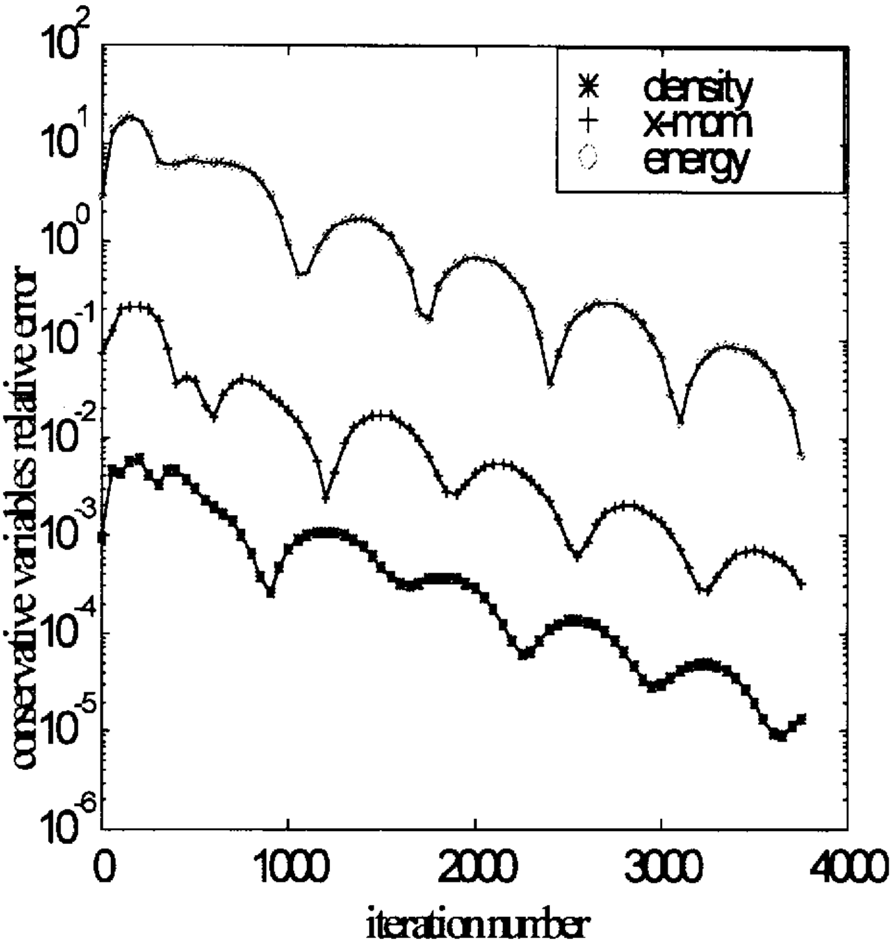

Figure 4.12. Conservative Variables Relative Error at High Mach Number and Constant Inlet Velocity (Case 5).

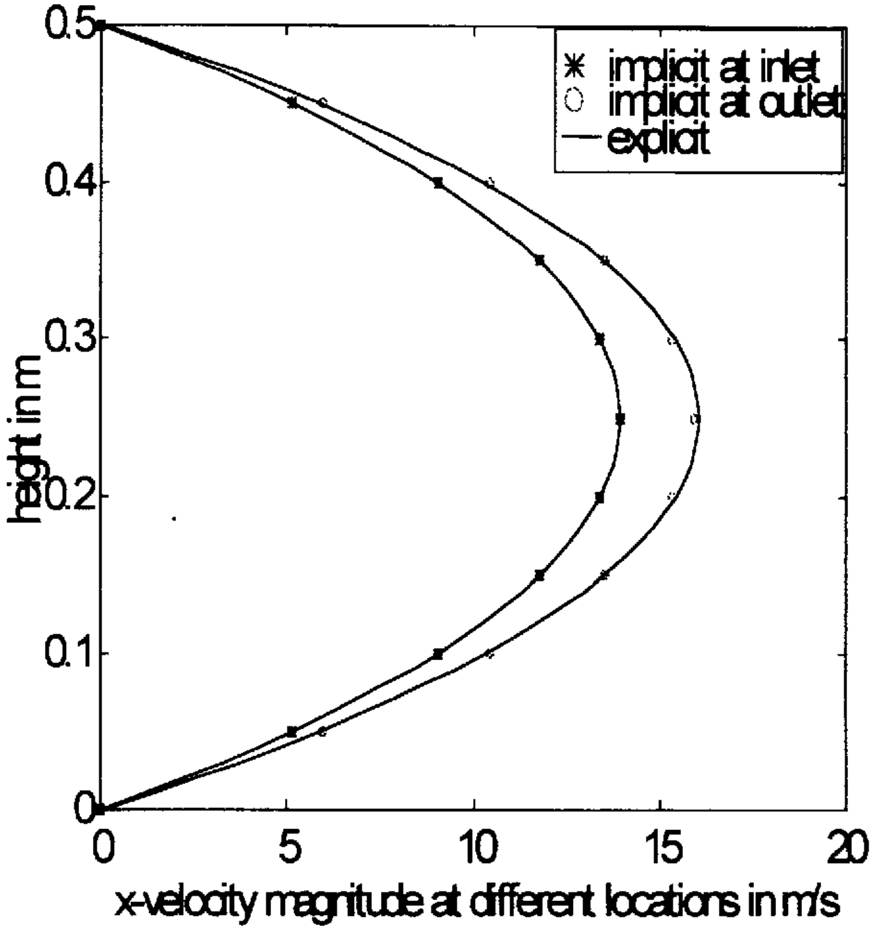

Figure 4.13. Velocity Distribution at High Mach Number and Constant Inlet Pressure (Case 6).

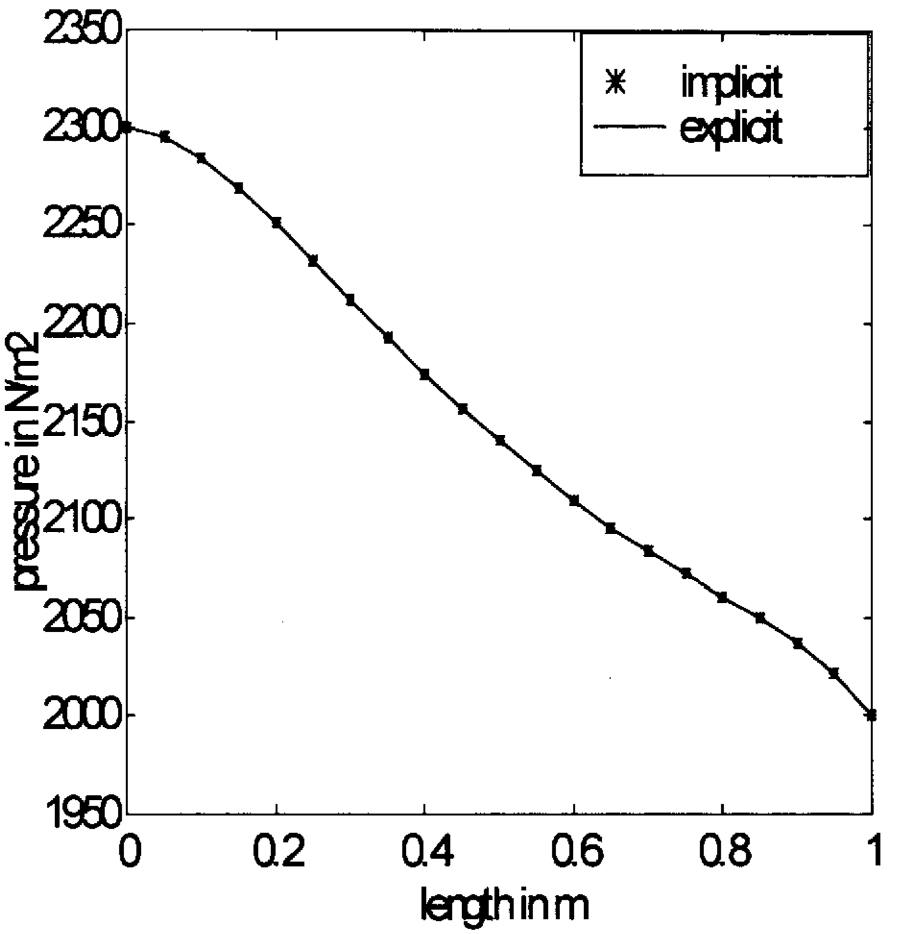

Figure 4.14. Pressure Distribution at High Mach Number and Constant Inlet Pressure (Case 6).

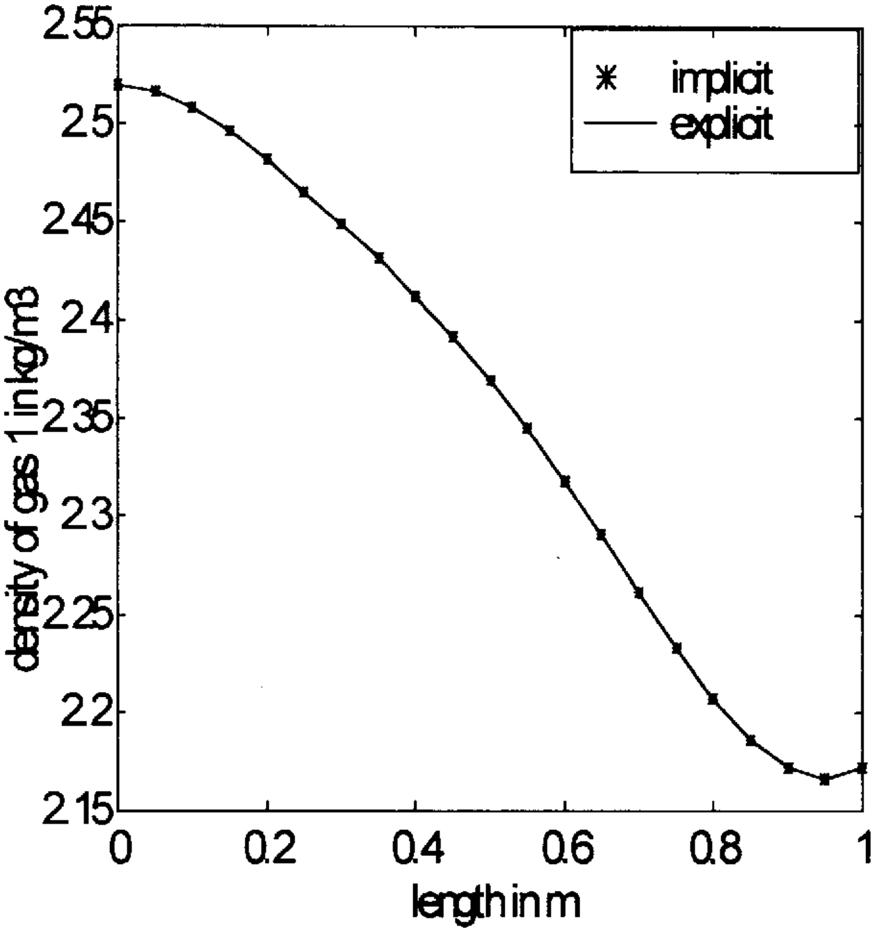

Figure 4.15. Density of Gas 1 at High Mach Number and Constant Inlet Pressure (Case 6).

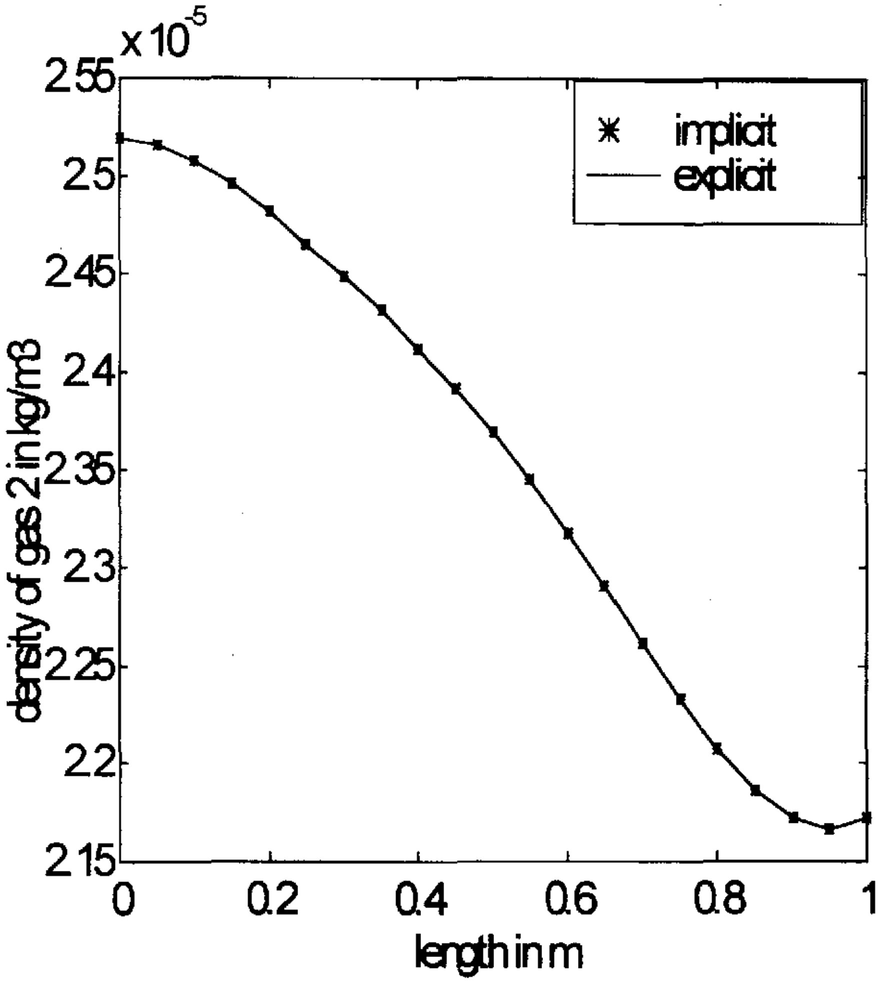

Figure 4.16. Density of Gas 2 at High Mach Number and Constant Inlet Pressure (Case 6).

The calculation results that were discussed so far are for one dimensional flow only. Some two dimensional cases will now be discussed. The conditions for the first two dimensional case, referred to as Case 7, are as follows:

Length = 1 m

Height = 0.5 m

Inlet density = .28 kg/m^3

$\mu = 0.001\ kg/ms$

Inlet pressure = 6050 m/s

Outlet pressure = 6000 N/m^2

(31 $\times$ 31) grid points with meshes clustered near the walls and the inlet and outlet using the stretching function discussed before.

Inlet location at x = 0m and y in the interval (0.3m - 0.5m)

Outlet location at x = 1m and y in the interval (0m - 0.2m)

Figure 4.17 shows the velocity vector magnitudes in two dimensions at low Mach number to simulate incompressible flow. Figure 4.18 shows the pressure contours for the same case. The values shown in Figure 4.18 are above the outlet pressure to generate clear contour lines. The results obtained in these calculations, including those in Figures 4.17 and 4.18 are in good agreement with those generated using the aforementioned MacCormack explicit scheme.

Case 8, to be discussed below, has the following parameters to simulate compressible flow:

Length = 1m

Height = 0.5 m

Inlet density of gas 1= 2.8 kg/m^3

Inlet density of gas 2= 0.000028 kg/m^3

$\mu = 0.01\ kg/ms$

Inlet pressure = 2400 m/s

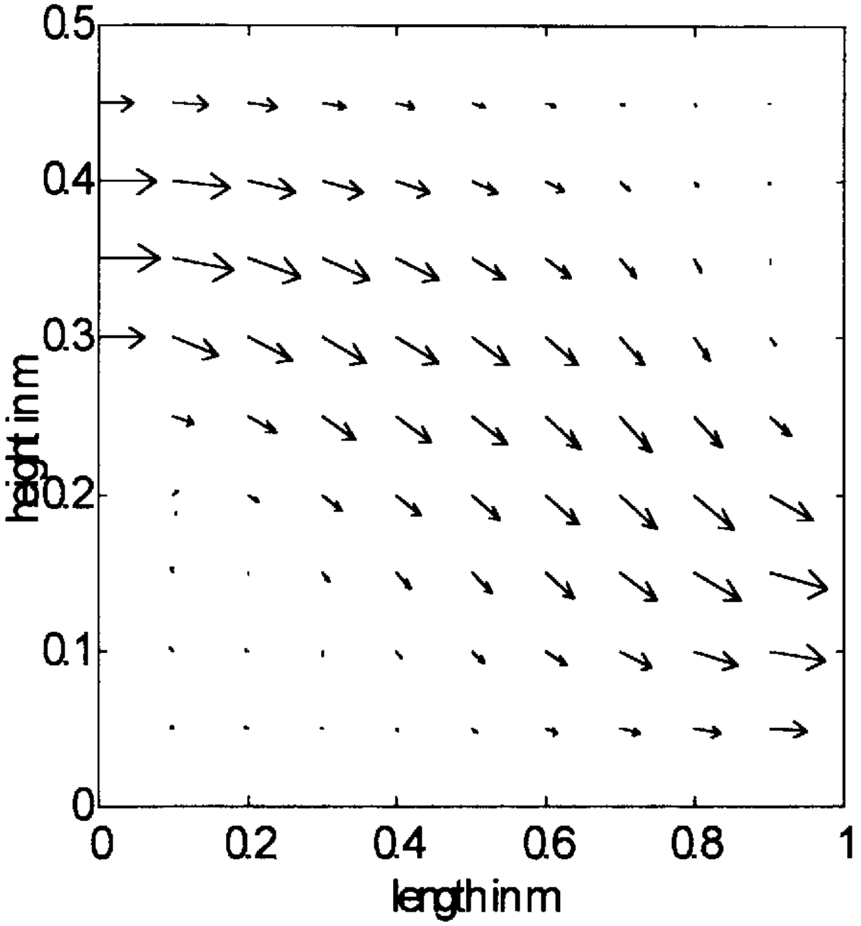

Figure 4.17. Velocity Vector Magnitude at Low Mach Number (Case 7) (scale $1mm = 1.63m/s$).

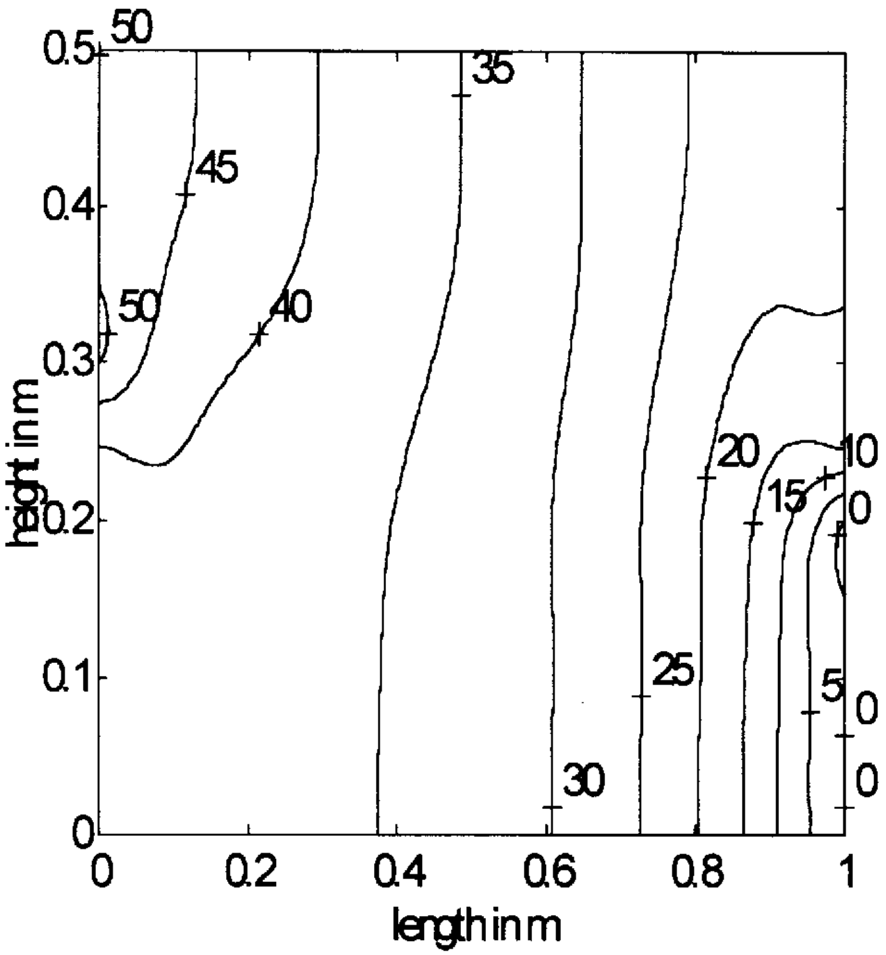

Figure 4.18. Pressure Distribution at Low Mach Number (Case 7) (N/m^2 above exit pressure).

Outlet pressure = 2000 N/m^2

(31×31) grid points with meshes clustered near the walls and the inlet and outlet using the stretching function discussed in section 3.7.

It can be seen that the velocity at the outlet increases (Figure 4.19), and the partial densities of gas 1 and gas 2 decrease (Figures 4.21 and 4.22), in order for the mass to be conserved. The pressure values shown in Figure 4.20 are shown in N/m^2, above the outlet pressure to show better contour contrast.

In summary, the aforementioned case studies indicate that the developed numerical scheme, when applied to an open flow systems (i.e., when Navier-Stokes equations are dealt with), produces predictions which agree with the analytical and numerical solutions. This confirms that the numerical scheme is essentially correct.

4.3. Flow in Porous Media

As mentioned before, were the MacCormak explicit scheme did not work when the porous media terms were included in the system of equations. Due to this reason, one dimensional analytical solutions and a simple numerical model were used to validate the results of the implicit factored scheme.

To simulate a system sufficiently simple for analytical solution, we impose the following assumptions:

- Steady state.
- Fully developed flow in a duct $2H$ in height, and infinitely wide.
- Constant porosity.
- Incompressible flow.
- Brinkman's flow.

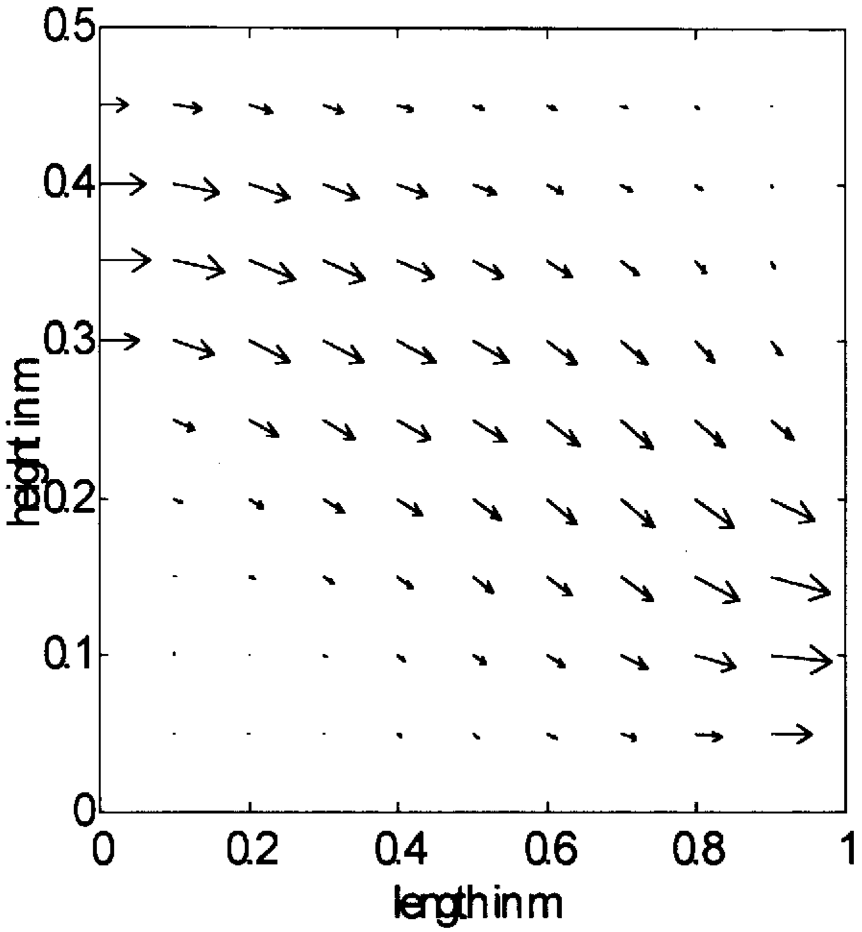

Figure 4.19. Velocity Vector Magnitude at High Mach Number (Case 8) (scale $1mm = 2.24m/s$).

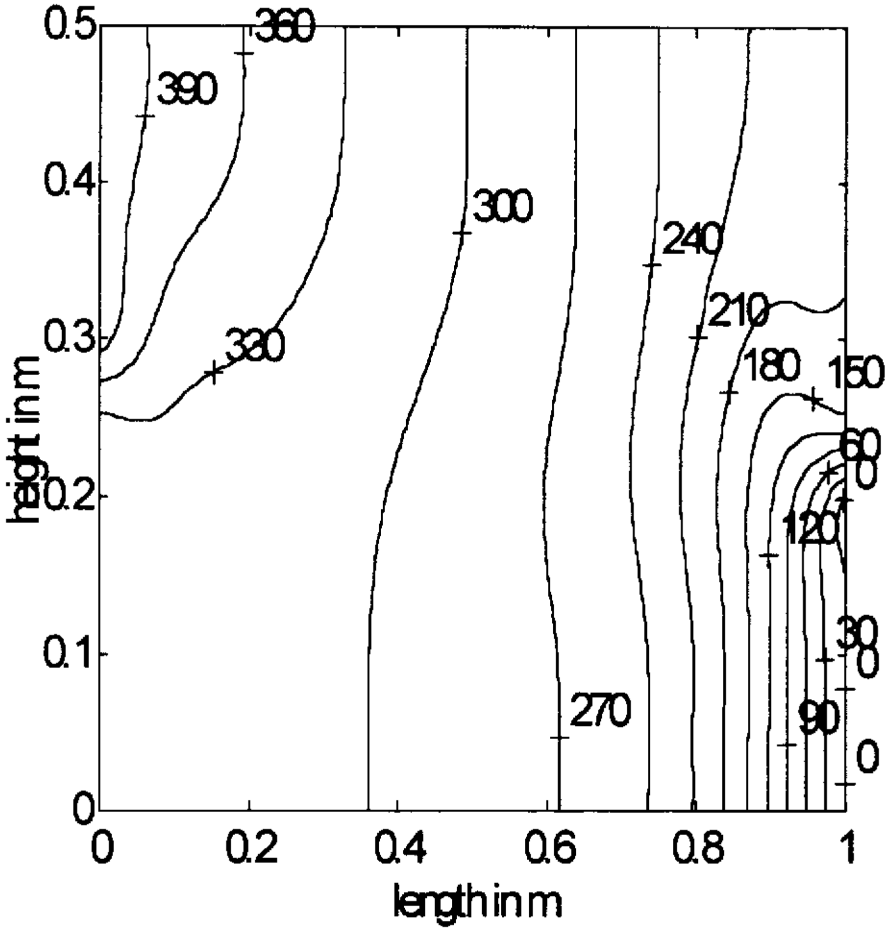

Figure 4.20 Pressure Distribution at High Mach Number (Case 8) (N/m^2 above exit pressure).

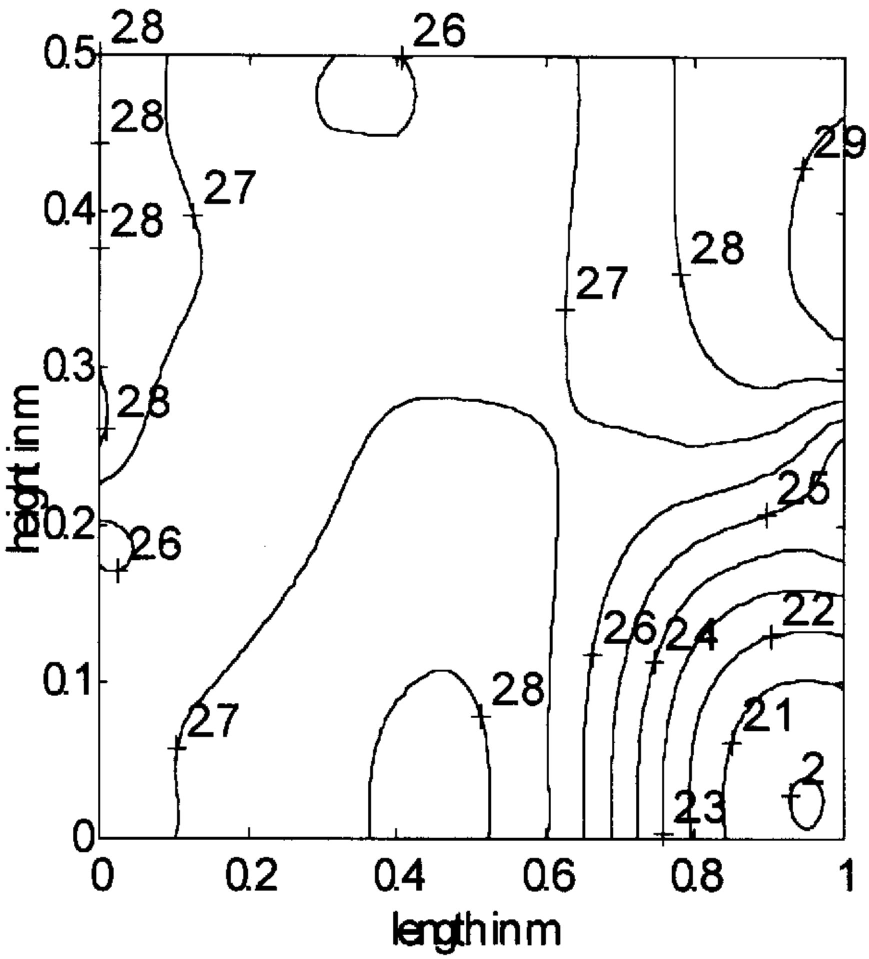

Figure 4.21. Density Distribution of Gas 1 at High Mach Number (Case 8) (in kg/m^3).

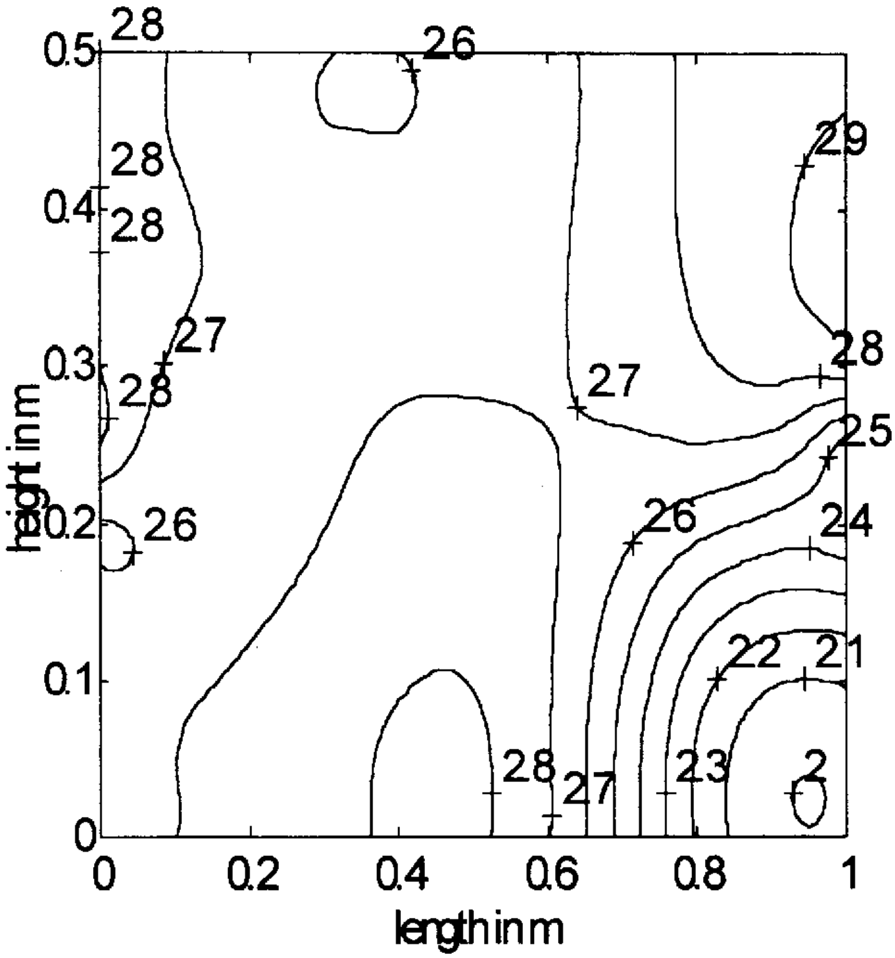

Figure 4.22. Density Distribution of Gas 2 at High Mach Number (Case 8) (density in $10^{-5} kg/m^3$).

The flow in the porous medium will then be governed by:

$$\mu \frac{\partial^2 u}{\partial y^2} = \frac{dp}{dx} + \frac{\mu \beta u}{K} \tag{4.3}$$

where K is the permeability of the porous medium. The solution of the above equation becomes

$$u = \frac{a}{b} \left\{ \frac{e^{\sqrt{b}y} + e^{-\sqrt{b}y}}{e^{\sqrt{b}H} + e^{-\sqrt{b}H}} - 1 \right\} \tag{4.4}$$

where $a = \frac{1}{\mu}\frac{dp}{dx}$, and $b = \frac{\beta}{K}$.

The above equation was used to validate a one dimensional packed bed Case 9, and, as depicted in Figure 4.23 the results obtained with the analytical and numerical solutions are in good agreement. Note that the inertial coefficients in Equations (2.16), (2.17), and (2.18) were set equal to zero in the implicit factored scheme to simulate the above case. The parameters used for the above calculations were as follows:

$\Delta x = 0.05$

$\Delta y = 0.025$

$\mu = 9.888 \times 10^{-6}$kg/ms

(21×21) grid points

Inlet density = 0.02 kg/m^3

$\beta = 0.4$

Particle diameter $dp = 5 \times 10^{-3}$m

Inlet pressure = 2000 N/m^3

Outlet pressure = 1990 N/m^2

The above porous medium case dealt with a two dimensional system. The adequacy of the model for three dimensional systems is now discussed.

To obtain an easy-to-verify base case for the three dimensional system, a separate incompressible computer program assuming Darcy's flow was developed. This was done by solving the following system of equations.

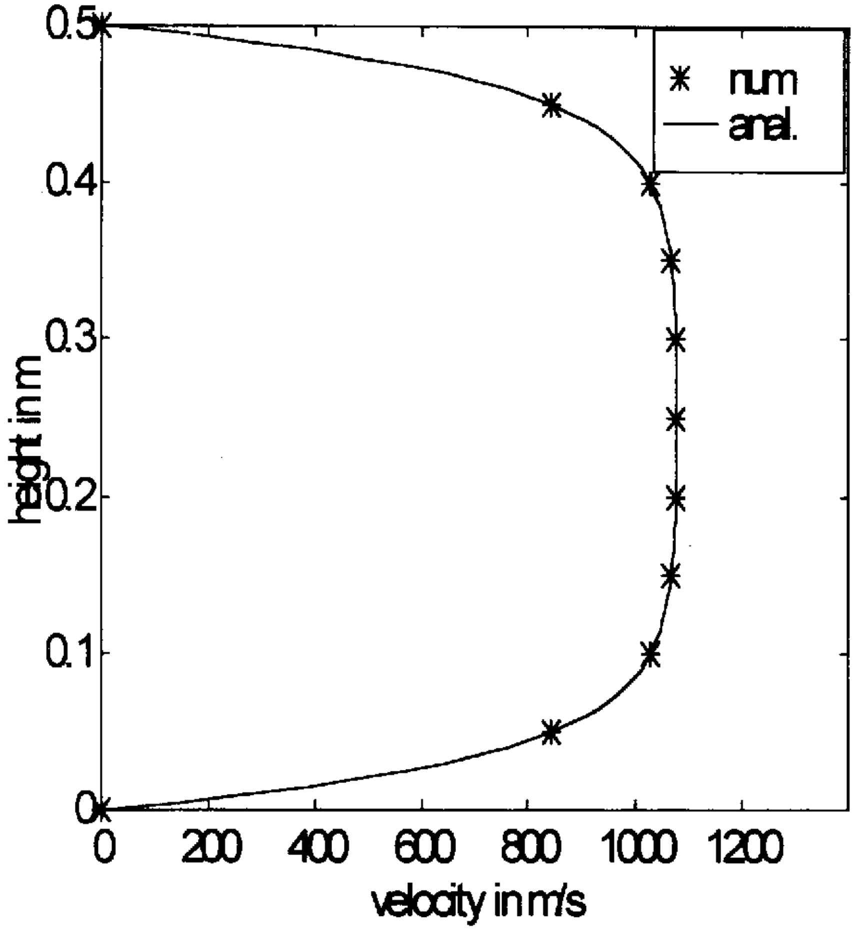

Figure 4.23. Pressure Distribution in a Packed Bed Porous Medium (Case 9).

- Incompressible continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4.3}$$

- Darcy's momentum equations in x, y, and z directions:

$$\frac{\partial p}{\partial x} = -\frac{\mu}{K} u \tag{4.4}$$

$$\frac{\partial p}{\partial y} = -\frac{\mu}{K} v \tag{4.5}$$

$$\frac{\partial p}{\partial z} = -\frac{\mu}{K} w \tag{4.6}$$

Assuming μ, β and K are constants and substituting u, v, and w from Equations (4.4), (4.5) and (4.6), respectively into Equation (4.3) one gets

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{4.7}$$

The solution of the above equation is simple, and can be done by imposing constant inlet and outlet pressure boundary conditions to the assumed system. When applied to a finite system, at the walls the normal derivative of the pressure is zero. Once the pressure distribution is established via the numerical solution of the above equations, the velocities can be evaluated using Equations (4.4), (4.5) and (4.6).

The above equations are solved for the following conditions (Case 10):

$\Delta x = .05$m

$\Delta y = 0.025$m

$\Delta z = 0.05$m

$\mu = 9.888 \times 10^{-6}$ kg/(m s)

$(21 \times 21 \times 21)$ grid points

Inlet density = 0.02 kg/m^3

$\beta = 0.4$

Particle diameter, $dp = 5 \times 10^{-3}$m

Inlet pressure = 20,000 N/m^2

Outlet pressure = 19800 N/m^2

The geometry of Case is shown in Figure 4.24.

Figures 4.25 and 4.26 show the velocity vector magnitude at the symmetry plane shown in Figure 4.24, generated from the implicit factored scheme and the simple model represented by Equations (4.4)-(4.7), respectively. Also Figure 4.26 and Figure 4.27 show the pressure contours evaluated at the symmetry plane shown in Figure 4.24, generated from the implicit factored scheme and the above simple model, respectively. As noted, the two solutions results are in good agreement.

The numerical model is now applied to a simple shell-and-tube condenser. This is done assuming a very simple one dimensional system. This simulation will be referred to as Case 11. The parameters used for this case are similar to those for the aforementioned Case 10, except that here the tube outer diameter was assumed to be $D_0 = 0.019m$, and the tubes were assumed to form a square lattice with the pitch being $P = 0.026m$. The governing equations are simplified by assuming that the flow is one dimensional, incompressible and inviscid, so that the governing momentum equation reduces to

$$\beta \frac{dp}{dx} = F_x \tag{4.8}$$

The above equation was solved analytically and compared with the numerical solution. Figures 4.29 and 4.30 compare the pressure and velocity profiles generated from the numerical and the analytical solution, with good agreement between them..

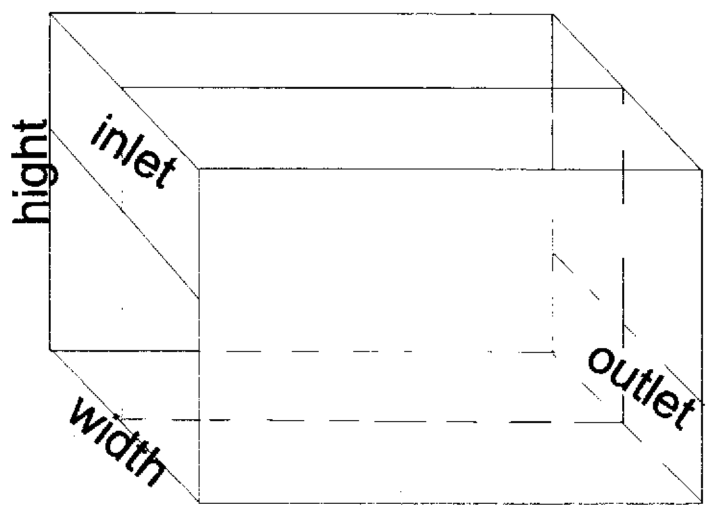

Figure 4.24. Three Dimensional Flow Geometry.

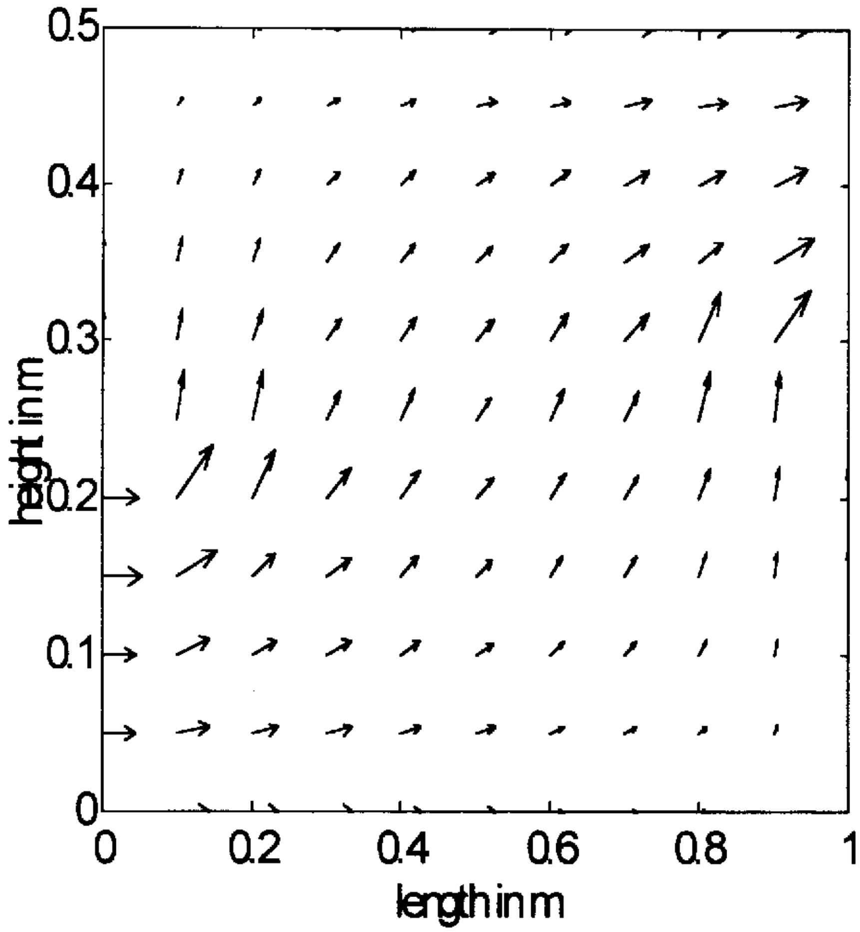

Figure 4.25. Velocity Vector Magnitude Generated from the Implicit Factored Scheme (Case 10)(scale $1mm = .615m/s$).

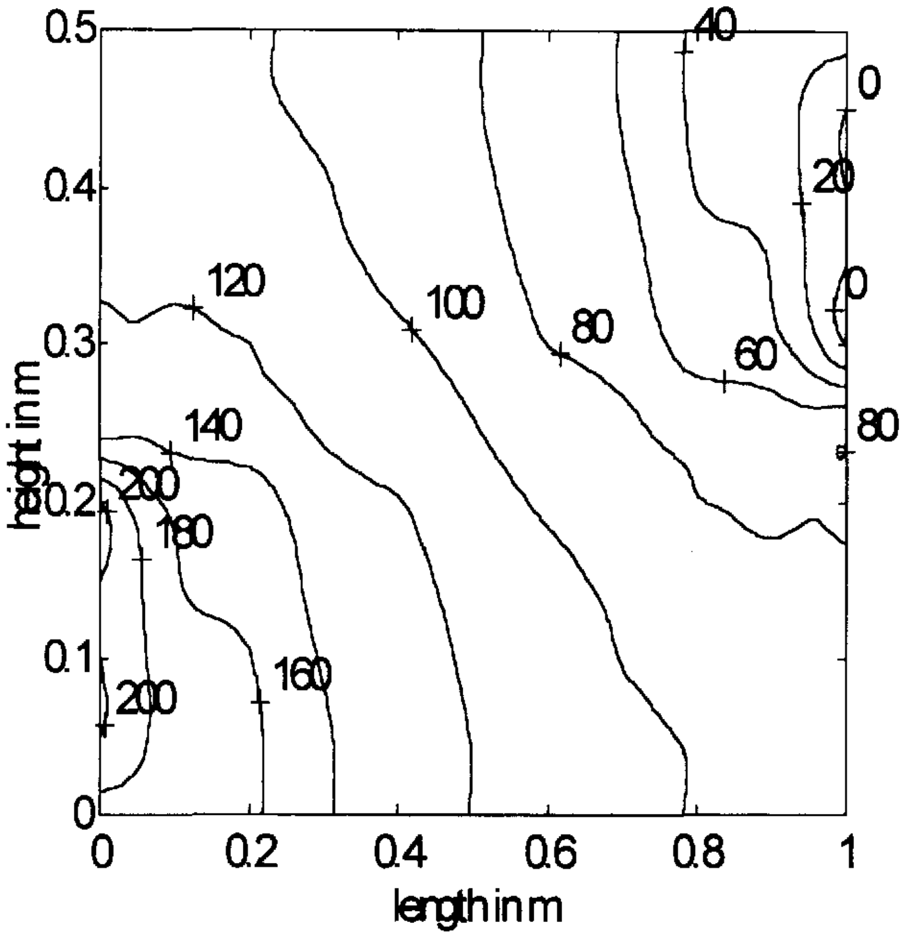

Figure 4.26. Pressure Contour Generated from the Implicit Factored Scheme (Case 10) (N/m^2 above exit pressure).

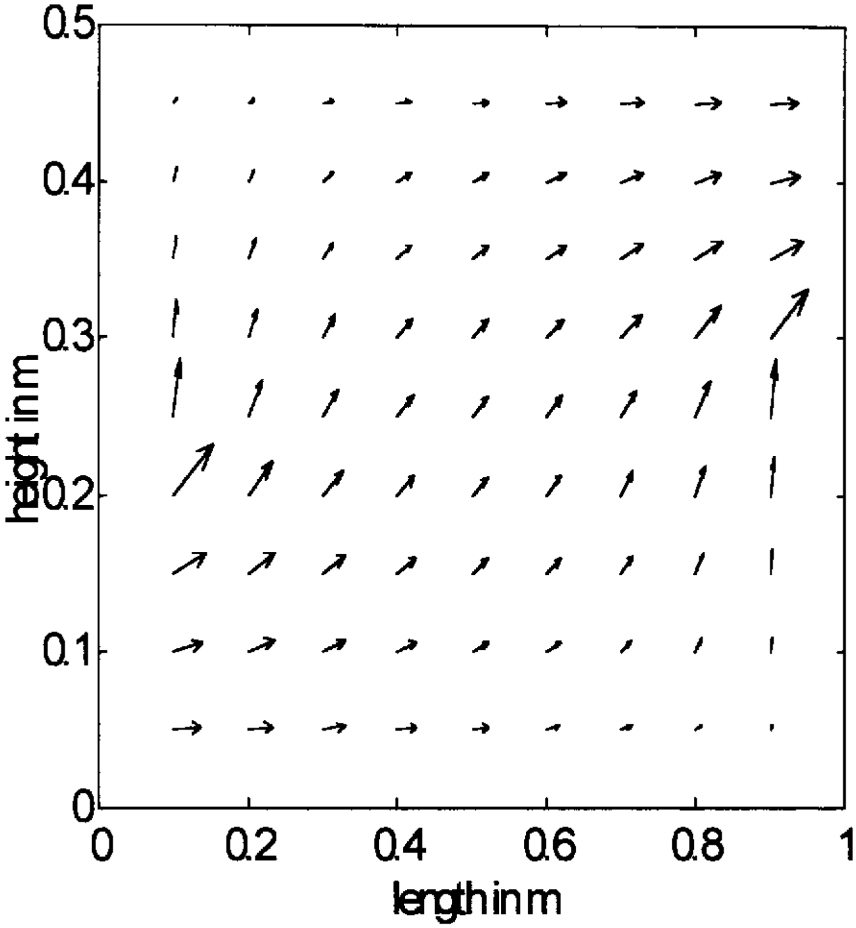

Figure 4.27. Velocity Vector Magnitude Generated from the Simple Model (Case 10)($1mm = .719m/s$).

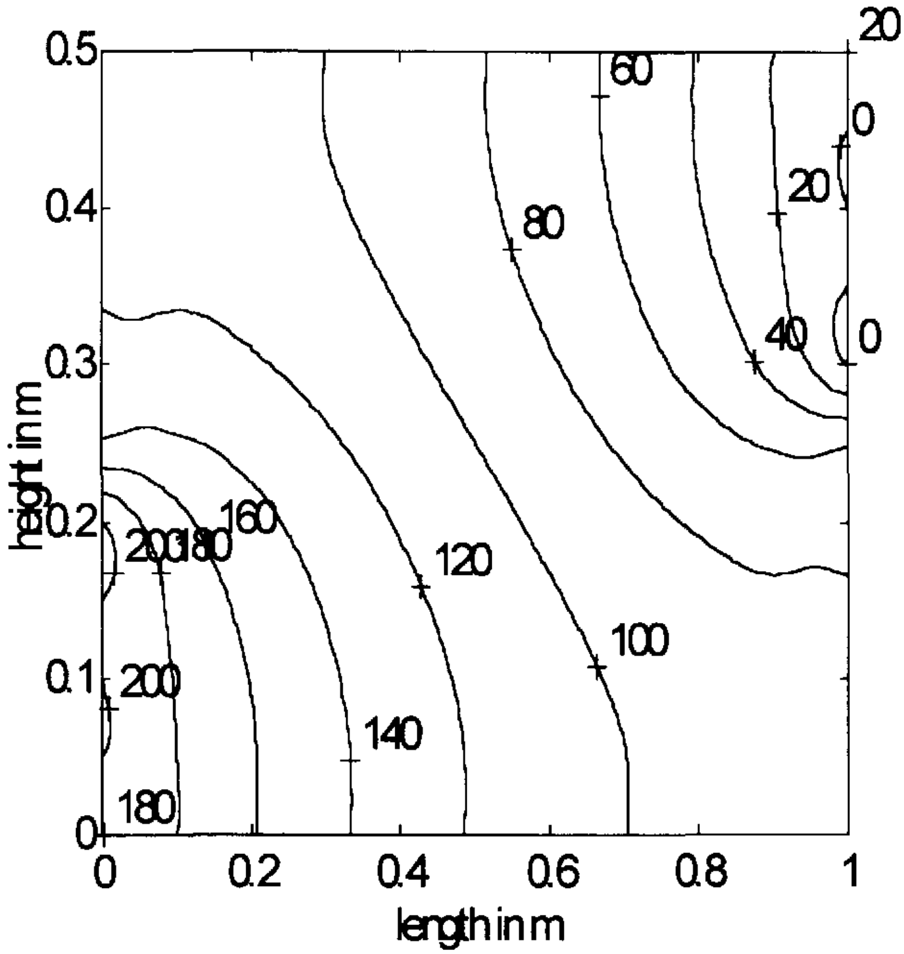

Figure 4.28. Pressure Field Generated from the Simple Model (Case 10) (N/m^2 above exit pressure).

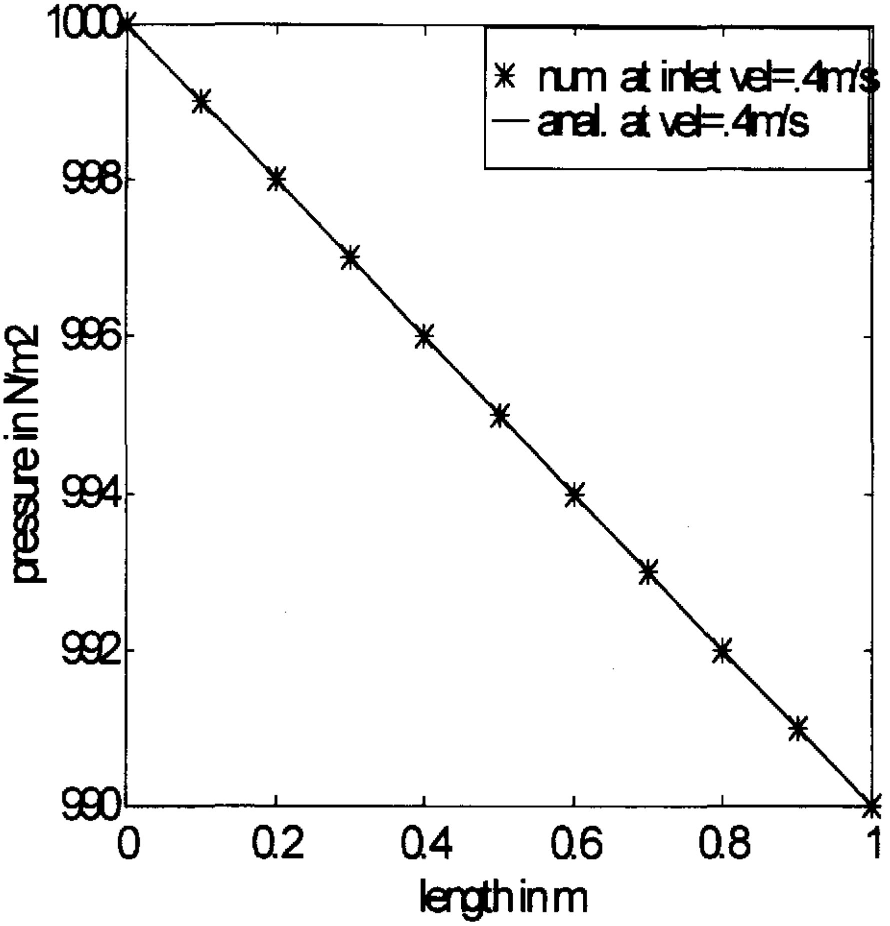

Figure 4.29. Pressure Field of a Shell and Tube (Case 11).

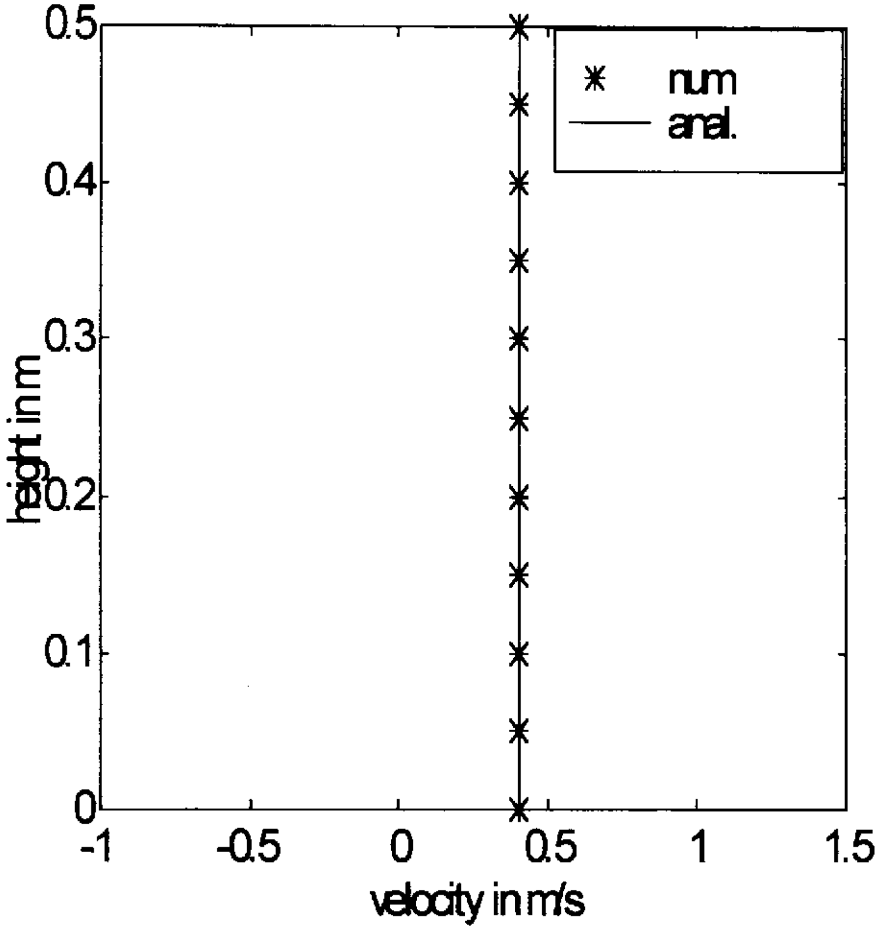

Figure 4.30. Velocity Field of a Shell and Tube (Case 11).

4.4. Condensation in Porous Media

In this section condensation, with and without noncondensables present, in shell-and-tube and packed bed condensers is modeled. The results that are discussed below are based on three dimensional calculations for the geometry depicted in Figure 4.24. This geometry was used in order to take advantage of the symmetry, and therefore reduce the required computer time. In setting up the simulations, the mesh was concentrated near the walls and the inlet and the outlet, using the transformation discussed in section 3.7. All the results presented here, after being evaluated at every grid point, are averaged cross-sectionally at equally spaced points in the x-direction.

Due to the absence of similar experience in the open literature, the results will be presented here and analyzed based on physical arguments.

Five cases are discussed for each of the shell-and-tube and the packed bed condensers. All cases have the following parameters:

Length = 1 m

Hight = 1 m

Width = 1 m

Inlet hight = .2 m

Outlet hight = .2 m

Outlet pressue = 2000 N/m^2

Inlet temperature = 350K

Inlet velocity = 20 m/s

Porosity β = .4

Shell-and-tube coolant inlet temperature =280. K

Packed bed particles centerline temperature =280. K

Shell-and-tube coolant velocity = 1.5 m/s.

The aforementioned cases differ in their inlet mass fraction of the noncondensables such that:

- Case 12 — pure condensation
- Case 13 — noncondensable inlet mass fraction = 0.0001
- Case 14 — noncondensable inlet mass fraction = 0.001
- Case 15 — noncondensable inlet mass fraction = 0.01
- Case 16 — noncondensable inlet mass fraction = 0.02

Figures 4.31 and 4.32 show the cross-sectional average velocity as a function of the x-coordinate for the shell-and-tube and the packed bed condensers, respectively. As expected, due to condensation, the velocity decreases as x increases.

It can be also seen that the reduction in the velocity increases as the inlet noncondensable mass fraction decreases. This phenomenon occurs because the condensation rate increases when the noncondensable concentration decreases.

Figures 4.33 and 4.34 represent the cross-sectional average mixture pressure along the x-direction. As expected, the pressure decreases as the x-increases.

Figures 4.35 and 4.36 show the cross-sectional average mixture temperature for the shell-and-tube and the packed bed, respectively. The temperature decreases as the x increases and this reduction in the temperature is due to condensation taking place in the systems, which leads to lower vapor partial pressure, and consequently lower saturation temperature.

Figures 4.37 and 4.38 are the cross-sectional average noncondensable mass fractions for shell-and-tube and packed bed condensers, respectively. The mass fractions increase as x increases, due to the partial removal of vapor due to condensation.

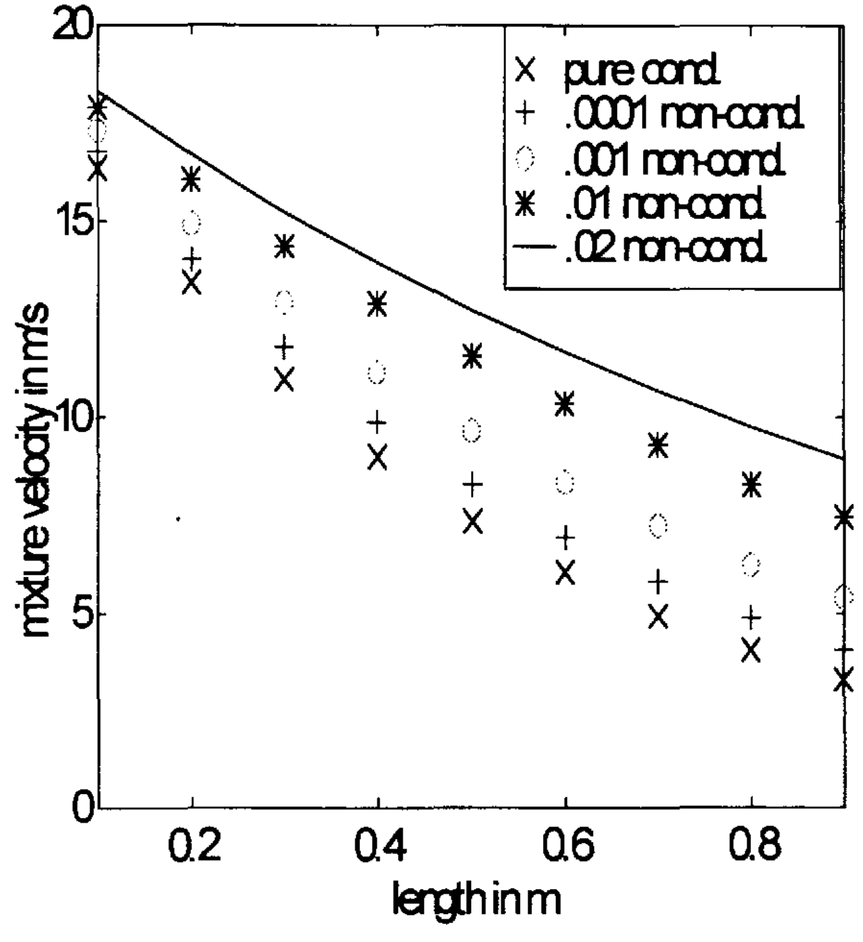

Figure 4.31. Cross-sectional Average Velocity of a Shell and Tube.

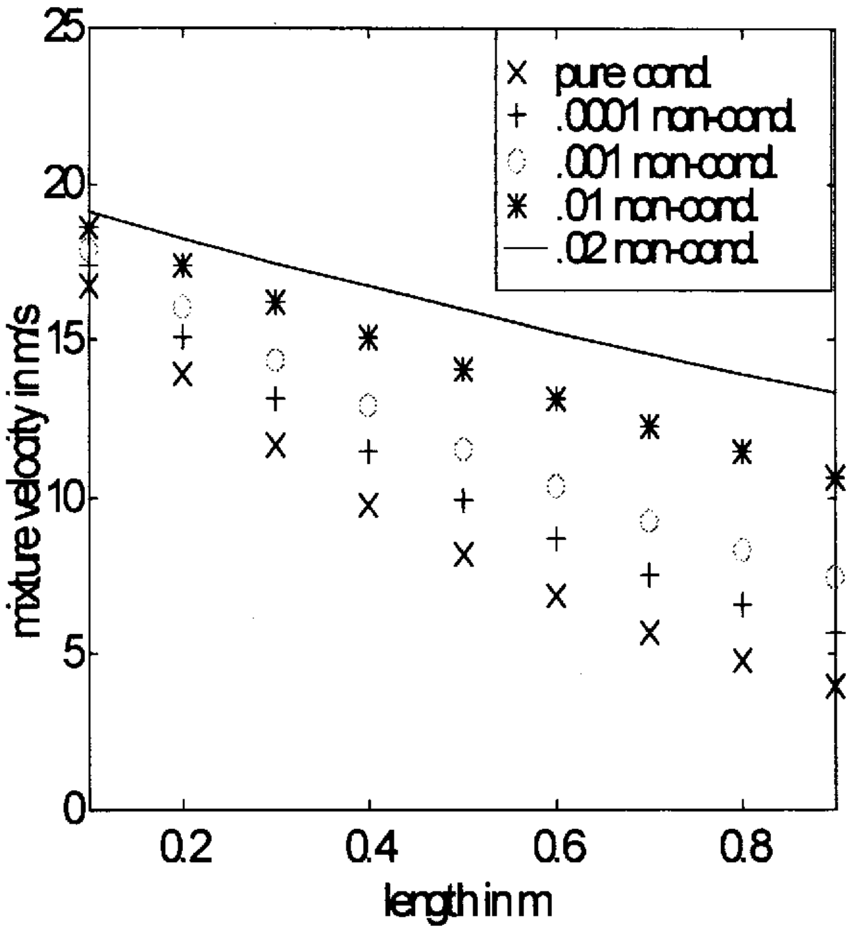

Figure 4.32. Cross-sectional Average Velocity of a Packed Bed.

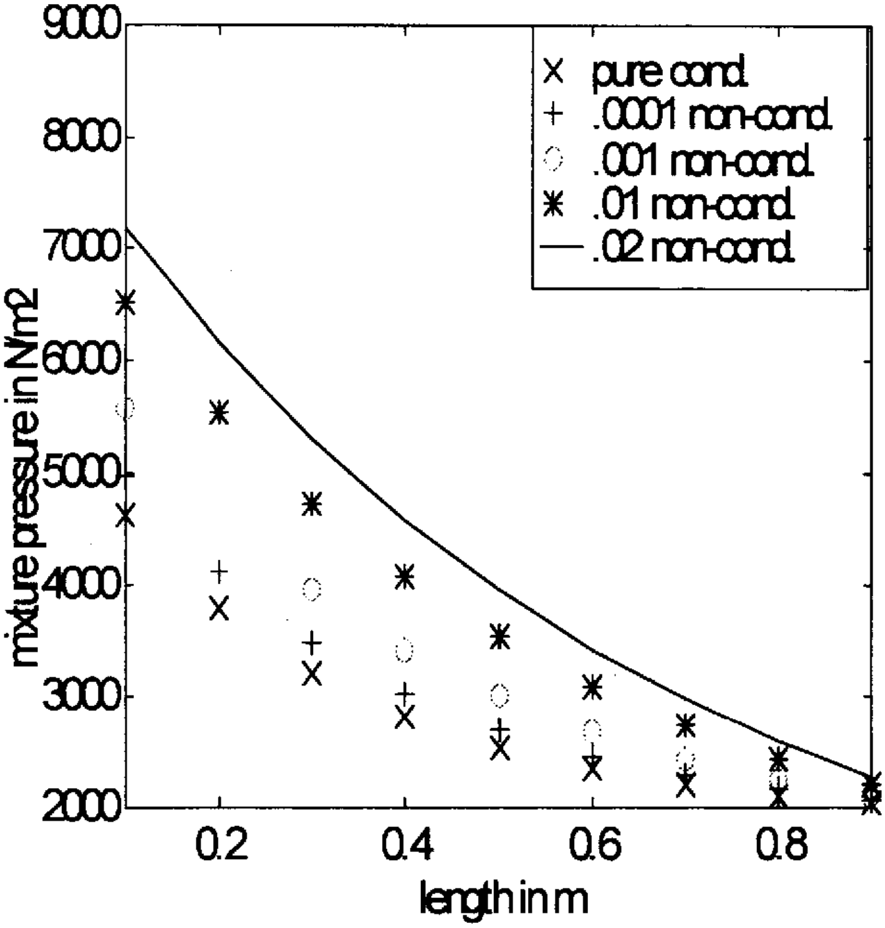

Figure 4.33. Cross-sectional Average Mixture Pressure of a Shell and Tube.

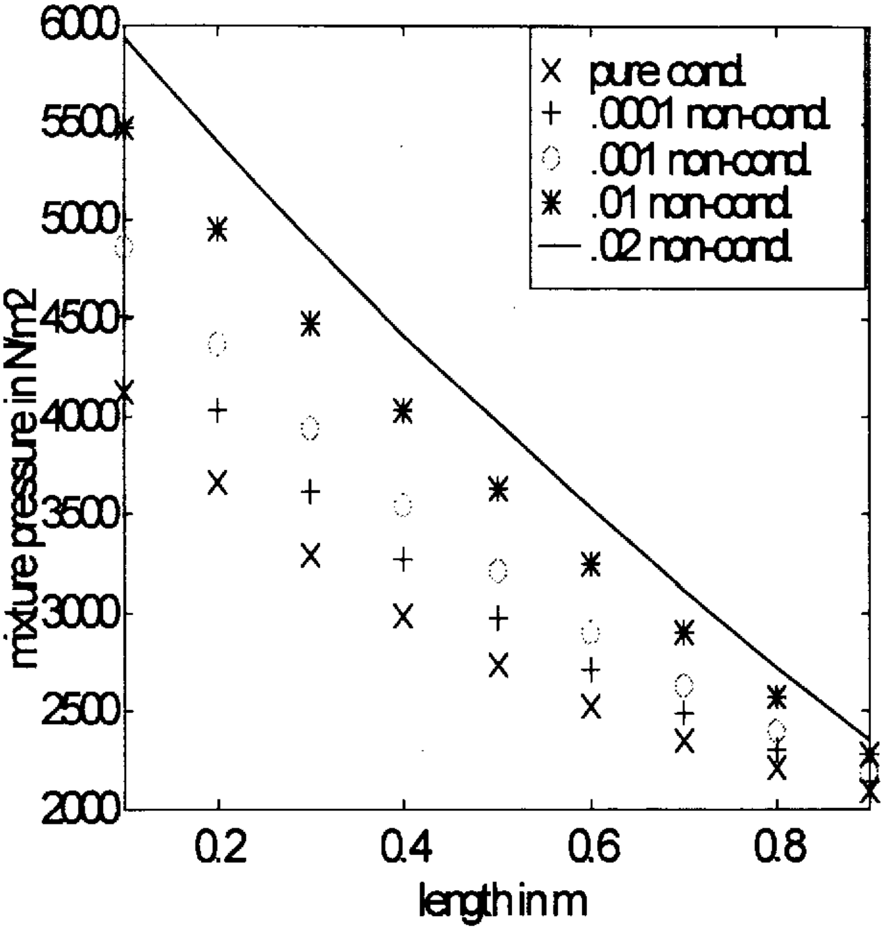

Figure 4.34. Cross-sectional Average Mixture Pressure of a Packed Bed.

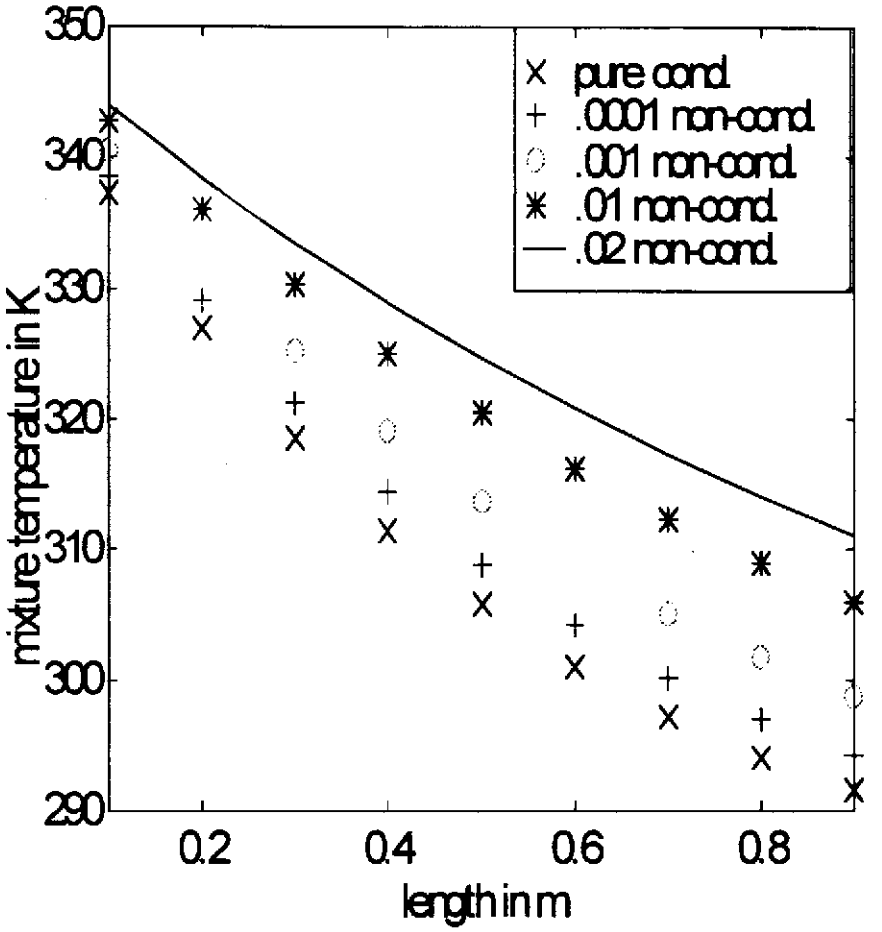

Figure 4.35. Cross-sectional Average Mixture Temperature for a Shell and Tube.

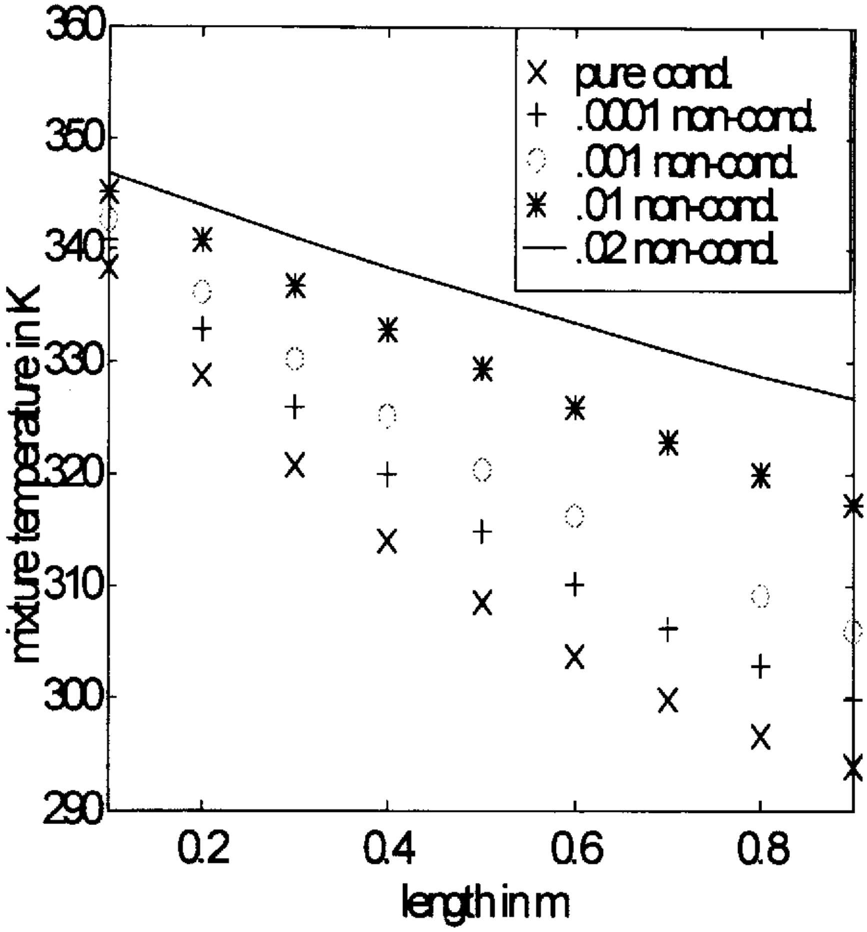

Figure 4.36. Cross-sectional Average Mixture Temperature for a Packed Bed.

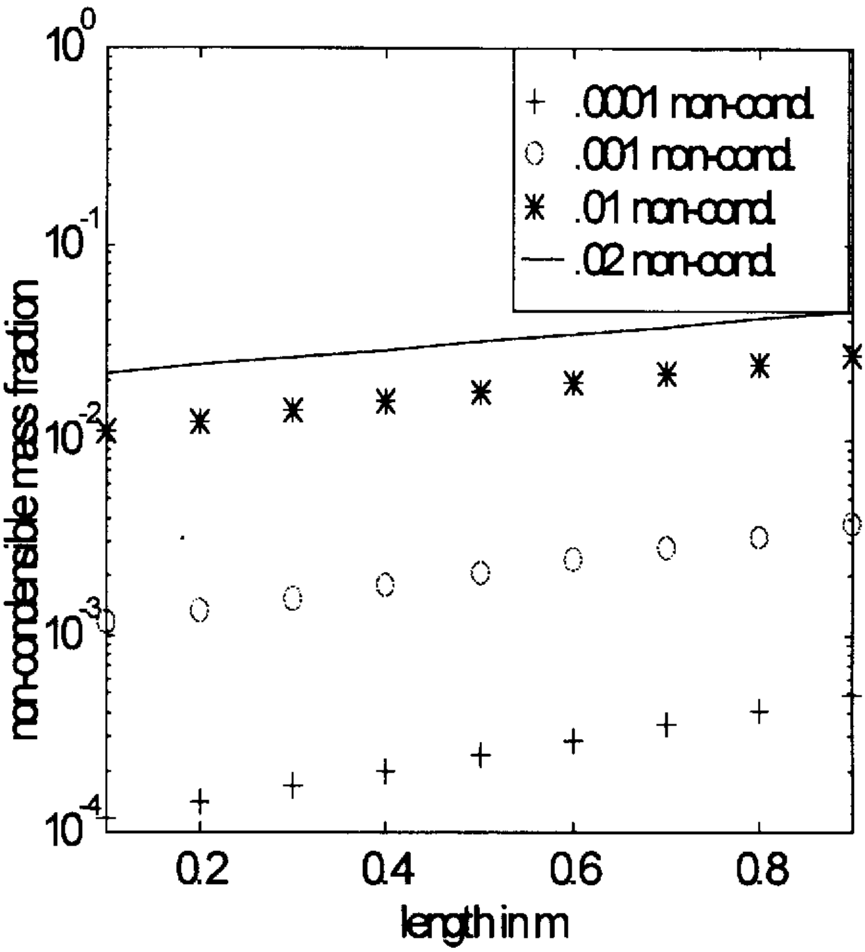

Figure 4.37. Cross-sectional Average Mass Fraction of a Shell and Tube.

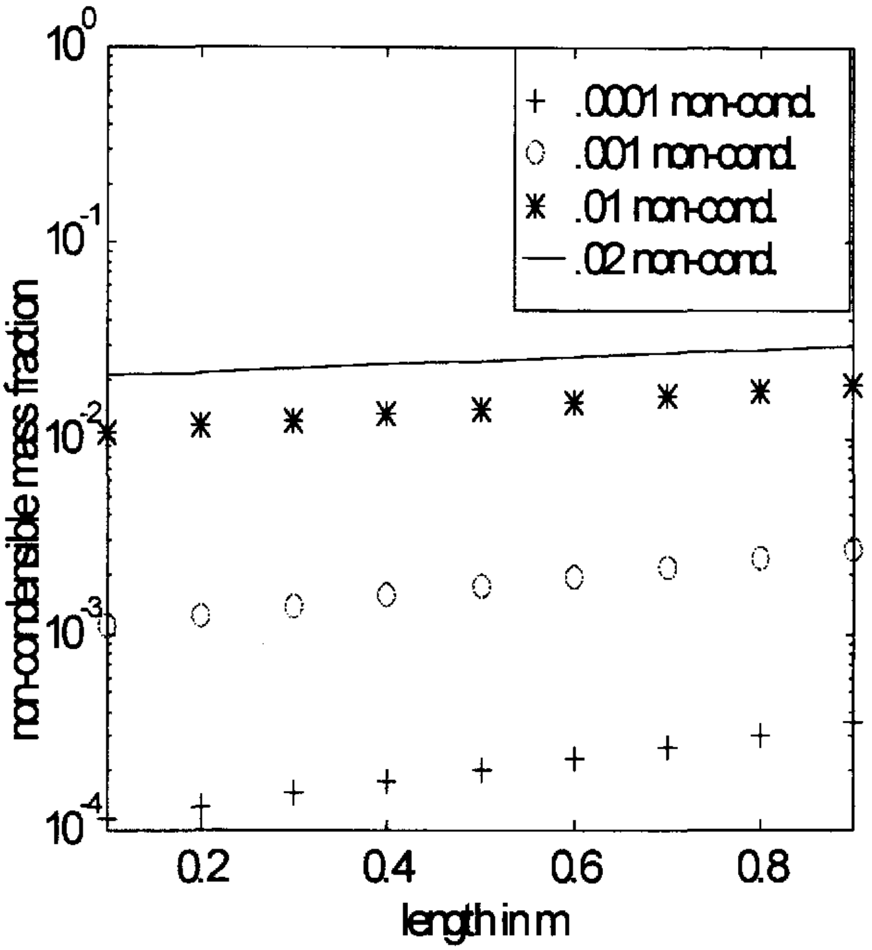

Figure 4.38. Cross-sectional Average Mass Fraction of a Packed Bed.

Figures 4.39 and 4.40 are the cross-sectional average steam partial pressures of shell-and-tube and packed bed condensers, respectively. The steam partial pressure follows the same trend of the mixture pressure.

Figures 4.41 and 4.42 show the cross-sectional average condensation rate for shell-and-tube and packed bed condensers, respectively. The figures show that the condensation rate decreases as x increases and this is mainly due to the increase in the noncondensables mass fraction.

Figures 4.43 and 4.44 are the cross-sectional average heat fluxes for shell-and-tube and packed bed condensers, respectively. The heat fluxes decease as x increases and this is mainly due to the increase in the mass fraction of the noncondensables as they form a heat and mass transfer resistance on the condensing surfaces.

As has been explained in Chapter 1, even 0.5% of noncondensables might decrease the heat transfer rate up to 50%. It is also noticed from Figure 4.44 that, according to the model, compared with pure vapor, 0.01% of noncondensable at the inlet, reduces the heat flux by 22%. With one percent of noncondensables at the inlet, however, the heat flux is reduced by 50%.

It should be mentioned that, for porous media and typical condensers, the effect of viscosity and thermal conduction in the fluid are negligibly small. As mentioned before in Chapter 2, although the conservation equations have been presented in laminar form, they can address the effect of turbulence by adding the turbulent eddy thermal and momentum diffusivities to the molecular kinematic viscosity and thermal diffusivity, respectively. To examine the significance of turbulence, some of the model calculations relevant to porous media and condensers were repeated, where the molecular viscosity and thermal conductivity were multiplied by 10. The results, as expected, showed no noticeable difference with corresponding calculations using the molecular viscos-

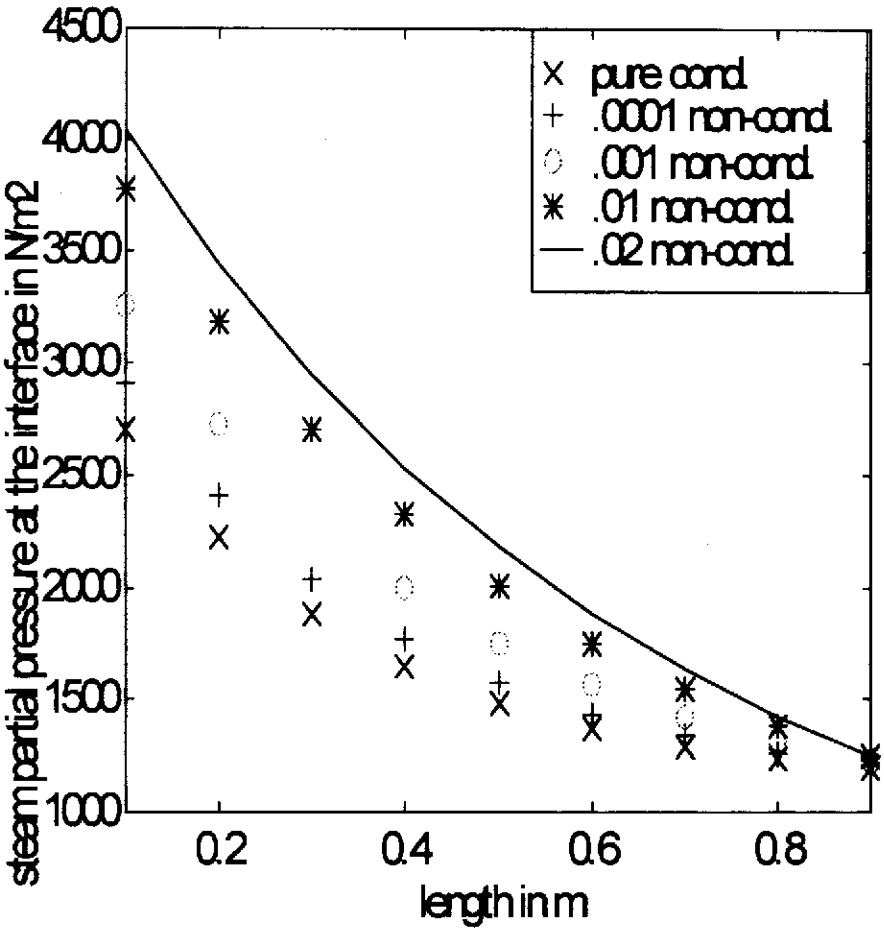

Figure 4.39. Cross-sectional Average Steam Partial Pressure of a Shell and Tube.

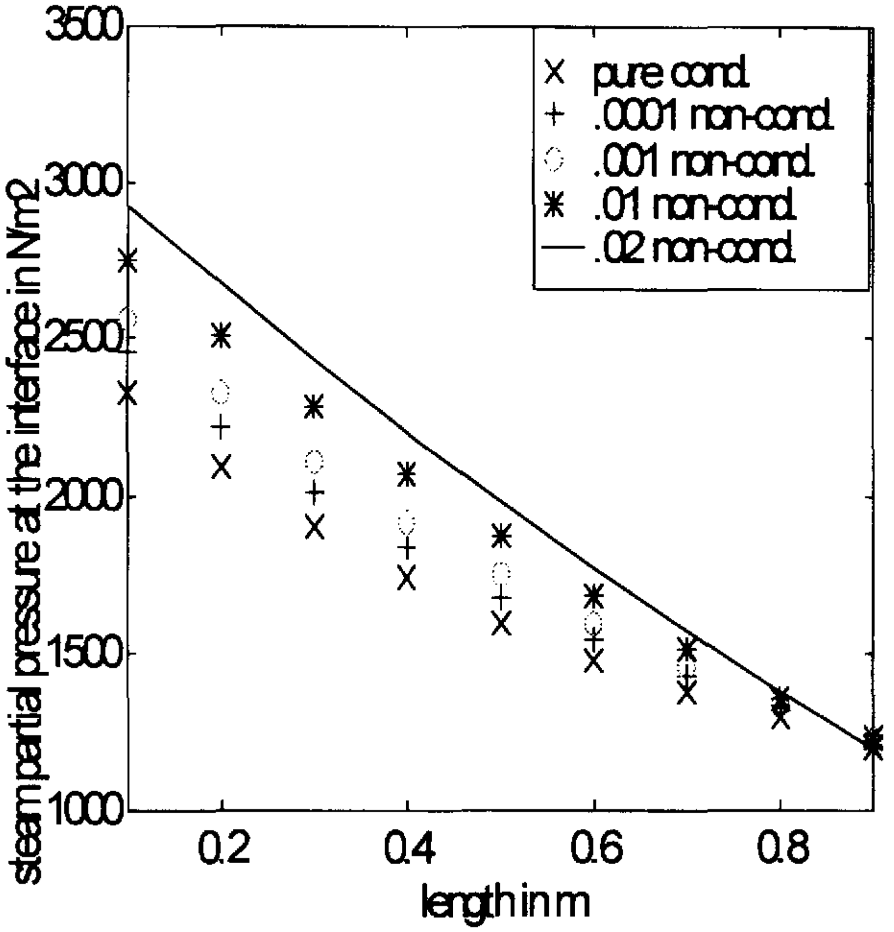

Figure 4.40. Cross-sectional Average Steam Partial Pressure of a Packed Bed.

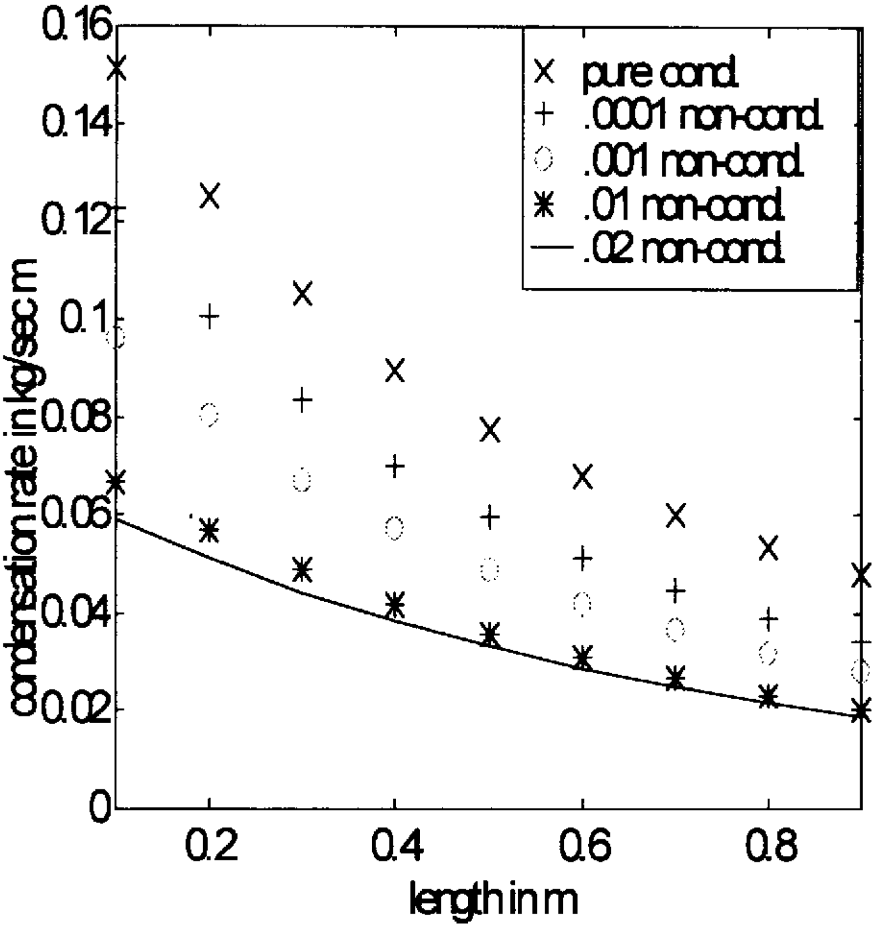

Figure 4.41. Cross-sectional Average Condensation Rate of a Shell and Tube.

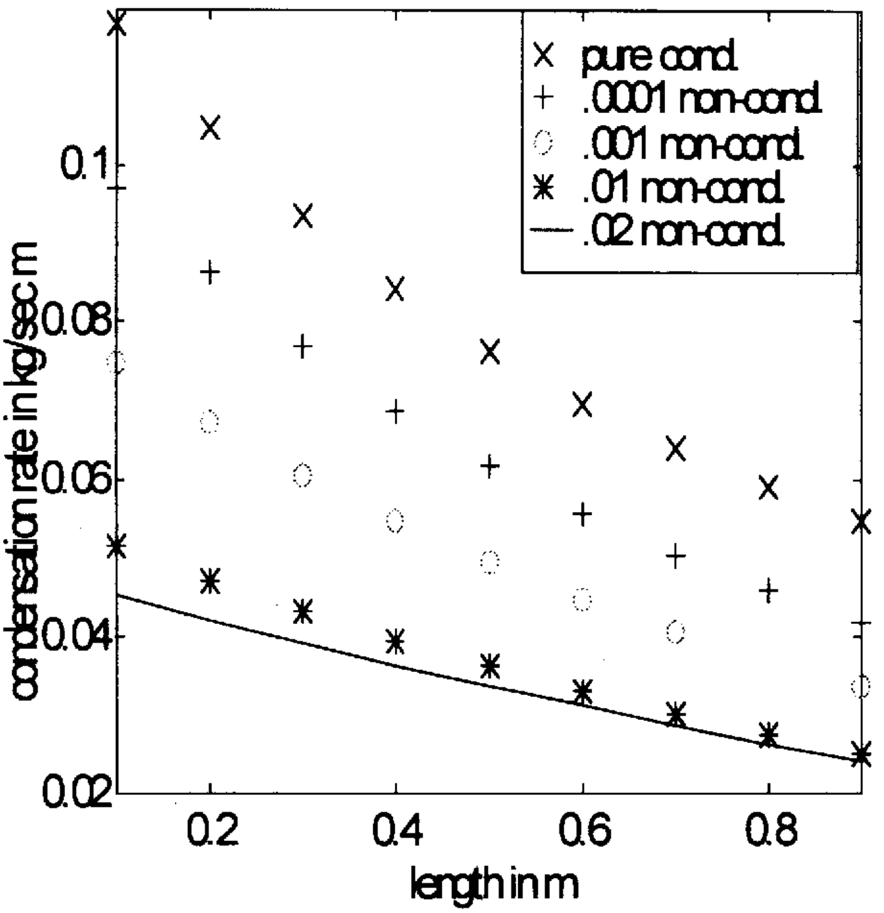

Figure 4.42. Cross-sectional Average Condensation Rate of a Packed Bed.

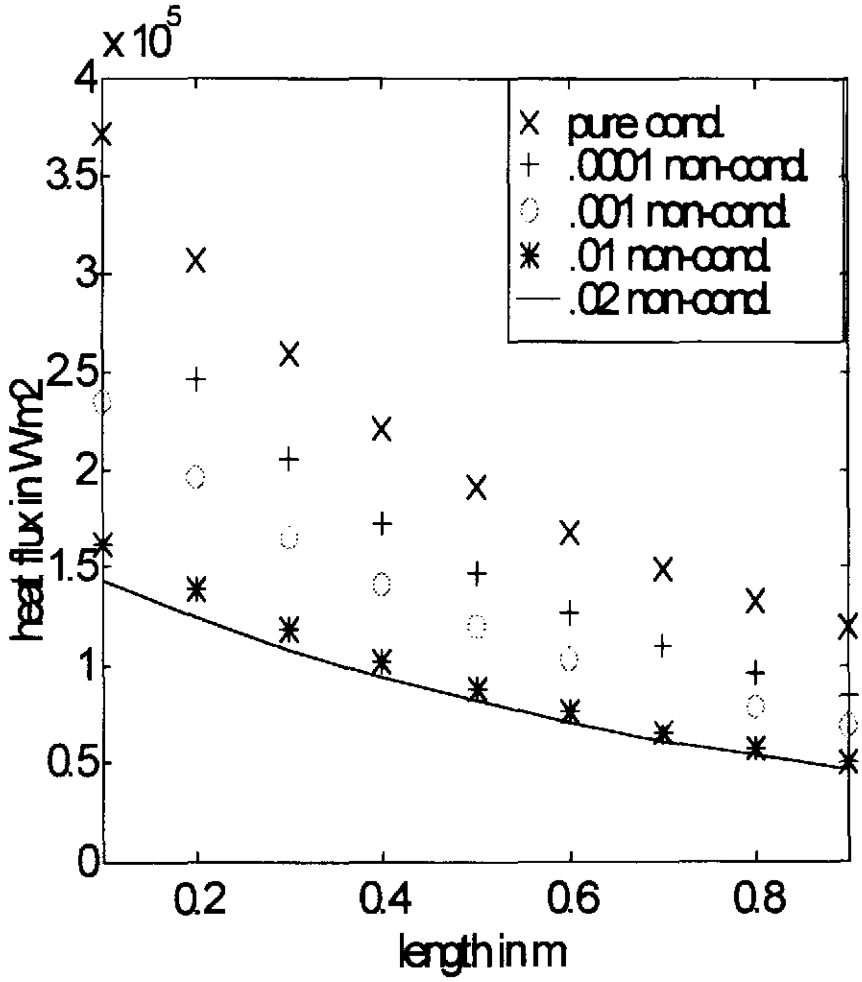

Figure 4.43. Cross-sectional Average Heat Flux of a shell and Tube.

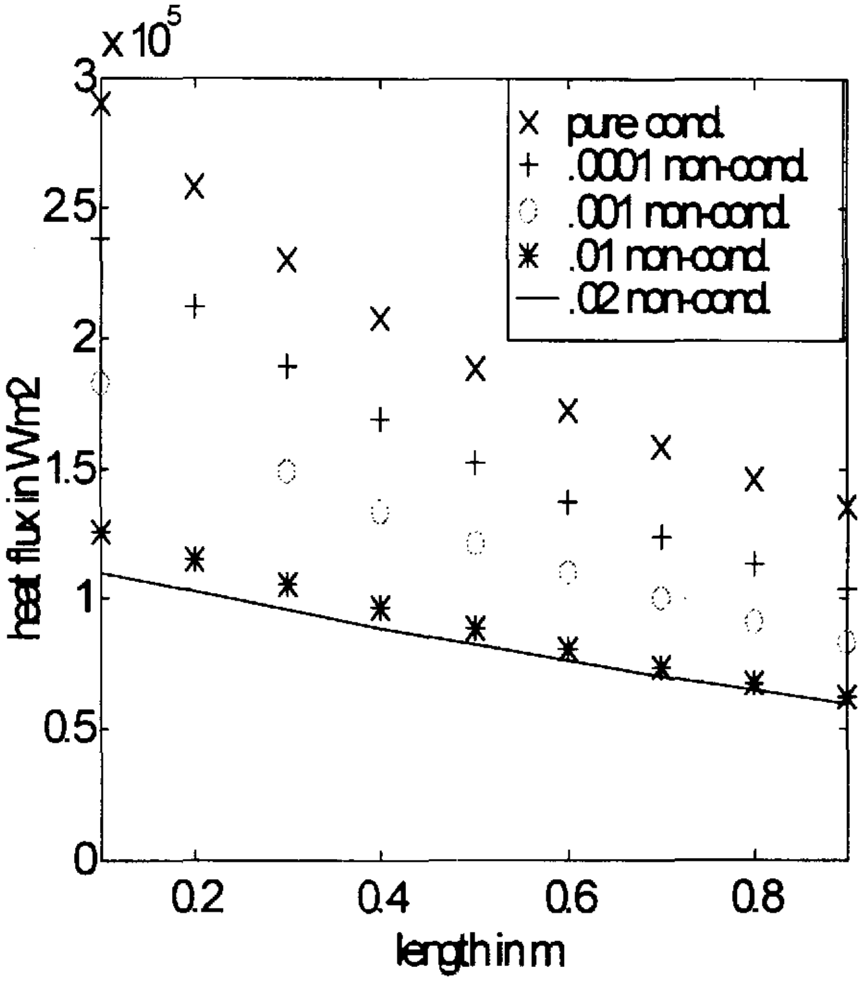

Figure 4.44. Cross-sectional Average Heat Flux of a Packed Bed.

ity and thermal conductivity. Also, no noticeable changes occurred as a result of dividing the fluid viscosity and thermal conductivity by 10. This indicated that the common practice of neglecting viscous and turbulent shear stresses, in comparison with the porous media frictional and pressure losses, is justified.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

Condensers are vital components of power plants and refrigeration systems, and many other widely-used industrial applications. Mechanistic modeling of flow and heat and mass transfer processes in condensers, based on the numerical solution of conservation equations, has been attempted by several investigators only recently. The most advanced published numerical models, , have major shortcomings. They do not account for the compressibility of the vapor-noncondnesables mixture. Most of them, furthermore, do not adequately model the combined heat and mass transfer process associated with condensate-vapor interface, and instead depend on purely empirical correlations. The development of a mechanistic model which resolves these shortcomings was the objective of this research.

Condensation in the presence of noncondensables, in condensers with complex geometries was mechanistically modeled in this thesis. The modeling was based on a rigorous representation of the vapor-noncondensable conservation equations flowing in porous media, accounting for the vapor-noncondensable compressibility effects. These conservation equations are numerically solved. For this numerical solution, the implicit factored scheme (IFS) was modified to address a general porous media formulation. A simple and innovative method was also developed, which makes it possible to include one or more noncondensable mass species conservation equations in the IFS scheme without significantly increasing the computational cost of the numerical solution scheme.

The numerical solution of the aforementioned conservation equations, which are referred to here as the macroscopic level model, is performed in conjunction with a microscopic-level model, based on the stagnant-film model, for calculating the heat and mass transfer processes at the interface between the condensate liquid and the vapor-noncondensable gas mixture.

The developed model was successfully applied to a large number of one , two and three dimensional problems involving condensation in channels, porous media, and packed bed and shell-and-tube condensers. In all the simulations the predictions of the numerical model developed in this closely agreed with analytical solutions or predictions made by other well-proven numerical solution methods.

5.2. Recommendations

The capabilities of the developed model can be significantly enhanced. The following is a list of improvements which will greatly contribute to the enhancement of the developed model.

- The macroscopic-level model treats the vapor and the noncondensable gas as ideal gases. These models should be modified such that the vapor properties can be obtained from realistic property routines.
- The volume occupied by the condensate in the secondary side of condensers is neglected in this model. The model should be modified to account for the condensate volume. This is particularly important for advanced condensers involving phase-change-material (PCM) particles, or structured packings, where the flow of the condensate may need to be mechanistically modeled separately.

• The developed computer code should be provided the capability of addressing current condenser geometries, including the effect of flow baffels.

• Finally, the computational time required for the numerical simulation of condensers should be reduced. This objective can be fulfilled by adapting the computer program to parallel or vectored computers.

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