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NUMERICAL ANALYSIS ON THE NATURAL CONVECTION IN A LONG HORIZONTAL PIPE WITH THERMAL STRATIFICATION

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ABSTRACT - In this paper, the steady 2-dimensional model for a long horizontal line with different end temperatures undergoing natural convection at very high Rayleigh number is proposed to numerically investigate the heat transfer and flow characteristics. The dimensionless governing equations are solved by using SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm which is developed using control volumes and staggered grids. The numerical results are verified by comparison with the operating PWR test data. The analysis focuses on the effects of variation of the heat transfer rates at the pipe surface, the thermal conductivities of the pipe material and the thickness of the pipe wall on the thermal statification. The results show that the heat transfer rate at the pipe surface is the controlling parameter. A significant reduction and disappearance of thermal stratification phenomenon is observed at the Biot number of 5.0×10^{-2}. The results also show that the increment of the thermal conductivity and thickness of the wall weakens the thermal stratification and somewhat reduces azimuthal temperature gradient in the pipe wall. Those effects are however minor, when compared with those due to the variation of the heat transfer rates at the surface of the pipe wall.

1. INTRODUCTION

Natural convection in long horizontal lines with different end temperatures can result in thermal stratification of the fluid. Thermal stratification in light water nuclear reactor (LWR) piping systems has recently been considered the subject of safety concerns [6,7].

The phenomenon of thermal stratification plays an important role in the piping integrity, because the significant thermal stresses may induce the failure and the unexpected deformation of the piping lines. Stratified flow is generated under a condition in which hotter fluid flows over a colder region of fluid.

The stability of the flow stratification is dependent on the differences in temperature and velocity of the flow. Greater temperature differences and lower velocities result in more stable stratification conditions. The Richardson number gives a measure of the stability of a stratified flow. It is a dimensionless parameter representing the ratio of buoyancy force to inertia force. If the Richardson number exceeds unity, the stratification may be stable. If the Richardson number is less than unity, the stratification is unstable and may become unstratified.

Hong[1] studied numerically natural circulations in a horizontal pipe. Bejan and Tien[2] modeled for the thermal-hydraulic aspects of stratified flow. Kimura and Bejan[3] found that the flow is characterized by heat transfer through the boundary layers at the hot and cold ends connected by a fully developed flow in the core region. Shiralkar and Tien[5] investigated high Rayleigh number convection in shallow enclosures with different end temperatures

Lubin and Kim[9] developed a model to predict the wall temperatures in long horizontal lines with different end temperatures undergoing natural convection at very high Rayleigh number. Lubin and Kim[11] treated the thermal stratification in line connected to a reactor coolant system as the pin model. Park and Youm[10] performed an unsteady 2-D numerical analysis of thermal stratification in a PWR plant surge line.

In this study, a steady 2-D numerical analysis is performed for the heat transfer and flow characteristics in a long horizontal line (the safety injection line) with different end temperatures undergoing natural convection at very high Rayleigh number. The calculation domain is assumed to be the rectangular section because the variation of temperature with angular direction is very small. The analysis focuses on the effects of variation of the heat transfer rates at the pipe surface, the thermal conductivities of pipe material and the thickness of the pipe wall on the thermal stratification.

2. MODEL FORMULATION

The safety injection line connects the safety injection tanks to the cold leg of the reactor coolant system of PWR as shown in Fig.1. The line runs from a safety injection nozzle, oriented in a vertical up position on the cold leg of the RCS. Typical lines have one or more long horizontal sections between vertical rises. Line size is 0.2 m nominal diameter and schedule of 160.

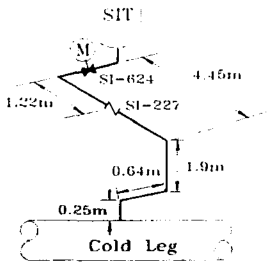


Figure 1 Isometric diagram on the safety injection line of PWR plant

In normal operation, the safety injection tank is isolated from the cold leg by a check valve that is normally closed. However the motor operated valve, that is used to isolate the safety injection tank, is open. The fluid temperature of RCS is varied from 38 °C at cold shutdown to 296 °C at full power operation. But fluid in the safety injection tanks is typically maintained about 38 °C as containment temperature.

In general, wall temperatures between the RCS and the check valve are close to the RCS temperatures and indicate small variation with angular location. However, those between the check valve and the motor operated valve, while lower than the RCS temperature due to the thermal resistance of valve, have top-to-bottom variations in wall temperature of about 60 °C.

Wall temperatures distributions were observed to be directly related to RCS temperature. As a result of this and absence of forced flow in the line, the observed wall temperature differences were credited to natural convection between a source of high temperature at the check valve and cold temperature close to the motor operated valve [11].

The large pipe diameter and high temperatures resulted in a Rayleigh number for natural convection on the order of magnitude of 10^{12}. An approximate region map for natural convection in long enclosures shows that natural convection for these Rayleigh numbers falls in what may be termed the "intrusion layer regions"[8].

Therefore, in this study, the calculation domain as Fig. 2 is selected to analyze the stratified flow. The horizontal pipe length between two valves, L, and the inner diameter of pipe , H, are 1.22 m and 0.2 m, respectively and the wall thickness, a, is 0.01 m. The temperature of hot fluid, T_h, is 149 °C and that of cold fluid, T_c, is 38 °C. Also, the ambient temperature is 38℃ and the equivalent heat transfer coefficient of insulated piping, h_∞, is 0.026 W/m^2K. The large line diameter and high temperatures result in a Rayleigh number for natural convection of the order of magnitude 10^{12}.

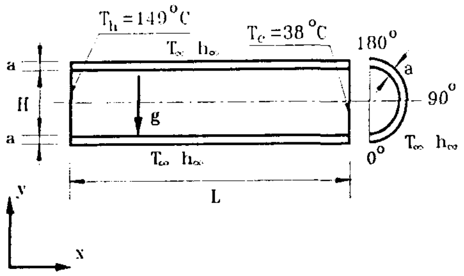


Figure 2 Schematic diagram of the calculation domain

The major assumptions to solve the governing equations are as follows:

(a) the flow of hot and cold fluids is 2 dimensional.

(b) the properties of fluid and solid except density in the body force term are treated as constant.

(c) the compressibility effects, viscous dissipation and radiation heat transfer of fluids are neglected.

The dimensionless governing equations for the steady 2-dimensional flow are derived as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \qquad (1)$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + C_1\{\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\} \qquad (2)$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + C_1\{\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\} + \frac{Ra}{Pr}T \qquad (3)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = C_2\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\} \qquad (4)$$

Dimensionless variables are defined as follows;

$$x = x^*/H, \quad y = y^*/H, \quad a = a^*/H, \quad u = u^*H/\nu$$

$$v = v^*H/\nu, \quad Ra = g\beta H^3(T_h^* - T_c^*)/(\alpha\nu), \quad Pr = \nu/\alpha,$$

$$T = (T^* - T_c^*)/(T_h^* - T_c^*), \quad p = p^*H^2/(\rho\nu^2) \qquad (5)$$

where asterisks represent the dimensional values. Also, C_1 and C_2 in Eqs. (2), (3) and (4) represent the diffusion coefficient in the momentum equations and the energy equation, respectively, which state

$$C_1 = \{\begin{matrix} 1.0 & \text{at fluid} \\ \infty & \text{at solid} \end{matrix} \qquad (6)$$

$$C_2 = \{\begin{matrix} 1/Pr & \text{at fluid} \\ (k_s/k_f)/Pr & \text{at solid} \end{matrix} \qquad (7)$$

The boundary conditions are as follows;

$$x = 0 ; \quad T = 1.0 \qquad (8)$$

$$x = L/H ; \quad T = 0.0 \qquad (9)$$

$$y = 0 ; \quad \frac{\partial T}{\partial y} = -Bi(T_s - T_\infty)/a \qquad (10)$$

$$y = 1+2a ; \quad \frac{\partial T}{\partial y} = -Bi(T_s - T_\infty)/a \qquad (11)$$

$$y = a \text{ and } 1+a ; \quad k_f\frac{\partial T_f}{\partial y} = k_s\frac{\partial T_s}{\partial y} \qquad (12)$$

The horizontal upper and lower walls are conducting wall, and then the vertical hot and cold walls are zero-thickness, non-conduction wall and constant temperature wall.

3. NUMERICAL ANALYSIS

The governing equations have been solved by the finite volume calculation procedure including SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm[4] which is developed using control volumes and staggered grids, the power law scheme, and TDMA (Tri-Diagonal Matrix Algorithm).

In order to improve convergence, the under relaxation factors 0.05, 0.05 and 0.1 respectively of velocity, pressure and temperature are applied. A grid distribution in the x and y direction is 64 and 42, respectively The grid node near the four walls is distributed into a denser node than that of core region..

The converged solutions are obtained when the error of energy balance is less than 0.1% and such that;

$$\left|\frac{\phi^{m+1} - \phi^m}{\phi^m}\right| < 10^{-2} \qquad (13)$$

The numerical results are compared with the measured values of a operating PWR plant to verify the analysis program[11]. This comparison is given in Fig. 3. The numerical results are shown to agree well with the plant measured data.

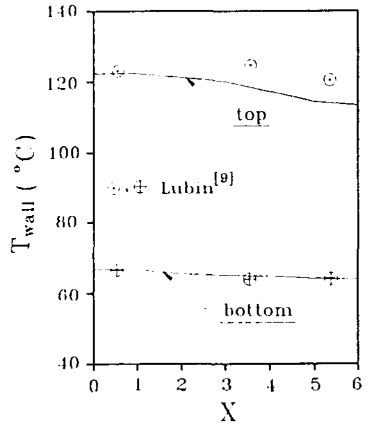


Figure 3 Comparison betwen plant test and our analysis data (at T_h=149℃ and T_c=38℃)

4. RESULTS AND DISCUSSION

The purpose of this analysis is to investigate the thermal stratification of the flow in a horizontal pipeline through a numerical analysis and to suggest a feasible design changes to prevent thermal stratification in the safety injection line of the PWR plant.

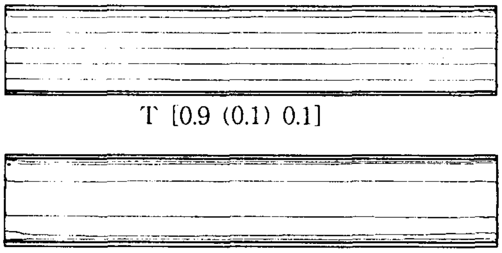
Therefore, the analysis is focused on the effects of variation of the heat transfer rates at the pipe surface, the thermal conductivities and the thickness of the pipe wall on the thermal stratification.

4-1 The effect of heat transfer rates of pipeline wall

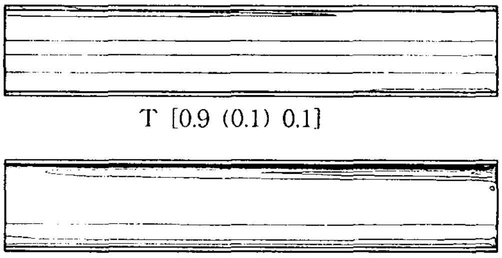
The dimensionless distribution of streamlines and isotherms for the variation of heat transfer rates of the pipe wall are shown in Fig. 4. The values in bracket denote [maximum (interval) minimum temperature value] of isotherms. Figure 4 (a) and (b) show distributions of streamlines and isotherms at Bi=5.0x10^{-5} and 5.0x10^{-2}, respectively.

In Fig. 4 (a), it is shown that thermal stratified flow occurs in the pipe line at the Biot number of 5.0x10^{-5}, i.e., hotter fluid flows the upper portion of the pipe line and colder fluid flows the lower portion of the pipe line. Heat is transferred through the top (hotter) intrusion layer and by conduction in the y-direction (circumferential direction) to the lower section of the pipe line, where it is then transferred to the bottom (cooler) intrusion layer. Figure 4(b) shows that the streamlines and isotherms are somewhat changed by the variation of heat transfer rates at the outside pipe wall, but stratification still exists.

Figure 5 shows the temperature distributions of pipe wall at the selected axial distance (x=3). This temperature distributions are calculated by the assumption that those of fluid are a function of circumferential angles because the temperature distribution at the same level is nearly equalized by the thermal stratification in the enclosures. The angular variation in wall temperature is the consequence of pipe wall conduction in the circumferential direction around the wall. The local variation in fluid temperatures will not appreciably alter the intrusion layer flow pattern[9].



(a) Bi=5.0x10^{-5}



(b) Bi=5.0x10^{-2}

Figure 4 The distribution of isotherm(upper) and streamline(bottom) at Gr=1.38x10^{12}, Pr=1.9, k_s/k_f=23 and a=0.05

It is known that the wall temperature difference between top and bottom of pipe significantly reduces as the heat transfer rate at the pipe wall increases, because of the mixing effect by natural convection. The results show that the thermal stratification exists in the pipe; however, a significant reduction of the temperature difference of pipe wall from top to bottom can be observed over the Biot number of 5x10^{-2}. So, the thermal stress of the pipe wall may be reduced significantly.

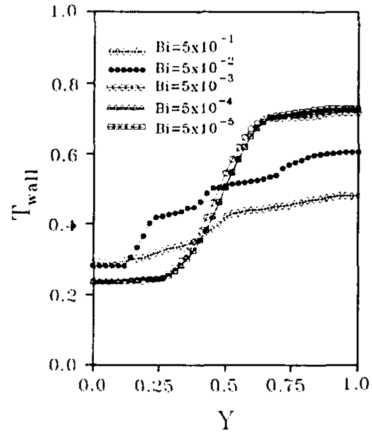


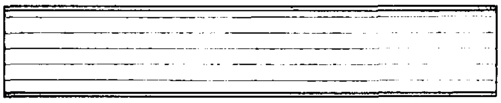
Figure 5 The temperature distribution for y-direction for various Biot numbers at x=3 (Gr=1.38x10^{12}, Pr=1.9, k_s/k_f=23 and a=0.05)

4-2 The effect of thermal conductivity of wall pipeline

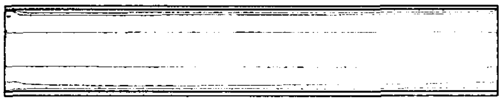
In order to see if the thermal conductivity of the wall pipeline might effect thermal stratification, the analysis is done only for the variation of thermal conductivity of pipeline with other conditions fixed. The distribution of streamlines and isotherms for various thermal conductivities of pipeline is shown in Fig. 6. In the case Bi = $5.0\text{x}10^{-5}$ and a = 0.05, Fig. 6 shows the distributions of streamlines and isotherms at k_s/k_f=23 and 575, respectively.

According to Fig. 6, it is shown that the pattern of streamlines and isotherms is nearly not changed, even if the thermal conductivity of pipeline increases.

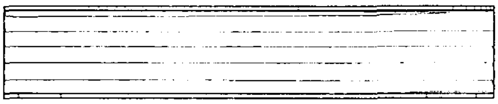
Also, as shown in Fig. 7, the temperature difference between top and bottom of pipe circumference is not changed as the thermal conductivity of pipeline increases.



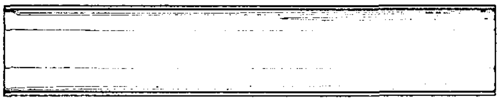
T [0.9 (0.1) 0.1]



(a) k_s/k_f=23



T [0.9 (0.1) 0.1]



(b) k_s/k_f=575

Figure 6 The distribution of isotherm(upper) and streamline(bottom) at Gr=$1.38\text{x}10^{12}$, Pr=1.9, Bi=$5\text{x}10^{-5}$ and a=0.05

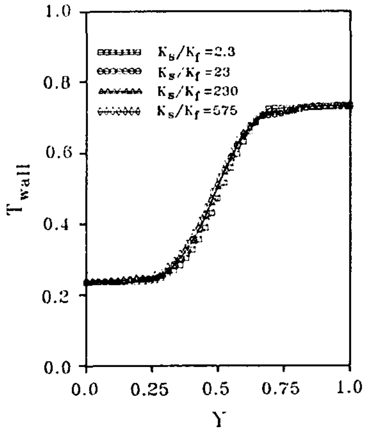
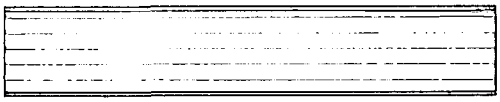


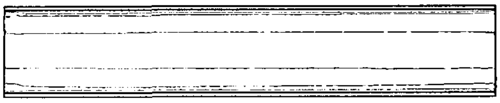
Figure 7 The temperature distribution for y-direction for various thermal conductivity at x=3 (Gr=$1.38\text{x}10^{12}$, Pr=1.9, Bi=$5.0\text{x}10^{-5}$ and a=0.05)

4-3 The effect of pipeline wall thickness

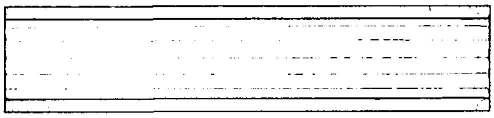
In order to see if the thickness of the pipeline might effect thermal stratification, the analysis is done only for the variation of pipeline thickness with other conditions fixed. The dimensionless distribution of streamlines and isotherms for the variation of the wall thickness are shown in Fig. 8. In the case Bi=$5\text{x}10^{-5}$ and k_s/k_f=23, Fig. 8 shows the distributions of streamlines and isotherms at a=0.05 and 0.15, respectively.



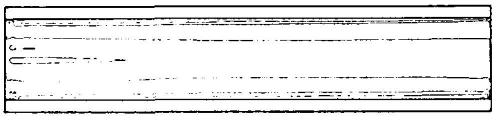
T [0.9 (0.1) 0.1]



(a) a=0.05



T [0.9 (0.1) 0.1]



(b) a=0.15

Figure 8 The distribution of isotherm(upper) and streamline(bottom) at Gr=$1.38\text{x}10^{12}$, Pr=1.9, k_s/k_f=23 and Bi=$5\text{x}10^{-5}$

According to Fig. 8, it is shown that the pattern of streamlines and isotherms is nearly not changed even if the thickness of pipeline increases. However, as shown in Fig. 9, the temperature difference between top and bottom of pipe circumference somewhat reduces as the thickness of pipeline increases, due to conduction effect through the wall.

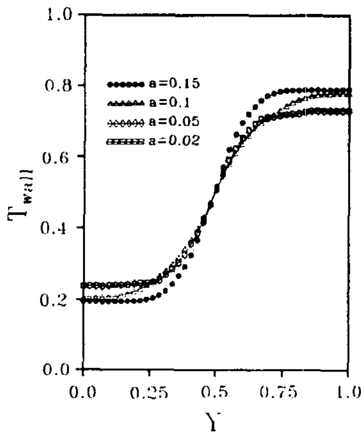


Figure 9 The temperature distribution for y-direction for various wall thickness at x=3 (Gr=1.38×10^{12}, Pr=1.9, k_s/k_f=23 and Bi=5.0×10^{-5})

5. CONCLUSIONS

The results show that the heat transfer rate at the pipe surface is the controlling parameter which can reduce thermal stratification in the pipeline and that the thermal stratification occurs at the Biot number of 5×10^{-5} which corresponds to the design and environmental conditions of the safety injection line of the PWR plant. A significant reduction and, eventually, the disappearance of the phenomenon are observed over the Biot number of 5.0×10^{-2}.

The results also show that the increase of the thermal conductivity and the thickness of the wall weakens the thermal stratification and reduces azimuthal temperature gradient in the pipe wall, but their influence is less pronounced than that due to the variation of the heat transfer rates at the surface of the pipe wall. Therefore, the increase of heat transfer rate at the surface of the pipe is a major factor to prevent thermal stratification of the flow in the safety injection line connected with the RCS main pipe line of the PWR plant.

NOMENCLATURE

a : thickness ratio of pipe
Bi : Biot number
C_1, C_2 : diffusion coefficient
h : heat transfer coefficient
H : length from top to bottom
k : thermal conductivity
L : length from left to right
P : pressure
Pr : Prandtl number
Ra : Rayleigh number
T : temperature
u, v : velocities in the x and y directions
x, y : cartesian coordinate
α : thermal diffusivity
β : coefficient of thermal expansion
θ : angle
υ : kinematic viscosity
ϕ : general dependent variable

Subscripts

c : cold
h : hot
f : fluid regions
s : solid regions, surface regions
∞ : environment

Superscripts

m : iteration number
* : physical quantity

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