Research Journal of Applied Sciences, Engineering and Technology 5(1): 332-338, 2013
DOI:10.19026/rjaset.5.5125
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: June 28, 2012 Accepted: July 19, 2012 Published: January 01, 2013

Research Article

Effect of Heat up Rate on Thermal Stratification in Horizontal Pipe

Athar Rasool, Sun Zhongning and Wang Jianjun
College of Nuclear Science and Technology, Harbin Engineering University, Harbin, Heilongjiang 150001, China

Abstract: The study is performed to analyze the effects of heat up rate on thermal stratification phenomenon in pressurizer surge line. The horizontal section of pressurizer surge line is considered for this study since significant thermal stratification is usually observed in horizontal sections of the pressurizer surge line. The tendency of thermal stratification reduces with increasing flow rates based on which four cases of heat up rates with increasing flow velocities are analyzed. The selected flow velocities of 0.01, 0.05, 0.1 and 0.2 m/sec for the study are calculated from the operating range of dimensionless Froude number 0.02-0.2 of pressurized water reactor type nuclear power plants. The horizontal pipe model inner diameter is 305 mm with thickness of 33.5 mm and length of four diameters. The Richardson number for the four cases is greater than unity and thermal stratification is likely to occur. The transient analysis is performed using commercially available software ANSYS CFX. The transient temperature distribution along the horizontal pipe wall with different heat up rates is represented in this study. Thermal stratification reduces with increase in heat up rate or flow velocity.

Keywords: Pressurizer surge line, reactor heat up rate, RNG K-Eturbulence model, thermel stratification

INTRODUCTION

Pressurized Water Reactor (PWR) type Nuclear Power Plant (NPP) has been widely used as commercial power source. Pressurizer is a key component of the primary loop of a PWR. It controls and compensates the pressure and volume surges in the primary loop. The pressurizer is connected with the hot leg of the primary loop through pressurizer surge line making it a vital part. Any damage to the pressurizer surge line influence the integrity of primary loop and hence hampers the operation of NPP. A schematic diagram of PWR is depicted in Fig. 1.

Thermal stratification: Thermal stratification in pressurizer surge line is well known phenomena. When during in-surge or out-surge hot fluid from hot leg or pressurizer flows in the pressurizer surge line already occupied with the cold fluid, distinct layers of fluid is formed due to density difference. Such flow is categorized as thermally stratified flow and the related phenomenon is known as thermal stratification (IAEA, 2003).

Pressurizer surge line: has a complex geometry it runs down from the pressurizer till the hot leg vertically and horizontally with varying slopes and curvatures. A generic pressurizer surge line layout is depicted in Fig. 2. Grebner and Hofler (1995) indicated that the thermal stratification is usually observed in horizontal section of the pressurizer surge line, since vertical portion is near to the pressurizer and there is enough mixing in the sections with varying slopes and curvatures.

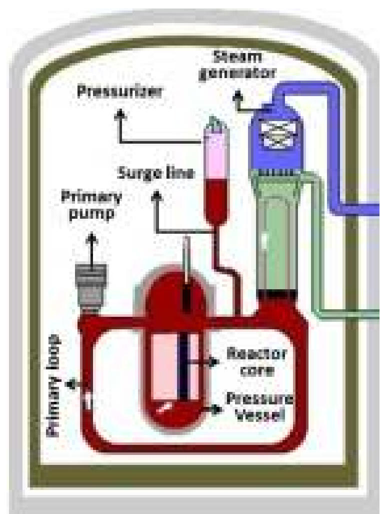

Fig. 1: Schematic diagram of Pressurized Water Reactor (PWR)

PWR operating conditions: The PWR type NPP operates at high pressure and temperature (15.5 MPa

Corresponding Author: Athar Rasool, College of Nuclear Science and Technology, Harbin Engineering University, Harbin, Heilongjiang 150001, China

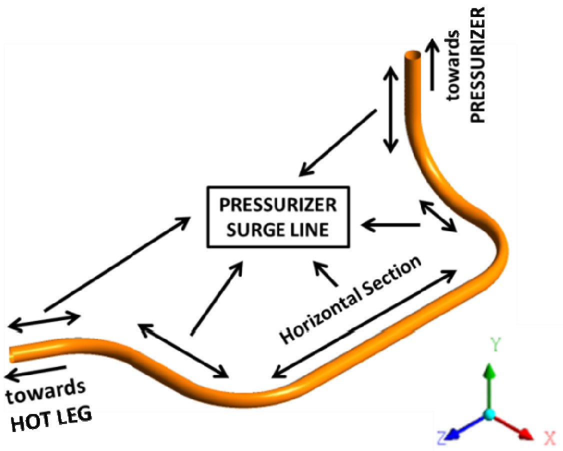

Fig. 2: Layout of pressurizer surge line

and 345°C). Shah and Conley (1989) discussed that the temperature difference between the hot leg fluid of the primary loop and the pressurizer fluid can be as high as 180ºC during heat up. The magnitude of the maximum temperature difference depends on the pressure at which a steam bubble forms in the pressurizer during heat up and the pressure at which the reactor coolant pumps are started. Prior to start of the reactor coolant pumps, the temperature of the coolant in the hot leg is typically 54ºC and the temperature of the coolant in the pressurizer can be as high as the saturation temperature 218ºC, which corresponds to the minimum pressure, typically 2.24 MPa at which the reactor coolant pumps can be operated. Grebner and Hofler (1995) discussed that the temperature difference between the hot leg fluid of the primary loop and the pressurizer fluid can be as high as 150°C during heat up phase.

Shah and Conley (1989) mentioned potential of thermal stratification is greatest during heat up and cool down phases of reactor operation because the difference between the pressurizer and hot leg temperatures is largest then. Similarly, (Kang and Jo, 2010) discussed that the significant thermal stratification in the pressurizer surge line occurs in the 2 modes of reactor operation starting up phase (heat up) at the reactor cold shut down condition and cooling-down at the normal operation condition. This makes both reactor operation modes bounding cases in terms of temperature gradients caused in the wall of the surge line.

Non-dimensional parameters: The surge lines were designed with the assumption that the coolant surges would sweep the whole cross section of the surge line piping but the actual flow pattern appears to be stratified (Shah and Conley, 1989). The thermal stratification can be defined with the help of non-dimensional parameters like Richardson or Froude numbers.

Richardson number: Is a non-dimensional parameter, which is directly proportional to Gravity (*g*), thermal expansion (*β*), temperature difference (*ΔT*) and characteristic length (*D*) and inversely proportional to the square of flow velocity (*v*). The expression for Richardson number (*Ri*) is given below:

$$\mathrm{Ri} = g\beta\Delta TD/v^2 \tag{1}$$

When 2 fluids at different temperatures flow through a space, the convection type can be determined based on the magnitude of the Richardson number. Shah and Conley (1989) mentioned the presence of stratified flow for Richardson number greater than unity and Kang and Jo (2010) mentioned for Richardson number above 10 the natural convection dominates the flow field and a strongly stratified flow can be maintained until either the temperature difference decreases or the flow velocity increases enough to lower the value of Richardson number below 0.1 or less.

Froude number: Is a non-dimensional parameter, which is directly proportional to flow velocity (*v*) and inversely proportional to the temperature difference (*ΔT*). Taupin *et al.* (1989) and Ensel *et al.* (1995) performed test for thermal stratification in pressurizer surge line and revealed that temperature profile in a stratified cross section is mainly correlated to Froude number, depending on the flow velocity and the temperature difference between hot leg and pressurizer. The expression of Froude number (*Fr*)is given below:

$$\mathrm{Fr} = \frac{v}{\sqrt{gD\Delta\rho/\rho}} \text{ with } \frac{\Delta\rho}{\rho} = 2\,\frac{\rho_{HL}-\rho_{PZR}}{\rho_{HL}+\rho_{PZR}} \tag{2}$$

where, *ρ* is the fluid density at hot leg (*HL*) and pressurizer (*PZR*) temperature. Above critical Froude number for high flow velocities stratification vanishes. XYZ mentioned that the pressurized water reactor type nuclear power plant operates in the range of Froude number 0.01 to 0.2. The damage to the pressurizer surge line due to thermal stratification has been reported since 1988 (NRC, 1988a, b, c). IAEA (2003) mentioned that high temperature difference in existence of thermal stratification can considerably affect the integrity of the pressurizer surge line. Initially thermal stratification effects have not been considered in the design of NPP. However, the new design of NPP incorporates the effects of thermal stratification phenomenon to the pressurizer surge line and subsequently is part of safety analysis report. Therefore, it is necessary to analyze and evaluate the thermal stratification phenomenon in pressurizer surge line of PWR. Kang and Jo (2008) highlighted that many researchers and scientists have used various methods and techniques to analyze this phenomenon. However

Table 1: Properties of pipe material and fluid

Parameters	Values
Pipe Material	ASME SA-312
Pipe inner diameter (ID)	305 mm
Pipe thickness (t)	33.5 mm
Density	8000 Kg/m3
Thermal conductivity	16.3 W/m-K
Specific heat capacity	500 J/kg-K
Thermal expansivity	17e-6 /K
Fluid (water)	IAPWS IF97
Fluid Initial Temperature	51.7 C
Fluid Inlet Velocity	0.05 m/sec
Fluid Inlet Velocity	0.05 m/sec
Reynolds number	0.283×10^5 - 1.05×10^5

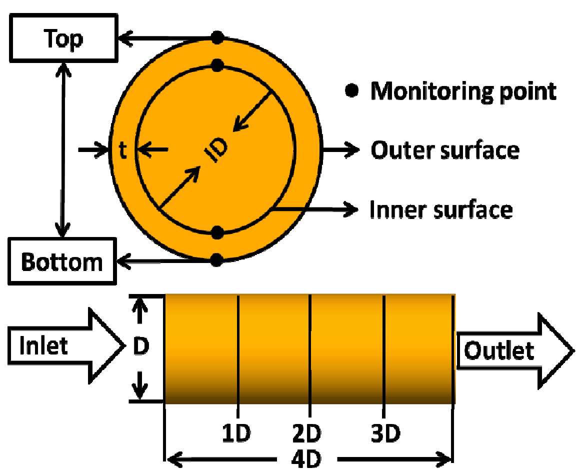

Fig. 3: Horizontal pipe layout and location of monitoring points and planes

with the breakthrough in computer technologies and advert of parallel processing it has been made possible to simulate such complex phenomena.

The study is performed to evaluate the effects on thermal stratification in horizontal sections of pressurizer surge line with increasing heat up rate. For the same 4 cases based on increasing flow velocities are considered. The horizontal pipe model is simulated using commercially available software ANSYS CFX. The transient temperature distribution along the horizontal pipe wall for the reactor starting up (heat up) phase at reactor cold shutdown condition is analyzed and represented.

MODEL DESCRIPTION

Geometric configuration and properties: The dimensions of horizontalpipe are selected on the basis of surge line dimensions. Generally pressurizer surge line is 250 to 350 mm diameter stainless steel pipe (Shah and Conley, 1989). The geometrical data and properties of pipe material and fluid are given in Table 1. IAPWS IF97, built in ANSYS CFX, is utilized for fluid properties in calculations (ANSYS, 2010a).

The horizontal pipe geometry configuration along with location of monitoring points (top to bottom inner and outer surface) and planes (at distance 1D to 3D) are depicted in fig. 3.

Problem Statement*:* In the present problem, 4 cases with different flow velocities based on general range of Froude number for PWR type NPP given in Table 2, are considered. The flow is stratified based on the Richardson number range for 4 cases given in Table 3, thus, the buoyancy force will strongly affect the flow field. Initially cold fluid at a specified temperature of 51.7ºC occupies the horizontal pipe maintaining a steady state condition. Then at a certain time hot fluid at a specified temperature of 218ºC begin to flow into the horizontal pipe, a typical out surge case. The pipe is horizontal with one inlet and outlet. The fluid flow in the horizontal pipe remains turbulent for the four cases as the Reynolds number range is large as shown in Table 1. The turbulent flow behavior is considered with the RNG K-E turbulence model. (K-E, RNG K-E and SST). For buoyancy calculations the density difference is evaluated directly using full buoyancy model. The reference pressure is equal to 2.2408 Mpa.

Table 2: Froude number for four cases

	Dia.	Temperature (°C)		Density (kg/m^3)		Acc.	Velocity	Froude
	D (m)	T_C	T_H	ρ_C	ρ_H	(m/s^2) g	(m/s) v	number (Fr)
Case 1	0.35	51.7	218	988.3	842.78	9.81	0.01	0.014
Case 2	0.35	51.7	218	988.3	842.78	9.81	0.05	0072
Case 3	0.35	51.7	218	988.3	842.78	9.81	0.10	0.145
Case 4	0.35	51.7	218	988.3	842.78	9.81	0.20	0.29

Table 3: Richardson number for four cases

	Dia.	Temperature (°C)		Acc.	Expansion Coefficient	Velocity	Richardson
	D (m)	T_C	T_H	(m/s^2) g	(1/K) β for ΔT_{avg}	(m/s) v	number (Ri)
Case 1	0.35	51.7	218	9.81	9.63×10^{-4}	0.01	4696
Case 2	0.35	51.7	218	9.81	9.63×10^{-4}	0.05	187
Case 3	0.35	51.7	218	9.81	9.63×10^{-4}	0.10	47
Case 4	0.35	51.7	218	9.81	9.63×10^{-4}	0.20	11

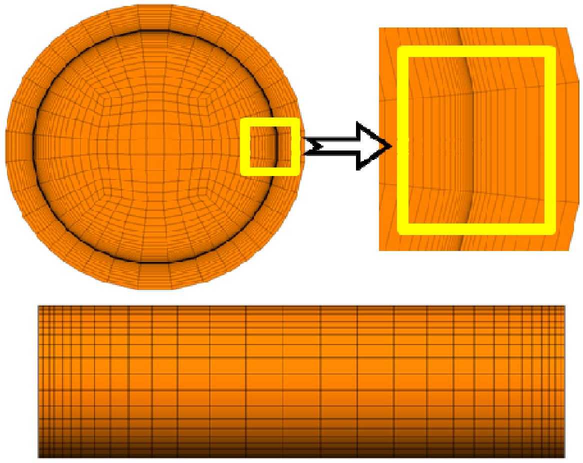

Fig. 4: Horizontal pipe grid scheme and grid density

Boundary Conditions: The solution domain consists of horizontal pipe, which can be further subdivided into two sub domains, fluid and solid domains. The fluid domain consists of flow field inside horizontal pipe. The solid domain consists of the region bounded by the inner and outer wall surfaces of horizontal pipe. To take into account the Fluid Structure Interaction (FSI) Conjugate Heat Transfer (CHT) analysis is incorporated into the CFD analysis. In solid domain, where there is no flow and conduction is the only mode of heat transfer, the conservation of energy eq. is simplified as the unsteady heat conduction eq. The Unsteady Reynolds Averaged Navies Stokes equations for conservation of mass, momentum, energy and turbulent quantities used in this study can be expressed in a Cartesian coordinate system as in reference (ANSYS, 2010a; White, 1991)

CFD analysis:

Model Mesh: To simulate the flow as accurately as possible both flow and fluid solid interface boundary regions are finely meshed using ANSYS ICEM. The grid density along the pipe length is less fine compared with radial or circumferential directions as shown in fig. 4.The fluid and solid domain is discredited into 43,065 hexahedral elements (30,537 elements in fluid domain and 12,528 elements in solid domain). The hexahedral elements type grid scheme is used due to its more realistic results. The overall mesh quality is greater than 0.65 on the scale from 0 to 1 based on ANSYS ICEM mesh quality criteria (ANSYS, 2010b). The aspect ratio, edge length ratio, element volume ratio and mesh expansion factor lies well within the specified criteria based on ANSYS CFX (ANSYS, 2010a). The same mesh is used for all simulations. The first node distance is approximated on the basis of boundary layer thickness for pipe (δ = 0.0324 D $Re^{-0.875}$) and the boundary layer is resolved using over 10 nodes. The overall grid expansion ratio of 1.2 is used Rasool *et al*. (2012). The same mesh is used for all cases.

Problem setup: The governing equations are discredited using the finite volume approach. The CFD calculations are performed for total time of 1000 sec with time step size of 0.1. The turbulent flow behavior is simulated using RNG K-E turbulence model. Flow near wall is treated using scalable wall functions, 1 of the built in user options in ANSYS CFX. Heat transfer in fluid and solid domains is simulated using total and thermal energy options respectively in ANSYSCFX, considering both conduction and convection in fluid domain and conduction in solid domain. The conservative interface flux option is selected for heat transfer between fluid and solid. High resolution advection scheme and 2nd order backward Euler transient scheme is used. The convergence criterion for all major parameters is determined at each time step when RMS residual is less than 10^{-3}. The convergence condition is met after 3 or 4 iterations at each time step, except for the initial time steps which requires up to 10 or more iterations.

RESULTS AND DISCUSSION

The transient progressions of temperature difference between the top and bottom inner wall and outer wall surfaces of horizontal pipe at a distance 2D for different heat up rates are depicted in Fig. 5& 6, respectively.

The top to bottom inner wall surfaces temperature difference is large in the beginning and quickly reduces and later on progressively stabilizes almost to uniform temperature difference for each case.

The top to bottom outer wall surfaces temperature difference increases initially and progressively decreases with the elapsed time.

Inner wall surfaces: The large temperature difference initially between the inner wall surfaces of horizontal pipe is due to the flow of hot fluid (218°C) in horizontal pipe already occupied with cold fluid (51.7ºC). The hot

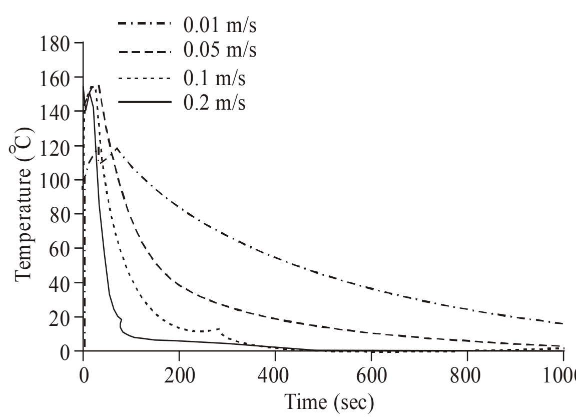

Fig. 5: Transient progressions of temperature difference for different heat up rates between top and bottom inner wall surfaces of cross section at a distance 2D

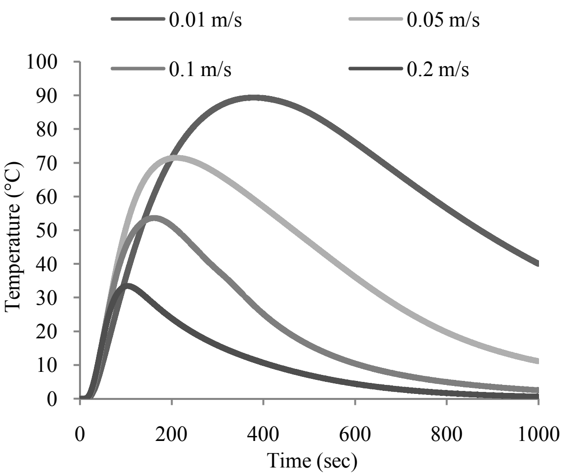

Fig. 6: Transient progressions of temperature difference for different heat up rates between top and bottom outer wall surfaces of cross section at a distance 2D

fluid having lesser density settles in the upper region of the horizontal pipe thus elevating the top inner wall surface temperature and resulting in large top to bottom temperature difference. The primary mode of heat transfer between fluid molecules is convection which is much quicker thus sharply reduces the top to bottom inner wall surfaces temperature difference. The hot fluid inflow is constant which keeps on increasing the bulk fluid temperature and thus progressively increasing the bottom inner wall surface temperature which in result reduces the top to bottom inner wall surfaces temperature difference.

Outer wall surfaces: The less quick progression of top to bottom outer wall surfaces temperature difference than top to bottom inner wall surfaces temperature difference is due to the mode of heat transfer. The heat transfer between the inner wall surfaces to the outer wall surfaces is only through conduction whereas convection takes place

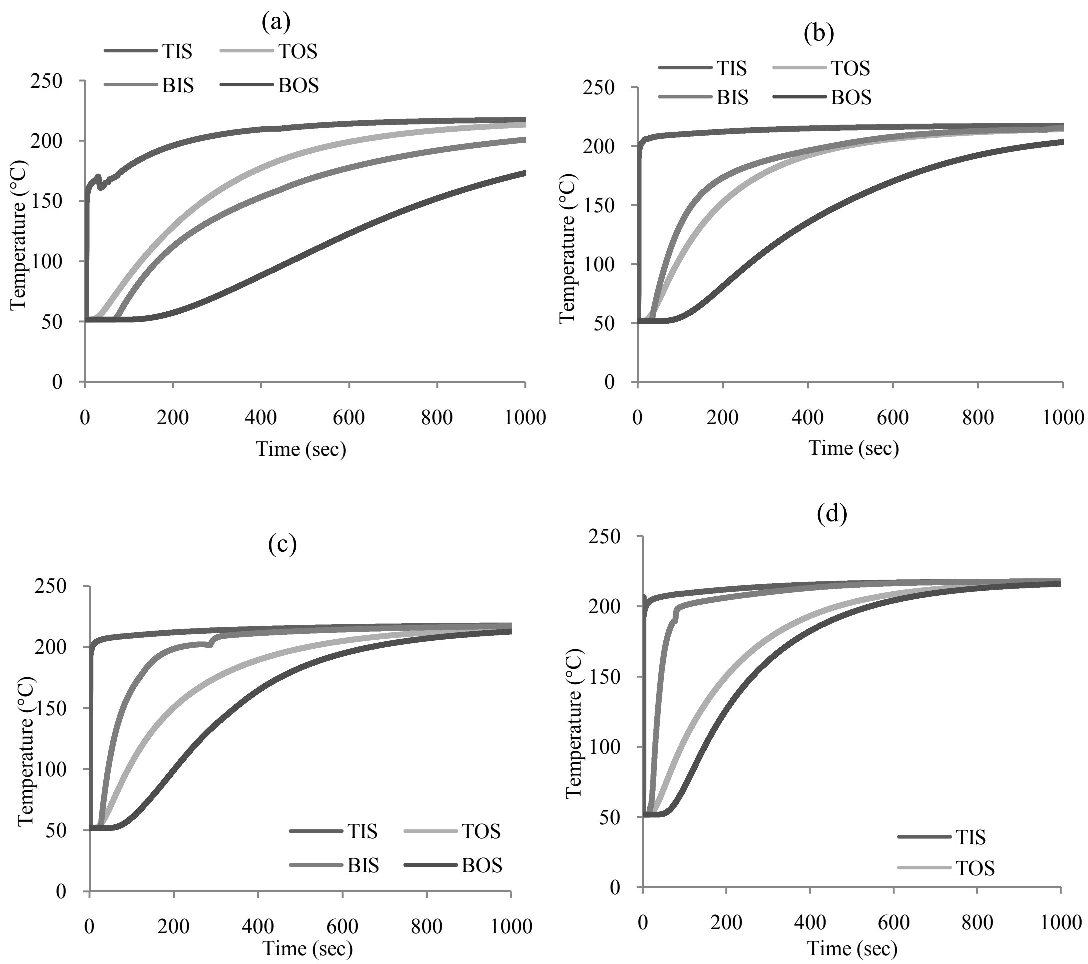

Fig. 7: Transient progressions of Top Inner Surface (TIS), Top Outer Surface (TOS), Bottom Inner Surface (BIS) and Bottom Outer Surface (BOS) temperatures for different heat up rates, (a) 0.01 m/s, (b) 0.05 m/s, (c) 0.1 m/s, (d) 0.2 m/s along cross section at a distance 2D

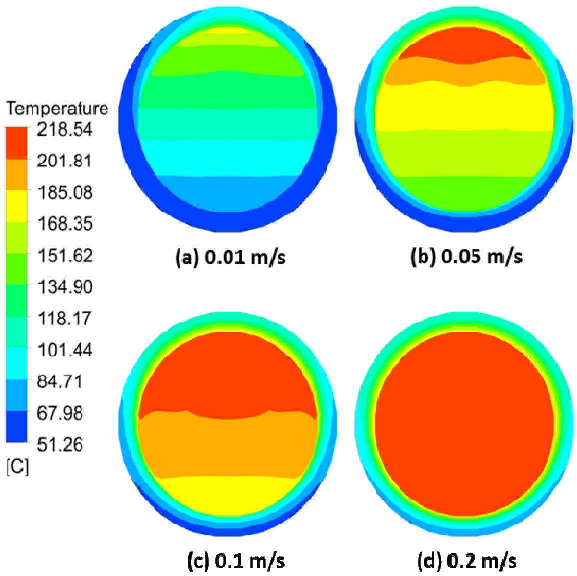

Fig. 7: Transient temperature distributions along the cross section at a distance 2D at elapsed time of 100 sec

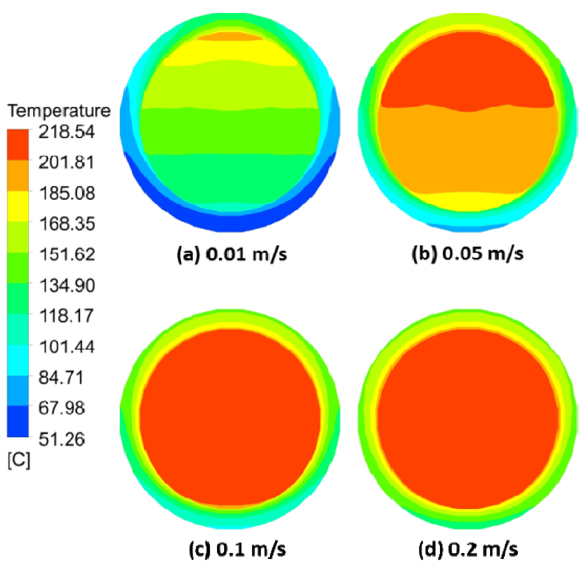

Fig. 8: Transient temperature distributions along the cross section at a distance 2D at elapsed time of 200 sec

between fluid molecules and is much quicker than conduction. The bulk fluid temperature slowly progresses towards uniformity which results in comparatively large top to bottom outer wall surfaces temperature difference. The top to bottom outer wall surfaces temperature difference significantly decreases towards the end of simulation period as the bulk fluid temperatures reaches homogeneity.

Figure. 7 depicts that with the increase in heat up rate the inner wall surfaces temperatures approach to homogeneity and similarly the outer wall surfaces temperature exhibits the same trend. Thus with the increase in heat up rate top to bottom temperature difference reduces.

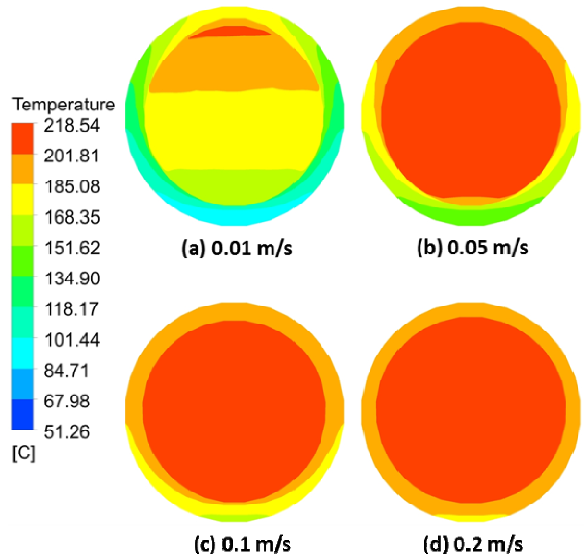

Fig. 9: Transient temperature distributions along the cross section at a distance 2D at elapsed time of 400 sec

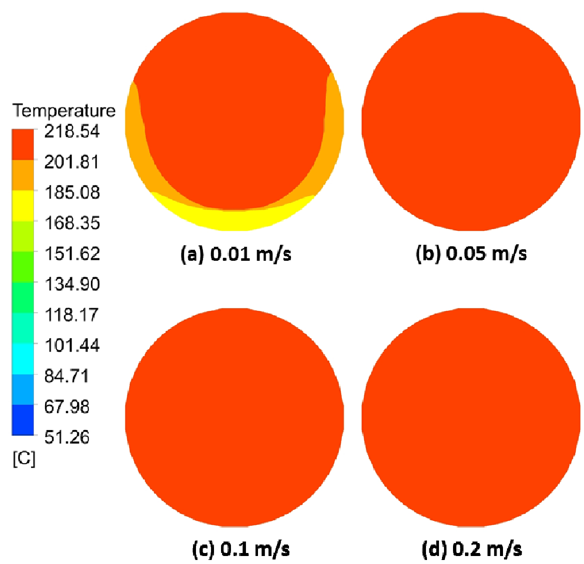

Fig. 10: Transient temperature distributions along the cross section at a distance 2D at elapsed time of 1000 sec

The transient temperature distributions along the cross section at a distance 2D at elapsed time of 100, 200, 400 and 1000 sec for different heat up rates are depicted in Fig. 8, 9, 10 and 11, respectively. It can be observed that with the increase of heat up rate the top to bottom temperature difference reduces. The maximum top to bottom temperature difference is observed at low flow velocity of 0.01 m/sec for which the Richardson number is very high as shown in Table 3, whereas it is minimum at flow velocity of 0.2 m/sec for which the local Richardson number is close to unity.

CONCLUSION

A simple horizontal pipe is considered to study the effects of heat up rate on thermal stratification of pressurizer surge line of PWR. The turbulent behavior of fluid flow is analyzed with RNG K-E turbulence model. The temperature distribution along the cross section is highly dependent on flow velocity and with increase of heat up rate top to bottom temperature difference reduces quickly with elapsed time. The maximum top to bottom inner and outer wall surfaces temperature difference is obtained for flow velocity of 0.01 m/sec and minimum top to bottom inner and outer wall surfaces temperature difference is obtained for flow velocity of 0.2 m/sec. Hence at low flow velocities the flow is highly stratified and the tendency of stratification reduces with increase in heat up rate. The results obtained verify the dependency of stratified flows on Richardson number.

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