Scientific Research

Numerical Simulation of PRHR System Based on CFD

Bin Jia, Jianping Jing, Xuedong Qiao, Chunming Zhang

Nuclear and Radiation Safety Center, Beijing, China
Email: athrun_jin@163.com

ABSTRACT

In this paper numerical simulation of PRHR HX and IRWST is demonstrated using FLUENT, and different numbers of C-type heat transfer tubes and coolant inlet temperature's effects for the residual heat removal capacity of PRHR HX, IRWST thermal stratification and natural circulation have been researched. It's found that at a constant flow area when heat transfer tubes' number increased outlet temperature of PRHR HX is lower, the whole water temperature of IRWST is higher, thermal stratification and natural circulation are more oblivious. At a constant mass flow when inlet temperature of PRHR HX increased, inlet flow velocity increases and outlet temperature is higher. But on the other hand the cooling rate increases at the same time, the average temperature of IRWST is higher, the range of thermal stratification expands and the velocity of natural circulation increases.

1. Introduction

Introducing passive concept into safety systems is typical character for the 3rd generation nuclear power plant. Currently many reactors under construction or under design use lots of this advanced concept both domestically and abroad.

AP1000 passive residual heat removal system [1] (PRHRS) is one of the important passive safety systems, it can take the advantage of the coolant density difference between in-core and C-type heat transfer tubes of passive residual heat removal heat exchanger (PRHR HX) as a driving force to establish natural circulation, and transfer heat to in-containment refueling water storage tank (IRWST) through PRHR HX, then remove the residual heat in the core under accident conditions and ensure the safety of the reactor. As two key devices in the system PRHR HX and IRWST directly affect whether the residual heat in the core can be removed under accident conditions, so it's necessary to research PRHR HX heat transfer performance and IRWST internal thermal stratification and natural circulation.

With advances in computer hardware technology and rapid development in computational fluid dynamics (CFD), it has become a very effective techniques that using numerical simulation to carry out fluid flow and heat transfer research for various heat exchangers [2,3]. Therefore in this paper numerical simulation for PRHR HX and IRWST has been taken via Fluent software, and our focus is the effect for PRHR HX heat transfer performance and IRWST internal thermal stratification and natural circulation when the C-type heat transfer tubes' number or the coolant inlet temperature changes.

## 2. Research Subjects and Mathematical Models

2.1. Research Subjects

In this paper AP1000 is seen as an example designed by Westinghouse, its PRHR HX is consisted of 689 bundle arranged C-type heat transfer tubes, inlet head and outlet head. Heat exchanger is submerged in IRWST, and it can remove residual heat from core by transferring it to IRWST in operation. In **Table 1** parameter [1,4,5] of IRWST and PRHR HX are listed, **Figure 1** is the PRHR system diagram.

Firstly on the basis of AP1000 PRHR HX various geometric, operating design parameters modeling and calculation are carried out. Though PRHR HX is consisted of lots of heat transfer tubes, but each tube's heat transfer process is relatively independent, heat transfer mechanism is the same. To reduce the amount of computation and research the effects of different number of C-type heat transfer tubes for PRHRS operation, and on the basis of total flow area unchanged and through changing tube size, physical models of 8-tube and 16-tube heat exchangers submerged in cubic IRWST are built respectively, as showed in **Figure 2**. Then on the basis of calculation result of 16-tube model at design

Table 1. Parameters for IRWST and PRHR HX of AP1000.

IRWST		PRHR HX	
parameter	number	parameter	number
Minimum water capacity(m^3)	2092	Heat load(J/s)	5.89E+07
Actual water capacity(m^3)	2132	Design flow(kg/h)	2.28E+05
Design pressure(Mpa)	0.034 (Measuring)	Inlet water temperature(℃)	297.2
Design temperature(℃)	65.6	Outlet water temperature(℃)	92.8
IRWST initial temperature(℃)	48.9	Design pressure(Mpa)	17.1 (Measuring)
Normal depth，mm	8534.4	Heat exchanger inlet pressure(Mpa)	15.5
Nominal depth，mm	8778.2	Design temperature(℃)	343.3
Material	Stainless steel	Number of heat transfer tubes	689
		Size of heat transfer tubes(mm)	19.05*1.65
		Spacing of heat transfer tubes(mm)	38
		Material	690Alloy
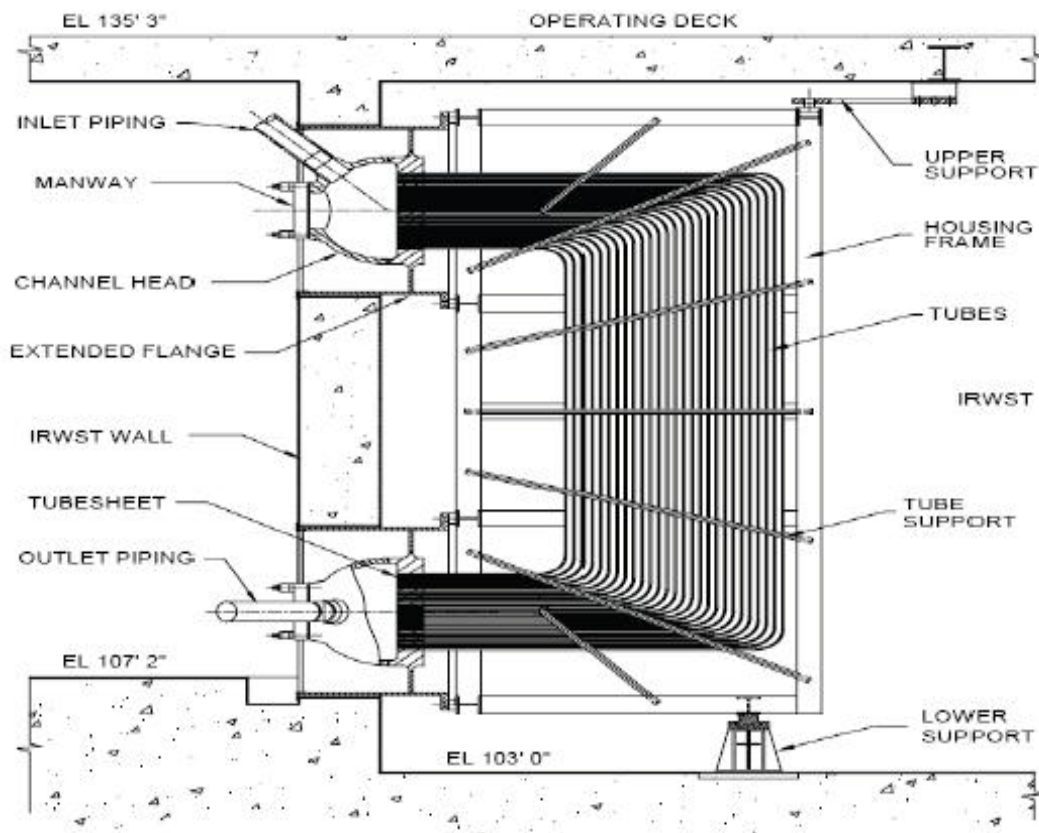
Figure 1. Schematic diagram of PRHR system.

operating condition, through changing coolant inlet temperature to research the effects for heat exchanger performance and IRWST stratification phenomena and natural circulation and master the law for much more heat
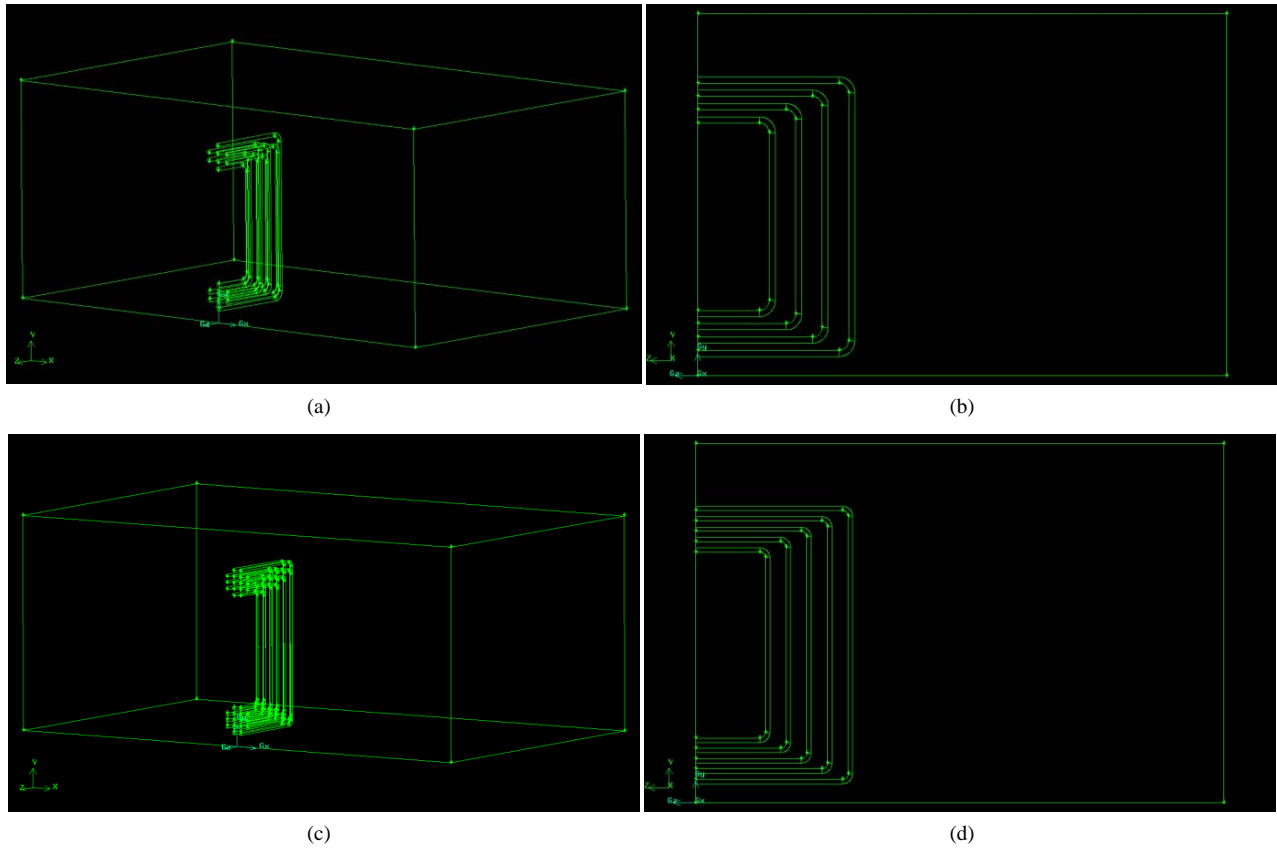
(a)

(b)

(c)

(d)

Figure 2. Diagram of system model, (a) and (b) for 8 tubes, (c) and (d) for 16 tubes.

transfer tubes modeling and calculation in future.

2.2. Mathematical Models

Since there is a big temperature difference between water in heat exchanger C-type tubes and water in IRWST, turbulence phenomenon will happen in the heat exchanger. Because of that, to close the Reynolds-averaged N - S equations, a turbulence model is necessary and k - ε equation is used, the corresponding equations are as follows [6,7].

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \left(\rho u \right) = S_m \tag{1}$$

Momentum equation:

$$\rho \left(\frac{\partial u}{\partial t} + u \bullet \nabla u \right) = \rho f + \nabla \bullet \sigma \tag{2}$$

Energy equation:

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \bullet \nabla T \right) + p \nabla u$$

$$= \left(\nabla \lambda \bullet \nabla \right) T + \rho q - \nabla q_r + \phi \tag{3}$$

k - ε equation:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j}$$

$$= p - \rho \varepsilon + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \tag{4}$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_j \xi)}{\partial x_j} = C_{\xi 1} \frac{\xi}{k} P_t - C_{\xi 2} \rho \frac{\xi^2}{k}$$

$$+ \frac{\partial}{\partial x_j} \left[(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \xi}{\partial x_j} \right] \tag{5}$$

$$\mu_t = \frac{C_\mu \rho k^2}{\xi} \tag{6}$$

In the formula: Sm is the source term, u is the flow velocity, λ is the thermal conductivity, qr is the heat transfer. For the k-ε equation, k and ε are turbulent kinetic energy and turbulent dissipation rate, P_t is the turbulent kinetic energy production term, μ_t is the turbulent viscosity coefficient, model constants are: $C_{\xi 1} = 1.44$, $C_{\xi 2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $C_\mu = 0.09$.

As the temperature of the coolant through the heat exchanger will be drastically reduced, while the refueling water tank will be heated, water temperature changing will directly cause changing in density, thereby affecting

the entire natural circulation and heat transfer process. So water density varied with temperature udf relation [8] is introduced into material properties table in FLUENT program. Since the density of water reaches the maximum at 3.98°C atmospheric pressure, density and temperature parabolic relation are selected:

$$\rho = \rho_0 \left[1 - \gamma \left(T - T_0 \right)^2 \right] \tag{7}$$

In the formula: ρ_0 is the maximum value of water density, T_0 is the water temperature at the same time, γ is the thermal expansion coefficient. Although PRHR HX design pressure is 16.9 Mpa, design temperature is 297.2°C, and the IRWST runs at atmospheric pressure, the design temperature is 48.9°C. However after verification, it's found that thermal expansion coefficients at two conditions are very close, with little effect on the calculation, the final γ is selected as $3.1e^{-6}$.

3. Simulation Results

3.1. Effect of Different C-Type Heat Transfer Tubes Number

At design parameters 8-tube and 16-tube heat exchanger models outlet temperature is demonstrated in **Table 2**, tube number is according to system model **Figure 2** from left to right and from top to bottom in order. It can be seen from both sets of data that because of long stroke for outer tubes, their cooling effect is better than inner ones'. Though comparing it's found that whether the characteristic tube or the average value the outlet temperature of 16-tube model is obviously lower than 8-tube. The reason is that on the basis of certain flow area increasing tube number means heat transfer area increases. Further heat transfer will be enhanced and performance of the heat exchanger will be improved.

The internal thermal stratification diagram of IRWST is showed in **Figure 3**, respectively longitudinal direction slitting figure along the width of the tank and transverse direction slitting figure along the height of the tank, **Figures 3(a)** and **(c)** are for 8-tube model, **Figures 3(b)** and **d** are for 16-tube model. By contrast, the thermal stratification phenomenon of 16-tube model is more obvious, the temperature of high temperature area is higher and

the range is larger, from **Figure 3(d)** it can be seen that thermal stratification has basically spread throughout the tank section.

3.2. Effect of Different Coolant Inlet Temperature

On the basis of 16-tube model effect of different coolant inlet temperature has been researched. Coolant outlet temperature changing through changing inlet temperature is demonstrated in **Table 3**. It's found that when inlet temperature increases the outlet temperature also increases. The reason is that when the whole flow is constant, increasing inlet temperature means increasing heat input, but the water loaded in IRWST is unchanged, so the outlet temperature will become higher.

Although with the inlet temperature increasing the outlet temperature has a clear upward trend, but PRHR HX cooling rate is increased too, the cooling rate equation is as follows.

$$\frac{T_{inlet} - T_{outlet}}{T_{inlet}} \times 100\% \tag{8}$$

T_{inlet} and T_{outlet} are coolant inlet and outlet temperature respectively. By calculation, when the inlet temperature is 275°C, 297.2°C and 325°C, the cooling rate is 24.99%, 25.87% and 26.87%. The reason is that when whole flow is constant, coolant volume will expand with higher temperature, and meanwhile the flow area is also constant the flow velocity of the coolant will improve. Thus the heat transfer coefficient [9] between the coolant and heat transfer tube wall will be increased and the heat transfer performance of PRHR HX will be enhanced.

Figures 4(a)-(c) and **(d)-(f)** are the internal thermal stratification diagrams of IRWST when temperature is 275°C, 297.2°C and 325°C and respectively longitudinal direction slitting figure along the width of the tank and transverse direction slitting figure along the height of the tank. When the coolant inlet temperature increases the water temperature of IRWST is also changing, the range of thermal stratification is expanding gradually, it means that the utilization of IRWST is improving. So once again it confirms that with inlet temperature rising

Table 2. Outlet temperature of 8 and 16 tubes models at designed inlet temperature.

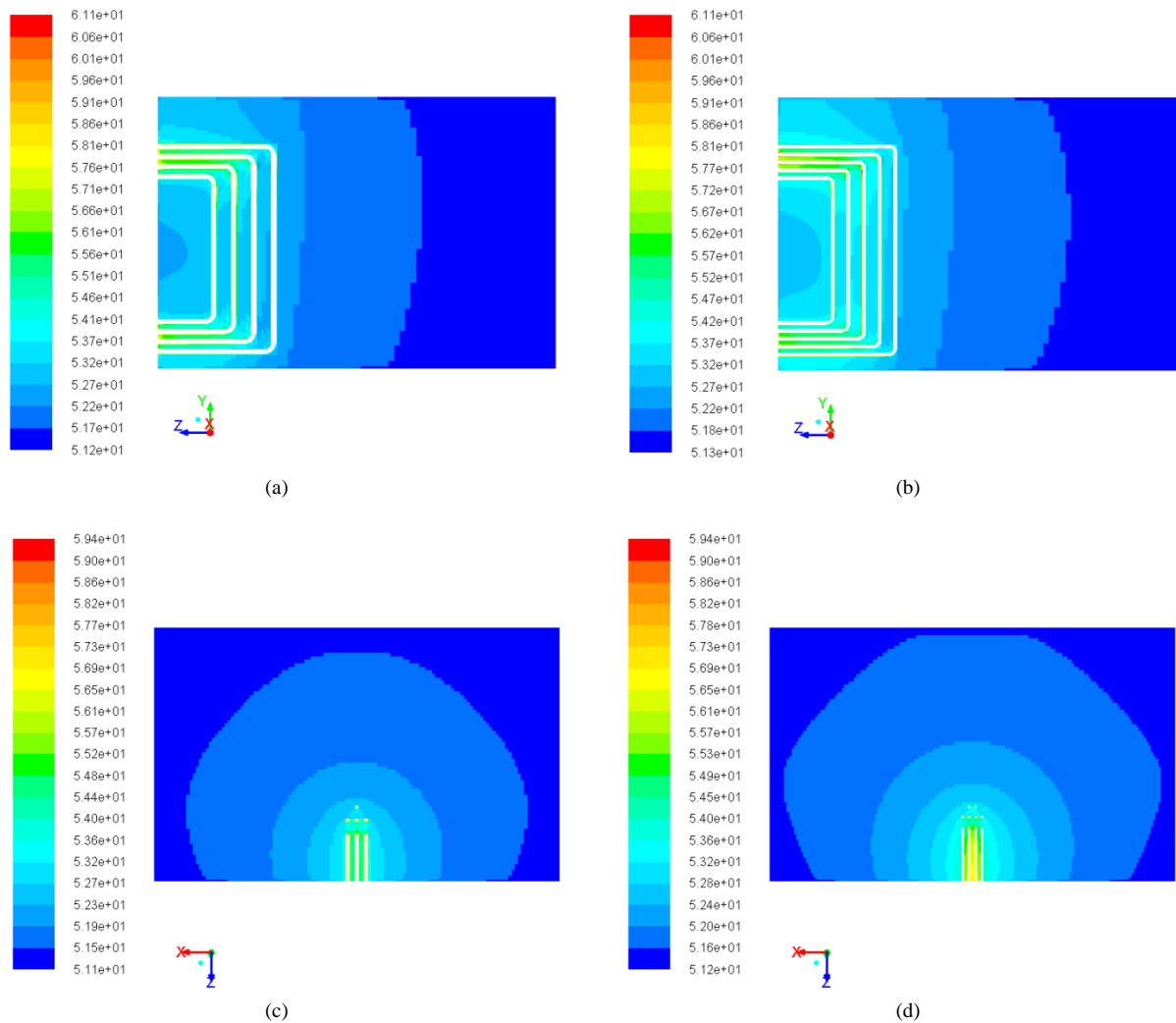| Unit (°C)	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5	Tube 6	Tube 7	Tube 8	Average
Outlet temperature(8)	224.06	232.02	236.22	231.95	240.75	244	240.78	249.81	237.45
	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5	Tube 6	Tube 7	Tube 8	
	201.68	201.67	209.72	213.39	213.52	209.76	219.29	224.03	220.32
Outlet temperature(16)	Tube 9	Tube10	Tube 11	Tube 12	Tube 13	Tube 14	Tube 15	Tube 16	
	224.07	219.39	227.69	230.24	230.17	227.51	236.44	236.57	

(a)

(b)

(c)

(d)

Figure 3. IRWST thermal stratification, (a) and (c) for 8 tubes, (b) and (d) for 16 tubes.

Table 3. Outlet temperature of 16 tubes model at different inlet temperature.

Unit (°C)	Tube 2	Tube 4	Tube 6	Tube 8	Tube10	Tube12	Tube14	Tube16	Average
Outlet temperature(275°C)	189.65	200.07	197.03	209.39	205.44	215.17	212.86	220.75	206.27
Outlet temperature(297.2°C)	201.67	213.39	209.76	224.03	219.39	230.24	227.51	236.57	220.32
Outlet temperature(325°C)	216.49	229.98	225.56	242.04	236.64	248.89	245.7	256.22	237.68

PRHRS performance is improved.

At the above three conditions velocity vector of natural circulation phenomena in IRWST is showed in **Figure 5**. **Figures 5(a)-(c)** are respectively corresponding to the inlet temperature 275°C, 297.2°C and 325°C.

When the water in IRWST is heated by PRHR HX, not only thermal stratification is built but also density stratification. Near the heat transfer tubes the temperature is higher and density decreases natural convection phenomena will occur. Meanwhile at the area that far away from the tubes but near the inner wall of IRWST the water temperature is relatively lower and density is relatively higher, then the natural circulation phenomena will be generated within the whole tank. As showed in **Figure 5**, with the increasing of coolant inlet temperature heat transfer inside IRWST is improved and velocity of natural circulation is increasing gradually, thus the heat transfer coefficient [9] between the coolant and heat transfer tube wall will be increased and the heat transfer performance of PRHR HX will be enhanced further.
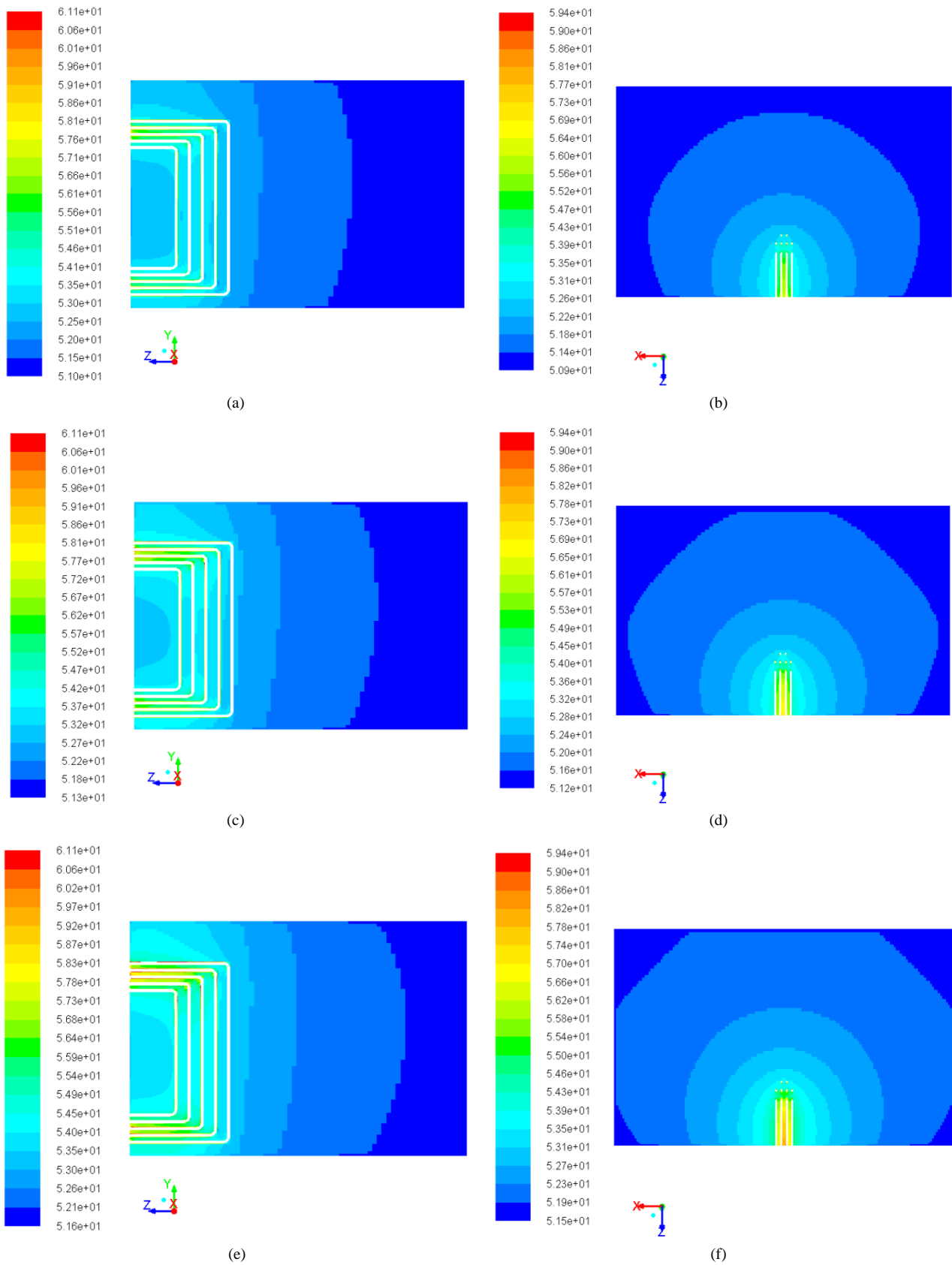
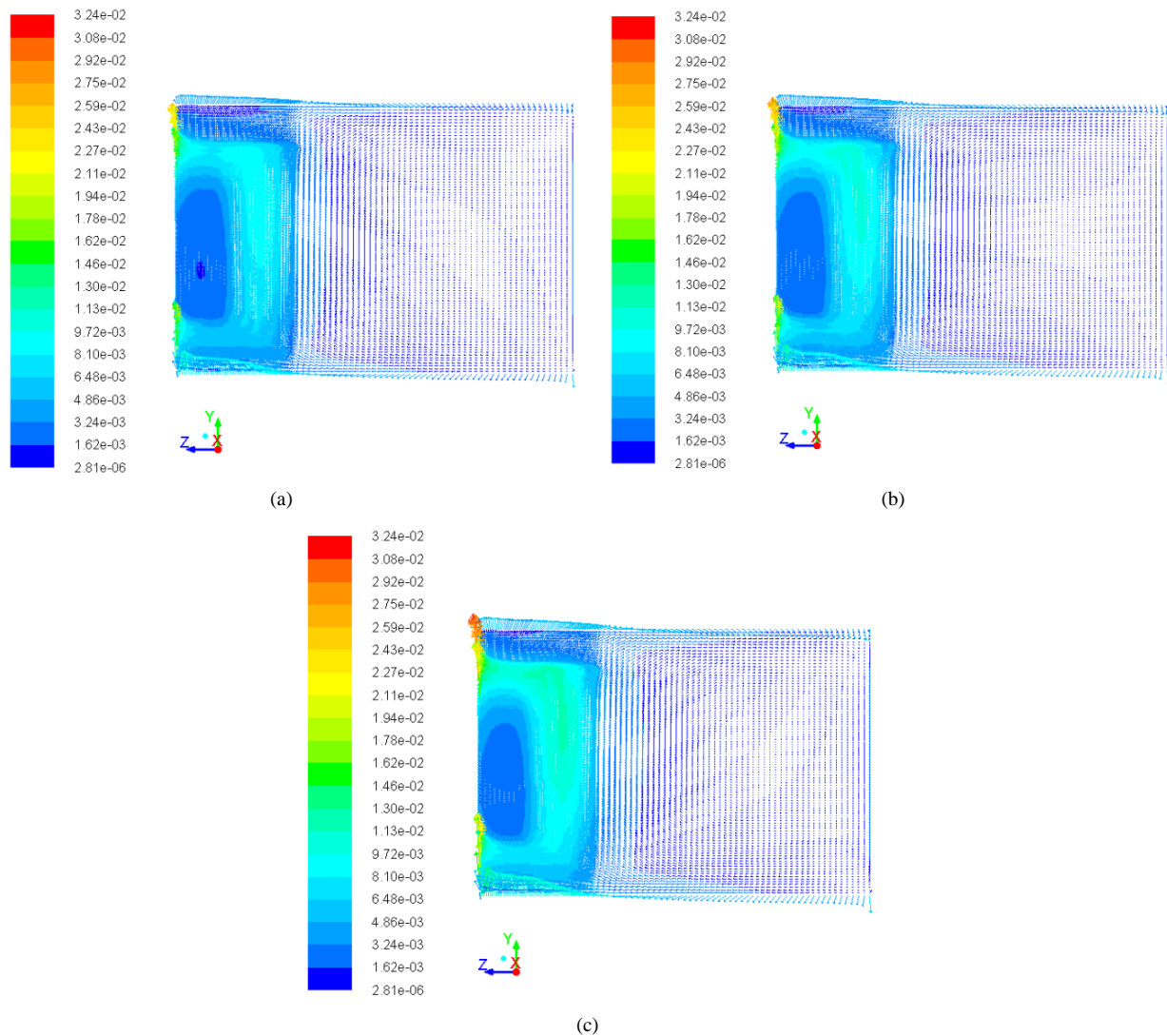Figure 4. IRWST thermal stratification, from left to right inlet temperature is increasing.

(a)

(b)

(c)

Figure 5. Natural circulation velocity vector of IRWST at different inlet temperature.

4. Conclusions

In this paper PRHRS is simulated with different number of C-type heat transfer tubes and different coolant inlet temperature via FLUENT software, the main conclusions are as follows:

1) Keep the total flow area of PRHR HX constant increasing the number of C-type heat exchanger tubes can increase the heat transfer area, thus heat transfer will be improved and the performance of PRHR HX will be enhanced.

2) Keep the number of C-type heat transfer tubes and overall flow constant increasing coolant inlet temperature the coolant will expand and flow velocity will increase too. The range of thermal stratification in IRWST will become larger and the velocity of natural circulation will increase.

3) With the increase in the coolant inlet temperature,

outlet temperature will also increase, but the cooling rate of the system to the coolant rises. It means the heat transfer performance of PRHR HX is improved to some extent, it can guarantee the PRHRS still be safe and reliable operation when the parameters are deviated from the design conditions.

5. Acknowledgements

REFERENCES

[1]   C.-G. Lin and Z.-S. Yu, "Passive Safety Advanced Power Plant AP1000," Atomic Energy Press, Beijing, 2008.

[2] K. Ikeda, Y. Makino and M. Hoshi, "Single-Phase CFD Applicability for Estimating Fluid Hot-Spot Locations in a 5*5 Fuel Rod Bundle," *Nuclear Engineering and Design*, Vol. 236, No. 11, 2006, pp. 1149-1154. http://dx.doi.org/10.1016/j.nucengdes.2005.11.006

[3] M. Kim, S. O. Yu and H. J. Kim, "Analyses on Fluid Flow and Heat Transfer inside Calandria Vessel of CANDU-6 Using CFD," *Nuclear Engineering and Design*, Vol. 236, No. 11, 2006, pp. 1155-1164. http://dx.doi.org/10.1016/j.nucengdes.2005.10.018

[4] L.-S. Li, K. Wang and X.-M. Song, "International Research Progress of CFD Application in Analysis of Nuclear Power System," *Nuclear Power Engineering*, Vol. 30, No. 5, 2009, pp. 28-33.

[5] Y.-J. Gao, "Analysis of Fabrication Process for AP1000 Passive Residual Heat Removal Heat Exchanger," *Nuclear Power Engineering*, Vol. 32, No. 2, 2011, pp. 107-

111.

[6] R.-J. Xue, C.-C. Deng and M.-J. Peng, "Numerical Simulation of Passive Residual Heat Removal Heat Exchanger," *Atomic Energy Science and Technology*, Vol. 44, No. 4, 2010, pp. 429-435.

[7] T.-Z. Ming, "Passive Residual Heat Removal Heat Exchanger Numiral Simulation and Design Research," Huazhong University of Science and Technology, Wuhan, 2003.

[8] Y.-B. Su, J. Lu and B.-F. Bai, "Numerical Simulation of Natural Convection and Heat Transfer of Water in Cavities," *Journal of Chemical Industry and Engineering* (*China*), Vol. 58, No. 11,2007, pp. 2715-2720.

[9] S.-M. Yang and W.-Q. Tao, "Heat Transfer," 4th Edition, Higher Education Press, Beijing, 2006.