A Numerical Analysis on Thermal Stratification Phenomenon by In-Leakage in a Branch Piping

Jong-Il Park*
Department of Building System Engineering, Dong-Eui University, 995, Eomgwang-No, Busanjin-Gu, Busan 614-714, Korea

Thermal stratification in the branch piping of power plants can be generated by turbulent penetration or by valve leakage. In this study, a numerical analysis was performed to estimate the thermal stratification phenomenon by in-leakage in the SIS branch piping of nuclear power plant. Leakage rate, leakage area and leakage location were selected as evaluation factors to investigate the thermal stratification effect. As a result of the thermal stratification effect according to leakage rate, the maximum temperature difference between top and bottom of the horizontal piping was evaluated to be about 185K when the valve leakage rate was about 10 times as much as the allowed leakage rate. For leakage rate more than 10 times the allowed leakage rate, the temperature difference was rapidly decreased due to the increased mixing effect. In the result according to leakage area, the magnitude of temperature difference was shown in order of 3%, 1% and 5% leakage area of the total disk area. In the thermal stratification effect, according to the leakage location, temperature difference when leakage occurred in the lower disk was considerably higher than that of when leakage occurred in the upper disk.

Key Words : Piping, Thermal Stratification Phenomenon, Numerical Analysis

Nomenclature

C_p : Specific heat
D : Hydraulic diameter
g : Acceleration of gravity
k : Turbulent kinetic energy
k_f : Thermal conductivity
T : Temperature
u : Component of velocity
β : Coefficient of thermal expansion
ε : Dissipation of turbulent kinetic energy
μ : Coefficient of viscosity
μ_t : Coefficient of turbulent viscosity
ρ : Density
$\sigma_t, \sigma_k, \sigma_\varepsilon$: Turbulent Prandtl number for T, k, ε

* **E-mail** : jipark@deu.ac.kr
TEL : +82-51-890-1985; **FAX** : +82-51-898-3462
Department of Building System Engineering, Dong-Eui University, 995, Eomgwang-No, Busanjin-Gu, Busan 614-714, Korea. (Manuscript **Received** February 25, 2005; **Revised** November 1, 2005)

1. Introduction

As more experience is accumulated in the operation of existing power plants, the long term effects of thermal-hydraulic phenomenon, not considered in the original designs, are being observed. One such phenomenon is thermal stratification, which has caused through-wall cracks, thermal fatigue, unexpected piping displacements and pipe support damage. Thermal stratification is a phenomenon that arises as temperature layers are formed due to the density difference between hot and cold water (EPRI, 1994; Roarty et al., 1994). Thermal stratification, because of its potential impact upon plant operations, has become a significant concern for nuclear power plants.

It has been reported that the thermal stratification phenomena in nuclear power plants are mainly observed in the pressurizer surge line, feed water system line, safety injection system (SIS) line, residual heat removal system line (or shutdown cooling system line), and chemical and volume control system line during the design transients (CEOG Owners Group, 1996 ; NRC, 1979, 1988, 1998). USNRC Bulletin 88-08 requires evaluating the thermal stratification effects for the main piping in nuclear power plants that are expected to experience thermal stratification using analytic evaluation, design improvement, or ultrasonic testing (NRC, 1998). In Korea, the evaluation studies for these piping have been actively carried out according to the recommendation of a regulatory body (KEPRI & KOPEC, 1999 ; Ahn 1996a, 1996b ; Park et al., 2001 ; Youm et al., 2000).

Thermal stratification can be generated by turbulent penetration. Turbulent penetration results in forced secondary flow in an otherwise stagnant branch line due to the RCS (reactor coolant system) flow (Kim, 1993). The relative magnitude and type of flow in the branch is related with the distance from the RCS. Also, thermal stratification can be generated by valve leakage. The leakage path is divided into in-leakage and out-leakage. In-leakage is that the source of leakage is a system with a greater operating pressure than the pressure of the pipe section being evaluated. One case in a PWR (pressurized water reactor) design is a charging system which is sometimes connected to an isolated system such as the SIS (safety injection system).

In this study, a numerical analysis was performed to estimate the thermal stratification phenomenon by in-leakage in the SIS branch piping connected to the RCS piping. Leakage rate, leakage area and leakage location were selected as evaluation factors to investigate the thermal stratification effect.

2. Model Description

2.1 Analysis scope

The schematic diagram of the SIS piping including the RCS piping is shown in Fig. 1. The SIS piping is connected to the RCS cold leg. The SIS supplies cold boric acid water to secure the

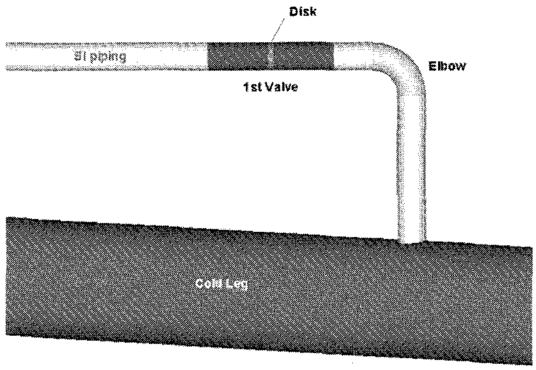


Fig. 1 The schematic diagram on the SIS piping connected to the RCS piping

core cooling and the shutdown margin during an accident. Because all valves in the SIS pipings are closed during normal or startup operating condition, fluid in the SIS piping is usually stagnated. Thus, it is possible that thermal stratification results from turbulent penetration or valve leakage. In case of accidents by foreign nuclear power plants due to the leakage, these accidents mainly result from in-leakage. It has been reported that the region of damage mostly appears in the elbow between the RCS piping and the 1^{st} valve of the SIS piping (EPRI, 2000).

A numerical analysis is performed to evaluate thermal stratification for the SIS piping when leakage path occurs through the first valve from the SIS to the RCS. The scope of analysis is from the first valve of the SIS piping to the cold leg because the forced secondary flow by the shearing effects of the RCS flow has to be considered. The inner diameter of the RCS cold leg piping is 0.7 m (27.5″). The nominal diameter of the SIS piping is 0.15 m (6″) of schedule 160.

2.2 Governing equations

Steady, incompressible and three dimensional conservation equations are used as governing equations for the thermal flow analysis. The standard k-ε model is used for the turbulent model and the Boussinesq's approximation is applied for the buoyancy effects. Assuming that the properties of all fluids and solids are constant under given temperature and pressure, the governing equations are as follows ;

Continuity equation

$$\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

Momentum equation

$$\frac{\partial}{\partial x_j}(\rho u_j u_i)=-\frac{\partial p}{\partial x_i}+\rho g_i \beta(T-T_{cold}) + \frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-23k\delta_{ij}\right] \tag{2}$$

Energy equation

$$\frac{\partial}{\partial x_j}(\rho u_j T)=\frac{\partial}{\partial x_j}\left\{\left(\frac{u_t}{\sigma_t}+\frac{k_f}{C_p}\right)\frac{\partial T}{\partial x_j}\right\} \tag{3}$$

Turbulent equation (standard k-ε)

$$\frac{\partial}{\partial x_j}(\rho u_j k)=\frac{\partial}{\partial x_j}\left[\left(u+\frac{u_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + G_b - \rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial x_j}(\rho u_j \varepsilon)=\frac{\partial}{\partial x_j}\left[\left(u+\frac{u_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}\left[C_1(P_k+G_b)-C_2\rho\varepsilon\right] \tag{5}$$

where, the coefficient, source term, and turbulent constants are as follows ;

$$\mu_t=\rho C_\mu k^2/\varepsilon$$

$$P_k=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$

$$G_b=-\frac{\mu_t}{\sigma_t}g_i\beta\frac{\partial T}{\partial x_i}$$

$$\sigma_t=0.85,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.3,\ C_\mu=0.09$$

$$C_1=1.44,\ C_2=1.92$$

2.3 Numerical schemes

The Fluent 5.5 code is used to analyze the thermal stratification resulting from the in-leakage in the SIS piping. The pressure field at each cell is calculated by SIMPLE algorithm and the convection term is determined by the upwind scheme. The convergence criteria are that residual is less than 1.0×10^{-5} for continuity and 1.0×10^{-7} for momentum, energy and turbulence. To improve the convergence, the under-relaxation factors on pressure, temperature, velocity, and turbulent terms were applied.

2.4 Boundary conditions

The grid system is shown in Fig. 2 and the

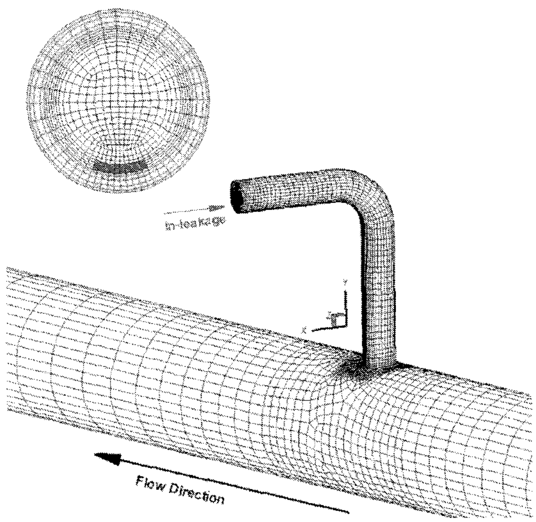


Fig. 2 Grid Systems

number of cells is 86,638. The valve leakage location is assumed to be in the bottom of the valve disk excepting the analysis for the influence of leakage location. The allowed leakage rate provided by the leak-test for this valve is used as the minimum leakage rate and the value is 0.0136 kg/s. Leakage area is assumed to be 3% of total disk area. The design temperature condition is used for boundary condition. The design temperature of the SIS and the RCS is 322K and 546K, respectively. The piping material is assumed to be SA 304.

3. Results and discussions

Figure 3 shows the vector plots and the streak lines from leakage inlet for 15 times leakage rate of the allowed leakage rate. Due to the turbulent penetration from the RCS piping, a strong upward flow is generated near the connection between the SIS piping and the RCS cold leg. At this time, the length of turbulent penetration from the RCS reaches the middle of the elbow but does not reach the horizontal piping. Therefore, stratification is stably generated in the horizontal piping. The hot and cold fluids are mixed around the weldment between the elbow and the vertical piping. The counter flow is formed in the vertical piping as shown in Fig 3. This is due to the

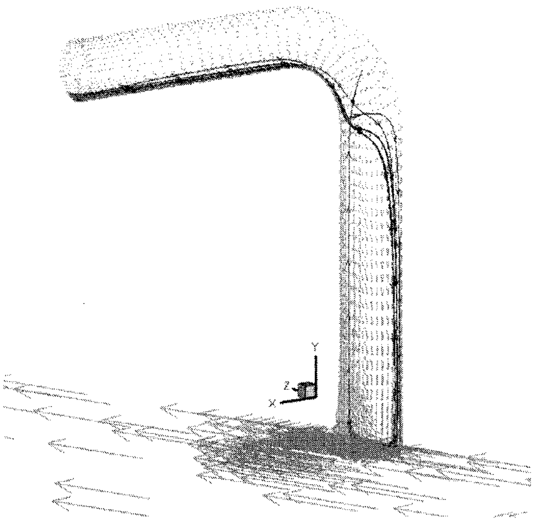
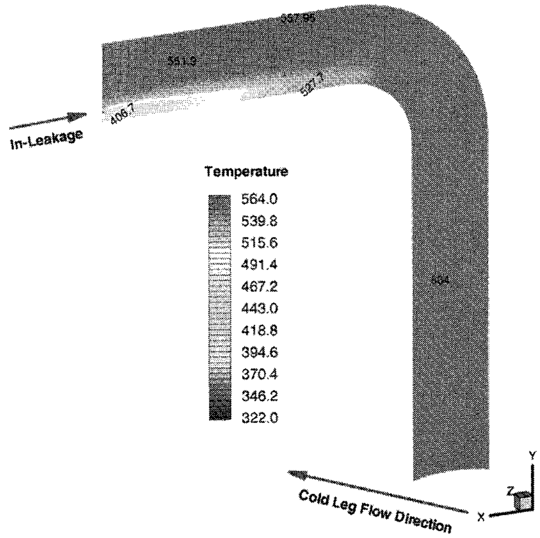
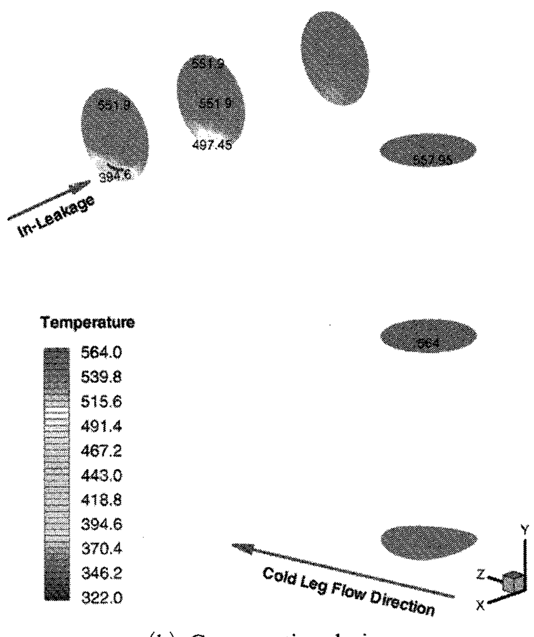


Fig. 3 Vector plots and streak lines



(a) Vertical-sectional view



(b) Cross-sectional view

Fig. 4 Temperature distributions for the allowed leakage rate

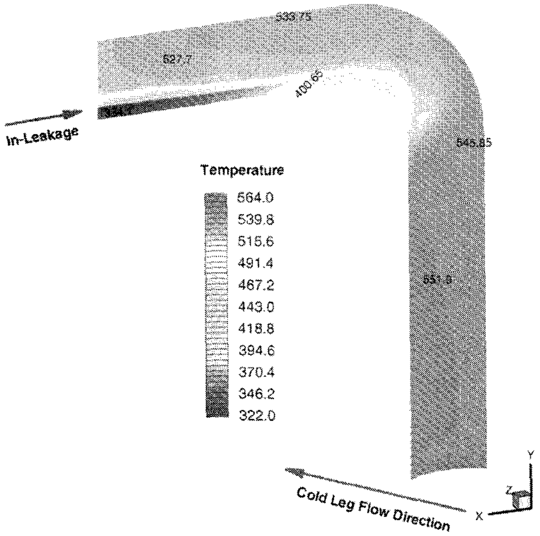
leakage flow to the RCS piping and penetration flow from the RCS piping. In the streak lines, it is observed that a part of leakage flow turns upward along with the penetration flow from the RCS piping.

3.1 Influence of the leakage rate

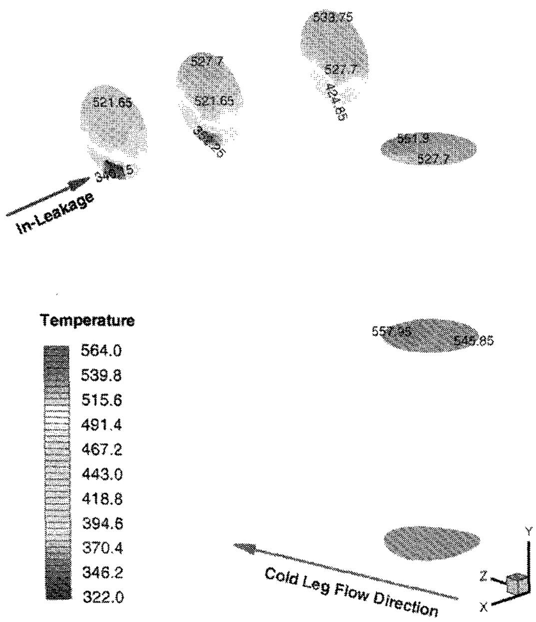
Figures 4, 5 and 6 show the temperature distributions in the SIS piping when the valve leakage rate is 1, 10, and 25 times of the allowed leakage rate, respectively.

For the allowed valve leakage rate, the temperature distributions of the SIS piping are showed in Fig. 4. The cold leakage fluid flows along with the lower of the horizontal piping, and is merged into the hot penetration fluid induced by the RCS flow in the front of elbow. When the leakage rate is increased to 10 times, the cold leakage flow reaches the elbow and the flow is mixed into the hot water of the vertical piping as shown in Fig. 5. When the leakage rate is increased to 25 times, as shown in Fig. 6, the cold leakage flow reaches the elbow and the flow is mixed into hot water of the vertical piping. The temperature difference between the top and bottom of piping is decreased because of thermal mixing effects in the horizontal piping.

In order to evaluate the effect of thermal stratification with the variations of leakage rate, a number of case studies were performed. Leakage rate was assumed to be increased from the allowed leakage rate to 100 times the allowed leakage rate to the maximum. The locations of point 1 (valve weldment) and point 2 (elbow weldment) for temperature estimation are shown in Fig. 7. Fig. 8 shows the inner wall temperature difference

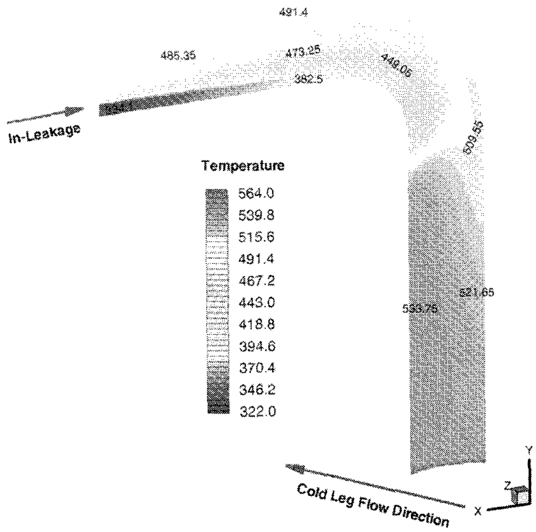


(a) Vertical-sectional view

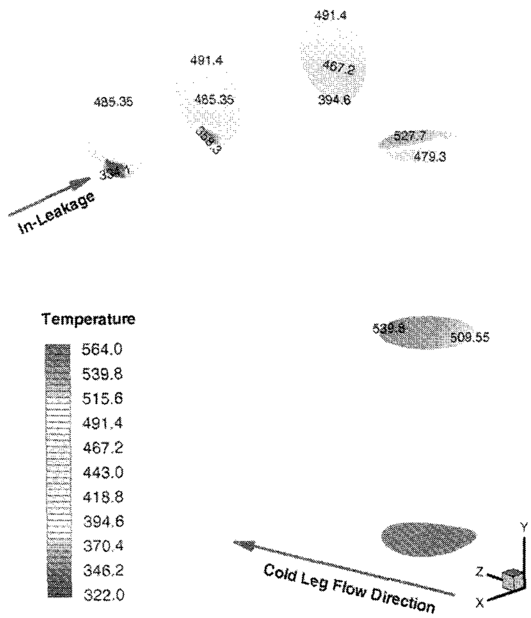


(b) Cross-sectional view

Fig. 5 Temperature distributions for 10 times of the allowed leakage rate



(a) Vertical-sectional view



(b) Cross-sectional view

Fig. 6 Temperature distributions for 25 times of the allowed leakage rate

between top and bottom at the point 1 and point 2 versus leakage rate. Up to 10 times the allowed leakage, the temperature difference at point 1 is rapidly increased with the leakage rate increment. However, the temperature difference is decreased of over 10 times the allowed leakage rate because of the increased mixing effect of the leakage flow. On the other hand, the temperature difference at point 2 is rapidly increased with the leakage rate increment up to 15 times the allowed leakage rate.

3.2 Influence of the leakage area

Figure 9 shows the temperature difference at point 1 and 2 in the SIS piping when the valve

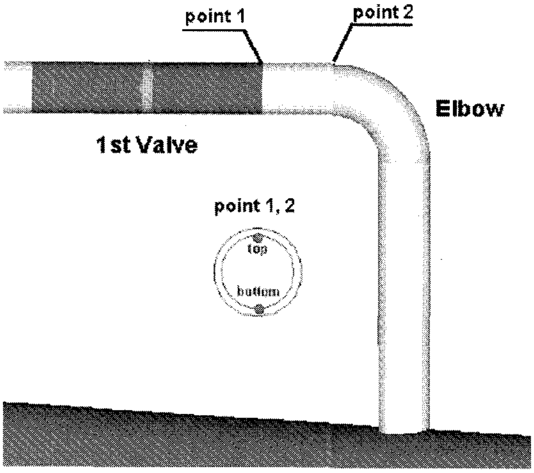


Fig. 7 Locations for temperature estimation

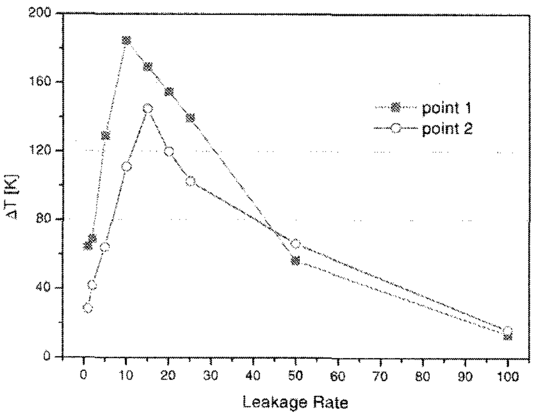


Fig. 8 Inner wall temperature difference between top and bottom versus leakage rate

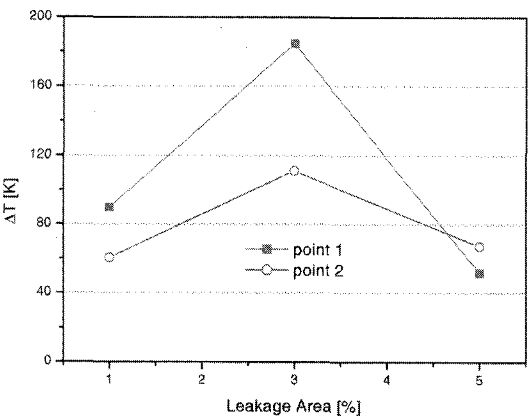
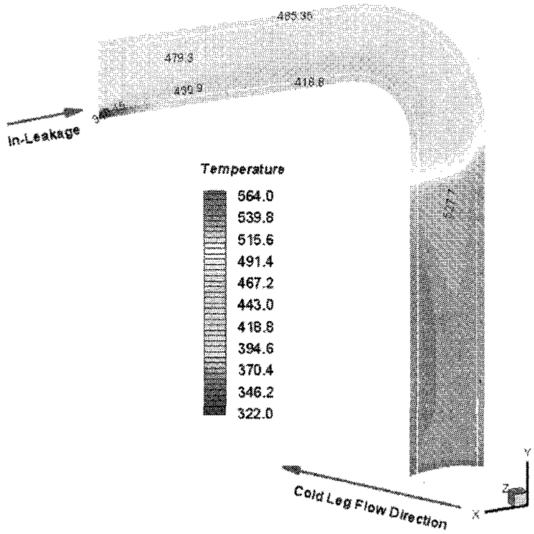
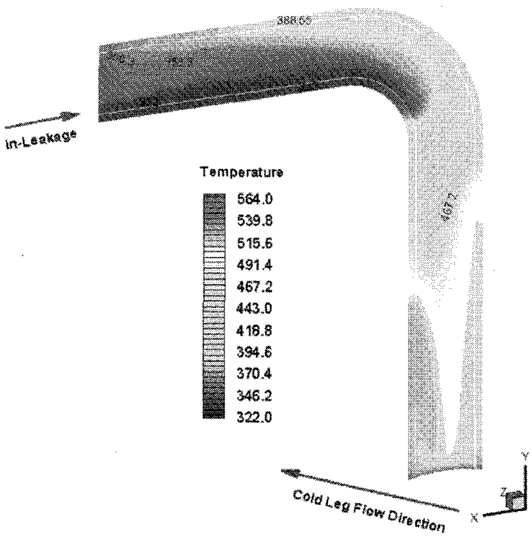


Fig. 9 Inner wall temperature difference between top and bottom versus leakage area

leakage area is 1%, 3% and 5% of total disk area. Leakage rate was assumed to be 10 times the allowed leakage rate. In the results, the temperature difference in the case of the 1% and 5% leakage area are lower than that in the case of 3% leakage area. In particular, the result of 5% leakage area shows that the temperature difference of point 2 is higher than that of point 1. The magnitude of temperature difference is shown in order of 3%, 1% and 5%. Fig. 10 shows the temperature



(a) 1% leakage area



(b) 5% leakage area

Fig. 10 Temperature distributions in the case of 1% and 5% leakage area of disk area distribution in the middle sectional area of the SIS piping to evaluate the effect of thermal stratification according to the variations of leakage area. Fig. 10(a) is the result of 1% leakage area and Fig. 10(b) is the result of 5% leakage area. The results of 1% and 5% leak age area show a weak thermal stratification effect compared with the result of 3% leakage area showed in the Fig. 5. The contour shape in the case of 1% leakage area is similar with the contour shape showed in Fig. 6, the result when leakage rate is increased. This is probably because of the increase of leakage velocity due to the decease of leakage area. Also, the decrease of thermal stratification in the 5% leakage area is probably because the region of the lower temperature is extended due to the increase of leakage area.

3.3 Influence of the leakage location

In this section, thermal stratification effect according to the leakage location is investigated. Fig. 11 is the result of temperature difference at point 1 and 2, in case the valve leakage occurs in the upper disk and the lower disk, respectively. Leakage area is 3% of disk area and leakage rate is 10 times the allowed leakage. In point 1, temperature difference when leakage occurs in the lower disk is 4.6 times higher than that of when leakage occurs in the upper of disk. In the point 2, temperature difference when leakage occurs in the lower of disk is 2.8 times higher than that of when leakage occurs in the upper disk. Fig. 12 shows temperature distribution in the middle sectional area when valve leakage occurs in the upper disk. The result shows temperature difference is considerably decreased compared with Fig. 5 when leakage occurs in the lower disk. This is because the mixing effect is increased due to the buoyancy effect.

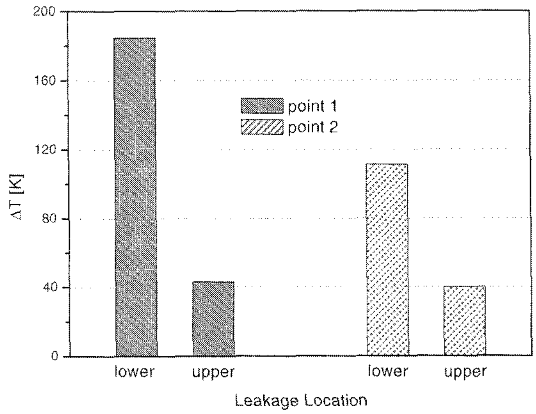


Fig. 11 Inner wall temperature difference between top and bottom versus leakage location

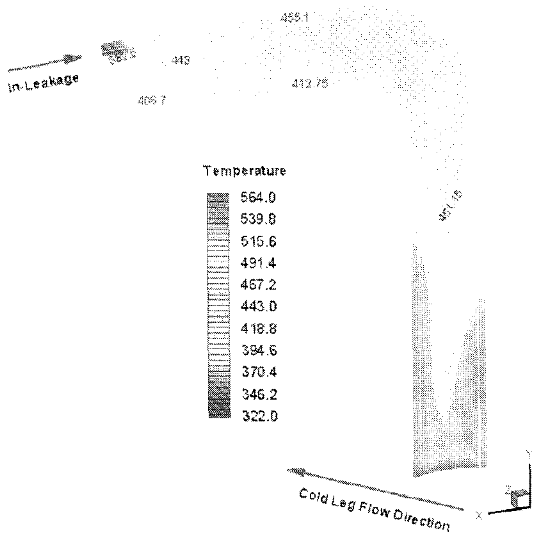


Fig. 12 Temperature distribution when valve leakage occurs in the upper of disk

4. Conclusions

In this study, a numerical analysis was performed to estimate thermal stratification phenomenon by in-leakage in the branch piping. Leakage rate, leakage area and leakage location were selected as evaluation factors to investigate the thermal stratification effect.

The temperature difference between the top and bottom of horizontal piping is different from the leakage rate even if leakage area is the same. The temperature difference is evaluated less than 50K for the allowed leakage. The maximum temperature difference is about 185K at the valve weldment when the leakage rate is 10 times of the allowed leakage rate. For leakage rate more than 10 times the allowed leakage rate, the temperature difference is rapidly decreased due to the increased mixing effect in the horizontal piping.

The temperature difference between the top and the bottom of horizontal piping is different with the leakage area even if leakage rate is same. As a result of temperature difference according to 1%, 3% and 5% leakage area of total disk area, the temperature difference in the case of the 1% and 5% leakage area are lower than that in the case of 3% leakage area. The magnitude of temperature difference is shown in order of 3%, 1% and 5%.

In the thermal stratification effect according to the leakage location, temperature difference when leakage occurs in the lower disk is considerably higher than that of when leakage occurs in the upper disk.

References

Ahn, J. S., Kim, E. K., Kim, S. B., Youm, H. K. and Park, M. H., 1996, "Numerical Analysis for Unsteady Thermal Stratified Turbulent Flow in a Horizontal Circular Cylinder," *Proc. of ICONE-4 Conference*.

Ahn, J. S., Ko, Y. S., Ko, D. Y., Park, M. H. and Youm, H. K., 1996, "Numerical Analysis on the Natural Convection in a Long Horizontal Pipe with Thermal Stratification," *Proc. of 14th UIT National Heat Transfer Conference*.

CEOG Owners Group, 1996, "Summary of Programs in Response to NRC Bulletin 88-08 (CEOG Task 866)," CE NPSD-1043.

EPRI, 1994, "Thermal Stratification, Cycling and Striping (TASCS)," TR-103581.

EPRI, 2000, "Operating Experience Regarding Thermal Fatigue of Unisolable Piping Connected to PWR Reactor Coolant Systems (MPR-25)," TR-1001006.

KEPRI & KOPEC, 1999, "Pressurized Thermal Shock Evaluation for Reactor Pressure Vessel of Kori Unit 1," Technical Report-TR. 96BJ12.J1999.81

Kim, J. H., Roidt, R. M., and Deardorff, A. F., 1993, "Thermal Stratification and Reactor Piping Integrity," *Nuclear Engineering and Design*, Vol. 139, No. 1, January 1993, pp. 83~96.

NRC, 1979, "Cracking in Feedwater System Piping," Bulletin No. 79-13.

NRC, 1988, "Pressurizer Surge Line Thermal Stratification," Bulletin No. 88-11.

NRC, 1998, "Thermal Stresses in Piping Connected to Reactor Coolant Systems," Bulletin No. 88-08.

Park, M. H., Kim, K. C. and Youm, H. K., 2001, "Numerical Study on Thermal Mixing Flow in Cold Leg during Loss of Coolant Accident," *Proc. of ASME PVP 2001 Conference*.

Roarty, D. H., Strauch, P. L. and Kim, J. H., 1994, "Thermal Stratification, Cycling and Striping Evaluation Methodology, Changing Priorities of Codes and Standards: Failure, Fatigue, and Creep," *Proc. of ASME PVP Conference*, Vol. 286, pp. 49~54.

Youm, H. K. et al., 2000, "Development of Numerical Analysis Model for Thermal Mixing in the Reactor Pressure Vessel," *Proc. of ASME PVP 2000 Conference*.