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Thermal Stratification Analyses for Arrangements of Pressurizer Surge Line

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1. Introduction

The thermal stratification phenomenon occurs in piping systems where two layers of the same liquid flow separately without mixing due to the difference in temperature (and density) and low velocities. When this is the case, hot fluid tends to float on the top of the cold (denser) fluid, resulting in the upper portion of the pipe being hotter than the lower portion. Under these conditions, overall bending stresses increase and local stresses can be created across the pipe. Therefore, the thermal stratification may influence the integrity of pipe.

In a Nuclear Power Plant (NPP), some safety related pipes connected to reactor coolant system are known to be potentially susceptible to fatigue failure resulting from thermal stratification. According to the international operating experiences, those are the pressurizer (PZR) surge line, the injection pipes of the emergency core cooling system and residual heat removal lines. In particular, during normal operation, the thermal stratification in PZR surge line can occur differently from the other two lines because hotter water flowing from the PZR to the hot leg flows over a layer of colder water through the PZR surge line. For this reason, it is considered that the thermal stratification in PZR surge line has been one of the significant issues for structural integrity of NPP.

Therefore, this study focuses on new arrangements of PZR surge line for reducing the thermal stratification during normal operation of NPP and analyzes what new arrangements can reduce the effect of thermal stratification through CFD calculation using FLUENT Ver.15.

2. Numerical Calculation

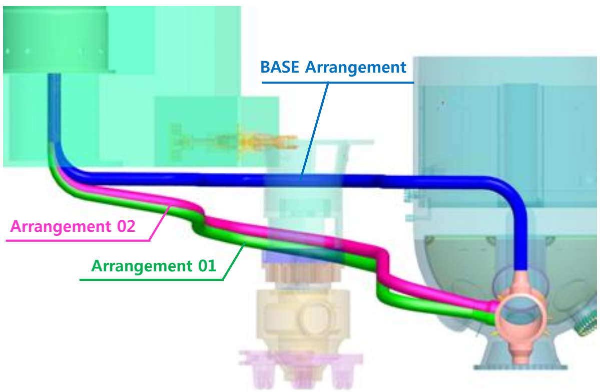


Fig. 1 Present and proposed pressurizer surge line arrangements

Fig. 1 shows the present and proposed PZR surge line arrangements. In BASE arrangement for domestic and Barakah NPPs both in operation and under construction, the slope of pressurizer surge line is less than 0.3° and the surge line is connected vertically to the hot leg. In the arrangements 01 and 02, the slopes of PZR surge line are 10° and 15°, and surge line is connected with the hot leg 7.5° and 8.5° above the center line, respectively. This present study only considers thermal fluid in the PZR surge line during normal operation. Because the same thermal hydraulic conditions are imposed on the PZR surge line [1], the steady state CFD analyses can be conducted during normal operation. Fig. 2 and Table I show PZR surge line arrangements and major temperature measurement sections and the detailed boundary condition [1]. The Shear Stress Transport (SST) turbulent model is used for calculation of thermal stratification flow phenomena as the previous studies [2, 3]. Also, the full buoyancy model and the change of water properties due to temperature change are considered in this study.

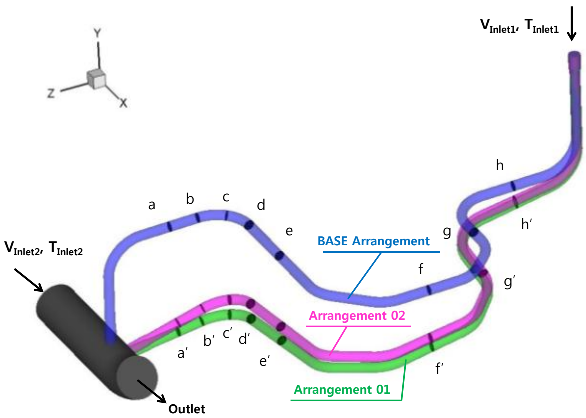


Fig. 2 Pressurizer surge line arrangements and major temperature measurement sections.

Table I Boundary conditions for CFD analyses

	CASE A	CASE B	CASE C
V_{Inlet1}	0.001328 m/s with 1.5 gpm	0.002656 m/s with 3.0 gpm	0.005312 m/s with 6.0 gpm
T_{Inlet1}	653 deg.F (618.15K)		
V_{Inlet2}	223150 gpm (15.76 m/s)		
T_{Inlet2}	615 deg.F (597.04 K)		
Outlet	Pressure Outlet		

3. Results and Discussion

3.1. Grid Dependency Study

For grid dependency study, CFD analyses were carried out by changing the number of grid for CASE C in BASE arrangement. Fig. 3 shows the temperature difference between the top and bottom at measurement sections of the PZR surge line. There are large gaps between the cases of 1.0M and 1.5M. However, there are good agreements between the cases of 1.5M and 2.0M. Thus, the case of 1.5M is selected for all simulations in this study.

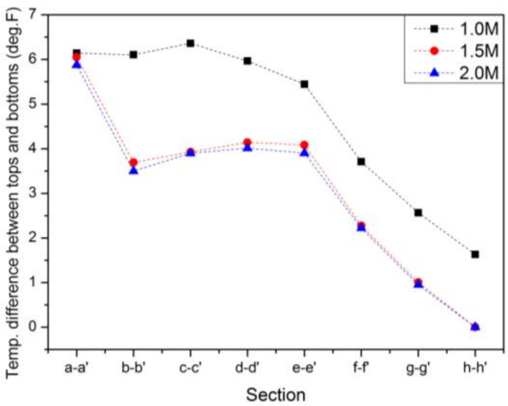


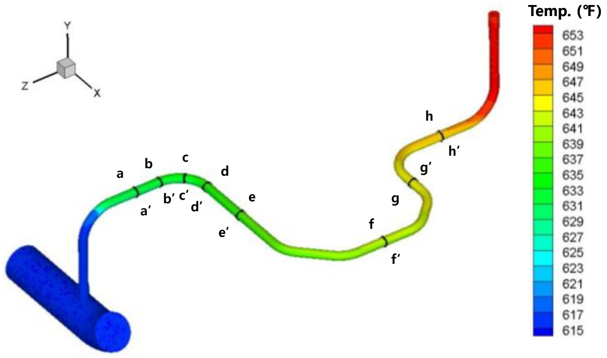
Fig. 3 Results of grid dependency study

3.2. Results

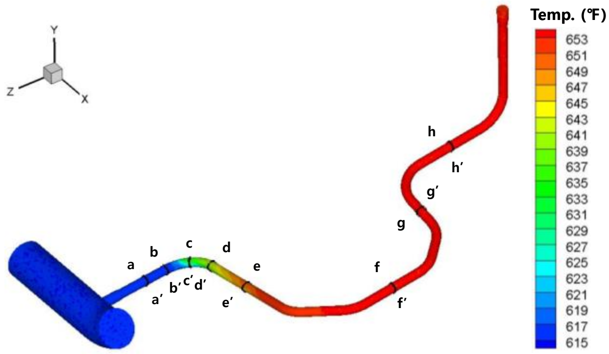
Fig. 4 and 5 show the temperature distributions and streamlines in CASE B for each arrangement, and Fig. 6 shows temperature distributions in CASE B for each section. The flow fields in BASE arrangement are simpler than other arrangements as shown in Fig. 5. In BASE arrangement, the hot fluid from the PZR floats in the top region of surge line and the cold fluid from the hot leg flows in the bottom region of surge line due to the density difference. Therefore, the thermal stratification phenomenon occurs throughout the PZR surge line.

In Arrangements 01 and 02, the hot fluid from PZR flows to a hot leg flow induced vortex. Due to the vortex, the thermal stratification occurs only in the mixing region of the two fluids (hot and cold). Also, the turbulent penetration by the vortex is more intensive compared with BASE because the surge line is connected almost horizontally to the hot leg. The generation of imbalanced temperature distributions in Arrangements 01 and 02 result from the intensive turbulent penetration and vortex of hot fluid.

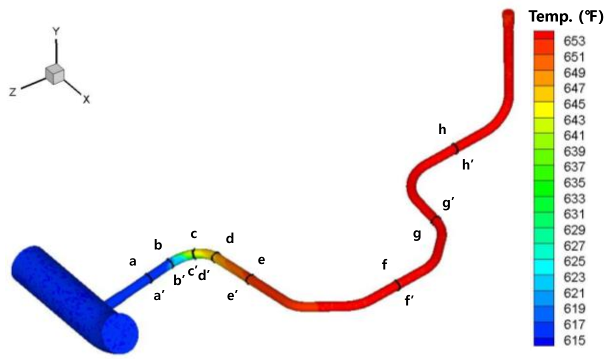
In general, hot fluid tends to float on the top of the cold fluid by buoyancy force. The BASE arrangement having a stable flow field follows that tendency. However, Arrangements 01 and 02 having inclined pipe and non-stable flow fields are different from that tendency, especially in the mixing region of the two fluids (sections b-b' ~ d-d'). The reason is that the



(a) BASE



(b) Arrangement 01



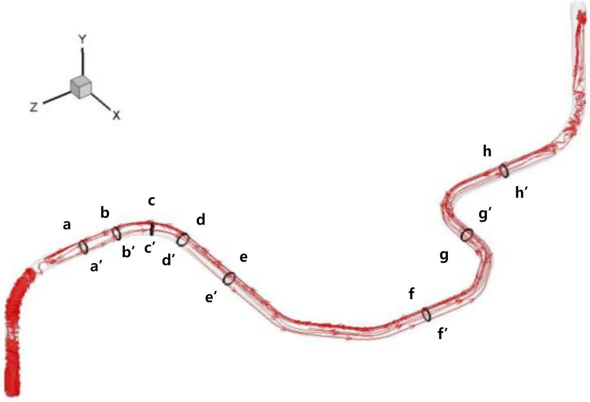
(c) Arrangement 02

Fig. 4 Temperature distributions in CASE B for each arrangement

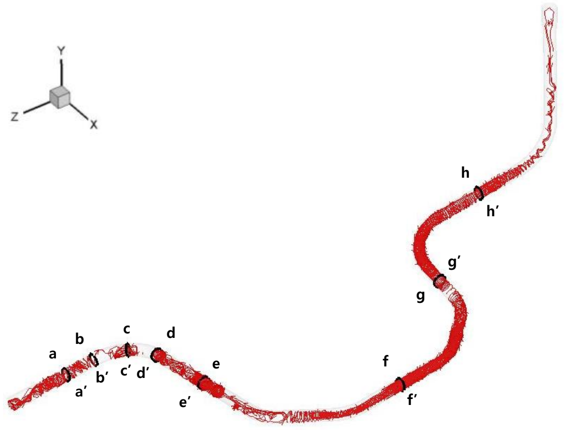
buoyancy force is weakened by other forces such as fluid vortex, velocity increase due to the slope of surge line and turbulent penetration.

Fig. 7 presents the temperature differences between the top and bottom sides for all CASEs. The BASE arrangement for each CASE has the apparent values of temperature differences between the top and bottom sides from sections a-a' to h-h', and CASE B shows the highest the temperature differences between the top and bottom sides. On the other hand, the temperature differences between the top and bottom sides from f-f' to h-h' sections for Arrangements 01 and 02 are negligible. However, the maximum temperature differences between tops and bottoms are higher than those of BASE arrangement in other sections.

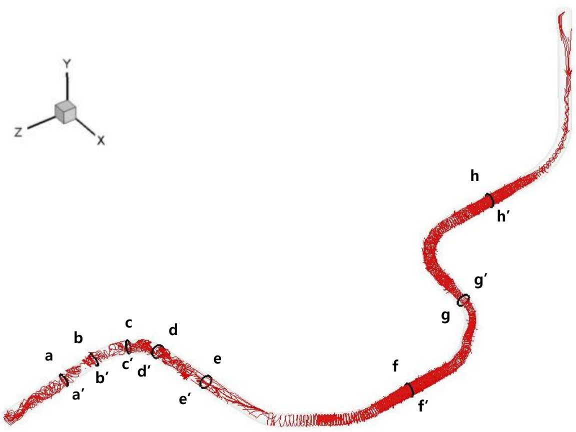
As shown in Fig. 7, the region of maximum temperature difference between the top and bottom sides moves toward the hot leg as the flow rate from PZR increases. This is considered to be due to the momentum increase of fluid from PZR compared with the same turbulent penetration force. In addition, the temperature differences between the top and bottom sides decrease from section e-e’ to h-h’ and thermal stratification regions are reduced as the flow rate from PZR increases.



(a) BASE

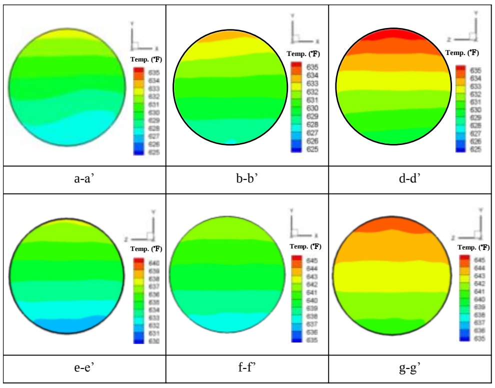


(b) Arrangement 01

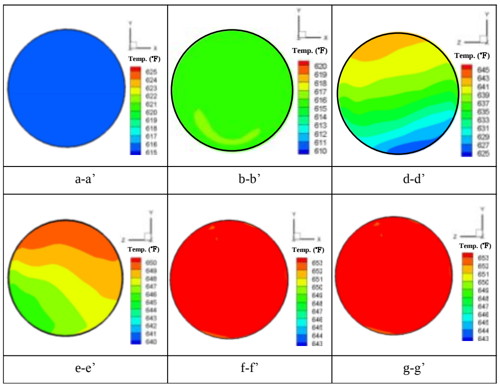


(c) Arrangement 02

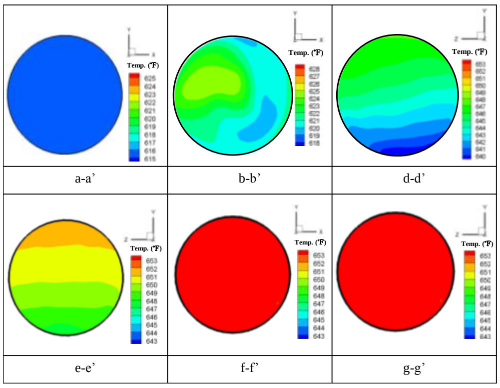
Fig. 5 Streamlines in CASE B for each arrangement



(a) BASE



(b) Arrangement 01



(c) Arrangement 02

Fig. 6 Temperature distributions in CASE B for each section

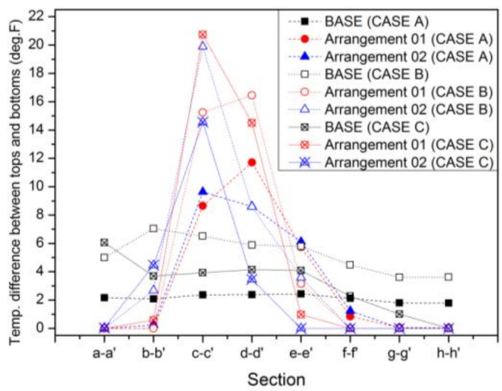


Fig. 7 Temperature differences between tops and bottoms for all case.

4. Conclusions

This study was suggests what new arrangement can reduce the effect of thermal stratification compared with the current arrangement of NPPs by using CFD analyses.

The results show that more global thermal stratification occurred in BASE arrangement throughout the PZR surge line compared with other arrangements. In addition, the increase of flow velocity from PZR resulted in the increase of maximum temperature difference between the top and bottom sides and the reduction of thermal stratification region. The reason is that the buoyancy force is weakened by other forces such as fluid vortex, velocity increase due to the slope of surge line and turbulent penetration.

Therefore, additional studies will be needed on which factor of the length of thermal stratification region or magnitude of temperature difference between the top and bottom sides have more influence on the integrity or fatigue of PZR surge line.

Acknowledgments

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