# SIMULATION OF THERMAL STRATIFICATION IN INLET NOZZLE OF STEAM GENERATOR

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Due to thermal hydraulics phenomena, such as thermal stratification, various events occur to the parts of a nuclear power plant during their lifetimes: e.g. cracked and dislocated pipes and thermally fatigued, bent, and damaged supports. Due to the operational characteristics of the parts of the steam generator feedwater inlet horizontal pipe, thermal stratification takes place particularly frequently. However, the thermal stress due to thermal stratification at the steam generator feedwater inlet horizontal pipe was not reflected in the design stage of old plants(Kori Unit No. 1, 2, 3 and 4, Yeonggwang Unit No. 1 and 2, and Uljin Unit No. 1 and 2; referred to as old-style power plants hereinafter). Accordingly, a verification experiment was performed for thermal stratification in the horizontal inlet nozzle steam generator of old-style plants. If thermal stratification occurred in the horizontal pipe of an old-style power plant, numerical analysis of the temperature distribution of the pipes and fluids was conducted. The temperature distributions were compared at the curved part of the pipe and the horizontal pipe before and after the installation of the improved thermal sleeves designed to alleviate thermal stress due to thermal stratification. The thermal stress reduction measure was proven effective at the steam generator inlet horizontal pipe and the curved part of the pipe.

**KEYWORDS** : S/G Inlet Nozzle, Thermal Stratification, Thermal Sleeve, Gap Effect

## 1. INTRODUCTION

Thermal stratification refers to the fact that low-flow fluids of different temperatures cannot mix with each other and exist separately inside power plant parts or pipes because of the difference in density. Various events occur to the parts of a nuclear power plant during their lifetimes due to thermal hydraulics phenomena, such as thermal stratification: e.g. broken and dislocated pipes, thermally fatigued, bent, and damaged supports. In the steam generator feedwater inlet horizontal pipe, because of its operational characteristics, thermal stratification takes place with particular frequency. US NRC requires, through Bulletin 79-13, 88-08 and 88-11, a demonstration of the integrity of those pipes expected to suffer thermal stratification, such as the main feedwater piping and the pipes connected to the reactor coolant system. In the Republic of Korea, it is recommended that several tests be conducted for the horizontal pipes among the branch pipes connected to the reactor coolant system. However, in old-style power plants, the thermal stress owing to the thermal stratification inside the pipe was not sufficiently reflected in the design stage.

Accordingly, we conducted a verification experiment on the likelihood of thermal stratification and thermal cycling according to the size of the pipes, the flux of the auxiliary feedwater, and the pipe layout in domestic power plants prior to KSNP (Kori Unit No. 1, 2, 3 and 4, Yeonggwang Unit No. 1 and 2 and Uljin Unit No 1 and 2; referred to as old-style power plants hereinafter), which have plenty of operating experiences and are highly likely to experience thermal stratification in the steam generator feedwater inlet horizontal pipe, and conducted a numerical analysis of the verification experiment. As a result of the experiment, a new modified thermal sleeve was proposed to remedy of thermal stratification. Which can cover both the horizontal and the bending regions of the pipe (Fig. 6(b)). This study also conducted a numerical analysis in actual power plants with and without new thermal sleeves, and the result of the numerical analysis will be utilized to evaluate the stress caused by thermal stratification in the pipes.

## 2. VERIFICATION EXPERIMENT AND SIMULATION

### 2.1 Verification Experiment

### *2.1.1 Experimental Apparatus*

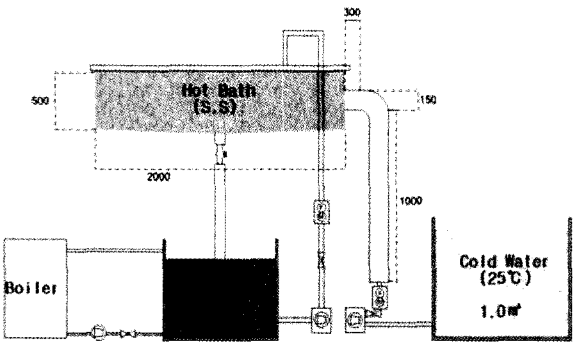


Fig. 1. Diagram of the Experiment Rig

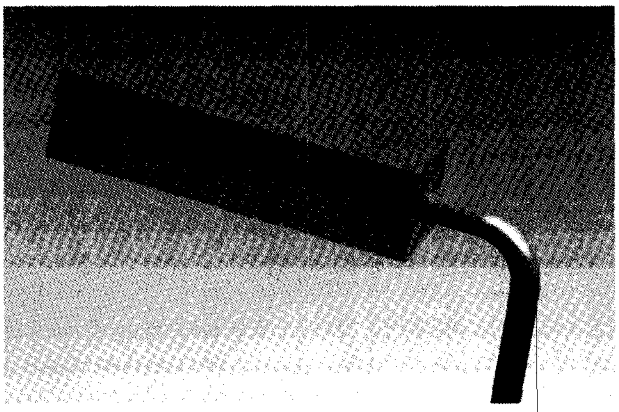
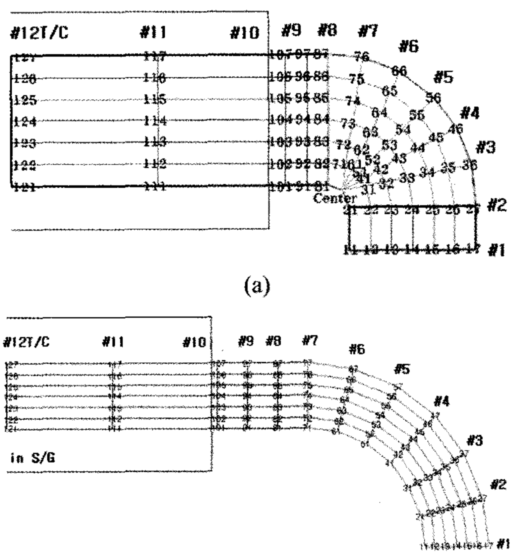


Fig. 2. Simplified Test Section (O-Ring and J-Nozzle)

To conduct an experiment on the thermal stratification behavior at the feedwater inlet horizontal pipes in the old-style power plants, an experimental apparatus was designed and manufactured on the basis of similarity with the Richardson dimensionless number (Ri). A diagram of the experimental apparatus is illustrated in Fig. 1.

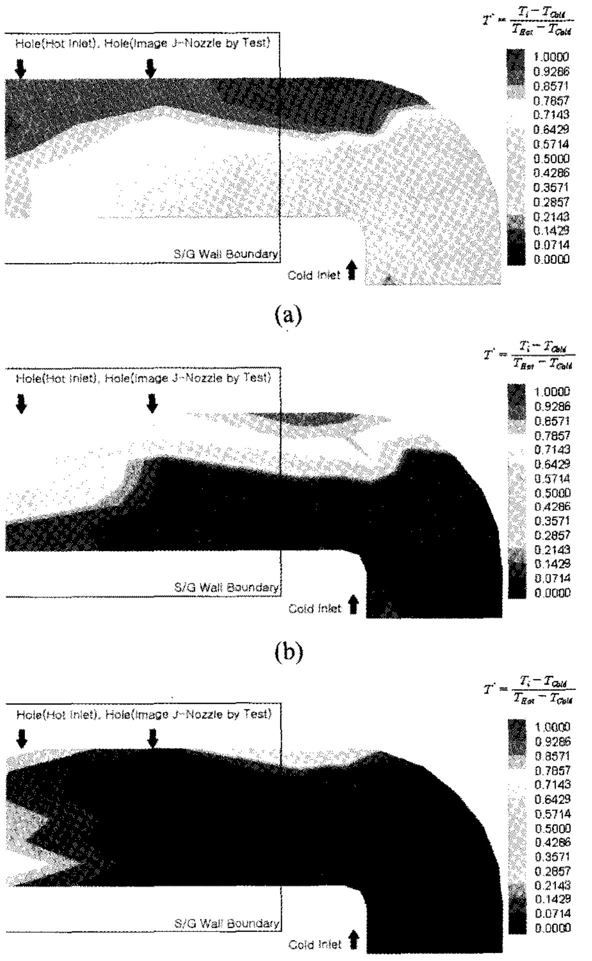
For the experiment the cold water tank and the hot water tank were filled with normal temperature (25°C) water, and a boiler was used to circulate the hot water in the high-temperature water tank to 75°C The hot water was filled through the J-nozzle and O-ring in the hot bath to the feedwater inlet horizontal pipe and the curved part of the pipe. The valve and flow meter were used to control the experimental flux of the cold water, and the water flowed from the bottom of the curved part of the feedwater inlet horizontal pipe to the O-ring inside the hot bath and met the hot water flowing from the steam generator at the feedwater inlet horizontal pipe. Fig. 2 shows the simplified O-ring and J-nozzle of steam generator, and Fig. 3 shows the location of thermocouples.



(a)

(b)

Fig. 3. Thermocouple Grid of the Horizontal Pipe (Top: Curvature 0D, Bottom: Curvature 1.5D)



(a)

(b)

(c)

Fig. 4. Temperature Distribution when $R_i$ is 72.4

### *2.1.2 Experiment Results*

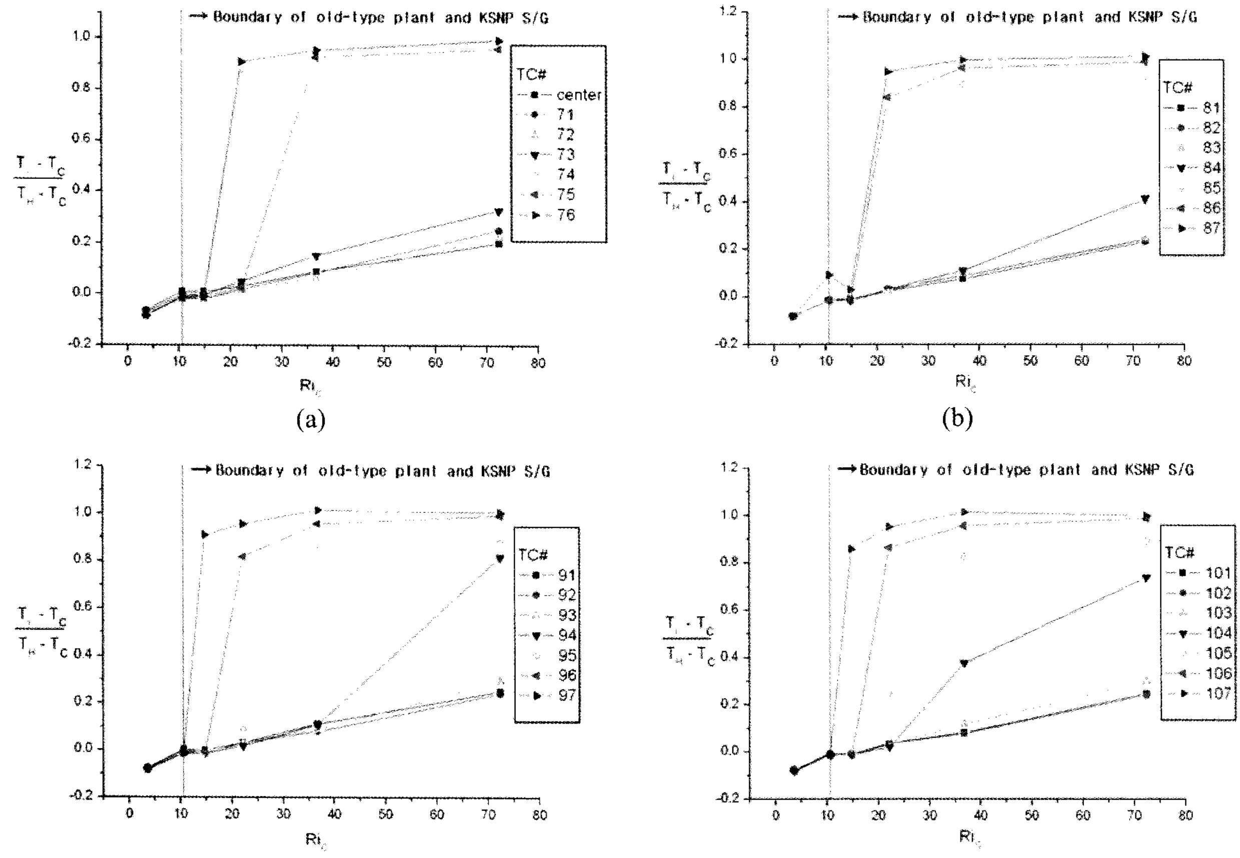
The verification experiment results showed that thermal stratification definitely occurred in the horizontal inlet pipe of an old-style plant (Figs. 4 (a) ~ (c)). Figs. 4 and 5 illustrate the temperature distribution of thermocouple groups 7, 8, 9, and 10 at about 60 sec. These groups were chosen because they showed that their locations were the most susceptible region to thermal fatigue due to thermal stratification. The vertical line in each figure is the minimum $R_i$ (10.6) at which thermal stratification occurs at the steam generator feedwater inlet horizontal pipe in an old-style power plant. If $R_i$ is greater than 10.6 with this vertical line at the center, thermal stratification occurs, and if $R_i$ is smaller than 10.6 (when the flux of the auxiliary feedwater gradually increases), thermal stratification only slightly takes place. The radius of the curvature had a certain degree of influence on the size and duration of the thermal island (Table 1), which is a hot region occurring at the top of the pipe downstream of the bend region.

The radius of the curvature of the steam generator feedwater inlet horizontal pipe in an old-style power plant has an insignificant effect on thermal stratification and has a slight effect on the size of the thermal island because the mass flux of the auxiliary feedwater (low-temperature water) are small, and thus the auxiliary feedwater flows into the horizontal pipe very slowly, regardless of the curvature. In addition, the hot water almost certainly has little effect on thermal stratification because, as the hot

**Table 1**. The Effect of Parameters on Thermal Stratification

| Plant type / Variables | Old-style power plant | KSNP |
|---|---|---|
| Thermal stratification Y/N | ○ | × |
| Effect of auxiliary feedwater mass flow rate | ○ | × |
| Effect of hot water mass flow rate | × | × |
| Effect of the curvature of the curved part | △ | × |

○: Strong ×: Weak △: Mild



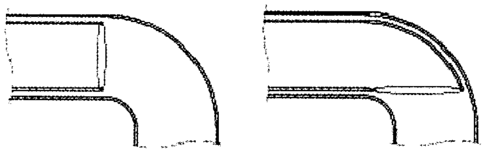
(a) (b)

(c) (d)

Fig. 5. Establishment of the Thermal Stratification Occurrence Standard (TC #9, 10 Group)

water flows in just above the outside of the feed ring inside the steam generator, the hot water could not flow into the horizontal pipe in large quantities and only a small amount slowly flowed into the upper part of the horizontal pipe. Also as shown in In Figs. 4 (a) ~ (c), thermal stratification was noticed not only in the horizontal region, but also the bending region. Therefore, there is a need for alternatives. However, the existing thermal sleeve can only cover the horizontal region downstream after the bend region (Shown Fig. 6(a)).

Accordingly, a new modified thermal sleeve is proposed which can cover both the horizontal part and the bend part (Fig. 6(b)).



(a) (b)

Fig. 6. The Existing T/S (a) and the Modified T/S (b)

## 2.2 Simulation of Experiments

To validate CFD codes and their model for the simulation of thermal stratification in the S/G inlet horizontal nozzle, a set of numerical analysis and comparison with the experimental results was conducted.

The ANSYS Work Bench 10.0 and CFX 10.0 were used.

### 2.2.1 Boundary Conditions

For boundary conditions of the numerical analysis, the simplified standard model is presented as illustrated in Fig. 7. In this model, the O-ring and J-nozzle were simplified as a straight pipe and plain holes. The simplification could not affect the results because their location is downstream far from the sensitive region.

The important input parameters are as follows:

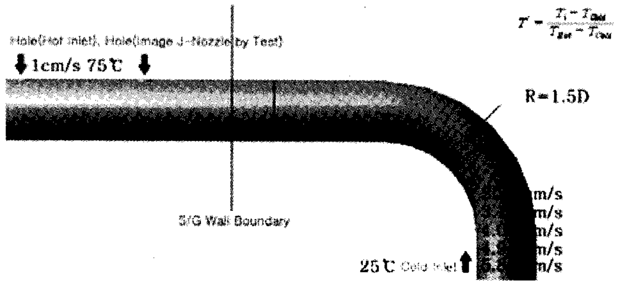


Fig. 7. Simplified Standard Model

Turbulence model: $\kappa$-$\varepsilon$

- Turbulence Schmidt number: 0.9
- Dissipation coefficient: 1.0

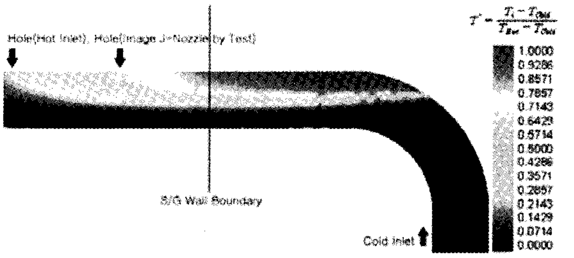
Wall influence on flow: No slip

Heat transfer coefficient: Adiabatic

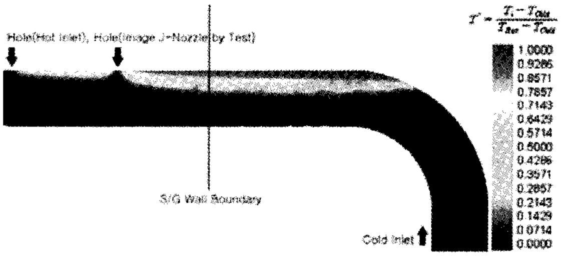
### 2.2.2 Numerical Results of the Experiments

As previously described in the thermal stratification verification experiment of the old-type plants, the code simulation results also showed that the thermal stratification occurred mostly in relation to the cold auxiliary feedwater. The numerical results showed that there was a slight temperature difference compared to the experiments. However, temperature distribution patterns were quite similar over the whole region. ($R_i$ >11.0)

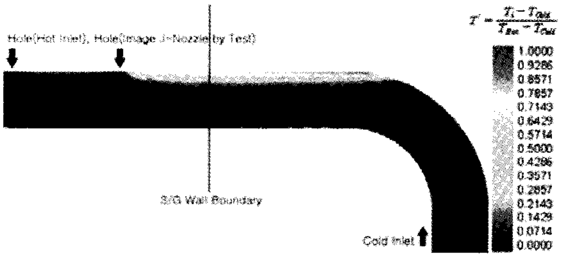
The numerical analysis results with the simple turbulent model ($\kappa$-$\varepsilon$) confirmed that the CFD code could simulate the thermal stratification of the S/G horizontal pipe very well. As the flux of the auxiliary feedwater is small compared to the size of the pipe, the intensity of the turbulent is not so great, and, therefore, a sophisticated turbulent flow model is not necessary.



(a) (t=120sec)



(b) (t=150sec)



(c) (t=180sec)

Fig. 8. Result of Numerical Analysis

## 3. THE SIMULATION OF AN ACTUAL POWER PLANT

To check the possibility of the CFX simulation for the thermal stratification of actual plant, as well as the effectiveness of the modified thermal sleeve, a set of simulations was executed. As the validation calculation of CFX for the thermal stratification experiment results was performed successfully, a simulation calculation was attempted for the thermal stratification in the steam generator feedwater inlet horizontal pipe of an old-style power plant (Kori plant). This section describes the general procedure necessary for computational analysis, the assumptions used in this computational analysis, the governing equations, simplification of modeling, and the boundary conditions and method of numerical analysis. Two cases of simulations were performed with and without a modified thermal sleeve. Also the sensitivities of the thermal sleeve thickness and gap were studied.

### 3.1 Assumptions

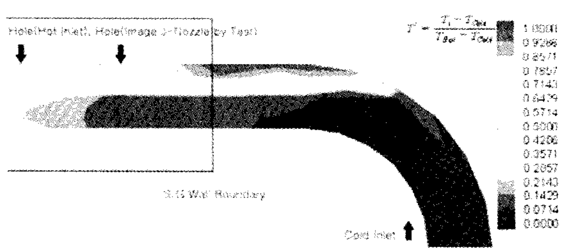
For an efficient numerical analysis of the thermal stratification based on the thermal stratification verification result at the steam generator feedwater inlet horizontal pipe in the existing power plants (power plants prior to KSNP), the following assumptions were made:

- The analysis model is from the part where the high-temperature water flows into the pipe to the part where the low-temperature water flows in.
- The analysis model considers the pipes and the flow field only.
- The high-temperature and low-temperature fluid are normal 3-dimensional flows coming in with a uniform velocity distribution.
- The change in the density of the fluid owing to the difference in temperature will only depend on the gravitational field.
- The thickness of the boundary interface (mixed region) between the high-temperature and low-temperature fluid is negligible.
- The intensity of the turbulent flow is 1% of the velocity of the primary flow.
- The compressibility effect, viscous dissipation, and radiation heat transfer of the fluid were ignored.
- In the early stage of computation, the temperature of all fluids in the pipe was 290°C (temperature of the high-temperature water).
- As for the water between the pipe and the T/S, only the density, heat conduction, and thermal expansion were considered, and it was calculated as a solid.

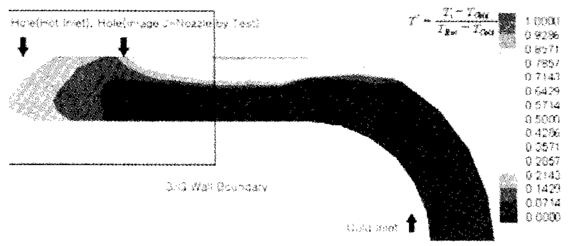
### 3.2 Simplification of Modeling

The scope of the numerical analysis is from the part where the low-temperature water flows in to the part where the high-temperature water flows in. Accordingly, as illustrated in Fig 10, the scope of the numerical analysis was from the point on the wall of the steam generator where the low-temperature water flows in at the feedwater inlet horizontal pipe and the curved part to the part where the high-temperature water flows in at the O-Ring and J-Nozzle.

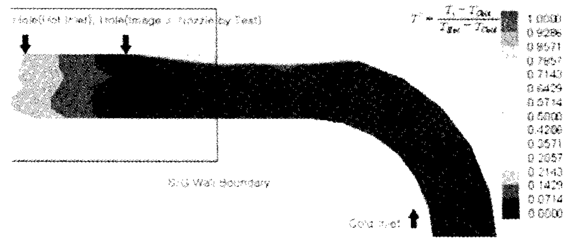
In addition, to create the grid prior to this computation, the mesh generation program of the ANSYS Work Bench 11.0 was used. There were about 256,000 grids, and they were concentrated in the flow field and the curved part of the pipe so that temperature could be accurately measured.



(a) (t=120sec)



(b) (t=150sec)



(c) (t=180sec)

Fig. 9. Experimental Result

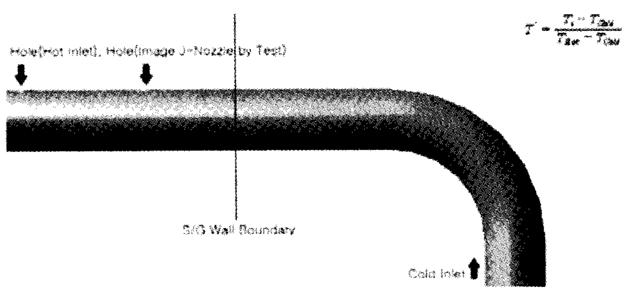


Fig. 10. Simplification of the Numerical Analysis Modeling

**Table 2.** Input Parameters

| | | |
|---|---|---|
| Fluid Model | Heat transfer model | Thermal energy |
| | Turbulent model | K-$\varepsilon$ model |
| | Buoyancy model | Production and dissipation |
| | Turbulent Schmidt No. | 0.9 |
| | Dissipation coefficient | 1.0 |
| Cold Inlet | Flow regime | Subsonic |
| | Mass and momentum | 23.3 kg/s<br>(1.4 $m^3$/min) |
| | Turbulence | Low (intensity:1.0%) |
| | Temperature | 40 °C |
| Hot Inlet | Flow regime | Subsonic |
| | Relative pressure | 13.7895 bar (opening) |
| | Turbulence | Zero gradient |
| | Temperature | 290 °C |
| Wall Conditions | Wall influence on flow | No slip |
| | Wall roughness | Smooth |
| | Heat transfer oefficient | Adiabatic |
| | Wall temp. | 290 °C |
| Initial Conditions | Pressure | 87.5634 bar |
| | Temperature | 290 °C |
| Solid Model | Wall thickness | 20 mm |
| | T/S thickness | 4 mm, 6 mm |
| | Gap | 1 mm, 2 mm |

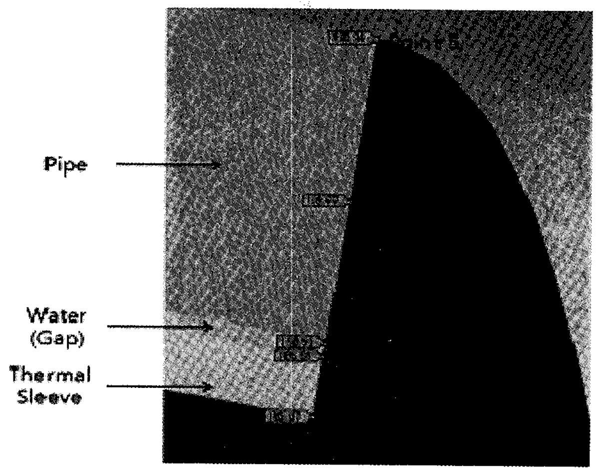
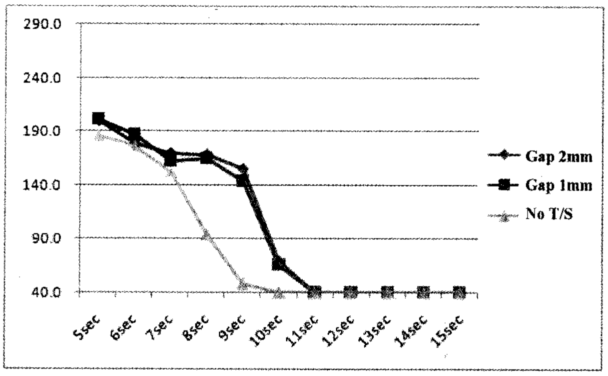
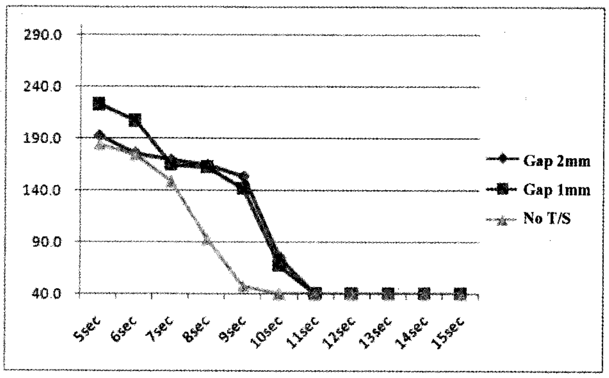


Fig. 11. Temperature Calculation Positions

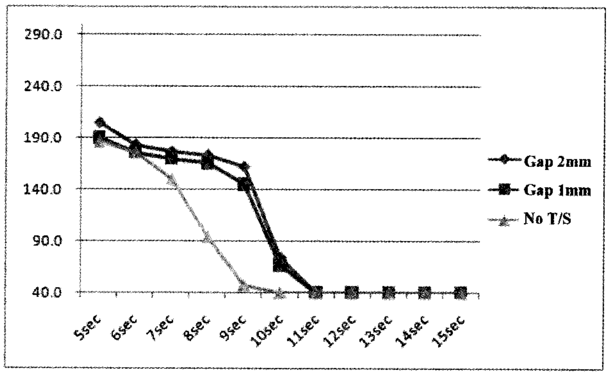
In addition, the calculated temperature was made dimensionless.



(a) Point 3



(b) Point 4



(c) Point 5

Fig. 12. Temperature Distribution at Point 5

## 3.3 Boundary Conditions

For boundary conditions of the numerical analysis, the simplified standard model is presented. The thermal stratification at the steam generator feedwater inlet horizontal pipe varies depending on the shape or flux of the pipe, but here the following boundary conditions were used, as shown in Table 2, since the numerical analysis was already conducted on the basis of the result and mechanism of the thermal stratification verification experiment at the steam generator feedwater inlet horizontal pipe.

The diameter of the pipe was D =0.364m, the size in an actual power plant. The physical properties of the fluid were the physical properties of water at 87.5634bar and 290°C The verification experiment found that, when Ri>10.6, thermal stratification occurred, and this numerical analysis was conducted when Ri = 38.04.

### 3.4 Result and Discussion of Numerical Analysis

According to the assumptions used for computational analysis, the governing equations, simplification of modeling, boundary conditions and the method of numerical analysis, the following numerical analysis results were obtained.

As illustrated in Fig. 11, temperature was calculated at a total of 5 points: the T/S outside the wall (Point 1), the T/S inside the wall (Point 2), the pipe outside the wall (Point 3), the pipe in the center (Point 4), and the pipe inside the wall (Point 5).

To exaggerate the temperature distribution, points 3, 4, and 5 where the temperature of the curved part of the pipe displayed the greatest difference, were selected.

To evaluate the effectiveness of the modified thermal sleeve, a set of simulations for the modified thermal sleeve were performed with variations of gap and thickness of the thermal sleeve. The simulation with the modified sleeve shows that the modification can reduce the temperature decrease rate of the pipe significantly (Fig. 12). However, the gap and the thickness were not so sensitive.

## 4. CONCLUSIONS

After the verification experiment and a set of code simulations, the following conclusions were drawn.

### 4.1 Occurrence of Thermal Stratification

The results of the verification experiment show that thermal stratification did not occur at KSNP, but it did at the old-style power plants.

### 4.2 Criteria of Occurrence of Thermal Stratification

The experiment revealed that thermal stratification occurred when the Richardson number is 10.6 or greater. On this basis, the criteria for the occurrence of thermal stratification was set at 10.0.

### 4.3 Applicability of CFX Code

Applicability of CFX (CFD) code to thermal stratification showed that CFD code could simulate thermal stratification quite well in a steam generator horizontal inlet pipe with a simple turbulent model ($\kappa$-$\varepsilon$ model)

### 4.4 Effectiveness of the Improved Thermal Sleeve

A T/S with an improved shape was proposed as a measure to prevent the occurrence of thermal stratification in S/G pipes. To prove the effectiveness of this proposed measure, the CFX code was used for simulation, and the results confirmed that there was a great difference in temperature between the pipes and the fluid. This indirectly verifies the effectiveness of the T/S.

### 4.5 Sensitivity Study of the Gap and Thickness

To check the effect of the T/S, the thickness of the T/S and the gap between the T/S and the pipe were changed, and their sensitivities were analyzed. As the gap and thickness increased, the difference in temperature between the fluid and the pipe rose, but not proportionally.

## RECOMMENDATIONS

To utilize the results of this study for the assessment of the safety of the pipes in a power plant, the following additional research is needed. The thermal stress of the pipes in existing power plants and the frequency according to the operating mode of the power plant need to be computed so that the CUF (Cumulative Usage Factor) can be calculated.

## ACKNOWLEDGEMENTS

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