••

Mechanical Science and Technology

Journal of Mechanical Science and Technology 21 (2007) 654~663

Experiments on Thermal Stratification in Inlet Nozzle of Steam Generator••

Sang-Nyung Kim[b], Cheol-Hong Kim[a,*], Bum-Su Youn[c], Hag-Ki Yum[d]

[a]*Department of Nuclear Engineering, Kyunghee University Seocheon-dong #1, Kiheung-gu, Youngin-city, Kyung-gi-do, 449-701, Korea*

(Manuscript Received June 14, 2006; Revised February 5, 2007; Accepted February 6, 2007)

Abstract

Nuclear power plant components suffer pipe shedding, cracking, thermal fatigue, bending and supporting bracket breakage during their life span. Notably, the horizontal inlet nozzle of steam generator is prone to thermal stratification frequently due to its operational characteristics. As a result, PWRs in many countries including the U.S.A. suffered a lot of pipe cracks and leakages around the late 1970s, as the thermal stress inflicted by thermal stratification formed in the horizontal inlet nozzle of steam generator during transition (auxiliary feedwater injection) was not reflected on power plant design.

Therefore, we classified the nuclear power plants in Korea into KSNP and Westinghouse-type(W) power plants (Kori # 1,2,3,4, Yeonggwang # 1,2 and Uljin # 1,2) and conducted an experiment on thermal stratification and thermal cycling in relation to the volume of auxiliary feedwater injected into the horizontal inlet nozzle of steam generator and hot water flowing back from steam generator. As a result, it was found out that KSNP was hardly prone to thermal stratification while thermal stratification occurred in the horizontal inlet nozzle of steam generator in Westinghouse-type(W) power plants, necessitating a solution to address such a phenomenon.••

Keywords: S/G inlet nozzle; Thermal stratification; Thermal cycling; Richardson number; Thermal fatigue; Crack

1. Introduction

Thermal stratification refers to layering of low-velocity fluids of different temperatures in power plant components or piping system due to density difference. Nuclear power plant components suffer pipe shedding, cracking, thermal fatigue, bending and supporting bracket breakage during their life span. Notably, the horizontal inlet nozzle of steam generator is prone to thermal stratification frequently due to its operational characteristics. Accordingly, the US Nuclear Regulatory Commission (NRC) requires the integrity of the nuclear power plant piping system exposed to potential thermal stratification such as main feedwater pipe and reactor coolant system pipe to be proven in the Bulletin 79-13, 88-08 and 88-11. In Korea as well, it is recommended in the regulations applicable to nuclear power plants that the horizontal pipe among the tributary pipes connected to reactor coolant system be subject to a variety of thermal stratification inspections. In addition, steam generator is a very critical component in terms of nuclear power plant integrity and safety. However, thermal stress resulting from thermal stratification within piping system was not reflected sufficiently on the design of

*Corresponding author. Tel.: +82 31 201 2561, Fax.: +82 31 202 8979
E-mail address: snkim@khu.ac.kr

W power plants in Korea.

Therefore, we conducted an experiment on the possibility of thermal stratification and thermal cycling in relation to a variety of auxiliary feedwater injection conditions relating to auxiliary feedwater volume, pipe diameter and shape against KSNP and W power plants (Kori #1,2,3,4, Yeonggwang #1,2 and Uljin #1,2, hereinafter referred to as 'W Power Plants' collectively) that have long been in service and prone to thermal stratification in the horizontal inlet nozzle of steam generator. Findings made in the experiment will be used for assessing thermal stress resulting from thermal stratification within the pipe system and developing solutions to address the issue.

2. T/S cases & operational conditions

2.1 Cases of thermal stratification in steam generators

As nuclear power plant operation experiences accumulated, thermal fatigue developed quite frequently in the inlet nozzle of steam generators in the nuclear power plants in the U.S.A. around the late 1970s (Table 1). Accordingly, the US NRC published Bulletin 79-13 that mandated an inspection on the feedwater pipe of all PWR steam generators.

Table 1. T/S and corrective actions in S/G..

Year	1979
Affected Plants	D.C. Cook Units 1 & 2, Salem Unit 1, Diablo Canyon, Surry Unit 1, San Onofre Unit 1, R. E. Ginna, H. B. Robinson Unit 2, Millstone Unit 2, Beaver Valley Unit 1, Palisades, Kewaunee, Yankee Rowei, Point Beach Unit 2, Maine Yankeei
Description	Cracks developed at 8 locations along the feedwater lines
Corrective Action	Issued Bulletin 79-13, Mandated volume inspection on Westinghouse & CE power plants and development of inspection plan
Year	1989
Affected Plants	Indian Point 2
Description	Crack/leakage developed in the inlet nozzle
Corrective Action	Conducted volume inspection
Year	1992
Affected Plants	Sequoyah 1
Description	Crack developed in the inlet nozzle
Corrective Action	Issued IN 93-20, recommended a review of feedwater line inspection method and corrective action. Cracks developed in 8 Westinghouse power plants & 2 CE power plants after 1992.

On the other hand, no instance of steam generator pipe crack ascribable to thermal stratification has been reported in Korea to date and the nuclear power plant regulator has issued neither recommendations nor pointed out issues pertaining to thermal stratification. However, it was confirmed in the experiment described herein that thermal stratification would be likely to occur in W power plants. Hence, pipe cracking re-sulting from thermal stress is anticipated as well.

Table 2. Operation parameters of respective power plants.

Operation Parameters \ Plant Type	W Power Plants		KSNP	
	min	max	min	max
Temp. Diff. between MFW and Aux. Feedwater (ΔT)	200	290	200	275
Avg. Thermal Expansion Coeff. (1/•)$\times 10^{-3}$	1.38	3.52	1.38	2.91
AFW Volume Range (m^3/min)	1.4	1.9	1.9	2.84
Richardson number	10.6	72.4	0.05	0.32
Inlet Nozzle Diameter (m)	0.364		0.146	
Curvature Radius of Inlet Pipe (D : Nozzle Diameter)	1.5D		1.5D	
Hot Water Volume Flowing into Horizontal Inlet Pipe (m^3/min)	Impossible to calculate water volume with accuracy (Test water volume was considered)			

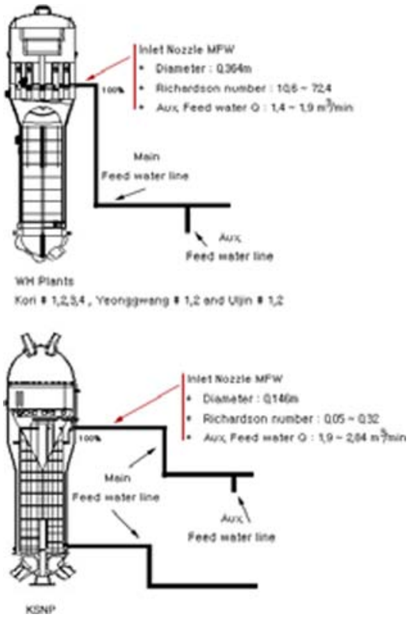

Fig. 1. Main feedwater and aux. feedwater lines of steam generators in W Power plants & KSNP.

2.2 Power plant operation parameters

Actual nuclear power plant operation parameters are highly critical to securing data required for determining test rig design, test matrix and test method. When the auxiliary feedwater system operates in a nuclear power plant, the temperature difference between the top and bottom water layers within the horizontal section of inlet pipe of steam generator widens up to 290• •

Respective operation parameters, pipe shape and layout in relation to auxiliary feedwater injection into the steam generators of W power plants and KSNP in response to the loss of main feedwater are provided in Table 2 and Fig. 1.

To be noted, main and auxiliary feedwater shares the same line in W power plants while main feedwater is injected through both top and bottom lines and auxiliary feedwater is routed only through top line in KSNP.

3. Test rig & test method

3.1 Test rig

This experiment was intended to test thermal stratification behavior in the horizontal inlet nozzle of steam generator in W power plant and the test was designed and fabricated on the basis of dynamic similarity, assuming R_i determined by the temperature difference between hot and cold water and its volume, etc. as a major dimensionless parameter. The test rig arrangement is as outlined in Fig. 2.

Notably, the steam generator O-ring was fabricated as a straight line and the J-nozzle with 6 simple 5 cm-wide holes at every 25 cm as shown in Fig. 3. The horizontal inlet nozzle was made out of 0.15 m-wide and 0.3 m-long transparent acrylic tube. Stainless steel plates were used to build the rectangular hot and cold water baths 0.5 m^3 and 1.0 m^3 respectively and each line was fitted with pump, flowmeter and valve. In addition, the hot water bath was circulated and heated by a boiler adequately. And the temperature distribution around spots of interest was measured by DAS (Data Acquisition System) through 0.127 mm-wide K-type thermocouples positioned as shown in Fig. 4.

3.1.1 Dynamic similarity

As thermal stratification is a part of natural convection, the dominant dimensionless parameter is Richardson number, namely .

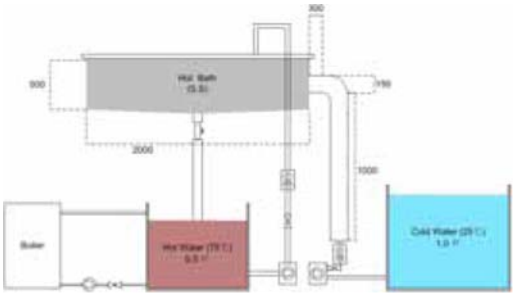

Fig. 2. Test Rig Diagram.

Fig. 3. Figure of o-ring and j-nozzle.

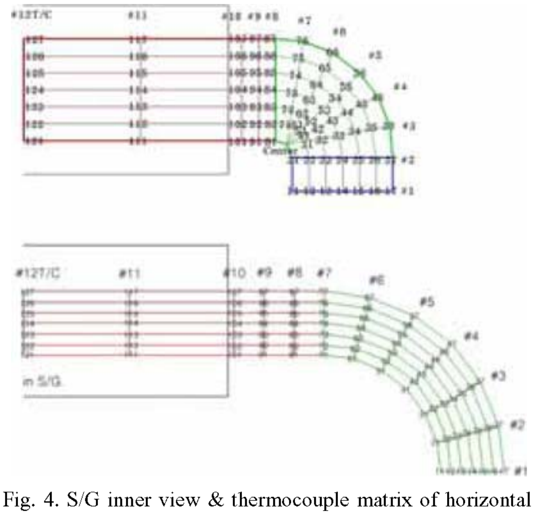

Fig. 4. S/G inner view & thermocouple matrix of horizontal inlet nozzle (top: curvature radius 0 D, bottom: curvature radius 1.5 D).

Here, the thermal expansion coefficient of water can be expressed as , where,   is representative temperature difference, D is pipe diameter, g is gravitational acceleration and u is flow velocity within the line.

Richardson number of the horizontal inlet nozzle when auxiliary feedwater is injected into the main feedwater line of steam generator in nuclear power plant is calculated as shown in Table 2.

3.1.2 Volume and temperature of hot & cold water

The auxiliary feedwater volume in this experiment was determined as shown in Table 3 by the equation described in the above based on the dimensionless parameter R_i.

In addition, since the hot water flow into the horizontal inlet nozzle through the feed-Ring inside steam generator is not expected to be constant but, varied widely, subject to operational conditions, it was determined at 1/5 times, 1/2 times, 1 times and 2 times auxiliary feedwater flow or 0.2, 0.5, 1.0 and 2.0 respectively. Furthermore, hot water injection flow varied as described in the above irregularly and reiteratively during the experiment and the temperatures of cold and hot water were set to 25• •and 75• • respectively with maintained at 50• .•

3.2 Test method

First of all, the hot and cold water baths were filled with room temperature water (25•) and the water in the hot water bath was heated to 75• .• The hot water was routed through the J-nozzle and the O-ring inside the hot water bath up to the curved spot of the horizontal inlet nozzle. Cold water flow was regulated by valve and flowmeter and cold water was routed from the bottom of the curved spot of the horizontal section of the inlet nozzle to the O-ring inside the hot water bath to meet the hot water flowing from steam generator in the horizontal inlet nozzle.

Table 3. Auxiliary feedwater flow.

Plant Type / R_i and Flow Velocity	W Power Plants	KSNP
R_i	10.6~72.4	0.05~0.32
AFW (*l/sec*)	0.395~1.035	5.95~15.0

Table 4. Test matrix.

Plant Type / Test Type	W Power Plant	KSNP	Remark
Aux. Feedwater and Hot Water Flows	Exp. A (Table 5)	Exp. B (Table 8)	C.R. 0D
Thermal Cycling Thermal Striping	Exp. AC Exp. AS (Table 6)	Exp. BC Exp. BS (Table 8)	C.R. 0D
Modification of Curvature Radius	Exp. AD (Table 7)	Exp. BD (Table 8)	C.R. 1.5D

Notably, as many scenarios as possible were assumed in the experiment with regard to thermal stratification and thermal cycling in the steam generator inlet nozzles of W power plants as well as KSNP to study how multiple parameters would impact thermal stratification in the horizontal inlet nozzle during auxiliary feedwater injection (Table 4). The temperature data obtained in the experiment was expressed as dimensionless temperature or by the following equation:

$$T^* = \frac{T_i - T_{Cold}}{T_{Hot} - T_{Cold}}$$

Where, T_{Hot}, T_{Cold} and refer to hot water temper-ature, cold water temperature defined for the experi-ment and the temperature of given spot.

4. Experiment results & discussions

Thermal stratification experiment was performed against the horizontal inlet nozzle of steam generator in W power plants and KSNP and the following results were produced.

4.1 W power plants S/G T/S experiment

Assuming that auxiliary feedwater was injected, temperature distribution in the horizontal inlet nozzle of the steam generator with cold water and hot water flow through J-nozzle and O-ring inside steam generator.

4.1.1 Experiment A

This experiment was intended to experiment thermal stratification in piping system where horizontal sec tion and vertical section were joined at 90°. The auxiliary

feedwater flow and the hot water flow used in each experiment are shown in Table 5 and the thermocouples are located inside the steam generator and the horizontal the inlet nozzle as illustrated in Fig. 4.

Thermal stratification started to develop 60 seconds after the hot water flow began to vary, as cold water flowed in from the bottom of the curved spot of the horizontal section. And 120 seconds after the experiment commenced, hot water began to stand at the top of the curved spot and the horizontal section with cold water flowing underneath. Then, 180 seconds later, the hot water standing in the curved spot began to disappear while the hot water in the top of the hori-

Table 5. Matrix of experiment A.

Exp. A	AFW (Cold Water)		Hot Water	Remark
	Ri	Flow (*l/sec*)	Flow Velocity (*l/sec*)	
A1	72.4	0.395	0.2 (1/5*Cold water)	Thermal Cycling and Thermal Striping tests were conducted in each experiment (Experiment AC, AS) Refer to Table 6
A2	36.8	0.555	0.2 (1/5*Cold water)	
A3	22.2	0.714	0.2 (1/5*Cold water)	
A4	14.8	0.874	0.2 (1/5*Cold water)	
A5	10.6	1.034	0.2 (1/5*Cold water)	
A6	72.4	0.395	0.5 (1/2*Cold water)	
A7	36.8	0.555	0.5 (1/2*Cold water)	
A8	22.2	0.714	0.5 (1/2*Cold water)	
A9	14.8	0.874	0.5 (1/2*Cold water)	
A10	10.6	1.034	0.5 (1/2*Cold water)	
A11	72.4	0.395	1.0 (1*Cold water)	
A12	36.8	0.555	1.0 (1*Cold water)	
A13	22.2	0.714	1.0 (1*Cold water)	
A14	14.8	0.874	1.0 (1*Cold water)	
A15	10.6	1.034	1.0 (1*Cold water)	
A16	72.4	0.395	2.0 (2*Cold water)	
A17	36.8	0.555	2.0 (2*Cold water)	
A18	22.2	0.714	2.0 (2*Cold water)	
A19	14.8	0.874	2.0 (2*Cold water)	
A20	10.6	1.034	2.0 (2*Cold water)	
A21	72.4	0.395	Irregular Iteration of Hot Water Flow	
A22	36.8	0.555	Irregular Iteration of Hot Water Flow	
A23	22.2	0.714	Irregular Iteration of Hot Water Flow	
A24	14.8	0.874	Irregular Iteration of Hot Water Flow	
A25	10.6	1.034	Irregular Iteration of Hot Water Flow	

zontal section continued to stand (forming thermal island). The thermal island was reduced significantly in size and existent locally. Then, over time, the hot water layer (thermal island) at the top of the horizontal section disappeared. (Fig. 5~7)

4.1.2 Experiment AC and AS

In the thermal stratification experiment targeting the horizontal inlet nozzle of the steam generators in W power plants, thermal layer boundaries were formed mostly at such locations where the thermocouple groups #6, #7, #8, #9 and #10 were installed.

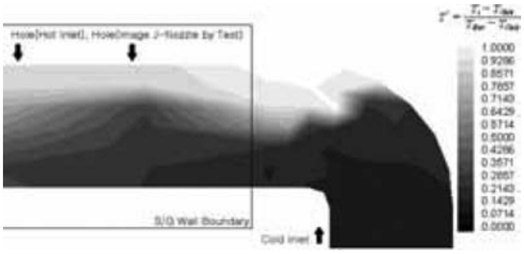

Fig. 5. Temperature distribution when R_i=36.8 (t=60 sec).

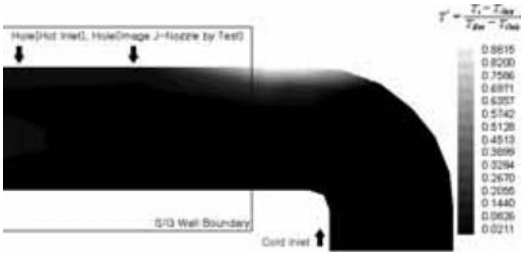

Fig. 6. Temperature distribution when R_i=36.8 (t=120 sec).

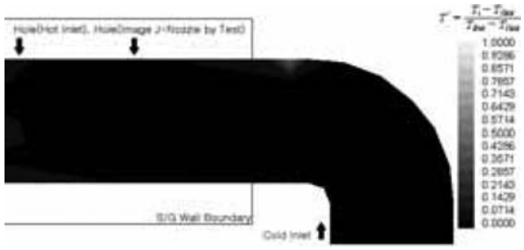

Fig. 7. Temperature distribution when R_i=36.8 (t=180 sec).

Therefore, such locations were selected as the spots of interest in thermal cycling & stripping development (Fig. 8, 9) and the thermal cycling experiments were performed (Table 6).

The time constant of the thermocouples used for the experiment was set at 4msec which was short enough to measure thermal cycling and stripping. Notably, in the thermal stripping experiment, temperature was measured at every second to fully account for the thermal cycling mechanism at the spots of interest.

Had there been thermal cycling mechanism, specific temperature distribution fluctuation would have appeared. However, as illustrated in Fig. 10, 11, it was confirmed that the temperature distribution of each thermocouple group converged toward the auxiliary feedwater temperature in time without any thermal cycle, which is deemed to be ascribable to the fact that the flow of auxiliary feedwater and hot water was small and the pressure variation inside the steam

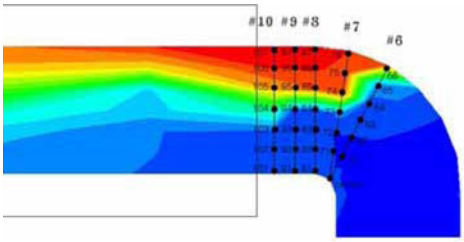

Fig. 8. Thermal cycling temp. measurement locations.

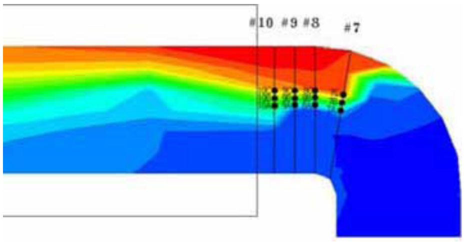

Fig. 9. Thermal stripping temp. measurement locations.

Table 6. Matrix of experiment AC and AS.

Experiment AC and AS		AFW (Cold Water) R_i	Temp. Measurement Locations TC Group	Remark
Thermal Cycling	AC1	72.4	TC # 6,7,8,9,10 Group	Refer to temp. measurement locations in Fig. 8 and Fig. 9
	AC2	36.8		
	AC3	22.2		
	AC4	14.8		
	AC5	10.6		
Thermal Striping	AS1	72.4	TC # 7,8,9,10 Group	
	AS2	36.8		
	AS3	22.2		
	AS4	14.8		
	AS5	10.6		

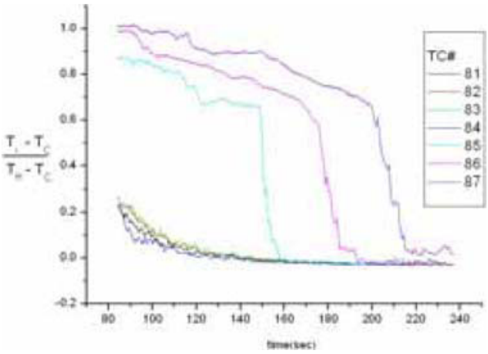

Fig. 10. Temp. distribution at TC #9 group (AC, R_i=72.4).

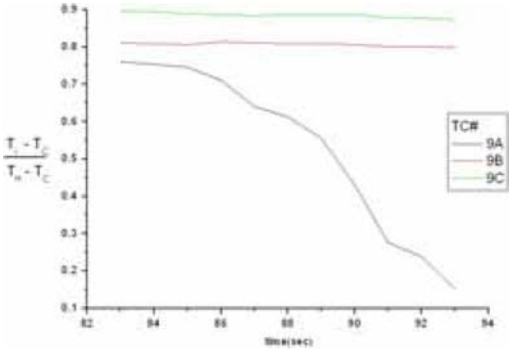

Fig. 11. Temp. distribution at TC #9 group (AS, R_i=72.4).

generator was not considered in this experiment.

4.1.3 Experiment AD

The curved section adjoining the horizontal inlet nozzle was shaped in consideration of the actual curvature radius in the power plants to experiment thermal stratification in the horizontal inlet nozzle of the steam generator in W power plants (Table 7).

When compared with the results of the experiments where curvature radius was not considered, auxiliary feedwater flowed upward a bit more slowly from the bottom of the curved section of the horizontal line (Fig. 12~15). However, it was found out that the curvature radius of the curved section adjoining the horizontal inlet nozzle in W power plant did not have any significant impact on thermal stratification in reference to the given flow range of auxiliary feedwater. However, it was observed that the thermal island was a bit more elongated (lengthwise).

4.2 KSNP S/G thermal stratification experiment

As for the experiment of thermal stratification in KSNP steam generators, auxiliary feedwater flow was set at 1.766(R_i=3.6). Although the value was not comparable to the volume range of auxiliary feedwater flow in actual KSNP, the experiment was very effective in confirming thermal stratification in KSNP steam generators. If thermal stratification would be minimal at the feedwater flow described in the value, it would be much more negligible at a greater water flow.

Notably, in the experiment on thermal stratification in KSNP steam generators that accounted for the actual curvature radius of power plants, the auxiliary feedwater flow was set at 4.5(R_i=0.672) which was much closer to the actual auxiliary feedwater flow in KSNP (Table 8).

Table 7. Matrix of experiment AD.

Exp. AD	AFW (Cold Water)		Hot Water	Remark
	R_i	Flow (*l/sec*)	Flow (*l/sec*)	
AD1	72.4	0.395	Irregular Iteration of Hot Water Flow	Curvature Radius 1.5D
AD2	36.8	0.555	Irregular Iteration of Hot Water Flow	
AD3	22.2	0.714	Irregular Iteration of Hot Water Flow	
AD4	14.8	0.874	Irregular Iteration of Hot Water Flow	
AD5	10.6	1.034	Irregular Iteration of Hot Water Flow	

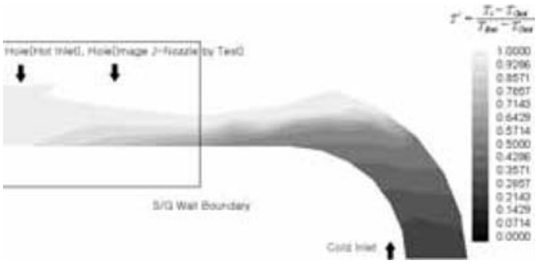

Fig. 12. Temp. distribution exp.AD R_i=72.4 (t=60sec).

Fig. 13. Temp. distribution exp.AD R_i=72.4 (t=120sec).

Fig. 14. Temp. distribution exp.AD R_i=72.4 (t=180sec).

4.2.1 Experiment B

Across the range of hot water flow variation, cold water flowed fast in across the entire diameter of the curved section of the horizontal line in 30 seconds and thermal stratification did not developed in the

Fig. 15. Temp. distribution exp.AD R_i=72.4 (t=240sec).

Table 8. Experiment B and BD.

Exp. B & BD	AFW (Cold Water)		Hot Water	C.R. Test (Y/N)	Remark
	R_i	Flow (*l/sec*)	Flow (*l/sec*)		
B	3.6	1.766	Irregular Iteration of Hot Water	×	Actual R_i Range in KSNP is 0.05 ~ 0.32.
BD	0.672	4.5	Irregular Iteration of Hot Water	O	

Fig. 16. Temp. distribution exp.B R_i=3.6 (t=30sec).

Fig. 17. Temp. distribution exp.BD R_i=0.672 (t=30sec).

horizontal inlet nozzle. Cold water was pushed like piston through the curved section and the horizontal inlet nozzle deep into the steam generator feed ring. In addition, variation of hot water flow had little bearing on thermal stratification (Fig. 16). Therefore, thermal cycling experiment (Experiment BC & BS) was not necessary.

4.2.2 Experiment BD

If thermal stratification does not occur in a AFW experiment(4.5; R_i=0.672) simulating the KSNP auxiliary feedwater flow range most closely, it would not appear at a greater volume as well.

In this experiment, cold water flowed significantly fast in across the entire cross section of the curved line of the horizontal section when 30 seconds passed and thermal stratification did not appear at the horizontal inlet nozzle (Fig. 17).

4.3 Discussion

One of the purposes of this experiment was to establish thermal stratification criteria. Figure 18~19 show temperature distribution at thermocouple group at #9 and #10 after 60 seconds passed. In each figure, the vertical line indicates the lowest R_i(10.6) where thermal stratification occurs in the horizontal inlet nozzle of the steam generator in W power plants. Around the vertical line, thermal stratification occurred when R_i was greater than 10.6 (auxiliary feedwater flow tapered off) while it hardly occurred when R_i was smaller than 10.6(auxiliary feedwater flow increased gradually). Notably, the curvature radius was found out to have considerable bearing on the size and the duration of thermal island (Table 9).

Given the findings made in this study, it is inferred that the curvature radius of the horizontal inlet nozzle of the steam generator in W power plants had little bearing on thermal stratification and considerable bearing on the size of thermal island, as the volume and the velocity of the auxiliary feedwater (cold water) flow were low and the cold water flowed into the horizontal section very slowly, irrespective of the curvature radius. In addition, it seems that hot water has little bearing on thermal stratification because hot water does not flow in large volume but in small volume and at low velocity toward the top of the horizontal section, as it is routed right over the top of the steam generator feed ring. Notably, thermal cycling and stripping hardly occurred, as the auxiliary feedwater(cold water) influx into the horizontal section was significantly small, hot water flow was small as well and the pressure fluctuation inside steam generator was not reflected on this experiment. Lastly, had hot water backflow been simulated in consideration of the conditions that would exist within steam generator when main feedwater injection capability is lost in power plants, it would have been possible to observe more complex thermal stratification. However, given that it is difficult to accurately account for the volume of hot water backflow at high temperature and high pressure conditions, the findings made in this experiment are deemed as base data accounting for occurrence or expansion of thermal stratification within steam generator.

Table 9. Comparison of T/S experiment results.

Plant Type / Exp. Parameter	W Power Plants	KSNP	Remark
Thermal Stratification	O	×	
Thermal Cycling	×	×	
Thermal Striping	×	×	
Impact of AFW (Cold Water) Flow on Thermal Stratification	O	×	
Impact of Hot Water Flow on Thermal Stratification	×	×	
Impact of Curvature Radius of Curved Section on Thermal Stratification	• •	×	

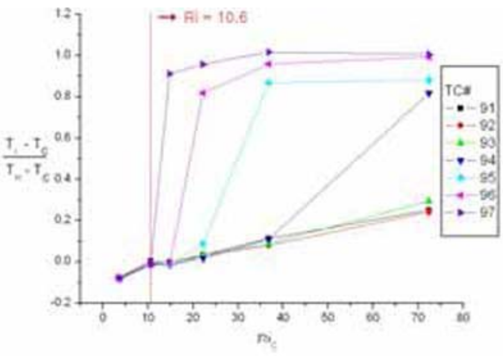

Fig. 18. T/S criteria (TC #9 group).

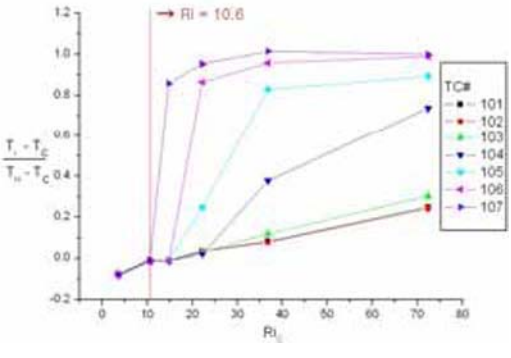

Fig. 19. T/S criteria (TC #10 group)

5. Conclusions

Thermal stratification that occurs in the horizontal inlet nozzle as be injected auxiliary feedwater which is one of the components highly critical to the operation and the safety of nuclear power plant threatens the integrity of the piping system in nuclear power plant. Therefore, we performed assessment of thermal stratification in the horizontal inlet nozzle of the steam generator in W power plants and KSNP in reference to auxiliary feedwater and hot water flows and curvature radius and conducted thermal cycling and stripping experiments as well to arrive at the following conclusions:

(1) Thermal stratification is highly likely to occur in the horizontal section of the steam generator inlet nozzle in the old power plants when auxiliary feedwater is injected;

(2) Thermal stratification is more at the mercy of the auxiliary feedwater flow than the flow conditions(hot water) within steam generator;

(3) Thermal cycling was hardly observed in the thermal cycling and stripping experiments targeting the horizontal inlet nozzles of the steam generator in W power plants;

(4) The curvature radius of the horizontal inlet nozzle of the steam generator in W power plants did not have significant impact on the thermal stratification in the piping system but had some impact on the size and the duration of thermal island;

(5) Thermal stratification development criteria for the horizontal inlet nozzle of steam generator was found to be $R_i>10$ in conservative terms;

(6) In the thermal stratification experiment targeting the horizontal inlet nozzle of the steam generator in KSNP, thermal stratification was hardly observed.

6. Recommendations

The results of this Experiment show that the following additional studies are needed.

Additional studies need to be performed in relation to the possibility of the development and expansion of thermal stratification by hot water flow routed from inside steam generator into piping system.

Nomenclature

g : Gravity acceleration
Gr : Grashof number
Re : Reynolds number
Ri : Richardson number

Greeks

β : Thermal expansion coefficient of water
ν : Kinematic viscosity of water
ρ : Density
Q : Volumetric
D : Nozzle Diameter
u : Velocity of flow
T : Temperature of fluid
L : Length

Subscript

H : Hot water
C : Cold water

Abbreviations

KSNP : Korea Standard Nuclear Power Plant
PWR : Pressure Water Reactor
S/G : Steam Generator
T/S : Thermal Stratification
RCS : Reactor Coolant System
MFW : Main Feedwater
AFW : Auxiliary Feedwater
TC : Thermocouple
W : Westinghouse-type

Acknowledgements

This work was supported by MOCIE through EIRC program, Korea Electric Power Research Institute (KEPRI).

References

Design Report No. Cenc-1940 Revision 01(Z-160-RA-C01-01), 1986, "Design Report For YONG-GWANG Nuclear Power Plant Units 3 And 4 Steam Generators."

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

KINS, KINS/Ar-267, 1994, "Numerical Analysis of Thermal Stratification Inside the Horizontal Pipe (I)."

P&ID Reactor Coolant System, 9-431-N105-001006.

P&ID Safety Injection/Shutdown Cooling System, 9-441-N105-001-004.

Magee, R., et. al., "J. M. Farley Unit 2 Engineering Evaluation of the Weld Joint Crack in the 6, April. 1988, "SI/RHR piping," WCAP-11789.

Safety Injection/Shutdown Cooling System PSDS, 9-441-N407-001.

United States Nuclear Regulatory Commission, Bulletin No. 79-13, June 25, 1979, "Cracking in Feedwater System Piping."

United States Nuclear Regulatory Commission, Bulletin No. 79-13, Revision 1, "Cracking in Feedwater System Piping," Aug. 30, 1979.

United States Nuclear Regulatory Commission, Bulletin No. 79-13, Revision 2, Oct. 16, 1979, "Cracking in Feedwater System Piping."

United States Nuclear Regulatory Commission, Bulletin No. 88-08, June 22, 1988 "Thermal Stresses in Piping Connected to Reactor Coolant Systems."

United States Nuclear Regulatory Commission, Bulletin No. 88-08, Supplement 2, Aug. 4, 1988 "Thermal Stresses in Piping Connected to Reactor Coolant Systems."

United States Nuclear Regulatory Commission, Bulletin No. 88-08, Supplement 3, April 11, 1989 "Thermal Stresses in Piping Connected to Reactor Coolant Systems."

United States Nuclear Regulatory Commission, Bulletin No. 88-11, Dec. 20, 1988, "Pressurizer Surge Line Thermal Stratification."

Westinghouse General Order HK 10600-AR6-AR5, April. 1980, "Korea Electric Company Ko-Ri Unit No. 2."