Experiments on the Thermal Stratification in the Branch of NPP

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The thermal stratification phenomena, frequently occurring in the component of nuclear power plant system such as pressurizer surge line, steam generator inlet nozzle, safety injection system (SIS), and chemical and volume control system (CVCS), can cause through-wall cracks, thermal fatigue, unexpected piping displacement and dislocation, and pipe support damage. The phenomenon is one of the unaccounted load in the design stage. However, the load have been found to be serious as nuclear power plant operation experience accumulates. In particular, the thermal stratification by the turbulent penetration or valve leak in the SIS and SCS pipe line can lead these safety systems to failure by the thermal fatigue. Therefore in this study an 1/10 scaledowned experimental rig had been designed and installed. And a series of experimental works had been executed to measure the temperature distribution (thermal stratification) in these systems by the turbulent penetration, valve leak, and heat transfer through valve. The results provide very valuable informations such as turbulent penetration depth, the possibility of thermal stratification by the heat transfer through valve, etc. Also the results are expected to be useful to understand the thermal stratification in these systems, establish the thermal stratification criteria and validate the calculation results by CFD Codes such as Fluent, Phenix, CFX.

Key Words: Thermal Stratification, Turbulent Penetration Depth, Safety Injection System, Shutdown Cooling System, Valve Leakage, Thermal Fatigue, Heat Transfer Through Valves

Nomenclature

D : Diameter of pipe
g : Gravity acceleration
L : Length
r : Radial coordinate
Gr : Grashof number
Re : Reynold number
Ri : Richardson number
u : Velocity of flow
T : Temperature of fluid

Greeks

β : Thermal expansion coefficient of water
ν : Kinematic viscosity of water
ρ : Density

Subscript

P : Prototype
M : Model
B : Bottom
T : Top
C : Cold Leg
H : Hot Leg

Abbreviations

RCS : Reactor Coolant System
SIS : Safety Injection System
SCS : Shutdown Cooling System

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RHRS : Residual Heat Removal System
CVCS : Chemical and Volume Control System

1. Introduction

The components of a nuclear power plant system are greatly affected during the course of their life by several thermal-hydraulic phenomena. Among them thermal stratification causes piping damage, thermal fatigue, piping dislocation, warpage, and pipe support damage. Thermal stratification phenomena refer to the fact that low-velocity fluids of different temperatures cannot be mixed and stay separated in the components of a nuclear power plant or pipes due to the difference in density. It occurs mostly in the pressurizer surge line, the feedwater system, the safety injection system, the residual heat removal system and the chemical volume control system. In addition, thermal stratification due to valve leakage, turbulent penetration, and heat transfer through valve happens to a branch pipe connected to a reactor coolant system that is stagnant during normal operation. Especially in the latter case, the thermal fatigue due to the thermal stratification of the safety system was not taken into consideration in the design stage, but as operational experience accumulates, its importance is increasingly emphasized.

Accordingly, in this study the authors selected a branch pipe connected to the reactor coolant system expected to develop thermal stratification in a domestic nuclear power plant, and conducted a verification test for thermal stratification due to main mechanism, such as turbulent penetration and valve leakage. The purpose of this study is to identify the main mechanisms and governing parameters of thermal stratification in the branch of domestic NPP, select areas for close examination where thermal stratification phenomena are likely to happen, establish the criteria for thermal stratification, and verify the results by CFD codes.

2. Thermal Stratification

2.1 Thermal stratification in the piping

When a horizontal pipe is stagnant or filled with a low velocity fluid of different temperatures, there is a pressure difference between the hot fluid and the cold fluid. So the hot or cold fluid flows into the hot or cold fluid. In particular, the hot fluid and the cold water cannot easily reach thermal equilibrium due to its physical property (high heat capacity and low thermal conduction), and the high-temperature water stays in the upper part of the pipe while the low-temperature fluid stays in the bottom of the pipe. In other words, the two fluids do not get mixed due to the difference in density by the temperature difference, and they are thermally separated from each other. This state is called thermal stratification.

If thermal stratification occurs inside a pipe, the heat transfer with the stratified fluid causes temperature difference of the pipe material, and thus the hot region will be subjected to compression and the cold region will be subjected to tension. In the NPP this stress distribution takes place periodically depending on how the reactor is operated, and may cause local fatigue on the pipe walls, thereby leading to fatigue cracks. In addition, in the mixing region where the thermal stratification interface is vibrating, large temperature differences are repeated innumerably owing to vibrations with a short cycle, thereby causing cyclical thermal stress. The stress applied additionally by the thermal stratification or thermal cycling is not so great as to immediately have a serious effect on the pipe, but the repetition of thermal stress in certain parts over an extended period of time may result in cracks induced by thermal fatigue.

2.2 Nondimensional number

The nondimensional number governing thermal stratification inside a fluid system with temperature differences is usually expressed as the Richardson Number. For thermal stratification is a type of natural convection in the pipe, the governing nondimensional number can be easily derived if the equation of motion for natural convection is made dimensionless. The Boussinesq's approximation method, which is usually employed for natural convection can also be effective.

Ri No. is the ratio of Gr No.(Grashof Number), which is natural convection, by the square of Re No.(Reynolds Number), which is the ratio of inertia force to viscous force. Like this Ri No. is used as the criterion for making out thermal stratification (natural convection).

3. Test Equipment and Method

3.1 Test equipment

Let us take a look at the hot leg and the cold leg of Uljin Nuclear Power Plant Units 3 and 4 (KSNP), which are the main subjects of this study. The hot leg refers to the two pipes 106.7 cm in diameter that connect the reactor vessel and steam generator. A shutdown cooling system outlet nozzle 40.6 cm in diameter is connected to the bottom of each hot leg. The cold leg is divided into the inlet and the outlet with the reactor coolant pump in the middle, and the outlet to be tested consists of 4 pipes 76.2 cm in diameter that connect the coolant pump and the reactor vessel. A safety injection nozzle 35.6 cm in diameter with a thermal sleeve is connected to each outlet. Here, the test will cover the main pipe through to the first valve of the branch pipe, and they are simplified in consideration of the experiment conditions. The test equipment was designed and manufactured in 1/10 length scale. Figure 1 illustrates the design drawing of the test experiment. Here, the safety injection system pipe and the shutdown cooling system pipe were installed on one main pipe. Also the second valve was omitted since the valve is not necessary in this experiment. The operation statuses of the valve are divided into valve isolation, valve leakage and inflow. An acryl card looking like a closed disk was made and installed for the temperature distribution experiment during valve isolation. The valve leakage simulation assumes that 5% of the valve cross section was destroyed and thus leakage and inflow take place. The detailed is shown in Figure 2. To exaggerate the heat transfer through the valve in the experiment the valve was simulated by 0.15 mm stainless card instead of the valve.

The flow rate of the test equipment was determined in consideration of the physical properties and boundary conditions of Uljin Nuclear Power Plant Units 3 and 4 in such a way as to ensure that Ri No., a dimensionless variable, is the same in the plant and the test. The test flow rate (velocity) is calculated as follows :

$$(Ri)_P=\frac{(g\beta\Delta TL)_P}{u_P^2}=(Ri)_M=\frac{(g\beta\Delta TL)_M}{u_M^2}$$

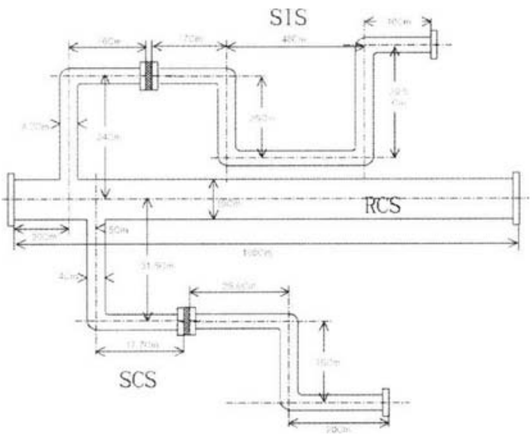

Fig. 1 Drawing of the piping of the test equipment

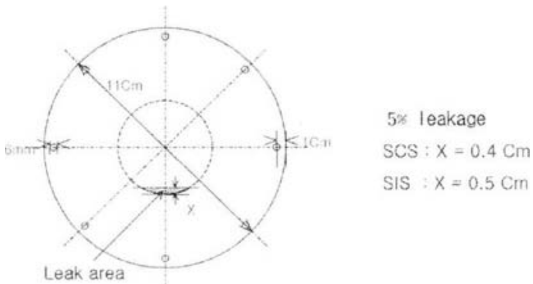

Fig. 2 Leak valve simulation

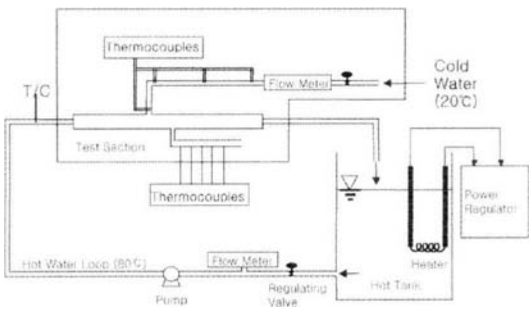

Fig. 3 Outline of the test equipment

$$\left(\frac{\bar{u}_M}{\bar{u}_P}\right)^2=\frac{(\beta\Delta TL)_M}{(\beta\Delta TL)_P}$$

$$\bar{u}_M=\sqrt{\frac{(\beta\Delta T_L)_M}{(\beta\Delta T_L)_P}}\cdot\bar{u}_P$$

On the other hand, if the scaling factor is 1/10, and the experiment $\Delta T=50°K$,

$\bar{u}_M=0.04125(\bar{u}_P)_H$: Hot Leg (SCS)

$\bar{u}_M=0.0663(\bar{u}_P)_C$: Cold Leg (SIS)

$\therefore\ (\dot{m}_H)_M=4.65$ kg/sec

$(\dot{m}_C)_M=5.875$ kg/sec

3.2 Test methods

The coolant used for this test was distilled water, and the test was conducted in the following way. First of all, hot water tank and the cold water tank are filled with water, and the heater in the hot water tank and the pump are used to heat the water in the tank evenly. If the water in the hot water tank reaches the test temperature, the water in the main pipe and the branch pipe is completely replaced by the water in the low-temperature tank. The air remaining in the pipe bend is completely discharged through the air vent valve. All valves are closed, and the pump connected to the hot water tank is started. The flow control valve of the main pipe is adjusted so that presetted flow rate is maintained and temperature distribution is measured by means of the Data Acquisition System.

Assuming normal operation of the reactor, the following tests were conducted.

3.2.1 Test of turbulent penetration depth for the SI pipe and the SCS pipe

With the thermocouple installed at the center of the pipe, individual pipes were tested separately.

3.2.2 Complete isolation test (completely isolated from the SI pipe and the SCS pipe, and no heat transfer through the valve)

The test was conducted under the assumption that the first valves of the SI pipe and the SCS pipe are completely isolated and there is no heat transfer through the valves. The thermocouple is installed horizontally in the vertical pipe, and vertically in the horizontal pipe.

3.2.3 Isolation test (completely isolated from the SI pipe and the SCS pipe, but there is some heat transfer through the valve)

The first valves of the SI pipe and the SCS pipe have no leakage, but to simulate a situation where there is some heat transfer through the valve, a 0.15 mm-thick stainless disk was used instead of the isolation valve for the test. The thermocouple was installed in the same way as in the complete isolation test.

3.2.4 Out-Leakage test for the SI pipe and the SCS pipe

The test was conducted under the assumption that the first valve of the branch pipe was damaged to an extent equivalent to the area of the leaking channel corresponding to 5% of the cross-sectional area of the pipe, and the second valve is isolated. The location of the leakage of the first valve was divided into the top and the bottom, and tests were conducted separately.

3.2.5 In-Leakage test for the SI pipe and the SCS pipe

The test was conducted under the assumption that the first valve of the branch was damaged to an extent equivalent to the area of the leaking channel corresponding to 5% of the cross-sectional area of the pipe, and the second valve is damaged as well, and thus cold fluid flows in at 0.5 gpm.

4. Test Results and Discussion

As mentioned in test methods, tests were conducted for turbulent penetration depth measurement, complete isolation (assuming not only isolation, but also no heat transfer through the valve), isolation (flow isolation but some heat transfer through the valve), Out-Leakage, and In-Leakage. The results of the tests are described below.

4.1 Turbulent penetration depth

Under the assumption that the first valve of the branch pipe is isolated, and there is no heat transfer through the valve, turbulent penetration depth tests for the SI pipe and the SCS pipe were conducted. As expected and shown in these experiments the turbulent penetration is active in the vertical pipe of both the SI pipe and the SCS pipe connected to the main pipe.

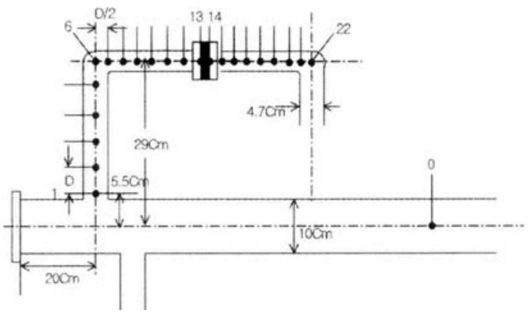

Fig. 4 Locations of the thermocouple in the SI pipe

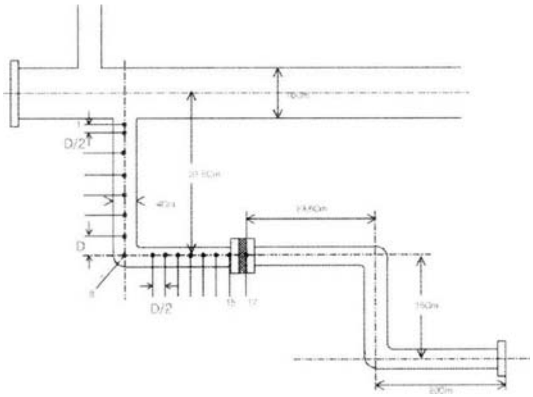

Fig. 5 Location of the thermocouple in the SCS pipe

In particular, in the SI pipe, within 10 seconds after the start of the test, penetration occurred down to the elbow, which is the end of the vertical pipe, and in the SCS pipe, turbulent penetration took place 1D depth from the elbow at 240 seconds, and after 600 seconds (10 minutes) turbulent penetration reached the middle of the elbow. Also, the temperature distribution of the horizontal pipe rose uniformly without any big difference in temperature for both the SI pipe and the SCS pipe. Figures 6 and 7 illustrate the temperature distribution at the locations marked in Figures 4 and 5. The temperature distribution of the horizontal pipe reveals that, when the vertical pipe is almost filled with hot fluid, convection takes place toward the horizontal pipe, thus increasing the temperature of the horizontal pipe. However, there is a difference in the time required for turbulent penetration in the SI pipe and the SCS pipe owing to the difference in buoyancy. When the hot fluid is in the bottom and the cold fluid is on the top as in the SI piping, the hot fluid can easily go upward through the cold fluid. However, when the situation is reverse, the hot fluid cannot easily penetrate into the cold fluid. This results in the penetration time difference.

4.2 Complete isolation

The test was conducted under the assumption that the first valve of the branch pipe is completely isolated, and there is no heat transfer through the valve. In the SI pipe, 300 seconds (5 minutes) after the test, there is no any salient

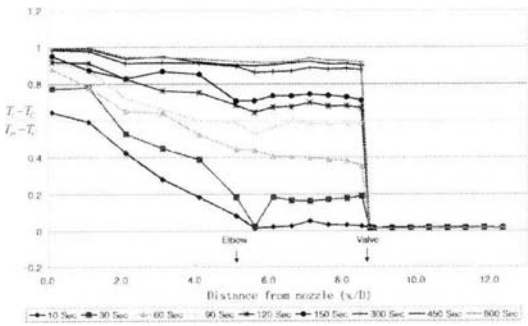

Fig. 6 Turbulent penetration depth in the SI pipe

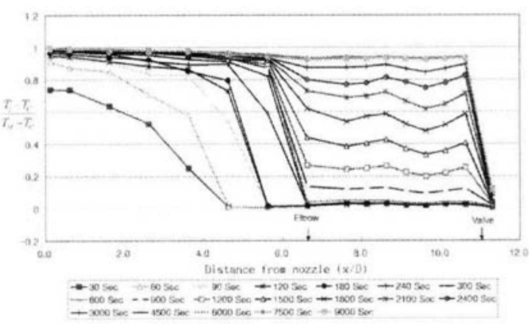

Fig. 7 Turbulent penetration depth in the SCS pipe

temperature difference between the top and bottom of the pipe (Fig. 8). That is, thermal stratification disappears, and the pipe is filled with hot fluid. In the SCS pipe the temperature distribution of the horizontal pipe shows that there is temperature difference between the top and

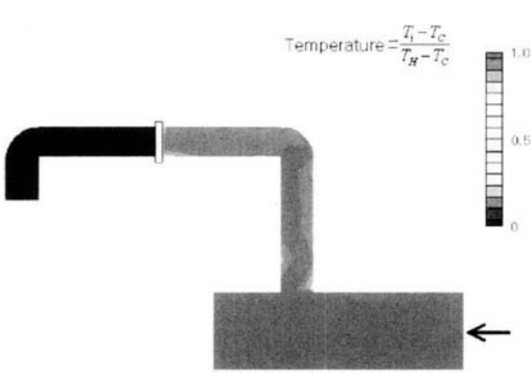

Fig. 8 Temperature distribution when the SI pipe is completely isolated (t=300s)

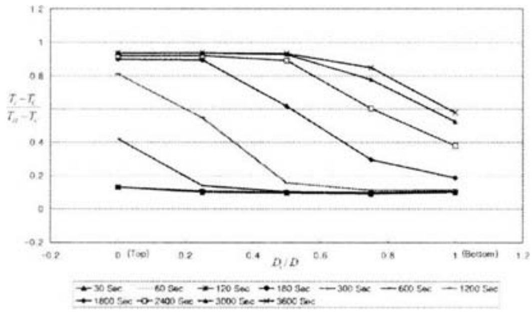

Fig. 9 Temperature distribution when the SCS pipe is completely isolated (D/2 from the valve)

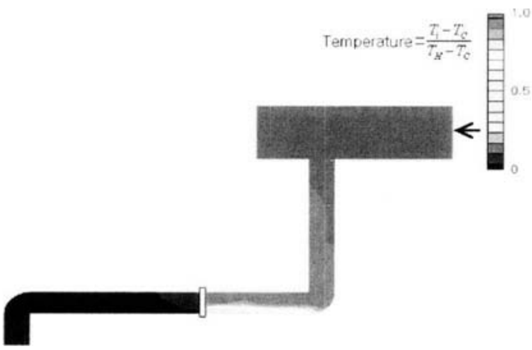

Fig. 10 Temperature distribution when the SCS pipe is completely isolated (t=1800s)

bottom of the horizontal pipe after 1 hour of the test, and thermal stratification is maintained. In particular, at D/2 from the valve thermal stratification was clearly seen as illustrated in Figures 9, and 10.

The Figure 8, 10 were simulated by the TECPLOT (a computer software for contour). In the simulation the temperatures were inputed point by point. All the contour simulations after this were done in the same way.

4.3 Isolated but with heat transfer through the valve

The test was conducted under the assumption that the first valve of the branch pipe is not damaged, but there is heat transfer through the valve. For this test, instead of an exact simulation valve, a 0.15 mm-thick stainless disk was used. The heat transfer can be exaggerated. In the SI pipe, as shown in Figures 11 and 12, thermal stratification occurs from 1D before the valve to the

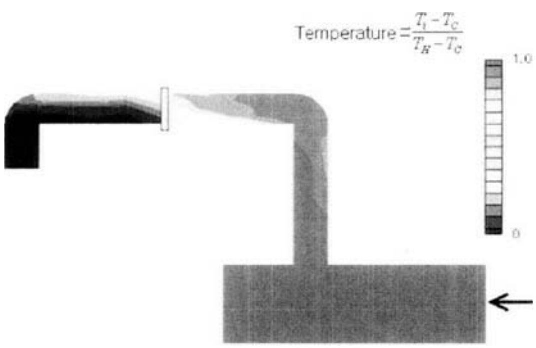

Fig. 11 The temperature distribution in the SI pipe with heat transfer through valve (t=300s)

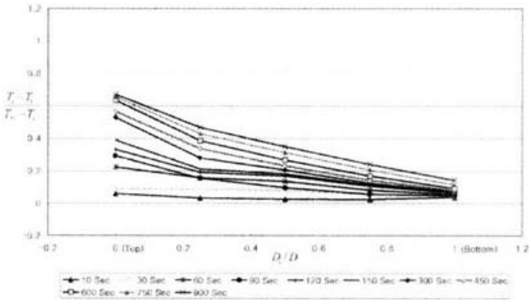

Fig. 12 The temperature distribution in the SI pipe with heat transfer through valve

horizontal pipe past the valve. In particular, thermal stratification is more salient near the valve. In the SCS pipe, thermal stratification takes place in the entire horizontal pipe before the valve as illustrated in Figure 13. However, instead of quantitatively simulating the heat transfer through the valve in the pipe of the power plant, this test, intended to measure the effect of heat transfer, tries to show that the heat transfer through the valve disk can generates thermal stratification in the piping.

4.4 Out leakage

This test was conducted under the assumption that the first valve disk of the branch pipe is damaged to an extent equivalent to 5% of the cross-section of the pipe, but the second valve is not damaged but isolated. This test is intended to measure thermal stratification (temperature distribution) of the pipe due to the damage of the valve. This test assumed that the valve disk was damaged in the top and bottom of the safety injection system piping and the shutdown cooling system piping, respectively. Four tests were conducted.

4.4.1 In case the upper part of the valve of the SI pipe is damaged

From the damaged part of the valve, hot fluid flows in at the part past the first valve, and there is a considerable temperature difference in the top and bottom of the pipe, thereby causing thermal stratification. In particular, within 3D of the valve, thermal stratification was found to be salient.

4.4.2 In case the bottom of the valve in the SI pipe is damaged

The hot fluid flows from the damaged opening at the bottom of the valve to the cold region past the valve, and the cold fluid moves into the hot region and stays in the bottom of the pipe. As the hot fluid flows in past the valve, it well mixed with the fluid in cold region. So there is no thermal stratification in the area past the valve. As the cold fluid flows into the hot region, it stays in the bottom of the pipe due to the difference in density, and gets slowly mixed.

4.4.3 In case the top of the SCS pipe valve is damaged

Through the damaged part in the top of the valve the exchange of hot and cold fluid resulted in thermal stratification in the entire horizontal pipe. In particular, in the area where the elbow

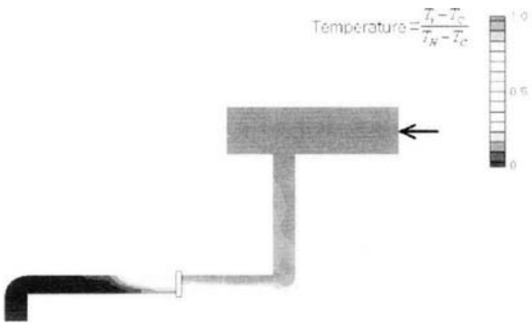

Fig. 13 The temperature distribution in the SCS pipe (t=3600s)

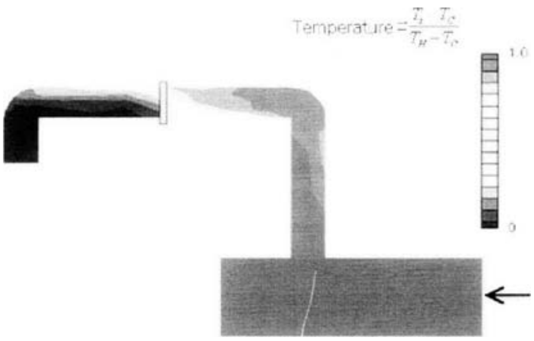

Fig. 14 The temperature distribution in SI pipe with valve leakage (top, t=1200s)

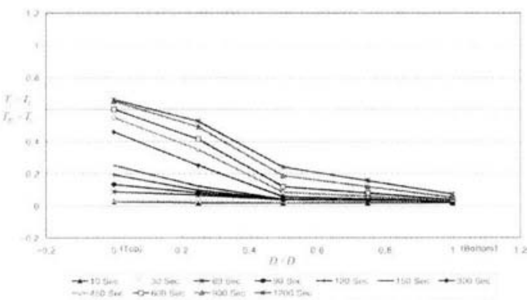

Fig. 15 The temperature distribution in SI pipe with valve leakage (top)

meets the horizontal pipe and within 1D from the valve, thermal stratification was salient. The thermal stratification near the elbow is thought to be caused by the mixing of the hot fluid owing to turbulent penetration with the cold fluid flowing in from the area past the valve.

4.4.4 In case the bottom of the SCS pipe valve is damaged

Through the damaged part in the bottom of the pipe the cold fluid flows into the hot region, whereas the fluid in the hot region flows into the cold region. An analysis of the temperature distribution reveals that thermal stratification takes place through the whole horizontal pipe. However, in the cold region, the temperature rises slowly along the entire horizontal pipe and it is difficult to say that there is any thermal stratification there.

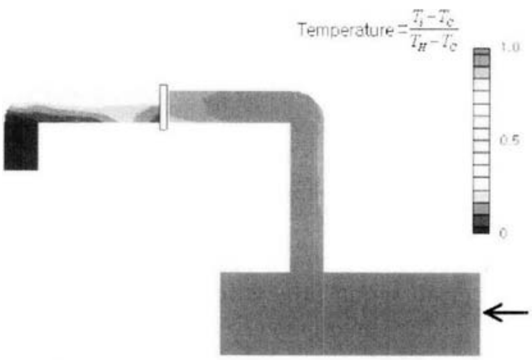

Fig. 16 The temperature distribution in SI pipe with valve leakage (bottom, t=1200s)

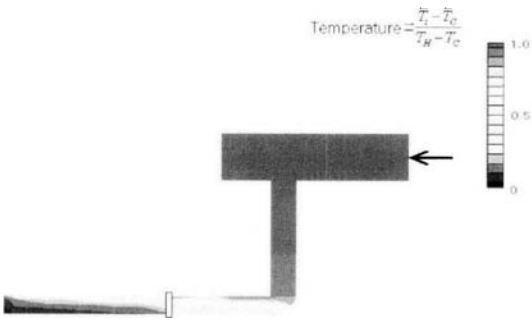

Fig. 17 SCS pipe valve leakage temperature distribution (top, t=3600s)

4.5 In leakage

This test was conducted under the assumption that the first valve disk damaged to an extent equivalent to 5% of the cross-sectional area of the channel, and the damage of the second valve caused the cold fluid to flow from the branch pipe to the main pipe. The amount of the cold fluid

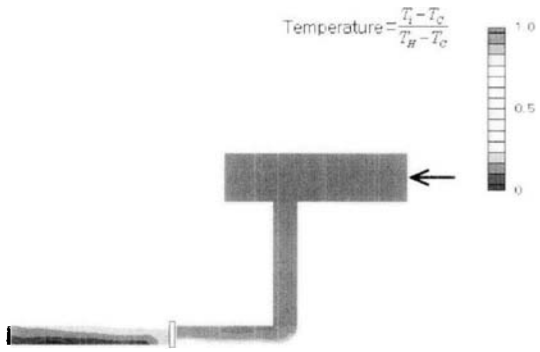

Fig. 18 SCS pipe valve leakage temperature distribution (bottom, t=3600s)

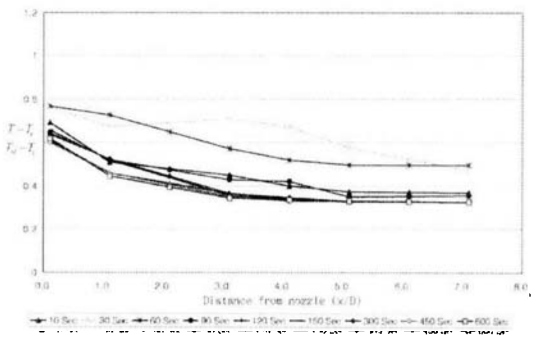

Fig. 19 The temperature profile in SI pipe (in leakage)

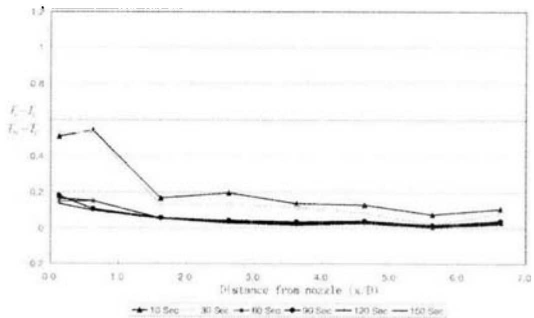

Fig. 20 The temperature profile in SCS pipe (in leakage)

flowing in from the cold leg was assumed to be 0.5 gpm. As shown in Figures 19 and 20, the turbulent penetration right after the start of the test causes the hot fluid to flow into the branch pipe, but as the valve leakage causes the cold fluid to flow in, the hot fluid is pushed to the entrance of the branch pipe. Therefore there is a periodic temperature oscillation in the pipe. This temperature oscillation can be confirmed by the temperature at 10 sec and 30 sec in the Figure 19. Actual plant condition requires consistent inflow of a small amount of cold fluid. So in future test this condition must be met.

5. Conclusions

In the shutdown cooling and the safety injection system, components of great importance to the safety of a nuclear power plant, turbulent penetration, valve leakage including the location of leakage and the presence of heat transfer through the valve could greatly affect the integrity of piping. After a series of thermal stratification experiments simulating these situations, following conclusions are derived.

(1) The depths of turbulent penetration from the reactor coolant system piping to the safety injection and the shutdown cooling pipe are up to the end of vertical pipe.

(2) The criterion for thermal stratification in this simulation test was determined to be 0.3. The criterion was defined as the ratio of temperature difference between the top and the bottom of the pipe ($\Delta T_{top}/\Delta T_{bottom}$) where ΔT_{top} and ΔT_{bottom} defined as the temperature difference between the initial temperature and the local temperature at the top and bottom, respectively. The converted temperature of this test was approximately 20°K, but the actual operation temperature of a nuclear power plant is 84°K and 75°K for the SCS and the SI pipe, respectively. This difference in temperature is quite large enough to identify thermal stratification. The value of 0.3 is same as by USNRC (220°F).

(3) If heat transfer through the valve disk in a nuclear power plant can be ignored, thermal stratification in the safety injection piping is very unlikely, but this test showed that thermal stratification near the valve of the shutdown cooling system is likely. However, if the heat transfer through the valve disk is large enough, thermal stratification is highly likely in the area past the first valve of the safety injection pipe, and in the entire horizontal pipe of the shutdown cooling piping.

(4) In case the first valve of the branch pipe is damaged, and in particular, the damaged part is the top of the disk, thermal stratification seems to spread. If thermal stratification can damage the valve, it is highly likely that the vicious circle of valve damage and thermal stratification will reproduce thermal stratification phenomena on an enlarged scale.

(5) According to this verification test concerning thermal stratification, the pipe requiring close monitoring for thermal stratification would be the shutdown cooling pipe. This verification test showed that the likelihood of thermal stratification around the valve of the shutdown cooling pipe is considerably higher than that near the safety injection pipe.

6. Recommendations

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

(1) Additional tests of turbulent penetration depth must be conducted systematically, and the dimensionless number must be displayed.

(2) The heat transfer through the valve must be better quantified since the heat transfer can occur in a power plant not just through the valve disk, but also through the body of the valve.

(3) 5% leakage in valve leakage tests seems to be excessive. Therefore, a more rational leakage model must be formulated.

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