Analysis of Thermal Stratification and Turbulence Penetration of RCS Branch Piping

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1. Introduction

Thermal stratification that occurs at the branch lines of safety injection systems in nuclear power plants causes thermal fatigue damage by incurring thermal stress, which is caused by branch line temperature variations from top to bottom [1]. In May 1979, it was reported that the safety feed water lines of the US nuclear power plants D.C. Cook No. 1 and No. 2 were damaged by thermal fatigue [2]. The safety injection system and the residual heat removal system are included in the emergency core cooling system. The core cooling system is a safety system designed to prevent severe accidents such as the Chernobyl and Fukushima nuclear accidents by cooling the nuclear reactor core and suppressing potential nuclear fission reactions.

Fig. 1 is a diagram that shows the safety injection system connected to the primary coolant system in a nuclear power plant. Through an investigation into the defects found in the Farley and Tihange nuclear power plants, defects were generated at the front end of the safety injection valve [3] and at the front and rear ends of the bending portion, as shown in Fig. 2. The primary cause of the defects was thermal fatigue owing to stratification, which was caused by the leakage of cooling water at the safety injection valve that was to be kept closed during operation [4]. Leakage at the safety injection valve causes high-temperature boiling inside the line and a decrease in pH owing to partially concentrated boric acid water (reduced to below pH 2).

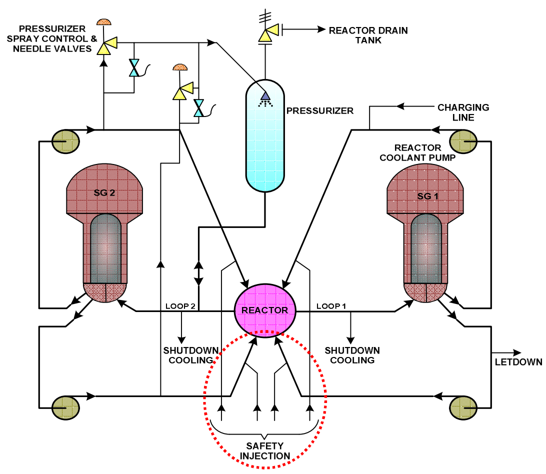


Fig. 1. Safety injection system in nuclear primary system.

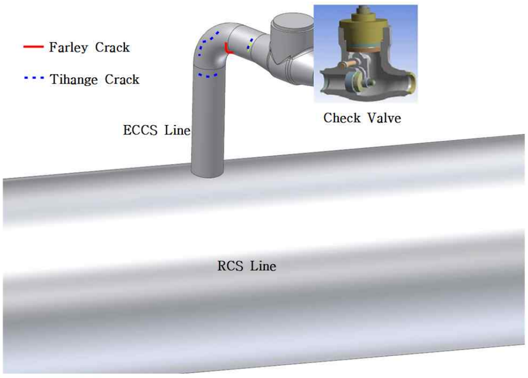


Fig. 2. Crack positions of ECCS line.

The results show that turbulence of the primary pipeline penetrates to the safety injection branch pipe by thermal striping at a low Reynolds number of reactor coolant system (RCS), but by thermal swirl at a high Reynolds number of RCS.

2. Methods and Condition

2.1 Flow Structure Interaction (FSI) Analysis

The purpose of FSI interpretation is to analyze the causes of the accident at Farley nuclear plant no. 2, where its pipelines were damaged. Through a comprehensive numerical analysis of its designed flow to prevent accidents and stress changes in the pipes based on the operation condition, the causes of the accident can be determined. The numerical analysis was conducted in the transient state [4] and a 3-D analysis was conducted in order to analyze the turbulent flow characteristics [5]. In this study, flow and structural grids were created for the analysis of FSI, and the contact of the two areas was specified as the interface. The temperature resulting from the transient flow analysis was saved in grid per time. The temperature saved in the interface was set to be a boundary condition for structural analysis. The commercial code used for the numerical analysis was ANSYS CFX.

2.2 Boundary Condition of Flow Analysis

To analyze the coolant pipe structure of Farley nuclear power plant no. 2, we used a one-way FSI method. The used grid models were the O-grid and full hexahedral mesh. Through grid optimization, 420,576 grids and 436,506 nodes were used. The forms of the mesh models are shown in Fig. 3. The working fluid in the pipe is steam that satisfies the International Association for the Properties of Water and Steam (IAPWS) IF97. The pressure range is from 1,000 to 30,000 kPa, and the temperature range is from 26.9 to 626.85 ℃. The boundary condition applied to the analysis was the same as the real operational condition of the nuclear power plant. The pressure was 15.5 MPa, the temperature of the RCS pipe was 292 ℃, and the temperature of the safety injection-type pipeline was 49 ℃. To see the vertical temperature variation of the horizontal branch pipe, monitoring points were inserted every 100 mm from sections A to F, as represented in Fig. 4. In the vertical pipeline, sections G and H were set.

One of the main purposes of this analysis is to investigate changing thermal-hydraulic phenomena in the branch pipe according to the flow rate of the leaking flow at the safety injection valve, and the influence of the thermal load occurring in the branch pipe. The leaking flow rate was set to be 31.54, 63.09, 94.63 and 126.18 cm^3/s. Owing to thermal stratification and turbulence penetration, 200 sec (it takes 200 sec for the temperature distribution values to stabilize) was set as the total time for each case. The time step was set at 0.01 sec in the early stage of the numerical analysis to stabilize the program. After a certain period, the time step was increased to 0.1 sec. For conditions such as flow, the operation conditions of the nuclear power plant were used. The conditions are listed in Table 1.

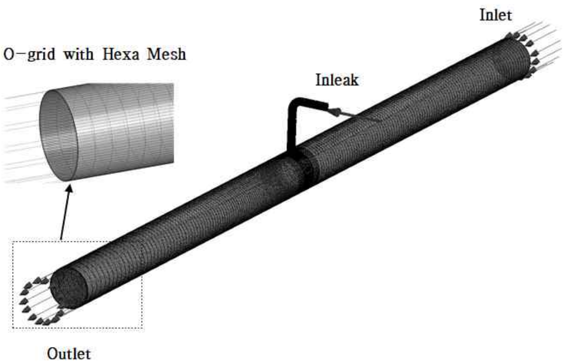


Fig. 3. Mesh model and boundary conditions.

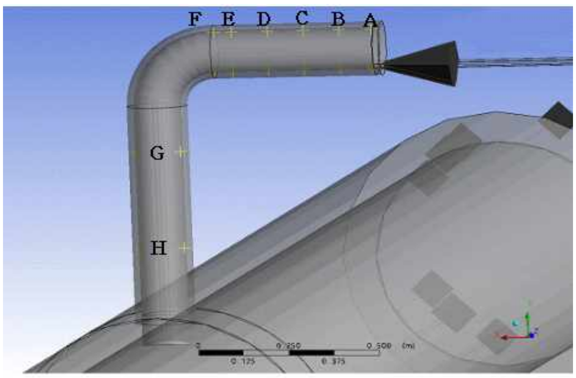


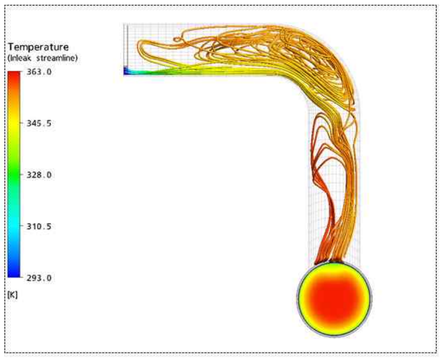
Fig. 4. Monitoring points and sections.

Table 1 FSI conditions for Farley #2 accident case studies

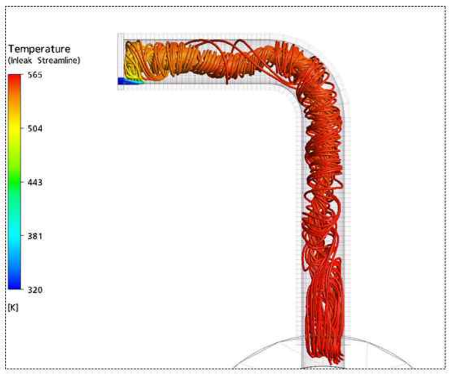
Case	Turbulent Model	Branch pipe condition		Main pipe condition	
		Flow rate [cm^3/s]	Velocity [m/s]	Flow rate [cm^3/s]	Velocity [m/s]
FSI 1	RSM	31.54	0.2052	5.58×10^6	14.59
FSI 2		63.09	0.4104		
FSI 3		94.63	0.6156		
FSI 4		126.18	0.8208		

3. Results and Discussion

The thermal hydraulic phenomena occurring inside the branch pipe are thermal stratification caused by the leakage of the safety injection valve, turbulence energy of the main pipe and thermal swirl in the branch pipe, turbulence penetration and thermal cycling by thermal striping, convective heat transfer between the leakage flow and turbulence penetration flow and heat transfer between working fluid and pipelines. However, as proven in the physical modeling experiment in Fig. 5, thermal striping occurs when the Reynolds number is low, but it is substituted with a thermal swirl in the branch pipe of the RCS line in an environment with a high temperature, high pressure and high Reynolds number. This situation is similar to that of Fraley nuclear plant no. 2. As shown in Fig. 5(b), thermal swirl owing to strong kinetic energy in the main pipe and leakage flow accelerates molecular diffusion and convective heat transfer in an RCS pipe given high Reynolds-number conditions.



(a) Striping swirl



(b) Thermal swirl
Fig. 5. Comparison between striping and thermal swirl.

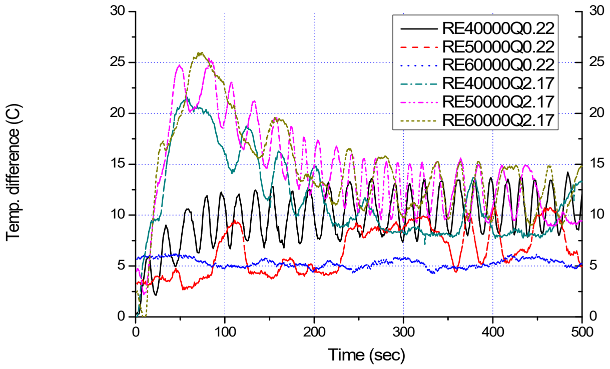
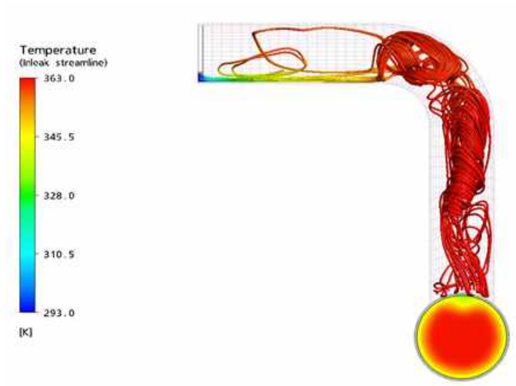
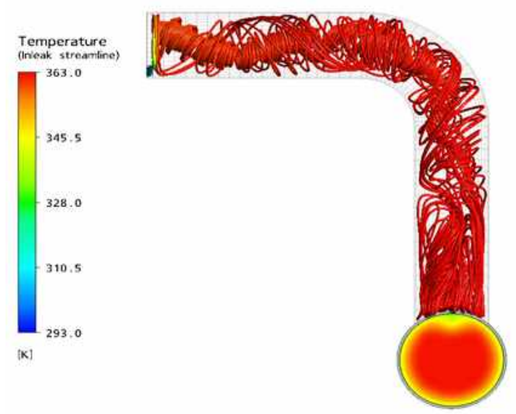


Fig. 6. Comparison of temperature difference at section B.



(a) Re = 5.6×10^5



(b) Re = 1.0×10^6

Fig. 7. Streamlines at Re = 5.6×10^5 and 1.0×10^6.

As shown in the physical modeling experiment of the coolant leakage of a safety injection valve, the larger the turbulence penetration into the branch pipe, the greater the interaction between the leakage fluid and turbulence penetration fluid in the high-Reynolds-number condition. This leads to relatively low temperature fluctuation and no periodic behavior. Fig. 6 shows the measurement results of the temperature distribution of section B according to Reynolds number changes in the main pipe when the leakage flow is 0.22 and 2.17 cm^3/sec. According to the fluid with a high Reynolds number, the turbulence kinetic energy of the main pipe accelerates thermal mixing and heat transfer inside the branch pipe, increasing the temperature inside the branch pipe and dismantling the periodic wave.

In addition, the Reynolds number of the main pipe, which is caused by thermal swirl, is below 1.0×10^6. As shown in Fig. 7, when the Reynolds number is lower than 1.0×10^6, the second wave in the thermal strip occurs in the branch pipe. The reason for thermal swirl in the branch pipe with a high Reynolds number is that the turbulence flow of the main pipe loses its symmetry because of decreasing leakage fluid and creates rotatory power to infiltrate the thermal swirl into the branch pipe.

The thermal swirl delivers thermal energy with high temperature and high-turbulence kinetic energy to the front of the safety injection valve, accelerating mixing between the leakage flow and thermal swirl, thus keeping down thermal stratification.

4. Conclusions

In this study, to find the parameters that affect the thermal stratification that occurs in the cold leg of a safety injection line, numerical study are performed. Thermal-hydraulic phenomena occurring in the branch pipe are thermal stratification, thermal striping, and thermal cycling (TASCS) (which were identified previously); turbulence mixing; and inertia of leakage flow. Because the normal operation condition of the main pipe of an RCS has a Reynolds number over 1.0×10^6, turbulence penetration occurring in the branch pipe mainly appears in the form of thermal swirl rather than thermal striping. And, Thermal swirl occurs by a rotational force created when the leakage flow with a high Reynolds number from the branch pipe loses its symmetry. The rotary motion delivers the high thermal energy and turbulent kinetic energy of the main pipe to the front of the branch pipe.

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