Assessment of Pressure Fluctuation Effect for Thermal Fatigue in a T-junction Using Thermo-Hydro Analysis

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1. Introduction

Recently, thermal fatigue due to mixing of the fluids having different temperatures has been considered as an important issue on the fatigue evaluation of nuclear piping. Mainly, this phenomenon occurs in a T-junction operating with the fluids consisted of different temperatures. Because of the turbulent mixing of hot and cold water, the temperature on the inner wall of the pipe fluctuates rapidly, causing the variation of thermal stresses in the pipe and resulting in high cycle thermal fatigue. In practice, cracking by high cycle thermal fatigue is reported at a T-junction in the residual heat removal system at Civaux unit 1 in France [1].

However, because of irregular flow inside the pipe, the pressure also fluctuates rapidly as well as temperature in the inner wall of the pipe. Therefore, in this paper, three-dimensional thermo-hydro analysis was performed for the mixing tee of the shutdown cooling system of the pressurized water reactor plant, examining the pressure variation at the pipe inner wall. Based on the analysis result, this study aims at assessing the pressure fluctuation effect on the thermal fatigue.

2. Thermo-hydro analysis

2.1 Geometry

The shutdown cooling system is operated to remove the decay heat that is existed in the reactor core during plant shutdown. At this time, the cold water that is passed through the heat exchanger of this system is joined with the hot water as shown in Fig. 1 [2]. The dimensions of the pipe and the flow conditions are summarized in Table I, where D_o and D_i denote outer and inner diameter, respectively. In order to reduce the total time that would be spent for the analysis, the inlet length, which is the distance from mixing point to each inlet, was modeled relatively short compared to the outlet length [3].

2.2 Analysis conditions

Table I: Pipe dimensions and operating conditions [3]

Parameter	Main pipe (Hot water)	Branch pipe (Cold water)
D_o [m]	0.273	0.273
D_i [m]	0.248	0.248
Temperature [°C]	177	60
Mean velocity [m/s]	1.672	3.345

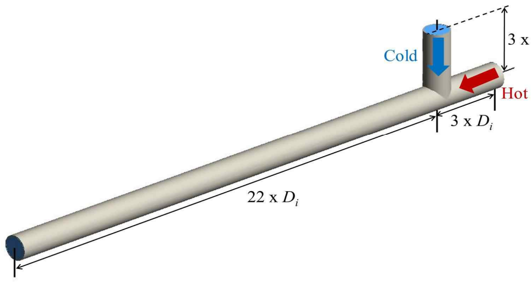

Fig. 1. Geometry for the thermo-hydro analysis

In the present study, Re_{hot_inlet} and Re_{cold_inlet} are about 2,446,348 and 1,756,575, respectively, belonging to the turbulent region. Therefore, a turbulent flow condition was applied for the thermo-hydro analysis, using a detached eddy simulation (DES) turbulence model. The transient analysis was performed for 15 seconds in total with a time step of 0.01 second, using a commercial CFD package, ANSYS CFX ver. 13.0.

In consideration of the fully developed velocity profiles as the inlet boundary condition, one-seventh power law velocity profiles (U) were applied, which is defined as follows.

$$U = U_{bulk}\left(1-\frac{r}{D_i/2}\right)^{1/7} \qquad (1)$$

where, U_{bulk} and D_i denote the mean bulk velocity and the pipe inner diameter, respectively, and r is the distance from the central axis of the pipe in radial direction [4].

The reference pressure of the operating fluid is 6.32 MPa, which is the design pressure for the shutdown cooling system considered in this paper.

2.3 Analysis result

As shown in Fig. 2, there is an irregular flow by the turbulent mixing of hot and cold water, showing the

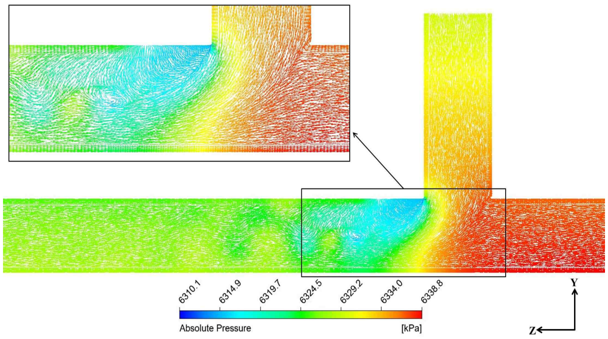

Fig. 2. Instantaneous velocity vector plot at 15.0s, colored by absolute pressure

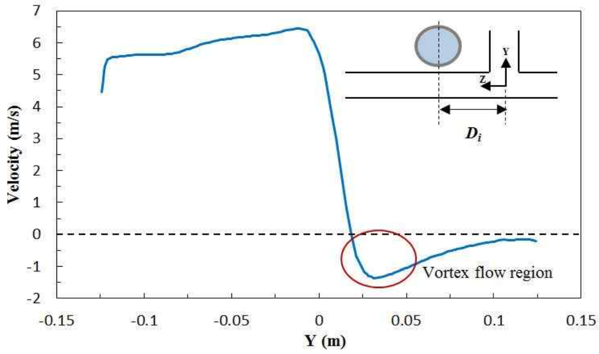

Fig. 3. Velocity profile at 15.0s ($z/D_i = 1$)

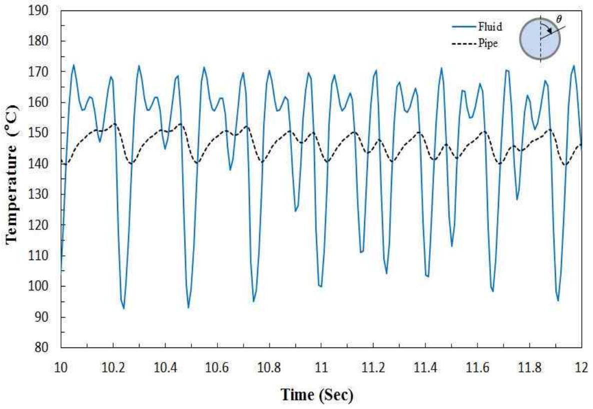

Fig. 4. Temperature fluctuation of fluid and pipe (inner wall of $z/D_i = 3$, θ=315°)

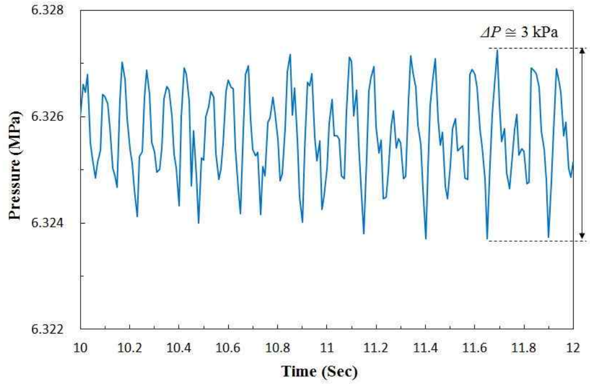

Fig. 5. Pressure fluctuation on the pipe inner wall ($z/D_i = 3$, θ=315°)

vortex immediately after mixing that is generated by flow separation, which usually occurs at the region having discontinuous or large curvature on the surface. It is known that the pressure is relatively lower at the separated region [4]. Fig. 3 shows the velocity profile at D_i away from the mixing point in z-axis direction. From it, negative velocity by the vortex flow can be confirmed.

Fig. 4 shows the temperature histories of fluid and pipe at maximum fluctuation point (z/D_i=3, θ=315°) of the pipe inner wall. Because of irregular flow inside the pipe, temperature is varied rapidly on the pipe inner wall depending on time.

The pressure is also changed on the inner wall of the pipe. Fig. 5 shows the pressure fluctuation at the maximum temperature variation point, showing irregular variation like it was shown in temperature.

However, the amplitude of pressure fluctuation is only about 3 kPa, which is relatively small, about 0.05% of the design pressure, compared to 6.32 MPa. Therefore, even though there is pressure fluctuation on the pipe inner wall, because the magnitude of the amplitude is very small compared to the design pressure, the effect would be insignificant when evaluating thermal fatigue.

3. Conclusions

In this paper, it is verified that there is pressure fluctuation as well as temperature on the inner wall of mixing tee operating with the fluids having different temperatures. However, since the amplitude of pressure is relatively smaller than design pressure of the shutdown cooling system, the effect wouldn't be important for the thermal fatigue. As a result, when evaluating thermal fatigue for the mixing tee, temperature fluctuation is dominant for this phenomenon, it can be reasonably assumed that the pressure is constant on the pipe inner wall.

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