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NUMERICAL ANALYSIS OF THERMAL STRIPING INDUCED TRANSIENT TEMPERATURE DISTRIBUTION INSIDE CENTRAL COLUMN STRUCTURE

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ABSTRACT

The thermal striping can generate fast random temperature fluctuation in fluid and will transfer it to structure. It will induce high cycle thermal fatigue in several components particularly in central column and should be concerned is for Sodium Cooled Fast Reactor(SFR). However, the recent research focus on the flow and temperature characteristics of fluid. The transient temperature distribution inside the solid structure is not comprehensive enough, which is important for analyzing cyclical thermal stresses and eventually the fatigue cracks of structure. In this study, coaxial jet model and large eddy simulation(LES) were used to simulate the fluid flow of upper plenum of SFR. The transient temperature distribution inside structure were studied by Heat-fluid-solid coupling analysis. The results show that thermal fluid-solid coupling simulation is feasible and accurate to analyze the temperature distribution of structure. The temperature fluctuation from the fluid to the structure surface is significantly attenuated. It can only be transferred to limited depth inside the structure. The results contribute to the high frequency thermal fatigue life prediction of nuclear component.

Keywords: thermal striping, transient temperature, large eddy simulation, coaxial jet model, central column

1. INTRODUCTION

During the operation of the nuclear reactor, due to the difference in coolant temperatures flowing through the different fuel rod, the temperature in upper plenum will fluctuate, which is thermal striping. It will induce alternating thermal stress and fatigue damage inside the adjacent component structure[1]. Equipment fatigue failure events due to thermal striping in various types of nuclear power plants around the world are not uncommon[2].

At present, most studies are devoted to the description of the fluid field and the analysis of the cause of the thermal striping. The fluid temperature fluctuations phenomenon in the reactor upper plenum can be simplified into a two-dimensional model[3]. In the case of parallel jets, jets are close to each other and two side jets alternately invade the central jet, causing the intermediate positions of the different jets to be alternately occupied by fluids of different temperatures, causing thermal striping. However, some scholars believe that the thermal striping in the upper plenum is a three-dimensional phenomenon[4,5], which is simplified into a coaxial injection model, and the three-dimensional temperature fluctuations characteristics and its influencing factors are analyzed.

The fluid is in contact with the component. The temperature of the fluid is transferred to the surface and inside of the structure under thermal striping, causing continuous changes of the structure temperature. The transfer of temperature from the fluid to the structure is usually accompanied by attenuation of the amplitude of the temperature fluctuation and delay of the phase. Wakamatsu et al [6] first used water and liquid sodium to experimentally study the attenuation characteristics of temperature fluctuations[7]. Subsequent studies have further refined the attenuation rate of temperature fluctuations by simulation and experiment[7]. However, the transient temperature distribution inside the solid structure is not comprehensive enough especially in coaxial jet model, which is important for analyzing cyclical thermal stresses and eventually the fatigue cracks of structure.

In this study, coaxial jet model and large eddy simulation(LES) were used to simulate the fluid flow of upper plenum. The surface and interior transient temperature distribution inside structure with different fluid velocity were studied by Heat-fluid-solid coupling analysis. Furthermore, the distribution and attenuation characteristics of the transient temperature were analyzed.

2. SIMULATION APPROACH

2.1 Numerical method

In this paper, the CFD software FLUENT is used to simulate the thermal striping phenomenon, which can simulate the fluid flow and the coupled heat conduction between the fluid and the solid structure. There have been many simulation methods, such as Reynolds equation (RNS) and large eddy simulation (LES) for numerical simulation of thermal oscillations in recent years. However RNS has limited success in predicting the thermal–hydraulic characteristics of the thermal striping. LES is a more accurate method to simulate thermal stripping. LES is a three-dimensional, time-dependent turbulence model. A filtering operation is applied to the Navier–Stokes equations to decompose the parameter into a filtered component and a residual component.

In LES, the Smagorinsky-Lilly model was used to calculate Sub-grid-scale (SGS) model stress tensor. In the Smagorinsky-Lilly model, the eddy-viscosity is expressed as follow:

$$\tau_{ij} = -2\mu_t \bar{S}_{ij} + \frac{1}{3}\tau_{kk}\delta_{ij}$$

in which, μ_t is the turbulent viscosity, modeled as $\mu_t = \rho L_S^2 |\bar{S}|$. $|\bar{S}|$ is the resolved strain rate defined as $|\bar{S}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ji}}$. The mixing length for sub-grid scales $L_s = \min(\kappa d, C_S V^{1/3})$, constant $C_S = 0.1$, κ is the von Karman constant equal to 0.42.

The rate-of-strain tensor for the resolved scale$\bar{S}_{ij}$ is defined as Eq.(5):

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

Finally, the sub-grid turbulent heat flux is calculated from the simple gradient diffusion hypothesis as

$$\bar{\tau}_{\theta i} = -\frac{v_l}{Pr_t}\frac{\partial \bar{T}}{\partial x_i}$$

In which, the value of Prandtl numberPr_t is 0.85.

2.2 Physical model

In this paper, a coaxial jet model was based on Cao Q [4] and then it was improved. In order to study the effect of thermal striping on the solid structure, a plate structure was placed above the jet with a thickness of 20 mm. The center circular area is the cold fluid inlet and the surrounding annular circular area is the hot fluid inlet as shown in Fig.1. A tetrahedral unstructured mesh is used with the number of cell approximately 2.6 million.

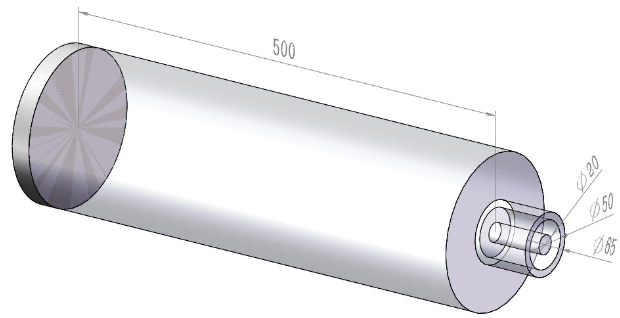

Fig 1 Physical model

2.3 Boundary condition

The inlet boundary conditions using velocity-inlet. The temperature difference between hot and cold fluid is 30K. Fluid medium is water.

	Velocity(m/s)		Temperature(k)	
	cold	hot	cold	hot
Case1	10	10	298.15	328.15
Case2	5	5	298.15	328.15

2.4 Date processing method

The temperature is normalized by the following equation:

$$T^* = \frac{T - T_{cold}}{T_{hot} - T_{cold}}$$

where T^* is normalized temperature at a given location. T_{hot} and T_{cold} are the temperature of inlet hot and cold fluids, respectively. The normalized mean temperature is calculated as follow:

$$\overline{T^*} = \frac{1}{N}\sum_{i=1}^{n} T^*$$

In order to characterize the time-averaged temperature fluctuation intensity, the normalized fluctuating temperature is defined as the root-mean square of temperature measurements:

$$T^*_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(T^*_i - \overline{T^*}\right)^2}$$

3. RESULT AND DISCUSSION

3.1 Temperature field

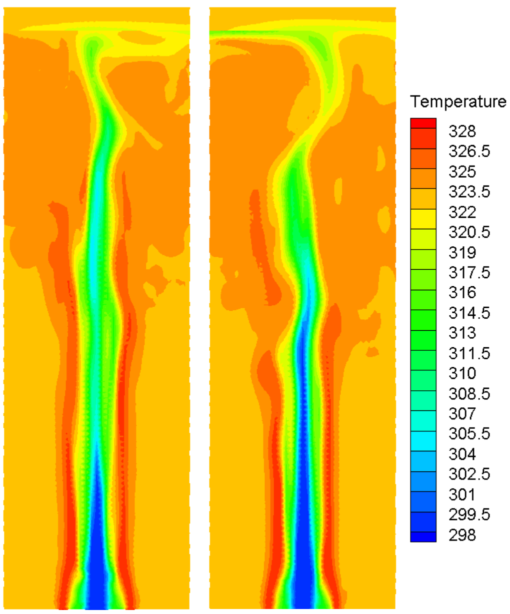

Fig 2 The temperature field for case 1 in vertical cross

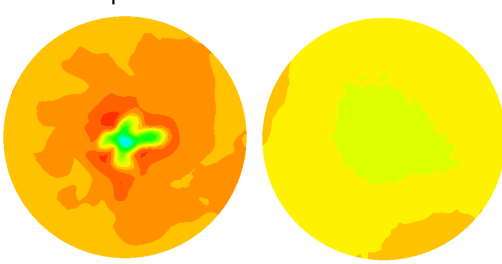

Fig 3 The temperature distribution inside the plate structure

The temperature field distribution of the fluid and structure are shown in Fig.1. The hot fluid approaches the center of the cold fluid and gradually mixes around the fluid inlet area. The jet movement over time is found in the area close to the structure surface, resulting in temperature constantly changes in the surface of the structure, which is the cause of the thermal striping. The presence of the plate structure makes the jet more steady than a jet without a solid structure.

Fig.3 shows the temperature distribution in the fluid and the surface of plate structure. The temperature distribution of the structure surface is asymmetrical.

3.2 Transient temperature

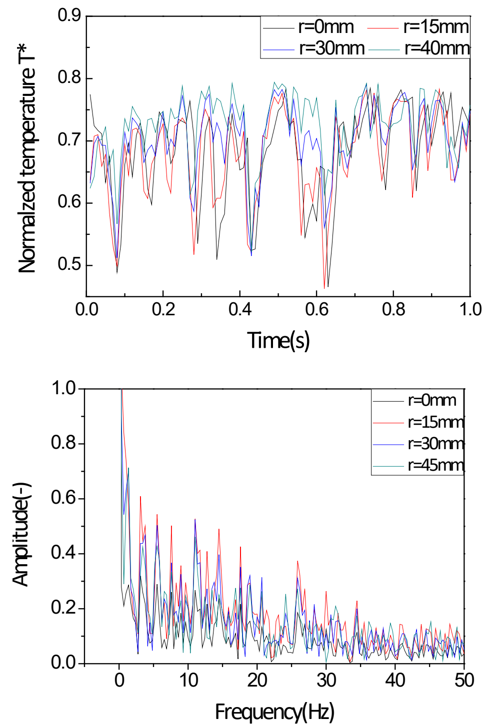

Fig 4 Normalized temperaure and frequency domains at the surface of structure for case1 along radial direction

The normalized temperature at different point on the surface of structure are shown in Fig.4. Temperature fluctuations causing by thermal striping with time are random, and the average temperature and temperature fluctuation amplitude are different at different points. For different inlet velocity, as the speed increases, the position of the fluid mixing zone increases, and the temperature fluctuation of the structural surface is more severe at higher velocity (Fig.5). Amplitude and frequency of temperature fluctuation were obtained by Fast Fourier Transform (FFT). There is a temperature fluctuation amplitude peak about 4Hz, which can cause more severe fatigue damage.

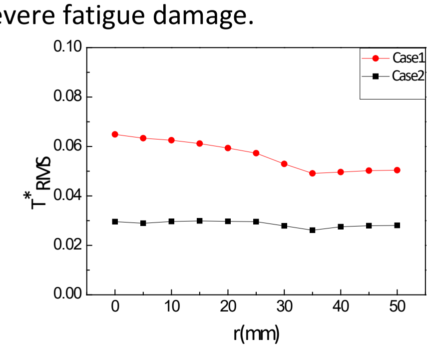

Fig 5 Normalized fluctuating temperature at the surface of structure along radial direction

In order to find the point where the temperature fluctuation is the most severe, the temperature fluctuation intensity of each point is analyzed in Fig.5. It is found that the temperature fluctuation for case1 at the position of r=0 is the most severe.

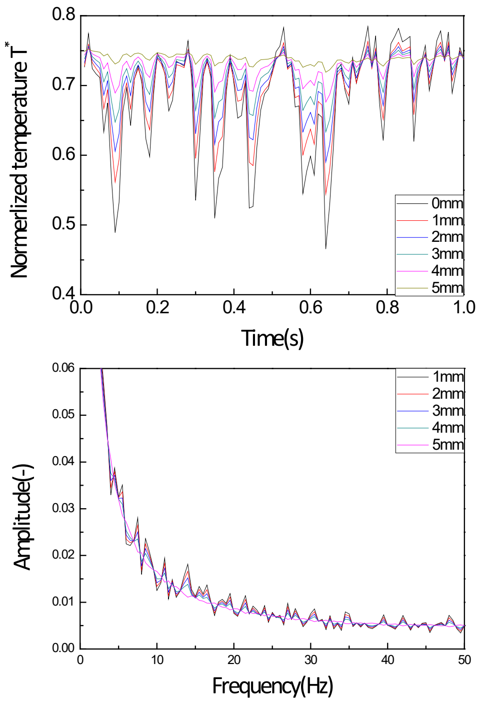

Fig 6 Normalized temperaure and frequency domains inside structure for case1 in r=0 along thickness direction

Take the point where the temperature fluctuation is the most severe as an example. Normalized transient temperature in structure surface and interior is demonstrated in Fig.6. As the depth increases, the temperature fluctuation amplitude decreases sharply. The transferred depth of thermal striping is about 5mm. Comparing the temperature fluctuation amplitude and frequency at different depths in the same position, it can be found that the high-frequency temperature fluctuations decay quickly, and the low-frequency temperature fluctuations have stronger penetration.

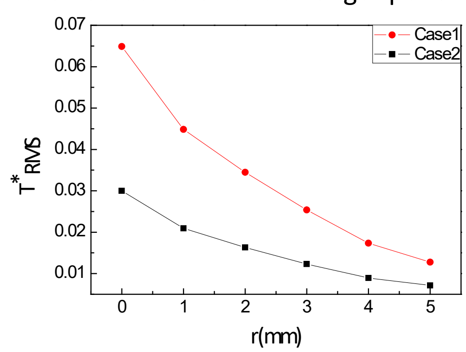

Fig 7 Normalized fluctuating temperature inside structure along thickness direction

Fig 7 shows the averaged temperature fluctuation intensity of the surface and interior of the structure. Thermal striping is significantly attenuated as the fluid is transferred to the surface of the structure. At a depth of 5 mm, the temperature fluctuation intensity drops to 15% of the flow field close to the structure.

4. CONCLUSIONS

The temperature fluctuations caused by thermal striping are completely random on structure surface. There is a temperature fluctuation amplitude peak about 4Hz, which can cause more severe fatigue damage. The temperature fluctuation intensity from the fluid to the structure is significantly attenuated. The thermal striping can only be transferred to limited depth about 5mm inside the structure in case1, in where the normalized fluctuating temperature is about 15% of the fluid close to the structure.

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