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Experimental Investigation of Temperature Fluctuation Characteristics Associated with Thermal Striping Phenomena

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ABSTRACT

Thermal striping is a phenomenon that the temperature constantly changes of the fluid and the contact solid structure, due to the mixing of fluids with different temperatures. When thermal striping occurs above the core of a nuclear reactor, it usually leads to fatigue failure of the solid structure near the center column. Existing research mainly focuses on the mixing phenomenon of different temperature fluids and temperature fluctuations in fluid by using CFD simulations. However, the experimental study on the temperature fluctuation characteristics of the surface and interior of the structure is limited. In this study, a thermal striping experiment setup based on coaxial jet is design and built. The temperature of the plate structure surface and interior was measured when cold and hot fluids were mixed in coaxial jet. The temperature distribution and fluctuation characteristics associated with thermal striping phenomena was analyzed.

Keywords: thermal striping, temperature response, coaxial jet, temperature fluctuation

NONMENCLATURE

Symbols	
n	Year
A_0	Exponential function coefficient
d	Depth, mm
f	Frequency
h	Plate height, mm
r	Radius, mm
r^*	Normalized radius
r_{Cold}	Inlet radius of cold fluid, mm
R_0	Exponential function coefficient
T	Temperature, ℃
T_{Cold}	Inlet temperature of cold fluid, ℃
T_{Hot}	Inlet temperature of hot fluid, ℃
T^*	Normalized temperature
T^*_{avg}	Normalized mean temperature
v	Flow velocity, m/s

1. INTRODUCTION

During the operation of nuclear reactors, due to the uneven temperature of fluids, for instance, mixing fluid streams with different temperatures, alternating thermal stress, and severe fatigue damage may be caused in the adjacent structure[1]. This phenomenon, defined as thermal striping, is pronounced at the upper plenum of nuclear reactors[2], pipe elbow[3], and T-junction[4]. At the upper plenum, due to the distribution characteristics of the core assemblies, there are many fuel assemblies around each control rod assembly at different distances. At the same time, the coolant flow of each channel around the fuel assembly is not always consistent. It leads to a different temperature profile of the coolant in each channel, resulting in thermal striping[5]. The most of previous research on temperature fluctuation induced by coaxial-jet was limited to the fluid field. However, this change will also be transferred to the adjacent solid structures, resulting in temperature fluctuations in solid structures[6]. On the other hand, a plate in the fluid also makes the flow field change. Therefore, to understand the mechanism of thermal stripping, it is imperative to study the temperature response of the flow field and structure surface caused by the coaxial-jet flow with a solid structure through experiment.

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In this study, the thermal striping phenomenon induced by the coaxial-jet was studied by experimental setup. The temperature of the plate structure surface and interior was measured when cold and hot fluids were mixed with coaxial jet. The temperature distribution and fluctuation characteristics associated with thermal striping phenomena was analyzed.

2. EXPERIMENT SETUP

2.1 *Experiment equipment*

The equipment can realize the measurement of fluid and structure surface temperature with different flow rates, different heights. The equipment consists of a hot fluid system, a cold fluid system, a mixing system, and a measurement system, as shown in Fig. 1

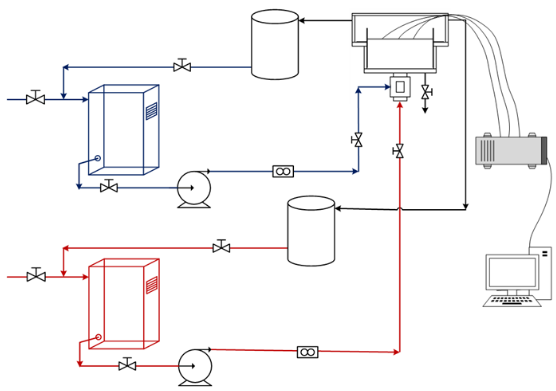

Fig. 1. Experimental equipment schematic

The cold (hot) fluid system provides fluid for the mixing system and controls parameters such as fluid temperature and flow rate. It also can recycle the mixed fluid. The mixing system provides coaxial jet and mixing space of the hot and cold fluids. The measurement system collects the temperature of the fluid and the surface of the structure in the thermal striping area through the thermocouples. The devices are connected by pipes, and there is a thermal insulation layer outside the pipes.

2.2 *Experiment scheme*

During the experiment, the temperature of the upper surface of the structure with different thicknesses is used to replace the temperature at a same depth inside the plate. Thermocouples are attached to the surface of the plate structure to achieve temperature testing. And the plate structure is fixed by a detachable bracket. The test points are arranged every 5mm to the left and right sides from the corresponding position of the center of the cold fluid, a total of 13 test points, as shown in Fig. 2. In order to exclude the influence of the fluid on the upper side, a thick layer of high-temperature glue is covered on the surface of the thermocouple when measuring the temperature of the plate upper surface. This allows the thermocouple to only be in contact with the metal plate structure and not the upper fluid.

The plate size is 100mm×100mm, and the thickness is 0.5mm,1mm and 2mm respectively. Its material is stainless steel 316, of which the density is 7.98g/cm^3, thermal conductivity is 15.1W/(m·K), and specific heat capacity is 0.502J/(g·K).

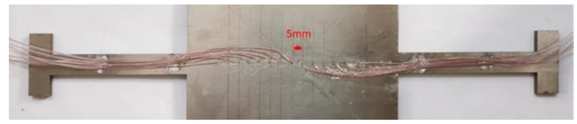

Fig. 2. Measuring points on the plate surface structure

The flow velocity *v* is 0.5m/s for all test cases. The plate height *h* is 30mm. The cold and hot water temperatures are set at 20°C and 40°C, respectively. The temperature sampling time interval is 0.01s, and the measurement time of a single test is about 180s. The experiment conditions are shown in Table 1.

Table 1 experiment conditions

	Height h (mm)	Depth *d* (mm)	Hot Tempe rature (℃)	Cold Tempe rature (℃)	Velo city (m/s)
Case 1	30	/	40	20	0.5
Case 2	30	0.5	40	20	0.5
Case 3	30	1	40	20	0.5
Case 4	30	2	40	20	0.5

2.3 *Date processing methods*

For the convenience of discussion, the temperature and radius in the text are expressed in normalization. The normalized temperature is:

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

Among them, T_{Cold} and T_{Hot} are the inlet temperature of cold fluid and hot fluid, and the average value measured by the test points of the inlet is adopted.

The normalized mean temperature is:

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

The normalized radius is the ratio of the radius to the cold fluid inlet radius:

$$r^* = \frac{r}{r_{Cold}}$$

where r_{Cold} is the cold fluid inlet which radius is 5mm.

3. RESULT AND DISCUSSION

3.1 Average temperature distribution

Compare the lower surface of the structure and at different depths. The temperature at different depths of the structure is shown in Fig. 3. The average temperature change is similar to the lower surface. And it shows that the plate structure height plays a decisive role in the distribution of normalized average temperature. At the center, the temperature increases with depth. This may be due to the good thermal conductivity of the metal plate, so the temperature distribution gradually becomes uniform with increasing depth.

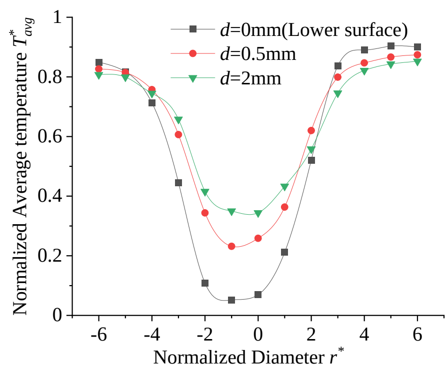

Fig. 3 Normalized average temperature on the lower surface and depth d=0.5mm,1mm and 2mm

3.2 Transient temperature response

The transient temperature of the different depths is shown in Fig. 4. It can be found that the frequency of temperature fluctuations inside structure is significantly

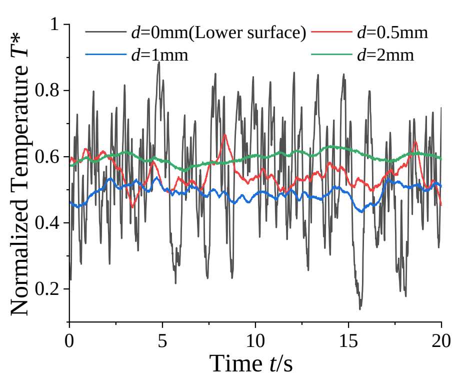

Fig. 4 The transient temperature of different depth at r*=2

reduced. The amplitude of temperature fluctuation decreases obviously with the increase of depth, and the decrease is the fastest from the lower surface to the depth *d*=0.5mm. As the depth increases, the location of the most severe temperature fluctuations is hardly changed. In the case of the plate structure height *h*=30mm, it is always at *r**=2.

In order to analyze the transient temperature response on the structural surface. More measurement points are arranged on the lower surface of the plate structure to analyze the causes of transient temperature changes. The cause of temperature fluctuation can be analyzed by the transient temperature distribution on the plate surface at different times, shown in Fig.5. Firstly, the cold fluid will expand and contract with time. For example, the cold fluid expands during 0.5-0.8s and contracts during 0.8-1.1s. Secondly, the jet center will swing with time. At 0.1s, the center of the cold fluid is at *r**=0. At 0.4s, the center moves downward. At 0.9s, the cold fluid center appears on the left. Finally, the shape of the jet will also change significantly. Sometimes, the temperature distribution on the plate surface presents a relatively regular circle. Sometimes, it will extend in different directions, such as 0s, 0.3s and0.6s. Most of the time, the shape of the jet is not very regular. Under the joint influence of these three factors, the temperature of each point on the plate surface fluctuated.

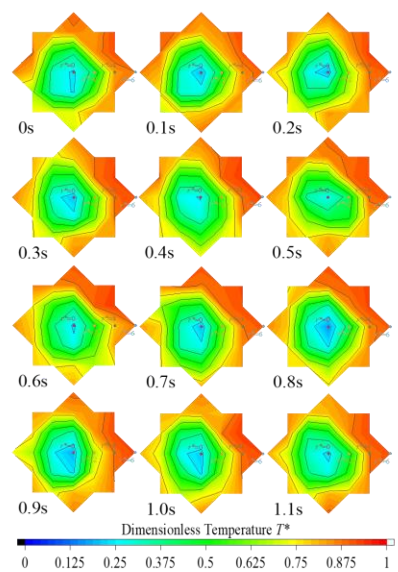

Fig. 5 The transient temperature distribution on the plate lower surface

3.3 Frequency domain response

In order to study the relationship between the amplitude and frequency of temperature fluctuations introduced by thermal striping, a large number of experimental samples were measured to statistically analyze their spectral relationships. The frequency domain of temperature fluctuations with different depth is shown in Fig. 6.

The temperature fluctuation amplitude is more severe in the frequency range and the temperature fluctuation in the low frequency range. The amplitude with different depths all shows an exponential form decay with increasing frequency. The temperature fluctuations amplitude can be fitted in an exponential form as:

$$A=A_0\exp(R_0 f)$$

where A is the amplitude of temperature fluctuation, f is the frequency. Comparing the fitting functions of the plate surface and depth h=0.5mm, 1mm, and 2mm, it can be found that the exponential function coefficient R_0 continuously decreases. This indicates that the temperature fluctuations amplitude decreases faster with depth. This also indicates that the deeper the depth, the smaller the frequency range of temperature fluctuation distribution. High frequency temperature fluctuations are difficult to transmit to the interior of the structure. A_0 continuously decreases with depth h, indicating that the amplitude decreases with depth h. And the higher the height, the lower the average amplitude.

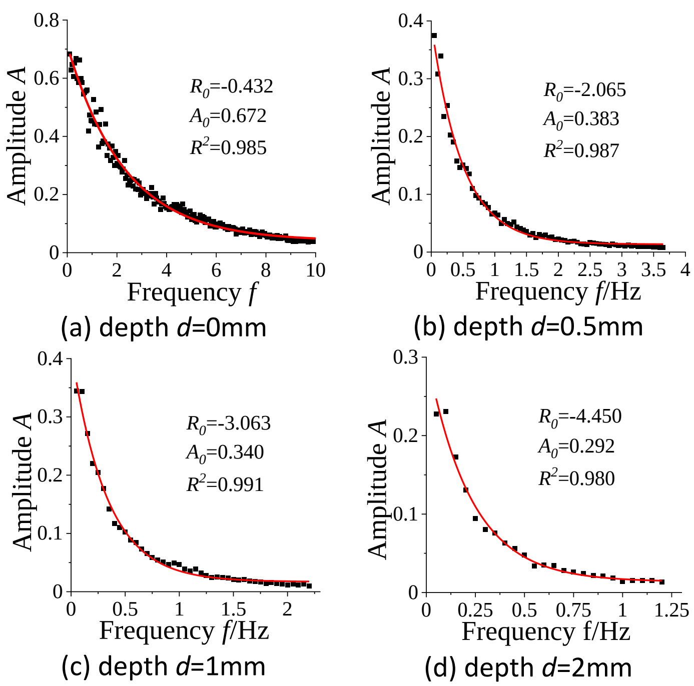

Fig. 6 Frequency domain with the lower surface and depth d=0.5mm, 1mm and 2mm

4. CONCLUSIONS

In this study, plate surface and interior temperature fluctuation is experimentally investigated with a setup based on the coaxial-jet model. The temperature distribution and fluctuation characteristics of the surface and interior of the structure was studied. The following conclusions can be drawn from the study.

(1) The average temperature at different depth change with radius is similar to the lower surface. The temperature distribution gradually becomes uniform with increasing depth.

(2) The amplitude of temperature fluctuation decreases obviously with the increase of depth. The fundamental reason for the temperature change on the plate surface is the instability of the jet.

(3) The amplitude of temperature fluctuations at different depths show an exponential form decay with increasing frequency. High frequency temperature fluctuations are difficult to transmit to the interior of the structure.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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