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Temperature fluctuation caused by coaxial-jet flow: Experiments on the effect of the velocity ratio $R \geqslant 1$

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HIGHLIGHTS

- The effect on temperature fluctuation from velocity ratio was studied by experiment.
- The distribution of time-averaged temperatures is the axial-symmetry in $R \geqslant 1$.
- The region of intense temperature fluctuation in $R = 1$ is different from that of $R > 1$.
- The intensity of temperature fluctuation under $R > 1$ is weaker than that of $R = 1$.

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ABSTRACT

The temperature fluctuation appears in the core outlet region due to the different of the temperature and velocity of the coolant, which can cause thermal stresses and the high-cycle thermal fatigue on solid boundaries. So, it is necessary to analyze the characteristics of the temperature fluctuation. In the present study, a comparative experiment was performed to analyze the effect on the temperature fluctuation caused by the coaxial-jet flow from the inlet cold and hot fluid velocity ratios ($R \geqslant 1$). In the condition of $R \geqslant 1$, the distribution of the time-averaged temperature is the axial-symmetry. In the cold fluid field, the temperature field is divided into four parts, including the first steady region, linear region, nonlinear region and the second steady region along the axial direction, while that is lack of the first steady state region in the hot fluid field. In the condition of $R = 1$, due to the velocity of the cold fluid is equivalent to that of the hot fluid, the cold fluid flow can be severely disturbed by the hot flow. The intense temperature fluctuation mainly distributed in the annular region at bottom region and the circular region in the upper region. While, in the condition of $R > 1$, the inertia of the cold fluid is larger than that of the hot fluid. The hot fluid will attach itself to the periphery of the cold fluid. The intense temperature fluctuation distributed in the annular region between the cold and hot fluid and the periphery of the hot fluid. However, the intensity of temperature fluctuation under $R > 1$ is weaker than that of $R = 1$.

1. Introduction

In the nuclear reactor, the distribution of the core power and the coolant flow are not completely uniform. Therefore, the temperature and velocity of the coolant out of different channels in the core may be different. The mixing flow of high and low temperature coolants may cause the temperature fluctuation of the coolant in the upper plenum, which may not only affect the temperature measurement of the core, but also cause the high-cycle thermal fatigue of the structures exposed to such temperature fluctuation. Generally, due to the large temperature difference in the core outlet region and the large thermal conductivity of the liquid metal sodium, the effect of the temperature fluctuation in upper plenum is more serious in the sodium-cooled fast reactor than the other water-cooled reactor (Tenchine et al., 2013). However, the uneven velocities of the coolant always affect the intensity and distribution of the temperature fluctuation. So, the effect of the cold and hot fluid velocity ratio on the temperature fluctuation caused by the coaxial-jet flow will be concerned in this paper.

Generally, research on the temperature fluctuation focus on fluid region, solid region and the coupling region of fluid and solid. In the fluid region, the temperature and velocity parameters were used to analyze the distribution and intensity of temperature fluctuation with experiment or simulation, which provide preliminary

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Nomenclature

r	position in radial direction (mm)
z	position in height direction (mm)
v	velocity (m/s)
t	time (s)
T	fluid temperature (°C)
T_c	inlet cold fluid temperature (°C)
T_h	inlet hot fluid temperature (°C)
$\triangle T_{hc}$	inlet cold and hot temperature difference (°C)
T_{avg}	average temperature (°C)
T_i^*	normalized temperature
T_{avg}^*	normalized average temperature
T_{RMS}^*	normalized RMS temperature
z^*	normalized height
r^*	normalized radius
D	the hydraulic diameter of inlet nozzles
R	the inlet cold and hot fluid velocity ratio
Greek symbols	
θ	position in azimuths counter-clockwise direction (°)
φ	diameter (mm)
Abbreviation	
TB	thermocouple-bridge
LES	large eddy simulation
PSD	power spectral density

thermal hydraulics data for the next step. Kimura et al. (2010a) carried out an experiment to study the temperature of the fluid in T-pipe junction with upstream elbow. The flow patterns and the PSD of temperature fluctuation were obtained to evaluate the high cycle thermal fatigue in the next step. Meanwhile, a large number of numerical simulation have been performed to calculate temperature fluctuation of the fluid. Tanaka et al. (2008) simulated temperature and velocity distributions in T-Junction piping system with LES approach. Howard and Serre (2015a) studied the mixing and thermal fluctuations induced in a mixing tee junction with circular cross-sections. In order to reduce the damage of temperature fluctuation, Lu et al. (2010) added a porous media in a mixing tee. In the solid region, in order to analyze thermal stress caused by fluid temperature fluctuation, Kasahara et al. (2002) developed a structural response function approach to predict stress amplitudes on structural surfaces from fluid temperature amplitudes and frequencies. Lejeail and Kasahara (2005) also derive a thermal fatigue evaluation method for temperature and fatigue evaluation of tubes and plates. With the development of computer technology, several research works were concerned with the coupled heat transfer from the fluid to the solid with the temperature fluctuation. Timperi (2014) studied a turbulent mixing of hot and cold water in a T-junction with LES method including conjugate heat transfer. Selvam et al. (2015b) also analyze thermal mixing of the fluids in in a T-junction with conjugate heat transfer.

In order to study the temperature fluctuation caused by the cold and hot coolant out of the core in a reactor, the simple models were used to simulate this situation. Generally, these classic structures include the parallel triple-jet model and coaxial-jet model. Tokuhiro and Kimura (1999) perform a water experiment to study a mixing phenomenon caused by the parallel triple-jet flow. The distribution characteristics of the temperature and velocity were obtained based on measuring instrument. Then, Nishimura et al. (2000) simulated the thermal mixing of the cold and hot fluids in the parallel triple-jet with the low Reynolds number turbulent stress and heat flux equation model, while large eddy simulation method was also used to simulate temperature fluctuation caused by the parallel triple-jet flow (Cao et al., 2012). The transient flow fields and PSD of temperature fluctuation were obtained to analyze the distribution of the amplitude and frequency of the temperature fluctuation. However, compared to the parallel triple-jet flows, the coaxial-jet flows are so similar to the flow situation in the upper plenum of the core in a reactor, where the cold flow out of the channels near the control rod is surrounded by the hot flow out of the channels near the fuel elements.

Tenchine and Moro (1997) carried out the experimental and numerical investigations on the mixing of the cold and hot fluids caused by the coaxial-jet flow using the liquid sodium and air as working fluids. The effect on the thermal mixing from different fluids was analyzed to predict the condition of the air instead of the sodium. Lu et al. (2012) performed an experiment to analyze the mixing process of the coaxial-jet cold and hot fluid flows based on the time and space distribution of the fluid parameters under the inlet velocity ratio of the cold and hot fluid $R = 1$.

In the present study, we also performed a water experiment in the coaxial-jet flows with 3D oscillatory quantities configured as a central cold jet and an outer hot jet with different inlet velocity ratio of the cold and hot fluid. Measured velocity and temperature parameters were used to compare the distribution characteristics under the condition $R \geqslant 1$.

2. Experiment

2.1. Test section

The test section is a cylinder with the diameter, $\varphi = 500$ mm, and the height, $z = 700$ mm, as shown in Fig. 1. It contains two

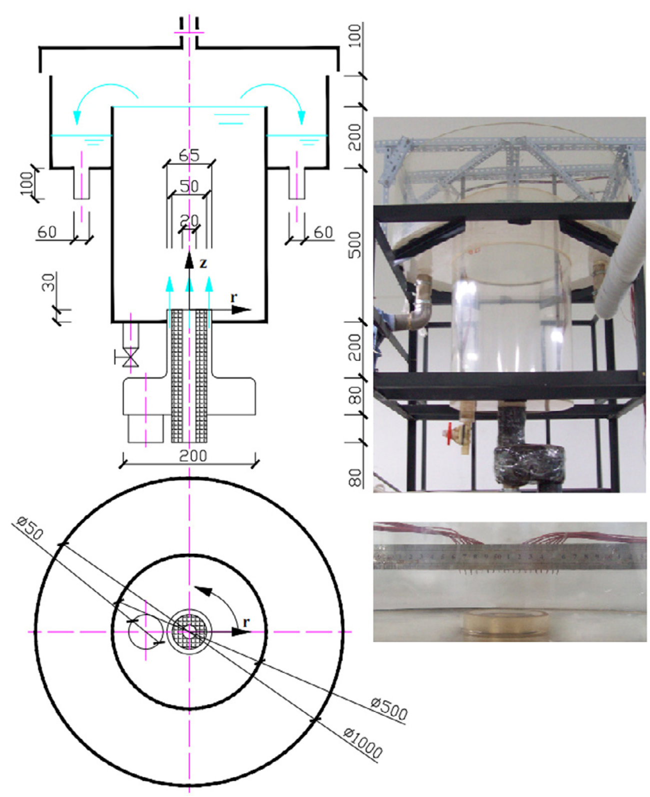

Fig. 1. Schematic of the test section.