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Technical Note

Experimental investigation on transfer characteristics of temperature fluctuation from liquid sodium to wall in parallel triple-jet

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Abstract

A quantitative evaluation on thermal striping, in which temperature fluctuation due to convective mixing causes thermal fatigue in structural components, is of importance for integrity of nuclear reactors and also general plants. Sodium cooled fast reactor had also several incidents of coolant leakage due to the high cycle thermal fatigue. A sodium experiment of parallel triple-jet configuration was performed to evaluate transfer characteristics of temperature fluctuation from fluid to structure. The non-stationary heat transfer characteristics could be represented by a heat transfer coefficient, which was constant in time and independent of the frequency of temperature fluctuation.

Keywords: Sodium cooled fast reactor; Temperature fluctuation; Thermal striping; Heat transfer; Transfer function

1. Introduction

In nuclear reactors and general plants, temperature fluctuation occurs in the region where hot and cold fluids are mixed. The temperature fluctuation may cause structural components high cycle thermal fatigue, i.e., thermal striping. In fast reactors, liquid metal sodium is used as the coolant and it has the high thermal conductivity. The thermal striping as a phenomenological problem in liquid metal cooled fast reactors was already recognized in the early 1980s by Wood [1], Brunings [2] and has subsequently been studied by Betts et al. [3], Moriya et al. [4], Muramatsu [5] and Tokuhiro et al. [6]. The structural failures due to the high cycle thermal fatigue have occurred not only in the liquid metal cooled fast reactors but also in light water reactors and various general plants (Japanese PWR Tomari-2 in 2003, French PWR CIVAUX in 1998, and so on).

The thermal striping phenomena could be divided into five processes; (1) occurrence of temperature fluctuation due to the convective mixing between hot and cold fluids, (2) attenuation of temperature fluctuation in the boundary layer near the structure, (3) heat transfer from the fluid to the structure, (4) thermal conduction in structure and (5) thermal fatigue in structure. As for thermal hydraulic behavior in the thermal striping phenomena, Tenchine et al. [7,8] investigated the mixing of co-axial jets of sodium and compared the results of sodium with those of air. Tokuhiro et al. [9,10] and Kimura et al. [11,12] have performed a water experiment in parallel triple-jet and evaluated the mixing process among the jets. Igarashi et al. [13,14] has carried out a water experiment with T-pipe configuration and classified flow regimes into three flow patterns dependent on the momentum ratio of the inlet velocities between the main and branch pipes. As for the numerical investigation, Muramatsu [15] has developed numerical methods to evaluate thermal hydraulics and heat transfer from fluid to structure. As for studies on the structure, Wu and Janne Carlsson [16] evaluated the

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Nomenclature

A	amplitude of temperature fluctuation
a	thermal diffusivity
Bi	Biot number
D	representative length
D_e	hydraulic diameter
F	Fourier transform of temperature fluctuation
f	frequency of temperature fluctuation
H	transfer function
h	heat transfer coefficient
N	number of experimental data
Nu	Nusselt number
P	power spectrum density
Re	Reynolds number
T	temperature
T^*_{avg}	normalized time-averaged temperature
T^*_{RMS}	normalized temperature fluctuation intensity (root-mean-square of temperature fluctuation)
t	time
V	discharged velocity
x	horizontal axis along the structural wall
y	axis normal to the structural wall
z	vertical axis along the structural wall
ΔT	temperature difference
ε	phase
φ	phase of temperature fluctuation
λ	thermal conductivity
ω	angular velocity
ξ	distance between two positions

Subscripts

c	cold jet
f	fluid
h	hot jet
w	wall

distribution of the thermal stress in a structural plate and Kasahara et al. [17,18] developed the structural response diagram dependent on the frequency of temperature fluctuation in the fluid on the assumption of connection between fluid and structure via a heat transfer coefficient, which is constant in time. When the transfer of temperature fluctuation from fluid to structure is evaluated, it is of importance to determine the heat transfer coefficient. When the wall is insulated at the boundary except for one boundary where the temperature fluctuation is transferred, the time-averaged heat flux at the wall surface is nearly equal to zero. Therefore, the heat transfer coefficient can not be obtained from the time-averaged heat flux. Choe and Kwong [19] predicted the wall temperature using a convolution integral of fluid temperature. In Choe's study, the heat transfer coefficient was adequately given by the trial-and-error method.

In order to estimate the thermal striping, the processes (2)–(4) are significant on the point of the attenuation of temperature fluctuations. The quantitative evaluation of the attenuation makes it possible to design the legitimate structure in the plants with its integrity. However, there are few studies, which use liquid metal as a working fluid. In addition, it is needed to acquire the heat transfer coefficient deterministically.

In this study, we performed a sodium experiment in the triple-parallel jets along a stainless steel wall. The triple jets were configured as a cold jet in the center and hot jets in both sides. This geometry corresponds to a simplified two dimensional configuration of reactor core outlet which has cold flow channels of control rods surrounded with hot channels of fuel subassemblies. The authors have already carried out the water experiment of the triple-parallel jets [11,12]. Then the velocity and temperature fields were well understood in the triple jets. For the transfer of temperature fluctuation from fluid to structure, we developed how to acquire the time-constant heat transfer coefficient deterministically and we verified that the heat transfer coefficient was appropriate for the thermal stress.

2. Experiment

2.1. Experimental apparatus

Fig. 1 shows the schematic of the test section and thermocouples arrangement in a thermocouple-tree and a test plate. Each of the discharged nozzles had a shape of rectangular 20 mm × 180 mm. The height of the nozzles from the bottom was 85 mm and the both sides of the nozzle blocks had slopes. Three porous plates and the quadrant reducer nozzle were set upstream of the each nozzle. Fig. 2 shows the time-averaged velocity distribution at 0.1 mm from the nozzle exit obtained from the water experiment with the same nozzle geometry as the sodium experiment. The spatial-averaged velocity at the nozzle was 0.5 m/s. The local velocity was measured by the particle image velocimetry [20]. The velocity distribution at the nozzle exit showed the flat profile overall. Therefore, we made an assumption that the discharged velocity profile at the nozzle outlet could be flat in the sodium experiment. The cold jet flowed out vertically in the center and the hot jets flowed out in both sides of the cold jet. The nozzles and mixing region were sandwiched by the two vertical plates. Thus, three jets flow along the walls and the temperature fluctuation in the fluid is transferred to the plates. As for the coordinates, x-axis is horizontal direction along the wall surface, y-axis is normal direction