Study on Convective Mixing for Thermal Striping Phenomena*
(Experimental Analyses on Mixing Process in Parallel Triple-Jet and Comparisons between Numerical Methods)

Nobuyuki KIMURA**, Motohiko NISHIMURA*** and Hideki KAMIDE**

A quantitative evaluation on the thermal striping, in which temperature fluctuation due to convective mixing imposes thermal fatigue on structures, is of importance for reactor safety. As for convective mixing, a water experiment was performed on vertical, parallel triple-jet: a cold jet at the center and hot jets in both sides. Three kinds of calculations based on the finite difference method for the experiment were carried out. Two types of turbulence models were used in the calculations, namely $k$-$\varepsilon$ two-equation turbulence model ($k$-$\varepsilon$ Model) and low Reynolds number turbulence stress and heat flux equation models (LRSFM). Furthermore, a quasi-direct numerical simulation (DNS) was performed. The DNS could simulate the time-averaged temperature field. The prominent frequency in temperature fluctuation obtained by the LRSFM was in good agreement with that in the experiment. The profile of power spectrum density of temperature fluctuations calculated by the DNS was close to the experimental results.

Key Words: Oscillatory Flow, Numerical Analysis, Jet, Turbulent Mixing, Direct Numerical Simulation

1. Introduction

In reactors, fluid which flows out of each subassembly (e.g. fuel subassemblies, control rod channels, blanket subassemblies) has so different temperature that mixing of fluid results in temperature fluctuation. The high thermal conductivity of sodium coolant in fast reactors transports temperature fluctuation well from flow to structural surfaces. Temperature fluctuation transferred to the structure causes high cycle thermal fatigue in structural materials. These phenomena are called thermal striping.

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(3), Moriya(4), Muramatsu(5) and Tokuhiro(6).

The processes of thermal striping are categorized as follows: 1) Occurrence of temperature fluctuation in fluid, 2) Attenuation of temperature fluctuation near structural surface, 3) Transfer of temperature fluctuation from fluid to structural surface, 4) Transfer of temperature fluctuation from structural surface to inside of structure and 5) Occurrence of thermal stress that may contribute initiation of a crack.

As for studies on thermal hydraulic behavior of the thermal striping, co-axial jets of sodium were investigated by Tenchine and Nam(7) while Tenchine and Moro(8) compared the results of sodium with air jets experiments. Muramatsu(9) has developed numerical methods to evaluate thermal hydraulics and heat transfer from fluid to structure.

Tokuhiro and Kimura(10) carried out a water experiment with vertical, parallel triple-jet configuration and evaluated the effects of discharged
velocities and temperature difference on the convective mixing among the jets using ultrasound Doppler velocimetry and thermocouples. Also Nishimura[11] simulated the mixing behavior of the oscillatory triple-jet using low Reynolds number turbulence stress and heat flux equation models (LRSFM)[12].

In this study, we performed three kinds of numerical analyses based on the finite difference method for a water experiment with the triple-jet configuration. First two methods used the turbulence models; $k$-$\varepsilon$ two-equation turbulence model and the LRSFM. Another computation is a quasi-direct numerical simulation. The experimental result was compared with the analyses using three different numerical methods. And the capability of these three methods for the convective mixing in the triple-jet was evaluated.

2. Experiment

Figure 1 shows an experimental test section. Discharged nozzle of the jets are immersed inside the test section. As noted in the top view, two partition plates sandwich four rectangular blocks, thereby restricting the flow of the discharged jets in these directions. The rectangular blocks and plates defined three discharged nozzles. The size of each nozzle is $20 \times 169$ mm. The representative length ($D$) is $20$ mm in the nozzle width. The center jet has lower temperature than the jets in both sides. Local temperatures are measured by a movable thermocouple (T/C) tree that consists of $39$ T/Cs facing vertically downward and horizontally spaced $5$ mm apart over a $190$ mm span. Each T/C is installed in a stainless steel tube of $1.0$ mm in diameter and the $5$ mm tip of the T/C is directly exposed to the flow. The T/Cs are JIS K-type ($0.3$ mm in diameter) with measurement error of $0.1^\circ$C. The local temperatures in the test section were measured by moving the T/C tree in each $10$ mm vertically. The sampling interval at each measured point was $0.02$ s and the number of the data ($N$) was $1,024$ (total of $20,48$ s).

In the experiment, the discharged velocities in the triple jets were equally $0.5$ m/s ($V_{in}$). The discharged temperatures of the hot jets in both sides were $21^\circ$C ($T_h$) and the one of the cold jet at the center was $26^\circ$C ($T_c$). The discharged temperature difference between the hot and the cold jets was $5^\circ$C ($\Delta T$).

3. Calculations

Numerical analyses based on the finite difference method were carried out using three kinds of mathematical models. The first two are the unsteady Reynolds averaged Navier–Stokes (URANS) computations, i.e. $k$-$\varepsilon$ two-equation turbulence model ($k$-$\varepsilon$ Model) and low Reynolds number turbulence stress and heat flux equation models (LRSFM)[12]. The third one is a quasi-direct numerical simulation (DNS), which does not use any turbulence model. Two in-house codes were applied: CASCADE[12] for the URANS computations and DINUS-3[13] for the DNS. Table 1 shows the numerical methods used in these codes.

Figure 2 shows the calculated domain and boundary conditions in the test section. The horizontal length contains the four rectangular blocks and edge blocks with arc, the vertical length is $540$ mm from the top of discharged nozzles. Typical width of the mesh is $2$ mm. In the calculation using the LRSFM, the width of the nearest mesh from structural surface is $0.2$ mm so as to non-dimensional distance from the surface ($y^+$) less than five[13]. As for the depth direc-

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Table 1 Numerical methods used in the codes

<table>
<thead>
<tr>
<th>Numerical Codes</th>
<th>CASCADE</th>
<th>DINUS-3</th>
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</thead>
<tbody>
<tr>
<td>Turbulence model</td>
<td>$k$-$\varepsilon$ Model</td>
<td>LRSFM</td>
</tr>
<tr>
<td>Coordinate</td>
<td>Cartesian Coordinate</td>
<td></td>
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<tr>
<td>Discretization</td>
<td>Finite Difference Method</td>
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<td>Time Integration</td>
<td>Euler (1st order)</td>
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<td>Convective term</td>
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<td>Diffusion term</td>
<td>Central (2nd order)</td>
<td>Central (2nd order)</td>
</tr>
<tr>
<td>Solution algorithm</td>
<td>SIMPLE/ANL</td>
<td>Leap/Frog</td>
</tr>
<tr>
<td>Matrix solver</td>
<td>MOCG</td>
<td>IOCG</td>
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tion, the numbers of meshes are one for the URANS computations (the $k$-$\varepsilon$ Model and the LRSFM), and three in the DNS to avoid accumulation of turbulence energy in depth direction.

As for the boundary conditions, each jet has uniform temperature at the discharged nozzle. Profiles of velocity and turbulence quantities at the inlet boundary are determined based on the preliminary analyses picking up a part of discharged nozzle. The velocity at the outflow boundary is determined to satisfy the mass conservation law. In these calculations, the upper and the side boundaries are set up as the outlet boundary. Therefore, the numerical divergence easily breaks out. To avoid diverging, the meshes facing the outflow boundary have solid faces perpendicular to the outlet surface like a straightener, which guides the flow to be normal to the boundary surface. One mesh has only one face of outlet boundary in CASCADE and DINUS-3 codes. Thus dummy cells are set up at the edge of the topside in the calculated domain. Temperatures at the boundaries are set at flow rate weighted average temperature between the hot and the cold jets. The surface frictions are set as a non-slip condition at the top of four blocks and as a slip condition at the edge blocks and the dummy meshes at the edges.

Time step widths of all calculations were 0.001 s. In the calculations using the $k$-$\varepsilon$ Model and the LRSFM, the simulated times were 3 and 10 s respectively. In the DNS, the simulated time was the same as the experiment (20.48 s) to well reproduce random fluctuations as seen in the experiment.

4. Results and Discussions

4.1 Visualized images

Figure 3 shows the visualized images in the experiment and the contours of instantaneous temperature profiles in the calculations. Temperature was normalized by the following equation;

$$T^* = \frac{T - T_0}{\Delta T},$$

where $T$ was a measured temperature and $T^*$ was a normalized temperature.

The visualized images showed that the hot jets were rolled-up and alternately mixed with the cold jet via the oscillatory motion. In the calculated result using the $k$-$\varepsilon$ Model, the mixing motion with fluid roll-up was not seen, though the jets slightly oscillated. The calculation using the LRSFM and the DNS, on the other hand, reproduced the oscillation of the hot and the cold jets observed in the experiment.

4.2 Comparisons of time-averaged temperature fields

Figure 4 shows the contours of the time-averaged temperature and the temperature fluctuation intensity.
Comparisons of contours of time-averaged temperature fields

The origin is at the centerline of the cold jet nozzle horizontally and at the top of the discharged nozzle blocks vertically. The horizontal (x) and vertical (z) positions are represented by the experimental length (D=20 mm) of the discharged nozzle. In the experiment and the DNS, the temperature fluctuation intensity, $T_{\text{rms}}$, is defined as a root-mean-square of the instantaneous temperature as follows:

$$T_{\text{rms}} = \sqrt{\frac{\sum (t_i - \overline{T})^2}{N}}.$$  

In the URANS calculations, on the other hand, the total temperature fluctuation intensity is defined as a summation of the temperature fluctuation intensities due to flow instability and turbulence. The intensity due to flow instability was obtained from the temperature variation in the transient calculation, while the intensity due to turbulence was obtained from the turbulent quantity conservation equation for $t'\overline{t'}$. Thereby the total temperature fluctuation intensity is acquired as follows.

It is assumed that an instantaneous temperature, $T$, is decomposed as follows:

$$T = T_{\text{avg}} + \overline{t} + t',$$  

where, $T_{\text{avg}}$ is the time-averaged temperature, $\overline{t}$ is a fluctuating component with lower frequency due to flow instability and $t'$ is a turbulence component with higher frequency.

Substitution of Eq.(3) into Eq.(2) brings:

$$T_{\text{rms}} = \sqrt{\frac{\sum (\overline{t} + t')^2}{N}}.$$  

Equation (2) is multiplied by itself and expanded,

$$T_{\text{rms}}^2 = \frac{1}{N} [\sum \overline{t}^2 + 2 \sum \overline{t}t' + \sum t'^2].$$  

Root-mean-squares of $\overline{t}$ and $t'$ are as follows:

$$\overline{t}_{\text{rms}} = \sqrt{\frac{\sum \overline{t}^2}{N}},$$  

$$t'_{\text{rms}} = \sqrt{\frac{\sum t'^2}{N}}.$$  

Equations (6) and (7) are substituted into Eq. (5).

$$T_{\text{rms}}^2 = \overline{t}_{\text{rms}}^2 + 2 \overline{tt'} + t'_{\text{rms}}^2.$$  

Here, $\overline{tt'}$ means the correlation between flow instability and turbulence in the temperature fluctuation. The correlation though equals zero because characteristic time scales of two fluctuating components are quite different (Reynolds and Hussain[14]). Then, Eq.(8) is approximated as follows:

$$T_{\text{rms}} = \sqrt{T_{\text{rms}}^2 + t'_{\text{rms}}^2}.$$  

Thus the temperature fluctuation intensity could be obtained from the two fluctuating components.

The normalized temperature fluctuation intensity is as follows:

$$T_{\text{rms}}^* = \frac{T_{\text{rms}}}{\Delta T}.$$  

From the contours of the time-averaged temperature, the temperature profile became uniform at $z/D \geq 10$ in the experiment. In the calculations using the $k-\varepsilon$ Model and the LRSFM, however, hot fluid portion was retained downstream, and the temperature fields were different from the experimental result at $z/D \geq 12.5$. In the DNS, temperature field was in good agreement with that in the experiment.

In the experiment, the temperature fluctuation intensity was large at $z/D = 3.5 - 7.5$ vertically and in the region between the hot and the cold jets horizontally. In the calculation using the $k-\varepsilon$ Model, temperature fluctuation intensity was larger at the neighborhood of the discharged nozzles and high intensity region was kept further downstream than the experimental result. In the calculation using the LRSFM, the temperature fluctuation intensity was evaluated well near the discharged nozzle and was more similar to the experimental one than in the $k-\varepsilon$ Model. And the potential cores of the hot jets, in which temperature was the same as the discharged temperature and temperature fluctuation intensity was nearly zero, obtained from the $k-\varepsilon$ Model and the LRSFM were extended downstream in comparison to the experimental result. In the calculation using the DNS, on the other hand, the temperature fluctuation intensity
field was in good agreement with that in the experiment.

Figure 5 shows the comparisons of the time-averaged temperature distributions in horizontal direction between the experiment and the numerical results. The vertical positions are $z/D=5$ and $z/D=7.5$ corresponding to the region with high temperature fluctuation intensity. At $z/D=5$, in the calculations using the $k-\varepsilon$ Model and the LRSFM, the horizontal positions of high temperature regions (around $x/D=\pm 1.8$, corresponding to the hot jets) were slightly close to cold jet in comparison to the experiment. And the cold jet (around $x/D=0.0$ in these cases) maintained the discharged temperature. Thus, the horizontal temperature gradients in the region between the hot and the cold jets calculated by the $k-\varepsilon$ Model and the LRSFM were larger than the experimental result. At $z/D=7.5$, the temperature around the center predicted with the LRSFM was in better agreement with the experimental result in comparison to the $k-\varepsilon$ Model due to well simulation of mixing behavior with roll-up. The calculated temperature at $x/D=0.0$ using the LRSFM was slightly higher than in the surrounding positions because the hot fluid branches stretching from the hot jets in both sides reached $x/D=0.0$ (the center in the cold jet) as shown in Fig. 3. The DNS could evaluate the experimental profiles of temperature well at both heights.

Figure 6 shows the comparisons of the temperature fluctuation intensity distributions in horizontal direction between the experimental and numerical results. The vertical positions are $z/D=5$ and $z/D=7.5$. The peak positions of the intensity obtained from the $k-\varepsilon$ Model, the LRSFM and the DNS were close to the experimental result. In the URANS calculations, the maximum temperature fluctuation intensities were overestimated, and the temperature fluctuation intensities at $x/D=0.0$ were underestimated in comparison to the experiment at $z/D=5$. And the calculated intensities with the $k-\varepsilon$ Model and the LRSFM retained high value at $z/D=7.5$. In the calculation using the DNS, the calculated temperature fluctuation intensity was in good agreement with the experimental result.

4.3 Comparisons of temperature fluctuation characteristics

Figure 7 shows the comparisons of the time
trends of temperature between the experimental and the numerical results. The measured position is $z/D=5$ vertically and $x/D=0.0$ (the center of the cold jet), 0.75 (the position between the hot and the cold jets) and 2.25 (the inner edge of the hot jet) horizontally. In the experiment, temperatures fluctuated periodically at $x/D=0.0$ and $z/D=0.75$. At $x/D=2.25$, the time trend of temperature intermittently showed lower temperature. In the calculation using the $k$-$\varepsilon$ Model, the amplitudes of temperature fluctuations were smaller than the experimental results at every position. It was shown in the visualized images that the calculation using the $k$-$\varepsilon$ Model could not reproduce the oscillation of the jets observed in the experiment. It is believed that the large amplitude of temperature fluctuations is caused by the oscillation of the jets which promoted the mixing of the hot and the cold jets. Thus, the numerical method using the $k$-$\varepsilon$ Model could not reproduce the temperature fluctuation characteristics. In the calculation using the LRSFM, the period and the wave form of temperature fluctuation were similar to the experimental results at $x/D=0.75$ where the temperature fluctuation intensity was high. At $x/D=0.0$ and $x/D=2.25$, however, the numerical result obtained from the LRSFM kept a nearly constant temperature. The numerical result obtained from the DNS, on the other hand, was similar to the experimental one though the calculated temperature had fluctuating components with high frequency in comparison to the experimental result. In particular, the DNS could reproduce the intermittent fluctuation surprisingly well which was seen in the experiment at $x/D=0.0$ and $x/D=2.25$.

When we compare the power spectrum density of temperature fluctuation, a time constant of the thermocouple should be considered. Artificial time delay was added to the calculated time trend of temperature to compare with the thermocouple data. A first-order delay is assumed to simulate the time delay of thermocouple as follows:

$$
T_n = T_{n-1} - \frac{T_n - T_{n-1}}{t_n - t_{n-1}} + \left( T_{n-1} - T_{n-1} \right) \exp \left( -\frac{t_n - t_{n-1}}{\tau} \right),
$$

where $t_n$ is a measured time, $T_n$ a measured temperature obtained from the thermocouple, $T_n'$ a revised temperature taking account of the first-order delay in the thermocouple, and $\tau$ a time constant of the thermocouple.

The numerical results were converted by applying Eq. (11). Here, it was assumed that the time constant ($\tau$) of the thermocouple of 0.3 mm in diameter used in the experiment was 0.02 s.

Figure 8 shows the comparisons of the power spectrum densities in temperature fluctuations between the experimental and the numerical results. The measured positions are the same as the positions in Fig. 7.

The prominent frequency was seen only at $x/D=0.75$ in the experiment where temperature fluctuation intensity was high due to the oscillation of the jets. The power spectrum density obtained from the LRSFM could reproduce this prominent frequency (2.3 Hz). The prominent frequencies obtained from the $k$-$\varepsilon$ Model and the DNS had lower power than in the experiment. The prominent frequency shifted to the lower component in the $k$-$\varepsilon$ Model and to the higher component in the DNS than in the experimental result. The high frequency components ($>3$ Hz) obtained from the $k$-$\varepsilon$ Model and the LRSFM had the lower powers than the experiment. Overall profile of the power spectrum density with the DNS was in good agreement with the experimental data.

As for the other position, $x/D=0.0$ and 2.25, it was shown that the power spectrum densities obtained from the DNS were in good agreements with the experimental results.

5. Conclusions

The experimental and the numerical investigations were performed to clarify mixing characteristics in thermal striping phenomena. In the experiment with quasi-planar vertical triple-jet configuration, special temporal behavior of the triple-jet was grasped by traversing the thermocouple tree. And the numerical simulation were carried out using thermal-hydraulic analysis codes based on the finite difference method. Two turbulence models were applied; the $k$-$\varepsilon$ two-equation turbulence model ($k$-$\varepsilon$ Model) and the
with respect to the oscillatory behavior.

2) The temperature fluctuation intensities obtained from the $k$-$\omega$ Model and the LRSFM were overestimated and the high intensities were retained downstream in comparison to the experimental result. On the other hand, the intensity obtained from the DNS was in good agreement with the experiment.

3) The time trends of temperature obtained from the LRSFM and the DNS could simulate the coherent fluctuation observed in the experiment. As for the intermittent temperature fluctuation observed at the center of the cold jet and at the inner edge of the hot jet, the result obtained from the DNS showed similar trend to the experiment.

4) The prominent frequency component due to the coherent oscillation of the jets could be predicted by the calculation using the LRSFM. The power spectrum density profiles of temperature fluctuations calculated with the DNS were in good agreements with the experiment.

It was shown that the DNS could simulate overall mixing phenomena of the multiple-jet in general while the LRSFM was capable of predicting the coherent motion in convective mixing due to flow instability.

**Acknowledgements**

The authors appreciate Dr. T. Muramatsu of Japan Nuclear Cycle Development Institute for useful discussion about numerical simulation and Prof. A. Tokuihiro of University Missouri-Rolla for his technical advice. In addition, the authors are grateful to Mr. Y. Miyake for his support in performing the calculations and to Mr. M. Itoh and Mr. Onuma for their technical and engineering supports in the experiment.

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