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Experimental Results of Turbulent Thermal Mixing Phenomena Using Sodium Parallel Jets

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Abstract

In the present the mean temperature and the temperature fluctuation of non-isothermal parallel liquid sodium jets were measured and analyzed changing the temperature difference and mean velocity of the hot and cold sodium. The sampling frequency and sampling time were 420Hz and three seconds, respectively. The wave-form characteristics were discussed in regard to the peak-to-peak amplitudes and the periods provided by a wave analysis. And also the correlations of the temperature fluctuation in rms value and the peak amplitude are derived. The overall mean accuracy ratios of the correlations are 1.07 and 1.08 with a standard deviation of 0.17 and 0.15, respectively.

1. Introduction

In an Advanced Liquid Metal Reactor(ALMR), jet flows of the liquid sodium coolant, flowing out from various positions of a core, have large temperature differences, i.e. around 150℃. Accordingly there is a possibility that large temperature fluctuations would occur in the jet flow and it could cause thermal fatigue on the surfaces of Upper Internal Structures(UIS). Thus it is important to estimate the characteristics of the temperature fluctuation to design UIS and to determine other flow conditions.

The characteristics of thermal striping in ALMR have generally been estimated from model tests, using sodium as a working fluid, because of various uncertainties regarding the temperature fluctuation phenomena. The results of experimental studies has been reported by K.E. Kasza and W.S. Colwell[1] in 180° inlet-leg angle pipe tee thermal mixers, C. Betts et al.[2] in PFR(Prototype Fast Reactor) scale model tests, M. Wakamatsu et al.[3], S. Ushijima et al.[4], and S. Moriya et al.[5] in coaxial jet tests, which compared sodium tests with water or air tests. They have been studied the effects of working fluids on temperature fluctuation phenomena due to turbulence mixing in mixing tee or non-isothermal coaxial jets.

In the present study temperature measurements were performed and analyzed in parallel non-isothermal jets using liquid sodium changing the temperature difference between hot and cold sodium and the mean velocity of the liquid sodium. The experimental facility used in the present study is the Sodium Thermal Hydraulic Test Facility(THTF)[6] which is composed of hot and cold sodium loops. All the experiments were carried out under the equal velocity condition of hot and cold sodium. The temperature sampling frequency and duration were 420Hz and 3 seconds, respectively. The wave-form characteristics were discussed in regard to the peak-to-peak amplitudes and the periods provided by a wave analysis, using zero-up-crossing method. And also the correlations of the temperature fluctuation in rms value and the peak amplitude are derived.

2. Experiments

2.1 Experimental Facility and Measuring Methods

The schematic diagram of the experimental facility used in the present study is shown in Fig.1. The flow system of the THTF[6] in Korea Atomic Energy Research Institute(KAERI) is composed of hot and cold sodium loops. Temperatures of the liquid sodium supplied to the test sections are kept constant with the power regulating system for the main heater and cooler in the loops. And the flow rates of the liquid sodium are controlled by two electromagnetic pumps.

The hot and cold parallel jets are formed in the stainless steel rectangular nozzles within the test section shown in Fig.2. The cross section of the rectangular nozzle is 5mm×50mm and the top of the nozzles are located 100mm above the bottom surface of the test section tank. Two nozzles are thermally insulated with ceramic fiber 3mm thick to prevent the heat transport between hot and cold sodium. The hot and cold sodium from the jet nozzles are mixed in the test section tank and then transported to the mixing tank through 1¼ inch outlet line pipes located 600mm above the bottom surface.

The temperature fluctuations of the liquid sodium were measured using K-type thermocouples. The 43 thermocouples were located in the thermocouple-comb at regular intervals of 5mm to measure the temperature fluctuations radially. And the thermocouple-comb could be moved up and down to measure the temperature fluctuation axially. The output voltages from the thermocouples were converted to temperatures and recorded on magnetic hard drive of workstation. The sampling frequency and duration were 420Hz and 3 seconds, respectively.

2.2 Experimental Conditions

All of the experiments were carried out under the condition of $v_1=v_2$ and the range of $2.6\times10^4 \leq Re \leq 6.6\times10^4$ and $20℃ \leq \Delta T \leq 100℃$. The v_1 and v_2 represent the velocity of the hot and cold liquid sodium at the outlet of the nozzles, respectively. And ΔT represents the temperature difference between hot and cold liquid sodium. The temperature fluctuations are measured at the height of 10, 20, 30, 40 and 50cm above the nozzles. Therefore, we obtained 100 sets of temperature fluctuation raw data from this experiment.

3. Experimental Results and Discussion

3.1 Average Temperature

In the case of v=1.0m/sec the dimensionless average temperature distribution is shown in Fig.3 and is defined as follows;

$T^* = (T - T_{mean}) / \Delta T$

where $\Delta T = T_{hot} - T_{cold}$.

In the case of h=10cm the T^* distributions with temperature difference ΔT have same shape and follows the general tendency. As shown in the figure the maximum and minimum values of T^* are approximately ±0.25 at $R \fallingdotseq \pm 1.5$cm in the case of h=10cm. And the average temperature values have a tendency to asymptote to the bulk mean temperature of the liquid sodium in the range of $|R| \geq 5$cm.

However, the absolute maximum and minimum values of T^* decrease with increasing axial height. The absolute values are 0.25, 0.1 and 0.05 in the case of h=10, 20 and over 30cm, respectively. From the figure the T^* distribution seems to be flattened in the range of $h \geq 30$cm.

3.2 Temperature Fluctuation

The temperature fluctuations at the centerline of the parallel jets are shown in Fig.4 in the case of $\Delta T = 100$℃ as an example. As shown in the figures the amplitude of the temperature fluctuation decreases with increasing the axial height and increases with increasing the temperature difference. The detailed analysis about the peak amplitude of the temperature fluctuation is described next section.

3.2.1 Comparison of the Temperature Fluctuation in rms Values

The maximum values of θ_{rms} appear at the centerline and increase with increasing ΔT. At the centerline the gradient of the average temperature is maximum so that θ_{rms} is biggest in that region. In the same manner with the average temperature distribution, the θ_{rms} tends to asymptote to the background level in the range of $|R| \geq 5$cm. The temperature fluctuation in rms values at the centerline are figured in Fig.5. In Fig.5 the variation of the rms values at v=1.0m/sec are presented. The symbols of θ_{rms} and θ^*_{rms} mean the rms value of temperature fluctuation and dimensionless rms value, respectively. The θ^*_{rms} is defined as follows:

$\theta^*_{rms} = \theta_{rms} / \Delta T$

From the figure and table the θ_{rms} decreases with increasing the height and increases linearly with increasing the temperature difference. However the liquid velocity seems to have little effect on the θ_{rms} in this experiment, i.e., in the range of $2.6 \times 10^4 \leq Re \leq 6.6 \times 10^4$. From the experimental data the θ_{rms} correlation is derived as follows;

$$\theta_{rms} = 0.5 + (0.0408 - 0.00135 \cdot h + 1.286 \times 10^{5} \cdot h^2) \cdot T \qquad (1)$$

The above correlation is applicable to sodium in the range of $10 \leq h \leq 50$cm, $20℃ \leq \Delta T \leq 100℃$ and $2.6 \times 10^4 \leq Re \leq 6.6 \times 10^4$. This correlation accuracy is evaluated and the overall mean accuracy ratio of the present correlation for 80 data points is 1.07, with a standard deviation of 0.174.

3.2.2 Peak Amplitudes and Periods of Temperature Fluctuation

In order to estimate the thermal fatigue damage due to thermal striping, it is necessary to examine the characteristics of the peak amplitudes and periods of temperature fluctuation. The peak amplitudes and periods of temperature fluctuation at the centerline are calculated based on the zero-up-crossing method. As an example the variations of peak amplitude at the centerline at v=1.0m/sec are shown in Fig.6. Generally the peak amplitude increases with decreasing the axial height and increasing the temperature difference. And also it seems to increase slightly with increasing the liquid velocity. From the experimental data the correlation of the peak amplitude is derived as follows;

$$A = \{1.0 + (0.1 - 0.00328 \cdot h + 3.21 \times 10^{-5} \cdot h^2) \cdot T\} \{0.783 + 0.234 \cdot v\} \qquad (2)$$

The above correlation is applicable to sodium in the range of $10 \leq h \leq 50$cm, $20℃ \leq \Delta T \leq 100℃$ and $2.6 \times 10^4 \leq Re \leq 6.6 \times 10^4$. This correlation accuracy is evaluated and the overall mean accuracy ratio of the present correlation for 80 data points is 1.08, with a standard deviation of 0.150. A visual comparison of the predicted and experimental peak amplitude is presented in Fig.7.

4. Conclusions

In the present study temperature measurements were made and analyzed in non-isothermal parallel jets using liquid sodium. From the experiments conclusions are as follows:

① The average temperature distributions follow the general tendency and they have a tendency to asymptote to the bulk mean temperature in the range of $|R| \geq 5$cm. The absolute maximum and minimum values of T^* decrease with increasing axial height and it seems to be flattened in the range of $h \geq 30$.

② The temperature fluctuation in rms value decreases with increasing the height and increases linearly with increasing the temperature difference.

③ The peak amplitude increases with decreasing the axial height and increasing the temperature difference. And also it seems to increase slightly with increasing the liquid velocity.

④ The correlations of the temperature fluctuation in rms value and the peak amplitude are derived as follows;

$$\theta_{rms} = 0.5 + (0.0408 - 0.00135 \cdot h + 1.286 \times 10^{-5} \cdot h^2) \cdot T$$

$$A = \{1.0 + (0.1 - 0.00328 \cdot h + 3.21 \times 10^{-5} \cdot h^2) \cdot T\} \cdot \{0.783 + 0.234 \cdot v\}$$

The above correlation is applicable to sodium in the range of $10 \leq h \leq 50$cm, $20℃ \leq \Delta T \leq 100℃$ and $2.6 \times 10^4 \leq Re \leq 6.6 \times 10^4$.

References

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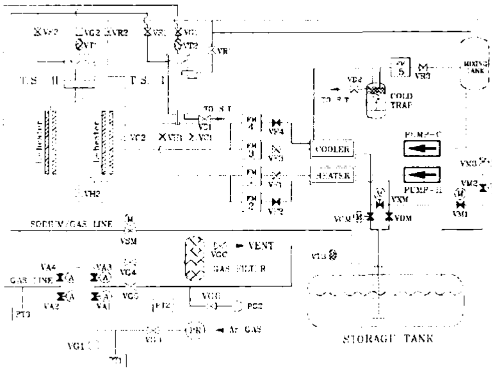


Fig. 1 Schematic diagram of THTF

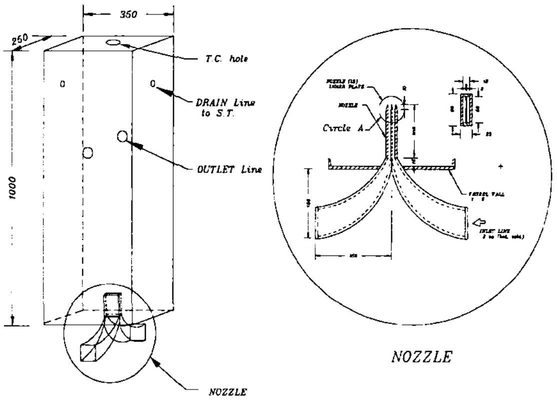


Fig.2 Test section and parallel jet nozzles

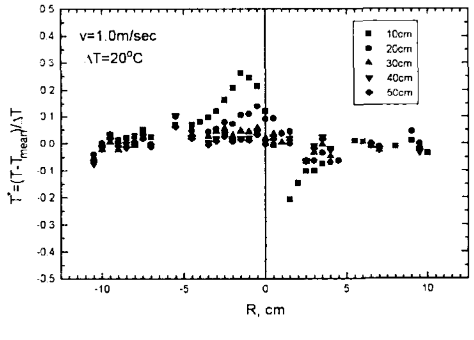


Fig. 3 Average temperature distribution at ⊿T=20℃

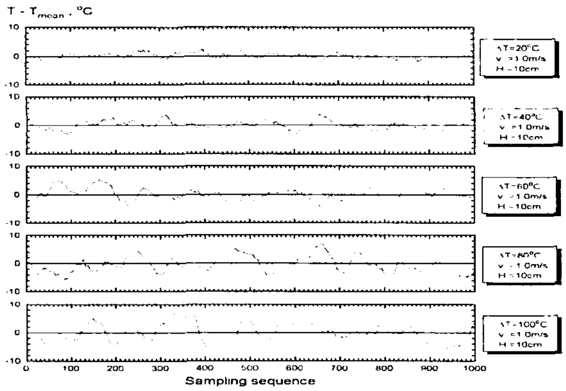
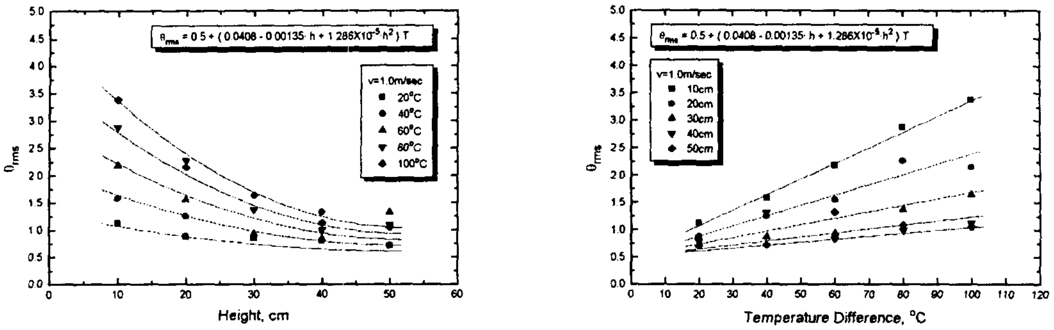
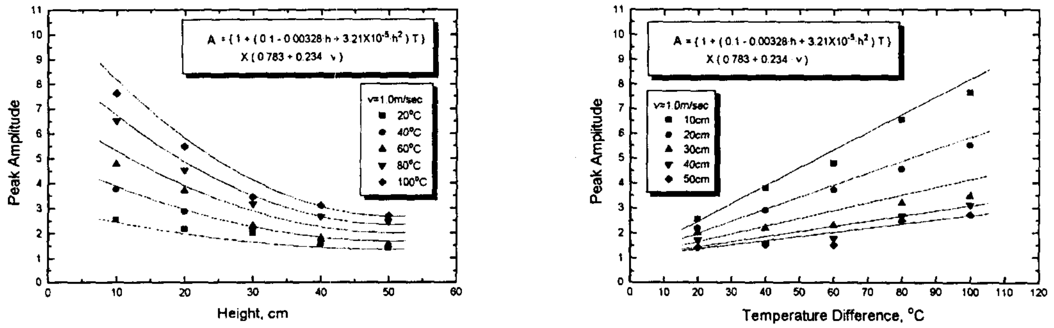


Fig. 4 Temperature fluctuations at the centerline (⊿T=100℃)



(a) according to the height (b) according to the temperature difference

Fig. 5 Temperature fluctuation in rms values at the centerline



(a) according to the height (b) according to the temperature difference

Fig. 6 Peak amplitude at the centerline

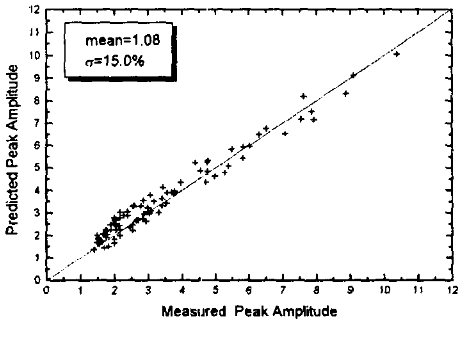


Fig. 7 Comparison of correlation and measured peak amplitude