LES Analysis of Thermal Striping in a Triple Jet Experiment

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1. Introduction

In a sodium-cooled fast reactor (SFR), each subassembly has an independent flow path and is separately assigned a flow rate. Therefore, outlet temperatures between adjacent subassemblies are different from each other. Coolant mixing with different temperatures causes temperature fluctuations in structure surfaces near the core exit. This phenomenon is called thermal striping, which can induce periodic thermal fatigues and deteriorate the integrity of the structures.

Recently, using the commercial CFD code, STAR-CCM+, a detailed evaluation was performed along the CRDM tube guide in the PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor)[1]. The thermal striping easily occurs due to the coolant mixing between the control rod subassembly and the fuel subassembly. The flow patterns are very fast and show complex behavior in the turbulent regime. However, a separate validation based on experimental data was not performed for the LES model used in the PGSFR evaluation.

In this works, the LES prediction with the commercial CFD code has been validated using the triple jet experiment conducted by Nam and Kim[2]. The capability of predicting the oscillatory temperature variation under the triple jet injection into a fluid (air) pool is estimated by comparing the numerical calculation and the experimental measurement.

2. Triple Jet Experiment

A schematic diagram of triple jet experiment to validate the present LES model is shown in Fig. 1. The test section consists of three inlet slots and an air pool with a rectangular duct. The hot jet is released in the center of slots between the cold jets. Large temperature fluctuation along the boundaries between the hot and cold jets was observed in the experiment. The oscillatory temperature fluctuation was highly dependent on the measuring position.

The slot width is equal to 0.015 m. The slot height is 0.15 m, ten times of the width. The gap distance between neighboring slots is 2.5 times of the width. The width of rectangular duct is 24 times of the slot width.

The inlet temperatures of the hot and cold jets were 65℃ and 41℃, respectively. Thus, the temperature difference between neighboring channels was 24℃. All the average velocity of each ejecting jet was equal to 10 m/s. The Grashof number was 1.1×10^4, which corresponds to a fully forced convection regime.

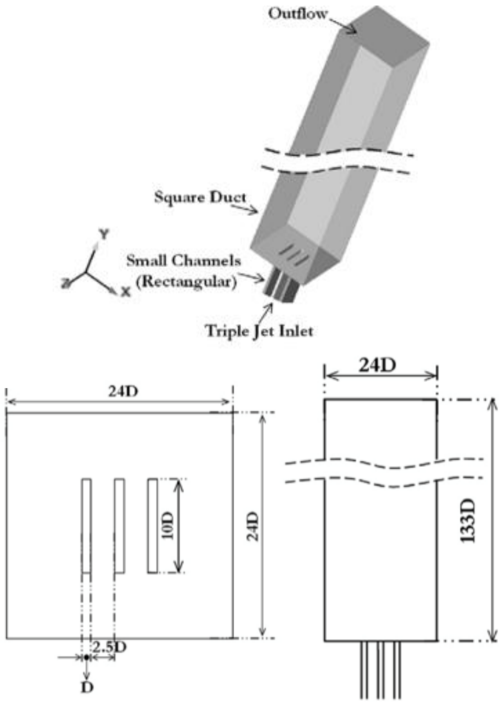
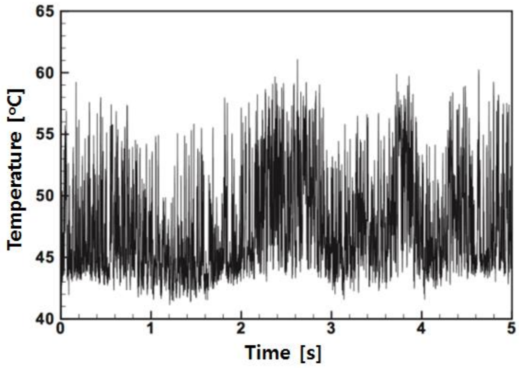


Fig. 1. Schematic diagram of triple jet geometry

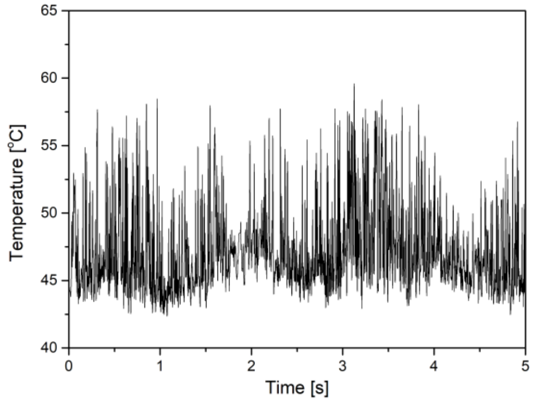
3. Numerical Simulation

A Large Eddy Simulation (LES) with the WALE sub-grid scale model is applied to predict turbulent and temperature fluctuation of the thermal striping in the triple jet experiment[3]. In general, the Reynolds Averaged Navier Stokes (RANS) model has been applied for the turbulent simulation in complex structures with high computation efficiency. However, the RANS model is inappropriate for the thermal striping in which flow and temperature rapidly oscillate within a short time. Thus, the experiment is evaluated by both RANS and LES models to elucidate the effects of small vortex along the boundary between two ejecting jets.

Numerical simulations were carried out using the finite volume CFD code, STAR-CCM+[4]. Three dimensional flow and temperature fluctuations were calculated under the unsteady condition. The total number of grids employed in the present analysis is about 4 million. The grid size near the ejecting slots was 2.5 mm, where fast and small vortex will occur. The other region in the computation domain unitized the grid of 5 mm. The velocity and temperature inlet conditions was given for each jet slot. The simulation flow outlet condition was the pressure boundary. The time step was 0.0002 seconds. The data sampling was performed for 5 seconds after the numerical calculation converged in the beginning.



(a) Experiment



(b) Large eddy simulation

Fig. 2. Time history of temperature at the measuring point (x/D=2, y/D=15, z/D=0)

Table I: Comparison of temperature data at the measuring point (x/D=2, y/D=15, z/D=0)

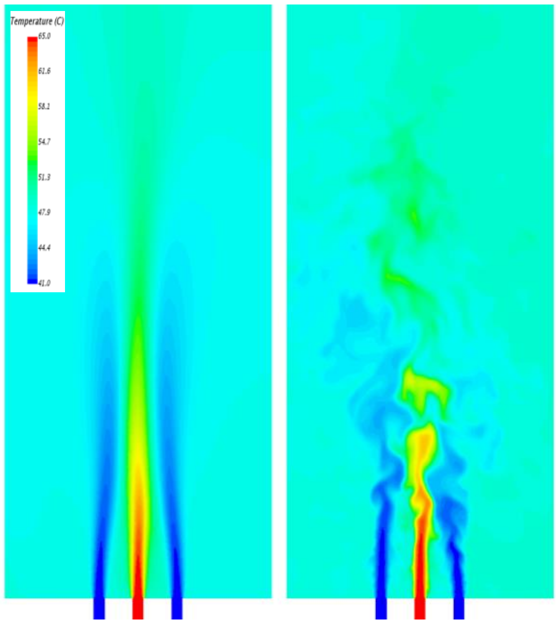
	Mean Temp.[℃]	RMS Temp. [℃]
Exp.	46.5	3.3
LES	47.1	3.1

4. Results and Discussion

The numerical and experimental results at a measuring point are displayed in Fig. 2. The temperature rapidly oscillates between the hot and cold jets. The LES prediction and experimental data reveals similar transient behavior. The mean and RMS (root mean square) values of the temperature fluctuation are summarized in Table I. The differences between the prediction and measurement for the mean and RMS temperature are about 1.3% and 6.1%, respectively.

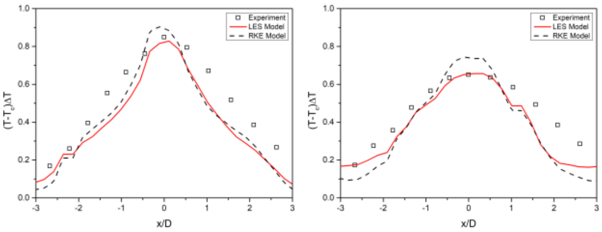
Figure 3 displays instantaneous temperature distributions of the RANS and LES models in the mid-plane. The oscillatory behavior of the temperature contour from the triple jet is apparently observed in the LES model. The turbulent flow and vortex generated from the jet slots enforce this pattern to fluctuate in space. As the triple jet flow progresses, the vortex size increases and the temperature difference gradually vanish. The RANS model reveals only the average temperature behavior and no obvious oscillatory pattern.

The time-averaged temperature profiles in the mid-plane are displayed in Fig. 4 by different downstream locations. The horizontal thermal mixing flattens the temperature profile at the downstream. Both LES and RANS models shows good agreement with the experiment. At y/D=18, the RANS model over-predicts the average temperature. At y/D=38, all the numerical calculations predict larger temperature than the experiment.

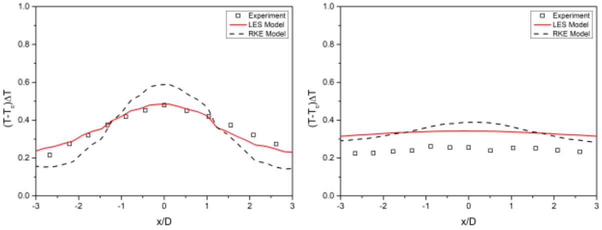


(a) Realizable k-ε Model (b) LES Model

Fig. 3. Instantaneous temperature contour in the mid-plane

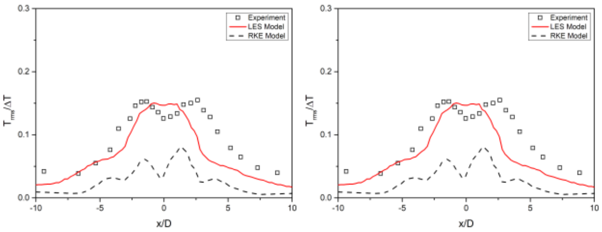


(a) y/D=7 (b) y/D=12



(c) y/D=18 (d) y/D=38

Fig. 4. Time-averaged temperature profiles in the mid-plane



(a) y/D=18 (b) y/D=25

Fig. 5. RMS temperature fluctuation profiles in the mid-plane

Figure 5 represents the RMS temperatures calculated for a total of 5 seconds. The LES model shows good agreement. The RANS model predicts smaller temperature compared to the experiment. The maximum RMS value at y/D=18 is 15.5% of the maximum temperature difference, which is close to 15.0% of the experiment. At y/D=25, the maximum RMS values of the LES model and experiment is 12.6% and 10.2%, respectively. The results show that the LES model correctly predicts the thermal stripping in which flow and temperature rapidly oscillate within a short time.

The triple jet experiment was conducted within an air pool, which has lower density and thermal conductivity compared to the sodium. However, since a thermocouple in sodium requires a thick protective shell, a thermal striping test under a sodium pool is difficult to ensure sufficiently fast response. Therefore, typical thermal striping tests are utilized with air or water coolant. The conservative limits for thermal striping are employed for a real reactor design based on the experiments.

5. Conclusions

The thermal striping in a triple jet experiment is evaluated by the LES and RANS models. These models are employed to characterize transient and spatial temperature variations generated from the triple jet. Strong temperature fluctuation is observed along a mixing region between two adjacent jets. However, the RANS model underestimates the temperature fluctuation. The LES model shows good agreement with the experiment in both averaged and RMS temperatures. The results demonstrate that the present LES model can be employed to predict the thermal stripping in SFRs.

ACKNOWLEDGEMENT

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