Large Eddy Simulation of Thermal Striping in a Triple Jet

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1. Introduction

Unsteady temperature fluctuations of non-isothermal turbulent jets are encountered in liquid metal cooled fast reactors (LMFR), and can cause thermal stresses on solid boundaries. An accurate prediction of the temperature fluctuations is important to assess the potential thermal fatigue damage to components, and this has been done by RANS turbulence modeling calculations with limited success. In this study, a large eddy simulation (LES) technique was applied to predict the temperature fluctuations of thermal striping observed in a triple jet. The triple jet model was used as a mock-up of the outlet of the fuel subassemblies in a nuclear fast reactor. The results show that LES predicted the highly oscillatory nature of unsteady thermal mixing of the triple jet. The LES results were in good agreement with the available experimental data in terms of the mean, RMS, skewness and kurtosis. The large amplitude of the temperature fluctuations associated with the thermal striping was captured correctly, demonstrating that LES can be used to analyze unsteady characteristics of thermal striping. Instantaneous and time mean thermal fields were further analyzed to assess the capability and accuracy of LES in the thermal striping study. The Spalart–Allmaras (SA) and realizable k-ε turbulence models were also considered along with the LES. It was found that these turbulence models produced a very small amplitude of fluctuations, and failed to predict the correct magnitude of unsteady thermal fluctuations, highlighting the limitations of the RANS approach in unsteady heat transfer simulations.

2. Triple Jet

In this study, a triple jet geometry was considered for numerical simulations to model the thermal striping phenomenon in the upper plenum of a liquid metal fast reactor. The triple jet geometry was chosen to be the same as in the experiments of Nam and Kim [1]. The geometry of the triple jet and the computational domain are given in Fig. 1. The three channels were attached to the base of the square duct, and the jets were issued from the nozzle. The experiment of Nam and Kim [1] was designed to be two-dimensional using nozzles with a rectangular cross section. In this study, we performed full three-dimensional numerical simulations using the LES technique. All of the geometric quantities were normalized with the nozzle width, D, equal to 0.015 m. The cross section of the square duct was identical to the test section used in the experiments [1]. The main square duct was 133D long, which is was long enough to capture the downstream behavior of triple jet mixing.

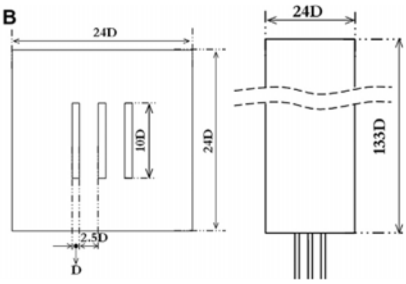


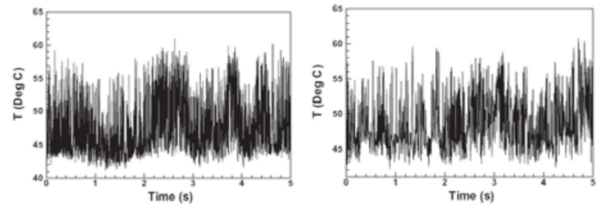
Fig. 1. A schematic diagram of triple jet geometry, top view, and side view.

3. Numerical Method

The above equations were solved using a second-order finite volume method and the PISO algorithm for pressure–velocity coupling. Non-iterative time advancement (NITA) was chosen for time control with a second order implicit scheme. For discretization, a second-order accurate bounded central differencing scheme was used. The second-order upwind scheme was used for turbulence model equations. Simulations were carried out using the finite-volume CFD code, FLUENT.

4. Results and Discussion

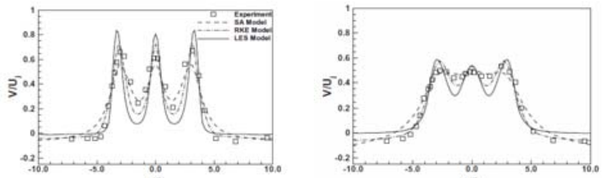
Several simulations were performed using fine computational grids (4×10^6) and the results were compared with the experiment of Nam and Kim [1] to ascertain the accuracy of the present LES study. First, the instantaneous temperature from LES with three different resolutions is monitored and compared with the experiment. Fig. 2 shows the time history of the temperature at a monitoring point(x/D=2, y/D=15 and z/D=0). The monitoring point was located between the hot and cold jets in the mid plane. The temperature was recorded at 1 kHz in the LES, while the experimental data was measured at 4 kHz. The experimental data shown in Fig. 2(a) clearly demonstrates a highly oscillating nature of the temperature fluctuations. The peak-to-peak temperature difference is about 20^{o}C. The results compare well with the experiment.



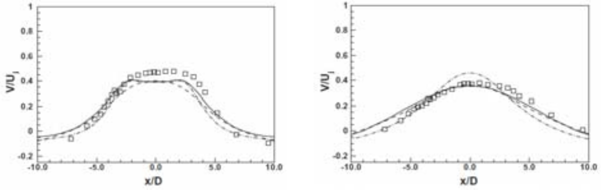
(a) Experiment, (b) LES

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

The vertical mean velocity profiles across the triple jet in the mid-plane are presented in Fig. 3. The LES results have a good overall agreement with the experimental data. The gradual transition of the triple jet until merging into a single jet flow is well predicted. Three peaks are still discernible at y/D=12, and they merge to form a broad peak at x/D=18. Further downstream at y/D=38 (Fig. 3(d)), the LES velocity profile looks very similar to a single jet profile, indicating that the mixing between the hot and cold jets is completed. The realizable k-ε model predicts a slower downstream mixing of a triple jet than the SA model, resulting in an over-prediction of the maximum velocity at y/D=38.

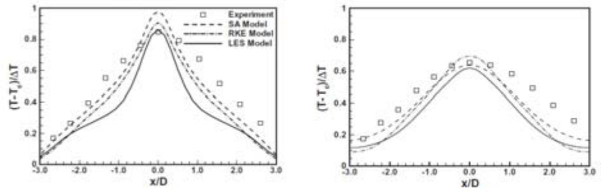


(a) y/D=7 (b) y/D=12

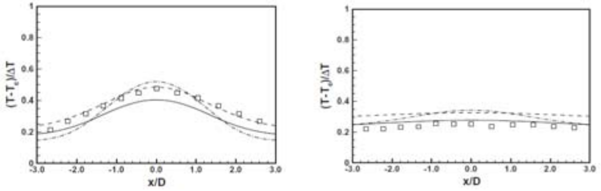


(c) y/D=18 (d) y/D=38

Fig. 3. The time-averaged velocity profiles.



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

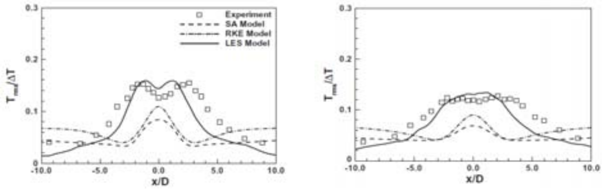


(c) y/D=18 (d) y/D=38

Fig. 4. The time-averaged temperature profiles.

The mean temperatures profiles at the same downstream locations are plotted in Fig. 4. Both the LES and turbulence models predict the mean temperature profile generally well, and the agreement with the experiment is reasonable. It is worth noting that the LES results are worse than the RANS results at y/D=7 in Fig. 4(a), which is related to the slow initial development of the jets. Again, the slower mixing of the realizable k-ε model is evident at y/D=18, where the maximum temperature is over-predicted.

The RMS temperature fluctuations are presented in Fig. 5. The LES results are in good agreement with the experimental data. As the jet mixing continues, the temperature fluctuations have peaks between the hot and cold jet locations as shown in Fig. 5(a). These double peaks are correctly predicted in the LES, while the RANS results predict only a single peak at the hot jet location. The large amplitude of temperature fluctuation is well predicted in the LES. Further downstream at y/D=25 (Fig. 5(b)), the temperature fluctuation has a broad peak, and the amplitude of the temperature fluctuation is still larger than 10% of DT. This clearly shows that the LES can predict the correct level of temperature fluctuations in the triple jet.



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

Fig. 5. The RMS temperature fluctuation profiles

5. Conclusions

In this study, numerical simulations of a non-isothermal triple jet flow were performed to assess the capability and accuracy of LES in a thermal striping study. The LES showed good agreement with the available experimental data. It is found that the LES predicted the correct amplitude of the temperature fluctuations, which are essential information to analyze the thermal striping phenomenon. The detailed characteristics of the temperature fluctuations including the skewness and kurtosis were also correctly predicted. This study clearly demonstrated the capability and potential of the LES in a thermal striping study for an LMFR.

REFERENCES

[1] H. Y. Nam, J. M. Kim, Thermal Striping Experimental Data. Internal Report, LMR/IOC-ST-002-04-Rev.0/04, KAERI, 2004.