Proceedings of the 18th UK Heat Transfer Conference
9-11 September 2024, Birmingham
UKHTC2024-111

ANALYSIS OF THERMAL STRATIFICATION IN A LIQUID SODIUM TEST FACILITY

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1. ABSTRACT

Numerical simulations of a test facility for sodium-cooled fast nuclear reactors are performed using RANS and LES to better understand these reactors' thermal stratification and mixing-jet phenomena. A thermal transient is simulated in which the temperature of the inlets, located at the bottom of the domain, decreases rapidly. Thermal stratification occurs above the outlet due to limited thermal mixing. The flow from the inlets is in the form of three jets, which are a significant source of temperature fluctuations due to the instability of the jets themselves and the interactions between them. The magnitude of the fluctuations remain elevated due to the delayed decrease in temperature near the bottom of the domain.

2. INTRODUCTION

Nuclear power has the potential to play an important role in energy generation in the 21st century, with threats such as climate change placing a premium on low-carbon energy sources. The sodium-cooled fast reactor (SFR) is a prospective Generation-IV reactor design with characteristics that make its use more favourable than existing designs. These advantages include the high conductivity and boiling point of the liquid sodium coolant, enabling effective cooling of the reactor core even during of loss of flow (LOF) accidents. However, there are challenges associated with introducing SFRs, particularly in the hot plenum, a large pool of liquid sodium that sits above the reactor core. Thermal hydraulic challenges include thermal stratification, which occurs in the hot plenum during reactor transients such as LOF accidents or during reactor shutdown, and thermal striping, which arises due to jets from the reactor core interacting with components above the core [1]. These phenomena can cause thermal stresses and fatigue that can reduce reactor service life. Stratification is also typically inaccurately predicted by RANS models, mainly due to turbulent heat flux modelling deficiencies [2]. As a result, new experimental facilities have been developed to give insights into these phenomena and to validate numerical tools. It is crucial to support such investigations with high-fidelity numerical simulations as they offer high spatial and temporal resolution of the three-dimensional flow phenomena.

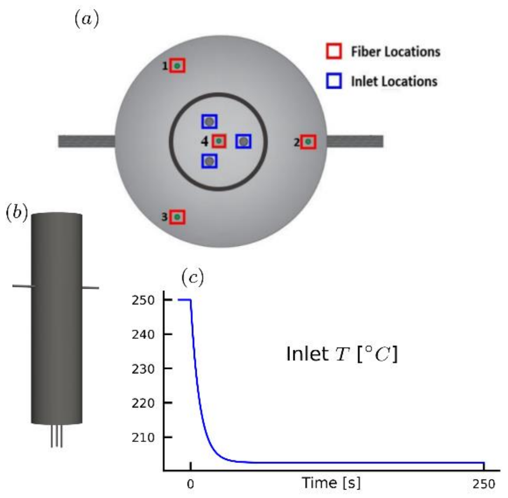

Figure 1-TSTF test section geometry. (a) Inlet and fibre-optic sensor layout. (b) Test section. (c) Inlet temperature change.

One of these experimental facilities is the Thermal Stratification Test Facility (TSTF) at the University of Wisconsin-Madison [3]. In this paper, we use Reynolds-averaged Navier-Stokes (RANS) simulations and large eddy simulation (LES) to investigate these phenomena in detail, using the former to characterise the whole transient and the latter to provide a detailed understanding of the interacting jets in the early stages of thermal stratification transients. The

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geometry of the TSTF test section is presented in Figure 1(b) and consists of a large vertical cylinder with three inlet pipes at the bottom of the test section and two outlet pipes at 0.83m from the bottom. The orientation of the inlet and outlet pipes can be observed in Figure 1(a).

3. METHODOLOGY

We match conditions from experiments designed to model LOF transients. The liquid sodium volume flow rate in the inlet pipes is 37 litres per minute throughout the experiment, with the initial temperature being 250°C. At $t = 0\ s$, the inlet temperature reduces (Figure 1(c)). The simulations have been performed using the finite volume solver Code_Saturne v8.0. The mesh was generated using ICEM CFD to produce a hexahedral block-structured mesh. The RANS and LES meshes contained 4.5 million and 82 million elements, respectively. The RANS simulation covered the entire 250-second transient, and the LES simulation covered the first 64 seconds.

The RANS simulation used the $k - \omega$ SST turbulence model for the Reynolds stresses, with the simple gradient diffusion hypothesis (SGDH) used to model the turbulent heat flux. The LES used the WALE subgrid-scale (SGS) model for the residual stress tensor and the SGDH for the SGS heat flux. The second-order linear upwind (SOLU) scheme was used for the spatial discretisation, and the least-squares scheme was used for the gradient reconstruction. The physical properties were defined using the correlations from Sobolev [4]. For the LES simulations, window averaging has been performed for the mean flow and turbulence statistics.

4. RESULTS

The RANS and LES models have been validated against experiment data from the facility. The experimental data consists of lines of vertical fibre-optic temperature sensors, whose locations and numbers are depicted in red in Figure 1(a). A comparison of temperature with height against the four fibres is shown in Figure 2(a-d) at various times. The results indicate that the LES and RANS compare well. At all times, the temperature varies over a small vertical distance. In this region, there are deviations between the simulations and the experiment, likely due to the inherent unsteadiness of the inlet jets, meaning the temperature distribution may vary somewhat between repeated runs.

After the onset of the transient, the cooler fluid originating in the inlet pipes results in jets, leading to cooler fluid penetrating deep into the test section. As time progresses, the temperature of the middle part of the test section reduces rapidly, but both the bottom and top parts remain at higher temperatures. The temperature tends to stratify around the outlets because the cooler fluid from the jets tends to leave the test section, with only limited mixing occurring with the hotter fluid above the outlet. Even in the late stage of the transient, the stratification height has only mildly increased. Eventually, the temperature reduces in the lower part of the test section as cooler fluid is transported to the bottom of the domain. This delayed temperature decrease is also indicated by the fibres in Figure 2, which shows that for $t \lesssim 100$, the lower part of the plenum is noticeably hotter than the middle part of the test section. For $t > 100$, the temperature is roughly uniform below the stratification height. The mean temperature also strongly affects the temperature fluctuations in the jets. The temperature variance $\overline{T'^2}$ (not presented) was found to remain elevated until the mean temperature in the lower part of the plenum decreases substantially.

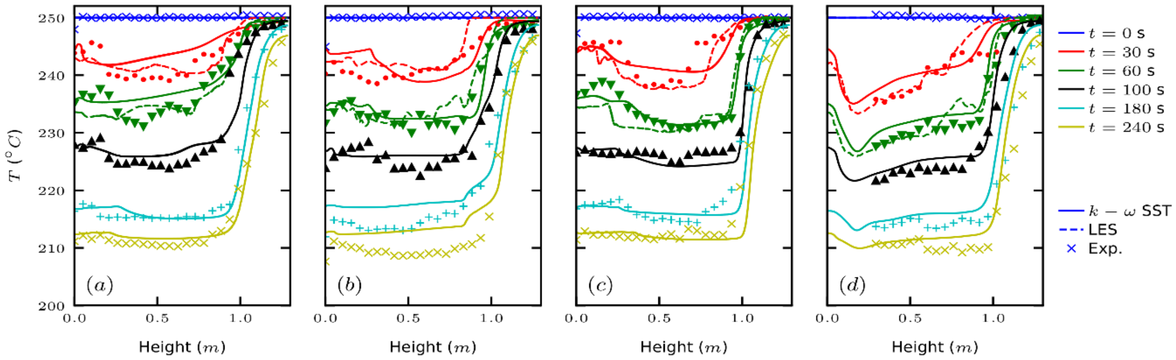

Figure 2-Validation for the LES and RANS models against experimental data. (a) fibre 1, (b) fibre 2, (c) fibre 3, (d) fibre 4.

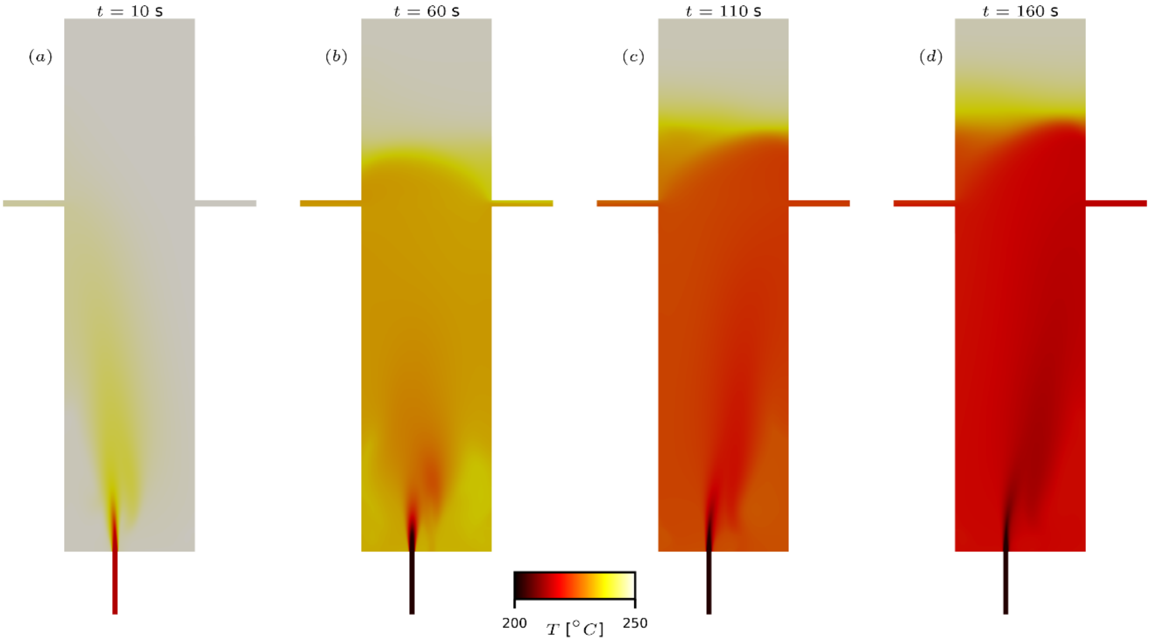

Figure 3-Temperature contours from the RANS simulations across the transient. (a-d) indicates the times from 10 to 160 seconds.

5. CONCLUSIONS

In this study, we have used RANS and LES to characterise the flow phenomena in a test facility for SFRs in experimental conditions representing LOF transients. The simulations validate well against available experimental data. The early stage of the transient is characterised by the cooler sodium from the inlets penetrating deep into the test section before eventually cooling the lower parts of the test section. Thermal stratification develops above the outlets due to limited mixing between the cooler fluid that tends to directly leave the domain through the outlets without mixing with the fluid above the outlet. The progression of cooler fluid to the bottom affects the temperature fluctuations associated with the jets, with further analysis of the jet results in the main paper.

ACKNOWLEDGMENT

The authors would like to thank Prof. Mark Anderson from the University of Wisconsin-Madison for providing experimental data. Thanks also to the EPSRC for funding (EP/T002395/1) and the UK Turbulence Consortium (EP/X035484/1) for computational resources on ARCHER2.

REFERENCES

[1] P. Chellapandi, S. Chetal and B. Raj, "Thermal striping limits for components of sodium-cooled fast spectrum reactors," *Nuclear Engineering and Design,* vol. 239, no. 12, pp. 2754-2765, 2009.

[2] G. Grötzbach, "Challenges in low-Prandtl number heat transfer simulation and modelling," *Nuclear Engineering and Design,* vol. 264, pp. 41-55, 2013.

[3] J. Schneider, "Thermal stratification in large pools of liquid sodium," University of Wisconsin-Madison, 2021, PhD Thesis.

[4] V. Sobolev, "Database of thermophysical properties of liquid metal coolants for GEN-IV," Belgian Nuclear Research Centre, SCK•CEN, 2011.