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INVESTIGATION OF FORCED AND NATURAL CONVECTION IN THE UPPER PLENUM OF A POOL-TYPE NUCLEAR FACILITY

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ABSTRACT

Large Eddy Simulations (LES) of a scaled test facility for a liquid metal cooled fast nuclear reactor (E-SCAPE) have been performed with the aim of improving the understanding of the turbulence and thermal-hydraulic phenomena in the upper plenum under different flow conditions. A high flow rate case (forced convection) and a low flow rate case (mixed convection) have been conducted based on the experiments conducted using the E-SCAPE facility. The flow is characterized by the interactions between the hot stream (arising from the centre of the core) and the cold stream (bypassing and surrounding the core). The results from the high-flow rate case indicates that under the normal operating conditions, there is a strong circulation loop driven by the jets from the barrel holes. This has led to the formation of a uniform temperature distribution across the plenum height indicating that there is effective mixing in the upper plenum. However, in the low flow rate case, the jets from the barrel holes are significantly weaker and do not result in an effective circulation in the plenum. In this case, there is a strong temperature gradient across plenum height resulting in thermal stratification.

1. INTRODUCTION

Liquid Metal Fast Reactors (LMFRs) are a prospective nuclear reactor design that has characteristics that make them one of the favourable choices among the advanced designs. The advantages include improved safety characteristics that result from the properties of the liquid metal coolant such as the high boiling point and thermal conductivity of liquid metals, which provide a degree of passive safety. These designs can also offer higher thermal efficiency and fuel utilisation. However, there are challenges associated with the introduction of such designs, some of which occur in the upper plenum particularly in off-design conditions. This includes thermal stratification and thermal striping which can induce stresses and fatigue on the components of the reactor. Beyond these design challenges, there are also CFD modelling challenges particularly in relation to the turbulent heat flux in liquid metal flows [1-2]. These issues are exacerbated in cases of natural and mixed convection where phenomena such as stratification are often incorrectly predicted. As a result of these issues, there is a need for both experiments and high-fidelity simulations of liquid metal fast reactors to help understand the physics of these flows and to validate computational tools for improved modelling.

To this end, the Belgian national nuclear research Centre SCK-CEN has developed the E-SCAPE test facility, which is a 1:6 scale model of the future LMFR, MYRRHA. The MYRRHA reactor is a pool-type reactor using lead-bismuth eutectic (LBE) as coolant. The purpose of the study described here is to conduct high-fidelity Large Eddy Simulations (LES) of the E-SCAPE facility to improve the understanding of the complex flow physics in the upper plenum and create datasets for benchmarking modelling tools. While there have been few studies [3-4] that have used LES in LMFRs, it has the potential to accurate predict fundamental liquid metal flows including highly oscillatory mixing jets and thus make it a suitable method for simulation of LMFRs. In this study, a forced and a mixed convection case are presented to replicate experiments from the E-SCAPE facility.

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2. METHODOLOGY

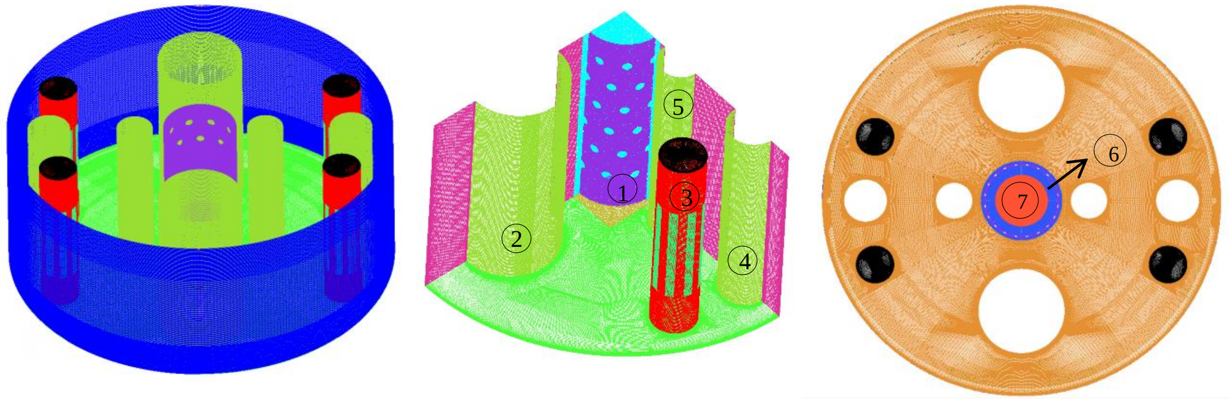
A schematic of E-SCAPE’s upper plenum is shown in Fig.1(a). E-SCAPE’s mock-up core outlet is made up of 7 concentric rings, and the outer ring is known as the bypass inlet. Hence in this model, the core outlet was made up of two parts. The 6 inner rings comprise the ‘active inlet’ with hotter fluid (red colour Fig.1(c)) and the outer ring as the ‘bypass inlet’ with cooler fluid (blue region (Fig.1(c)). In this study, the Above Core Structure (ACS) is treated implicitly using a porous media approach so that the physics of the pool can be well-resolved while the pressure losses from the ACS can still be represented resulting in an appropriate mass flow distribution through the barrel holes (The barrel is depicted in purple in Fig.1(b)). Simialar to the practice adopted by Koloszar et al. [5] and Toti et al. [6], an explicit momentum source term was added to account for the pressure losses in the ACS region. Both radial and axial source terms included based on the inertial term of Forchheimer’s equation. The resulting Forchheimer coefficients were calculated using correlations for the pressure losses in rod bundles [7-8].

The boundary conditions are based on experiments [9] that have been conducted on the E-SCAPE facility. An overview of the conditions can be seen in Table.1. These cases have been selected to understand the behaviour of the thermal hydraulics in the upper plenum region under both forced and mixed convection conditions.

Table 1: Table indicating the E-SCAPE cases to be simulated.

Case	Experiment I.D.	Pumps (kg/s)	Power (kW)
Case 1 Forced	F80% P80% BP0%	93.2	66.4
Case 2 Mixed	F20% P80% BP0%	23.4	66.4

ICEM CFD has been used to create a partially structured mesh. An unstructured tetrahedral mesh has been used to mesh the region around the barrel with a hexahedral blocked mesh for the remainder of the domain and ‘O-grids’ around the cylindrical surfaces to reduce numerical diffusion. The unstructured and blocking meshes are merged to create a conformal interface using a layer of pyramids. The total number of elements used for these simulations was 83 million.



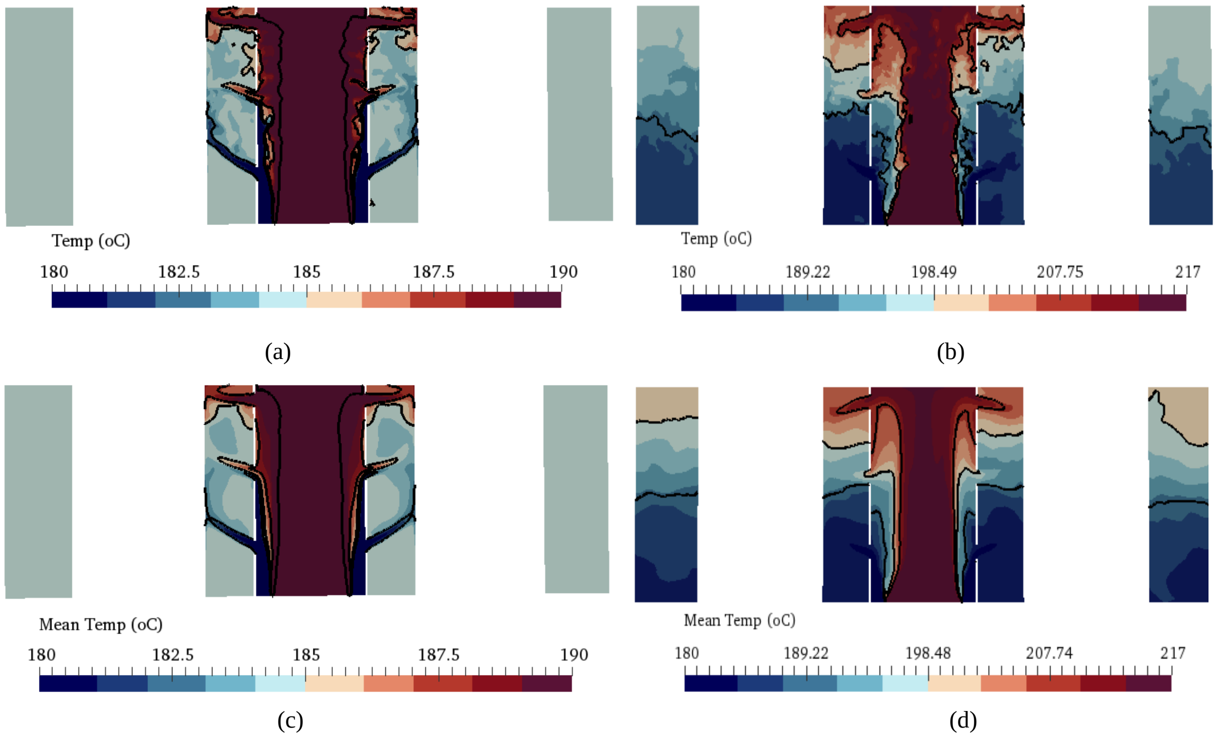
(a) (b) (c)

Figure 1 Schematic of the E-SCAPE model and mesh methodology from different views (a) Full model; (b) Quarter representation; (c) Top view; (1) Barrel wall; (2) In-vessel fuel handling machines (IVHFM); (3) Heat exchanger; (4) Pump; (5) Silicon-doping devices; (6) Bypass inlet (blue region); (7) Active inlet (red region).

The open-source CFD solver Code-Saturne was used, and the WALE model was used to model the sub-grid scale stresses for LES. Literature indicated [10] that this model would be most effective for liquid metal flows and complex geometries. The thermal properties of the LBE are incorporated from the correlations reported by Sobolev [11]. The physical properties are dependent on temperature and the buoyancy is included in both cases. The Second-Order Linear Upwind (SOLU) convective scheme was used to discretize the governing equation. A time step of 5×10^{-4} s was used, which ensured the CFL to be less than 1 at most locations to maintain simulation stability. The SIMPLEC pressure-velocity coupling algorithm was used with a relaxation factor of 0.5.

3. RESULTS AND DISCUSSION

To understand the behaviour of the fluid in the upper plenum of E-scape model the instantaneous and mean temperature distributions along the different horizontal and vertical planes are presented. The distributions along the vertical plane in direction of the IVHM (labelled 2 in Fig.1(b)) can be seen in Fig.2. Figs 2 (a and c) represent the instantaneous and mean temperature distribution under the normal operation (forced convection). Within the barel region, the hot plume rises from the centre of the core outlet reaching the free surface before spreading out through the upper barrel holes as high momentum jets. The cooler LBE from the core bypass passes through the lower sets of barrel holes. All the jets appear strong and impinge onto the IVFHM. Away from the jets, both the instantaneous and mean temperature contours indicate that the temperature is largely uniform across the plenum height. It is clear that in the forced convection case, there is sufficient mixing even at locations far from the jets, for example on the other side of the IVFHM. This contrasts with the Figs 2 (b and d), which show the mean and instantaneous temperature contours from the mixed convection case. While the barrel hole jets are still present, they are considerably weaker. Inside the barrel, the effect of buoyancy is clear with the accumulation of hotter LBE near the free surface before it leaves through the barrel holes. It is also clear that the temperature is stratified with the hotter fluid remaining in the upper part of the plenum and the cooler fluid, which has passed through the lower barrel holes, staying in the lower part of the plenum.

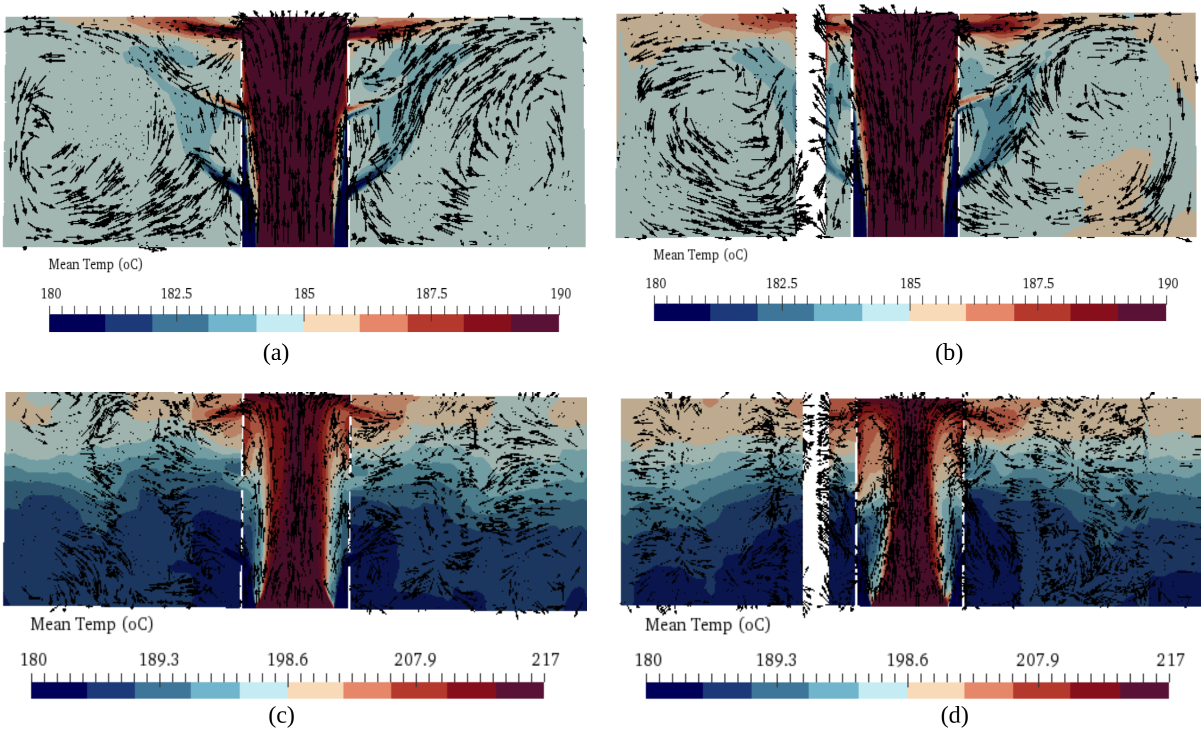


(a) (b) (c) (d)

Figure 2: Instantaneous and mean temperature distribution along the vertical midplane in the IVHM direction under different flow conditions; (a and c) for forced convection case; (b and d) mixed convection case.

The main cause of the differences observed above are revealed in Fig.3, which shows the mean temperature overlayed with mean velocity vectors in a vertical plane away from structures such as the

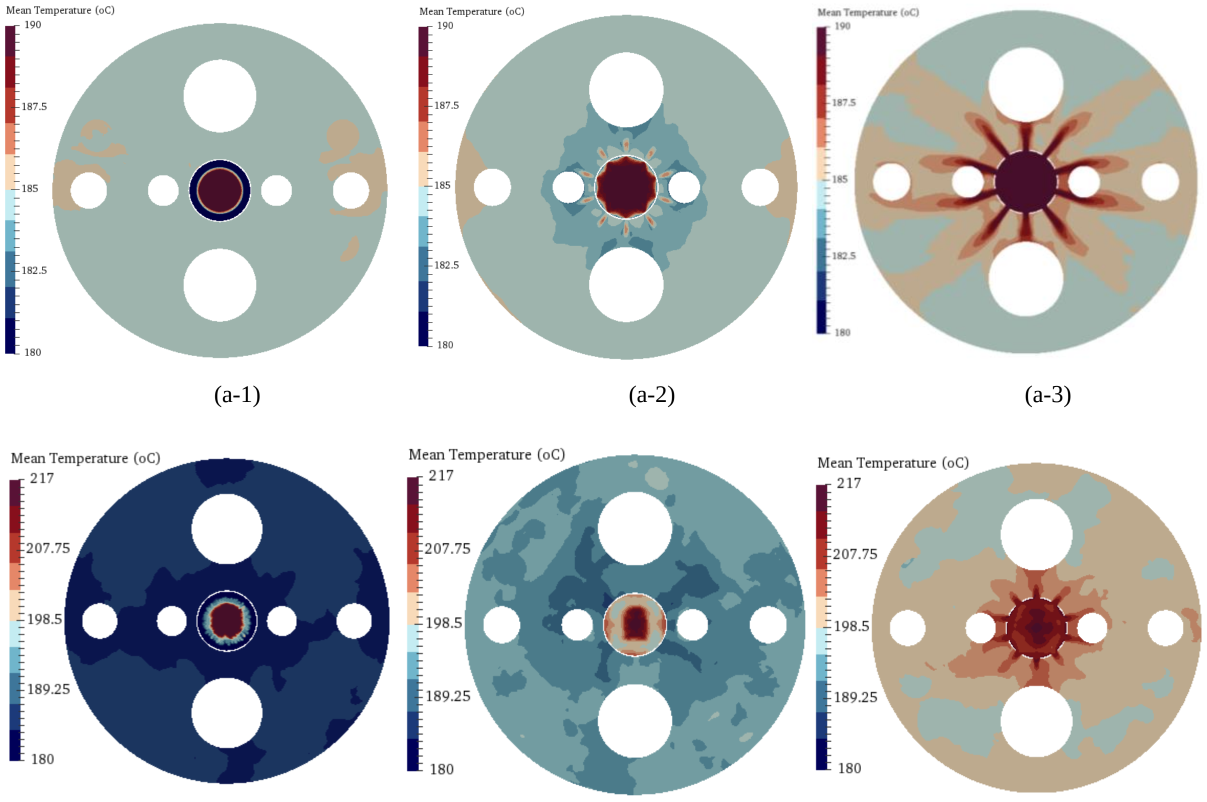
IVFHM with flow from the barrel behaving as free jets. Figs. 3 (a and b) show that for the forced convection there is a large-scale circulation throughout the upper plenum. Such a circulation appears largely absent from the mixed convection case (Figs 3 (c and d)) indicating that this circulation has an significant role in preventing the stratification of the plenum.



(a) (b) (c) (d)

Figure 3 Velocity vector superimposed in the temperature contours at different planes for forced (a and b) and mixed convection cases (c and d); (a and c) plane along with the free jet, (b and d) plane along the jet interacting with SD direction.

The temperature distributions across the horizontal plane for forced and mixed convection cases at different heights of the upper plenum are reported in Fig.4 using coutour plots. The horizontal surfaces are chosen in such a way to observe the temperature distributions close to the bottom (near the inlet), middle, and close to an upper surface of the upper plenum. From Figs 4 (a-1, a-2 and a-3), it can be noticed that for the forced convection there is a largely uniform temperature distribution in the upper plenum region although there is a slight non-uniformity with some slightly cooler fluid present in Fig. 4 (a-2). Fig. 3(a) indicates that this is caused by the cooler fluid transported by the lower jets, which are angled upwards as the fluid retaining significant upward momentum. This suggests that both the lower and the upper jets contribute significantly to the large-scale circulation in the forced convection case. However, in the case of the mixed convection, the fluid velocity is significantly reduced, and the jets are noticeably weaker particularly in the upper parts of the plenum as indicated by comparing Fig. 4 (b-3) with Fig 4 (a-3). The resultant effect of the lack of circulation can also be observed with the temperature reasonably uniform across each plane but increasing with height from figs 4 (b-1 to b-3)



(a-1) (a-2) (a-3)

(b-1) (b-2) (b-3)

Figure 4 Temperature distribution at different levels of the upper plenum. (a-1), (a-2), (a-3) Case 1: forced convection; (b-1), (b-2), (b-3) Case 2: mixed convection.

4. SUMMARY

The paper presented the development of an LES model of the upper plenum region of E-SCAPE, a test facility for a future LMFR. The results show interesting differences between the flow behaviours between high and low flow rate cases, which behave as forced and mixed convection, respectively. The model developed incorporated a porous media approach incorporating momentum source terms for the above core structure to account for the pressure losses in this region without the computational cost of a full simulation of this region. This enabled a detailed investigation of the flow behaviour in the rest of the upper plenum with a feasible mesh size. The high flow-rate case was shown to result in the fluid of different temperatures in the upper plenum being well mixed due to a large-scale circulation, which resulted from high-speed jets from the barel. This large-scale circulation was observed to be absent in the low flow rate case due to the weaker strength of these jets. This resulted in the presence of the thermal stratification in the upper plenum across height.

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