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CFD MODELLING OF LEAD SOLIDIFICATION AND NATURAL CONVECTION FOR THE WESTINGHOUSE LEAD-COOLED FAST REACTOR

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1. ABSTRACT

Motivated by the current development of the Westinghouse Lead-cooled Fast Reactor, this study presents transient CFD simulations of solidification within a pool type vessel cooled externally by the forced convection of air using STAR-CCM+. Results indicate the melting-solidification model within STAR-CCM+ can reproduce the solidification front as it moves past a mock-up LFR fuel bundle included within the vessel. However, comparisons with experimental data reveal that the CFD under-predicts the solidification rate and thus further work is required to address these discrepancies.

2. INTRODUCTION

Lead-cooled fast reactors (LFR) are one of several Generation IV reactor technologies that uses a liquid metal as the primary coolant. Whilst lead has several favourable characteristics, its relatively high freezing point (327°C) means coolant solidification is a unique phenomenon that could occur during off-design scenarios. The ability to predict lead solidification, and thus the need to assess current solidification modelling capability, is therefore essential to the development of LFRs. However, compared to other thermal-hydraulic areas of interest, relatively little research on reactor related coolant solidification exists in the open literature. In support of the development of the new Westinghouse LFR [1], and with support from the UK-BEIS AMR Phase 2 programme, the LEad FREEZing (LEFREEZ) facility has been constructed to conduct lead freezing and re-melting tests to determine whether such events will damage or deform reactor components. In one of the experiments, initially liquid lead contained within a cylindrical vessel is frozen by the forced convection of air within a jacket which surrounds the vessel. The vessel contains a reduced-size mock-up of a fuel bundle, comprising 19 pins arranged in a hexagonal lattice. A solidification front is expected to develop from the lower vessel walls and progress through the vessel and mock-up bundle. This paper presents CFD modelling of lead solidification within the LEFREEZ facility using STAR-CCM+ (v2022.1). Our approach is first validated against a test case that considers the melting of Tin. Then, 3D transient computations are presented and compared with experimental data from the LEFREEZ testing campaigns.

3. NUMERICAL METHDOLOGY

To model solidification, STAR-CCM+ incorporates a ‘melting-solidification’ model [2] which is a sub model of the Volume of Fluid type. This is an enthalpy-based formulation which takes the volume fraction of the liquid phase to occupy the entire fluid domain and introduces a solid volume fraction, α_s, to represent the proportion of a cell in the solid phase. To account for the necessary restriction of motion once the liquid has solidified, we activate the ‘flow-stop’ model within STAR-CCM+, which completely stops the flow once the relative solid volume fraction (α_s) within a cell has reached a specified value ($f_s = 0.02$).

4. MELTING AND SOLIDIFICATION OF TIN

To help validate our approach, we first reproduce a test case that considers the melting [3] of Tin as illustrated schematically in Figure 1. In this, initially solid tin is melted between vertical walls kept at different, but uniform, temperatures such that $\Delta T = 3$ K (providing a Rayleigh number $Ra = 2.5 \times 10^5$). The detailed 2D

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laminar calculations are described by the authors as a 'reference calculation'. Figure 1 also compares the evolution of the liquid-solid with comparisons against published data, where laminar results are obtained for increasing values of the flow-stop fraction (f_s). Excellent agreement with the reference data is obtained for cases where $f_s < 0.2$, but significant deviation occurs at the highest value of f_s considered ($f_s = 0.5$). Here, the flow is not stopped until half of any given cell has solidified and this artificially, and erroneously, allows energy to be convected away, accelerating the melting process. A further validation test case modelling the solidification of Tin (not presented here) showed good agreement with experimental data, and highted that the activation of the k-ε turbulence model improves agreement with the experiment, correcting a deformation in the interface shape predicted by the laminar case.

4. LEAD SOLIDIFICATION IN THE LEFREEZ FACILITY

Transient 3D simulations are performed of the expected solidification front within the LEFREEZ facility. The geometry is illustrated in Figure 2, where multiple simulation regions are joined with conjugate heat transfer interfaces. The main experimental vessel (diameter D_i) is surrounded by a stainless-steel jacket that creates an air channel $0.1D_i$ wide, with two inlets ($0.28D_i$) and two outlets ($0.3D_i$). A fan provides a steady flow of air at ambient conditions ($Re = 39{,}029$) into the jacket allowing the vessel to be cooled by forced convection. Radiation heat transfer between the vessel wall and outer jacket wall is included. The k-ε model is applied to the air region in high-Re form and the lead region in low-Re form. The air jacket is additionally insulated by a thickness of rock wool, which is modelled using a thermal resistance approach that includes both radiative and convective losses. A 19-pin mock-up fuel bundle, surrounded by a hexagonal stainless-steel wrapper, is partially submerged in the vessel. Following mesh and time-step sensitivity tests the final mesh comprised 31,414,600 cells. Due to available symmetry, only half of the vessel is modelled, and the simulation was run until the lead had completely solidified.

Figure 2 further presents time-history of the average solid volume fraction within the lead domain and compares the bulk temperature of the exiting air with the experiment. Qualitative agreement between the CFD and the experimental temperature outlet variation is relatively good, with the CFD correctly capturing the step initial decrease in outlet bulk temperature as the initial hot stagnant air is removed. Quantitative agreement between the CFD and the experiment is generally good, though there are two notable differences. The first is the prediction of the initial transient, which is much quicker in the CFD. The second is the subsequent rate of decrease in the outlet bulk temperature, which is observed to be moderately higher in the experiment. A composite image, also presented in Figure 2, shows the evolution of the solidification interface within the vessel and highlights the complex nature of the predicted flow field. The presentation will include additional and more detailed comparisons with experimental data, along with a series of animations highlighting the predicted flow features and physics.

5. CONCLUSIONS

Transient simulations of liquid metal solidification have been conducted using STAR-CCM+ in support of the development of the Westinghouse LFR. The approach was first validated against a test case considering the melting of Tin and showed strong sensitivity to a model parameter (f_s). The methodology was then used to model solidification of lead within the LEFREEZ facility, which comprises a vessel cooled by the forced convection of air. The results reproduced the predicted progression of the solidification front, and demonstrated that the melting-solidification model within STAR-CCM+ can produce results which are consistent with expected behaviour. However, further interrogation of the numerical simulations is required to better understand quantitative discrepancies with the LEFREEZ experiment.

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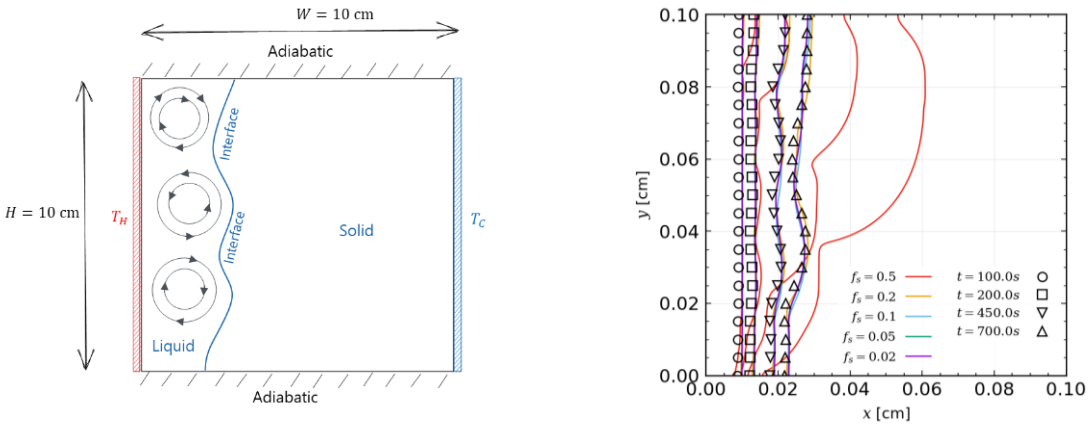

Figure 1: Melting of Tin within a rectangular cavity showing case schematic (left) and the influence of the flow stop parameter (f_s) on the simulated interface position as compared against published reference data (right).

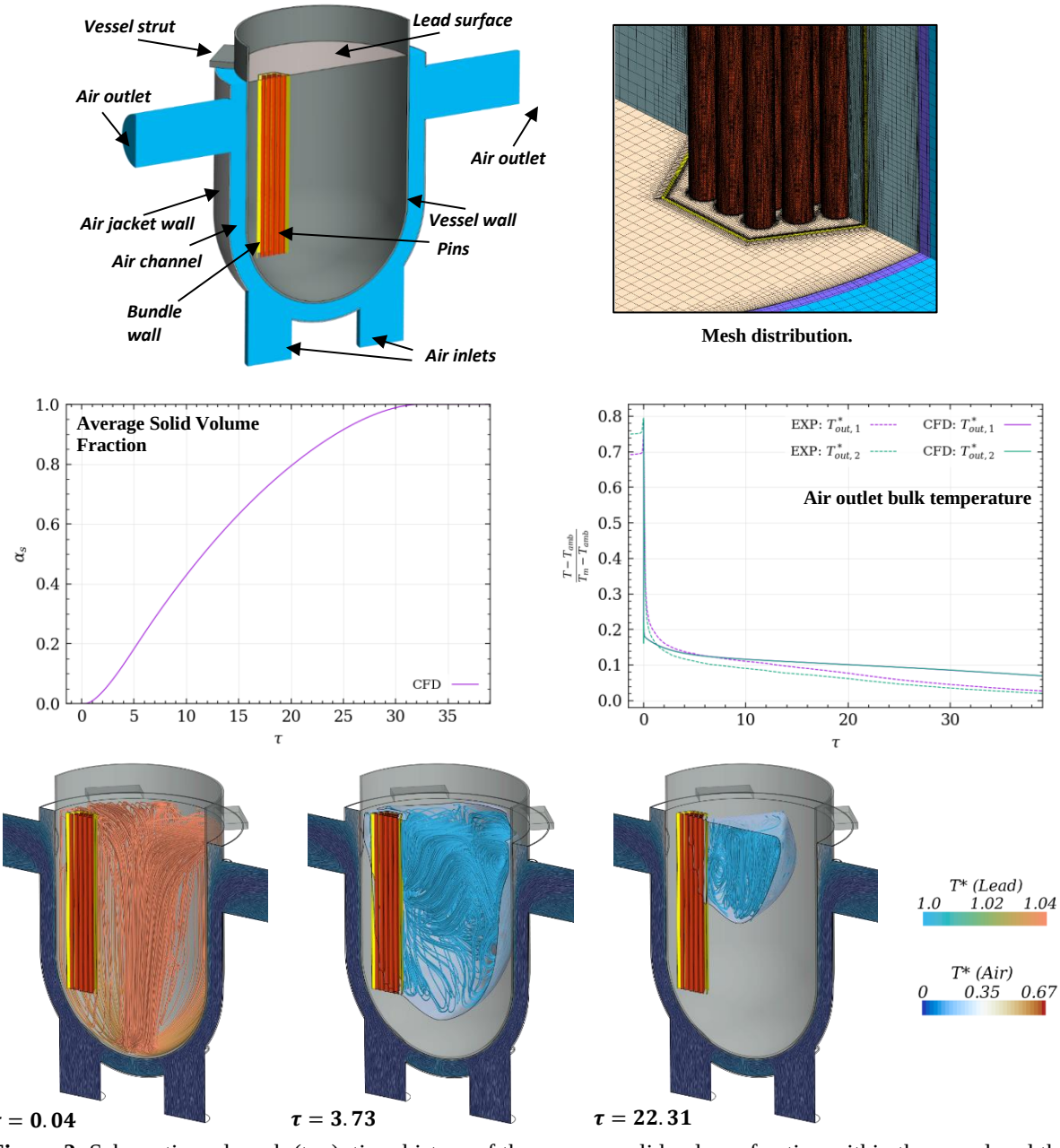

Figure 2: Schematic and mesh (top), time-history of the average solid volume fraction within the vessel and the air outlet bulk temperature with comparisons against the experiment (middle), and composite image showing 3D velocity streamlines within the lead, 2D velocity streamlines within the air, and the inferred interface position at selected times (bottom).