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A Multiphysics Model for Analysis of Inert Gas Bubbles in Molten Salt Fast Reactor – Part 2: Application and Results

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ABSTRACT

The Molten Salt Fast Reactor (MSFR) developed in the framework of the H2020 SAMOFAR project is a circulating fuel nuclear reactor in which a mixture of molten thorium and uranium fluorides acts as fuel and coolant simultaneously. The dual role of molten salt, as nuclear fuel and coolant, in MSFR, and MSRs in general, results in a complex, highly coupled system that poses a challenge in modelling and simulation. Among these features is the presence of gas bubbles in the molten fuel which necessitates the use of two-phase models to accurately simulate reactor behaviour.

This paper presents the implementation of two-phase flow model equations in COMSOL Multiphysics and its application to a simplified MSFR core geometry proposed under the EURATOM EVOL project. The model has been validated by comparison of thermal hydraulic and neutronic results for the case of single phase flow with a previous single-phase study available in literature. The two-phase studies highlight the impact of gas bubbles on the thermal hydraulics and neutronics of MSFR and the void feedback coefficient is evaluated based on the average void fraction in the core. The spatial dependence of the bubbling feedback coefficient is analysed based on comparison with Monte Carlo simulations performed using homogeneous bubble distribution in the core. The outcomes of the present analysis serve as a reference point for further investigation of bubbling system as a reactivity control method for MSFR.

1 INTRODUCTION

The Molten Salt Fast Reactor (MSFR), the reference circulating fuel reactor under the framework of Generation IV reactors being developed under the HORIZON2020 SAMOFAR project, features a molten fluoride salt that acts as both the fuel and coolant. This peculiar feature of MSFR poses a challenge in reactor design and modelling. The fuel salt velocity significantly influences the delayed neutron precursor (DNP) distribution in the core and subsequently the reactor kinetics. Moreover, the bubbling system envisaged for the on-line removal of fission products results in an additional variable affecting the reactor dynamics of MSFR. An additional application of the bubbling system foreseen in the MSFR design is in reactivity control by exploiting the highly negative void feedback coefficient inherent to MSRs. For the objective of reactivity control, the impact of void distribution on neutronics must be computed and a void reactivity feedback coefficient must be defined. However, under the current state-of-the-art in MSFR modelling, the impact of the voids has been defined mainly by adopting a homogeneous void distribution. This approach results in unrealistic assumptions and less accurate results. Better results can be obtained by coupling CFD with neutronics to simulate the two-phase flow of salt/bubble mixture.

In the companion paper by Bajpai et al. (hereafter referred to as Part I), a numerical model based on coupling CFD and neutronics for simulation of two-phase flows in circulating fuel reactors was presented. In this paper a COMSOL Multiphysics model based on the governing equations presented in Part 1 has been developed and applied to predict the steady state behaviour and bubbling feedback coefficient of MSFR. In Section 2, a brief description of the multiphysics model has been presented. In Section 3, the main thermal-hydraulic, neutronic and bubbling feedback results have been presented.

2 MULTIPHYSICS MODELLING

The conceptual design of MSFR proposed under the EVOL project has a cylindrical core geometry with 16 external loops for fuel recirculation [1]. In the present work, this nearly axial-symmetric core geometry has been extended to the complete primary circuit by approximating the 16 external recirculation loops with a single annular loop. This modelling approach leads to drawbacks such as pressure drop due to mixing effects in out-of core part of primary loop and the impossibility to predict some localised effects in core such as the flow pattern in the vicinity of core inlet and outlet [2]. However, the simplified geometry is a reasonable modelling choice for the purpose of assessment of bubbling system behaviour and it allows for a two-dimensional axially-symmetric COMSOL model reducing computational costs and time required for the simulation. The simplified benchmark geometry is illustrated in Figure 1. COMSOL Multiphysics is a finite element analysis, solver and multiphysics simulation software.

Though the two-dimensional model can not explicitly represent the pumps and heat exchangers, replacing the physical components by volumetric forces and heat sources or sinks respectively serves as a good approximation. The pump has been simulated by a volume force in the direction of flow to establish a nominal fuel salt flow rate of 4.5 $\mathrm{m}^3\,\mathrm{s}^{-1}$. The heat exchange with the intermediate circuit has been modelled using a heat sink proportional to the temperature difference between the primary and secondary circuits and the heat transfer coefficient has been taken as the harmonic mean of the heat transfer coefficients on each side of heat exchanger [2]. Bubble inlet was defined at the bottom of the core near the centre of the core and the outlet was defined at the top surface of the core close to recirculation loop outlet, as shown in Figure 2.

3 STEADY STATE REACTOR BEHAVIOUR

3.1 Thermal Hydraulics

The multiphysics model developed based on the equations presented in Part 1 was validated by a comparison of thermal hydraulic results with a previous study performed by Fiorina

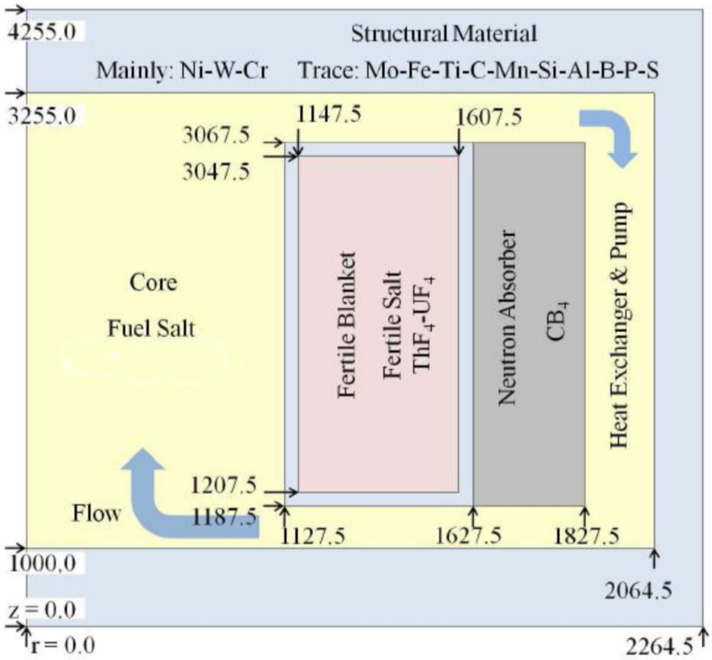

Figure 1: Axially-symmetric MSFR benchmark geometry [3]

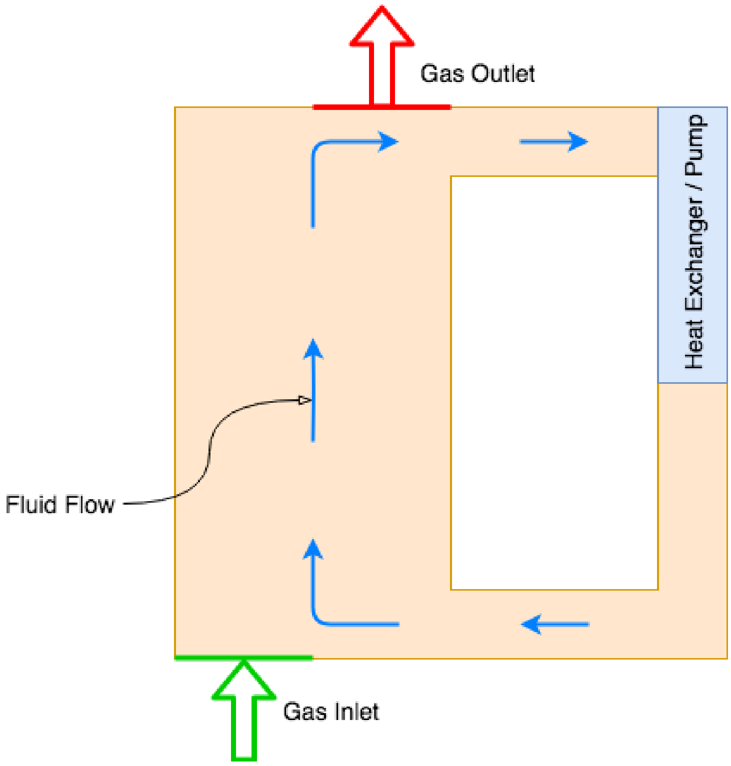

Figure 2: Schematic description of the geometry used in multiphysics model

et al [4]. While a single-phase model was employed in [4], a zero void fraction was imposed in the present model to achieve the desired results and the results, as shown in Figures 3, 4 & 5 of the two studies show good agreement. As a consequence of the benchmark geometry shape and the inertial motion of the fuel salt entering the reactor core from recirculation loop, a wide recirculation zone exists close to the blankets, while the fuel is nearly stagnating at the core centre, close to the axial reflectors. Furthermore, the temperature in the recirculation zone is higher than the temperature at the outlet and can be attributed to the reduced heat transfer due the reduced flow near the blanket and the buildup of DNPs and consequently an increase in decay heat in that region. Though the increased temperatures can lead to higher thermal stresses in the structural material, the problem has been resolved by employing an hourglass shaped core under the SAMOFAR project [5]. However, since the present work focusses on the application of the developed model to predict the reactivity feedback of the bubbles, the simplified geometry has been employed.

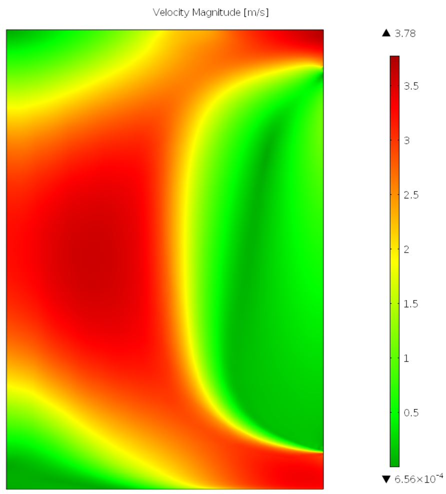

Figure 3: Velocity field in core ($\mathrm{m\,s^{-1}}$) in single-phase flows

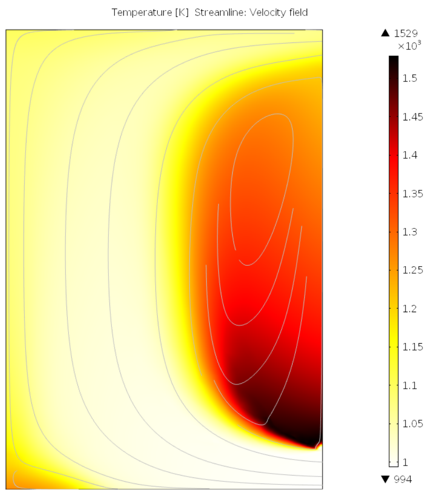

Figure 4: Temperature in core (K) with velocity streamlines in single-phase flow

In the case of two-phase flows, as a consequence of bubble induced turbulence, a higher fuel salt velocity compared to single-phase flow has been observed. However, a comparison of the temperature profile obtained from single-phase and two-phase studies reveals little difference in the simulated temperature profiles. This observation can be attributed to almost equal turbulent dynamic viscosity, and subsequently turbulent conductivity, achieved in the two cases. Turbulent viscosity depends on turbulent kinetic energy and dissipation rate predicted by the $k - \epsilon$ turbulence model. At the small bubble void fractions in the present work, the difference between turbulent kinetic energies and dissipation rates for the two cases is minute resulting in virtually identical turbulent viscosities.

3.2 Neutronics

For validation, the theoretical normalised prompt neutron flux profile for a solid fuelled reactor and the simulated normalised prompt neutron flux profile for MSFR were compared, and, as shown in Figure 8 and Figure 9, the agreement between the theoretical and simulated profiles validates the a-priori assumption in Part 1 that the fuel salt motion does not significantly affect the prompt neutron flux distribution. However, the delayed neutron precursors drift along

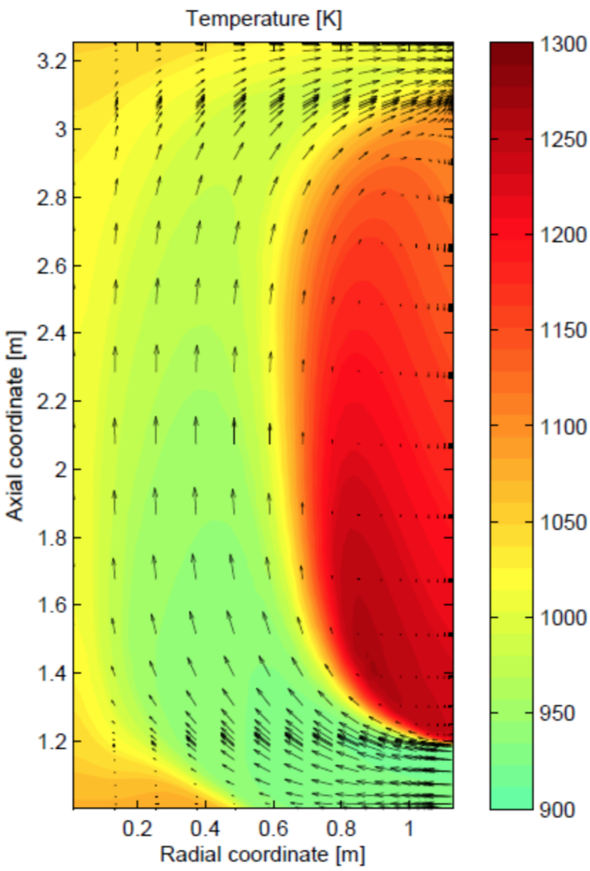

Figure 5: Velocity and temperature distribution in core as predicted by Fiorina et al. [4]

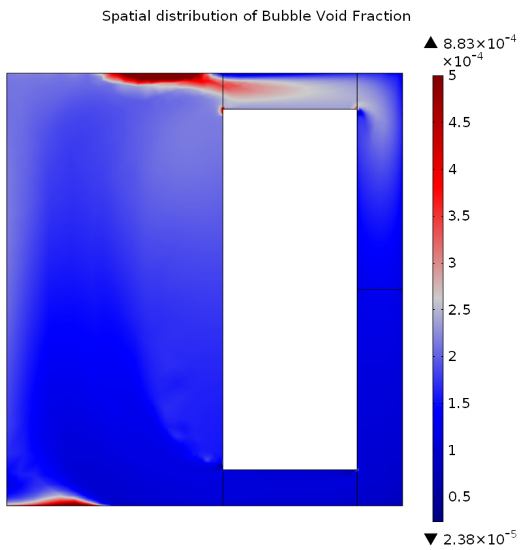

Figure 6: Void distribution corresponding to nominal bubble flow rate

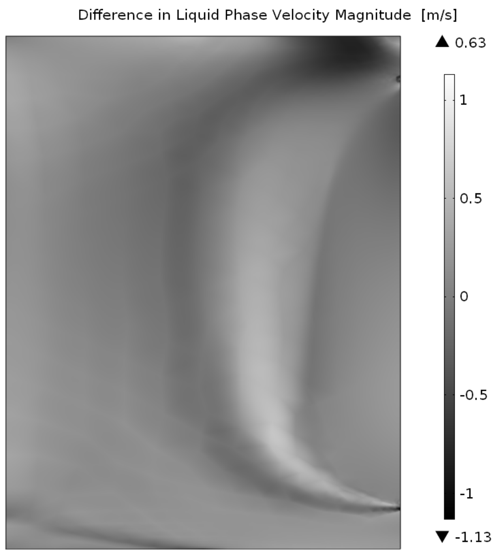

Figure 7: Difference in liquid phase velocities for single and two-phase flows in core

with the fuel and show a higher concentration towards the top of the reactor. Moreover, the DNPs get transported to the recirculation loop and decay outside the core, leading to a reduction in the effective multiplication factor in the core. The spatial distribution of prompt neutrons and DNP in MSFR has been shown in Figures 10 & 11. While a single DNP group has been modelled in this work, it can be conjectured that fluid flow has different impact on distributions of different precursors. In fact, the precursors with smaller decay constants (longer lifetime) flow further downstream compared to precursors with larger decay constants (shorter lifetime). Therefore, it can be concluded that the liquid-fuel flow has stronger effects on the precursors with longer lifetimes [4, 6].

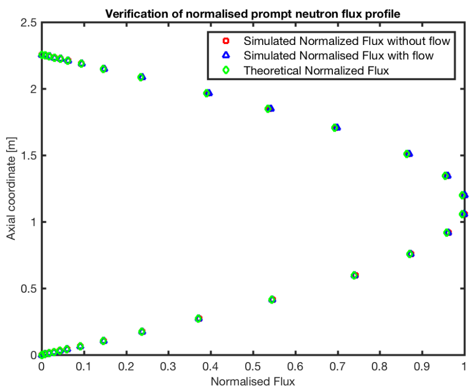

Figure 8: Normalised prompt neutron concentration

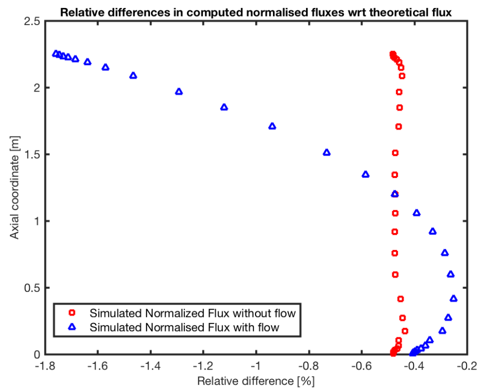

Figure 9: Relative difference between theoretical & computed prompt neutron flux

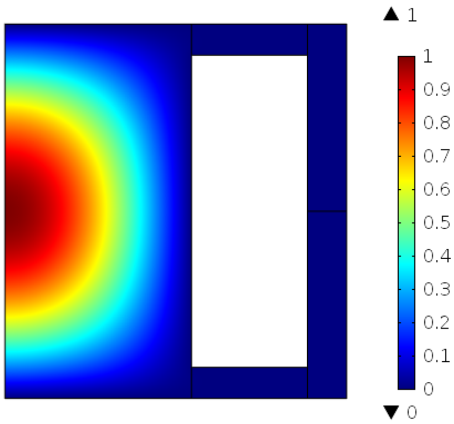

Figure 10: Normalised prompt neutron distribution in MSFR

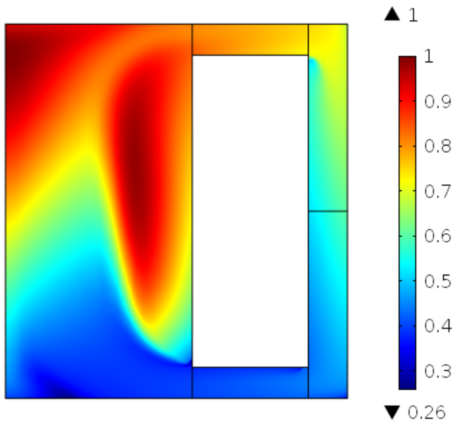

Figure 11: Normalised DNP distribution in MSFR

The bubbles, however, can have a significant influence on both prompt neutrons and DNPs. The bubbles affect both the effective macroscopic cross sections of the fuel salt as well as the spatial distribution of fuel-salt in the core, thus impacting the prompt neutron and DNP concentrations through both spatial and importance effects. However, in the present work, owing to the very low void fractions, the impact of the bubbles has been observed only to a very small extent. Figure 12 shows the normalised prompt neutron profile along the axis for simulated flow with bubbles and theoretical flow without bubbles and the relative difference between the two cases has been shown in Figure 13.

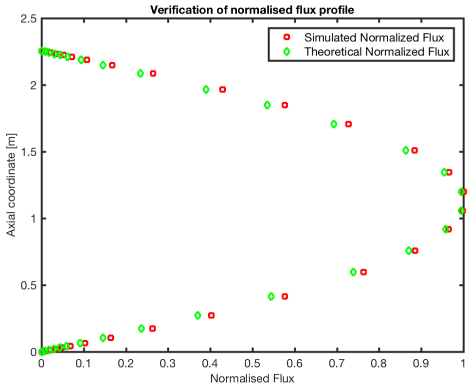

Figure 12: Two-phase normalised prompt neutron distribution

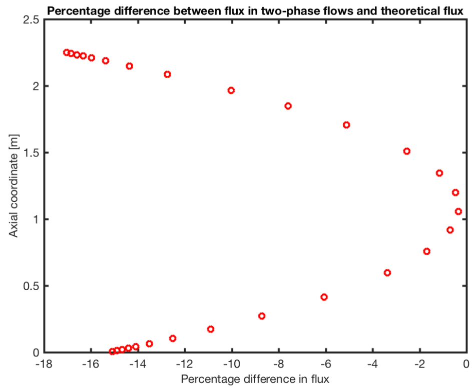

Figure 13: Relative difference between theoretical & computed two-phase flux

The bubbles also provide an additional transport mechanism for DNPs some of which are constituted by metallic species that are not soluble in the molten fluoride matrix. These precursors may leave the fuel circuit due to extraction by gas bubbling or deposition in cold metallic surfaces in the out-of-core part of the loop [7]. This results in a reduction in the effective multiplication factor of the core as shown in Table 1. Figure 14 shows the spatial distribution of the difference in prompt neutron fluxes for single-phase and two-phase flows and Figure 15 shows a similar distribution for DNPs

Table 1: Multiplication factors for different types of fuel flow

Non-circulating fuel	Single-phase circulating fuel	Two-phase circulating fuel
0.9802	0.9781	0.9669

3.3 Bubbling Feedback

The bubbling feedback coefficient was evaluated on the basis of the spatial distribution of the bubbles (shown in figure 6) using first-order perturbation theory and the resulting coefficients were compared with those obtained by Brovchenko et al. using simulations performed with uniform void fractions [8]. At the nominal air mass flow rate prescribed under the SAMOFAR project, that is 20 ltr/sector/min, the bubbles provide a negative reactivity insertion equal to -1.3104 pcm for an average void fraction equal to 1.3817×10^{-4}%. This corresponds to a bubbling feedback coefficient equal to -105.8514 pcm/% which is lower than the bubbling feedback obtained under SAMOFAR using Monte Carlo simulations. The difference in two predictions can mainly be attributed to the differences in the two modelling approaches. These differences include, but are not limited to, the one-group diffusion approximation and the use of volume averaged methods in order to minimise the associated computational costs.

In order to better predict the impact of bubbles, computations for different mass flow rate of the gas were performed and the obtained results have been reported in Table 2. Owing to the same inlet/outlet boundary conditions and flow, the spatial distribution of the bubbles for different mass flow rates was similar to the one shown in figure voidfrac and while only a tiny change was observed in the bubbling feedback coefficient corresponding to different mass flow rates, a further comparison with the uniform void fraction study [8] and another study by Cervi

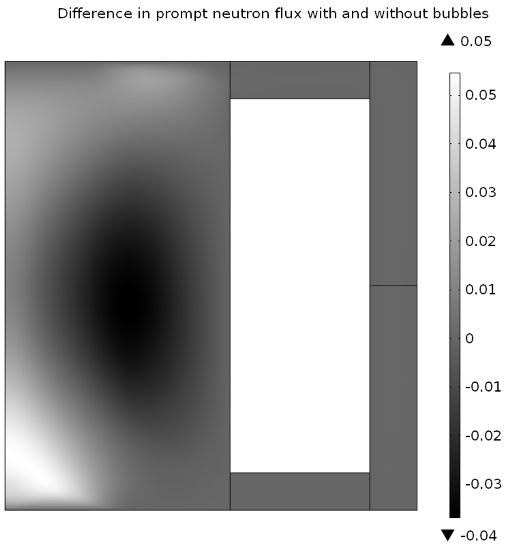

Figure 14: Difference in prompt neutron flux for single and two phase flows

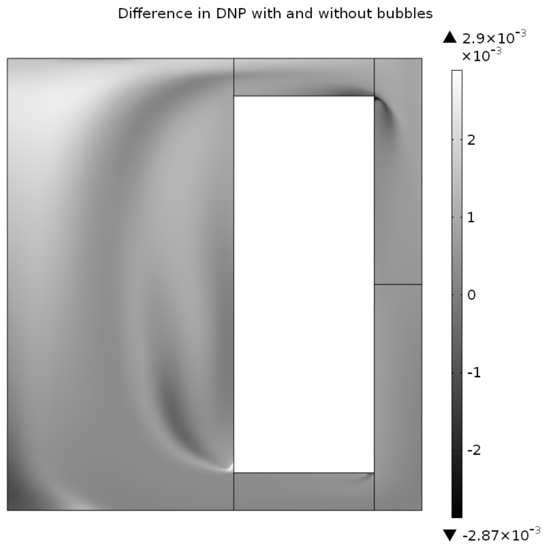

Figure 15: Difference in DNP concentration for single and two phase flows

Table 2: Reactivity change versus average core void fraction

Void Fraction [%]	Multiplication Factor	Void Coefficient [pcm/%]
0.00	$0.979\,900$	
0.69×10^{-4}	$0.979\,880$	-105.61
1.38×10^{-4}	$0.979\,875$	-105.78
1.72×10^{-4}	$0.979\,869$	-105.77
2.07×10^{-4}	$0.979\,862$	-106.46
2.76×10^{-4}	$0.979\,849$	-105.74
3.44×10^{-4}	$0.979\,837$	-105.72

et al. [9] demonstrates the dependence of the bubbling feedback coefficient on the gas bubble distribution within the core. In fact, the results by Cervi et al. [9] show a significant difference in the values of bubbling feedback coefficient for different void fractions as opposed to the present work. This discrepancy arises from difference in bubble inlet and outlet boundaries. While Cervi et al. considered the bubble inlet as an injection and the outlet as a suction, resulting in the bubbles being concentrated in a smooth streamline close to the centre of the core, distributed inlet and outlet were considered in this work, resulting in accumulation of bubbles in areas of low neutronic importance. Moreover, such an accumulation also contributes to comparatively lower bubbling feedback coefficient as mentioned before. Furthermore, for very small void fractions, as in the present case, the distribution remains relatively unaffected for different void fractions, thus contributing to the predicted values of $\alpha_{bubbling}$.

4 CONCLUSION

In this paper, a multiphysics approach coupling Euler-Euler two-fluid model for bubbly flow and heat transfer with one-group diffusion equation for neutronics and transport equation for DNP has been developed. The impact of inert gas bubbles on reactivity was modelled using the bubbling coefficient $\alpha_{bubbling}$ defined as the average reactivity change per unit bubble void fraction. The COMSOL Multiphysics model was validated by comparison with a previous study and was used to simulate the steady state neutronics and thermal hydraulic behaviour of MSFR and to assess the reactivity feedback provided by gas bubbles.

Simulation results have exhibited the impact of inert gas bubbles on the thermal hydraulic and neutronic behaviour showing that, in bubbly flows, bubble-induced turbulence leads to an increase in the salt velocity although the temperature field remains relatively unchanged at very small void fractions as used in the current work. Furthermore, the neutronics results show that both the neutron flux and the DNP concentration are affected by the gas bubbles and the bubble distribution has a significant impact on the reactivity insertion.

Although the current work has been able to develop a baseline multiphysics approach to model inert gas bubbles in the Molten Salt Fast Reactors (MSFR), it is only a starting point for modelling of bubbling system in the MSFR. The model can be further improved by employing multi-group diffusion approximation and using multiple neutron precursor groups instead of one-group approximation. In order to be able to predict the spatial importance of the inert gas bubbles, an adjoint perturbation based analysis model can be implemented within the present model. The two-phase simulation model will help in more accurate prediction of MSFR behaviour and be able to provide the necessary information required for using gas bubbles as a reactivity control method for MSFR.

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