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Abstract

Steam generator tube rupture (SGTR) accident is an important scenario needed to be considered in the safety analysis of lead-based fast reactors. When the steam generator tube breaks close to the main pump, water vapor will enter the reactor core, resulting in a two-phase flow of heavy liquid metal and water vapor in fuel assemblies. The thermal-hydraulic problems caused by the SGTR accident may seriously threaten reactor core's safety performance. In this paper, the open source CFD calculation software OpenFOAM was used to encapsulate the improved Euler method into the self-developed solver LBEsteamEulerFoam. By changing different heating boundary conditions and inlet coolant types, the two-phase flow in the fuel assembly with different inlet gas content was simulated under various accident conditions. The calculation results show that the water vapor may accumulate in edge and corner channels. With the increase of inlet water vapor content, outlet coolant velocity increases gradually. When the inlet water vapor content is more than 15%, the outlet coolant temperature rises sharply with strong temperature fluctuation. When the inlet water vapor content is in the range of 5% to 20%, the upper part of the fuel assembly will gradually accumulate to form large bubbles. Compared with the VOF method, Euler method has higher computational efficiency. However, Euler method may cause an underestimation of the void fraction, so it still needs to be calibrated with future experimental data of the two-phase flow in fuel assembly.

Full Text

Preamble

CFD Analysis of a CiADS Fuel Assembly During a Steam Generator Tube Rupture Accident Based on the LBEsteamEulerFoam Solver

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Abstract

Steam generator tube rupture (SGTR) accidents represent a critical safety analysis scenario for lead-based fast reactors. When a steam generator tube breaks near the main pump, high-pressure water vapor injects into the reactor core, creating a two-phase flow of heavy liquid metal coolant and water vapor within the fuel assemblies. The resulting thermal-hydraulic phenomena can severely compromise core safety performance. This study employs the open-source CFD software OpenFOAM to implement an improved Eulerian method in a self-developed solver called LBEsteamEulerFoam. By varying heating boundary conditions and inlet coolant compositions, we simulated two-phase flow behavior in a fuel assembly across different inlet gas volume fractions under various accident conditions. The results demonstrate that water vapor tends to accumulate in edge and corner subchannels. As inlet water vapor content increases, the outlet coolant velocity rises progressively. When inlet vapor content exceeds 15%, the outlet coolant temperature increases sharply with pronounced temperature fluctuations. For inlet vapor contents between 5% and 20%, large bubbles gradually accumulate in the upper portion of the fuel assembly. Compared with the Volume of Fluid (VOF) method, the Eulerian approach offers significantly higher computational efficiency; however, it may underestimate the void fraction, necessitating future calibration against experimental two-phase flow data from fuel assemblies.

Keywords: Steam generator tube rupture, CiADS, CFD simulations, two-phase flow

1 Introduction

In 2002, six advanced nuclear energy systems, including lead-based fast reactors (LFRs), were formally designated as Generation IV reactors [?]. LFRs feature significantly simplified structures compared to other reactor designs [?] and offer advantages such as excellent nuclear fuel transmutation capability, favorable economics, and inherent safety characteristics [?]. Consequently, numerous countries have invested substantial resources in their development. China approved the China Initiative Accelerator Driven System (CiADS) in 2015 [?], which comprises three subsystems: an accelerator, a spallation target, and a subcritical fast neutron reactor cooled by liquid lead-bismuth eutectic (LBE) [?, ?]. The steam generator (SG) serves as a core heat transfer component in reactor systems. LFRs typically adopt a pool-type design where the core, main pumps, and steam generators are immersed together in the primary vessel coolant [?]. This configuration separates pressurized water in the secondary loop from liquid LBE only by the SG heat transfer tube walls. Numerous tube bundles are implemented to enhance heat exchange capability, creating large pressure and temperature differentials across tube walls that induce significant thermal and mechanical stresses. Combined with coolant vibration and corrosion in both primary and secondary circuits, heat transfer tubes may become the weakest link in the primary system [?], making SGTR accidents a non-negligible risk.

When an SG tube ruptures, high-pressure subcooled water from the secondary circuit injects into low-pressure, high-temperature LBE in the primary circuit, rapidly vaporizing into steam and forming a liquid metal-steam two-phase flow [?]. Current international research on SGTR accidents in lead-based reactors remains in its early stages. Experimental studies have investigated water-liquid metal interaction mechanisms. Sibamoto et al. [?] designed a probe capable of simultaneously measuring temperature and phase state in liquid metal-water-vapor multiphase flows, examining cavity formation, surface-mode boiling, and temperature distributions. Sa et al. [?] constructed an experimental apparatus for dripping molten liquid metal into water to study steam explosion mechanisms between water and lead-bismuth alloys during SGTR accidents. Subsequently, Sa et al. [?] used an alcohol solution to simulate water and fluorinated liquid to simulate LBE, investigating alcohol injection into high-temperature fluorinated liquid to simulate direct-contact boiling between water and high-temperature liquid metal. Dostal et al. [?] built a direct-contact boiling loop for water and LBE to study two-phase boiling heat transfer. Huang et al. [?, ?] conducted experiments on contact fragmentation of high-temperature LBE droplets and liquid columns with subcooled water. Deng et al. [?] performed numerous experiments injecting water lumps into molten lead pools at Sun Yat-sen University.

Due to lead-bismuth's radiation-shielding properties, gamma-ray imaging of two-phase flow patterns remains unclear [?], necessitating numerical simulations for multiphase flow problems in SGTR accidents. Wang et al. [?] used the SIMMER-III safety analysis code to evaluate pressure evolution, water vapor migration in the primary circuit, and core entry potential during SGTR accidents. Ciampichetti et al. [?] employed SIMMER-III to simulate high-pressure water-LBE interaction during SGTR accidents, preliminarily assessing cover gas pressure changes and vapor core entry probability. Zhixing et al. [?] simulated upper and lower head rupture accidents in a small forced-circulation LBE-cooled reactor, finding small amounts of steam migrated into the core under lower head fracture conditions. Dinh's study indicated that when SG rupture occurs near the main pump, water vapor is inevitably transported to the core in large quantities within the active zone [?], causing reactivity changes in fuel rods, heat transfer deterioration, and reactor safety threats. Therefore, investigating two-phase flow in fuel assemblies during SGTR accidents is crucial. Since X-ray imaging cannot characterize internal flow fields in LFR fuel assemblies [?], numerical simulations provide essential thermal-hydraulic parameters. Gu et al. [?] developed the MPC-LBE multi-physics coupling code for LBE-cooled pool reactors. Liu et al. [?] evaluated five turbulent Prandtl number models to accurately predict heat transfer characteristics of low-Prandtl-number fluids in rod bundle subchannels. Yunxiang et al. [?] used the k-ω SST model to study single-phase flow fields in lead-based reactors. Zhou et al. [?] calculated friction pressure drop in wire-wrapped rod bundles, showing friction coefficient dependence on parameters such as rod count and wire diameter ratio. Suzuki et al. [?] investigated two-phase bubble flow in LBE. Wang et al. [?] developed a thermal-hydraulic analysis code for LFR annular fuel based on a closed parallel multichannel model and quantum genetic algorithm. Lanting et al. [?] numerically simulated bubble flow in liquid heavy metals, analyzing morphological changes during bubble rise. Jeltsov et al. [?] studied bubble accumulation and flow in cores during SGTR accidents, indicating small bubbles are more likely to remain in the core.

SGTR accidents are critical for severe accident analysis in LFR development. Fuel assembly two-phase flow during SGTR accidents directly impacts LFR design safety. Currently, few studies address two-phase flow in LFR fuel assemblies, and experimental methods remain immature. Therefore, this study employs open-source OpenFOAM software to predict fuel assembly two-phase flow under SGTR accident conditions, providing technical support for subsequent experimental methods and validating LFR design and development.

* * *

2.1 Governing Equations of the LBEsteamEulerFoam Solver

The Eulerian method treats each phase as a mutually permeable continuum, enabling each phase to possess independent physical properties including pressure, temperature, and velocity. When simulating gas-liquid two-phase flow using this approach, interphase forces must be analyzed to close the governing equations. In liquid metal gas-liquid two-phase flows, interphase mass transfer is generally neglected, and the governing equation is:

$$\frac{\partial(\alpha_i\rho_i\mathbf{u}_i)}{\partial t}+\nabla\cdot(\alpha_i\rho_i\mathbf{u}_i\mathbf{u}_i)=-\alpha_i\nabla p+\nabla\cdot(\alpha_i\mu_i(\nabla\mathbf{u}_i+(\nabla\mathbf{u}_i)^T))+\alpha_i\rho_i\mathbf{g}+\mathbf{F}_{ij}$$

where α_i, ρ_i, and $\mathbf{u}_i$ represent the macroscopic volume fraction, density, and velocity of phase i, respectively, and $\mathbf{F}_{ij}$ denotes the interphase force between gas and liquid phases. This force primarily represents momentum transfer between phases, resulting from combined actions of various forces [**?**]:

$$\mathbf{F}_{ij}=\mathbf{F}_D+\mathbf{F}_L+\mathbf{F}_{WL}+\mathbf{F}_{TD}+\mathbf{F}_{VM}$$

where $\mathbf{F}_D$ represents drag force from relative gas-liquid motion, $\mathbf{F}_L$ denotes lift and lateral forces from pressure differences perpendicular to bubble motion, $\mathbf{F}_{WL}$ is wall lubrication force generated by slip velocity near walls, $\mathbf{F}_{TD}$ represents turbulent diffusion force from liquid turbulence acting on bubbles, and $\mathbf{F}_{VM}$ is virtual mass force from relative acceleration changes.

The drag force on a single bubble can be expressed as [**?**]:

$$\mathbf{F}_D=\frac{3}{4}C_D\frac{\rho_l}{d_b}\alpha_g|\mathbf{u}_r|\mathbf{u}_r$$

The shear-induced lift force on a bubble is [**?**]:

$$\mathbf{F}_L=-C_L\rho_l\alpha_g\mathbf{u}_r\times(\nabla\times\mathbf{u}_l)$$

The mathematical expression for wall lubrication force is [**?**]:

$$\mathbf{F}_{WL}=C_{WL}\rho_l\alpha_g|\mathbf{u}_{rw}|^2\mathbf{n}_w$$

The turbulence dispersion force model is [**?**]:

$$\mathbf{F}_{TD}=-C_{TD}\rho_l k_l\nabla\alpha_g$$

The virtual mass force can be expressed as [**?**]:

$$\mathbf{F}_{VM}=C_{VM}\rho_l\alpha_g\left(\frac{D\mathbf{u}_g}{Dt}-\frac{D\mathbf{u}_l}{Dt}\right)$$

where C_D, ρ_l, $\mathbf{u}_r$, and d_b represent the bubble drag coefficient, liquid density, relative velocity between phases, and bubble diameter, respectively. C_L is the lift coefficient, α_g is the gas phase volume fraction, and $\mathbf{u}_l$ is the liquid phase velocity. C_{WL} is the wall lubrication force coefficient, $\mathbf{u}_{rw}$ is the tangential component of relative velocity at the wall, and $\mathbf{n}_w$ is the wall unit normal vector. C_{TD} is the turbulence dispersion coefficient, k_l is the liquid phase turbulent kinetic energy, and C_{VM} is the virtual mass force coefficient.

The standard k- model [?] provides the simplest and most economical turbulence modeling approach, offering good convergence and accurate predictions for pipe flows and shear flows. The turbulent kinetic energy k and its dissipation rate ε are expressed as:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{u} k) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right) + G_k - \rho\varepsilon$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \mathbf{u} \varepsilon) = \nabla \cdot \left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_{\varepsilon 1} \frac{\varepsilon}{k} G_k - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k}$$

These equations are coupled through:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

where μ is the laminar dynamic viscosity, μ_t is the turbulent dynamic viscosity, σ_k and σ_ε are diffusion Prandtl numbers, and the model constants C_μ, $C_{\varepsilon 1}$, and $C_{\varepsilon 2}$ are 0.09, 1.44, and 1.92, respectively.

The Prandtl number for liquid LBE is nonlinear. Since turbulence effects were considered in subsequent calculations, the LBE Prandtl number was modified [?] as:

$$Pr_t = 4.12 + 0.0175 \cdot Pe^{0.69} \quad \text{for} \quad Pe < 1000$$
$$Pr_t = 11.5 \quad \text{for} \quad Pe \geq 1000$$

OpenFOAM provides numerous operators for solving partial differential equations. In this study, each physical quantity in the governing equations was first defined on the open-source platform to enable numerical calculation during operations. The governing equations were then assembled using OpenFOAM operators, which provide both explicit and implicit calculation methods for conservation equations. A second-order discretization scheme was employed to ensure computational accuracy. The improved governing equations were encapsulated within OpenFOAM as a self-developed solver named LBEsteamEulerFoam, capable of simulating liquid lead/lead-bismuth and water vapor two-phase flows.

2.2 Meshing the CiADS Assembly

In advanced LFR designs, fuel rods are typically arranged in triangular pitch within hexagonal assemblies. Assembly subchannels are classified into three types: interior, edge, and corner. This study employed CiADS subcritical reactor fuel assembly parameters [?] for simulation. The computational domain covered the active region of the fuel assembly with an axial height of 720 mm. The regular hexagonal fuel assembly contained 60 fuel rods with a central stainless-steel rod serving as a locking mechanism to prevent assembly flotation in liquid LBE. Fuel rod diameter was 13.1 mm with a pin pitch of 15.1 mm.

A structured grid was used for model discretization to ensure two-phase flow calculation accuracy. Grid partitioning results are shown in Fig. 1a [Figure 1: see original paper], with boundary layer settings on fuel rod outer surfaces detailed in Fig. 1b. The mesh was verified using OpenFOAM's "checkMesh" utility, confirming it met computational requirements. The total cell count was 2,303,680 with maximum skewness of 0.544, orthogonal quality exceeding 0.7, and Y-plus values approximately 30.

2.3 Boundary Conditions and Mesh Independence Analysis

Numerical simulations require appropriate boundary conditions based on actual operating conditions. The CiADS design methodology [?, ?] was used to establish boundary conditions listed in Table 1 . Transient simulations were performed to investigate bubble behavior under different heating conditions, with three cases defined in Table 2 . Due to the lack of reliable experimental data for lead-based reactor fuel assembly two-phase flows, the gas-liquid mixture was assumed uniformly mixed when passing through the main pump. The assembly inlet was specified as a uniform mixture of both phases, with gas content representing the volume fraction occupied by gas in the mesh. Gas content was varied from 1% to 30% to assess impacts on bubble distribution, velocity, and other operational parameters.

A mesh independence study was conducted to eliminate grid effects on solution accuracy. Five grid densities were generated for the fuel assembly model, with maximum temperature and velocity at the assembly outlet selected as independence metrics. Fig. 2 [Figure 2: see original paper] presents results for all five grids. The 2,303,680-cell grid yielded similar results to the 2,786,670-cell grid, while the 1,678,372-cell grid showed significant deviation. Solutions with 5,467,372 and 12,072,264 cells were comparable to the 2,303,680-cell case but required substantially longer computation times. Balancing accuracy and efficiency, the 2,303,680-cell grid was selected for subsequent calculations.

2.4 Coolant Properties

Liquid LBE served as the CiADS fuel assembly coolant. Due to Pb-Bi's unique thermal properties, calculations differed from conventional coolants, requiring experimentally measured and fitted thermophysical correlations [?] listed in Table 3 . Steam properties from the international IAPWS-IF97 standard [?] were defined in the OpenFOAM material database.

2.5 Simulation Model Verification

Due to liquid LBE's opacity and X-ray detection difficulties, experimental data for LBE two-phase flows are scarce. To verify LBEsteamEulerFoam accuracy for lead-based fast reactor simulations, single-phase flow in a wire-wrapped LBE-cooled assembly was simulated by setting inlet gas content to 1×10^{-6} without interphase force closure, corresponding to the oxygen control level in LBE loops. In 2016, KIT performed a 19-rod bundle wire-wrapped fuel assembly heat transfer experiment using LBE coolant in the THEADES loop vertical section. Experimental boundary conditions were: inlet temperature $T_{in} = 473$ K, inlet mass flow rate $M = 19.18$ kg/s, and total heating power $Q = 197.04$ kW, uniformly distributed along each rod's heated length. Following the MYRRHA reactor design, experimental data from Pacio [?] and results from the validated SACOS-PB subchannel code [?] were compared under identical conditions. SACOS-PB is an essential tool for reactor thermal-hydraulic design and safety analysis. To improve computational efficiency, periodic inlet/outlet boundaries were applied based on spacer wire periodicity. Pacio selected three axial measurement positions in the heated section; data at 820 mm axial height were chosen for comparison due to greater gas-liquid two-phase flow sensitivity to axial variation. Measurements were arranged in five subchannels (3, 14, 15, 29, and 39), with calculated center positions extracted for comparison. Fig. 3 [Figure 3: see original paper] compares coolant temperatures across subchannels at the 820 mm active zone axial height.

As shown in Fig. 3, coolant temperatures vary among subchannels on the same cross-section, with higher temperatures in interior channels near the central rod bundle compared to edge and corner channels. SACOS-PB and LBEsteamEulerFoam results agreed well under identical conditions, with maximum relative error below 1.13%. Compared to experimental data, LBEsteamEulerFoam's maximum relative error was less than 4.17%. These results confirm the solver's accuracy and high precision for 10^{-6} gas content, validating its use for subsequent two-phase flow simulations.

3.1 Bubble Accumulation

Fig. 4 [Figure 4: see original paper] illustrates bubble distributions in Case 1 with 10% water vapor content at the fuel assembly inlet. Due to the transient nature of multiphase flow calculations, three typical bubble distribution scenarios were analyzed at middle and outlet sections, with data extracted at three time points and normalized. Error bars represent calculation fluctuations. Bubbles accumulated in edge and corner channels, with increasing accumulation over time. These results inform liquid heavy metal aggregation analysis in fuel assemblies. Significant temperature distortion occurs in bubble accumulation regions, necessitating improved fuel assembly box high-temperature resistance for SGTR accidents. Greater bubble aggregation occurred in outlet edge channels compared to middle sections, indicating bubble accumulation during upward transport through the assembly.

Corner channels feature two walls meeting at 120°, creating flow influenced by both assembly box and fuel rod walls. This region's smaller heating area complicates flow characteristics, producing non-uniform coolant velocity distributions across the cross-section with lower velocities in corner channels. As coolant flows through the fuel assembly, bubbles are dragged from high-velocity to low-velocity regions, resulting in accumulation at edge and corner channels.

3.2 Outlet Section Velocity

Fig. 5 [Figure 5: see original paper] shows maximum two-phase fluid velocity at the fuel assembly outlet. Thirty datasets with gas contents from 1% to 30% were calculated for three cases. Due to water vapor's low density and expansion effects, two-phase flow velocity strongly correlates with inlet vapor content. Maximum liquid metal velocity at the outlet increased with inlet water vapor content. For inlet vapor content below 15%, outlet velocity fluctuations were small with gradual growth. Above 15% inlet vapor content, two-phase flow velocity fluctuations became significant and increased progressively, indicating gas phase presence and migration disturbed coolant flow. Fixed-temperature heating conditions produced larger two-phase flow velocities at high gas contents compared to other cases. Cosine axial power distribution produced larger velocity fluctuations at the outlet.

Steam bubble expansion relates two-phase flow velocity to inlet steam content. The less dense gas phase forms large bubbles axially, occupying greater cross-sectional area. Without phase change between LBE and steam bubbles, liquid phase cross-sectional area decreases, and by continuity, liquid-phase velocity increases. Both phase velocities increase by different magnitudes. The Eulerian method employs separate Navier-Stokes equations for each phase, making it more suitable for high-gas-content two-phase flow simulations. Interphase lift forces may increase gas-phase velocity, but gas-phase velocity growth remains smaller than liquid-phase growth due to greater resistance.

3.3 Temperature Distributions at Middle and Outlet Sections

During SGTR accidents, fuel assembly coolant temperature is affected by water vapor content, which significantly influences fuel assembly design parameters such as material selection and geometry. Fig. 6a [Figure 6: see original paper] shows maximum coolant temperature variation in the axial mid-section as inlet vapor content increases from 1% to 30%. Since temperature changes were less pronounced for fixed-temperature heating, fixed heat flux and cosine distribution cases were analyzed. As inlet vapor content increased from 1% to 15%, mid-section maximum coolant temperature rose slowly, with vapor content not yet dominating two-phase flow. Above 15% inlet vapor content, coolant temperature increased significantly with obvious fluctuations, providing insight into fuel rod thermal fatigue resistance.

Fig. 6b shows inlet vapor content versus outlet section temperature for fixed and cosine-shaped heat fluxes. Below 15% inlet vapor content, assembly coolant temperature remained within the fuel assembly's designed safety range with small fluctuations, indicating tolerance to small water vapor amounts under normal operation. Above 15% inlet vapor content, outlet coolant maximum temperature increased noticeably with more significant fluctuations, suggesting the fuel assembly must withstand greater thermal stress and fatigue.

Fig. 6c illustrates axial temperature distributions for fuel rods 2 and 40 under cosine-distributed heat flux. Single-phase flow temperature differences between rods were minimal due to absence of spacer wire cross-mixing. In two-phase flow, both fuel rods' axial temperatures increased with height, but fuel rod 2's cladding surface temperature rise exceeded that of fuel rod 40. The maximum temperature growth rate occurred at $Z = 0.36$ m, where linear power density peaked. Fuel rod 2's outlet temperature approached 850 K, considerably higher than CiADS design calculations [?]. This instantaneous calculation showed the grid location with maximum gas content changed over time, with contour results demonstrating bubble accumulation in edge and corner channels. The assembly outlet's hottest locations were typically distributed in interior channels.

Steam's relatively low specific heat capacity yields much lower cladding cooling capacity in the gas phase compared to liquid LBE, potentially causing unexpected temperature increases. Simultaneously, narrow subchannel areas within the fuel assembly may become blocked by large bubbles near the outlet, causing heat transfer deterioration. With cosine-distributed heat flux, maximum linear power rating occurred at $Z = 0.36$ m, where bubble accumulation could significantly deteriorate the heat transfer coefficient between cladding surface and coolant. The relatively thin cladding wall's limited heat capacity may cause local overheating.

3.4 Maximum Steam Volumetric Fraction

Figs. 7a–c [Figure 7: see original paper] show relationships between maximum vapor content in middle and outlet sections versus inlet vapor content. Maximum grid gas holdup at the outlet exceeded that in the middle section. As described in Section 3.1, greater bubble accumulation occurred in outlet edge channels than middle section edge channels, indicating bubble accumulation during upward transport through subchannels. Below 2% inlet gas content, maximum grid gas holdup differences between outlet and middle sections were slight, indicating negligible bubble accumulation and no large bubble formation. As inlet vapor content increased from 5% to 15%, outlet section grid gas holdup increased steeply, showing rapid maximum vapor content growth during this process.

Moreover, outlet section grid gas holdup growth slope exceeded that of the middle section, indicating large bubbles gradually accumulated in the fuel assembly upper region. Above 15% inlet gas content, maximum grid gas content growth rate moderated, gradually approaching maximum values. Above 25% inlet gas content, differences between outlet and middle section maximum gas content became small, indicating bubble coalescence saturation in the assembly upper region at higher gas contents. Grid gas content percentage increased due to large bubble presence, with maximum grid gas content rising with axial height.

3.5 Comparison with the VOF Model

Currently, few studies address two-phase flow in LFR fuel assemblies, and experimental methods remain immature. Multiphase flow simulations are categorized into interface-capturing models (VOF method) and high-phase-fraction multiphase flow models. The VOF method tracks interfaces between immiscible fluids. Sheng et al. [**?**] used VOF to simulate ADS fuel assembly two-phase flow with varying inlet vapor contents, heating conditions, and coolants, showing water vapor accumulation and significant temperature fluctuations. Due to experimental data scarcity, Eulerian results were compared with VOF calculations. Fig. 8a [Figure 8: see original paper] compares water vapor bubble accumulation at edge and corner channels calculated by both methods. Bubbles accumulated into clusters in corner channels, with greater aggregation than in edge channels. VOF method produced larger bubbles in corner channels and greater side channel aggregation than the Eulerian method. Bubble aggregation degree significantly influenced coolant velocity and temperature.

Fig. 8b compares maximum fuel assembly outlet temperatures from both methods. Maximum component outlet temperature increased gradually with inlet vapor content, rising significantly above 15% inlet vapor content. Both solvers showed good agreement in trend, with maximum temperature relative error below 5.83%. LBEsteamFoam solver required 42.3 hours to simulate 10 seconds post-accident, while LBEsteamEulerFoam needed only 1.64 hours with identical hardware.

The Eulerian method demonstrates higher computational efficiency than VOF for LFR fuel assembly two-phase flows. The methods differ significantly in mesh requirements: VOF performs direct multiphase flow simulation similar to DNS and must capture phase boundaries, requiring finer meshes; the Eulerian method does not need to resolve phase boundaries precisely, thus requiring coarser meshes and enabling higher efficiency. While VOF captures phase boundaries well and describes bubble accumulation in corner and edge channels effectively, the Eulerian method's independent phase properties better describe parameters such as bubble diameter, interphase force models, and multi-scale distributions, offering unique advantages for high-phase-fraction flows. However, Eulerian method deviations from VOF results necessitate further experimental verification. Fuel assembly test facilities require assembly boxes since bubbles accumulate at edge and corner channels, with measurement points arranged in these regions to monitor water vapor phase in two-phase flow.

4 Conclusions

Investigating steam generator tube rupture accidents enhances lead-based fast reactor safety. This study used open-source CFD software OpenFOAM to calculate liquid heavy metal-water vapor two-phase flow in fuel assemblies. By varying heating boundary conditions, we analyzed bubble aggregation, velocity, temperature, and maximum cross-sectional grid gas content under different operating conditions, yielding the following conclusions:

1) At the fuel assembly outlet, bubbles preferentially accumulate in edge and corner channels near the assembly box, with greater accumulation in corner channels than edge channels. As inlet water vapor content increases, fuel assembly outlet two-phase flow velocity increases.

2) Increasing inlet vapor content gradually raises fuel assembly internal temperature. Due to water vapor's poor heat conduction, maximum achievable coolant temperature in the fuel assembly may increase. Below 15% inlet vapor content, maximum outlet temperature remains within design limits. Above 15% inlet vapor content, maximum outlet temperature rises sharply, easily reaching fuel rod operating limits and affecting fuel assembly safety. Temperature fluctuations also increase above 15% inlet vapor content, exacerbating thermal fatigue stress on fuel rods and assembly boxes.

3) Maximum grid gas content at the fuel assembly outlet increases gradually with inlet steam content. Below 5% inlet vapor content, the gas phase is not dominant. Between 5% and 20% inlet vapor content, large bubbles gradually accumulate in the fuel assembly upper region. Extensive bubble

coalescence and breakup significantly increase maximum grid gas content at assembly cross-sections. Above 20% inlet gas content, maximum grid gas content shows no obvious upward trend.

4) Compared with VOF, the Eulerian method offers higher computational efficiency for LFR fuel assembly two-phase flows. Each Eulerian phase has independent physical properties, enabling better description of parameters such as bubble diameter, interphase force models, and multi-scale distributions. However, the Eulerian method may underestimate void fraction, potentially leading to underestimation of positive reactivity feedback in lead-based reactors, necessitating future cross-validation with two-phase flow experimental data.

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Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Yun-Xiang Li, Lu Meng, Zi-Nan Huang, Song Li, Di-Si Wang, Bo Liu, You-Peng Zhang, Tian-Ji Peng, Lu Zhang, Xing-Kang Su, and Wei Jiang. The first draft was written by Yun-Xiang Li, and all authors commented on previous manuscript versions. All authors read and approved the final manuscript.

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