Phase behavior evolution in the interaction of lead–bismuth liquid metal and water

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Abstract

The vapor diffusion and transport resulting from steam generator tube rupture (SGTR) accidents are a majorconcern threatening lead-based reactor core safety. In this study, a high-parameter SGTR experimental platformand the multiphase multi-physics processes numerical simulation were developed to investigate the phasebehavior and interaction mechanisms. This study revealed the interaction mechanisms of lead–bismuth liquidmetal and water driven by flash vaporization, jet direct contact boiling, and film boiling. The migration andevolution of the discrete phases (vapor–water mixture) were inferred from the temperature transient laws anda numerical simulation. The results revealed that the evolution of the discrete phases consists of three stages:cavity formation, flanking diffusion, and stable up-floating. The jet pressure significantly extended the disturbanceperiod. Variations in the water temperature mainly affected the decompression boiling process, alteringthe diffusion region of the discrete phases. The temperature of the liquid metal and the duration of the jet had aminimal impact on the behavior of the discrete phases. This study provides a crucial reference for constructinga complete picture of accident evolution.

Full Text

Preamble

Phase Behavior Evolution in the Interaction of Lead–Bismuth Liquid Metal and Water

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The vapor diffusion and transport resulting from steam generator tube rupture (SGTR) accidents represent a major threat to lead-based reactor core safety. In

this study, we developed a high-parameter SGTR experimental platform and conducted multiphase, multi-physics numerical simulations to investigate phase behavior and interaction mechanisms. Our work reveals the interaction mechanisms between lead–bismuth liquid metal and water driven by flash vaporization, jet direct contact boiling, and film boiling. The migration and evolution of discrete phases (vapor–water mixture) were inferred from temperature transient laws and numerical simulation. The results show that discrete phase evolution consists of three stages: cavity formation, flanking diffusion, and stable up-floating. Jet pressure significantly extended the disturbance period, while variations in water temperature primarily affected the decompression boiling process, altering the diffusion region of the discrete phases. The temperature of the liquid metal and the duration of the jet had minimal impact on discrete phase behavior. This study provides a crucial reference for constructing a complete picture of accident evolution.

Keywords: Discrete phases migration; LBE–water interaction; Steam generator tube rupture; Lead-cooled fast reactors

Introduction

Lead-cooled fast reactors, considered highly promising Generation-IV nuclear energy systems, have garnered significant attention from the international nuclear energy community [?, ?]. An SGTR accident in a lead-cooled fast reactor can trigger a series of complex chain reactions [?], resulting in fluctuations in core power [?]. When high-pressure subcooled water comes into direct contact with high-temperature liquid metal, intense heat and mass transfer occurs. The generation of large amounts of vapor leads to pressure accumulation in the system, and bubbles may be carried by the coolant into the core. Furthermore, direct contact between cold and hot fluids can cause the liquid metal to lose heat and potentially solidify. Thus, consequence assessment of SGTR accidents and research on mitigation measures are essential for advancing lead-cooled fast reactors toward commercial deployment [?, ?].

Fig. 1 [Figure 1: see original paper] shows a schematic diagram of an SGTR accident in a lead-cooled fast reactor. The accident involves strong thermodynamic and kinetic interactions between lead–bismuth eutectic liquid metal (LBE) and water [?], resulting in complex multiphase flow phenomena. Bubbles induced by these interactions can cause severe core power fluctuations if they enter the core [?]. The migration and evolution path of discrete phases within the continuous phase (LBE) is a direct prerequisite for understanding bubble entry into the core.

The complexity of boiling multiphase flows combined with the light-shielding properties of liquid metals poses significant challenges to understanding phase evolution during interactions. Consequently, the mechanisms governing phase evolution in LBE-water interactions remain poorly understood [?, ?, ?]. The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) was among the earliest international institutions to focus on this type of accident, though its primary concern was validation of SIMMER codes rather than discrete phase migration [?].

Other researchers have examined metal fragmentation mechanisms by observing liquid metal droplets entering a water pool. For example, Huang et al. [?] used a high-speed camera to record the fragmentation behavior of molten LBE underwater. Similarly, Tan et al. [?] conducted experiments using the VTMCI facility by injecting molten lead–bismuth amorphous alloy into water in free-fall mode, investigating the effects of experimental parameters such as water temperature, LBE temperature, melt penetration rate, and water depth on molten LBE fragmentation. However, this experimental approach differs from the phenomenon of water jetting into liquid metal following SGTR.

Subsequently, radiographic imaging techniques were developed to investigate bubble flow behavior [?, ?, ?]. However, lead–bismuth liquid metals, commonly used as radiation shielding materials, exhibit strong absorption of radiation particles, resulting in lower imaging resolution [?]. Ultrasound technology, initially utilized in the medical industry and other fields, was later adapted to observe bubble behavior within liquid metals. Murakawa et al. [?] developed an ultrasound computed tomography (UCT) system consisting of eight ultrasound transducers to reconstruct three-dimensional images of gas bubbles, though the reconstructed images did not include velocity data, preventing acquisition of bubble position and motion information. Although existing ultrasound techniques can examine certain parameters (velocity and displacement) [?, ?], capturing transient phase interface evolution and motion characteristics remains challenging.

Numerical simulations employing interface evolution and tracking methods have been developed to analyze multiphase behavior [?, ?, ?]. The SIMMER code possesses unique advantages for simulating severe accidents in metal-cooled fast reactors [?, ?, ?]. Although verified in the LIFUS5 series of experiments, the lack of a multiphase flow structure in the code causes deviations between numerical results and test data. Huang et al. [?] replicated the LIFUS5/Mod2 experiments using MC3D and concluded that additional experiments and physical modeling were required to improve MC3D capabilities. Yakush et al. [?] demonstrated the significant potential of the Volume of Fluid (VOF) method for complex multiphase flow numerical calculations by simulating interactions between water and molten metal in non-boiling states, with plans to explore boiling state interactions in future work. Ling et al. [?] combined VOF and level set methods to track moving interfaces during phase transitions, proving competitive in terms of accuracy. In summary, due to the complexity of multiphase interactions, numerical simulation methods remain in the exploratory stage.

Discrete phase diffusion and evolution are crucial for constructing a complete picture of SGTR accidents and further understanding bubble migration. However, the opacity of liquid metals and the complexity of multiphase interactions make the phase behavior mechanism and evolution process difficult to fully comprehend. In this research, we conducted experiments and developed numerical simulations to examine the mechanisms underlying LBE–water interactions and reproduced the migration and evolution behavior of discrete phases in LBE–water interactions based on transient temperature data and numerical simulations within the liquid metal.

II. Experimental and Numerical Simulation Methods

A. Test Platform and Procedure

The LIJI test platform for LBE–water interactions, designed by Shanghai Jiao Tong University, was used to study discrete phase migration and evolution. The layout of LIJI is illustrated in Fig. 2 [Figure 2: see original paper], with detailed system information available in a previous paper [?].

The experimental pipeline included LBE, water, and gas lines, corresponding to the red, green, and blue lines in Fig. 2. The experimental setup consisted of five subsystems: water preheating, LBE preheating, reaction and unloading, flue gas purification, and remote measurement and control. The water preheating system comprised equipment including the deionized water tank S1, water preheating tank S2, solenoid valve V5, and high-pressure argon gas source control valve V1, with the primary purpose of controlling water preheating and pressurization. The LBE preheating system consisted of equipment including the argon gas source control valve V8, preheating tank S4, and lead valves Vpb1, Vpb2, and Vpb3, used to melt and heat the liquid metal. The reaction and unloading system comprised the reaction tank S3 and recovery tank S5, used to conduct experiments and recover liquid metal afterward. The flue gas purification and remote measurement systems were auxiliary subsystems used to prevent the spread of toxic lead fumes and enable remote experimentation, consisting of equipment including a heat exchanger (HX), dust collector (DC), scrubber tower (CST), fan (AP), alkali solution tank (MS), and dehumidifier (DH).

In the setup, S2 and S4 were heating tanks for water and liquid metal, respectively, corresponding to the green and red tanks in Fig. 2. After being heated to the required temperature and pressure in S2 and S4, the water and liquid metal were introduced into the reaction tank S3 (the orange tank in Fig. 2) using pressure and gravity. As shown in Fig. 3 [Figure 3: see original paper], high-precision guided wave radar (1 mm resolution, 3 mm accuracy) measured changes in the LBE liquid level. Since the molten lead tank was directly connected to the test section, a drop in its liquid level corresponded to a rise in the test section. After the experiment, all liquid metal in the test body flowed into the recovery tank S5, with the liquid metal level verified by cutting open the S5 tank. The high-speed solenoid valve V5 was installed on the jet pipeline to control the jet via valve opening and closing. When the LBE parameters in test section S3 reached the preset working conditions, the high-speed responsive solenoid valve V5 opened to precisely control the water jet time (with a jet flow rate error of less than 2.5% and a jet time of 0.5 s). Table 1 provides an overview of the test conditions for this study.

B. Test Section and Measurement

This study focused primarily on the diffusion behavior of the vapor–water mixture within the liquid metal after high-pressure subcooled water was injected into a high-temperature liquid metal pool. Numerous bubbles were generated within the liquid metal, rising into the cover gas space due to buoyancy. The pressurization rate of the cover gas indicated the interaction mechanism between the liquid metal and water. Therefore, the main test data included the cover gas pressure inside the reaction tank (p1) and transient temperature data from measurement points within the liquid metal (T4–T11). The pressure evolution of the cover gas reflected the intensity of phase change, while temperature transients at measurement points indicated vapor–water mixture passage, aiding mapping of its diffusion behavior. Other measurement points were auxiliary and are not included in this paper.

Fig. 4 [Figure 4: see original paper] shows a schematic diagram of the test section with the distribution of internal measurement points. Inside S3, 12 thermocouples and 2 transient pressure transducers with high-frequency response (10 kHz) were installed. The test section's total volume was 60 L, with liquid metal occupying 30 L. The nozzle diameter was 10 mm, and a high-pressure check valve was installed at the nozzle end to prevent lead-bismuth backflow. Measurement errors are summarized in Table 2. The physical properties of LBE were determined using recommended relationships from the Pb-Bi Metal Handbook [?]:

$$
\begin{aligned}
\kappa_{lm} &= 3.61 + 0.01517T - 1.741 \times 10^{-6}T^2 \\
\mu_{lm} &= 94.94 \times 10^{-7}e^{754.1/T} \\
c_{p,lm} &= 159 - 0.0272T + 7.12 \times 10^{-6}T^2 \\
\rho_{lm} &= 11096 - 1.3236T \\
\beta_{lm} &= 8383.2 - T
\end{aligned}
$$

C. Numerical Simulation Methods

Numerical simulations of LBE–water interactions were carried out using the ANSYS Computational Fluid Dynamics (CFD) software to support experimental data and aid understanding of phase behavior evolution characteristics and interaction mechanisms. The geometry model and liquid metal physical properties are presented in Subsection 2.2. Vapor was treated as an ideal gas with physical properties taken from the U.S. National Institute of Standards and Technology (NIST) database. The cover gas did not directly participate in LBE–water interaction, so it was modeled as vapor to reduce simulation complexity. The VOF method was employed to track the phase interface, and a User-Defined Function (UDF) program was utilized to adjust mass and energy transfer due to phase change. Energy transfer was calculated as the product of the mass rate induced by phase change and latent heat. The three main conservation equations used in the VOF model are:

$$\frac{\partial(\alpha_i\rho_i)}{\partial t} + \nabla\cdot(\alpha_i\rho_i\mathbf{u}_i) = \dot{m}$$

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla\cdot(\rho\mathbf{u}\mathbf{u}) = -\nabla p + \nabla\cdot\left[\mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] + \rho\mathbf{g} + \mathbf{F}_{vol}$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla\cdot(\mathbf{u}(\rho E + p)) = \nabla\cdot\left(k\nabla T - \sum_j h_j\mathbf{J}_j + \tau_{eff}\cdot\mathbf{u}\right) + S_h$$

where subscript i represents liquid or gas, $\dot{m}$ is the mass transfer rate, $\mathbf{u}^T$ is the transpose of the velocity matrix, μ is viscosity, $\mathbf{F}_{vol}$ is the volume force, k is effective thermal conductivity, and $\mathbf{J}_j$ is the diffusion flux of components. The first three terms on the right side represent energy transfer due to heat conduction, species diffusion, and viscous dissipation, with source terms.

The turbulence model chosen was the Realizable $k-\epsilon$ model, an optimized version of the standard turbulence model that becomes more suitable for jets with the introduction of averaged flow concepts. For temperature-driven phase change evaporation phenomena, the Lee model can describe these processes. As shown in Eq. 9, the pressure-driven flashing process was converted into a multiphase mass flow inlet by calculating the mass flow rate and void fraction after flashing. The calculation process is as follows.

Based on Dalton's law of partial pressures, principles of isentropic expansion, and the ideal gas assumption, the vapor–water mixture after flashing can be expressed as:

$$P = P_{Air} + P_{H_2O,g}$$

$$x_g = \frac{(s_{l1} - s_{la})}{(s_{ga} - s_{la})}$$

$$\dot{m}_g = \frac{(m_g + m_l)}{t_j}$$

In these expressions, p is the pressure (measured by the p03-1 sensor inside the nozzle), x_g is the mass vapor fraction, s_{l1} is the initial state entropy of the water, subscript a denotes the saturated state, and R is the ideal gas constant.

During flash evaporation, the sensitivity of vapor temperature change to system pressure is small compared to the mass flow rate, so the effect of temperature change rate is omitted. Therefore, Eq. 12 can be rewritten as:

$$\dot{m}_g = \text{coeff} \cdot \alpha_l \rho_l \frac{(T_l - T_{sat})}{T_{sat}}$$

The Lee model is a semi-empirical formulation with a wide range of evaporation coefficients:

$$\dot{m}_{lg} = \text{coeff} \cdot \alpha_l \rho_l \frac{(T_l - T_{sat})}{T_{sat}}$$

where coeff is the evaporation coefficient (dynamically adjusted using the UDF program in this study based on experimental data from different cases), α_l is the liquid phase fraction, and T_l is the liquid phase temperature. Condensation was not involved in this study, so the condensation phase change was not considered.

It is worth noting that the Lee model has limited applicability to pressure-driven flash vaporization phase change mechanisms. The high-pressure, high-temperature water jet was accompanied by depressurization flash evaporation. As shown in Fig. 5 [Figure 5: see original paper], flashing is a non-equilibrium, strong transient phase change behavior. Therefore, direct simulation of flashing in LBE–high-temperature water interactions was impractical.

The wall boundary condition was defined as constant wall temperature, consistent with the experimental setup involving constant-temperature wall heating. Initial conditions included: the computational domain contained 30 L of liquid metal and 30 L of cover gas, the initial temperature was determined by experimental conditions, and the initial pressure was atmospheric.

The geometry was sealed without an outlet, and the mass flux inlet condition caused repeated iterations of the total inlet pressure, making numerical convergence extremely difficult. Therefore, a structured grid was used to minimize numerical errors, ensuring grid quality ranged from 0.95 to 1.0 (Fig. 6 [Figure 6: see original paper]). To reduce grid number influence on results, grids of 5w, 21w, 40w, 62w, and 72w were used to test instantaneous cover gas pressurization at the jet moment. As shown in Fig. 7 [Figure 7: see original paper], 62w grids ensured both high accuracy and time efficiency. The Semi-Implicit Method for Pressure Linked Equations Consistent (SIMPLEC) algorithm decoupled the velocity-pressure relationship, with density, momentum, and energy equations discretized using the second-order upwind format and the higher-order Quadratic Upwind Interpolation of Convective Kinematics (QUICK) format for volume fraction. The minimum time step was 10^{-5} s, and 10^{-4} s was used as the minimum criterion for forced convergence of residuals.

III. Results and Discussion

A. Physical Mechanism for LBE–Water Interaction

Fig. 8 [Figure 8: see original paper] illustrates pressurization during LBE–water interaction. The data indicate that interaction between high-temperature lead–bismuth liquid metal and high-pressure subcooled water occurred in three stages. The physical mechanisms were as follows.

First, high-pressure subcooled water began to flash after solenoid valve V5 opened, and the resulting vapor–water mixture entered the liquid metal pool. Large amounts of vapor accumulated in the sealed reaction tank S3, causing gradual system pressure increase. Consequently, the vapor fraction from flashing decreased until the pressure inside the reaction vessel matched the saturation pressure of the initial water temperature, at which point flashing ended. In the second stage, single-phase water entered the pool when driven by the pressure difference. The third stage began when the valve was manually closed or when the pressure inside the reaction vessel equaled the initial jet pressure, at which point the flow lost its driving force. Therefore, the turning point of the first stage corresponded to the saturation pressure of the initial water temperature. For example, in cases (a), (b), and (c), the corresponding saturation pressures for the initial water temperatures were 0.789 MPa, 0.61 MPa, and 0.99 MPa, respectively. Furthermore, since cover gas pressure did not represent pressure near the nozzle after flashing, the turning point data were not entirely consistent, though generally close.

Fig. 9 [Figure 9: see original paper] summarizes the physical mechanisms of the three stages described above. In the first stage, the mixture with high vapor fraction entered the melt pool due to depressurized flash evaporation. Flashing led to formation of large amounts of vapor, accompanied by decreased heat transfer capacity. At this stage, heat transfer primarily occurred through boiling of liquid water surrounded by vapor in a hot environment. Consequently, the mass balance of this vapor can be expressed as:

$$\dot{m}_g = \dot{m}_{g,int} + \dot{m}_{l,int}\dot{Q}_{lm}$$

where $\dot{m}$ denotes mass flow rate, subscript g, in represents vapor entering the melt pool, and $\dot{Q}_{lm}$ is the dimensionless constant of the phase change rate initiated by film boiling.

Fig. 10 [Figure 10: see original paper] compares the impact of the flashing stage on pressure increase at various water temperatures. Test data below the saturation pressure corresponding to the initial water temperature were categorized as part of the flashing stage (e.g., $p_{sat,152°C} = 0.5$ MPa). The corresponding pressurization rates were 0.34 MPa/s at 126°C, and 0.57 MPa/s and 0.64 MPa/s at 140°C and 152°C, respectively.

As pressure inside the melt pool gradually increased, vapor mass generated by flashing diminished until internal pressure matched the saturation pressure of the initial water temperature. The process then entered the second stage, known as jet direct contact boiling, governed by the transient Bernoulli equation. Due to direct contact between subcooled water and hot liquid metal, the boiling mode during this stage was unstable film boiling (transition boiling):

$$\dot{m}_g = \dot{m}_{l,int}\dot{Q}_{tran}$$

where $\dot{Q}_{tran}$ is the dimensionless number for the equivalent transition boiling phase change rate.

The third stage was marked by flow cessation, occurring in two scenarios: valve closure due to external factors (cases a and b in Fig. 8), or loss of jet driving force when internal melt pool pressure equaled external jet pressure. After entering the third stage, the heat transfer pattern stabilized without external interference. Residual liquid water surrounded by vapor floated up inside the liquid metal, producing small amounts of vapor:

$$\dot{m}_g = m_{l,lm}\dot{Q}_{lm}$$

where $m_{l,lm}$ is the liquid water remaining inside the melt pool.

Flash evaporation corresponds to the fastest phase change rate, followed by jet direct contact boiling. Thus, the three phases correspond to decreasing pressurization rates in the order described, as shown in the experimental data illustrated in Fig. 8.

B. Behavior and Migration of Discrete Phases

First, it should be clarified that sharp temperature fluctuations detected by thermocouples inside the molten pool indicated water or vapor passing through that measurement point. Instantaneous temperature fluctuations were not indicative of the lead–bismuth temperature itself.

As shown in Fig. 11 [Figure 11: see original paper], the jet pipe pressure p03-2 recovery time was taken as the actual injection time. The spray release began at 21.4 s, and T10 (the measurement point closest to the nozzle) started to plunge at 21.6 s, indicating discrete phase passage through the T10 measurement point. The pressure sensor output frequency was much higher than that of the temperature sensor. Assuming the moment at which the pressure sensor detected a pressure drop corresponded to the start of the jet, and comparing the turning points of p03-2 and T10 while ignoring the time for water to travel from the pipe outlet to the measurement point, we estimated that the time uncertainty of the thermocouple reflecting discrete phase migration was less than 2.2%. Therefore, transient behavior and migration path of vapor/water could be understood based on temperature transient laws. It is important to note that the thermocouple response method is intended for steady-state conditions with large temperature differences. When a thermocouple's sensing element is in an unstable external environment, its response time becomes inadequate.

The specific assessment was grounded on the following criteria and assumptions: (1) transient drops in temperature profiles indicated presence of low-temperature discrete phases passing through the test point; (2) the sequence of temperature transients determined the migration path of discrete phases; (3) the jet process was assumed to be axially symmetric; and (4) only the first temperature drop was analyzed when the test point was in a steady state.

Fig. 12a displays typical temperature transient data during an LBE–water interaction. Fig. 12b gives the distribution of test points inside the liquid metal, with some points geometrically symmetrized. Fig. 12c depicts discrete phase evolution at typical moments following the jet. The moment when T10 started to fall was assumed as 0 s, with subsequent phase evolution pictures based on this criterion.

Fig. 13 [Figure 13: see original paper] presents a comparison of pressure at point p2 obtained from CFD with test data. The results show good agreement between numerical simulation and test data, with deviation primarily observed in the flashing stage. This deviation resulted from neglecting mass transfer from temperature-driven boiling during flashing and from bias in flashing mass calculation.

Fig. 14 [Figure 14: see original paper] shows a comparison of test and CFD results regarding discrete phase behavior, illustrating temperature and pressure variations resulting from LBE–water interaction. In the test, the moment when probe T10 near the nozzle started to drop was defined as 0 s. The instantaneous jet impact on the molten pool generated pressure peaks, as shown in Fig. 14d. Continued phase change increased pressure within the molten pool. A large cavity region formed in the liquid metal melt pool after approximately 0.2 s. Subsequently, temperatures at test points T10 and T11 in the vertical direction rose after the jet stopped (2 s), signaling departure of discrete phases from the region. Large amounts of water boiled during direct contact between hot and cold fluids, and the main stream of discrete phases began to float under buoyancy action. At the stable stage, numerous bubbles floated upward and exited the LBE pool. The discrete phase was heated immediately upon injection into the molten pool, broke through the liquid surface, and entered the cover gas chamber. The cover gas temperature decreased slightly after mixing with vapor generated by phase change.

Fig. 15 [Figure 15: see original paper] compares discrete phase diffusion for different pressures. Because evolutionary processes varied for each condition, we present key moments when discrete phase behavior changed as typical snapshots rather than sorting by fixed time intervals. Fig. 15b and Fig. 15c illustrate that as jet pressure increased, the phase evolution process accelerated noticeably and cavities emerged earlier, with formation time reducing from 0.2 s to 0.1 s and 0 s.

Additionally, according to Dinh's theory [?], the proportion of vapor generated due to decompression boiling correlated with the initial specific entropy of water. Consequently, increasing jet pressure led to a higher proportion of vapor after decompression boiling, resulting in larger discrete phase regions. For example, at 2 MPa, the flanking discrete phase region was substantially larger than in the two lower-pressure cases. Nonetheless, the phase evolution process remained similar, progressing through three stages: large cavity formation, flanking diffusion, and stable up-floating.

Fig. 16a [Figure 16: see original paper] compares phase evolution at various jet times. The cavity appeared at 0 s for $t_j = 2$ s, followed by sequential phases of flanking diffusion and steady up-floating, similar to Fig. 15. With increasing jet time, the amount of water entering the melt pool increased, but the effect on flow pattern was small. Additionally, as jet time increased, heat transfer between water and liquid metal increased. For example, average temperature drops in the molten pool were 10.12°C, 11.0°C, and 13.2°C, respectively. It is worth noting that the set jet time was not equal to the actual spray time. The set jet time was determined by the solenoid valve V5 open time, while the actual spray time was influenced by both pipeline pressure and test section pressure, as discussed by the authors in a previous paper [?]. Furthermore, a larger flanking diffusion area increased the likelihood of discrete phase capture by LBE.

Fig. 16b illustrates the effect of melt pool temperature on phase evolution. The overall evolution process was relatively similar, with large cavity appearance at 0.1–0.2 s. After approximately 1 s, the jet stopped and flanking diffusion was generated. The rise in melt pool temperature accelerated temperature-driven phase transition but had minimal impact on overall flow pattern evolution. Experimental results indicated that LBE liquid metal temperature had less impact on discrete phase behavior. While liquid metal temperature could affect boiling behavior at the microscale, when temperatures exceed the Leidenfrost temperature, bubble nucleation boiling may transition to film boiling, decreasing heat transfer capacity. However, high-pressure water jets entering a molten pool induce significant churning effects that disrupt gas films. Therefore, with these combined influences, phase evolution in the temperature range of this study was less sensitive to melt pool temperature.

Results for different water temperatures are presented in Fig. 16c. No decompression boiling occurred at 84°C, consequently delaying cavity emergence to 0.6 seconds compared to the other two decompression boiling cases (0.2 s). Water, being much denser than vapor, caused water jets to penetrate deeper. However, the primary phase change mode at this point was temperature-driven boiling, so expansion of the vapor-water mixed discrete phase was much slower.

Therefore, after LBE–water interaction, evolution of the cavity composed of vapor–water mixture within the liquid metal mainly exhibited V-shaped diffusion. The formation of a cavity in the liquid metal from the vapor–water mixture is a typical example of a negative buoyancy jet, where buoyancy direction is opposite to jet momentum direction. Evolution of this cavity type is governed by the interplay among inertial forces, drag, gravity, and buoyancy:

$$\rho_{mix}\frac{du}{dt} = (\rho_{lm} - \rho_{mix})g - C_d\rho_{lm}u^2$$

where subscripts mix and lm represent the vapor–water mixture and liquid metal, respectively, u is mixture jet velocity, and C_d is the drag coefficient.

According to the principle of conservation of momentum, the change in jet momentum equals the vector sum of external forces:

$$\rho_{mix}u^2 \propto (\rho_{lm} - \rho_{mix})gl$$

where l is the maximum jet penetration depth. Therefore, the maximum jet depth can be expressed as:

$$l = \frac{\rho_{mix}u^2}{2(\rho_{lm} - \rho_{mix})g}$$

The above equation requires specific experimental data to quantify coefficients, which is beyond the scope of this study. The primary objective was to utilize this theoretical framework to analyze and interpret jet cavity evolution. According to Zhang et al. [**?**], jet penetration depth in lead–bismuth liquid metal can be approximated by the following empirical correlation:

$$\frac{l}{d} = \left(\frac{\rho_{mix}}{\rho_{lm}}\right)^{0.64} Fr^{0.64}, \quad 4.99 \times 10^3 < Fr < 1.25 \times 10^4$$

$$\frac{l}{d} = \left(\frac{\rho_{mix}}{\rho_{lm}}\right)^{0.32} Fr^{0.32}, \quad 1.25 \times 10^4 < Fr < 2.53 \times 10^5$$

where d is the characteristic jet scale, typically taken as the jet nozzle diameter, and Fr is the Froude number given by $Fr = u^2/(gd)$.

According to jet penetration depth analysis, for a low-density steam–water mixture jet impacting high-density liquid metal, the jet reaches maximum penetration depth due to buoyancy effects. This behavior contrasts with high-density jets entering low-density media, such as liquid metal jets entering water, where the jet penetrates directly to the container bottom. Regarding cavity evolution from flashing vapor–water mixture impact on liquid metal pools, jet penetration depth was relatively small due to density differences, with buoyancy dominating upward and lateral diffusion of the mixture, resulting in an upper-wide, lower-narrow V-shaped cavity. Furthermore, larger density differences produced more pronounced lateral expansion of the V-shaped cavity. Conversely, if liquid metal were jetted into water, the cavity might assume an inverted V-shape (lower-wide, upper-narrow) due to insufficient buoyancy. In summary, for negative buoyancy jets, V-shaped cavity formation resulted from mechanical competition between jet inertia and buoyancy.

IV. Conclusions

In this study, experiments and numerical simulations were combined to investigate discrete phase migration behavior following LBE liquid metal–water interaction. Based on temperature transient laws and numerical simulation methods for lead–water interaction with multi-physical processes, we inferred evolution behavior of vapor-water discrete phases resulting from interactions with varying thermal parameters.

High-pressure subcooled water jet injection into lead–bismuth liquid metal is a complex interaction dominated by three physical mechanisms. Depressurized flash evaporation provides the initial major contribution to pressurization. Once melt pool pressure exceeds the saturation pressure of the initial water temperature, flash vaporization ends and temperature-driven boiling begins. Finally, when the valve closes or internal pressure matches jet pressure, the driving force dissipates.

The discrete phases in this study exhibited V-shaped diffusion in the molten pool after jet termination, then entered a stable floating stage, with small differences observed across different working conditions. Furthermore, the phase evolution process was consistent, progressing through three stages: cavity formation, flanking diffusion, and stable up-floating. Longer and higher-pressure jets markedly increased post-interaction perturbation, leading to more complex discrete phase migration behavior. Higher vapor mass fraction after decompression boiling resulted in larger diffusion areas for discrete phases, with decompression boiling primarily influenced by initial water pressure and temperature. Additionally, LBE liquid metal temperature and jet time had less impact on discrete phase behavior. This study provides an important reference for deeper understanding of SGTR accidents and validation of numerical simulations for complex multi-physics processes in multiphase flows.

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