Experimental Investigation of Bubble Dynamics in gas-LBE Two-Phase Flow Across Diverse Pipe Geometries

Authors: Zhang, Dr. Hong, Wan, Dr. Lingfeng, Wang, Dr. Di, Sun, Prof. Wan, Tang, Prof. Simiao, Pan, Prof. Liangming, Zhu, Prof. Longxiang, Zhu, Prof. Longxiang

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Abstract

Lead-bismuth Eutectic (LBE) is a promising coolant material for next-generation fast reactors. After a Steam Generator Tube Rupture (SGTR) accident in LBE-cooled Fast Reactors (LFRs), the subcooled water enters the high-temperature LBE and generates bubbles, which may impede the flow of coolant, deteriorate core thermal performance and threaten nuclear safety. For the safety analysis of LFRs, it is necessary to carry out experiments to acquire bubble behavior characteristics in molten LBE. In this paper, a gas-liquid LBE two-phase flow experiment was conducted in circular pipes with diameters of 4 cm, 5 cm, 7 cm and 9 cm. First, detailed radial and axial distributions of void fraction, bubble velocity, interfacial area concentration, chord length and bubble frequency were revealed. We found that the void fraction exhibited a core-peak distribution across the flow cross-section. Bubble velocities stabilized beyond 10 pipe diameters downstream, while bubble chord lengths followed a lognormal distribution whose mean and standard deviation increased with axial flow development. The drift velocity initially increased with channel diameter before reaching a plateau. Furthermore, a positive relationship existed between bubble velocity and chord length in the short chord length range, though this correlation diminished for larger chord lengths. Finally, both the mean value and fluctuation amplitude of differential pressure signals showed strong dependencies on void fraction. Distinct Power Spectral Density (PSD) peaks were observed when void fractions equal 0.38 and 0.47, while spectral entropy and low-frequency energy ratio demonstrated systematic relationships with void fraction, providing potential indicators for flow regime identifications.

Full Text

Preamble

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Hong Zhang,[1],[2] Ling-Feng Wan,[1],[2] Di Wang,[3] Wan Sun,[1],[2] Si-Miao Tang,[1],[2] Liang-Ming Pan,[1],[2] and Long-Xiang Zhu[1],[2],†

[1]Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Chongqing 400044, China
[2]Department of Nuclear Engineering and Technology, Chongqing University, Chongqing 400044, China
[3]China Nuclear Power Technology Research Institute Co., Ltd, Shenzhen 518000, China

Lead-bismuth eutectic (LBE) is a promising coolant material for next-generation fast reactors. Following a Steam Generator Tube Rupture (SGTR) accident in LBE-cooled Fast Reactors (LFRs), subcooled water enters the high-temperature LBE and generates bubbles, which may impede coolant flow, deteriorate core thermal performance, and threaten nuclear safety. For safety analysis of LFRs, experiments are necessary to acquire bubble behavior characteristics in molten LBE. This paper presents a gas-liquid LBE two-phase flow experiment conducted in circular pipes with diameters of 4 cm, 5 cm, 7 cm, and 9 cm. First, detailed radial and axial distributions of void fraction, bubble velocity, interfacial area concentration, chord length, and bubble frequency were revealed. We found that void fraction exhibited a core-peak distribution across the flow cross-section. Bubble velocities stabilized beyond 10 pipe diameters downstream, while bubble chord lengths followed a lognormal distribution whose mean and standard deviation increased with axial flow development.

The drift velocity initially increased with channel diameter before reaching a plateau. Furthermore, a positive relationship existed between bubble velocity and chord length in the short chord length range, though this correlation diminished for larger chord lengths. Finally, both the mean value and fluctuation amplitude of differential pressure signals showed strong dependencies on void fraction. Distinct Power Spectral Density (PSD) peaks were observed when void fractions equaled 0.38 and 0.47, while spectral entropy and low-frequency energy ratio demonstrated systematic relationships with void fraction, providing potential indicators for flow regime identification.

Keywords: Two-phase flow experiment; LBE-cooled fast reactor; Void fraction; Two-sensor probe

INTRODUCTION

As the world population grows, economies expand, and expectations for living standards continue to rise, the demand for clean energy and a sustainable environment will only increase, making nuclear power a vital component of sustainable energy systems. LBE-cooled Fast Reactors (LFRs) represent an important reactor type among fourth-generation nuclear reactors, demonstrating potential advantages in reactor miniaturization, sustainable development, and economic viability. Lead-based alloys (lead or lead-bismuth eutectic (LBE)) are utilized as primary coolant due to their excellent thermal, chemical, and neutron physical properties. The steam generator (SG), a critical component of LFRs, serves to transfer heat from the reactor core. Steam Generator Tube Rupture (SGTR), classified as a Design Extension Condition (DEC), exhibits high probability and severe consequences in the primary system of LFRs.

In an SGTR accident, high-pressure water from the secondary side rapidly intrudes into the LBE coolant of the primary loop, undergoing four stages: (1) high-pressure water jet formation, (2) Coolant-Coolant Interaction (CCI), (3) steam bubble migration and distribution in the primary loop, and (4) bubble entrainment and retention in the reactor core. Among these phenomena, the migration and entrainment of bubbles in LBE could obstruct coolant flow, impair heat removal from the core, and potentially introduce positive cavitation reactivity due to bubbles entrained into the core. Both the thermal-hydraulic characteristics and neutronic behavior of LFRs are critical for reactor safety analysis, and significant research efforts have been devoted to these aspects. Following the SGTR accident, the thermal-hydraulic and neutronic response characteristics of the reactor become unpredictable when massive bubbles transport in the LBE pool, because understanding of bubble migration and distribution in LBE remains limited due to insufficient experimental data. Therefore, it is imperative to experimentally investigate bubble dynamics in liquid LBE for safety analysis of SGTR in LFRs.

The gas-LBE two-phase flow is special. Molten LBE, with elevated temperature, large density, large surface tension, and viscosity, differs from other common fluids in bubble dynamics. Liu et al. established a three-dimensional numerical model based on the Coupled Level-Set and Volume of Fluid (CLSVOF) method to simulate the injection of high-pressure steam bubbles into a high-temperature LBE molten pool. Through integrated analysis of bubble trajectories, velocities, and diameters in conjunction with force equilibrium equations, they quantified the drag coefficients of steam bubbles within liquid LBE. Liu et al. simulated the motion of a water vapor bubble rising in molten LBE and observed that the rising terminal velocities of 8 mm, 10 mm, and 12 mm bubbles at 200°C calculated by the Volume of Fluid (VOF) model were approximately 0.20 m/s, 0.22 m/s, and 0.23 m/s, respectively. Using the diffuse interface method, Wang et al. conducted numerical simulations to study the interfacial dynamics of a single nitrogen bubble rising in liquid LBE. Their results demonstrated agreement with Grace's empirical correlation. Li et al. employed the open-source computational fluid dynamics (CFD) software OpenFOAM to numerically simulate the two-phase flow of LBE and water vapor within a fuel assembly. Their findings revealed that water vapor tended to accumulate in peripheral and corner channels. Furthermore, when the inlet vapor content exceeded 15%, the outlet coolant temperature exhibited a sharp increase accompanied by significant temperature fluctuations. To investigate steam transport characteristics during SGTR accidents in LFRs, Zhang et al. conducted numerical simulations of LBE-water/steam multiphase flow within the reactor pool. They found that the maximum void fraction in the core occurred when the rupture was located at the SG outlet nearest to the pump duct, representing the most severe accident scenario. They also identified that the peak core void fraction exhibited a positive correlation with secondary circuit pressure. These simulation studies revealed the behavior characteristics of bubble transportation in LBE, and following the SGTR accident, bubble migration within the reactor could lead to deterioration of core heat removal, potentially harming reactor safety.

Phase distribution characteristics such as void fraction, bubble frequency, bubble size, and gas velocity in static molten metals were measured by some researchers. Other researchers conducted liquid metal-gas two-phase flow experiments under forced convection conditions in flowing liquid metals. The liquid metals analyzed in these studies, including mercury, molten iron, Wood's metal, GaInSn, gallium, and LBE, are listed in Table 1 with their thermophysical properties.

The high temperature, strong corrosion effects, and flow blockage make gas-LBE two-phase flow experiments inherently challenging. Furthermore, the opaque nature of LBE renders conventional optical observation methods inapplicable. Additionally, the high attenuation of X-rays and γ-rays severely limits the use of radiography techniques in such experiments. Compared with water, liquid metals typically exhibit significantly higher density, elevated surface tension, and increased viscosity, leading to distinct bubble dynamics. Consequently, experimental investigations of gas-LBE two-phase flow remain limited due to experimental and measurement complexities, which hinders comprehensive investigation into gas-LBE two-phase flow.

Zhang et al. investigated the terminal rise velocity of single bubbles in opaque liquid metals by injecting argon gas into four transparent liquids (water, glycerol, ethanol, and FC-3283). They developed a correlation to predict bubble ascent velocities in gas-liquid metal bubbly flows. Deng et al. conducted many experiments involving the injection of water lumps into molten lead pools and LBE pools. Their studies enhanced understanding of melt-water interactions and yielded an expanded experimental dataset on temperature and pressure evolution characteristics during the CCI stage within the SGTR accident. Huang et al. injected pressurized water into a molten LBE pool to investigate pressure build-up characteristics within the interaction vessel. Their experiments revealed that increasing the injection duration resulted in only a limited enhancement effect on pressure. Tan et al. conducted experiments involving injecting water into molten lead-bismuth non-eutectic (LBNE) alloy to investigate their interaction under severe nuclear accident conditions. Through comparative analysis with LBE experimental data, they observed that LBNE generated larger debris fragments, less spherical debris fragments, and more porous debris beds. He et al. investigated the flow rate and temperature characteristics of a venturi nozzle flow meter operated in the PREKY facility. Their study demonstrated that the flow meter exhibited a measurement uncertainty of $±$5% within the flow velocity range of 0.6–2.0 m/s. Due to the inherent instability of natural circulation systems, flow instability could easily occur during the operation of natural circulation LFRs. In gas-LBE systems, the flow instability effect could be more pronounced. Experimental studies using molten LBE have predominantly focused on global macroscopic parameter measurements, such as temperature, pressure, and flow rate, while lacking quantitative data on local bubble dynamics within LBE flows. Although a limited number of experiments employing transparent fluids measured bubble characteristics, the applicability of these findings to actual LBE systems required rigorous validation through dedicated gas-LBE experiments.

In summary, test data on gas-LBE two-phase flow are rare due to the shielding properties of liquid LBE against light, the corrosive properties, and so on, making it difficult to analyze the process of bubble migration and distribution in LBE. In addition, the reliability of simulation methods or experimental methods using transparent media is difficult to guarantee due to the need for experimental data. To accurately assess bubble migration and distribution characteristics in liquid LBE, it is necessary to perform gas-LBE two-phase flow experiments, especially in terms of tests under diverse conditions and measurements on local parameters. Therefore, this paper experimentally investigated gas-LBE two-phase flows in vertical pipes with diverse geometries under various flow rates. First, the local cross-sectional and axial distribution features of void fraction, gas velocity, interfacial area concentration, bubble frequency, and chord length were revealed by the utilization of two-sensor electrical conductivity probes (EC probes). Then, the distributions of bubble chord length were identified regarding the bubble velocity. In addition, by analyzing the differential pressure Power Spectral Density (PSD), the features such as low-frequency energy ratio, spectral entropy, and peaks in frequency domain showed a close relationship with the void fraction.

II. EXPERIMENT AND MEASUREMENT

A. Test Facility

The gas-LBE two-phase flow experiment facility was developed at Chongqing University (CQU). Fig. 1a shows the layout of the test facility. This facility consists of the LBE circulation system, gas injection system, gas filtration and emission system, LBE storage tank, and measurement system. Fig. 1b illustrates the schematic of a test section and EC probes.

In this research, the outlet pressure of the separator was atmospheric pressure as the cover gas pressure in LFRs is typically atmospheric, and the temperature of the test section was 200°C. In the mixer, LBE was mixed with nitrogen gas and then pumped upward into the test section. The high-pressure gas injected was preheated to 200°C in the gas injection pipeline. For a stable gas supply, a gas buffer tank was set between the mass flow controller and the gas source. The separator was located on the outlet of the test section, and the separated gas was first filtered by activated carbon, then by acetic acid, and finally left the exhaust line. The LBE storage tank was covered by argon gas during storage time. Before experiments, the LBE in the tank was heated to 200°C and then was pressed into the LBE circulation system.

To obtain uniform bubbles in size and spatial distribution, this study employed a mixer containing a cylindrical porous medium made of titanium with a diameter of 60 mm and a length of 250 mm. The porous media had an average pore diameter of 20 µm and an average porosity of 30%. The inflow LBE and the inflow gas were fully mixed in the mixer and then flowed together upward into the test section. The liquid LBE utilized in this study contained 44.5\$$\pm 1.5wt\pm$\$1.5 wt% bismuth, with total impurities less than 100 ppm and single impurity less than 10 ppm according to the manufacturer's report. The pressurized gas injected was pure nitrogen (99.99%), avoiding interaction between the LBE and gas.

The measurement system consisted of measuring temperature, pressure, flow flux, and local bubble parameters. In addition to temperature monitoring at the inlet and outlet of the test section, over 30 thermocouples were installed at various locations both inside and outside the pipes of the LBE circulation system to monitor the real-time temperature of the LBE and prevent blockage due to solidification. Pressure measurements were performed at the inlet and outlet of the test sections. Additionally, differential pressure measurements were conducted around the EC probe location to compare the void fraction results obtained from the EC probes and the differential pressure transmitter. The LBE flow rate was measured by a venturi flow meter, while the gas flow rate was controlled by two gas flow controllers with two different ranges. In the liquid LBE-nitrogen two-phase flow, bubble characteristics such as void fraction, bubble velocity, and chord length were measured by the two-sensor EC probes.

B. Test Section and EC Probe

This study performed experiments on four stainless steel (S31603) pipe test sections with distinct inner diameters of 4 cm, 5 cm, 7 cm, and 9 cm. The diameter of the test section influences the characteristics of bubbles. Kataoka and Ishii stated that for vessels with a dimensionless diameter much larger than 30 (corresponding to 6 cm for LBE-nitrogen at 200°C), slug bubbles cannot be sustained due to interfacial instability and subsequently disintegrate into cap bubbles. Hibiki and Ishii suggested that drift velocity would rise and reach a constant with increasing channel diameter. The dimensionless diameter D_h^* is defined by Eq. 1:

$$D_h^* = D_h \sqrt{\frac{\sigma_f}{g(\rho_f - \rho_g)}}$$

where D_h, σ_f, g, ρ_f, and ρ_g are the hydraulic diameter, surface tension, acceleration of gravity, density of liquid phase, and density of gas phase, respectively.

The lower limit of D_h^* is constrained by the fixed dimensions of EC probes, while the upper diameter limit is restricted by practical considerations such as facility height and LBE loadage. Therefore, the test sections in this paper contained both large and small pipes for gas-LBE two-phase flow, with corresponding dimensionless diameters of 20, 25, 35, and 45, respectively.

In the test section, three two-sensor EC probes were employed to measure two-phase flow parameters. Probe ports (see Fig. 1b) were located at axial locations $Z^* = Z/D_h = [5, 10, 20]$, corresponding to port 1, port 2, and port 3, where Z^* and Z represent the dimensionless and real axial locations. The ten radial probe measuring positions at each port are non-dimensionalized as $r^* = r/R$ (see Table 2), where r is the radial location of the probe sensor tip and R stands for the pipe radius.

The two-sensor EC probes were developed by the Multiphase Flow and Interface Phenomena Laboratory (MFIP) and were designed for use in high-temperature, highly corrosive, and strongly erosive environments. When the conductive liquid touches the sensor tip, the probe outputs a low voltage, while when the non-conductive gas touches the sensor, it outputs a high voltage. The two sensors of one probe had different lengths, so the gas velocity could be measured by $v_g = \Delta L/\Delta t$, where ΔL is the length difference between the two sensor tips and Δt is the time difference between two interface signals. Under all experimental conditions, each EC probe signal was recorded at a sampling rate of 50 kHz.

C. Test Procedure

After a stable gas-LBE two-phase flow was established, a step motor was employed to incrementally traverse the EC probe along the radial direction of the pipe cross-section, measuring void fraction data at 10 different radial measurement points. Before formal gas-LBE two-phase experiments, single-phase LBE up-filling tests were conducted. First, the gas injection pipeline was blocked by a plug. Then, by controlling the argon pressure introduced into the LBE storage tank, the liquid LBE flowed through the venturi flow meter smoothly. When the single-phase LBE entered the test section, the inlet pressure started to rise. This method allowed calibration of the LBE venturi flow rate based on the pressure rise measured at the inlet of the test section. Fig. 2 compares the mass of LBE flowing into the test section measured by two different methods, as shown in Eq. 2 and Eq. 3:

$$\Delta M_{\text{pressure gauge}} = \pi R^2 \frac{(p_{\text{end}} - p_{\text{start}})}{\rho_f g}$$

$$\Delta M_{\text{venturi}} = (t_{\text{end}} - t_{\text{start}}) Q_f$$

where p, R, ρ_f, t, and Q_f represent the test section inlet pressure, the radius of the test section, the density of LBE, the recorded time, and the average flow rate given by the venturi flow meter, respectively. The subscripts "start" and "end" indicate the start and end of the recording time.

The gravitational pressure drop in vertical gas-LBE two-phase flow is mainly governed by the mixture's average density. Consequently, the volumetric void fraction over a specific test section length could be determined through differential pressure measurements. As shown in Fig. 3, differential pressure measurements were deployed at the EC probe measurement location. Variations in void fraction within the test section cause density changes in the two-phase mixture, which subsequently result in gravitational pressure drop changes. The correlation between volumetric void fraction α_2 and Δp is shown in Eq. 4–Eq. 7. When the tip of the EC probe is located at the center height of the differential pressure measurement, the volumetric void fraction α_2 could represent the void fraction $\langle \alpha \rangle_{dp}$ measured by the differential pressure, where $\langle \rangle$ denotes the area-averaged quantity.

$$p_1 = p_0 + \rho_f h_1 (1 - \alpha_1) g$$

$$p_2 = p_0 + \rho_f h_1 (1 - \alpha_1) g + \rho_f (h_2 - h_1)(1 - \alpha_2) g$$

$$\Delta p = \rho_f (h_2 - h_1)(1 - \alpha_2) g$$

$$\alpha_2 = 1 - \frac{\Delta p}{\rho_f (h_2 - h_1) g}$$

In Fig. 4, $\langle \alpha_{\text{probe}} \rangle$ means the area-averaged void fraction measured by EC probe across the test section. For a specific bubble type, the time-averaged void fraction was calculated as:

$$\langle \alpha \rangle = \frac{1}{\Omega} \sum_{i=1}^{N_b} \delta t_i$$

where Ω is the sampling time, N_b is the number of the specific bubble type, and δt_i is the time duration of the i-th bubble. For a specific bubble type, the time-averaged velocity is calculated as:

$$\langle v_g \rangle = \frac{\sum_{i=1}^{N_b} v_i}{N_b}$$

where v_i stands for the leading-edge velocity of the i-th bubble. The typical normalized signal and step signal from bubbles in LBE are shown in Fig. 5, with a signal-to-noise ratio over 10. Sensor 0 and sensor 1 represent the long needle and the short needle, respectively. In this paper, the length difference between the two is usually 1 mm.

Due to the significant impact of bubble morphology on two-phase flow parameters, the bubbles are categorized into two groups: group 1 (spherical/distorted bubbles) and group 2 (cap/slug-shaped bubbles). Classification is achieved by detecting the chord length of bubbles passing through the first sensor, with the chord length defined as:

$$L_i = v_i \times \delta t_i$$

In this study, the classification standard of bubbles was proposed by Ishii based on the maximum chord length of a bubble. The limit for spherical bubbles ($D_{s,\max}$) is given as:

$$D_{s,\max} = 4\sqrt{\frac{\sigma_f}{g(\rho_f - \rho_g)}} N_{\mu f}^{-1/3}$$

$$N_{\mu f} = \left(\frac{\rho_f \sigma_f}{\mu_f^2}\right)^{1/2} \sqrt{\frac{\sigma_f}{g(\rho_f - \rho_g)}}$$

where σ_f, ρ_f, ρ_g, $N_{\mu f}$, μ_f, and g are the surface tension, the liquid phase density, the gas phase density, the viscosity number, the liquid phase dynamic viscosity, and the gravitational acceleration, respectively. The maximum diameter limits for distorted bubbles ($D_{d,\max}$) and for cap bubbles ($D_{c,\max}$) are given as:

$$D_{d,\max} = 4\sqrt{\frac{\sigma_f}{g(\rho_f - \rho_g)}}$$

$$D_{c,\max} = 40\sqrt{\frac{\sigma_f}{g(\rho_f - \rho_g)}}$$

D. Uncertainty

In this experiment, the accuracy classes of the venturi flow meter, the mass flow controllers, and the pressure transmitters are Class 1, corresponding to a maximum uncertainty of 1%. Under all operational conditions, each EC probe signal is recorded at a sampling rate of 50 kHz, and the corresponding maximum uncertainties of two-phase parameters are summarized in Table 3, inferred by existing uncertainty and sensitivity studies.

Table 3. Measurement uncertainty.

Measurement parameter	Range	Uncertainty
Void Fraction (–)		$±$10%
Gas Velocity (m/s)		$±$10%
LBE flow rate (t/h)		$±$1%
Gas flow rate 1 (SLM)		$±$1%
Gas flow rate 2 (SLM)		$±$1%
Pressure (MPa)		$±$0.25%
Differential pressure (kPa)		$±$0.25%

III. RESULTS AND DISCUSSION

A. Local Flow Parameters

1. Radial Distribution Characteristics Bankoff was the first scholar to analyze radial phase distribution characteristics. He proposed a variable density single-fluid model, assuming that the gas-phase velocity and void fraction distribution follow exponential laws, meaning both are maximized at the tube center and decrease monotonically along the radial direction. Zuber introduced the drift-flux model, which employed similar assumptions for calculating void fraction and gas-phase velocity, and this void fraction formulation has been widely adopted. Fig. 6 exhibits the local distribution characteristics of void fraction α, gas velocity v_g, interfacial area concentration (IAC) a_i, chord length L_b, and bubble frequency f_b at Port 1 in a pipe with a diameter of 4 cm, under the condition of $\langle j_f \rangle = 0$ and $T = 200°C$. Under these conditions with diverse j_g, core- peaked distributions of void fraction were observed in all four conditions, consistent with Bankoff's prediction, as shown in Fig. 6a. As the void fraction increased with higher gas flow rates, the gas velocity exhibited a slight decrease (Fig. 6b). This phenomenon might be explained by the transition of flow regime. Simultaneously, the total IAC rose with the superficial gas velocity, but the observed increases were predominantly attributed to group 1 bubbles, while the IAC of group 2 bubbles remained relatively stable (Fig. 6c). The chord length of group 2 also exhibited a core-peak profile. Under conditions of high superficial gas velocity, the chord length of the bubble was close to or even larger than the diameter of the flow channel, indicating that stable slug bubbles existed in the flow channel (Fig. 6d). Fig. 6e shows that the increase of superficial gas velocity only induced limited growth in bubble frequency.

2. Axial Development Characteristics When a mixture of bubbles and a large-density liquid flows upward, it experiences a rapid pressure drop, triggering accelerated bubble expansion and obvious void fraction growth. Owing to the high density of LBE, this expansion effect is more pronounced than in gas-water two-phase systems. Fig. 7 reveals the axial development characteristics in a pipe with a diameter of 5 cm under the condition of $\langle j_f \rangle \approx 0.14$ m/s. Fig. 7a clearly demonstrates that the area-averaged void fraction $\langle \alpha \rangle$ increased with both elevated gas superficial velocity and higher axial flow positions, reflecting the cumulative effects of gas-phase expansion. In terms of the area-averaged gas velocity $\langle v_g \rangle$ (Fig. 7b), the profile at Port 1 showed some irregular and unstable behavior, while remaining stable when reaching Port 2. This development feature indicated that the entrance effect at Port 1 continued to exert influence on bubble velocities. At Port 3, there was a positive correlation between gas velocity and gas flow rate. The reductions in IAC $\langle a_i \rangle$ and bubble frequency $\langle f_b \rangle$ (see Fig. 7c and Fig. 7d) indicated that bubble coalescence dominated during bubble ascent in LBE under these conditions, resulting in a significant increase in the Sauter mean diameter $\langle D_{sm} \rangle$ (see Fig. 7e).

The Sauter mean diameter $\langle D_{sm} \rangle$ is defined as:

$$\langle D_{sm} \rangle = \frac{6\langle \alpha \rangle}{\langle a_i \rangle}$$

In liquid LBE, gas bubbles are typically non-spherical, resulting in discrepancies between the Sauter mean diameter and bubble chord length. The observed variation in these discrepancies (see Fig. 7f) indicated that bubbles undergo significant deformation as they transport from Port 1 to Port 2. Under these conditions, when bubbles first entered the test section from the mixer, they generally exhibited chord lengths greater than the Sauter mean diameter. This discrepancy gradually diminished as the bubbles ascended. After reaching Port 2, the discrepancy between chord length and Sauter mean diameter tended to stabilize.

3. Influence of Pipe Size The drift-flux model has been widely applied to gas-liquid two-phase flows. Recent studies have developed specialized drift-flux correlations for LBE systems based on publicly available experimental data. This model incorporates two critical parameters: the distribution parameter and drift velocity, which respectively account for phase distribution non-uniformity and relative phase motion. Zuber and Findlay considered key hydrodynamic factors including local phase distribution patterns, flow field characteristics, and interfacial momentum transfer-induced velocity differentials between phases. They established a one-dimensional drift-flux correlation model for determining area-averaged void fraction in two-phase flows:

$$\langle\langle v_g \rangle\rangle = \frac{\langle \alpha v_g \rangle}{\langle \alpha \rangle} = C_0 \langle j \rangle + \langle\langle v_{gj} \rangle\rangle = C_0 (\langle j_g \rangle + \langle j_f \rangle) + \langle\langle v_{gj} \rangle\rangle$$

where C_0 and $\langle\langle v_{gj} \rangle\rangle$ are the distribution parameter and drift velocity, respectively. $\langle\rangle$ and $\langle\langle\rangle\rangle$ denote area-averaged and void fraction-weighted mean quantities, respectively. The distribution parameter, C_0, and the void fraction-weighted mean drift velocity, $\langle\langle v_{gj} \rangle\rangle$, are respectively defined by:

$$C_0 = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle}$$

$$\langle\langle v_{gj} \rangle\rangle = \frac{\langle \alpha v_{gj} \rangle}{\langle \alpha \rangle}$$

where $v_{gj} = v_g - j$.

The distribution parameter quantifies the non-uniform distribution effect of void fraction and phase velocities. Meanwhile, the drift velocity expresses the non-uniform distribution influence of void fraction and the relative velocity. Through analytical studies of fully developed turbulent bubbly flows, Ishii empirically determined the asymptotic distribution parameter C_∞ to adopt values of 1.2 for circular pipe geometries and 1.35 for rectangular channel configurations, and gave the correlation as Eq. 19. Mou et al. conducted two-phase flow measurements in a gas-liquid Wood's alloy molten pool and observed that the distribution parameter approached a value of 1.07.

Fig. 8 presents a comparison among the distribution parameters across diverse experimental sections in the present study. As illustrated in Fig. 8, the mean values of the distribution parameter in each test section fall between 1.0 and 1.2. The data used for Fig. 8 are collected from port 2 regarding stable bubble velocities and are calculated by Eq. 17. However, with increasing diameter D_h, C_0 experienced a slight rise to about 1.2, which suited the prediction of Ishii's model well. According to the experimental results, there is no obvious influence of pipe size on distribution parameter, and the correlation developed by Ishii is recommended for drift-flux model in gas-LBE two-phase flows.

Kocamustafaogullari and Ishii investigated the dominant influence of large cap bubbles on drift velocity in gas-liquid systems and developed the following semi-empirical correlation for drift velocity in vertical cap-bubbly flow regimes:

$$\langle\langle v_{gj} \rangle\rangle = \sqrt{\frac{g D_h (\rho_f - \rho_g)}{\rho_f}} \times \begin{cases} 0.35 \left(\frac{\sigma_f}{g(\rho_f - \rho_g) D_h^2} \right)^{0.25} & D_h^* \leq 30 \\ 1.18 & D_h^* > 30 \end{cases}$$

As demonstrated in Eq. 20, the drift velocity exhibits a positive correlation with channel diameter when $D_h^* \leq 30$, where cap and slug bubble dynamics remain constrained by channel wall confinement effects. However, for $D_h^* > 30$, the drift velocity plateaus, independent of further diameter increases. This asymptotic behavior arises because cap bubbles attain their maximum stable size, significantly reducing hydrodynamic restrictions imposed by the channel walls. Fig. 9 shows the drift velocity predicted by Eq. 20 and the drift velocity measured in the current experiments. The void fractions here for $\langle\langle v_{gj} \rangle\rangle$ analysis fall within a wide range from 0.02 to 0.71 at all ports. The experimental drift velocities and model-predicted values demonstrate good agreement in both trend and numerical magnitude, indicating that the model of Kocamustafaogullari and Ishii maintains applicability not only in gas-water systems but also in liquid LBE environments.

B. Distribution Characteristics of Chord Length

The particle size distribution is typically dependent on its formation mechanisms and measurement conditions. Commonly observed distribution types include lognormal, exponential, Weibull, and gamma distributions. Particle size may also approximate a normal distribution when influenced by multiple independent additive factors with limited dispersion. Particle size distributions typically conform to a lognormal distribution when growth or fragmentation processes are governed by multiplicative stochastic factors, particularly in systems where large particles exist. This condition suits the distribution of gas bubble chord length in liquid. Experimentally, the lognormal distribution has been observed in research by Mou et al. However, the bubble data used by Mou et al. for chord length distribution analysis were confined to measurements taken exclusively at a single height and one central position within a static molten metal pool.

In this study, the data for chord length distribution analysis are from the ten cross-section radial positions at three diverse port heights, i.e., all the bubble chord length data measured in a whole test section. In this section, the kernel density was estimated based on the chord length obtained from a 7-cm diameter circular pipe, followed by evaluation of the agreement between the experimental cumulative probability distribution and the standard lognormal distribution. Shown in Fig. 10, the P-P (Probability-Probability) test diagram, a scatter diagram that compares the cumulative probabilities of observed sample data against the theoretical cumulative probabilities of a specified distribution (a lognormal), provides a visual assessment of how well the chord length conforms to a particular probability distribution. The P-P test results in Fig. 10 demonstrate that the measured bubble chord lengths across the entire cross-section at all three ports conform to a lognormal distribution.

Additionally, the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were applied to evaluate the distribution characteristics of L_b. The definitions of AIC and BIC are as follows:

$$\mathrm{AIC} = -2\ln(\hat{L}_b) + 2k$$

$$\mathrm{BIC} = -2\ln(\hat{L}_b) + 2k\ln N_b$$

where k is the number of model parameters, N_b is the sample size (total bubble number), and $\hat{L}_b$ is the maximized likelihood value. A lower AIC value or a lower BIC value indicates better fitness of the distribution function. Compared with AIC, BIC incorporates sample size into its penalty term, making it more suitable for model selection in large-sample scenarios. In Table 4, the sample size of the bubble number N_b is 94,688. Model selection was performed by identifying the distribution with the minimum AIC or BIC values, and the chord length distribution of bubbles in LBE best conforms to a lognormal distribution.

Table 4. AIC and BIC values for five functions, $D_h = 7$ cm.

Distribution	AIC (e-5)	BIC (e-5)
Weibull	1.23	1.24
Gamma	1.21	1.22
Normal	1.35	1.36
Lognormal	**1.18**	**1.19**
EXP	1.42	1.43

As bubble chord length increases, the drag area generally increases, while bubble morphology evolves simultaneously. These coupled transitions induce dynamic variations in both the drag and buoyancy forces exerted by the LBE on the bubbles, consequently driving continuous adjustments in their rise velocities. Fig. 11a–d present a comparative analysis of the relationship between bubble chord lengths and velocities at different measurement ports in 5-cm and 9-cm diameter test sections. At Port 1, the median bubble velocity v_b in both test sections increases with bubble chord length, accompanied by a continuous rise in the InterQuartile Range (IQR). This upward trend is significantly more pronounced in the 9-cm diameter pipe, where both velocity and IQR exhibit stronger dependence on chord length scaling. As the two-phase flow develops axially along the test section, bubble velocities exhibit a stabilization trend. Specifically, at Ports 2 (Fig. 11d) and Port 3 (Fig. 11c), when chord lengths exceed 24 mm, bubble velocities cease to increase with further chord length growth. Meanwhile, the IQR of velocities in the 5-cm diameter tube diminishes progressively with increasing chord length, indicating a reduction in the dispersion of velocity distribution.

Fig. 11e and Fig. 11f present the fitted parameters of the lognormal distributions (where μ represents the mean value and σ the standard deviation) for all port locations in both experimental tubes. In Fig. 11e and f, both the mean (μ) and standard deviation (σ) of the chord length distribution progressively increase during bubble ascent. Notably, the value of μ in the 9-cm diameter tube exhibits a more pronounced increase (from 1.6601 to 2.3121), reflecting stronger size evolution dynamics in a larger geometry. The geometric mean (μ) of the lognormal distribution reveals that the most prevalent bubble chord lengths in LBE are clustered around 2 mm. Bubbles within this dominant size range exhibit spherical morphology, consistent with surface tension-dominated regimes at small scales. Fig. 11g and Fig. 11h, diagrams of the cumulative distribution function (CDF) for chord length, demonstrate that the median bubble chord length in the 5-cm diameter pipe is significantly larger than that observed in the 9-cm one. The 50% layer here refers to the bubble region where the number of bubbles, sorted by chord length from smallest to largest, accounts for half of the total quantity. The 50% layers in both pipes increase with axial locations, while the gap between layers also extends in larger pipes, indicating a stronger expansion effect.

C. Analysis of Differential Pressure Signals

In gas-liquid two-phase flow systems, the geometric distribution of phases is termed the two-phase flow pattern or flow regime. Different flow regimes exhibit unique hydrodynamic and thermal characteristics. Conventional flow regime identification methods, such as visual observation, high-speed photography, and X-ray imaging, are not feasible for LBE systems due to material opacity and radiation shielding constraints. Zhou et al. classified flow regimes by synergistically analyzing time-domain differential pressure signals and their PSD functions in gas-water systems. The present paper also examines the temporal fluctuations and PSD functions of differential pressure signals under varying gas superficial velocities in gas-LBE systems, providing foundational data for flow regime identification in such opaque liquid metal systems.

This subsection analyzes 360 sets of differential pressure signals, each corresponding to an area-averaged void fraction measurement. Differential pressure datasets were acquired over a 60-second sampling duration at 10 Hz. The PSD computation process utilizes the Pwelch function, which implements Welch's averaged periodogram method. The mathematical procedure involves the following sequential steps: segmentation, windowing (Hann window), Fourier transform, squaring, and averaging. Combining all steps, the Welch PSD estimate is:

$$P_{xx}[k] = \frac{K \cdot f_s}{S} \sum_{i=1}^{K} \left| \sum_{n=0}^{L-1} x_i[n] \cdot w[n] \cdot e^{-j2\pi kn/N_{\mathrm{FFT}}} \right|^2$$

where the input signal $x_i[n]$ of each segment is defined as:

$$x_i[n] = x[n + (i-1)(L-D)]$$

The variables K, f_s, S, L, N_{FFT}, and D represent segment count, sampling frequency, window energy, length of each segment, points of Fast Fourier Transform (FFT), and overlap, respectively. The $w[n]$ here is the Hanning window function.

In Eq. 24, the unit of P_{xx} is MPa^2/Hz. For more intuitive analysis of PSD characteristics, the unit should be converted to dB/Hz using the formula:

$$P_{xx,\mathrm{dB}} = 10 \cdot \log_{10}\left(\frac{P_{xx}}{P_{\mathrm{reference}}}\right)$$

where $P_{\mathrm{reference}}$ is set as 1 MPa^2/Hz.

The passage of larger bubbles through the pipe cross-section occupies more spatial volume and requires longer transit times, resulting in extended periods of pressure fluctuations. According to the inverse relationship between frequency and period, longer periods correspond to lower frequencies. Consequently, large bubbles typically manifest as low-frequency components in PSD signals. Since stable large bubbles serve as critical discriminators for flow regime classification, this section focuses on low-frequency PSD characteristics. Fig. 12 illustrates the Δp signal fluctuations and PSD distributions with varying void fractions. From time-domain analysis, as α increased, the mixture density decreased, leading to a reduction in gravitational pressure drop. Meanwhile, larger bubbles induced stronger amplitude perturbations in Δp signals during their passage through the measurement zone. From frequency-domain analysis, when void fractions were 0.10 and 0.20, the PSD signals remained relatively stable across the measured frequency domain, with no significant peaks observed. Notably, the PSD peaks near 0 Hz were considered noise. When $\alpha = 0.20$, minor fluctuations in the PSD signals were detected around 1 Hz. However, at void fractions of 0.38 and 0.47, significant increases in Δp fluctuation amplitudes were observed, accompanied by distinct PSD peaks near 1 Hz. These features might suggest the formation of periodic slug bubbles, marking the existence of slug flow regime. As the void fraction further increased to $\alpha = 0.60$, the Δp fluctuations remained highly violent. However, the PSD peaks near 1 Hz gradually diminished, suggesting a possibility of slug bubble disintegration and transition from slug flow to churn flow regime.

Spectral entropy is an indicator implemented to quantify the complexity and randomness of PSD energy distribution in signal processing. It transforms the distribution of frequency domain energy into a measure of signal disorder through the concept of information entropy:

$$\text{Spectral entropy} = -\sum_i \frac{P_{xx}(f_i)}{\sum_f P_{xx}(f)} \log_2\left(\frac{P_{xx}(f_i)}{\sum_f P_{xx}(f)}\right)$$

The larger the spectral entropy, the more dispersed the signal energy is in the frequency domain. The smaller the spectral entropy, the more concentrated the energy is in a few frequency components. As Fig. 14 illustrates, spectral entropy increased with void fraction and stabilized once α exceeded 0.3. Higher spectral entropy indicates a broader distribution of PSD frequency components and heightened stochasticity, reflecting greater complexity in bubble-size distributions.

Fig. 13 categorizes the differential pressure PSD signals under various void fractions and quantifies their low-frequency energy ratio (ratio of spectral energy below 1 Hz to total energy). The low-frequency components of Δp signals are typically attributed to large bubble dynamics. As shown in Fig. 13, the low-frequency energy ratio increased with void fraction when $\alpha < 0.30$, but gradually declined when $\alpha > 0.35$, reflecting distinct hydrodynamic regimes of the two-phase flow.

IV. CONCLUSION

This study conducted gas-liquid LBE two-phase flow experiments in pipes with diameters of 4 cm, 5 cm, 7 cm, and 9 cm under diverse phase flow rates. Two-sensor EC probes were employed to obtain local parameters, including void fraction, gas velocity, interfacial area concentration, bubble chord length, and bubble frequency at multiple radial positions and axial heights. We discovered the pipe size influence on drift-flux model parameters, and the distribution patterns of bubble chord lengths and their correlations with bubble velocities. Moreover, differential pressure signals at a probe location were processed to calculate power spectral density (PSD) energy spectra, and their frequency-domain characteristics were investigated. The key findings are summarized as follows:

1. The void fraction in the gas-liquid two-phase flow generally exhibited a core-peak distribution across the cross-section. As the gas flow rate increased, the growth of interfacial concentration primarily originated from group 1 bubbles. The chord length of group 1 bubbles showed uniform distribution across the channel cross-section, while group 2 bubbles displayed a core-peak distribution trend. As the gas-LBE mixture flowed upward, bubble velocity stabilized from 10 diameters height, with interfacial concentration and bubble frequency exhibiting decreasing trends. In pipes with small diameters, the drift velocity increased with channel diameter, while in pipes with large diameters, the drift velocity showed no trend of increase.
2. Analysis of the relationship between bubble chord length and bubble velocity revealed that stable bubble velocity ceased to increase once the chord length reached a certain value. The chord length distribution conformed to a lognormal pattern, with both the mean value and standard deviation of the distribution increasing with measurement height.
3. The deviations between the volumetric void fraction by differential pressure measurements and the area-averaged void fractions by conductivity probes fall within \$±\$0.1. The fluctuation amplitude of differential pres-

sure signals increased with void fraction. Notably, the power spectral density of differential pressure signals exhibited peaks at 1 Hz under specific void fraction conditions, which may correspond to the formation and transition of slug flow regimes within the channel.

These experimental data would contribute to the development of drag coefficient models, drift-flux correlations, and the identification of flow regimes in gas-LBE systems. These developments would enable accurate prediction of bubble migration and distribution in LBE coolant following SGTR accidents in LFRs, and consequently contribute to the assessment of core safety risks.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Hong Zhang, Ling-Feng Wan, Di Wang, Wan Sun, Si-Miao Tang, Liang-Ming Pan, and Long-Xiang Zhu. The first draft of the manuscript was written by Hong Zhang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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