EXPERIMENTAL STUDY OF THE BEHAVIOR OF A SINGLE AIR BUBBLE RISING IN A RECTANGULAR CHANNEL USING THE INTEGRATION OF THE OPTICAL VISUALIZATION METHOD AND THE BUBMASK TOOL

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ABSTRACT

Thermal-hydraulic safety is crucial in nuclear reactors, where water is both a coolant and a neutron moderator. Water removes heat from the reactor core as a coolant, preventing overheating and ensuring stable operation. Its high specific heat capacity and thermal conductivity facilitate effective heat transfer. As a moderator, water slows fast neutrons through elastic scattering with hydrogen nuclei, increasing neutron capture probability and sustaining a controlled chain reaction. However, vapor bubble formation reduces fluid density, affecting neutron moderation and heat transfer. A lower hydrogen density decreases neutron scattering efficiency, while excessive void formation can hinder cooling, increasing the risk of dry-out. Understanding these effects is essential for accurate two-phase flow modeling and reactor safety assessment. Bubble behavior of interest includes velocity, shape, trajectory, deformation, and void fraction. This study investigated the rising behavior of a single air bubble in a rectangular channel through optical visualization techniques and the BubMask image processing tool. A high-speed camera is used to record moving images of the measurement object. Then, the online available deep learning tool for image processing, BubMask, is used. It is an automated bubble detection and mask extraction tool. The experiment considered and compared the velocity, shape, and deformation of a single air bubble rising freely in a rectangular channel. Thereby also evaluating the accuracy of the model used.

Keywords: behavior of a single air bubble, optical visualization, BubMask tool, deep learning, rectangular channel

I. INTRODUCTION

Two-phase flows are commonly found in various industrial systems. Understanding the motion and interaction of gas bubbles within a liquid is essential for developing strategies that enhance process efficiency, ensure operational safety, and maintain product quality [1]. In nuclear reactors, thermal-hydraulic safety critically depends on the behavior of the coolant, which acts as both a heat transfer medium and a neutron moderator. The formation of vapor bubbles lowers fluid density, impairs heat transfer, and affects reactor reactivity. Excessive void generation can lead to dry-out conditions, posing significant safety risks. Accurately capturing these phenomena is crucial for two-phase flow modeling and reactor safety assessments.

While numerical simulations are widely used to evaluate these internal processes, discrepancies between simulation and reality necessitate experimental validation to ensure model reliability. This study aims to develop an experimental system for observing and analyzing gas–liquid two-phase flow, providing data for model validation and deeper insight into bubble dynamics.

Key flow parameters include void fraction, velocity, turbulence, and bubble shape. Optical Visualization Techniques (OVT), particularly high-speed imaging, are widely used to capture bubble behavior and estimate flow characteristics due to their clarity, noninvasive nature, and scalability across systems ranging from microfluidics to industrial setups [2–5]. Ultrasonic methods such as Ultrasonic Velocity Profiling (UVP) can also measure velocity profiles in both phases via Doppler shift detection [6,7], but characterizing rising bubbles often requires multiple probes and complex signal processing [8–10]. Given its practical advantages, OVT is employed in this study for experimental measurements.

This study is part of a broader effort to develop diagnostic methods for analyzing two-phase flow and detecting the onset of boiling in reactor-like channels. As an initial step toward this goal, the present work focuses on the experimental observation and analysis of a single rising gas bubble. Optical Visualization Technique (OVT) is employed to capture bubble dynamics. At the same time, deep-learning methods, using the BubMask tool, are applied to extract key bubble characteristics—including shape and velocity—from optical data.

II. MEASUREMENT METHOD

II.A. Optical Visualization Method

Optical Visualization Technique (OVT) refers to a class of non-intrusive measurement methods that employ light-based imaging, typically high-speed cameras, to capture and analyze the motion of physical objects or flow phenomena. These techniques provide high-resolution visual data, making them particularly effective for studying fluid dynamics, material behavior, and multiphase flows. In two-phase flow research, OVT enables detailed observation of key characteristics such as flow structure, phase distribution, interface dynamics, and velocity fields, without disturbing the system. Its high spatial and temporal resolution makes it especially valuable for capturing transient phenomena such as bubble formation, motion, and interaction.

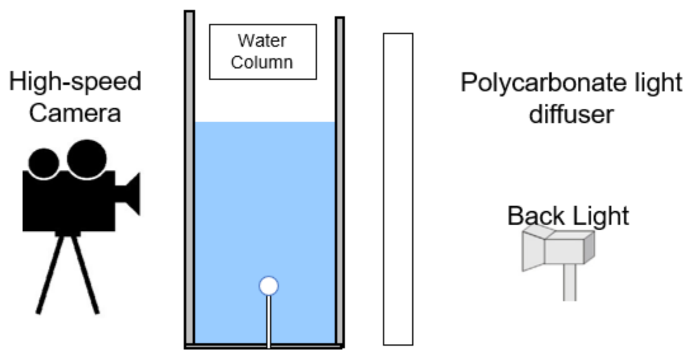


FIGURE 1. OPTICAL VISUALIZATION METHOD.

In this study, OVT is employed to observe the rise of gas bubbles in a liquid. Key parameters—including bubble shape, trajectory, and velocity—can be accurately extracted by recording their motion over time using a high-speed camera.

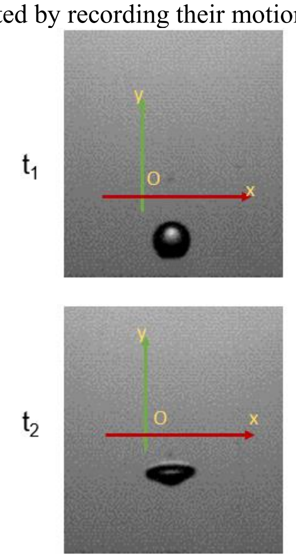


FIGURE 2. BUBBLE INFORMATION.

For instance, the bubble velocity v can be determined from two consecutive frames recorded at different times t_1 and t_2, corresponding to vertical positions y_1 and y_2 , respectively, using the following expression [11]:

$$v = \frac{y_2 - y_1}{t_2 - t_1} \tag{1}$$

II.B. Experimental setup

The experimental setup consists of a transparent rectangular tank made of acrylic (mica), measuring 50 mm in width, 50 mm in depth, and 500 mm in height. The tank was filled with tap water up to a height of 385 mm, and all measurements were conducted at a laboratory room temperature of 26.2 °C. After six hours of static conditions, assuming that the water temperature equilibrated with the ambient room temperature is reasonable. This thermal equilibrium naturally occurs based on thermodynamic principles: when water and air are in contact, they exchange heat through the surface. If the water is warmer than the air, heat is transferred from the water to the air, and vice versa. This process continues until the temperature difference is eliminated, leading to thermal equilibrium between the two media.

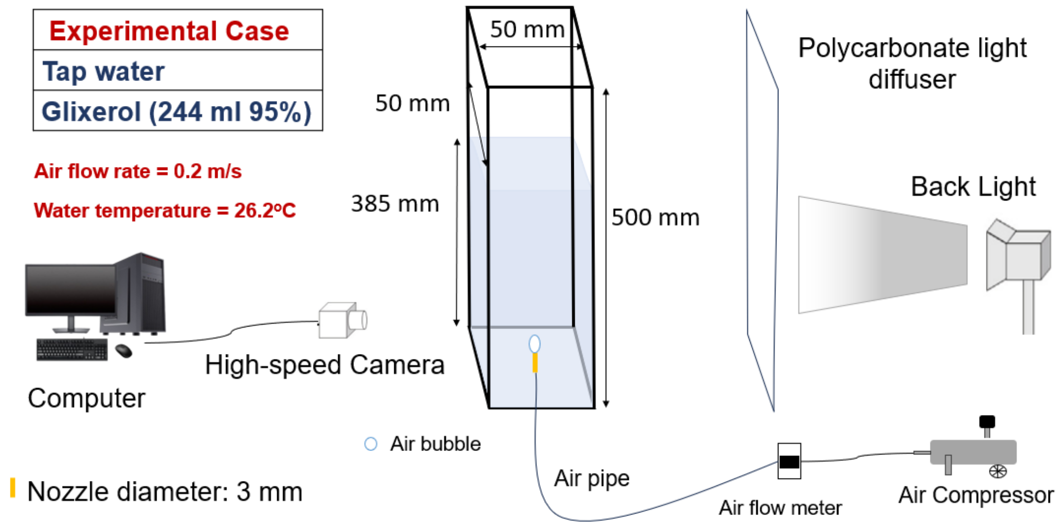


FIGURE 3. EXPERIMENTAL APPARATUS.

In the controlled laboratory environment, room temperature remains stable due to air-conditioning systems, allowing the water to reach ambient temperature more easily. Moreover, water's high specific heat capacity enables it to retain heat efficiently, slowing temperature fluctuations and maintaining uniform thermal conditions. Significantly, since no external heating or cooling is applied, the system stabilizes without thermal interference.

The target of this study is single air bubbles generated from a 3 mm nozzle connected to an air compressor. A pressure control valve regulates the gas flow, ensuring consistent air injection across experiments. This control enables isolated bubbles to form one at a time without coalescence or interaction. According to the flowmeter, the gas flow rate entering the tank is approximately 0.2 m/s, sufficiently low to allow individual rising bubbles to form.

During the bubble rising process, a high-speed camera was used to capture the motion of the bubbles. This device can record fast-moving objects with an exposure time of less than 1/1000 second and a frame rate of up to 1000 frames per second. It enables the visualization of rapid dynamics through sequential still images. To ensure clear and high-contrast images, a polycarbonate light diffuser was placed opposite the camera, with a backlight source positioned behind it to create a uniform background. The recorded images were stored on a computer for subsequent detailed analysis.

II.C. BubMask tool

II.C.1. Deep learning with BubMask tool

Optical visualization techniques are widely adopted in experimental studies across various fields, from microscale biological systems to large-scale industrial processes [4]. This thesis uses Optical Visualization Technique (OVT) to observe gas–liquid two-phase flow without disturbing the flow field, offering a significant advantage over invasive methods in capturing interfacial dynamics.

However, identifying individual bubbles remains challenging, especially in overlapping groups. Traditional image processing methods, such as Hough transform [4], breakpoint method [4], and Watershed transform [4], have shown effectiveness but are often insufficient for complex multi-bubble images.

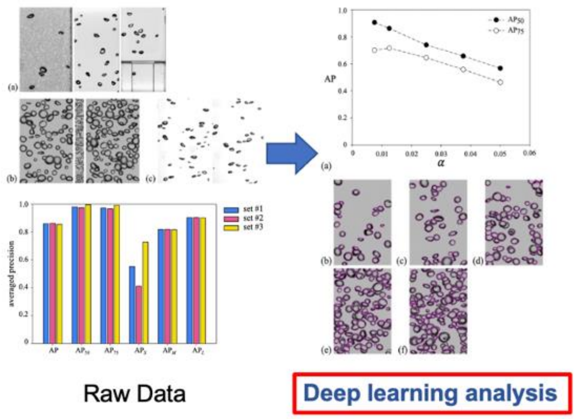
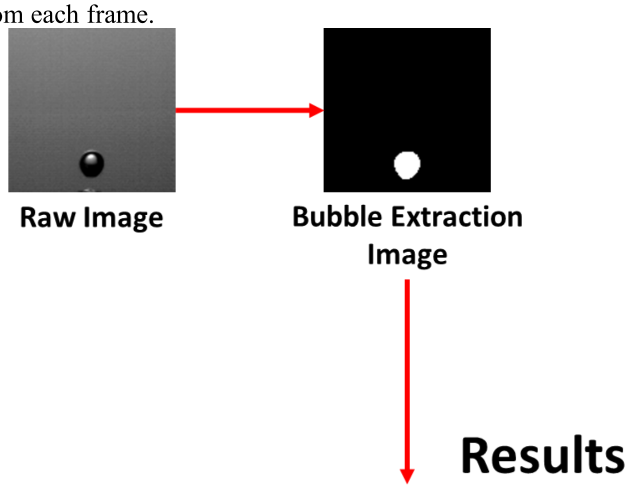


FIGURE 4. THE EXPERIMENTAL IMAGES WERE PROCESSED AND ANALYZED WITH BUBMASK [4].

Recent advances in deep learning provide promising solutions. Notably, Yewon Kim and Hyungmin Park trained a Mask R-CNN model to automatically detect and segment bubbles in two-phase flows [4]. Their method achieves over 95% accuracy, operates twice as fast as traditional approaches, and eliminates the need for manual threshold tuning. Moreover, the tool is open-source, significantly reducing data processing costs.

II.C.2. Image processing and measurement using BubMask

The rising motion of gas bubbles was captured using a high-speed camera, providing time-resolved image sequences. These images were then processed with BubMask, a deep learning-based image analysis tool designed to extract individual bubble masks from each frame.



x (m)	y (m)	Orientation (rad)	Axis_major_length (m)	Axis_minor_length (m)	Area (m^2)	Frame_number	Mask_number
0.0173	0.0026	-0.7501	0.0048	0.0047	1.77E-05	872	1

FIGURE 5. BUBMASK IMAGE ANALYSIS PROCEDURE.

These masks obtained quantitative features such as centroid position, projected area, and orientation angle. This information forms the basis for characterizing bubble dynamics, including shape evolution, rise trajectory, and velocity at different motion stages.

II.C.3. Evaluation of BubMask accuracy

While BubMask can extract object shape and size, the accuracy of such measurements must be validated in experimental studies. Therefore, to standardize the measurement method in this research, two steel spheres with fixed but different diameters were employed for calibration and verification.

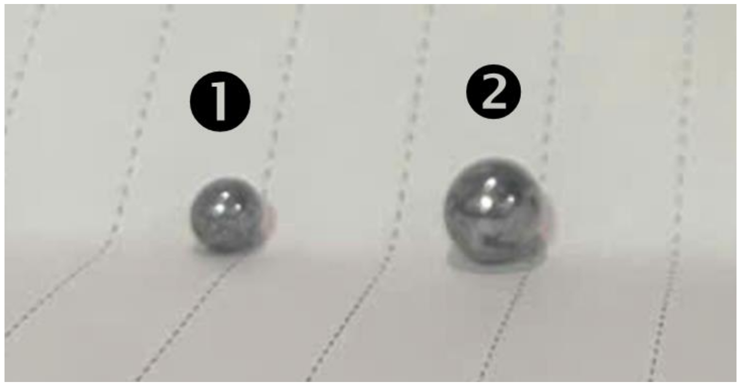


FIGURE 6. STEEL BALLS FOR VALIDATION.

TABLE I. The diameters of the steel balls.

Steel Ball	Normalization Diameter (mm)
1	3.96
2	5.56

Under the experimental setup and measurement conditions shown in Figure 3, the gas supply was closed during this validation test. Steel spheres were released from a height of 500 mm above the bottom of the tank. The high-speed camera captured real-time images of the falling spheres (Figure 7a). Like the gas bubble analysis, BubMask detected and outlined the moving spheres (Figure 7b), followed by segmentation and binary image extraction (Figure 7c). Key parameters such as area and position were extracted from these processed images for further analysis.

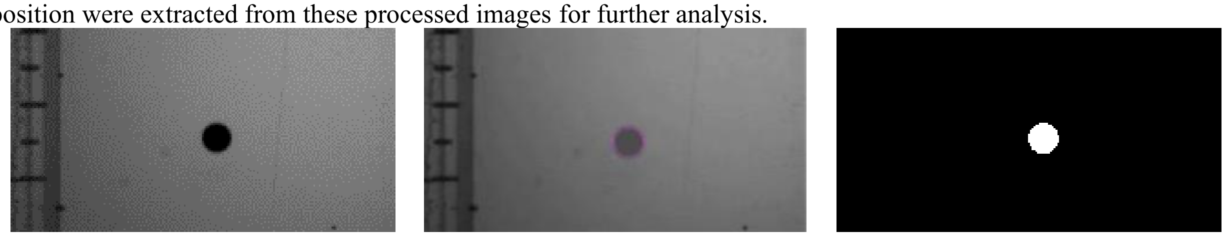


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FIGURE 7. DETECTION AND 2D MASK EXTRACTION OF A SPHERICAL STEEL BALL WITH A DIAMETER OF 3.96 MM.

Following data processing, the discrepancy between the measured diameters of the steel balls and their known reference values is analyzed to assess the measurement accuracy of the method. The deviation between the experimental and reference diameters was computed using the following expression:

$$Deviation = \left|\frac{Reference\ Diameter - Measured\ Diameter}{Reference\ Diameter}\right| \times 100\% \tag{2}$$

TABLE II. Deviation of the measured diameter from the reference value.

Steel Ball	Reference Diameter (mm)	Measured Diameter (mm)	Error (%)
1	3.96	4.04	**1.98**
2	5.56	5.49	**1.26**

The deviations between the measured and reference diameters presented in Table II are below 2%, indicating a high level of measurement accuracy. Minor discrepancies may stem from experimental conditions, image processing, or other technical factors. Nonetheless, the low deviation confirms the reliability of the measurement method, supporting its applicability for further analysis.

III. RESULTS AND DISCUSSION

III.A. Bubble shape evolution through different rising stages

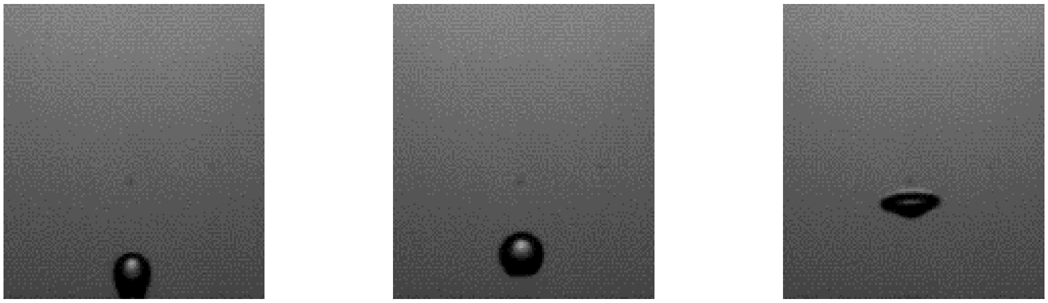

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FIGURE 8. BUBBLE SHAPE DURING RISE.

The formation and morphological evolution of a single air bubble rising in water can be divided into three distinct stages, as illustrated in Figure 8. Each stage reflects the dominance of different physical forces affecting the bubble's geometry:

Stage 1 – Initial formation: At the nozzle tip, surface adhesion between the liquid and solid holds the bubble momentarily. This adhesion force stretches the bubble vertically, resulting in an upright oval shape (Figure 8a).

Stage 2 – Detachment from the nozzle: Once the buoyant force overcomes adhesion, the bubble detaches and tends to restore a spherical shape due to surface tension. This near-spherical geometry indicates a transient balance of forces and is used to define the bubble diameter (Figure 8b).

Stage 3 – Ascending phase: As the bubble rises, increasing velocity and pressure differences between the front and rear, along with fluid drag, cause horizontal elongation and vertical compression. The bubble transforms into a horizontally oriented oval shape (Figure 8c).

These observations confirm that bubble morphology is governed by the interplay between buoyancy, drag, surface tension, and wetting forces during its ascent.

III.B. Velocity of a single gas bubble rising in a water column

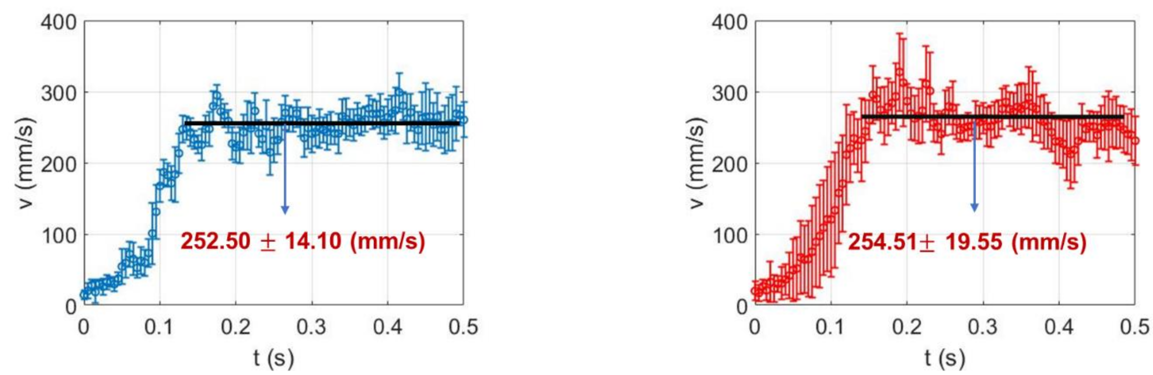

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FIGURE 9. VELOCITY OF A SINGLE GAS BUBBLE RISING IN A WATER COLUMN OVER TIME FROM THE NOZZLE POSITION.

In the experiment, the rising motion of single gas bubbles was recorded using a high-speed camera. The captured images were then processed with the deep learning tool BubMask, which extracted detailed information on bubble shape, position, and velocity over time. The results show that the velocity of the bubble is not constant but varies across different stages of its ascent. This variation reflects the complex interplay between buoyancy, liquid drag, and environmental disturbances.

Right after the bubble detaches from the nozzle at the early stage, buoyancy is the dominant force, causing rapid acceleration. The drag force increases proportionally as the bubble speeds, especially in deformed bubbles with greater frontal area. Over time, a balance is established between buoyancy and drag, resulting in a more stable velocity during the later stages of motion.

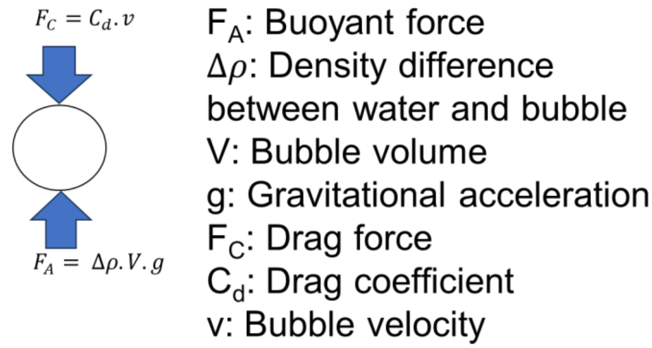

FIGURE 10. FORCES ACTING ON A FREELY RISING SINGLE GAS BUBBLE IN WATER.

When a gas bubble rises in water, it experiences a drag force, which is influenced by velocity, size, shape, and fluid properties. This force plays a key role in controlling bubble motion [12]. When buoyancy and drag balance out, the bubble reaches a terminal velocity. The average terminal velocity in tap water is about 252.5 mm/s, as shown in Figure 9a, consistent with theories of bubbles in still liquids. The velocity profile changes significantly when adding 244 ml of 95% glycerol (Figure 9b). The acceleration phase is longer due to higher viscosity, and after reaching a peak, the velocity fluctuates and slightly decreases instead of remaining stable. This is caused by increased viscous drag and nonlinear fluid interactions. As shown in Figure 10, the buoyancy force remains constant since the bubble volume does not change. However, the drag varies with the bubble shape, which continuously deforms during rising. This leads to different equilibrium velocities. In addition, local vortex formation around the bubble contributes to unsteady motion by introducing fluctuating lift and drag forces.

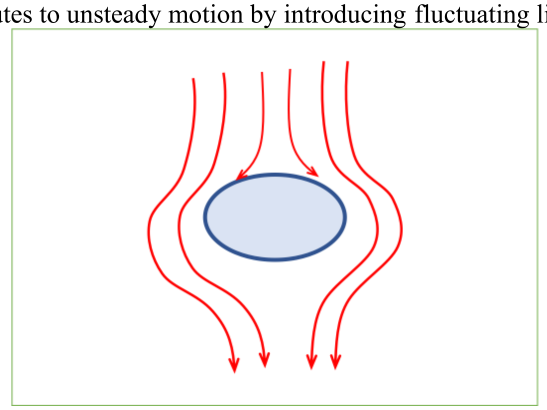

FIGURE 11. ILLUSTRATION OF THE RELATIVE MOTION OF THE SURROUNDING FLUID AROUND A RISING GAS BUBBLE.

IV. CONCLUSIONS

This study presented an experimental investigation of the rising behavior of a single air bubble in a rectangular water column, using the Optical Visualization Technique (OVT) combined with the deep learning-based BubMask tool. High-speed imaging enabled accurate tracking of bubble motion, while BubMask provided reliable extraction of key parameters such as shape and velocity.

The results show that bubble velocity is not constant but varies with rising stages, reflecting the complex balance between buoyancy, drag, and fluid interaction. In tap water, the measured terminal velocity is consistent with theoretical models. When glycerol is added, noticeable changes in the velocity profile are observed. However, due to the short observation time and limited field of view of the camera, these trends should be interpreted cautiously and require further validation.

Validation tests using steel spheres demonstrated that the image-based measurement method is accurate, with deviations below 2%. These findings confirm the applicability and reliability of the integrated OVT–BubMask approach for analyzing bubble dynamics in multiphase flows and provide a basis for future studies on complex flow conditions such as boiling and bubble interactions.

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