

Article

Accumulation Characteristics of Bubbles in Typical Oil Passages of Transformers

Tonglei Wang ^{1,*}, Zhengguang Chen ², Shitianyi Tan ³ , Yuandi Lin ¹, Yong Ma ¹ and Shaoqi Wang ³ ¹ Electric Power Research Institute, State Grid Jiangsu Electric Power Co., Ltd., Nanjing 211103, China² State Grid Corporation of China, Beijing 100032, China³ State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an 710049, China; pudding2018@stu.xjtu.edu.cn (S.T.)

* Correspondence: wangtonglei@yeah.net

Abstract

The presence of bubbles severely threatens the insulation safety of power transformers. Understanding bubble accumulation characteristics is essential for predicting potential insulation weaknesses. In this study, we propose a Euler–Lagrange two-phase flow model, combined with an experimental platform, to investigate the accumulation and growth characteristics of bubbles in typical oil channels. The continuous phase flow field is solved within the Eulerian framework, while discrete bubble trajectories are tracked using the Lagrangian approach, simultaneously accounting for drag, buoyancy, and friction forces. The results indicate that bubbles primarily accumulate on the top insulating paper surfaces within horizontal and corner oil channels. In horizontal channels, the accumulation rate correlates positively with flow velocity and bubble concentration; furthermore, paper overlapping gaps intercept sliding bubbles, promoting their coalescence into larger ones. Conversely, at channel corners, the accumulation length and rate decrease as flow velocity increases, with accumulation weakening significantly when the velocity exceeds 0.6 m/s. Additionally, bubble growth is highly sensitive to flow velocity and temperature: higher velocities inhibit bubble coalescence, whereas elevated temperatures accelerate both coalescence and growth. Ultimately, this research reveals the fundamental accumulation laws of bubbles in transformer oil channels, providing a reliable analytical tool and theoretical reference for assessing bubble-induced insulation risks.

Keywords: oil paper insulation; accumulation of bubbles; oil immersed transformer; two-phase flow; fluid mechanics



Academic Editor: Satoru Okamoto

Received: 5 June 2026

Revised: 8 July 2026

Accepted: 15 July 2026

Published: 18 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Power transformers are critical components that determine the stability and power supply quality of power grids [1–3]. Bubbles generated in transformer oil due to factors such as multiple physical fields, moisture, aging, and partial discharge represent a critical threat leading to insulation failure [4–7]. Specifically, extensive investigations reported in the Chinese literature have elucidated these fundamental mechanisms. For instance, Gao et al. found that under the coupled effects of moisture and high temperature, bubbles hundreds of micrometers in size can nucleate from the oil-impregnated paper surface [4]. These bubbles may either detach and migrate within the oil or form accumulations in horizontal structures. Regarding bubble dynamics under electrical stress, Zhang et al. experimentally observed that bubbles in a uniform electric field undergo periodic elongation along the

field direction as they rise vertically, with the deformation degree positively correlated with the electric field strength [5]. In contrast, in a non-uniform electric field, bubbles tend to migrate towards regions of weaker field strength, gradually deviating further from the high-voltage electrode as the voltage increases. Furthermore, based on the principle of virtual work, Cai et al. derived analytical expressions for the electric field force acting on bubbles. Their simulations revealed that non-uniform electric fields significantly increase the retention time of bubbles between electrodes, thereby elevating the probability of forming hazardous continuous “bubble bridges” along the motion paths [7]. As bubbles migrate, accumulate, and grow in size along with the oil flow, the risk of failure escalates significantly. Consequently, investigating the accumulation characteristics of bubbles in oil is of great significance for enhancing the insulation performance of the equipment.

Under the influence of multi-physical fields, bubbles are subjected to a combination of buoyancy, flow field drag forces, and interfacial forces, undergoing complex processes of deformation, migration, and coalescence [8]. The core of this dynamic behavior is the drag force, which is composed of viscous drag and pressure drag, and its dominant mechanism varies with different flow regimes [8,9]. Existing studies have established empirical formulas for the drag coefficient of spherical bubbles under various flow regimes, laying a solid foundation for quantitative analysis [10–13].

Initially, bubbles evolving from the insulating paper surface are only hundreds of micrometers in size [14], posing a limited individual threat. However, once they coalesce into millimeter-scale bubbles, they exacerbate electric field distortion and trigger catastrophic consequences. In the typical low-velocity (<0.2 m/s) laminar flow environment of transformers, the probability of random bubble collisions in the bulk oil is extremely low. Therefore, coalescence primarily occurs exclusively at specific structural accumulation sites (such as corner stagnation zones and paper overlapping gaps), where migrating bubbles are trapped and forced into tight interfacial contact, forming stable swarms that undergo continuous coalescence [15]. Research indicates that the paper surface releases gas under the coupled effects of high temperature and moisture [14,16]. These bubbles can detach from the paper, migrate within the oil, and are prone to accumulate and grow on horizontal oil channel structures or the surfaces of winding static rings [17,18]. Thus, accurately predicting bubble accumulation characteristics in typical oil channel structures is a prerequisite for assessing insulation hazards.

To address this issue, existing numerical methods based on phase interface tracking, such as the classic Volume of Fluid (VOF) method [19] and the level-set method [20], can finely depict bubble interface deformation and contact; however, these microscopic simulations harbor uncertainties and entail prohibitive computational costs [21–23]. Conversely, some studies simplify bubbles as discrete particles to solve their trajectories within a macroscopic grid. While this approach is more efficient, it relies heavily on the accuracy of interfacial force modeling, and models tailored to specific accumulation sites remain imperfect [18].

To this end, guided by foundational multiphase flow theories [24] and recent advancements in Eulerian-Lagrangian computational methods published in Applied Sciences [25,26], this study proposes a two-phase flow model for bubble migration based on the Euler-Lagrange framework, balancing computational efficiency and accuracy at the engineering scale. This model discretely tracks bubbles within a macroscopic flow field while simultaneously accounting for the effects of drag, buoyancy, and wall friction forces. Furthermore, an experimental platform was constructed. By comparing the simulation and experimental results, this study reveals the bubble accumulation sites and growth laws under various operating conditions. This not only verifies the effectiveness of the proposed model but also provides a novel tool for assessing insulation risks.

2. Materials and Methods

2.1. Numerical Modeling

Analyzing bubble migration and accumulation requires solving the gas–liquid two-phase flow motion. According to fluid dynamics theory, the Euler–Lagrange framework [24,27] is suitable for conditions where the volume fraction of the discrete bubble phase is less than 10–12%. This framework captures comprehensive information on bubble motion and accurately calculates the complex force interactions between the bubbles and the oil–paper insulation.

2.1.1. Governing Equations for the Continuous Phase

In the Euler–Lagrange framework, the two-phase flow is categorized into continuous and discrete phases based on their relative concentrations. The continuous phase is described using the Eulerian system, where the spatial distribution of fluid properties is solved through continuity, momentum, and energy conservation equations.

Assuming the liquid phase is incompressible, its motion satisfies the continuity equation:

$$\frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l \mathbf{u}) = 0 \quad (1)$$

where ρ_l is the density of the liquid phase and $\mathbf{u}$ is the liquid velocity vector.

Under operating pressures, the compressibility of insulating oil is negligible. The momentum conservation equation is governed by the Navier–Stokes equations for incompressible fluids:

$$\rho_l \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla p + \nabla \cdot \mu_l (\nabla \mathbf{u} + \nabla \mathbf{u}^T) + \rho_l \mathbf{g} - \mathbf{F}_{\text{ex}} \quad (2)$$

where μ_l is the dynamic viscosity, p is the pressure, and $\mathbf{g}$ is the gravitational acceleration.

The four terms on the right side of Equation (2) represent the pressure gradient force, viscous force, gravity, and the discrete phase interaction force, respectively. The interaction force $\mathbf{F}_{\text{ex}}$ denotes the feedback force exerted by the bubbles on the oil flow, calculated as the sum of forces exerted by all discrete bubbles within a unit volume:

$$\mathbf{F}_{\text{ex}} = -\frac{1}{V_{\text{cell}}} \sum \frac{3\mathbf{F}_D}{4\pi R^3 \rho_g} \Delta m_g \Delta t \quad (3)$$

where V_{cell} is the volume of the Eulerian computational cell, $\mathbf{F}_D$ is the drag force on the bubbles, Δm_g is the mass flow rate of the discrete phase, and Δt is the discrete phase time step.

In this study, the two-way coupling momentum exchange (Equation (3)) is updated at every continuous phase time step. Although the global bubble volume fraction is low (e.g., 0.1%), continuous accumulation at specific structural sites leads to a significantly elevated local discrete phase concentration. Retaining the full two-way coupling ensures physical fidelity in capturing the localized feedback effects of dense bubble swarms on the surrounding flow field.

Heat transfer within the fluid follows the energy conservation equation:

$$\rho_l C_p \frac{\partial T}{\partial t} + \rho_l C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (4)$$

where C_p is the specific heat capacity, k is the thermal conductivity, T is the temperature, and Q is the volumetric heat source.

The continuous phase motion is solved using the Finite Volume Method (FVM). The computational domain is partitioned into a series of non-overlapping control volumes,

each represented by a node. Equations (1), (2) and (4) are discretized within these control volumes to obtain the flow field parameters.

A grid independence study was conducted to eliminate mesh-induced errors. Testing a baseline mesh of 268,945 nodes against a doubled-density mesh showed negligible variations in the computed flow and temperature fields. Thus, the 268,945-node mesh was adopted to balance computational efficiency and solving accuracy.

2.1.2. Governing Equations for the Discrete Phase

The discrete phase is described using the Lagrangian system, which tracks the motion of individual bubbles based on Newtonian dynamics. Phase interactions are incorporated via momentum and energy exchange terms in the continuous phase equations and via force balances in the discrete phase equations.

The migration of each bubble within the flow field is solved using Newton's second law:

$$\frac{4}{3}\pi R^3 \rho_g \frac{d\mathbf{u}_b}{dt} = \mathbf{F}_B + \mathbf{F}_D + \mathbf{F}_F \quad (5)$$

where R is the bubble radius, ρ_g is the gas density, and $\mathbf{u}_b$ is the bubble migration velocity.

The three terms on the right side of Equation (5) represent the forces acting on the bubble: buoyancy $\mathbf{F}_B$, drag force $\mathbf{F}_D$ between the bubble and oil, and friction $\mathbf{F}_F$ between the bubble and the paper surface. Due to the density difference between the gas and insulating oil, the buoyancy is calculated as:

$$\mathbf{F}_B = \frac{4}{3}\pi R^3 (\rho_1 - \rho_g) \mathbf{g} \quad (6)$$

The drag force $\mathbf{F}_D$, exerted by the continuous phase, acts in the direction opposite to the relative motion between the bubble and the oil:

$$\mathbf{F}_D = -C_D \text{Re} \frac{\pi}{4} \mu_1 R \cdot \mathbf{u}_{\text{slip}} \quad (7)$$

The drag coefficient C_D is determined using the Schiller–Naumann model [10]:

$$C_D = \begin{cases} 24/\text{Re}(1 + 0.15\text{Re}^{0.687}), & \text{Re} \leq 1000 \\ 0.44, & \text{Re} > 1000 \end{cases} \quad (8)$$

where Re is the bubble Reynolds number ($\text{Re} = 2\rho_1 \mathbf{u}_{\text{slip}} R / \mu_1$), representing the ratio of inertial forces to viscous forces. $\mathbf{u}_{\text{slip}}$ represents the relative motion speed between the bubble and the oil.

It should be noted that the Schiller–Naumann model is derived for spherical particles. Based on our experimental observations, severe interface deformation of bubbles in the transformer oil occurs only when the bubble radius exceeds 1.25 mm. For the micro-bubbles investigated in this study (radius up to 500 μm), the surface tension of the oil dominates over the localized hydrodynamic forces, maintaining the bubbles in a stable, nearly spherical shape. Therefore, the application of this drag model is accurate and appropriate within our investigated size range.

When a bubble contacts the insulating paper, it experiences a friction force $\mathbf{F}_F$ acting opposite to its motion:

$$\mathbf{F}_F = -k\sqrt{\text{Bo}_\perp} \cdot R \cdot \sigma \cdot \text{Ca}^{2/3} \mathbf{u}_b / |\mathbf{u}_b| \quad (9)$$

where k is the empirical friction coefficient. Through analysis of the bubble migration data recorded in our experimental platform under stable contact conditions with the insulating paper, the value of k is determined to be 12.16, with a high goodness of fit

($R^2 = 96.99\%$). Additionally, σ is the surface tension coefficient, $Bo_{\perp}$ is the normal Bond number ($Bo_{\perp} = 4\rho_l g_{\perp} R^2 / \sigma$), and Ca is the Capillary number ($Ca = \mathbf{u}_{\text{slip}} \mu_l / \sigma$). These dimensionless numbers quantify the contact pressure and the ratio of viscous forces to surface tension, respectively.

The migration trajectory is obtained by integrating Equation (5) over discrete time steps, providing the motion parameters of each bubble along its entire path.

It should be emphasized that the formulations for these micro-mechanical forces (buoyancy, drag, and friction) depend exclusively on local fluid dynamics and the interfacial characteristics of the insulating material. Because the Eulerian framework dynamically computes the local flow field across different structural scales, these force parameters do not require recalibration when the model is applied to transformers of different capacities and macroscopic geometries. This inherent scale independence ensures the broad generalizability of the proposed Euler-Lagrange model in practical engineering applications.

2.1.3. Spatial Distribution Statistics of Discrete Phase Parameters

A large number of discrete phase bubbles exist in the oil-paper insulation. By solving the migration process of each bubble using Equation (5), the spatial position and velocity parameters of each bubble are obtained within the Lagrangian framework. By conducting statistical analysis on the discrete phase parameters within the control surfaces and control volumes, the spatial distributions of parameters such as bubble concentration and average bubble size in the Eulerian framework are acquired.

For a two-phase flow inlet with a bubble concentration of c_g , given the continuous phase flow rate V_0 , the inlet gas flow rate can be determined as $V_g = c_g / (1 - c_g) V_0$. Under the Eulerian framework, the computational grid divides the inlet plane with an area of S into several control surfaces. Assuming the discrete phase bubble flow is uniformly distributed across the inlet plane, the discrete phase bubble flow rate entering a specific control surface with an area of ΔS can be calculated as $\Delta V = V_g \cdot \Delta S / S$.

The discrete phase bubbles are injected from the control surfaces of the inlet plane in the form of multiple bubble parcels. A bubble parcel consists of a specific flow rate of single-sized bubbles injected from a single control surface. If the bubble radius follows a distribution function $f(R)$, the radius distribution range is divided into N intervals. For the i th interval, the bubble radius is R_i , the relative concentration is $f(R_i)$, and the corresponding flow rate is determined accordingly. Each control surface injects N bubble parcels of varying radii, and the sum of the flow rates of all parcels equals the total bubble flow rate for that specific control surface.

Under the Eulerian framework, the computational domain is divided into numerous control volumes, and multiple bubble parcels may pass through a single control volume. If M bubble parcels pass through a control volume within a given time step, the discrete phase parameters in this control volume during that time step are calculated as the mean values of the parameters of these M parcels, as expressed in Equation (10):

$$\bar{\phi} = \sum_{i=1}^M \phi_i t_i n_i / \sum_{i=1}^M t_i n_i \quad (10)$$

where $\bar{\phi}$ is the mean value of the discrete phase parameters within the control volume; ϕ_i is the discrete phase parameter of the i th bubble parcel; t_i is the residence time of the i th bubble parcel within the control volume; and n_i is the number of bubbles contained in the i th bubble parcel. Using Equation (10) to perform statistical analysis on the discrete phase parameters in each control volume yields the spatial distribution of the discrete phase parameters mapped onto the Eulerian framework.

In the simulation model, the oil channel inlet comprises 100 control surfaces. Into each control surface, 20 bubble parcels of different sizes are injected. The flow rate of each bubble parcel is determined based on the area of its corresponding control surface and the bubble size distribution function $f(R_i)$. In this study, $f(R_i)$ follows a log-normal distribution, expressed as $\ln(R) \sim N(\mu, \sigma^2)$. Based on our experimental curve fitting, for bubbles with an average radius of 20 μm , the distribution parameters are $\mu = 2.8763, \sigma = 0.2614$; for bubbles with an average radius of 188 μm , the parameters are $\mu = 4.8195, \sigma = 0.2813$. The simulation time step is set to 1 s, with a total simulation duration of 60 s. At each time step, 2000 bubble parcels are injected. Over the entire simulation process, the migration trajectories of 120,000 bubble parcels are tracked, and the bubble parameters within the computational grid are statistically recorded at each moment.

2.2. Experimental Setup

To investigate the migration and accumulation behavior of bubbles within the oil-paper insulation system, an experimental platform with adjustable parameters (channel geometry, flow velocity, temperature, and bubble concentration) was constructed. As shown in Figure 1, the system consists of a typical oil channel experimental chamber, an oil flow loop, a bubble introduction module, a temperature control module, and an observation module.

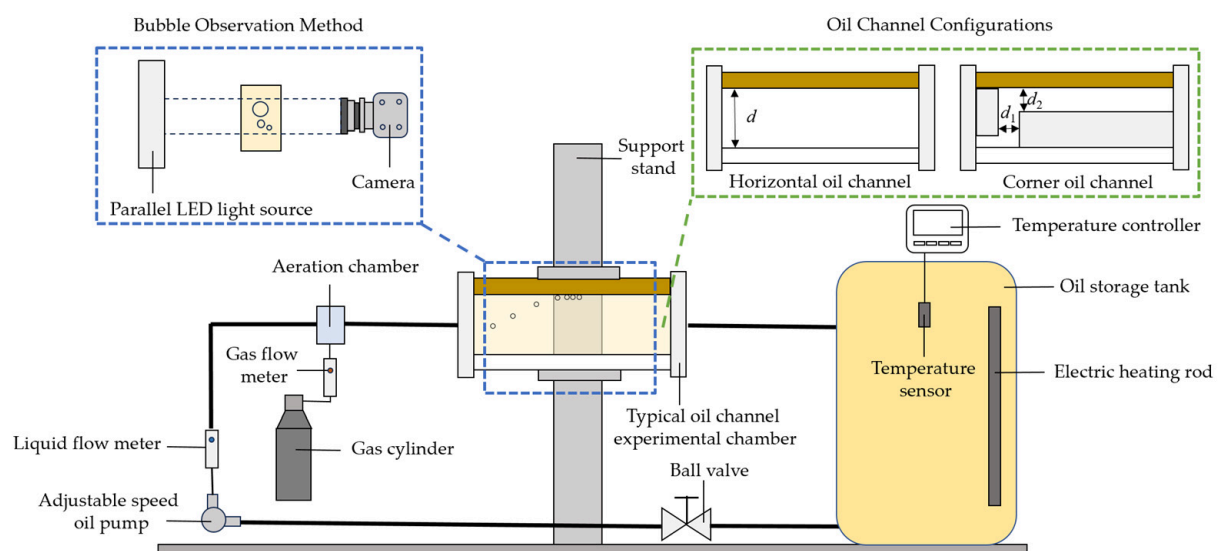


Figure 1. Schematic of the typical oil channel bubble accumulation experimental platform.

The typical oil channel experimental chamber is a rectangular transparent acrylic structure measuring 300 mm in length with a cross-section of 30 × 60 mm. The inner walls are lined with insulating pressboard (specifically, the actual insulation material corresponding to the ODFPS-700000/750 model transformer (Xi'an XD Transformer Co., Ltd., Xi'an, China)). It should be noted that while this industrial-grade material is highly representative, the macroscopic surface roughness and porosity of pressboards from different transformer models or manufacturers may vary slightly due to diverse manufacturing and pressing processes. Such variances would primarily affect the empirical friction coefficient in real-world scenarios. By adjusting the thickness of the electrodes and spacer blocks, the width of the oil channel can be flexibly varied within the range of 6 to 30 mm.

The fluid loop is a closed circuit formed by connecting an oil storage tank, an oil pump, a flow meter, an aeration chamber, and the experimental chamber in series. The storage tank integrates a closed-loop temperature control system to maintain a constant oil temperature. It features a “top-inlet, bottom-outlet” design and a large buffer volume

to ensure that returning bubbles naturally escape, thereby guaranteeing the purity of the pumped oil flow. Furthermore, the oil level in the tank is consistently maintained at the maximum to prevent air intake. The experimental oil pump is regulated via pulse-width modulation (PWM), providing a flow rate coverage of 0 to 25 L/min. This corresponds to an oil channel flow velocity of 0 to 0.3 m/s, which perfectly aligns with the actual operating conditions of power transformers. A flow meter is incorporated for real-time monitoring to ensure a constant and stable flow rate.

Micro-bubbles are introduced using an aeration method. After being regulated by a gas flow meter, the gas flow passes through an alumina microporous ceramic disc (20 mm in diameter and 2 mm in thickness) located at the bottom of the aeration chamber, where it is sheared by the high-speed oil flow to form bubble swarms. The size distribution of the introduced bubbles is predominantly determined by the pore size of the alumina microporous ceramic disc, while the oil and gas flow rates have a negligible effect on this distribution. Therefore, two pore size specifications (0.1 μm and 0.3 μm) are utilized in the experiment to obtain bubbles with different log-normal size distributions (average radii of 20 μm and 188 μm , respectively). The camera recording system comprises a parallel LED light source and a high-resolution camera (Nikon D810, Nikon Corporation, Tokyo, Japan) operating at a resolution of 3840×2160 pixels and a frame rate of 60 fps. Videos of the bubble accumulation process are captured during the experiment. To process the bubble images, we employed a MATLAB R2023a (The MathWorks, Inc., Natick, MA, USA) bubble recognition script built upon a robust, state-of-the-art ellipse detection algorithm based on arc-support line segments [28]. The high localization accuracy of this algorithm has been rigorously validated in previous literature, thereby ensuring reliable extraction of bubble feature parameters (such as size and position with low uncertainty) and effectively eliminating manual measurement errors. This automated image processing approach ensures the extraction of accurate bubble feature parameters and effectively eliminates manual measurement errors.

3. Results and Discussion

The geometry of transformer oil channels and the flow field distribution dictate that bubbles are prone to accumulate on the top paper surfaces of horizontal channels and corner channels. Combining experimental and simulation approaches, this section analyzes the accumulation rates and growth characteristics of bubbles at these two typical accumulation sites.

A comprehensive sensitivity analysis was conducted to quantify the influence of key model parameters. The tests revealed that the accumulation calculation is insensitive to minor fluctuations in the empirical friction coefficient k , ensuring the robustness of the predictions. Conversely, the model is highly sensitive to the choice of the drag coefficient model. To determine the most appropriate formulation, the steady-state rising velocities of bubbles in oil were calculated using three drag models—Schiller–Naumann, Ma & Ahmadi, and Mei, whose mathematical expressions are summarized in Table 1—and were subsequently compared with experimental measurements (as shown in Figure 2) [10–12]. Because the small-sized micro-bubbles in the oil experience negligible deformation and remain approximately spherical, their actual steady-state rising velocities exhibited the highest degree of agreement with the calculations derived from the Schiller–Naumann model. Consequently, the Schiller–Naumann model was conclusively selected to accurately describe the drag force on the spherical bubbles in the oil.

Table 1. Summary of the drag coefficient models used for comparison.

Drag Coefficient Model	Expression
Schiller & Nauman (1935) [10]	$C_D = \begin{cases} 24/Re(1 + 0.15Re^{0.687}), & Re \leq 1000 \\ 0.44, & Re > 1000 \end{cases}$
Ma & Ahmadi (1990) [11]	$C_D = \frac{24}{Re}(1 + 0.1Re^{0.75})$
Mei (1994) [12]	$C_D = \frac{24}{Re} \left\{ \frac{2}{3} + \left[\frac{12}{Re} + 0.75 \left(1 + \frac{3.315}{\sqrt{Re}} \right) \right]^{-1} \right\}$

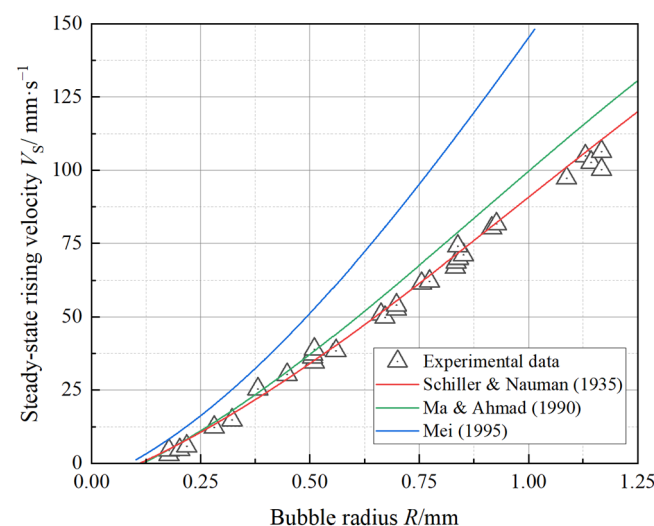


Figure 2. Comparison of the steady-state rising velocities of micro-bubbles calculated by different drag coefficient models and experimental measurements [10–12]. Operating conditions: insulating oil at 25 °C.

3.1. Accumulation Rate on the Top Paper of Horizontal Channels

As bubbles migrate through horizontal oil channels, they rise to the top insulating paper surface and slide slowly. Because their sliding velocity is significantly lower than their horizontal migration velocity, bubbles readily accumulate on this top surface. Using the two-phase flow simulation, the gas flow rate at various cross-sections of the oil channel was statistically analyzed. It is important to note that both in the experimental setup and the numerical model, the insulating oil is considered fully saturated, meaning gas dissolution into the liquid phase is negligible during the short migration period. Furthermore, the channel is completely sealed, ensuring no gas escapes. Therefore, based on the principle of mass conservation, the bubble accumulation rate on the top paper from the inlet to any horizontal position can be accurately determined by calculating the difference between the gas flow rate at the inlet and that at the respective horizontal cross-section.

Figure 3 illustrates the results under a bubble content of 0.1% and a flow velocity of 0.2 m/s. The data indicate that larger bubbles exhibit a faster rising velocity and a shorter horizontal migration distance, thereby resulting in a larger accumulated volume per unit time. Notably, the accumulation rate of bubbles with an average radius of 188 µm on the top paper of the horizontal channel is significantly higher than that of bubbles with an average radius of 20 µm.

For bubbles of a specific size, the accumulation rate on the top surface increases with the horizontal distance. When this distance exceeds 150 mm, the accumulation rate exhibits linear growth, indicating that the accumulation rate per unit area reaches a stable state. By evaluating the bubble accumulation rate and the corresponding top paper area within the horizontal distance range of 150 mm to 250 mm in the experimental chamber, the bubble accumulation rate per unit area was calculated to be 1.3592×10^{-5} m/s. Physically, this

parameter represents the volume of gas accumulating per unit time per unit area of the top paper (m^3/s per m^2). It essentially quantifies the growth velocity of the equivalent thickness of the accumulated bubble layer.

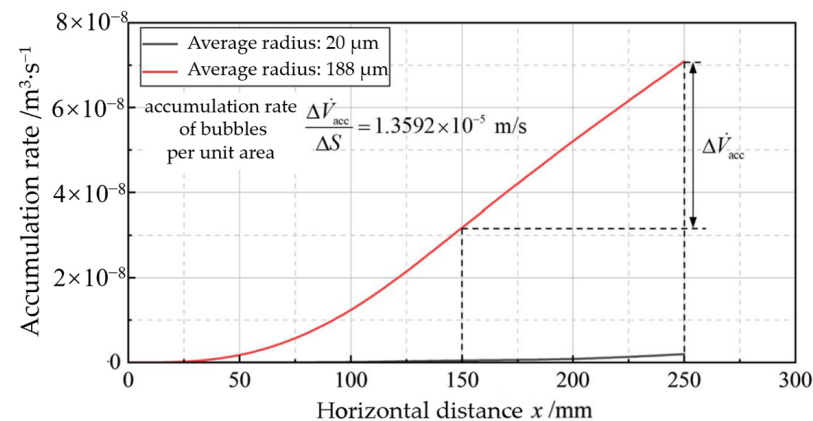


Figure 3. Simulated accumulation rate of bubbles at the top paper of the horizontal oil channel. Operating conditions: flow velocity of 0.2 m/s and discrete phase bubble content of 0.1%.

Flow velocity and bubble content are critical parameters influencing the bubble accumulation rate on the top paper surface of horizontal oil channels. The calculated results under various operating conditions are illustrated in Figures 4 and 5. Because the cross-sectional gas flow rate is directly proportional to both the flow velocity and the bubble content, the accumulation rate per unit area on the top surface follows the same proportionality. In other words, higher flow velocities and greater bubble contents lead to a correspondingly larger accumulation rate.

3.2. Accumulation Rate on the Top Paper of Corner Channels

The low-velocity region at the top of the channel corner causes bubbles to stagnate upon contacting the paper surface, leading to stable accumulation. Setting the bubble content at 0.1% and the average bubble radius at 188 μm , the bubble accumulation process under various flow velocities was experimentally observed. The average length of the stable accumulation sites was measured, with the mean value derived from ten repeated trials.

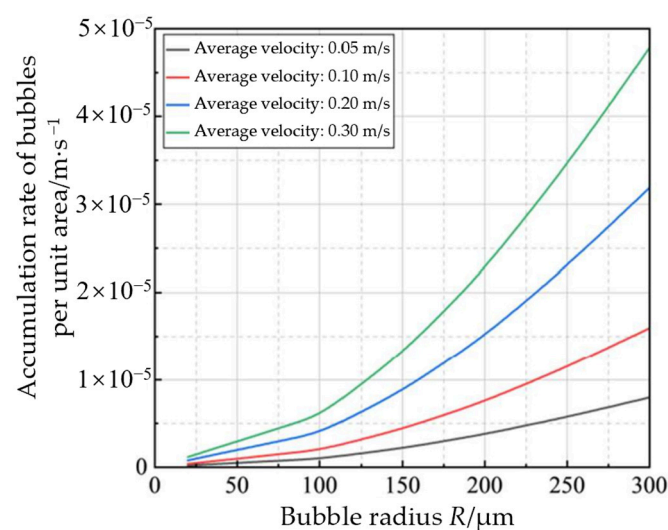


Figure 4. Simulated accumulation rate of bubbles at the top paper of the horizontal oil channel under different flow velocities. Operating conditions: varying flow velocities (0.05–0.30 m/s) with a fixed bubble content of 0.1%.

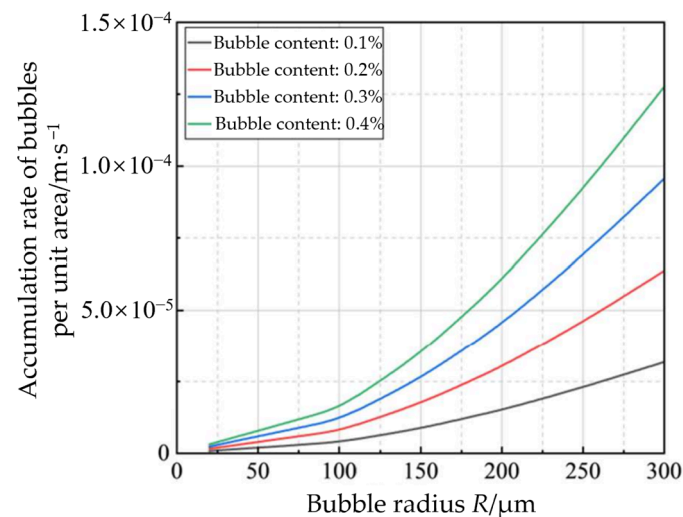


Figure 5. Simulated accumulation rate of bubbles at the top paper of the horizontal oil channel under different bubble contents. Operating conditions: varying bubble contents (0.1–0.4%) with a fixed flow velocity of 0.2 m/s.

Figure 6 illustrates the results across flow velocities ranging from 0.1 to 0.8 m/s. When the flow velocity is less than 0.6 m/s, the accumulation length decreases by approximately 1 mm with increasing velocity, primarily due to the shrinkage of the low-velocity region. However, when the flow velocity exceeds 0.6 m/s, the number of bubbles entering this region drops sharply, causing a significant reduction in the accumulation length. At 0.75 m/s, the accumulation is reduced to a single row of bubbles. If the flow velocity is further increased, all bubbles will be swept into the horizontal channel, and accumulation at the corner will cease completely. This drastic decrease in bubble accumulation beyond the critical threshold of 0.6 m/s can be mechanistically explained by the competition between local fluid shear forces and stagnation retention forces. The corner geometry inherently creates a localized flow separation and stagnation zone, into which bubbles naturally migrate via buoyancy. However, as the bulk flow velocity exceeds 0.6 m/s, two critical hydrodynamic shifts occur. First, the high local Reynolds number forces the main flow streamlines closer to the corner apex, drastically shrinking the physical volume of the low-velocity stagnation region. Second, the localized fluid shear stress acting on the insulating paper surface increases significantly. Consequently, the local shear-induced drag force exerted on a stagnated bubble completely overwhelms the combined retention forces—namely, the buoyancy pushing against the top wall and the resulting static friction. As a result, bubbles are physically stripped from the paper surface and swept downstream by the bulk flow before they can establish stable contact or accumulate.

It should be noted that due to the pump capacity limits of the current experimental loop, robust optical observations were restricted to flow velocities up to 0.3 m/s. Consequently, the behaviors in the high-velocity regime (from 0.3 m/s to 0.8 m/s)—particularly the sharp decrease in corner accumulation when the velocity exceeds 0.6 m/s—are theoretically predicted by the validated Euler-Lagrange model based on local shear stress mechanisms. While these model-driven predictions provide critical physical thresholds for engineering design, future experimental validation utilizing a high-speed flow loop is warranted to further corroborate these findings.

The simulated accumulation rates at the corner top under various operating conditions are presented in Figures 7 and 8. Figure 7 indicates that the difference in accumulation rates between 0.1 m/s and 0.3 m/s is marginal. Because larger bubbles possess greater inertia and buoyancy, they more readily enter the low-velocity region, leading to a significant

increase in the accumulation rate as the bubble radius increases. When the flow velocity rises to 0.6 m/s, only bubbles with a radius greater than 200 μm can accumulate, and their rate is substantially lower than under low-velocity conditions. At 0.75 m/s, only bubbles exceeding 500 μm can accumulate, with the rate approaching zero. These simulation findings align perfectly with the significant reduction in accumulation observed in the experiments (Figure 5). Furthermore, Figure 8 demonstrates that at an average flow velocity of 0.1 m/s, the accumulation rate rises with an increase in bubble concentration.

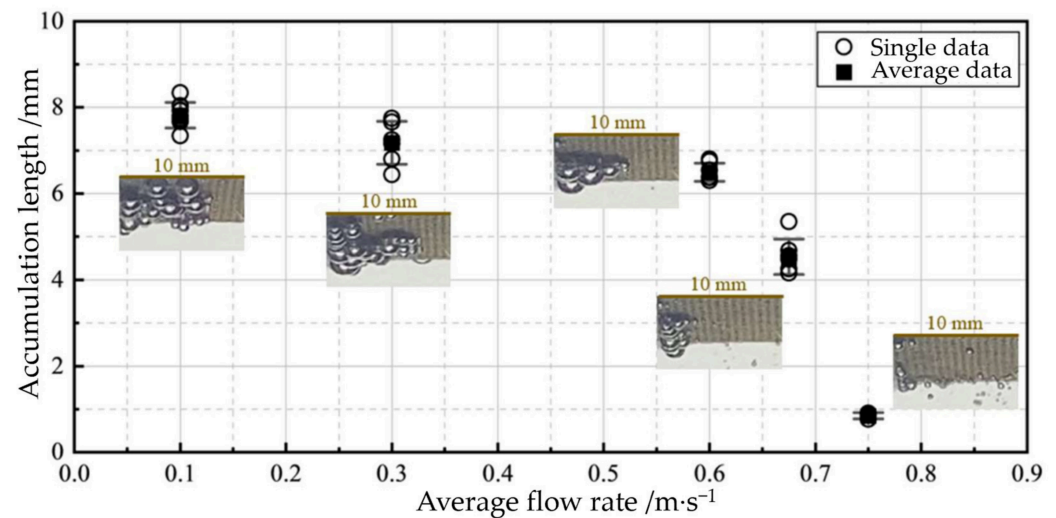


Figure 6. Length of bubble accumulation sites on the top paper of the corner channel. (10 replicates per condition) Operating conditions: initial average bubble radius of 188 μm and bubble content of 0.1% under varying flow velocities.

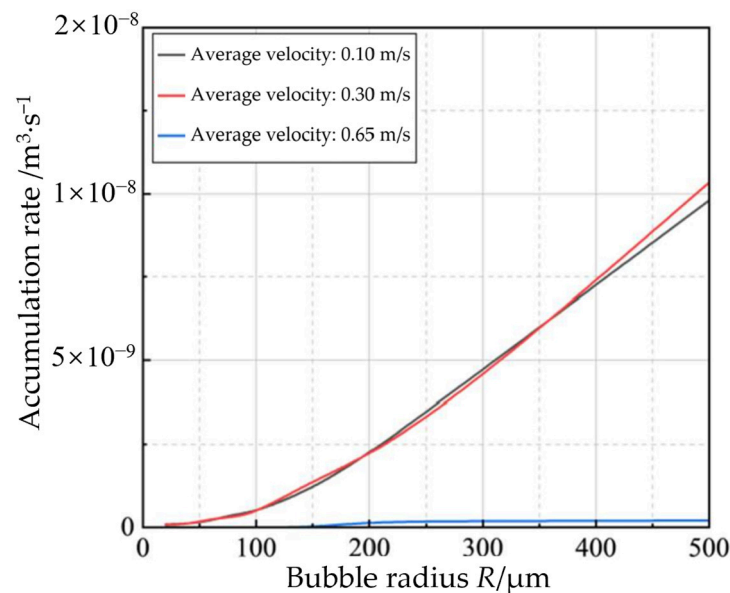


Figure 7. Simulated bubble accumulation rate at the accumulation sites on the top paper of the corner channel under different flow velocities. Operating conditions: varying average flow velocities (0.10–0.75 m/s) with a fixed bubble content of 0.1%.

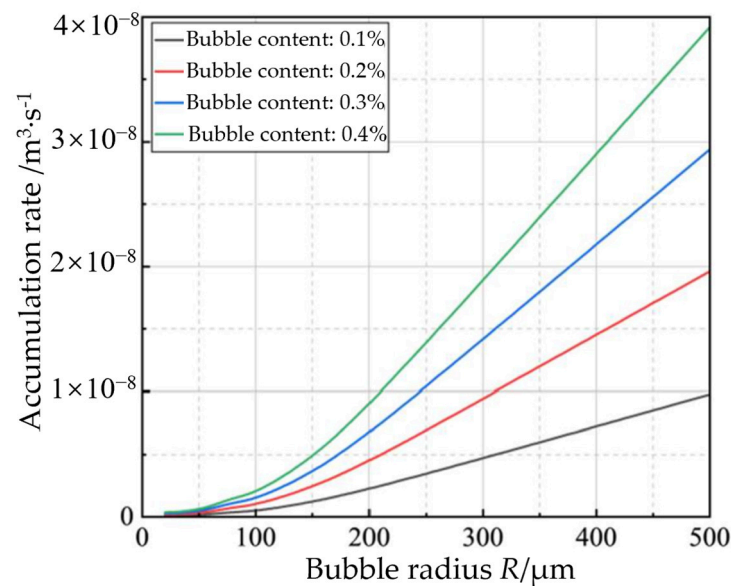


Figure 8. Simulated bubble accumulation rate at the accumulation sites on the top paper of the corner channel under different bubble concentrations. Operating conditions: varying bubble contents (0.1–0.4%) with a fixed average flow velocity of 0.1 m/s.

3.3. Growth Characteristics of Accumulated Bubbles on the Top Paper of Horizontal Channels

Experiments observed that bubbles with an average radius of 188 μm accumulated in swarms on the top paper surface of horizontal oil channels. The size of the bubbles within these accumulated swarms was significantly larger than that of the bubbles suspended in the oil, and the size of the accumulated bubbles on the paper surface increased with the horizontal distance. Because bubbles accumulate in swarms on the paper surface of horizontal channels, continuous bubble coalescence occurs as the swarms slide along the surface, leading to an increase in bubble size. It is important to emphasize that this continuous coalescence is physically distinct from random collisions in the bulk flow; it strictly occurs when bubbles are forced into tight contact by specific structural barriers (such as paper overlapping gaps). According to the research by Sun et al., when the bubble coalescence process continuously occurs within such a stable accumulated bubble swarm, the theoretical maximum growth rate of the accumulated bubbles can be expressed as Equation (11) [29]:

$$\frac{dR}{dt} = 0.47(0.000773T + 0.1432)/R^{1.13} \quad (11)$$

where R is the radius of the accumulated bubble and T is the temperature.

By coupling Equation (11) with the dynamic equations, the theoretical curve of the maximum bubble radius varying with distance was obtained, as shown in Figure 9.

This curve was then compared with the mean values from 50 experiments conducted at 50 mm and 250 mm. The results indicate that bubbles coalesce and grow while sliding, with their size increasing as the distance extends. The experimental mean values are slightly smaller than the simulated values and exhibit greater dispersion. This discrepancy arises because the simulation is based on the ideal assumption of stable interfacial contact and continuous coalescence. In reality, unstable contact disrupts continuous coalescence, and under low accumulation rates, it is even difficult to form contacting bubble swarms.

Figure 10 presents the theoretical curves of the maximum bubble radius varying with distance under different flow velocities, along with the mean values of 50 experiments at a specific horizontal distance of 250 mm. This specific location (250 mm) was selected as a standardized benchmark because it sits well within the fully developed region (>150 mm) of the 300 mm channel. At this downstream location, the bubble swarms have undergone

sufficient sliding and coalescence to reach a stable accumulation state, making it the most representative site to observe the final maximum bubble size and clearly evaluate the restrictive impact of flow velocity.

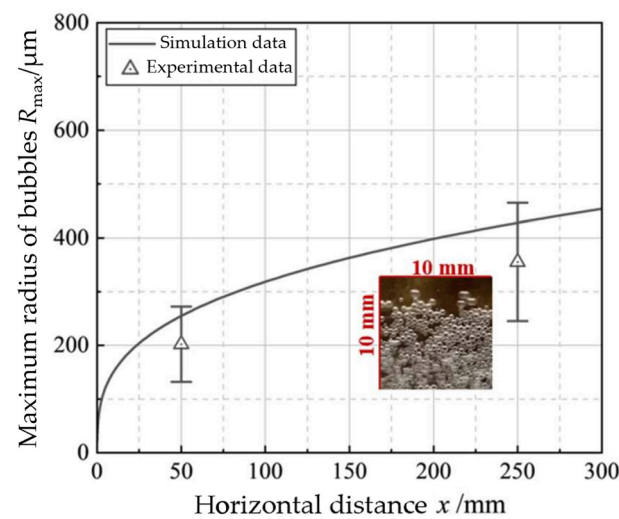


Figure 9. Comparison between the simulated and experimental maximum radius of accumulated bubbles on the top paper of the horizontal oil channel at different horizontal distances. The scatter symbols represent the experimental measurements (averaged over 50 replicates, with error bars indicating standard deviation), while the solid line denotes the theoretical simulation results. Operating conditions: insulating oil at 25 °C and an initial average bubble radius of 188 μ m.

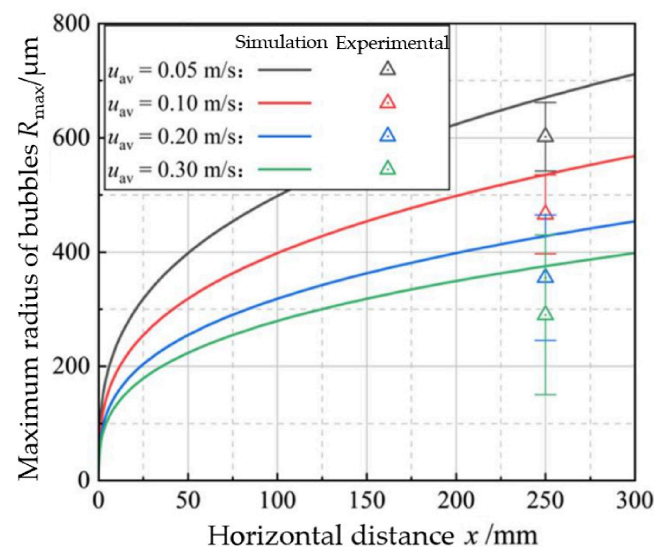


Figure 10. Comparison between the simulated and experimental maximum radius of accumulated bubbles on the top paper of the horizontal oil channel (averaged over 50 replicates), while the solid lines denote the theoretical fitting results. Operating conditions: varying flow velocities (0.05–0.30 m/s), insulating oil at 25 °C, and horizontal distance at 250 mm.

The results show that an increase in flow velocity accelerates the sliding of accumulated bubbles on the paper surface and shortens the accumulation time, thereby reducing the theoretical maximum size. The experimental measurements align with the theoretical trends: the maximum radius of accumulated bubbles on the paper surface decreases as the flow velocity increases. However, the experimental mean values are smaller than the theoretical curves, and the standard deviation of multiple experimental results is relatively large, increasing further with higher flow velocities. Specifically, at low flow velocities, the

experimental maximum sizes demonstrate close agreement with the theoretical predictions, showing minimal deviations and relatively narrow error margins. Because bubbles are more likely to form swarms with stable contact under lower velocity conditions, the continuous coalescence process remains highly consistent with the theoretical assumptions. Conversely, at higher flow velocities, the discrepancy between the experimental mean values and the theoretical curves widens significantly, accompanied by a noticeable expansion of the standard deviation (as indicated by the widening error bars). This growing discrepancy is fundamentally attributed to the theoretical model's assumption of idealized, continuous interfacial contact. In actual experiments, higher flow velocities induce stronger local shear and flow disturbances, causing unstable bouncing and intermittent contact among the sliding bubbles. This dynamic disruption periodically interrupts the continuous coalescence process, thereby resulting in actual maximum sizes that are notably smaller than the theoretical predictions.

Figure 11 displays the theoretical curves and experimental mean values of the maximum radius of accumulated bubbles on the top paper of the horizontal oil channel varying with horizontal distance at an average flow velocity of 0.05 m/s under different temperatures. The results indicate that elevated temperatures accelerate the coalescence and growth process of accumulated bubbles. At a given horizontal distance, the maximum radius of accumulated bubbles increases with rising temperature.

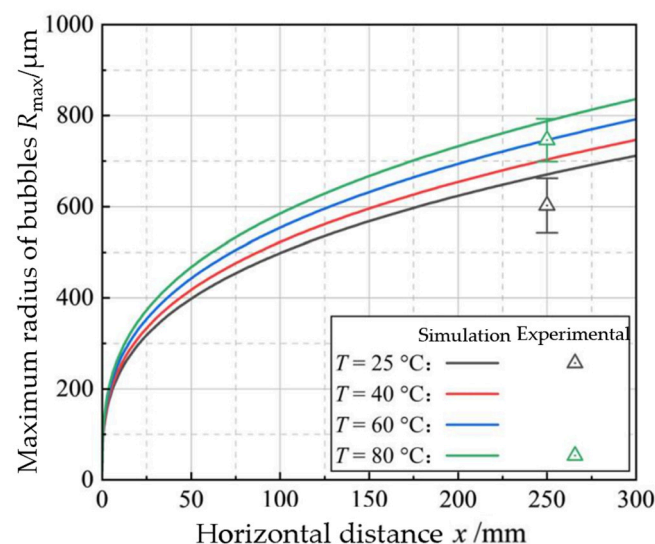


Figure 11. Comparison between the simulated and experimental maximum radius of accumulated bubbles on the top paper of the horizontal oil channel under different temperatures. The scatter symbols represent the experimental measurements (averaged over 50 replicates), while the solid lines denote the theoretical fitting results. Operating conditions: varying temperatures (25–80 °C), an average flow velocity of 0.05 m/s, and horizontal distance at 250 mm.

To fully comprehend the coupled influence of these two critical parameters, it is essential to recognize that bubble growth is not determined by a simple static response surface, but rather by an integral process bridged by Equation (11) and the kinematic residence time. Specifically, temperature (T) governs the thermodynamics of the system; as indicated by Equation (11), elevated temperatures exponentially increase the theoretical coalescence growth rate. Conversely, flow velocity (v) governs the kinematics of the system. The velocity determines the sliding speed of the bubble swarm, thereby dictating the total residence time available for continuous coalescence before the bubbles are swept downstream. Therefore, the final maximum bubble radius ($R_{\max}$) is fundamentally the time-integral of the growth rate over this available residence time. A higher temperature

steepens the growth curve, while a lower flow velocity extends the integration time, both synergistically leading to severe bubble enlargement.

Due to manufacturing processes, paper overlapping gaps exist in oil-paper insulation, which significantly affect bubble accumulation at the top of horizontal oil channels. These gaps intercept small bubbles, forming stable contacting swarms that continuously coalesce and grow. As shown in Figure 12, the experimental values of the maximum bubble radius at different accumulation times closely match the theoretical curves. As their size increases, the bubbles are eventually flushed out of the overlapping gaps by the flow field. Their critical size is determined by the gap height and flow velocity.

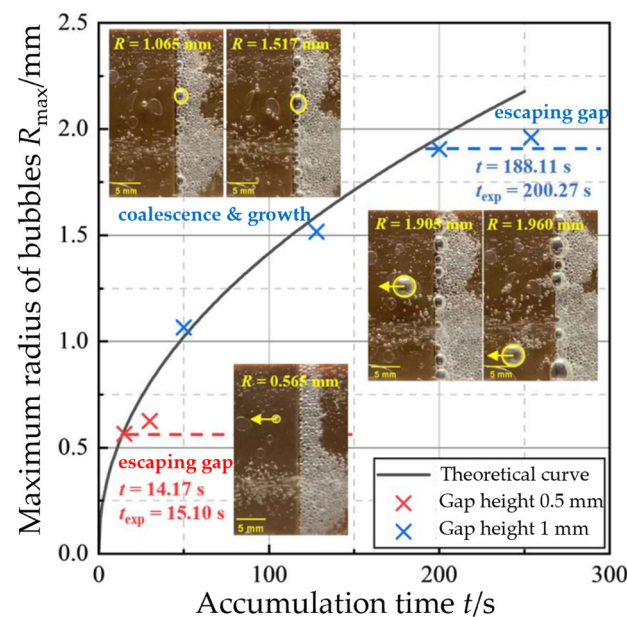


Figure 12. Comparison between the theoretical and experimental maximum radius of accumulated bubbles over time at the paper overlapping gaps in the horizontal oil channel. The cross scatter symbols represent the experimental measurements, while the solid line denotes the theoretical growth curve. Operating conditions: paper gap heights of 0.5 mm and 1.0 mm, and insulating oil at 25 °C.

Figure 13 illustrates the radius of bubbles escaping the gaps under various operating conditions. A higher paper overlapping gap allows for the accumulation and eventual release of larger bubbles. Conversely, an increase in oil flow velocity promotes the detachment of bubbles from the gaps, resulting in a slight decrease in the size of the escaping bubbles. Consequently, if paper overlapping gaps are present on the top surface of a horizontal oil channel, bubbles will stably accumulate and continuously coalesce at these gaps, ultimately forming large-scale bubbles comparable to the gap height, thereby posing a severe threat to insulation safety.

3.4. Growth Characteristics of Accumulated Bubbles on the Top Paper of Corner Channels

After entering the low-velocity region at the corner, bubbles stagnate and accumulate. Over time, they form bubble swarms and undergo continuous coalescence and growth. Figures 14 and 15 illustrate the accumulation and growth process of bubbles with an average radius of 188 μm on the top paper of the corner channel, under the conditions of an average flow velocity of 0.1 m/s and a bubble content of 0.1%. As shown in Figure 14, bubbles accumulate on the top paper of the corner channel at a rate of $3.15 \times 10^{-9} \text{ m/s}$, forming a stable accumulation site with a length of approximately 7 mm. At this site, the bubbles remain stationary with stable contact, allowing continuous coalescence to occur. Consequently, the maximum bubble size increases over time, and the experimental values closely align with the theoretical curve.

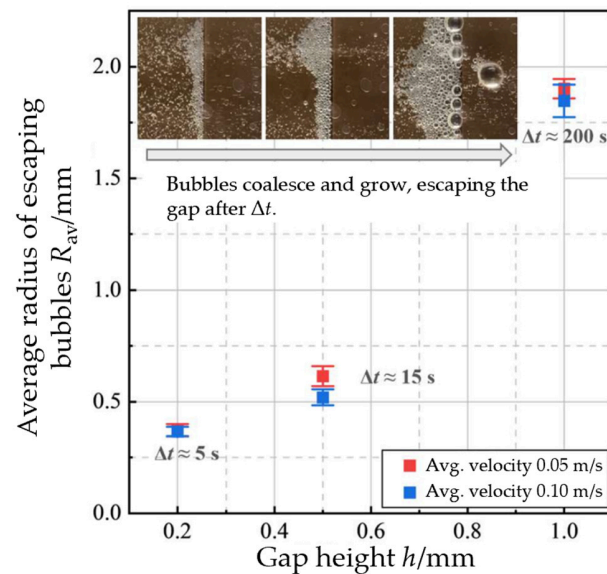


Figure 13. Average size of bubbles escaping from the paper overlapping gaps in the horizontal oil channel. The scatter symbols represent the experimental measurements (with error bars indicating standard deviation) across different gap heights and flow velocities.

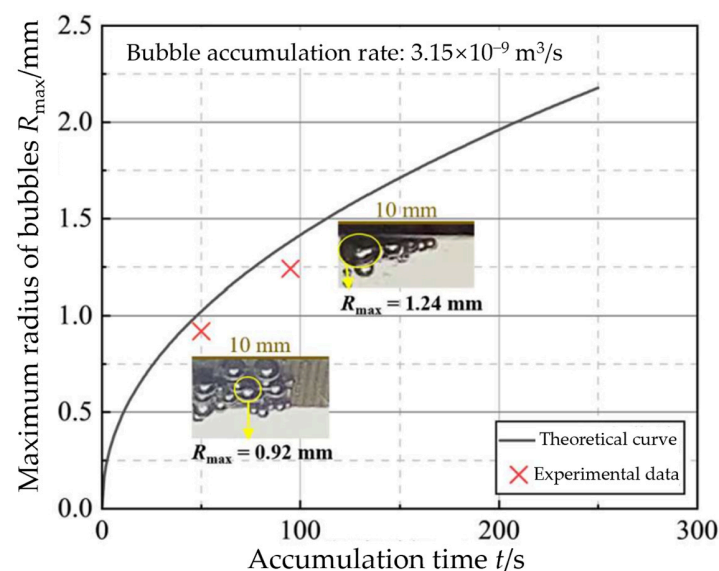


Figure 14. Comparison between the theoretical and experimental maximum radius of accumulated bubbles on the top paper of the corner oil channel. The cross scatter symbols represent the experimental measurements, while the solid line denotes the theoretical growth curve. Operating conditions: an average flow velocity of 0.1 m/s, a bubble content of 0.1%, and an initial average bubble radius of 188 μ m.

Temperature is a critical factor determining accumulation and growth, as the coalescence rate is positively correlated with temperature. Figure 15 presents the theoretical curves under different temperatures, alongside the mean values from 50 experimental measurements of the maximum accumulated bubble radius after accumulation times of 1 min, 2 min, and 4 min at 25 °C and 80 °C. The results demonstrate that elevated temperatures accelerate the growth process of accumulated bubbles on the top paper of the corner channel. Within the same accumulation timeframe, the maximum radius of the accumulated bubbles increases with rising temperature. Because the bubbles at the corner accumulate in stable swarms, their growth characteristics are highly consistent with the theoretical curves.

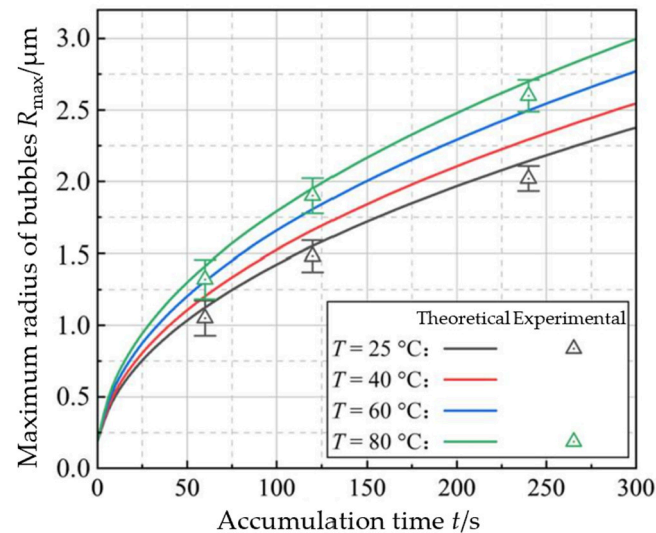


Figure 15. Comparison between the theoretical and experimental maximum radius of accumulated bubbles on the top paper of the corner oil channel under different temperatures. The scatter symbols represent the experimental measurements (averaged over 50 replicates, with error bars indicating standard deviation), while the solid lines denote the theoretical growth curves. Operating conditions: insulating oil temperatures ranging from 25 to 80 °C, an average flow velocity of 0.1 m/s, and a bubble content of 0.1%.

4. Conclusions

In this study, a two-phase flow model for bubble migration and accumulation based on the Euler–Lagrange framework was established, and a corresponding experimental platform for typical oil channels was constructed. By combining numerical simulations with experimental observations, the bubble accumulation process within typical oil channel flow fields was comprehensively investigated. The accumulation sites and growth laws under various flow velocities and temperatures were revealed. The main conclusions are as follows:

1. Bubbles primarily accumulate on the top insulating paper surfaces of both horizontal channels and channel corners. The accumulation rate is fundamentally determined by the flow velocity and bubble content.
2. In horizontal channels, bubbles slide slowly along the top paper surface under the combined effects of drag and friction forces, thereby forming accumulations. Paper overlapping gaps intercept these sliding bubbles, causing them to accumulate in swarms and grow continuously. Ultimately, they form large-scale bubbles comparable to the gap height before escaping. Furthermore, the bubble accumulation rate per unit area on the top surface is directly proportional to both the flow velocity and the bubble content.
3. The low-velocity region at the top of channel corners is highly prone to bubble stagnation, leading to the formation of accumulated bubble swarms. The length of these accumulation sites decreases as the flow velocity increases. Notably, when the flow velocity exceeds 0.6 m/s, both the accumulation length and the accumulation rate drop sharply.
4. The growth characteristics of accumulated bubbles are closely correlated with flow velocity and temperature. Continuous coalescence among accumulated bubbles drives their size growth. An increase in flow velocity accelerates the sliding motion, drastically reducing the residence time available for bubbles to contact and merge, which consequently restricts the final size of the accumulated bubbles.

Ultimately, this study elucidates the complex dynamics of bubble accumulation in transformer oil channels, providing a crucial theoretical basis and an effective analytical framework for assessing bubble-induced insulation risks and optimizing the internal structural design of power transformers.

It should be noted that while the artificial aeration method employed in this study enables precise control over initial bubble size and concentration for fundamental mechanism investigations, it represents a simplification of real-world conditions. In actual operating transformers, bubbles typically nucleate and evolve directly from the micropores of the oil-impregnated insulating paper under coupled thermal-electrical stresses and moisture vaporization, which may lead to broader size distributions and more complex initial detachment dynamics. Future research will aim to incorporate these realistic nucleation behaviors to further bridge the gap between experimental models and field applications.

Author Contributions: Conceptualization, T.W. and Y.M.; methodology, T.W. and Z.C.; software, Y.L.; validation, S.T., Y.L. and S.W.; formal analysis, T.W. and Z.C.; investigation, S.T. and S.W.; resources, Y.M.; data curation, Y.L. and S.W.; writing—original draft preparation, T.W.; writing—review and editing, Z.C. and Y.M.; visualization, S.T. and Y.L.; supervision, Y.M.; project administration, Y.M.; funding acquisition, Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Project of State Grid Jiangsu Electric Power Co., Ltd., grant number J2025073.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript, the authors used Google’s Gemini (3.1 Pro) for the purposes of English translation and language polishing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: Authors Tonglei Wang, Yuandi Lin and Yong Ma were employed by the company State Grid Jiangsu Electric Power Co., Ltd. Author Zhengguang Chen was employed by the company State Grid Corporation of China. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from State Grid Jiangsu Electric Power Co., Ltd. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

FVM	Finite Volume Method
PWM	Pulse-Width Modulation
LED	Light-Emitting Diode

References

1. Susa, D.; Lehtonen, M. Dynamic thermal modeling of power transformers: Further development-part II. *IEEE Trans. Power Deliv.* **2006**, *21*, 1971–1980. [[CrossRef](#)]
2. Liu, Z. *Ultra High Voltage AC/DC Power Grid*; China Electric Power Press: Beijing, China, 2013. (In Chinese)
3. Shi, W.; Qiu, Y.; Zhang, Q. *High Voltage Engineering Technology*, 2nd ed.; Machinery Industry Press: Beijing, China, 2017. (In Chinese)

4. Gao, M. Study on the Characteristics and Mechanism of Thermal Bubble Formation in Oil-Immersed Insulation Paper. Ph.D. Thesis, Xi'an Jiaotong University, Xi'an, China, 2020. (In Chinese)
5. Zhang, R.; Zhang, Q.; Wu, Z. Mechanism of microbubble generation in transformer oil under operating conditions. In Proceedings of the Academic Annual Meeting of the High Voltage Professional Committee of the Chinese Society of Electrical Engineering, Shenyang, China, 22–23 August 2019. (In Chinese)
6. Guo, C. Study on the Formation Mechanism and Gas Production Characteristics of Oil Paper Insulation Bubbles Under Vibration. Ph.D. Thesis, Xi'an Jiaotong University, Xi'an, China, 2023. (In Chinese)
7. Cai, D. Simulation Study on the Influence of Bubbles on Liquid Insulation Performance. Master's Thesis, National University of Defense Technology, Changsha, China, 2011. (In Chinese)
8. Clift, R.; Grace, J.R.; Weber, M.E. *Bubbles, Drops, and Particles*; Academic Press: London, UK, 1978.
9. Gong, S.; Gao, N.; Zeng, L.; Li, A.; Liu, X.; Tang, Q.; Li, L. A correlation model of drag coefficient for bubbles/droplets in a wide Reynolds number range. *Chin. J. Process Eng.* **2021**, *21*, 649–657. (In Chinese)
10. Schiller, L.; Nauman, A.Z. A drag coefficient correlation. *Zeit. Ver. Deutsch. Ing.* **1935**, *77*, 51–86.
11. Ma, D.; Ahmadi, G. A thermodynamical formulation for dispersed multiphase turbulent flows—II: Simple shear flows for dense mixtures. *Int. J. Multiph. Flow* **1990**, *16*, 341–351. [[CrossRef](#)]
12. Mei, R.; Klausner, J.F.; Lawrence, C.J. A note on the history force on a spherical bubble at finite Reynolds number. *Phys. Fluids* **1994**, *6*, 418–420. [[CrossRef](#)]
13. Laín, S.; Bröder, D.; Sommerfeld, M.; Göz, M. Modelling hydrodynamics and turbulence in a bubble column using the Euler–Lagrange procedure. *Int. J. Multiph. Flow* **2002**, *28*, 1381–1407. [[CrossRef](#)]
14. Gao, M.; Zhang, Q.; Ding, Y.; Wang, T.; Ni, H.; Yuan, W. Investigation on bubbling phenomenon in oil-paper insulation. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 2362–2370. [[CrossRef](#)]
15. Liao, Y.; Lucas, D. A literature review on mechanisms and models for the coalescence process of fluid particles. *Chem. Eng. Sci.* **2010**, *65*, 2851–2864. [[CrossRef](#)]
16. Przybyłek, P.; Moranda, H.; Walczak, K.; Moscicka-Grzesiak, H. The bubble effect in bushings—Investigations on models. *IEEE Trans. Dielectr. Electr. Insul.* **2015**, *22*, 3405–3412. [[CrossRef](#)]
17. Doncuk, J.; Trnka, P.; Pihera, J. Failure gas generation within the oil-paper insulation system of shunt reactor. In Proceedings of the 2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Montreal, QC, Canada, 14–17 October 2012; pp. 371–374.
18. Zheng, Y.; Zhao, T.; Tong, Y.; Chao, N. Simulation of the movement characteristics of micro-bubbles in the oil gap of transformer. In Proceedings of the 2021 IEEE Electrical Insulation Conference (EIC), Denver, CO, USA, 7–28 June 2021; pp. 141–144.
19. Hirt, C.W.; Nichols, B.D. Volume of fluid (VOF) method for the dynamics of free boundaries. *J. Comput. Phys.* **1981**, *39*, 201–225. [[CrossRef](#)]
20. Sussman, M.; Smereka, P.; Osher, S. A level set approach for computing solutions to incompressible two-phase flow. *J. Comput. Phys.* **1994**, *114*, 146–159. [[CrossRef](#)]
21. Liu, S.; Han, J.; Zhang, N.; Zhang, F. Coalescence behavior of bubbles in transformer oil and its effect on electric field distribution. *High Volt. Eng.* **2023**, *49*, 3534–3543. (In Chinese)
22. Mirjalili, S.; Jain, S.; Dodd, M. Interface-capturing methods for two-phase flows: An overview and recent developments. *Cent. Turbul. Res. Annu. Res. Brief.* **2017**, *13*, 117–135.
23. Mirjalili, S.; Ivey, C.B.; Mani, A. Comparison between the diffuse interface and volume of fluid methods for simulating two-phase flows. *Int. J. Multiph. Flow* **2019**, *116*, 221–238. [[CrossRef](#)]
24. Ishii, M.; Hibiki, T. *Thermo-Fluid Dynamics of Two-Phase Flow*; Springer: New York, NY, USA, 2006.
25. Ku, G.; Cheong, C.; Park, I.; Seol, H. Numerical Investigation of Tip Vortex Cavitation Inception and Noise of Underwater Propellers of Submarine Using Sequential Eulerian–Lagrangian Approaches. *Appl. Sci.* **2020**, *10*, 8721. [[CrossRef](#)]
26. Kong, L.; Yang, Y.; Cai, R.; Zhang, H.; Lyu, W. Application of a Coupled Eulerian–Lagrangian Approach to the Shape and Force of Scientific Balloons. *Appl. Sci.* **2025**, *15*, 1517. [[CrossRef](#)]
27. Guo, L. *Two Phase and Multiphase Flow Dynamics*; Xi'an Jiaotong University Press: Xi'an, China, 2002. (In Chinese)
28. Lu, C.; Xia, S.; Shao, M.; Fu, Y. Arc-support line segments revisited: An efficient high-quality ellipse detection. *IEEE Trans. Image Process.* **2020**, *29*, 768–781. [[CrossRef](#)]
29. Sun, Y.; Zhang, Q.; Wu, Z.; Song, J.; Tan, S.; Wang, S. Bubble migration and accumulation in oil-paper insulation: Modeling of coalescence-induced size evolution. *IEEE Trans. Dielectr. Electr. Insul.* **2025**, *32*, 281–288. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.