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Dynamics of Gas-Phase Bubble Defects in Transformer Oil Ducts Under Electro-Thermo-Hydrodynamic Coupled Fields

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Abstract: Insulation degradation in oil-immersed power transformers is critically influenced by gas-phase bubble impurities within oil ducts. This study establishes a multiphysics-coupled model based on phase-field theory, where the relative dielectric constants of bubbles and insulating oil are defined as 1 and 2.2, respectively. The governing equations integrate the Cahn-Hilliard phase-field equation, Navier-Stokes hydrodynamic equations, and electrostatic Poisson equation. Numerical simulations under representative operating conditions (oil flow velocity: $0.3m*s^{-1}$, average electric field intensity: $2.0kV*mm^{-1}$) elucidate the dynamic processes of bubble migration, deformation, and coalescence in electro-thermo-hydrodynamic coupled fields. The results demonstrate that fluidic fields primarily govern bubble migration, while electric fields significantly modulate interfacial tension distributions, thereby driving bubble coalescence and fragmentation behaviors. The proposed theoretical framework for bubble dynamics provides critical insights into the insulation design of transformer oil ducts. Furthermore, the developed quantitative model offers a foundation for optimizing duct structures and advancing real-time monitoring systems in industrial applications.

Keywords: Transformer Oil Insulation; Multiphysics Coupling; Phase-Field Method; Bubble Interfacial Dynamics; Dielectric Constant Ratio

1. Introduction

Oil-immersed power transformers, serving as critical infrastructure in modern power grids, exhibit insulation reliability that directly governs the operational safety and stability of electrical systems[1]. As depicted in Figure 1 [2]; While insulating oil fulfills dual functions of heat dissipation and electrical insulation, it is persistently subjected to electro-thermal-fluid multiphysics coupling effects[4]. Notably, the generation and evolution of gaseous bubble impurities within oil ducts have been identified as a critical trigger for partial discharges and insulation failure[5]. Recent advancements in this domain have primarily focused on three interconnected research thrusts: bubble nucleation mechanisms, multiphysics-coupled dynamic behaviors, and advanced numerical simulation methodologies[6].

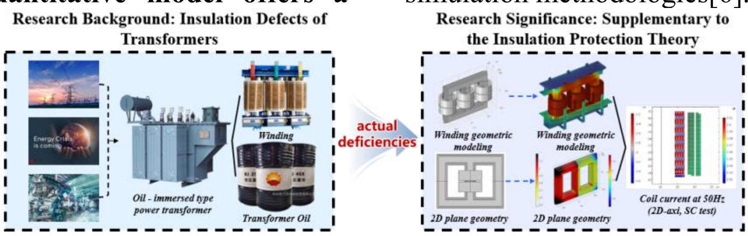

Figure 1. Mechanism of Bubble Formation in Transformer Oil Ducts

The formation mechanisms of internal bubbles in power transformers originate from dual pathways: manufacturing residues and operational interactions[7]. During fabrication stages, constrained by vacuum impregnation processes, residual micro-air pockets(0.1-0.3vol%) and adsorbed aqueous films (10-50mm thickness) persist on active surfaces, serving as nucleation sites for microbubbles under thermal cycling conditions[8]. Operational degradation manifests through two synergistic pathways: (i) seal degradation-induced moisture ingress exacerbated by extreme meteorological events (e.g., torrential rainfall below 0^{O}C), and (ii) thermal decomposition of mineral insulating oil (C25-C40 alkanes) at sustained operational temperatures (120-150^{O}C). Following Arrhenius kinetics (Ea≈98 kJ/mol), preferential cleavage of lower-bond-energy C-C bonds (347 kJ/mol vs C-H 413 kJ/mol) liberates characteristic gases (H_2, CH_4, C_2H_4), with hydrogen production rates reaching 0.12 mL/h·kVA as specified in IEC 60296[9-10]. Bubbles generated through these dual mechanisms migrate within oil circulation while undergoing local field-dependent morphological evolution (critical diameter 15-100mm under 3-5 kV/mm gradients), ultimately governing the spatiotemporal evolution of dielectric strength.

Current studies on the motion characteristics of gaseous impurities under complex operating conditions primarily focus on the dynamic response mechanisms of complex systems under multi-physics interactions. The core objective lies in elucidating the energy-momentum-charge transfer laws among electric, flow, and thermal fields[11]. A theoretical framework for electro-thermo-fluidic coupling has been established by integrating Maxwell's equations, Navier-Stokes equations, and energy conservation equations, thereby quantifying the regulatory effects of multi-field synergies on medium behavior[12]. For instance, in dielectric media such as insulating oils, multi-field coupled models effectively characterize electric field-driven carrier migration, temperature gradients induced by Joule heating, and feedback effects of thermal expansion forces on fluid motion[13]. Experimentally, synchronized multi-physics measurement techniques enable synergistic observation of bubble deformation, thermal convection vortices, and spatial charge distribution[14]. However, existing research faces limitations in dynamically modeling transient strong-coupling conditions (pulsed electrothermal shocks, turbulence-electrothermal coupling), while the influence mechanisms of individual physical fields on motion characteristics remain unclear. Additionally, the resolution of cross-scale interfacial effects and nonlinear parametric sensitivity requires in-depth exploration[15]. Therefore, this study focuses on analyzing the motion characteristics of gaseous impurities under electro-thermo-fluidic fields and elucidating the impact of these physical fields on dynamic processes, aiming to address critical gaps in multi-field coupling mechanisms under extreme operational scenarios.

2. Analysis of the Kinetic Model for Gas-Phase Impurities

2.1 Force Analysis of Gaseous Impurities

In the coupled electro-thermal-fluid multi-physical-field environment during the operation of a transformer, the suspended bubbles in the transformer oil are subjected to seven key forces(As depicted in Figure 2). The differences in physical properties such as dielectric constants and densities between the transformer oil and the bubbles, combined with the synergistic effects of the electric field, flow field, and thermal field, and the possible presence of charges on the bubble surface due to complex physical processes, all these factors together result in the bubbles being acted upon by forces. At the microscopic level, the intermolecular interactions and the changes in physical properties caused by temperature variations are also the sources of the forces acting on the bubbles.

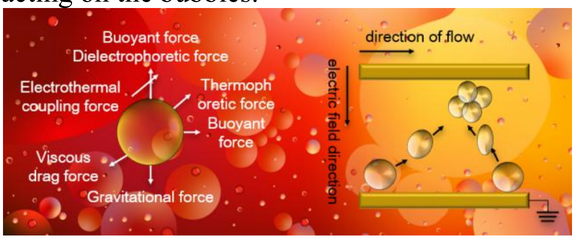

Figure 2. Analysis of Bubble Motion
Characteristics and Forces Acting on Bubbles

During the actual operation of the transformer, different physical fields correspond to different forces(As depicted in Table 1). The electric field is the main controlling factor for the dielectrophoretic force and the Coulomb force. When the transformer is in operation and the electric field is formed, these two forces act on the bubbles immediately. The flow field controls the viscous drag force. When the transformer oil is circulating, the viscous drag force affects the bubbles. The thermal field dominates the thermophoretic force and the electro-thermal coupling force. The heat generated during the operation of the transformer causes non-uniform temperature distribution in the oil, forming a thermal field, and thus generating these two forces. The buoyant force depends only on the density difference between the oil and the bubbles. If there is a density difference, the bubbles will be subject to the buoyant force

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under any operating conditions.

Table 1. Summary of Force Analysis on Bubbles in Insulating Oil

Type of Force	Mathematical Expression	Main influencing factors
Dielectrophoretic force	$F_{EDL} = 2\pi R^3 \varepsilon_0 \varepsilon_{oil} K \nabla E^2$ $(K = \frac{\varepsilon_{gas} - \varepsilon_{oil}}{\varepsilon_{gas} + 2\varepsilon_{oil}})$	Electric field gradient(∇E) Dielectric constant ratio(e_r)
Coulomb force	$F_q = \sigma_s \cdot E \cdot A + \frac{\sigma_s^2 A}{8\varepsilon_0}$	Surface charge density(s_S) Electric field intensity(E)
Buoyant force	$F_b = (\rho_{oil} - \rho_{gas}) g V_b$	Density contrast(Dr) Bubble volume(V_b)
Gravitational force	$F_g = \rho_{gas} g V_b$	Gas density(r_{gas}) Gravitational acceleration(g)
Viscous drag force	$F_{drag} = 6\pi\mu R u_{rel}(1 + 0.15Re^{0.687})$ $Re = \frac{2R\rho u_{rel}}{\mu}$	Oil viscosity (m) Relative velocity (u_{rel}) Reynolds number (Re)
Thermophoretic force	$F_{therm} =- 6\pi R\mu K_T \frac{\nabla T}{T}$ $(K_T \approx 0.5 - 0.9)$	Temperature gradient (∇T) Thermophoretic coefficient (K_T)
Electrothermal coupling force	$F_{ET} = \frac{\varepsilon_0 E^2}{2} \frac{\partial \varepsilon_r}{\partial T} \nabla T \cdot V_b$	Temperature coefficient of permittivity ($\frac{\partial \varepsilon_r}{\partial T}$) Electric field intensity (E)

These forces have various effects on the motion characteristics of the bubbles. The dielectrophoretic force and the Coulomb force drive the bubbles to migrate directionally in the electric field, directly changing the distribution state of the bubbles in the oil and affecting their positions in the direction of the electric field. The viscous drag force hinders the movement of the bubbles, plays a major restrictive role in the longitudinal migration process, and significantly reduces the bubble movement speed. The combined action of the thermophoretic force and the electro-thermal coupling force causes the trajectory of the bubbles to deviate, changing their original direction of motion. Although the buoyant force is relatively small, it also participates in the force-balance system of the bubbles. Together with other forces, it jointly determines the dynamic behavior of the bubbles in the transformer oil, thereby affecting the operational performance of the transformer.

2.2 Analysis of Physical Field Environments

The coupling effects of electro-thermal-fluid multiphysics fields in transformer oil ducts dynamically regulate the migration, deformation, and coalescence of bubbles through energy transfer, momentum exchange, and charge migration processes. By integrating actual operating conditions with numerical simulation methods, this study systematically elucidates their interaction mechanisms and engineering implications. The interaction between electric and flow fields governs bubble migration through dielectrophoretic forces and viscous drag. A high-voltage electric field (E>2.0kV/mm) induces dielectrophoretic forces, driving bubbles toward regions of higher electric field intensity. Conversely, oil flow velocity (u>0.3m/s) generates viscous drag, compelling bubbles to follow the flow direction. The competition between these forces is quantified by the Electrohydrodynamic number (As depicted in Table 2). When N>1 the electric field dominates; otherwise, the flow field prevails. Numerical simulations reveal that localized EHD flows (Reynolds number Re<10) in high-field regions (e.g., winding gaps) generate micro-vortices, exacerbating interfacial deformation.

The thermal field modulates electric field distribution and electrothermal coupling forces(F_{ET}) via temperature-dependent dielectric constants ($\frac{\partial \varepsilon_r}{\partial T}$≈-0.02K⁻¹).Joule heating induces a temperature rise (ΔT≈10K), reducing oil viscosity (m) and accelerating bubble migration. Simultaneously, thermophoretic forces (F_{therm}) and electrothermal coupling forces near cooling fins create inter-bubble attractions, shortening coalescence time by 30%. Both experiments and simulations demonstrate that in high-temperature regions(T>393.15K) reduced surface tension lowers the critical Weber number(We=0.5), promoting bubble fragmentation(As depicted in Table 2).

Table 2. Summary of Force Analysis on Bubbles in Insulating Oil

Coupling Type	Dimensionless Number	Expression	Physical Meaning
Electric field-flow field coupling	EHD(n)	$EHD = \frac{\varepsilon_0 \varepsilon_r E^2 L}{\mu u}$	The ratio of electric field energy to viscous dissipation
Electric field-thermal field coupling	We(n)	$We = \frac{\partial \varepsilon_r E^2 L^2}{\partial T \Delta T}$	The relative intensity of electrothermal effect and temperature gradient
Electric field-thermal field coupling	Peclet(n)	$Peclet = \frac{uL}{\alpha}$	The competitive effects of convection and heat conduction

The flow field redistributes heat via forced convection, while thermal gradients inversely alter flow structures through viscosity variations. High-speed oil flow(u=0.3m/s) suppresses thermal boundary layer thickness and mitigates local temperature gradients. Additionally, decreased viscosity(m (T)) reduces viscous drag, enhancing bubble migration rates by 20% in low-velocity zones (e.g., duct bends). Under multiphysics coupling, bubble trajectories exhibit spiral oscillations, with normalized displacement ($\frac{\Delta x}{L}$) positively correlated with the Peclet number(As depicted in Table 2).

3. Analysis of Simulation Results of Gas-Phase Impurities

Regarding the simulation of the motion characteristics of bubbles in the oil duct, the force directions acting on the bubbles can mainly be divided into two types: the horizontal direction and the vertical direction. Due to the differences in the bubble motion trajectories and degrees of movement, the forces acting on the bubbles in these two directions are in a state of dynamic change (as shown in Figure 3). Therefore, the transient motion model of suspended bubbles constructed based on the finite-element model can analyze the motion characteristics and discharge mechanism of bubbles by numerically examining the relevant parameters of bubbles under different states and at different time intervals. This provides guiding ideas for the design of the oil duct in transformers.

3.1 Analysis of Fluid Field Environment

For the modeling of the transformer oil duct, this paper mainly adopts a transient model based on the phase-field method for the electro-thermal-fluid coupled physical field. Specifically, it focuses on simulating the single-bubble motion model in a horizontal oil duct. The specific relevant parameters are shown in Table 3.

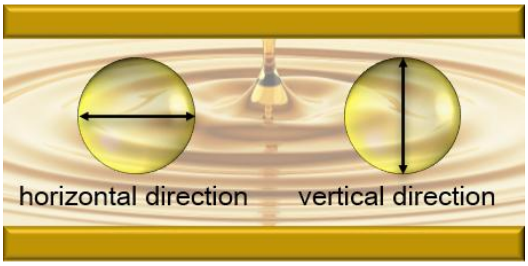


Figure 3. Schematic Diagram of Different Force Directions of Gas-Phase Impurities

Upon a meticulous analysis of the movement directions of suspended bubbles, it becomes evident that the most pronounced alterations in the primary movement trends of bubbles take place precisely in the horizontal and vertical directions. The movement states of bubbles at diverse time intervals are vividly illustrated in Figure 4. Through a comprehensive comparison of various parameters, it is clearly observable that the size of bubbles exerts the most substantial influence on their movement characteristics.

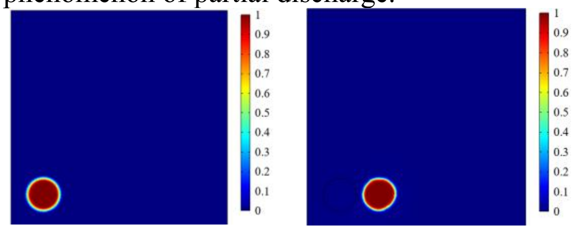
By closely observing the trajectory of the bubble, it can be discerned that under the influence of the electric field force, there exists a conspicuous upward-floating process of the bubble. This phenomenon indicates that the surface charge of the bubble undergoes polarization under the effect of the electrical length, thereby causing the bubble to deform in multiple directions.

Table 3. Summary of Force Analysis on Bubbles in Insulating Oil

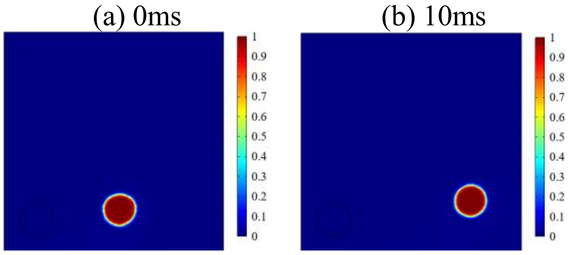
Parameter Name	Parameter Expression	Parameter Value	Parameter Description
W	10[mm]	0.01m	Width of the horizontal oil duct
L	10[mm]	0.01m	Length of the horizontal oil duct

U0	20[kV]	20000V	Voltage of the upper plate
rhoo	850[kg/m^3]	$850kg*m^{-3}$	Density of the insulating oil
muo	0.0060[Pa*s]	0.0060Pa*s	Dynamic viscosity of the insulating oil
V0	0.3[m/s]	$0.3m*s^{-1}$	Flow velocity in the horizontal oil duct
R0	0.75[mm]	0.00075m	Length of the bubble radius
U_max	1.1*V0	$0.33m*s^{-1}$	Mobility adjustment parameter
Sigma	0.030[N/m]	$0.03N*m^{-1}$	Surface tension coefficient

Specifically, the fluid field predominantly affects the deformation in the horizontal direction, whereas the electric field acts on the stretching process of the bubble in the vertical direction. The heat-transfer field modulates the motion state of the bubble primarily by exerting an impact on the parameters of both the fluid field and the electric field. Under the synergistic action of these three fields, the bubble is effectively precluded from over-extending in a solitary direction, thus averting the breakdown phenomenon of partial discharge.



(a) 0ms (b) 10ms

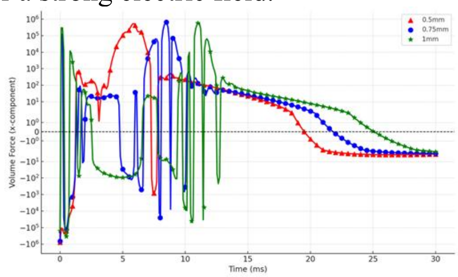


(c) 20ms (d) 30ms

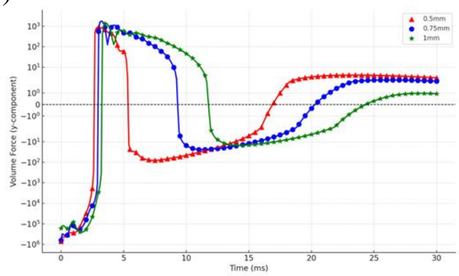
Figure 4. Schematic Diagrams of the Motion Trajectories of Bubbles in Different Periods

Upon conducting a comprehensive analysis of the forces exerted on the bubbles, it becomes apparent that the forces acting on the bubbles can be approximated as the resultant forces along the horizontal and vertical directions. On this basis, the projections of the volume forces imposed on bubbles of varying sizes in the x-and y-directions can be calculated. Ultimately, an in-depth analysis of the force-bearing process of the bubbles in these specific directions can be achieved. By simulating the motion trajectories of three suspended bubbles with distinct sizes, the variation processes of the volume forces in the two directions are derived, as depicted in Figure 5.

When conducting an in-depth and meticulous analysis of the volume forces acting on bubbles at different time points, it becomes clear that the forces on bubbles in any direction can present both positive and negative values. This is mainly due to the comprehensive modulation of multiple physical fields. This force-bearing mechanism effectively prevents bubbles from growing unrestrictedly in one direction, thus avoiding the partial-discharge phenomenon. In the oil duct of a forced-commutation transformer especially, the oil flow velocity makes it difficult for bubbles to accumulate and coalesce in the same area. Smaller-volume bubbles respond more quickly to force influence. A careful examination of the graphs reveals a negative-correlation between bubble volume and the movement process. Larger bubbles face greater resistance to the combined driving of multiple physical fields. However, these large-sized bubbles remaining in the oil duct are more likely to experience the breakdown effect under a strong electric field.



(a) Volume force in the horizontal direction



(b) Volume force in the vertical direction

Figure 5. Schematic Diagrams of the Volume Forces of Bubbles of Different sizes in the Force-Receiving Directions

3.2 Analysis of Temperature Field Environment

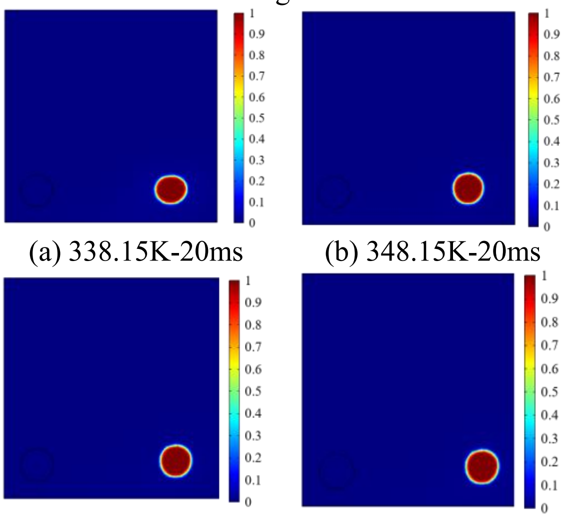
The main influence mechanism of the

heat-transfer field lies in its ability to modify the relevant parameters of the fluid and electric fields, significantly affecting bubble motion characteristics. In actual simulations, given the diverse transformers and the negligible impact of temperature on fluids at low velocities, the oil-duct flow velocity is set to 0.5 m/s in the simulation environment. Moreover, by comprehensively analyzing various-specification transformers, the basic oil-temperature parameters of common ones are derived and presented in Table 4.

Table 4. Summary of Force Analysis on Bubbles in Insulating Oil

Types of transformers	Oil-immersed self-cooled or air-cooled transformer	Forced oil circulation air-cooled transformer	Forced oil circulation water-cooled transformer
the maximum oil temperature	368.15K	348.15K	348.15K
the minimum oil temperature	358.15K	338.15K	338.15K

Through simulation using finite-element software, the motion states of bubbles at the same moment under different temperatures are obtained as shown in Figure 6.



(a) 338.15K-20ms (b) 348.15K-20ms

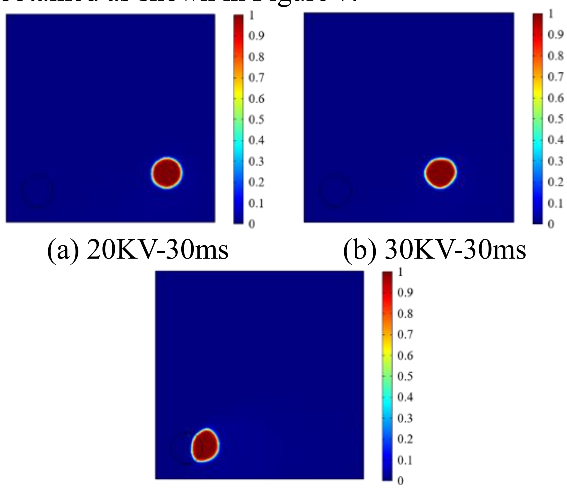
(c) 358.15K-20ms (d) 368.15K-20ms

Figure 6. Schematic Diagrams of Bubble Movement Positions at Different Temperatures

An analysis of the above-mentioned bubble motion trajectories reveals that temperature changes have a significant promoting effect on the bubble motion trajectories. The high-temperature environment has a greater impact mechanism on the fluid-field environment. In terms of the motion characteristics of bubbles, the high-temperature environment directly acts on the surface tension of bubbles and reduces the liquid viscosity. There is a particularly obvious positive-correlation promoting effect on the horizontal motion velocity of bubbles.

3.3 Analysis of Electric Field Environment

Regarding the influence mechanism of the electric field on bubbles, the motion characteristics of bubbles are observed mainly by changing the plate voltage of the horizontal oil duct. By comparing the motion of bubbles within the same time under different voltages, the motion characteristics of bubbles are obtained as shown in Figure 7.



(a) 20KV-30ms (b) 30KV-30ms

(c) 40KV-30ms

Figure 7. Schematic Diagrams of Bubble movement positions at different temperatures

By observing Figure 7, it is evident that the electric field significantly lags the bubble movement. Under the electric field force, bubbles deform more vertically and displace less horizontally.

Bubble deformation mainly results from force imbalance due to increased electric field force, with the electric field force and surface tension jointly affecting the surface shape. According to Coulomb's law, higher voltage strengthens the electric field, increasing the electric field force on the bubble surface. The opposing tensile forces along the electric field stretch the bubble, causing greater deformation. Moreover, as the voltage rises, the electric field force's stretching effect overrides the interfacial tension's constraint, making the bubble deform more to balance the two forces.

Regarding horizontal displacement, when the voltage increases, the electric field force on the bubble grows. However, the bubble also encounters viscous resistance in the liquid. As the electric field force increases, so does the viscous resistance. When they reach equilibrium, the resultant force on the bubble decreases, slowing it down. Additionally, increased voltage may alter the liquid's conductivity, changing its properties like viscosity. According to Stokes' law, this further impedes the bubble's movement and slows its speed.

4. Analysis of Simulation Results of Gas-Phase Impurities

(1) A phase-field-based multiphysics-coupling model was developed, with relative dielectric constants of bubbles and insulating oil set as 1 and 2.2. By integrating the Cahn-Hilliard phase-field, Navier-Stokes, and electrostatic Poisson equations, it simulated bubble behavior in the electro-thermo-hydrodynamic coupled field of transformer oil ducts.

(2) In the coupled-field, bubbles are under multiple forces. The fluid field drives bubble migration, the electric field modifies interfacial tension, and the thermal field impacts bubble motion via parameter changes. These fields are coupled, jointly governing bubble migration, deformation, and coalescence.

(3) Simulations showed that bubble size significantly influences motion. Small bubbles respond faster to forces, and large ones are prone to breakdown in strong electric fields. Temperature promotes bubble motion, with high temperatures reducing viscosity and altering surface tension to speed up horizontal movement. The electric field lags bubble motion, leading to more vertical deformation and less horizontal displacement.

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References

[1] Shan Jing, Cheng Yangchun, Liu Mengjun, et al. Wiener Model for the Evolution Law of Characteristic Gases in Transformer Overheating Faults [J/OL]. High Voltage Engineering, 1-13 [2025-02-06].

[2] Wang Xiang, Yang Lijun, Wang Ke, et al. Thermodynamic Calculation Method for the Content of Gases Generated by the Thermal Decomposition of Transformer Oil Based on the Arc Partition Theory [J/OL]. High Voltage Engineering, 1-10 [2025-02-06].

[3] Liu Yunpeng, Liu Yijin, Zhao Tao, et al. Research on the Movement of Free Conductive Particles in Transformer Oil under AC Conditions and the Induced Partial Discharge Characteristics [J/OL]. Journal of North China Electric Power University (Natural Science Edition), 1-12 [2025-02-06].

[4] Li Qingquan, Zhu Ran, Li Shuqi, et al. Review of Electro-Thermal Coupling Numerical Calculation Methods for Converter Transformers [J]. High Voltage Engineering, 2024, 50(10): 4734-4748.

[5] Wang Zhuofei, Zhang Cheng, Zhang Yao, et al. Characteristics of Pressure Waves in the Initial Stage of Arc Discharge in Transformer Oil under Power-Frequency AC Voltage [J/OL]. Proceedings of the CSEE, 1-12 [2025-02-06].

[6] Li Jifang, Zhou Yifan, Zhou Xingyao, et al. Influence of Local Discharge of Bubbles in Transformer Oil on Insulation Performance [J]. Science Technology and Engineering, 2024, 24(17): 7159-7167.

[7] Yang Chaojie. Research on the Mechanism of Thermal-Induced Bubble Effect and Bubble Discharge Characteristics in Oil-Paper Insulation [D]. North China Electric Power University (Beijing), 2024.

[8] Zhang Ziyue. Research on the Dynamic Evolution Characteristics of Partial Discharge and Suspended Bubbles in Transformer Insulating Oil [D]. Shandong University, 2022.

[9] Zhang Yongze, Tang Ju, Pan Cheng, et al. Influence of Oil Flow Velocity on the Breakdown Characteristics of Transformer Oil Containing Bubbles [J]. Transactions of China Electrotechnical Society, 2022, 37(02): 479-487.

[10] Liu Qiushi, Li Qingmin, Niyomugabo E. Ladislas, et al. Dynamic Characteristics and Migration Mechanisms of Bubbles in Insulating Oil under Extremely Non-Uniform Electric Fields [J]. Proceedings of the CSEE, 2022, 42(09): 3460-3470.

[11] Yao Yuhang, Tao Xiantao, Yu Mengyue, et al. DC Breakdown Characteristics of Flowing Transformer Oil Containing Free Metal Particles [J]. Transactions of China Electrotechnical Society, 2023, 38(S1): 157-167.

[12] Qi Bo, Wei Zhen, Li Chengrong, et al. Phenomena and Characteristics of Surface Discharge along Oil-Paper Insulation in AC-DC Composite Electric Fields [J]. Transactions of China Electrotechnical Society, 2016, 31(10): 59-67.

[13] Wang Yongqiang, Zhong Zhao, Xie Jun, et al. Influence of Temperature on the Surface Discharge of Insulating Paperboards with Different Degrees of Aging [J]. High Voltage Engineering, 2017, 43(08): 2724-2732.

[14] Wu Jinyuan. Research on the Influence of Local Overheating on the Discharge Characteristics of Oil-Paper Insulation [D]. Southwest Jiaotong University, 2019.

[15] Ding Renjie, Duan Lian, Luo Ziqiu, et al. Simulation Analysis of the Temperature Field and Flow Field during the Cold-Start Process of Oil-Immersed Transformers under Extremely Cold Conditions [J]. Science Technology and Engineering, 2021, 21(35): 15043-15051.