Analysis of Bubble Motion Characteristics in Oil Based on Level Set Method

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Abstract. At present, transformer oil is the primary insulation method for large power transformers, and the dynamic behavior of bubbles in transformer oil can impact the insulation performance of transformer oil. Therefore, based on the level set method in this paper, the motion characteristics of bubbles in two structures, a horizontal oil channel and a vertical oil channel, under various conditions of different bubble numbers, different flow velocities, and different bubble sizes are studied using finite element simulation. The simulation results show that the kinetic behavior of bubbles becomes more complicated as the radius increases, the number of bubbles increases, and the flow velocity increases. At the same time, the bubble expansion and deformation is a cyclic process due to the electric field force, laminar flow and surface tension in the bubble suspension process.

Keywords: Transformer oil, Bubble, Kinetic behavior, Oil channel structure, Level set method.

1. Introduction

In recent years, the State Grid Corporation has vigorously developed long-distance ultra-high voltage transmission technology and has completed and implemented several ultra-high voltage transmission projects [1]. The power transformer is the core device of a high-voltage transmission network. The quality of transformer oil, as the main internal insulation method of large power transformers, determines the insulation level of the transformer. Suspension bubbles, as typical insulation defects in transformer oil, are likely to cause partial discharges and lead to transformer oil degradation, which may eventually brew serious transformer accidents if ignored. However, the suspension bubbles in the transformer oil channel are subject to the comprehensive effect of electromagnetic, temperature, and fluid fields, presenting extremely complex morphological evolution and movement law. An in-depth study of the mechanism of bubbles is beneficial to analyze the mechanism related to the partial discharge of transformer oil caused by bubbles, which is of great significance in preventing faults such as bubble discharge.

At this stage, domestic and foreign researchers have conducted many studies on the kinetic behavior of bubbles in insulating oil under the action of electric field and have achieved a series of results. Dan Cai [2], a scholar from the National University of Defense Technology, found that the partial discharge (PD) phenomenon occurs when there is a significant electric field enhancement inside the bubble and the millimeter bubble significantly impacts insulation performance. Góngora-Nieto [3], a foreign scholar, suggested that the intensity of bubble PD is affected by the bubble's size, location, and type of gas. H. Shiota of Mitsubishi Electric [4] designed an experimental device for bubble discharge in insulating oil and found that the bubble size dramatically influences the bubble PD characteristics. The larger the bubble size, the lower the corresponding initial discharge voltage and the more intense the PD. Gadzhiev [5] of the Joint Institute of High Temperature of the Russian Academy of Sciences compared the effect of air bubbles and SF6 bubbles on the insulation properties of transformer oil and found that air bubbles reduce the breakdown voltage of transformer oil more significantly, so the type of gas also affects the PD characteristics. The literature [6-9] made an in-depth study on bubbles' kinetic characteristics and migration mechanism under extremely inhomogeneous electric fields. By simulating the inhomogeneous electric field in insulating oil, it was found that the inhomogeneous electric field force has a stretching and pushing effect on bubbles, accelerates the rise of bubbles, makes the detachment time of bubbles shorter, and stretches the

bubbles in the direction parallel to the electric field force. The results show that the electric field has some influence on the motion and shape of bubbles which in turn affects the PD characteristics. Yongze Zhang [10] and other scholars have concluded that the position and initial velocity of the bubble motion have a more significant influence on the motion and deformation of the bubble. In addition to the above influencing factors, Xiao Chang [11] and other scholars studied the discharge characteristics of bubbles in flowing insulating oil and found that the bubble content inside the insulating oil and the oil flow rate have a direct influence on the PD characteristics through the detection of PD faults. The above studies mainly focus on the behavior of bubbles under electric fields. Domestic and foreign Scholars have conducted many studies on the motion, deformation, and aggregation of bubbles in the liquid phase under different electric fields. However, their studies focus more on electric fields, and most neglect bubble motion under the action of coupled multi-physics fields. Moreover, few of them conduct simulation studies.

Based on the domestic and foreign research results, this paper studies the tracking method of the gas-liquid two-phase flow interface of suspension bubbles based on the level set method. The effects of bubble motion on the insulation performance of transformer oil are studied under two different structures of horizontal and vertical oil channels with the number of bubbles being 1, 2 and 3, the liquid flow velocity being 0.01m/s, 0.02m/s and 0.03m/s, and the radius of bubbles being 0.5mm, 1.0mm and 1.5mm, respectively.

2. Principle analysis section

2.1. Flow-electricity-thermal coupling principle

2.1.1. Mathematical model of electric-field-flow field coupling

Due to the "small bridge theory", the bubbles in transformers are in the strong electric and magnetic fields generated by the internal transformer winding. Changes in the electromagnetic field will affect the positive and negative ions of the bubble deflection and bubble polarization. When the electric field changes, the force of the bubble inside the transformer will change. The movement of the bubbles will affect the distribution of the flow field-the final current thermal field to complete the coupling.

To analyze the motion of the bubble, use Maxwell's system of equations, which can be used to analyze the dynamics of the electromagnetic field. The differential form of the expression of one is as follows.

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0} \tag{1}$$

There is no charge within it and the electric field has zero spin can be expressed as

$$\nabla \cdot \boldsymbol{E} = 0 \tag{2}$$

The Maxwell stress tensor T can be calculated from the electric field strength E and the potential shift vector D as follows in an electrostatic field.

$$T = \boldsymbol{E}\boldsymbol{D}^{\boldsymbol{T}} - \frac{1}{2}\left(\boldsymbol{E} \cdot \boldsymbol{D}\right)\mathrm{I} \tag{3}$$

2.1.2. Flow field-temperature field coupling control equation

Inside the transformer, the eddy current field of the core winding will produce eddy current loss, and the winding itself also has power loss to produce Joule heat. The energy lost is converted into heat energy, which is transferred to the insulating oil through thermal radiation and heat conduction. The fluid such as insulating oil and air bubbles transfers heat between them through thermal convection, which in turn makes the fluid temperature change. Fluid temperature changes so that the dynamic fluid viscosity and fluid density r in the N-S equation also change. The greater the fluid's

dynamic viscosity, the smaller the fluid rate. So the N-S equation launched by u also changes, u parameters change, the generalized heat transfer equation launched by the fluid temperature T also changes, and then the dynamic fluid viscosity also changes—the flow field and temperature field to complete the coupling.

The motion of the fluid is mainly affected by the electric field force, viscous force and gravity. Assuming that the gas-liquid are insoluble in each other and insulating oil for incompressible Newtonian fluid, the Navier-Stokes equations can be used to describe the fluid motion. According to the conservation of momentum and conservation of mass, there are:

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\Delta\boldsymbol{u}\right)=-\Delta\boldsymbol{p}+\boldsymbol{F}_{st}+\rho\boldsymbol{g}+\boldsymbol{F}_{e}+$$

$$\nabla\cdot\left(\mu\left(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^{T}\right)-\frac{2}{3}\mu(\nabla\cdot\boldsymbol{u})\mathrm{I}\right) \tag{4}$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0 \tag{5}$$

Where $\boldsymbol{u}$ is the fluid velocity, $\boldsymbol{p}$ *is* the fluid pressure, r *is the* fluid density,μ is the fluid dynamic viscosity, **g** is the gravitational acceleration vector, I is *the* unit matrix, $\boldsymbol{F_e}$ is the electric field force acting on the fluid, and $\boldsymbol{F_{st}}$ is the surface tension.

The effect of the electric field on the flow field is mainly achieved by the electric field force $\boldsymbol{F_e}$ acting on the fluid cell. The electric field force $\boldsymbol{F_e}$ can be expressed as expressed as

$$\boldsymbol{F}_{\mathrm{e}}=\nabla\cdot\boldsymbol{T} \tag{6}$$

Then according to Maxwell's stress tensor $\boldsymbol{T}$, the electric field force can again be expressed as

$$\boldsymbol{F_e}=\nabla\cdot\left(\boldsymbol{E}\boldsymbol{D}^{T}-\frac{1}{2}(\boldsymbol{E}\cdot\boldsymbol{D})\mathrm{I}\right) \tag{7}$$

The flow field and temperature field are coupled in the process of using the generalized heat transfer equation to analyze the relationship between fluid temperature and velocity, whose expression is shown below.

$$\rho\mathrm{C}_{\mathrm{p}}\frac{\partial T}{\partial t}+\rho\mathrm{C}_{\mathrm{p}}\boldsymbol{u}\cdot\nabla T=\nabla\cdot(k\nabla T)+Q \tag{8}$$

Where ***u is the*** fluid velocity, r is the density, $\mathrm{C_p}$ is the heat capacity, *T is the* temperature, and *Q* is the heat the system absorbs.

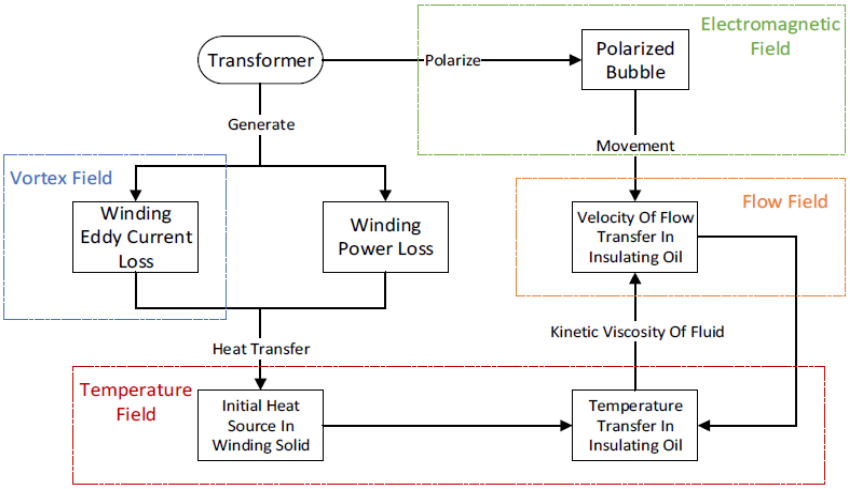


Figure 1. Schematic diagram of multi-physics field coupling

2.2. Bubble force analysis

2.2.1. State of motion of bubbles

According to Stokes' law, the floating speed of bubbles is proportional to the size of bubbles and inversely proportional to the oil's viscosity. The bubbles in the transformer oil are tiny, and it isn't easy to float by its buoyancy. Due to the stirring effect of the submerged oil pump, the microfine bubbles become emulsion bubbles through the valve port at high speed. Even if the bubbles stay in the oil long enough, it is tough to float by their buoyancy. Therefore, the bubbles in the transformer oil in the internal oil channel of the transformer case mostly always remain suspended and moving.

2.2.2. Forces on the bubble and mathematical formula

In oil-immersed electrical equipment, in the insulating oil, the most significant impact on the overall migration path of the bubble is the electric field force, pumping force, buoyancy, gravity, resistance, and surface tension.

Buoyancy force on the bubble.

$$\boldsymbol{F_B} = \frac{V}{\rho_{\text{liq}}\mathbf{g}} \tag{9}$$

Gravity on the bubble.

$$\boldsymbol{F_G} = V\rho_{gas}\mathbf{g} \tag{10}$$

The resistance of the bubble in the process of suspension movement under the action of the combined force is

$$\boldsymbol{F_D} = \frac{1}{2}\pi r_s C_D \rho_{gas} v_b^2 \tag{11}$$

The bubble will be polarized charge at the gas-liquid interface under the action of external electric field, which makes the bubble in the electric field The electric field force on the bubble is

$$\boldsymbol{F_E} = 2\pi\varepsilon_b r_b^3 \left(\frac{\varepsilon_b - \varepsilon_1}{\varepsilon_b + 2\varepsilon_1} \right) \nabla \mathbf{E}^2 \tag{12}$$

Under the action of forced oil circulation (submerged oil pump), the bubble will move along the oil channel inside the electrical equipment, so that the The pumping force on the bubble is.

$$\boldsymbol{F_I} = \frac{\mathrm{P}}{v_b} \tag{13}$$

The surface tension is mainly to promote the bubble surface contraction so that the bubble as far as possible to maintain the spherical shape, the expression is:

$$\boldsymbol{F_S} = -2\pi r_S \sigma sin\theta \tag{14}$$

Where, $\mathcal{E}_b$ is the dielectric constant of the bubble, r_b is the radius of the bubble, ε_1 is the dielectric constant of the liquid, **E** is the electric field strength; P is the power of the submerged pump, v_b is the movement rate of the bubble. ρ_{liq}, ρ_{gas} are the densities of the liquid and gas, respectively, **g** is the acceleration of gravity ($9.8 m/s^2$), V is the volume of the bubble; r_s is the contact radius, θ is the contact angle, C_D is the drag coefficient, σ is the surface tension coefficient. coefficient.

Among them, the combined force of electric field force, pumping force, buoyancy force, gravity and drag force determines the bubble's trajectory. And the combined force and surface tension determines the shape change of the bubble during the suspension process.

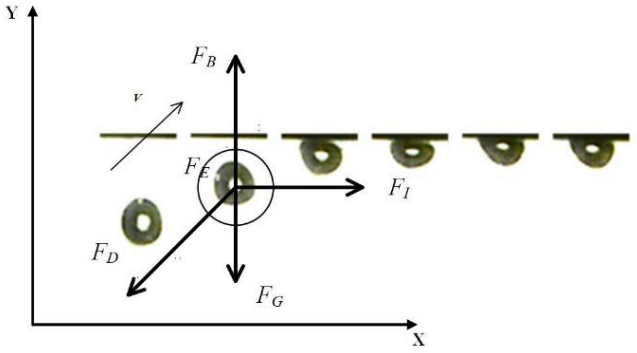


Figure 2. Suspension bubble force analysis

2.2.3. Force analysis diagram of suspended bubble

After the bubble is created, it will move upward faster to reach the upper pole plate. After calculation, since the combined force in the horizontal direction is greater than the combined force in the vertical direction, the bubble will continue to move horizontally to the right in the oil plate. Furthermore, at this time, the pressure on the right side of the bubble is greater than the pressure on the left side, which makes the left part of the bubble move to the right side, resulting in the deformation of the bubble. Moreover, the surface tension drives the bubble to remain as spherical as possible, and the bubble then becomes moving in a horizontal ellipsoidal shape. The force and general shape of the suspended bubble are shown in Fig. 2.

2.3. Horizontal set method

2.3.1. Introduction to the horizontal set method

Currently, the level set method is mainly used in multi-media fluid mechanics and interface propagation. It can also be applied to analyze the variation of bubbles in the gas-liquid two-phase flow system of transformer oil. The main idea is to represent the change of the structure interface in a particular dimension by the change of a function in a higher dimensional space with time. The "level" refers to the horizontal plane with a fixed value of c, where c is generally taken as 0. The "set" refers to the set of all curves obtained by the intersection of the two interfaces in the process of structural. For example, to represent the change of the material interface W in N dimensions, it is necessary to construct a function belonging to N+1 dimensions with time. By solving the equation, the corresponding zero contours can be obtained. These zero contours represent the N-dimensional space, and thus, the change of W can be represented.

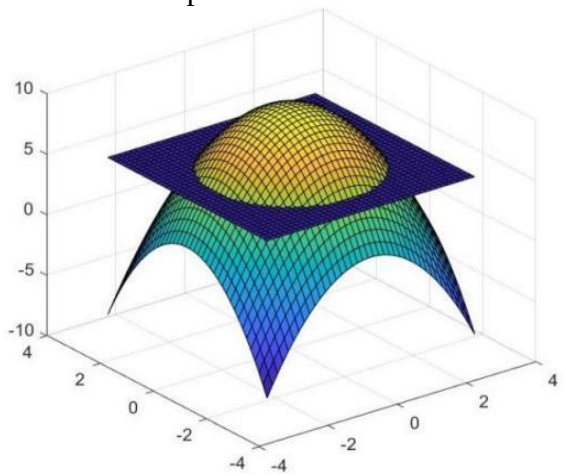


Figure 3. Horizontal set method example diagram

Therefore, construct the function $\Phi(x,t)=0$, and for any moment *t*, the solution of this equation represents the change in W. Then the representation of the surface W in N+1 dimensions, described by $\Phi(x,t)$, is as follows:

$$\begin{cases} \Phi(x,t) > 0, x \in \Omega \\ \Phi(x,t) = 0, x \in \partial\Omega \\ \Phi(x,t) < 0, x \in D \setminus \Omega \end{cases} \tag{15}$$

By deriving the derivative on the boundary with respect to the time variable *t*, the boundary condition can be obtained as

$$\frac{\partial \Phi}{\partial t} + \nabla\Phi \cdot \frac{dx}{dt} = 0 \tag{16}$$

Finally, the specific changes in the structural interface lead to

$$\frac{\partial \Phi}{\partial t} + V_n \cdot \left|\nabla\Phi\right| = 0 \tag{17}$$

Where Vn denotes the normal velocity component of the boundary change.

The equation (17) is the level set equation. It represents that the variation of F(x,t) with time is equivalent to the variation of F(x,t) in the gradient direction with a velocity of Vn , which eventually intersects to obtain the interface W through constant variation.

2.3.2. Implementation of the level set method in simulation

Two-phase flow problems are flow problems that contain two phases of matter in two states. Compared to the single-phase flow system, the complexity of the two-phase flow problem lies in the fact that the various parameters in the two phases change dramatically at the intersection.

The present study focuses on the problem of bubble tracking in the intersection of gas-liquid two-phase flow. In the simulation process, the gas-liquid two-phase boundary can be modeled in detail to solve the numerical simulation of two-phase flow. For example, the shape of the gas-liquid intersection between the bubble and the transformer oil can be analyzed in detail. It is called the separated multiphase flow method. In the study of gas-liquid two-phase flow, the interface between the two phases represents the equivalence surface of the level set function.

The level set method is field-based and can be solved in two phases. The level set method is developed from a mathematical point of view, and its representation of the color function is related to the fluid flow through a convective term.

In the study of multiphase flow models, the level set method contains fewer physical fields and uses only one transport equation in the simulation, making it more stable from the numerical point of view. It can take into account the stability of the variables. In addition, the level set method has better applicability and can accurately show the interface.

To solve the level set function by the finite element method, we need to solve three equations: one N-S equation, one continuity equation and one transport. For the specific operation, it is necessary to add the laminar physical field interface and set the transient for phase initialization. COMSOL products needed in laminar flow are the microfluidic module or the CFD module. As for turbulence, the available turbulence models are RANS, k-e. As for turbulence, the available turbulence models are RANS, k-e and so on. The COMSOL product required is the CFD module.

3. Simulation modeling and analysis of results

3.1. Model Definition

3.1.1. Structural modeling

In order to simulate the motion characteristics of air bubbles in transformer oil under the action of electric field, two structural models of vertical oil channel and horizontal oil channel are constructed in this paper.

The vertical oil channel model is shown in Fig.4. The potential is added on the left side of the simulation model and grounded on the right side. The lower part is the oil flow inlet, and the upper part is the outlet. Two bubbles of the same size are placed at the inlet.

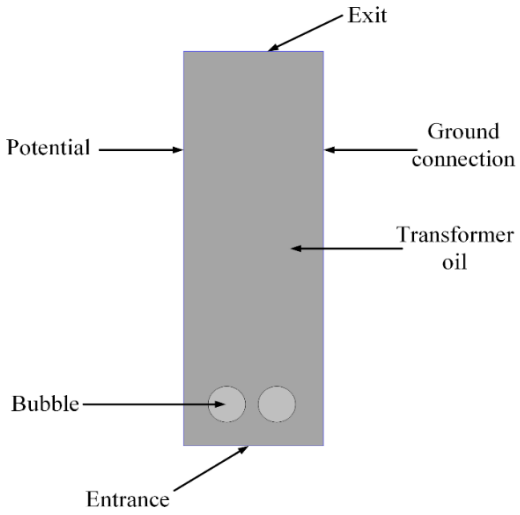


Figure 4. Vertical oil channel simulation model

In order to better simulate the movement characteristics of air bubbles in the transformer oil, set the transformer height to 30mm, and width to 10mm. And place 2 bubbles of 3mm diameter at the entrance.

The horizontal oil channel model is shown in Fig. 5. The potential is added above the model and grounded below. The oil channel is 10mm high and 30mm wide. And place 2 bubbles of 3mm diameter at the entrance.

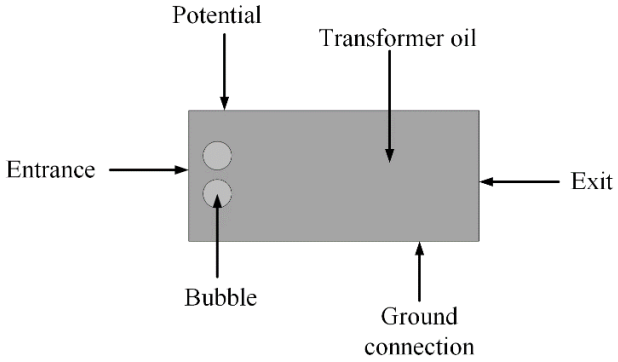


Figure 5. Horizontal oil channel simulation model

3.1.2. Material properties

The same material properties are used in the vertical and horizontal oil channels. The simulation model consists of two materials, air and transformer oil. According to the internal characteristics of the transformer, the parameters such as specific heat capacity, density, and thermal conductivity of the air material are set as a function of temperature. The parameters such as dynamic viscosity, specific heat capacity, and density of the transformer oil are also set as a function of temperature.

3.1.3. Mesh sectioning and boundary condition setting

In the analysis of the vertical oil channel model using the finite element method, in order to calculate the movement of the air bubbles in the transformer oil more accurately and conveniently, in this paper, the model is calculated with the mesh dissection as shown in Fig.6 and Fig.7. Among them, the transformer oil part uses coarsened mesh size in order to reduce the calculation time. In contrast, the bubble uses an extremely refined mesh, thus facilitating a more accurate calculation of the effect of bubble motion on the transformer oil performance.

In the vertical oil channel, as shown in Fig.6, the model is set up with the oil flow inlet below and the oil flow outlet above. The left side is high potential, and the right side is grounded. In the horizontal oil channel, as shown in Fig.7, set the model with the oil flow inlet on the left side and the oil flow outlet on the right side. The upper part is high potential, and the lower part is grounded.

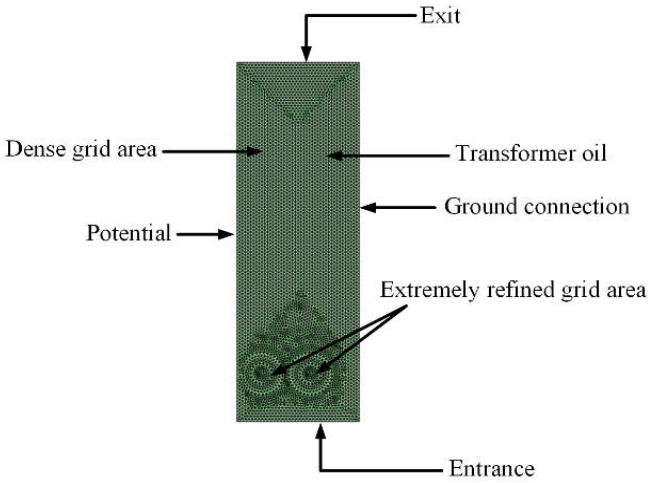


Figure 6. Vertical oil channel mesh segmentation and boundary conditions

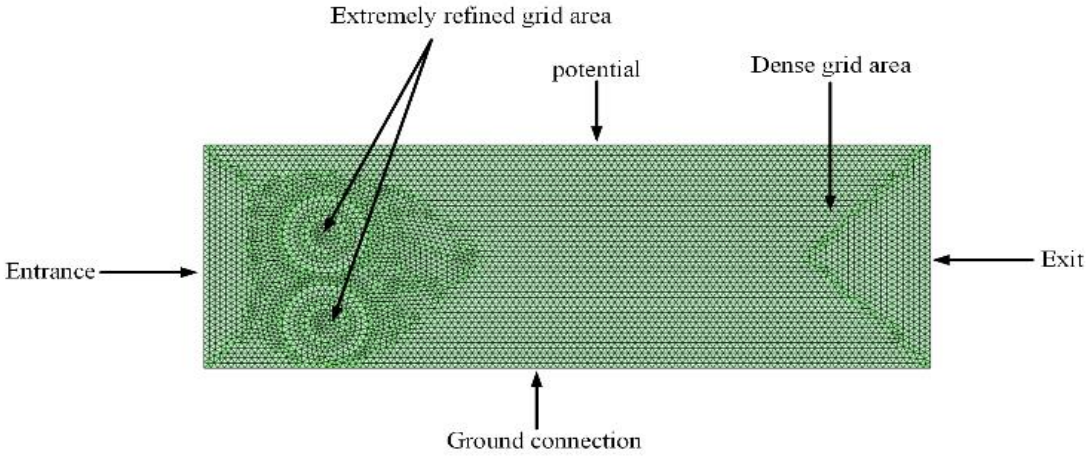
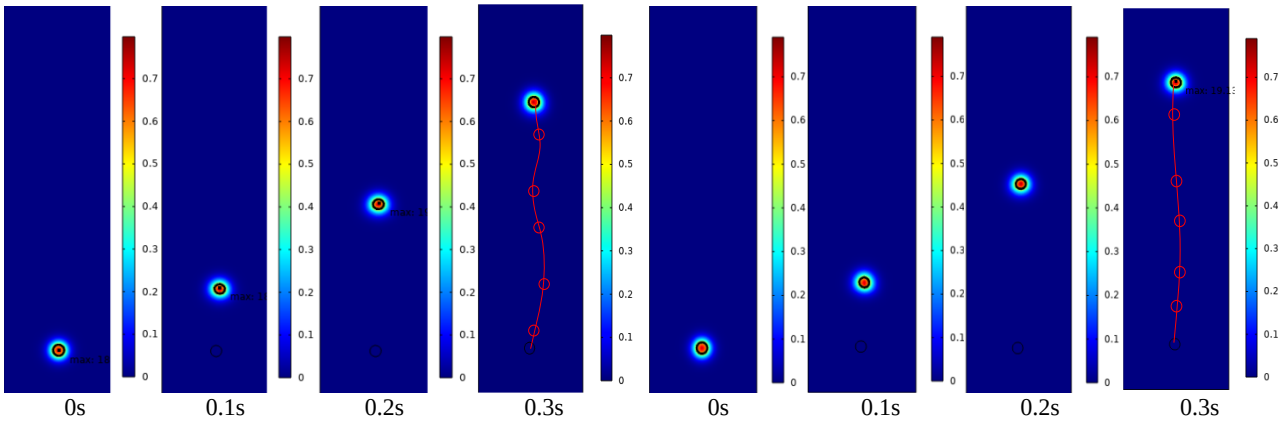


Figure 7. Horizontal oil channel mesh segmentation and boundary conditions

3.2. Simulation results and analysis

Based on the simulation model of bubble motion in the transformer's vertical and horizontal oil channels, the motion characteristics of bubbles along the oil channel in transformer oil with different bubble radius sizes, bubble numbers and flow rates are studied.

3.2.1. Vertical oil channel simulation results and analysis



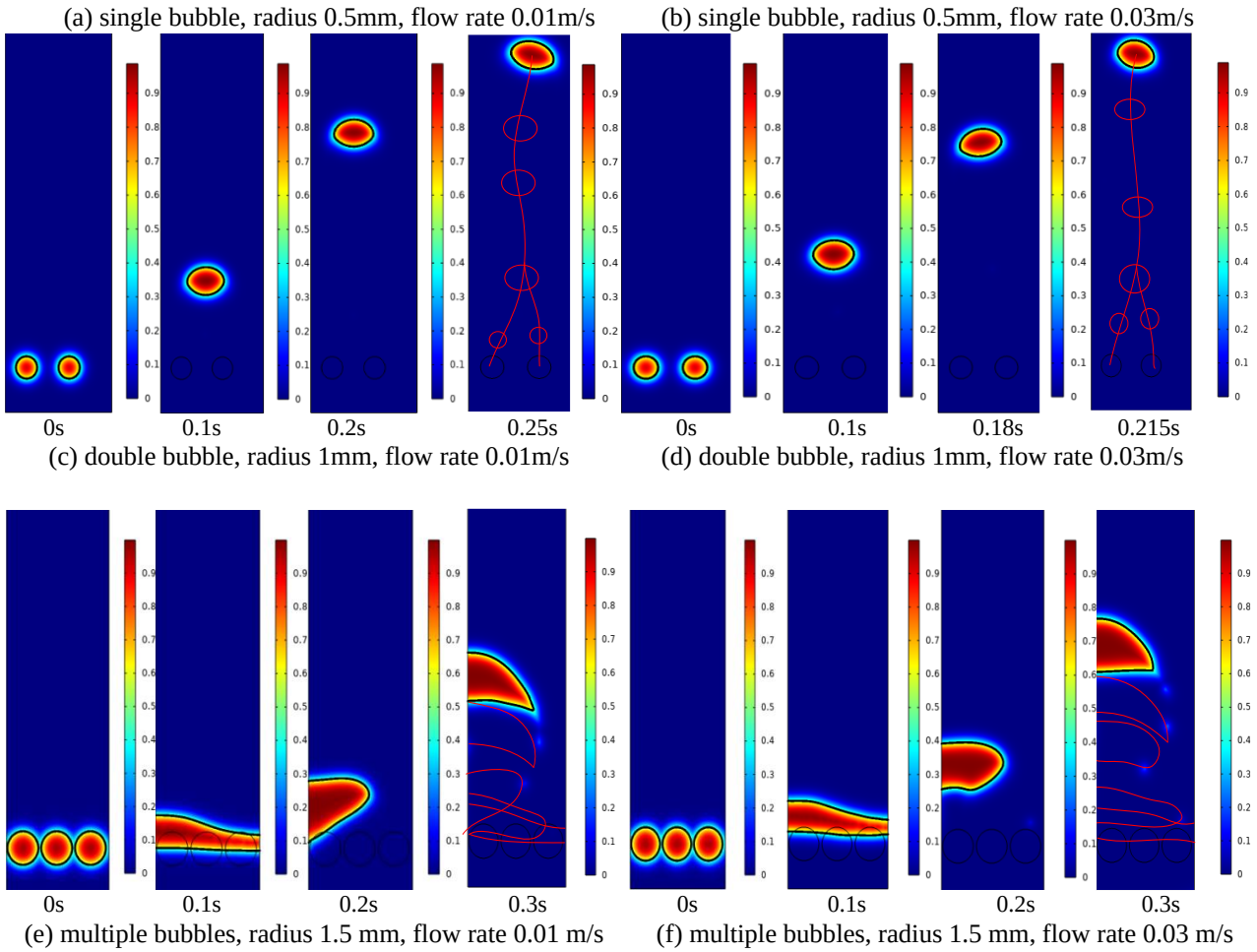


Figure 8. vertical oil channel simulation results

By comparing the bubble trajectories in the same radius and number of bubbles, it can be found that the flow velocity determines the distance of bubbles. The faster the flow rate, the higher the pressure difference between the upper and lower bubble interface and the more pronounced the bubble. Then compare the longitudinal bubble trajectories, the larger the bubble radius and the more bubbles at a specific flow rate, the more complicated the motion behavior and deformation.

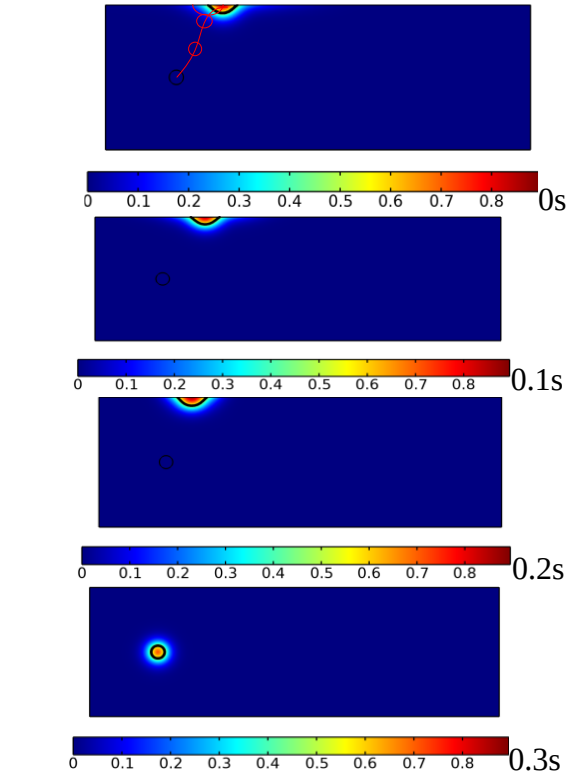
When it is a single bubble, the bubble's upward motion trajectory shows "s" type trajectory, and the faster the flow rate, the faster the bubble moves upward and the more pronounced the "s"-shaped path. When the radius is 0.5mm, the bubble deformation is not apparent during its upward movement along the vertical oil channel. When the bubble radius increases to 1.0mm or 1.5mm, the bubble will be stretched in the horizontal direction and become elliptical under the combined force of electric field force.

When it is a double bubble, in the bubble radius of 0.5mm, because the bubble radius is small and the initial bubble center position is 4mm apart, the two bubble rise trajectory does not interfere with each other, each with "s" route up. The deformation of each of the two bubbles is not apparent. When the bubble's radius becomes 1.0mm and 1.5mm, the two bubbles first synthesize into one bubble and then move upward. In the process of movement after synthesis by the electric field force and other combined forces of the bubble horizontal direction stretching, deformation of elliptical shape.

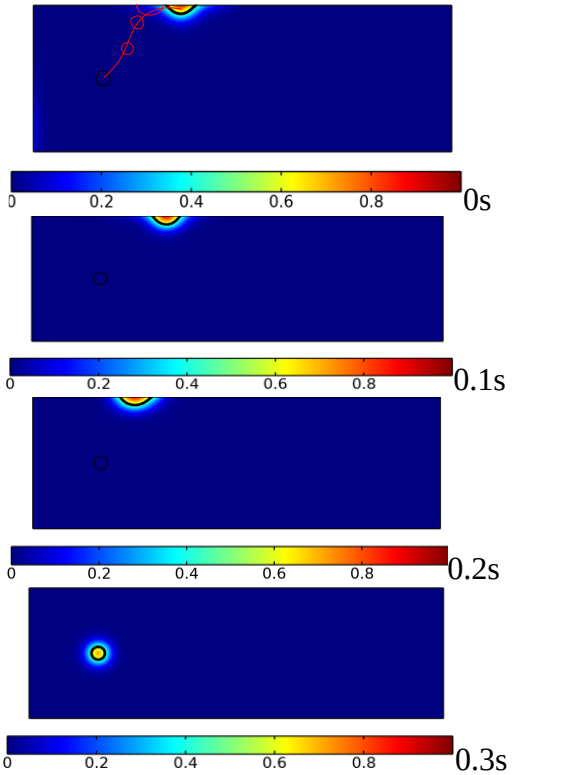
When it is multi-bubble, in the bubble radius of 0.5mm, three bubbles are first synthesized into one bubble and then rise in the horizontal direction with a stretched ellipse along the vertical oil channel. In the bubble radius of 1.0mm and 1.5mm, after the three bubbles are combined into one bubble, they move upward against the left oil channel wall. In the process of migration under the action of electric field force, the bubble interface stretched to the right, and due to the influence of surface tension, the bubble's right interface was stretched and then shrunk. Then because the bubble

is stretched by the pressure difference between the upper and lower interface and the electric field force, the bubble will repeat the deformation process.

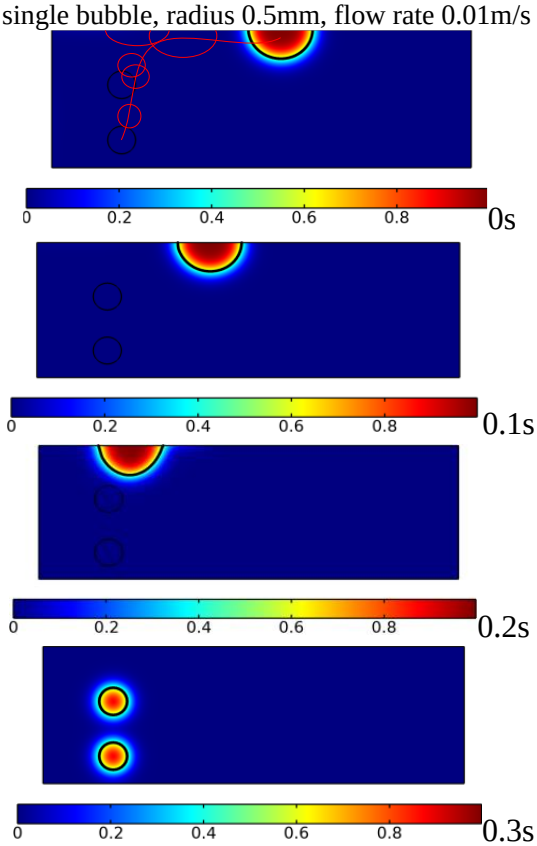
3.2.2. Horizontal oil channel simulation results and analysis



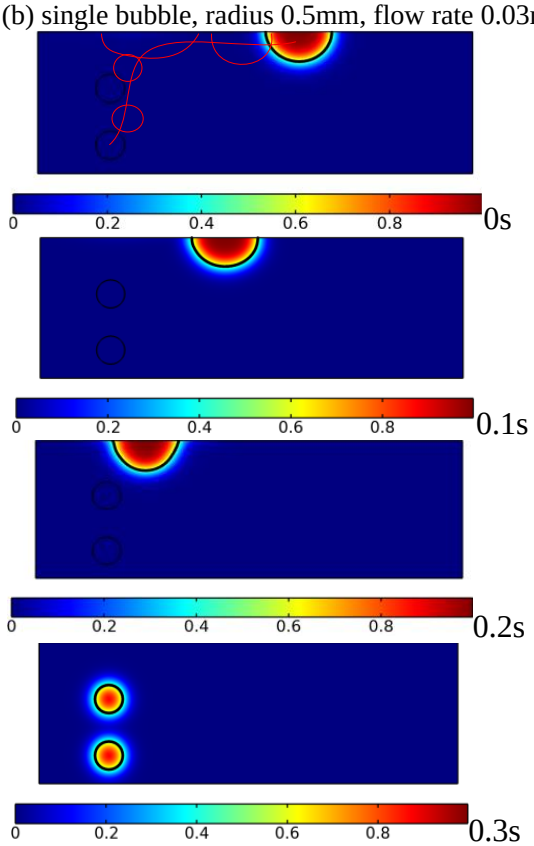
(a) single bubble, radius 0.5mm, flow rate 0.01m/s



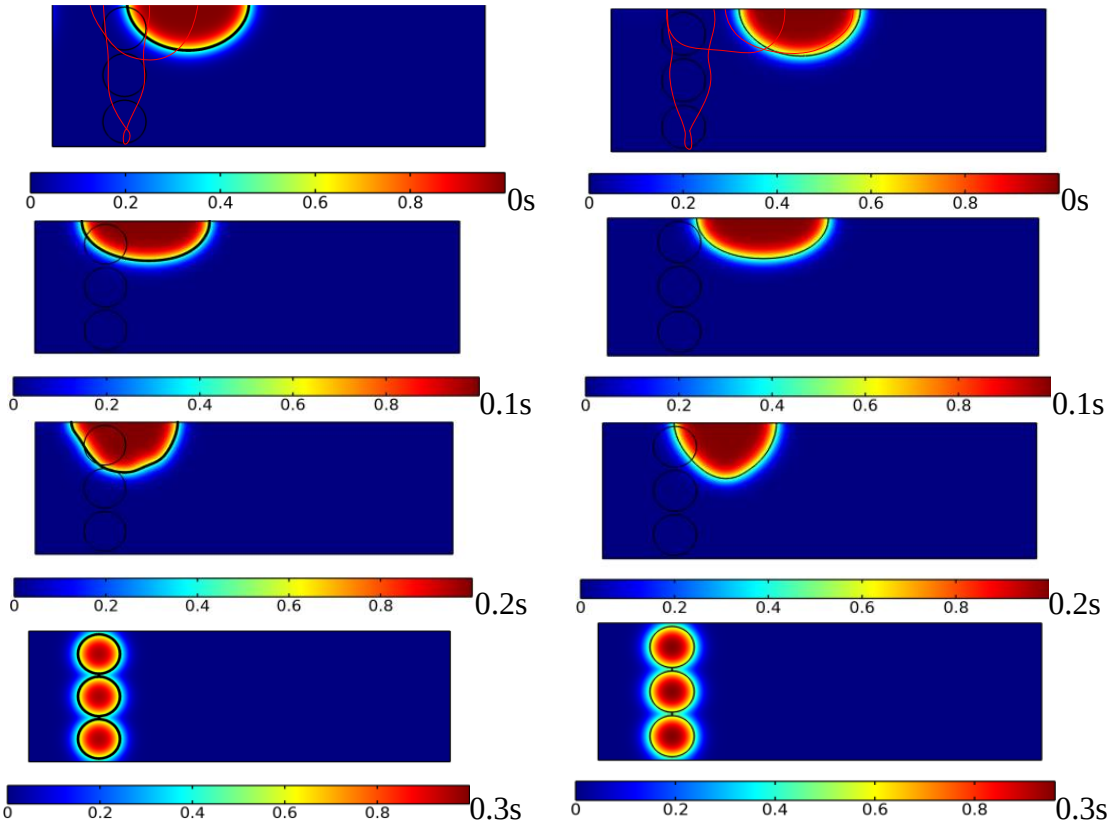
(b) single bubble, radius 0.5mm, flow rate 0.03m/s



(c) double bubble, radius 1.0mm, flow rate 0.01m/s



(d) double bubble, radius 1.0mm, flow rate 0.03m/s



(e) multiple bubbles, radius 1.5 mm, flow rate 0.01 m/s (f) multiple bubbles, radius 1.5 m, flow rate 0.03 m/s

Figure 9. horizontal oil channel simulation results

In the horizontal oil channel simulation, similar to the simulation results of the vertical oil channel, the horizontal comparison shows that when the bubble radius and the number of bubbles are sure, the flow rate determines the traverse distance of bubbles along the horizontal oil channel. The vertical comparison shows that when the flow rate is specific, the larger the bubble radius and the larger the number of bubbles, the more complicated the motion characteristics.

When it is a single bubble, it moves to the right along the oil channel with the flow rate and floats upward under the buoyancy force. When the bubble radius is 0.5mm and 1.0mm, the interface deformation is not apparent in the horizontal axis during the rising process because of the small bubble diameter.

When it is a double bubble, the two bubbles first move to the right under the action of the flow rate while floating upward by buoyancy, and the upper bubble first reaches the upper oil channel wall. Then the two bubbles are combined into one, moving slowly to the right against the upper oil channel. In the rising stage of the two bubbles, the bubble has a more obvious stretching deformation in the horizontal axis due to the electric field force. While the synthetic bubble is moving against the wall of the upper oil channel, the lower interface of the bubble is stretched downward by the electric field force, but due to the surface tension, the bubble interface contracts. Then this deformation process is repeated. However, when the bubble radius is 0.5 mm or 1.0 mm, the deformation repetition process is less evident due to the limitation of the bubble's radius.

When it is a multi-bubble, due to the close distance between the bubble circle center, Multiple bubbles are first combined into one bubble at the beginning and contracted upward to the oil channel wall under surface tension and buoyancy. At this time, when the bubble radius is 1.5 mm, the bubble radius is larger, so the repeated deformation process of the interface under the bubble is more obvious.

4. Conclusion

This paper presents a simulation study of the dynamics of bubbles in vertical and horizontal oil channels of transformers. Based on the level set method, the gas-liquid two-phase flow interface of

the suspended bubbles is traced and the flow, electrical and thermal multi-physical fields are coupled for the suspended bubbles in the transformer oil channel. The following conclusions are obtained:

(1) In the vertical oil channel, the upward suspension trajectory of the bubble shows an "s" shape, and the greater the flow velocity, the more pronounced the "s" trajectory. During the bubble motion, the bubble's interface stretches and deforms into an ellipse horizontally under laminar flow and electric field force. The surface tension contracts the bubble, and the deformation process is repeated. Moreover, the larger the bubble's radius, the more pronounced the repeated deformation process.

(2) In the horizontal oil channel, the bubble moves to the right at the initial stage by the effect of flow velocity and hangs upward under the action of buoyancy. It reaches the upper oil channel wall and then moves slowly along the flow velocity to the right, close to the oil channel wall. In the process of upward suspension, the bubble is stretched and deformed in the horizontal axis under the pressure difference between the upper and lower interface. After reaching the upper channel wall, similar to the bubble in the vertical channel, the bubble deformation process is repeated under electric field force and surface tension.

(3) In the electric field force, laminar flow and surface tension, the deformation in bubble suspension is a cyclic process. The larger the bubble's radius, the more pronounced the repeated process.

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