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Characterizations of air bubble movement in different transformer oil channel structures

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Abstract: *Due to the limited production technology and various external factors, there are impurities and suspended air bubbles in transformer oil, which can quickly form "small bridges" in the high field strength area and lead to transformer breakdown. This paper establishes a simulation model of gas-liquid two-phase flow under the coupling of electric-fluid-thermal multi-physical fields based on the level set method. The motion characteristics of bubbles are investigated under different flow rates, oil channels, and numbers of bubbles. The effects of single-bubble deformation and multi-bubble fusion on electric field distortion are analyzed with the bubbles' maximum field strength change curve. The results of the study show that the maximum internal field strength decreases when the bubbles in the horizontal and vertical oil channels are deformed in the direction of the electric field and increases when they are deformed in the direction perpendicular to the electric field, the greater the velocity of the oil flow the more severe the bubble deformation and the more serious the field distortion. In the case of dual oil channels, the maximum field strength inside the bubble depends mainly on the deformation of the bubble in the horizontal oil channel, and the fusion of multiple bubbles results in severe field distortion at the bubble intersection.*

Keywords: *Transformer; Oil insulation; Suspended air bubbles; Horizontal-vertical dual oil channel model*

1. Introduction

China proposes to build a clean, low-carbon, safe, and efficient modern energy system for the development of comprehensive energy. The development and construction of a new generation of power systems are major strategic support for the overall promotion of the energy revolution; transformers are the core components of the power system transmission and distribution and improve the quality of power transmission, its safe and stable operation is essential for the entire power grid[1];However, transformers are subjected to a combination of external factors during regular operation, such as overheating the oil paper, partial discharge in the oil paper insulation and other equipment failures[2]; At present, sizeable domestic power transformers are generally oil-immersed power transformers; the quality of its internal insulating oil is one of the factors that determine the insulation performance of the transformer, based on the current production process, in the production, transportation, operation process of the transformer will be more or fewer metal impurities and air bubbles and other non-metallic impurities exist in the transformer oil[3]. The suspension bubble in transformer oil is one of the critical non-metallic impurities affecting the insulation performance of transformer oil; because the suspension bubble dielectric strength is lower than that of transformer oil, the bubble in transformer oil is very easy to partial discharge when passing through high field strength area when its further evolution will make metal impurities and bubbles and other non-metallic impurities gather to form "small bridge", which will reduce the insulation performance of transformer [4].

Oommen[5]and Liu Yunpeng [6] et al. analyzed the process of bubble generation and its evolution, and the two established a mathematical and empirical formula capable of fitting the temperature of bubble evolution and a formula for calculating the radius during bubble warming by simulating experiments on bubble generation and studying the physical process of bubble generation. Cai Dan [7] and Liu Qiushi [8] have achieved bubble aggregation into bridges, and two scholars have proposed the cut-off zone and bubble pair clumping into bridges, respectively. Dan Cai from the National University of Defense Technology believes that bubbles gather along the cut-off line in the cut-off zone to form small bridges; Liu Qiushi from North China Electric Power University analyses that bubbles move directionally under the action of electric field forces and vibrations and that multiple bubble clumps will gather to form small bridges during the movement. Tang Ju[9] and R. Zhang [10] Professor Tang Torch's group studied the effect of flowing and fixed oil on the deformation and partial discharge of bubbles. The results showed that the horizontal deformation of bubbles in fixed oil is severe and causes significant electric field distortion, while the deformation rate and electric field distortion of bubbles in flowing oil is weakened by the electric and flowing fields, resulting in a reduced probability of partial discharge. Zhang Rui from Xi'an Jiao Tong University studied the dynamic behaviors of bubbles under the action of uniform and non-uniform electric fields. The results show that bubbles move towards the low field strength region under non-uniform electric fields and therefore have no significant effect on the insulation properties of the liquid. Still, the accumulation of surface charge of bubbles under uniform electric fields is one of the causal factors affecting the breakdown of the liquid. The theoretical mechanisms developed by the scholars mentioned above on the generation, deformation, aggregation, and trajectory of bubbles in horizontal oil channels are relatively well established, but few scholars have investigated the effect of vertical oil channels and the simultaneous presence of two types of oil channels on the movement characteristics of bubbles.

In summary, this paper establishes a simulation model of the gas-liquid two-phase flow of suspended bubbles under the coupling of electric-fluid-thermal multi-physical fields based on the horizontal set method and investigates the motion characteristics, deformation, and the effect of multi-bubble fusion phenomenon of bubbles in different flow rates and oil channels, and then explores its effect on the electric field distortion of transformer oil.

2. Theoretical Analysis of the kinematic properties of air bubbles in the oil

The suspended bubbles in the insulating oil of a transformer are one of the most important factors affecting its insulation performance. The bubbles in the oil show complex movement and partial discharge characteristics under the joint action of several physical fields.

2.1 Fundamentals of multi-physics field coupling

2.1.1 Electromagnetic field control equations

The main body of the transformer is the core and coil winding made of magnetic material. When the coil is energized, an electromagnetic field is generated around the winding, which affects the insulating properties of the insulating oil, mainly in terms of the movement characteristics of the bubbles in the insulating oil and the partial discharge characteristics. This paper gives Maxwell's equations according to electromagnetic field theory, as shown in equation (1).

$$\begin{cases}\nabla\cdot\mathbf{D}=\rho\\ \nabla\times\boldsymbol{E}=-\dfrac{\partial\boldsymbol{B}}{\partial\boldsymbol{t}}\\ \nabla\cdot\mathbf{B}=0\\ \nabla\times\boldsymbol{H}=\boldsymbol{J}+\dfrac{\partial\boldsymbol{D}}{\partial\boldsymbol{t}}\end{cases}\tag{1}$$

In the formula: $\boldsymbol{E}$ is the electric field strength; $\boldsymbol{D}$ is a potential shift; $\boldsymbol{H}$ is the magnetic field strength; $\boldsymbol{B}$ is the magnetic induction strength; $\boldsymbol{J}$ is the current density; r is the charge density.

2.1.2 Flow and temperature field control equations

The transformer in the normal operation process will produce no-load losses and load losses and other losses, the loss of heat generated through the oil circulation and transformer oil tank and heat sink thermal convection for heat dissipation, transformer oil in the flow process is regarded as incompressible mutually incompatible ideal fluid, this paper establishes the temperature - flow field coupling field under the Navier-Stokes set of equations, heat transfer control equations as shown in equations (2)-(6) [11].

$$\rho(\frac{\partial\boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u})=\boldsymbol{F}+\boldsymbol{F}_{\mathrm{st}}+\rho\boldsymbol{g}+\nabla\left[-p\boldsymbol{I}+\boldsymbol{K}\right]\tag{2}$$

$$\rho\nabla\cdot\boldsymbol{u}=0\tag{3}$$

ISSN 2706-655X Vol.5, Issue 7: 42-49, DOI: 10.25236/IJFET.2023.050707

$$\boldsymbol{K} = \mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) \tag{4}$$

In the formula: p is the fluid pressure; $\boldsymbol{I}$ is the unit tensor; $\boldsymbol{K}$ is the viscous shear stress tensor; $\boldsymbol{F}$ is the volume force on the bubble; $\boldsymbol{g}$ is the acceleration of gravity.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{u} \cdot \nabla T + \nabla \cdot q = Q + h(T_{ext} - T) \tag{5}$$

$$q = -k\nabla T \tag{6}$$

In the formula: C_p is the heat capacity of the fluid at constant pressure; T is the absolute temperature; q is the conduction heat flux; k is the thermal conductivity of the fluid; $\boldsymbol{u}$ is the fluid velocity field; Q is the heat source.

2.1.3 Basic Principles of current thermal coupling

The insulating oil system containing bubbles involves a multi-physical field coupling of an electric field - flow field - temperature field. The losses generated inside the transformer will cause the internal temperature to rise, and the temperature field will influence the dynamic viscosity of the flow field, which will affect the flow rate of the fluid, and the flow rate will further affect the heat dissipation generated by the transformer losses. Therefore, we establish a current-thermal coupling model to investigate the effect of electric field force, fluid traction, and surface tension on the bubbles in the vertical oil channel, and the electric field-temperature field-flow field coupling model of insulating oil containing bubbles constructed in this paper is shown in Figure 1.

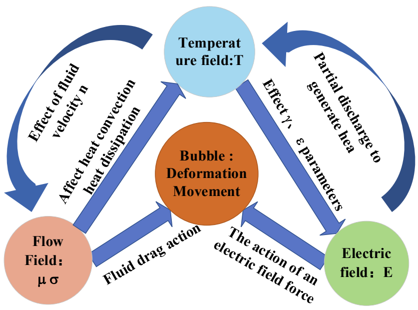


Figure 1: Coupled electric-temperature-flow field model for insulating oils containing air bubbles

2.2 Force analysis of bubbles in oil and mathematical model of their dynamics

2.2.1 Inconsistent capitalization of the forces on the bubble and its mathematical model

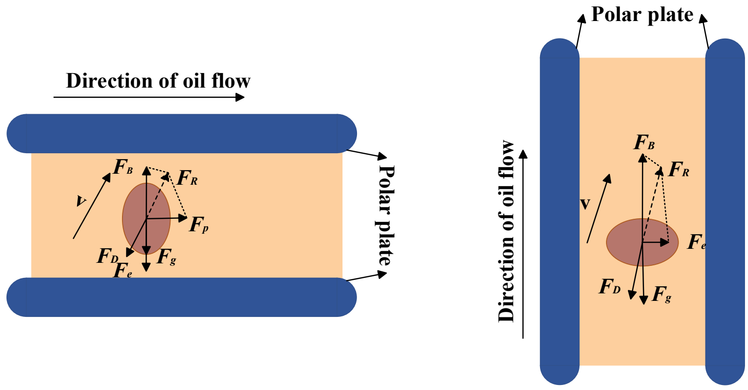
Bubbles in the insulating oil generate an electric charge on the surface due to polarization under an electric field; the surface charge generates an electric field force under the electric field $\boldsymbol{F_e}$. In addition to the fluid traction $\boldsymbol{F_D}$ of the fluid under the action of the flow field is also subject to buoyancy $\boldsymbol{F_B}$ and gravity $\boldsymbol{F_G}$. The combined force $\boldsymbol{F_R}$ of $\boldsymbol{F_e}$, $\boldsymbol{F_B}$, $\boldsymbol{F_G}$, and $\boldsymbol{F_D}$ mainly affects the trajectory of the air bubbles in the oil channel, Surface tension Fst keeps bubbles somewhat spherical. The surface tension of the force on the bubble $\boldsymbol{F_{st}}$,Fluid traction $\boldsymbol{F_D}$,Combined force $\boldsymbol{F_h}$ of buoyancy $\boldsymbol{F_B}$ and gravity $\boldsymbol{F_G}$,Electric field force $\boldsymbol{F_e}$,Oil pump thrust $\boldsymbol{F_p}$ The mathematical equation is shown in equation (7)[12][13].

$$\begin{cases} \boldsymbol{F}_{st} = -2\pi r_s \sigma \sin\theta \\ \boldsymbol{F}_D = -4\pi\mu r \boldsymbol{u} \\ \boldsymbol{F}_{\mathbf{h}} = \dfrac{4}{3}\pi r^3 (\rho_{oil} - \rho_{gas})\boldsymbol{g} \\ \boldsymbol{F}_e = \nabla \cdot \left[\boldsymbol{E}\boldsymbol{D}^{\mathrm{T}} - \dfrac{1}{2}(\boldsymbol{E}\cdot\boldsymbol{D})\boldsymbol{I} \right] \\ \boldsymbol{F_P} = P / \boldsymbol{u} \end{cases} \tag{7}$$

ISSN 2706-655X Vol.5, Issue 7: 42-49, DOI: 10.25236/IJFET.2023.050707

In the formula: r_s is the contact radius; s is the surface tension coefficient; q is the contact angle; r_{oil} is the transformer oil density; r_{gas} is the bubble density; P is the power of the submersible oil pump.

Individual bubbles will migrate and deform under the action of electric field forces and fluid drag, but in practice, bubbles have a complex distribution in oil. Multiple small bubbles may encounter each other during movement to form large bubbles, which may split under the action of oil dynamics to form two bubbles or break up to form small bubble clusters, mainly because the surface tension is not sufficient to maintain the spherical shape. Therefore, the movement of bubbles under different distributions, sizes, and electric field strengths is characterized by migration, deformation, aggregation, splitting, and rupture [11]. The force analysis of a single bubble in a horizontal and vertical oil channel is shown in Fig.2.



(a) Force analysis of air bubbles in horizontal oil channels (b) Force analysis of air bubbles in vertical oil channels

Figure 2: Force analysis of air bubbles in the oil channel

2.2.2 The level set approach to tracking fluid interfaces

The level set method is a numerical technique for capturing the interface of two incompatible fluids. The essence of the method is to use a zero-contour surface of one dimension higher than the target to partition the target boundary of one dimension lower, which has the advantage of low-latitude solid topological variability. This paper gives the density and viscosity equations for separating two-phase fluid interfaces under multi-physics field coupling, as shown in equations (8) (9).

$$\frac{\partial \phi}{\partial t} + \boldsymbol{u} \cdot \nabla \phi = \gamma \nabla \cdot (\zeta_{ls} \nabla \phi - \phi(1-\phi)\frac{\nabla \phi}{|\nabla \phi|}) \tag{8}$$

$$\begin{cases} \rho = \rho_{gas} + (\rho_{oil} - \rho_{gas})\phi \\ \mu = \mu_{gas} + (\mu_{oil} - \mu_{gas})\phi \end{cases} \tag{9}$$

In the formula: x_{ls} is an interface thickness control parameter used to control the thickness of the area where the level set function changes; g is the reinitialization parameter, which determines the total amount of reinitialization. Where the bubble-insulating oil intersection is represented by the level set function f=0.5, inside the bubble f=0, and in the insulating oil f=1.

3. Construction of the simulation model and Analysis of the results

Table 1: Bubble and transformer oil simulation parameter setting

Parameter properties	**Parameter values**	**Parameter properties**	**Parameter values**
The relative dielectric constant of bubbles	1	The relative dielectric constant of transformer oil	2.4
Bubble power viscosity	1.8e-5 Pa·s	Transformer oil power viscosity	0.0167 Pa·s
Air bubble density	1.2 kg·m^{-3}	Transformer oil density	875 kg·m^{-3}
Thermal conductivity of air bubbles	0.295 W·(m·K)$^{-1}$	Thermal conductivity of transformer oil	0.1065 W·(m·K)$^{-1}$
Surface tension coefficient	0.031 N·m^{-1}		

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Many factors influence the motion characteristics of bubbles in the oil. This paper mainly investigates how the oil flow rate, oil channel structure, and the number of bubbles affect the motion characteristics of bubbles, firstly, the effect of different oil channel structures such as horizontal oil channels, vertical oil channels, and horizontal-vertical double oil channels on the motion characteristics of bubbles is constructed respectively, and then the effect of oil flow rate and the number of bubbles on the motion characteristics of bubbles is further investigated. The simulation parameters of bubbles and transformer oil are shown in Table 1.

3.1 Movement characteristics of air bubbles in horizontal oil channel structures

In this paper, a horizontal transformer oil channel model was first constructed with a channel width of 20mm and a bubble diameter of 3mm. The movement characteristics of the bubble at different flow rates and its effect on the distortion of the field strength were investigated under the application of 15kV DC voltage, and the simulation results are shown in Figure 3.

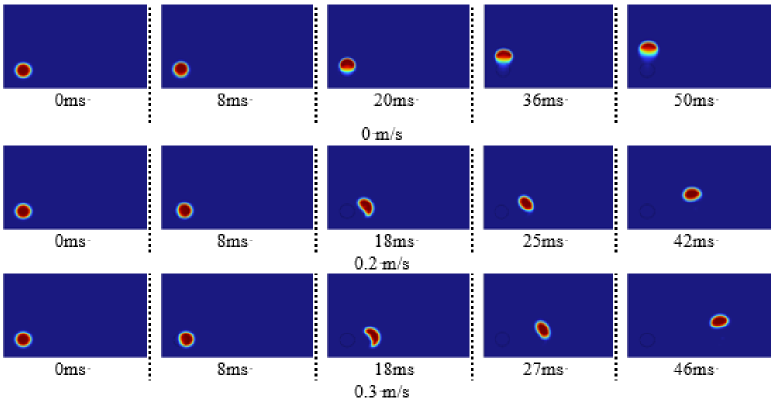

Figure 3: Bubble movement characteristics in horizontal oil channels at different oil flow rates

Figure 3 shows the bubble under different flow velocities; the bubble is stretched into a vertical ellipse along the electric field direction under the action of the electric field force. Then the bubble is squeezed in the horizontal direction around 18ms when the bubble deformation is most serious, in which the speed reaches 0.2m/s and above, the bubble is concave inwards, and the two sides are stretched in the horizontal direction in the shape of a cap, after which the bubble springs back into a vertical ellipse due to the increase of pressure inside the bubble. After 30ms, the bubble gradually changes from a vertical ellipse to a horizontal ellipse as it approaches the pole plate. The bubble gradually changes from a round to a vertical ellipse and then to a horizontal ellipse during the whole process; According to the curve of Fig.4, it is concluded that the maximum internal field strength decreases when the bubble is deformed along the electric field direction and increases when the bubble is deformed along the perpendicular electric field direction, the bubble gradually changes to horizontal ellipse when the flow velocity is 0m/s, so its maximum internal field strength is slowly increasing trend, while the bubble deformation becomes more serious when the flow velocity increases, it will be in The vertical ellipse and the cap-shaped bubble will change back and forth, the cap-shaped bubble due to the bubble tail inward concave, its concave will accumulate a large number of surface polarization charge resulting in severe field distortion, so its internal maximum field strength is oscillating trend, the greater the flow velocity oscillation more violent.

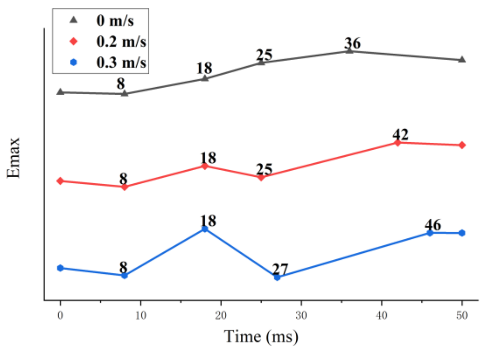

Figure 4: Variation curve of the maximum field strength Emax inside the bubble at different flow rates in the horizontal oil channel

ISSN 2706-655X Vol.5, Issue 7: 42-49, DOI: 10.25236/IJFET.2023.050707

3.2 Movement characteristics of air bubbles in vertical oil channel structures

In this paper, a vertical oil channel model of a transformer of the same size and voltage is constructed to investigate bubbles' motion and deformation characteristics at different flow rates and their effect on the distortion of field strength. The simulation results are shown in Fig.5.

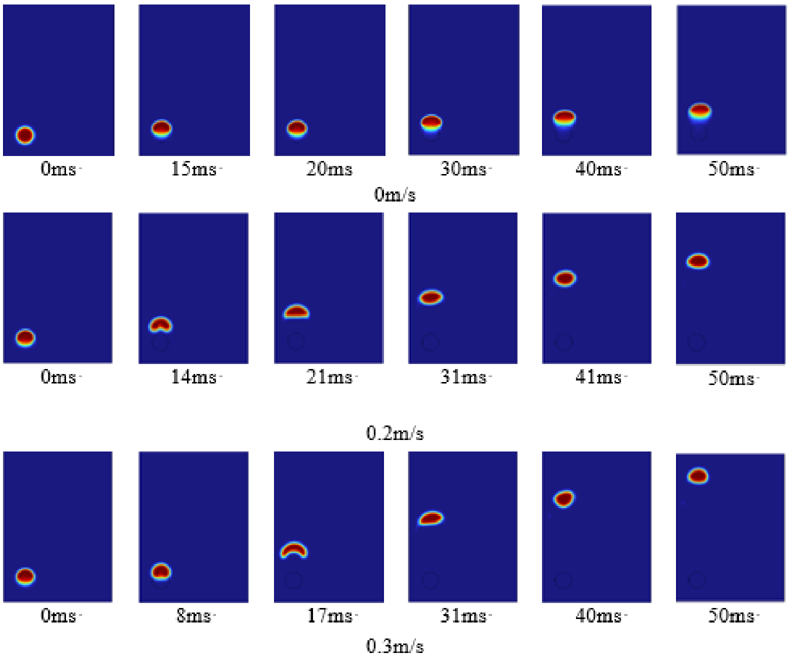

Figure 5: Bubble movement characteristics at different oil flow rates in vertical oil channels

Fig.5 shows that the bubble in the vertical oil channel is mainly presented as a horizontal ellipse under the joint action of electric field force and buoyancy; due to inertia, the bubble changes back and forth between the horizontal ellipse and cap shape and finally tends to horizontal ellipse in general. Combined with the curve in Fig.6, the same as the horizontal oil channel, the maximum internal field strength decreases when the bubble deforms along the electric field direction; the bubble gradually changes to a horizontal ellipse when the flow velocity is 0m/s, so its internal maximum field strength slowly decreases, while the bubble deformation is more serious when the flow velocity increases, it will change back and forth between the horizontal ellipse and the cap shape, and finally tends to the horizontal ellipse, so its internal maximum field strength is oscillating decreasing trend, the greater the flow velocity, the more violent the oscillation.

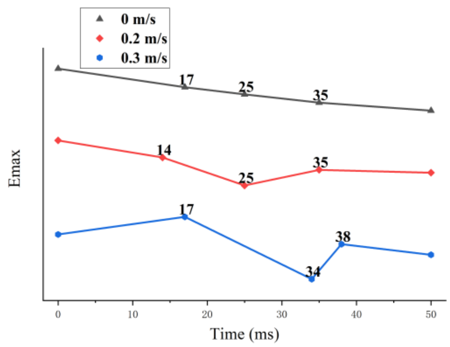

Figure 6: Variation curve of the maximum field strength Emax inside the bubble at different flow rates in the vertical oil channel

3.3 Influence of bubble movement characteristics in a horizontal-vertical dual oil channel structure

In practice, both vertical and horizontal oil channels exist simultaneously. In this paper, a dual oil channel structure model is constructed to investigate the effect of different numbers of bubbles on the motion characteristics of bubbles when both conditions exist simultaneously. The results of the dual oil channel model with different numbers of bubbles are shown in Fig.7.

ISSN 2706-655X Vol.5, Issue 7: 42-49, DOI: 10.25236/IJFET.2023.050707

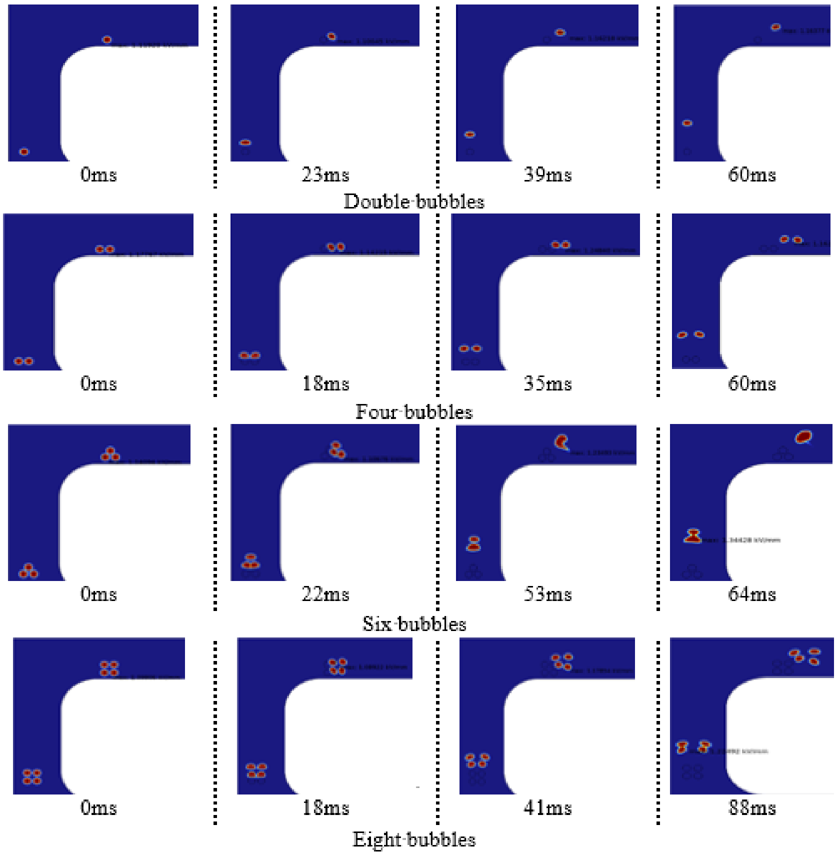

Figure 7: Bubble motion characteristics for different numbers of bubbles in a dual oil channel model

From Fig.7, in the two-bubble case, the horizontal and vertical oil channels are the same as those analyzed earlier, so we will not repeat them here. In the four-bubble case, even though the rear bubble in the horizontal channel is subject to the wake effect of the front bubble, bubble fusion does not occur due to bubble spacing and flow velocity. In contrast, the two bubbles in the vertical channel do spiral upward movement. In the case of six and eight bubbles, the wake effect intensifies, and multiple bubbles fuse. According to the curves in Fig.8, the bubbles will accumulate a large amount of surface charge on their contact surfaces during the process of approaching and completing the fusion, which will intensify the field distortion, and the field strength will decrease after the bubbles have completed the fusion to form large bubbles. Still, the bubble shape changes are complex, and when the distortion of large bubbles is severe, the uneven distribution of surface charge will quickly lead to electric field distortion. This paper concludes that when both vertical and horizontal oil channels are present, the maximum field strength lasts the longest in the horizontal channel, and the maximum field strength inside the bubble mainly depends on the degree of distortion of the bubble perpendicular to the electric field direction and the degree of its own distortion.

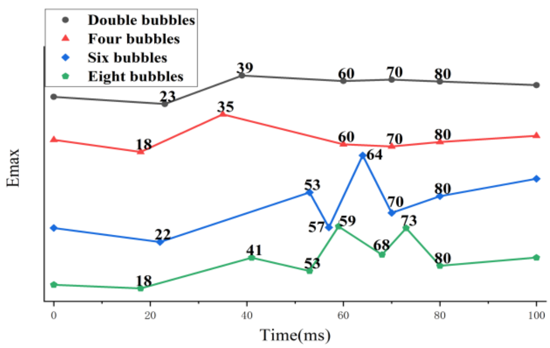

Figure 8: Variation of the maximum field strength Emax inside the bubble for different numbers of bubbles in the dual oil channel model

4. Conclusion

In this paper, a model of gas-liquid two-phase flow under the coupling of electric-fluid-thermal physical fields based on the level set method is constructed. The effect of single-bubble deformation and multi-bubble fusion on electric field distortion is analyzed in conjunction with the maximum field strength variation curve inside the bubble, and the following conclusions are obtained:

(1) The movement characteristics and deformation of the bubbles in the horizontal and vertical oil channels at different oil flow velocities are essentially the same, the maximum internal field strength decreases when the bubbles are deformed along the electric field direction and increases when the bubbles are deformed along the direction perpendicular to the electric field.

(2) In the case of dual oil channels, the maximum field strength inside the bubble depends mainly on the degree of bubble deformation in the horizontal oil channel, the bubble intersection of multiple bubbles in the process of fusion of severe field distortion, the greater the number of bubbles, the more likely to occur bubble fusion phenomenon and the fusion of the formation of large bubble deformation will also lead to field distortion.

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