Journal of Electrotechnology, Electrical Engineering and Management (2022)
Clausius Scientific Press, Canada
DOI: 10.23977/jeeem.2022.050207
ISSN 2560-6697 Vol. 5 Num. 2

Comparative Analysis of Simulation and Analysis of Bubble Motion Characteristics in Transformer Oil Based on Horizontal Set Method and Phase Field Method

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Keywords: Transformer, Insulating oil, Suspension bubble, Multiphysics, Bubble motion

Abstract: Large power transformer is the key equipment for realizing power energy transmission and voltage conversion in the power system, but in actual operation, its internal transformer oil is prone to cause partial discharge of suspended bubbles due to various factors, which endangers the safe operation of the transformer. Therefore, this paper conducts simulation research on the generation mechanism and motion law of suspended bubbles in transformer oil, first of all, based on Comsol simulation software, the motion model of suspended bubbles is constructed, considering the degree of distortion of bubbles and the regular characteristics of motion trajectories under different bubble number, initial position, size, and other influencing factors, and then comparing and analyzing the difference between the simulation results under the horizontal set method and the phase field method two interface tracking methods, and finally obtaining the multi-faceted motion mechanism of suspended bubbles in multiple physics.

1. Introduction

With the gradual expansion of the process of urbanization in China, the normal operation of the power grid has become one of the guarantees for social and economic operation. As shown in **FIG.1**. Among them, the transformer, as an important hub in the process of power transportation, often causes internal paralysis due to the PD phenomenon in the process of work, causing the country to suffer huge economic losses. Therefore, the analysis of the generation mechanism and source of suspended bubbles, the analysis and study of the gas-liquid two-phase flow interface tracking method, and the simulation and analysis of the motion characteristics of air bubbles in transformer oil under multiphysics coupling have become the top priorities. This project will start from the above three parts of the research content, explore the various mechanisms between bubble generation and motion, and provide guidance for the operation and maintenance process of transformers.

Figure 1: Schematic diagram of the transformer

In recent years, the research on suspended bubbles in transformers has mainly focused on the chemical composition analysis of bubbles, the motion state of bubbles inside the physics field, and the simulation analysis of multiphysics coupling. There is still a lack of systematic research on the mechanism of bubble generation. At present, for the study of suspended bubbles, scholars Xiao Chang, Xiao Fafu, and others point out that the bubbles in the two states of flow and rest should be studied separately and their influencing factors should be summarized. Finally, after a lot of experimentation, it was pointed out that the bubbles were at a stable peak at a temperature between 60 degrees and 70 degrees [1]; Meijer and other scholars have pointed out that the real hazard to the transformer is the bubble in a relatively stationary state by constructing a model of bubble discharge. In the use of transformers, electrons collide with liquid molecules to produce gases through dissociation [2]. Scholar Liu Zhiyuan pointed out that the flow rate and temperature of the insulating oil have an impact on the movement of the bubbles [3]. This is related to the fact that the internal environment of the transformer is coupled with multiple physics [4]. On the one hand, the transformer contains three kinds of physics current, heat, and electricity [5]; On the other hand, the bubbles are in an environment where gas-liquid two-phase flows [6]. In the environment of high temperature and high pressure, the transformer oil itself, as an organic matter extracted from petroleum, will produce decomposition and produce gas, of which the chemical bonds such as carbon-carbon single bond, carbon-carbon double bond, carbon-carbon triple bond are broken in the high-temperature environment [7], forming a gas generation method based on the substitution reaction, and exists in the form of bubbles in the insulating oil However, the above research is based on the condition that the transformer itself is an ideal model completely isolated from the outside world [8]; In the actual production and work links, the loss of the transformer also needs to be considered [9]; In addition, the simulation analysis of the coupling of the bubble itself and the multiphysics field and the interface tracking study of the gas-liquid two-phase flow is still in an incomplete stage [10].

The horizontal set method and phase field method modules provided by Comsol simulation software are built for the motion characteristics of suspended bubbles in the oil channel, providing a multi-physics coupled simulation environment to simulate the complexity of the transformer's internal environment as much as possible. In addition, the study of the motion characteristics of suspended bubbles can also provide practical application value for its engineering background. This adds a guarantee to the safety of the transformer.

2. Analysis of bubble generation mechanism and kinetic model

2.1. A brief description of the bubble generation mechanism and source analysis

Due to the complexity of the actual working conditions of the transformer, there are many sources of gas that form bubbles. Therefore, in the actual analysis process, the generation mechanism of air bubbles is classified and processed, and it is mainly divided into three categories. That is the introduction of external gases, the generation of internal gases, and the introduction of gases in engineering backgrounds.

The introduction of external gases: In the actual environment, due to the high strength and high duration of the transformer itself. The transformer will reduce its airtightness due to equipment aging, damage, and other reasons, which will lead to the introduction of external gases. Among them, the main reasons for the introduction of moisture are transformer maintenance, respiration, poor airtightness, and other reasons [9]; In addition, the harsh conditions of the external environment will also have an impact on the introduction of external gases. For example, in the southern region of China and some northeast regions, some transformers will be damp under the influence of long-term rainstorms, hail, and other rain and snow weather, and the inside of the transformer will be in a high-temperature and high-pressure environment for a long time, and the moisture introduced by moisture will enter the transformer oil in the form of bubbles and precipitate, resulting in the introduction of external gases.

Generation of internal gases: The internal gas generation mechanism of transformers is mainly the precipitation of gases by insulating oil in a multiphysics coupled environment. In the actual production and work process, the pressure-changing oil and some of its impurities will be heated and energized in the high temperature and high-pressure environment, resulting in decomposition, so that part of the gas precipitation [11]. The main characteristic gases in the suspended bubbles are carbon monoxide (CO), methane (CH_4), ethylene (C_2H_4), carbon dioxide (CO_2), hydrogen (H_2), and so on [7]. This is because the multiphysics will promote the free hydrogen atoms to have high activation energy with the free radical, making it easier for other groups to bind, resulting in a substitution reaction, resulting in a large number of their hydrocarbon bonds breaking to form synthetic hydrocarbon gases In addition, the electronic currency has a heating effect on the transformer oil, which leads to the generation of gas; Collisions between electrons and liquid molecules can also lead to dissociation to produce gases; In addition, in this extreme operating environment, the action of voltage leads to shock waves in the transformer oil, and the cavitation of the shock wave will also lead to the appearance of bubbles.

Gas introduction in the context of engineering: The current mechanism for the generation of suspended bubbles in transformers is established under the condition that the transformer itself is an ideal model completely isolated from the outside world; In the actual production and work links, due to engineering factors, the introduction of external gases in the transformer production link will also be caused. The first is because the insulating oil will cause the introduction of gas during the filling process; Secondly, because the surface of the electrode and transformer material is non-wetting material, this leads to a part of the very small bubbles adhering to the surface of the device when filling the insulating oil [4]. In the process of operation, this part of the bubble will precipitate with the increase of voltage and temperature and exist inside the transformer in the form of suspended bubbles.

2.2. Analysis of a mathematical model of bubble dynamic behavior

2.2.1. Mathematical model of temperature field and flow field of bubbles in transformer oil

For the bubbles, because the suspended bubbles move in the insulating oil, the internal temperature field of the transformer as a whole presents a heat transfer mechanism of heat convection. That is, inside a fluid with a certain flow rate, the heat transfer of the suspended bubbles is carried out through the flow of insulating oil.

Due to the presence of thermal convection, the local energy transfer of the insulating oil occurs, so the mathematical model inside the flow field relies on a generalized heat transfer equation to make the build. In addition, due to the conservation of energy in the system, the Navistax equation needs to be introduced to supplement it [12]. Namely:

$$\rho C_P \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q - \rho C_P u \cdot \nabla T + \tau : S + \frac{T}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \left(\frac{\partial P_a}{\partial t} + u \cdot \nabla p_a\right) \tag{1}$$

$$\rho \cdot C_P \left(\frac{\partial T}{\partial t} + (u \cdot \nabla) T\right) = -(\nabla \cdot q) + \tau : S - \frac{T}{\rho}\frac{\partial p}{\partial T}\Big|_p \left(\frac{\partial p}{\partial t} + (u \cdot \nabla) p\right) + Q \tag{2}$$

In the process of building the actual mathematical model, the equation is more complex and has many variables, which increases the difficulty of modeling. Therefore, the above formula can be combined and simplified:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u \cdot \nabla T + \nabla \cdot (-k\nabla T) = Q \tag{3}$$

After the formula is simplified, the temperature field is combined with the fluid field, so that the energy absorbed by the suspended bubble through thermal convection can be obtained by combining the material properties with the parameters in the velocity field; For the study of transients that occur in the context of multiphysics coupling, it can be seen that when a transient t=0 is analyzed, the immediate formula, the formula is continuously simplified to:

$$\rho C_P \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q \tag{4}$$

Through the simplification of the formula, the construction of the multiphysics coupled mathematical model can finally be achieved, and the expected research goal is achieved: that is, transient study and comparative analysis of suspended bubbles and their environments.

2.2.2. Force and motion trajectory analysis of air bubbles

Due to the complex operating conditions of the transformer, there are many sources of gas, and the phenomenon of breaking, aggregation, and distortion will occur between the bubbles, resulting in different chemical compositions and physical properties between the suspended bubbles. However, in the analysis of force and trajectory, the study of insulating oil can be emphasized. The mechanism of action between various forces is inferred from the distortion of the bubble and the trajectory of the movement.

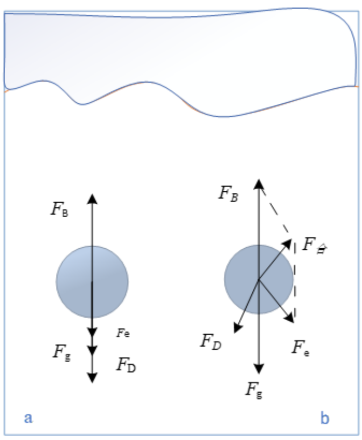

Figure 2: Schematic diagram of the force of suspended bubbles. (a) Vertical ascent phase (b) After the direction is changed

In oil-immersed electrical equipment, the forces that affect the motion characteristics of suspended bubbles are mainly the following four types, that is, electric field forces $\boldsymbol{F_e}$, buoyancy $\boldsymbol{F_b}$, Viscous resistanc $\boldsymbol{F_d}$ and gravity $\boldsymbol{F_g}$, In addition, the surface tension of the bubble itself makes the bubble in a steady state, prompting the surface of the bubble to shrink, so that the bubble remains spherical as much as possible, and its size is related to the temperature and the nature of the interfacial two-phase substance. The bubble force diagrams at different stages are shown in the following **FIG. 2** shown.

When analyzing suspended air bubbles, the size and direction of various forces should be considered first. Due to the complex internal environment of the transformer, the forces need to be analyzed in the context of coupling. According to the analysis, the core force causing bubble distortion and trajectory generation and change is the electric field force. Among the various forces of suspended bubbles, gravity and buoyancy can be analyzed as conservative forces in the oil channel, while viscous resistance is opposite to the direction of the combined force of the trajectory, so the electric field force should be analyzed.

$$\begin{cases} F_e = \nabla \cdot T - \varepsilon_0 \mu_0 \dfrac{\partial S}{\partial t} \\ F_g = mg \\ F_b = \rho g V \\ F_d = -4\pi \mu r v \\ F = ma \end{cases} \tag{5}$$

Which the analysis of the electric field shows that the influence of the electric field on the suspended bubble is realized by the electric field force Fe acting on the fluid unit at the interface of the gas-liquid two-phase flow, so it is necessary to introduce the Maxwell stress tensor to calculate the electric field force at the interface; the analysis of the bubble trajectory shows that because the bubble is in the environment of multiple force coupling, its trajectory needs to introduce Newton's second law and the decomposition of various Since the bubble is moving in the insulating oil, it needs to be calculated by the buoyancy formula; the bubble will also receive the viscous resistance of the insulating oil during its movement, and the viscous resistance also needs to be solved; the final trajectory of the bubble is determined by the coupling of various forces, so Newton's second law needs to be introduced in the force analysis process[13]. The force analysis for the suspended bubble is shown by Equation 5.

Therefore, the suspension bubbles are distorted under the coupling of various forces inside the insulating oil, and they are also moving in a reasonable direction. The direction of its force is the tangent direction of the trajectory.

3. Comparative analysis of simulation results

3.1. Comparative analysis of bubble distortion degree under different methods

Since the degree of distortion of suspended bubbles in the insulating oil can be reflected by the force at the gas-liquid two-phase flow interface, the stress on the surface of the suspended bubbles is simulated by two tracking methods and the results are compared, and the specific force characterization diagram is shown in **FIG 3** and **FIG 4**.

In the simulation process, it is considered that there are many possibilities for bubble distortion and that there is a phenomenon of mutual influence between bubbles. Therefore, when modeling, the suspension bubble is set to a circular bubble with a radius of 1.5mm, and the oil channel model with a height of 30mm and a width of 10mm is constructed to facilitate the observation of the motion characteristics of the bubbles. In addition, to simulate the complex working environment inside the transformer, the internal material is selected as the insulating oil, and the initial temperature is set to 333.15K; the internal gas of the bubble is selected as air, to reflect the main introduction of the gas and the composition [14].

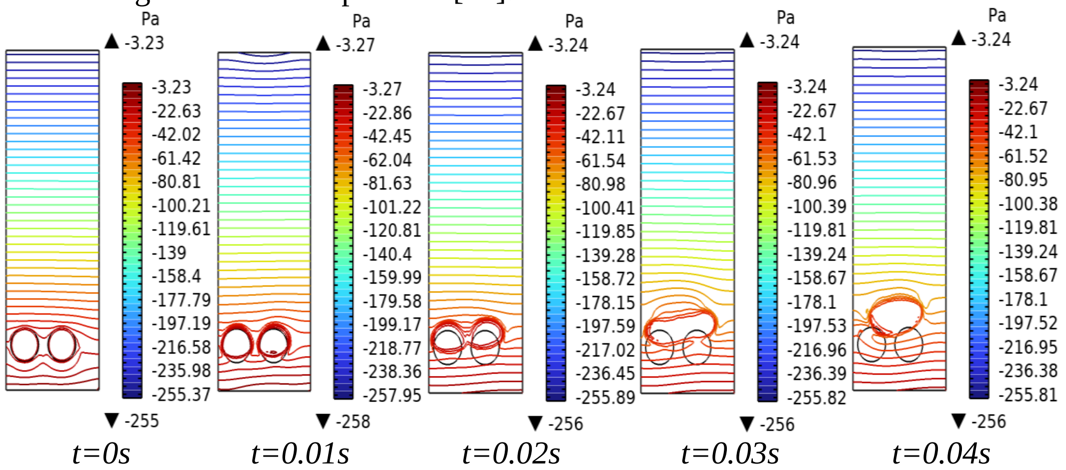

Figure 3: Phase field method simulates the force change of the surface of suspended bubbles

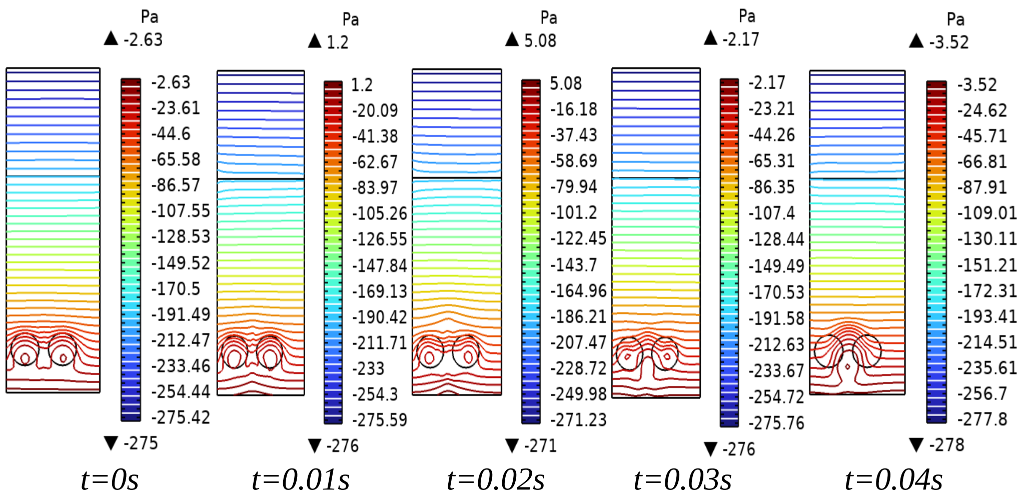

Figure 4: Horizontal set method simulates the change of force on the surface of suspended bubbles

Through the analysis and comparison of the results, it can be seen that both the phase field method and the horizontal set method can depict the phenomenon of fusion and fragmentation between the degree of distortion of suspended bubbles and the bubbles. Both analytical methods indicate that suspended bubbles gradually aggregate and fuse to form larger bubbles under multiphysics coupling conditions [15]. The principle of the transformer being broken down due to excessive PD phenomenon is explained.

When the bubbles occur in the phenomenon of distortion and aggregation, each suspended bubble will gradually flatten and gradually move closer to each other, and after the contact between the bubbles, the pressure on the bubble surface will have a tendency to decrease, so when the surface pressure of the bubble decreases or the fusion phenomenon ends, the bubble will have an upward floating and re-ellipsoidal bubble trend due to the increase in volume.

The analysis of the two tracking methods shows that the simulation accuracy of the phase field method is greater than that of the horizontal set method, which has a certain relationship with its calculation principle. In addition, due to the high simulation accuracy of the phase field method, the calculation amount is large and the simulation time is longe [16]; The phase field method can analyze the force analysis of the gas-liquid two-phase flow interface, but it cannot analyze the pressure of the gas inside the bubble; The horizontal set method can simulate the interaction between the distortion of the bubble surface and the bubble, and can also simulate the gas pressure inside the bubble. However, the horizontal set method does not accurately describe the interaction between bubbles, and cannot well express the state and change law of the interface between multiple bubbles.

3.2. Comparative analysis of bubble trajectory under different methods

Since the bubbles moving inside the insulating oil often face surface distortion, bubble fusion, force size change, and other influencing factors, in the model, construction to introduce two circular bubbles with a radius of 1.5mm in the oil channel model of 30mm high and 10mm wide, to observe the movement trajectory of the bubbles, the specific trajectory is characterized as **FIG 5** and **FIG 6**.

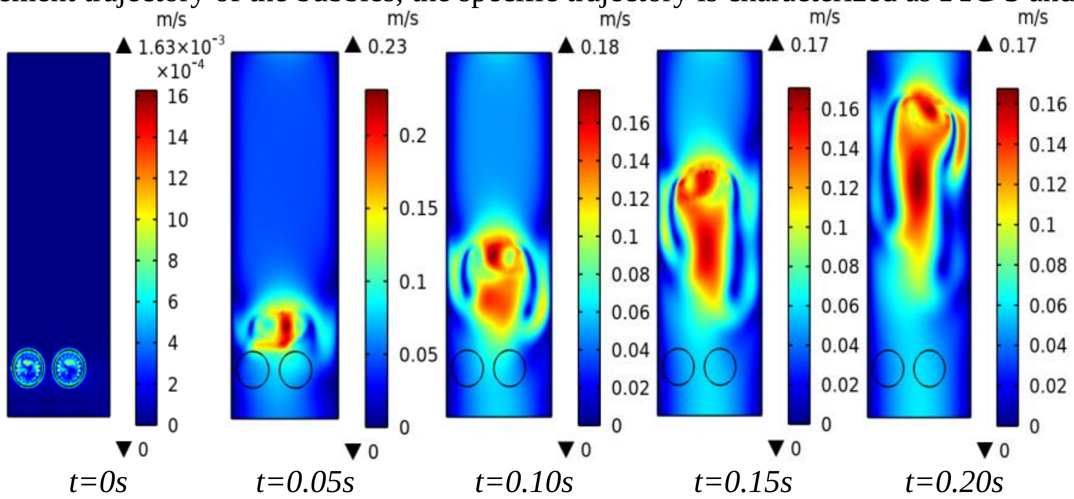

Figure 5: Phase field method simulates the change of the trajectory of suspended bubbles

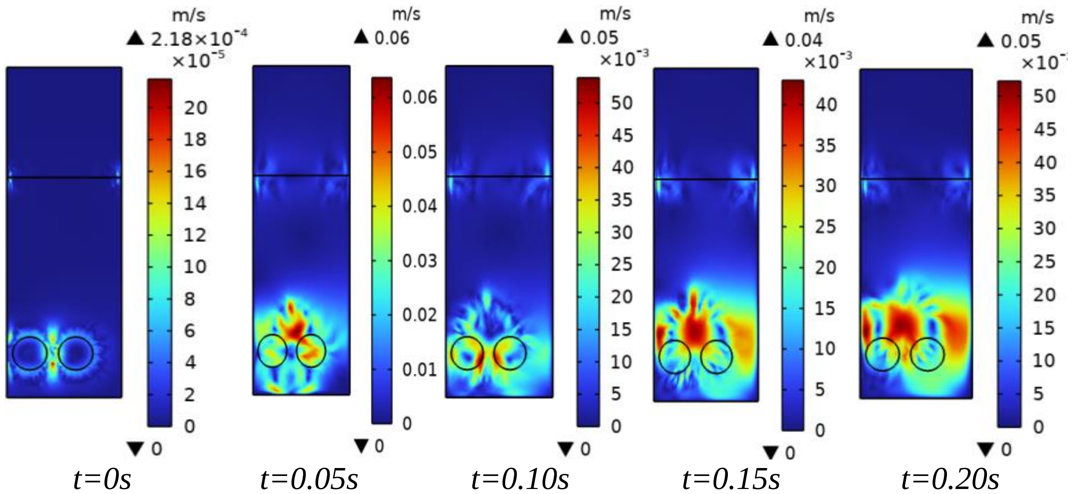

Figure 6: Horizontal set method simulates the change of floating bubble trajectory

Through the analysis of the simulation results, it is known that the bubbles also move to each other during the movement. For example, the fusion between air bubbles. In the process of movement, both tracking methods point out that the bubble as a whole shows the characteristics of accelerated motion during the floating process, and as the volume and speed increase at the same time, the bubble will gradually be elongated and lead to bubble analysis or breakage, and finally the bubble will escape from the interior of the insulating oil after accelerating the process of floating [13].

4. Conclusion

In this paper, using the internal suspension bubbles of the transformer as the background, the suspension bubbles are simulated and studied by two different tracking methods, and the motion characteristics are tried to analyze the motion characteristics and summarize the results of different tracking methods, and the following conclusions are mainly drawn:

(1) There are many internal gas generation mechanisms of the transformer, most of which are due to the introduction of the outside world, which is related to the defects of the special working environment and production process of the transformer; The force of the bubble inside the insulating oil is very complicated, but the force that causes the bubble to move is mainly the electric field force.

(2) The simulation accuracy of the phase field method is higher than that of the horizontal set method, but the simulation range is small and the simulation object is relatively single; The horizontal set method simulation accuracy is small, but the simulation object is more comprehensive, and the simulation of objects in different states can be simulated under specific motion characteristics, and the simulation processing at the junction of different objects is more blurred.

(3) During the movement of suspended bubbles, not only the bubbles themselves are in motion, but also the phenomenon of breaking, aggregation, and fusion between the bubbles will occur, and the two can be carried out at the same time.

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