Simulation Study on Motion of Metal Particles During Translation of Flat Plate Electrode

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Abstract A two-dimensional flat plate electrode advection model is established, and the SST k-ω turbulence model is selected to study the insulating oil motion according to the plate motion. The N-S equation of the impinging oil flow is constructed by the Eulerian method, and the kinetic equation of the metal particles is constructed by the Lagrangian method, and they are coupled by the interaction forces for the solid–liquid two-phase flow. The simulation is carried out to obtain the flow state of insulating oil when the flat plate is moving and the motion of metal particles under multiple forces. It has been found that during the translation of flat electrodes, the particles also develop a "small bridges", which may cause breakdown.

Keywords Turbulence · Solid–liquid two-phase flow · Metal particles

1 Introduction

In the process of high-voltage power transmission, the reliable operation of electrical equipment is the key to ensuring the safety of the power grid. Insulating oil, as the most commonly used liquid insulating medium in electrical equipment, closely

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influences the insulating performance of electrical equipment. Metal particles, as one of the most common impurities in the most insulating oil, can seriously reduce the quality of the insulating oil and damage the insulating properties of electrical equipment, bringing harm to the electrical equipment and the power grid. The main reason is that the movement and accumulation of metal particles with good electrical conductivity can cause distortions in the internal electric field of the equipment, triggering partial discharges or even breakdown [1]. The main sources of particles in insulating oils are external particles originally contained in the oil and internal particles generated by vibration and friction during the installation and maintenance of the equipment [2, 3]. Although the insulating oil is filtered before entering electrical equipment such as transformers to reduce the concentration of impurities in the oil, some metallic and non-metallic particles remain. It is mainly metal parts that vibrate and rub against each other inside the equipment, so the majority of particles are metal.

At present, domestic and international research on the motion of particles in insulating oils inside equipment has focused on the motion of particles in static or low-flowing insulating oils. For static insulating oil, S. Birlasekaran from Australia has studied the motion of metal spheres between parallel flat plate electrodes in a DC field [4], scholars from the University of Genoa, Italy have investigated the motion of metal particles between sphere-plane electrodes in DC and AC fields respectively [5, 6], while C. Choi and others have studied the motion of metal particles between flat plate electrodes in uniform and non-uniform electric fields [7], R. Sarathi of the Indian Institute of Technology studied the motion of metal particles between flat plate electrodes under composite voltages [8]. On the basis of this study, Wang Youyuan and others from Chongqing University in China studied the motion of metal particles between flat plate electrodes, needle-plate electrodes and double-ball electrodes at different ratios of composite voltages [9]. For insulating oil with low flow rate, Tang Ju et al. from Chongqing University investigated the motion of metal particles between flat plates under laminar flow of insulating oil with AC and DC electric field and AC-DC composite electric field [10–13]. Based on the existing research, it can be seen that for static insulating oil, the electric field plays a dominant role in the motion of the metal particles, including the electric field force effect on the charged metal particles and the dielectrophoretic force effect of the non-uniform electric field as the driving force of the particle motion, while the fluid traction force of the insulating oil on the particles is presented as resistance. For insulating oil flowing at low flow rates, as the direction of flow is generally perpendicular to the direction of the electric field, the forces on the metal particles in the electric field direction and the laws of motion are similar to those in the case of static insulating oil, while in the direction of insulating oil flow, the fluid provides the driving force for the particles and the particles move in the same direction as the fluid, with the final motion of the particles resulting from the superposition of the states in both directions.

In electrical equipment, however, in addition to static and low-flow laminar flow states, there is the possibility of turbulence in the insulating oil. In the case of an on-load tap-changer, for example, the contact movement, up to 5–8 m/s, during switching action results in a complex movement of metal particles under the action of the impinging oil flow and the electric field. In this paper, a simulation is carried out with a flat electrode model to study the movement of metal particles in this case. The simulation allows the motion of the metal particles to be digitized and facilitates the study of the internal motion mechanism and the external influences [14].

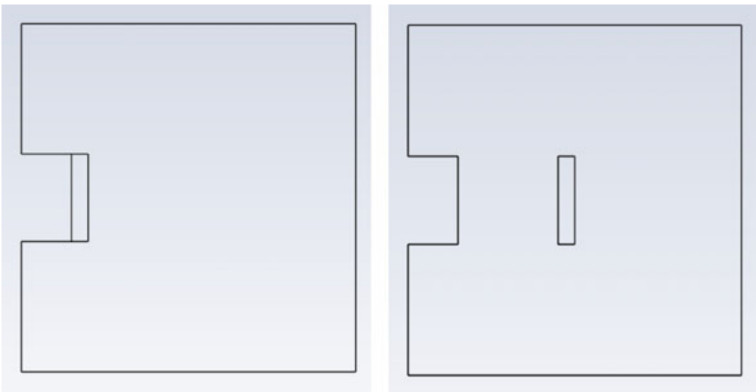
2 Simulation Model

In this paper, a two-dimensional simulation model is established using the translation of the flat plate electrodes to imitate the motion of the switch contacts. At the initial moment, the gap between the two flat plates is zero, and the flat plates are subjected to a uniform acceleration followed by a uniform deceleration with the same acceleration magnitude, and the motion lasts for 12 m illiseconds, resulting in a distance of 60 mm between the two flat plate electrodes (Fig. 1).

2.1 Insulation Oil Flow Model

The insulating oil, as a continuous phase, needs to be studied using the Eulerian method, and because of the fast movement of the switch contacts and the complex internal structure, the SST k-ω model is chosen to simulate the fluid motion. According to the Reynolds time-averaged equation:

$$v_0 = \overline{v_0} + v_0' \tag{1}$$



(a) Initial moment (b) Ending moment.

Fig. 1 Schematic diagram of flat plate flat motion the N-S equation of the turbulence model obtained is:

$$\rho\frac{\partial\overline{v_0}}{\partial t}+\rho(\overline{v_0}\cdot\nabla)\overline{v_0}=\rho g-\nabla\overline{p}+\mu\nabla^2\overline{v_0}+R+S \tag{2}$$

while the Reynolds stress is:

$$R=R(v_0') \tag{3}$$

where ρ is the fluid density, v_0 is the fluid velocity, p is the fluid pressure, R is the Reynolds stress, S is the external force.

2.2 Metal Particle Motion Mode

Since the concentration of metal particles in the insulating oil is small enough to be studied as a discrete phase, the Lagrangian method is used to analyze the forces on individual metal particles, and the kinetic equation of the particles during fluid motion is:

$$\frac{4}{3}\pi R^3\rho_p\frac{dv_p}{dt}=F_G+F_{Bu}+F_D+F_{Am}+F_{Mn}+F_{Sf}+F_p \tag{4}$$

where ρ_p, v_p and R are the density, velocity and radius of the particle, F_G, F_{Bu}, F_D, F_{Am}, F_{Mn}, F_{Sf}, F_p are the gravitational force, buoyancy force, fluid drag force, virtual mass force, Magnus lift force, Saffman force and pressure gradient force on the particle.

Besides, since it is a flat plate electrode, it can be considered as a uniform electric field in the middle, so the dielectric swimming force is not considered. And for the charged particles, the electric field force is:

$$F_E=Eq \tag{5}$$

The charge of charged metal particles comes from the charge transfer when the metal particles collide with the electrode and the value is:

$$q=\frac{2\pi^3\varepsilon R^2E_0}{3} \tag{6}$$

Then the kinetic equation of the charged metal particles is:

$$\frac{4}{3}\pi R^3\rho_p\frac{dv_p}{dt}=F_G+F_{Bu}+F_D+F_{Am}+F_{Mn}+F_{Sf}+F_p+F_E \tag{7}$$

2.3 Solid–liquid Two-Phase Flow Model

The motion model of metal particles in insulating oil can be studied by the solid–liquid two-phase flow model. The external forces S on the insulating oil in Eq. (2) are the force of the moving flat plate and the reaction force of the metal particles on the fluid, whose magnitude is related to the velocity of the metal particles; the external forces F_D, F_{Am}, F_{Mn}, F_{Sf}, F_p on the metal particles in Eq. (4) are related to the fluid velocity of the insulating oil. Thus the solid and liquid phases are coupled by interaction forces and the results are presented by the velocity.

3 Simulation Results

Ansys Fluent was used to simulate the motion of metal particles subjected to both fluid forces and electric field forces when a flat plate electrode is translating.

3.1 Simulation Results of Fluid Motion

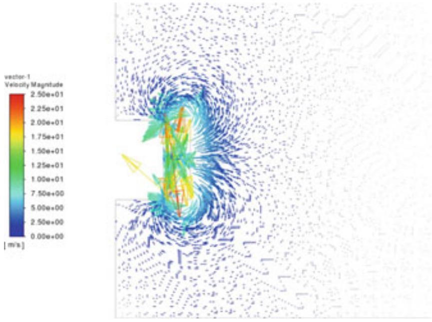
The motion of the flat plate was carried out for 12 ms and the simulation lasted 20ms, with a uniform acceleration followed by a uniform deceleration of the same magnitude, and the results were selected for analysis at 3, 6, 9, 12, 15 and 18 ms (Fig. 2).

From the velocity vector diagram of the insulating oil fluid, it can be seen that during the motion of the flat plate, the motion of both sides of the middle axis of the plate is symmetrical, and the insulating oil shows the motion of vortex. In the initial stage of movement, the gap between the flat plate is small, only a symmetrical pair of vortex, with the expansion of the gap between the flat plate, a new pair of vortex on one side of the stationary plate in the opposite direction to the original vortex.

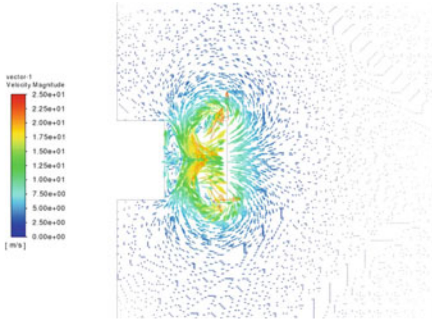
3.2 Simulation Results of Metal Particles Motion

Similarly the positions of the metal particles at 3, 6, 9, 12, 15 and 18 ms were selected for analysis (Fig. 3).

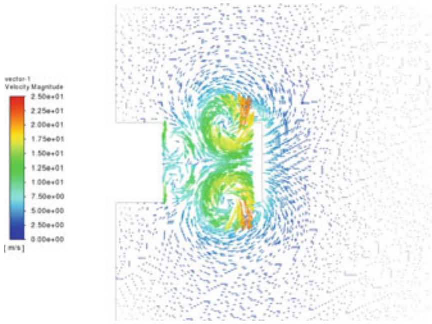
As can be seen from the trajectory of the metal particles, the direction of motion of the metal particles is essentially the same as the direction of velocity of the fluid, so initially, the metal particles enter the inter-plate gap from the side close to the stationary plate. As the motion of the fluid is symmetrical about the central axis, the velocities in the vertical direction are of the same magnitude and in opposite directions at the central position, while in the horizontal direction the velocities are



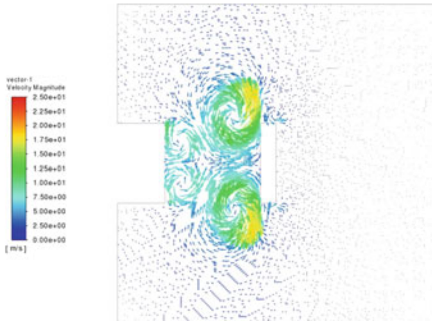
(a) 3ms



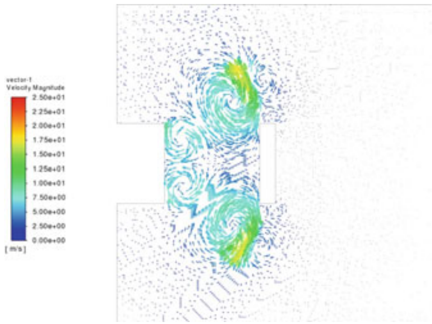
(b) 6ms



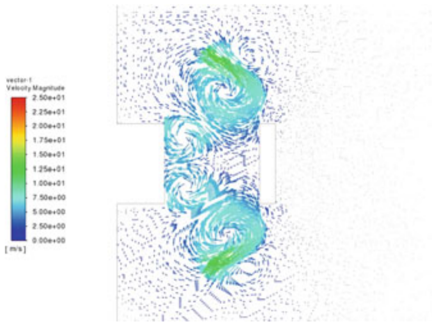
(c) 9ms



(d) 12ms



(e) 15ms



(f) 18ms

Fig. 2 Fluid velocity vector diagram

of the same magnitude and in the same direction. The metal particles therefore create a 'bridge' of particles at the central axis. As the velocity of the metal particles is much less than the fluid velocity, the 'bridge' of metal particles does not cross the gap until after the plate has finished moving.

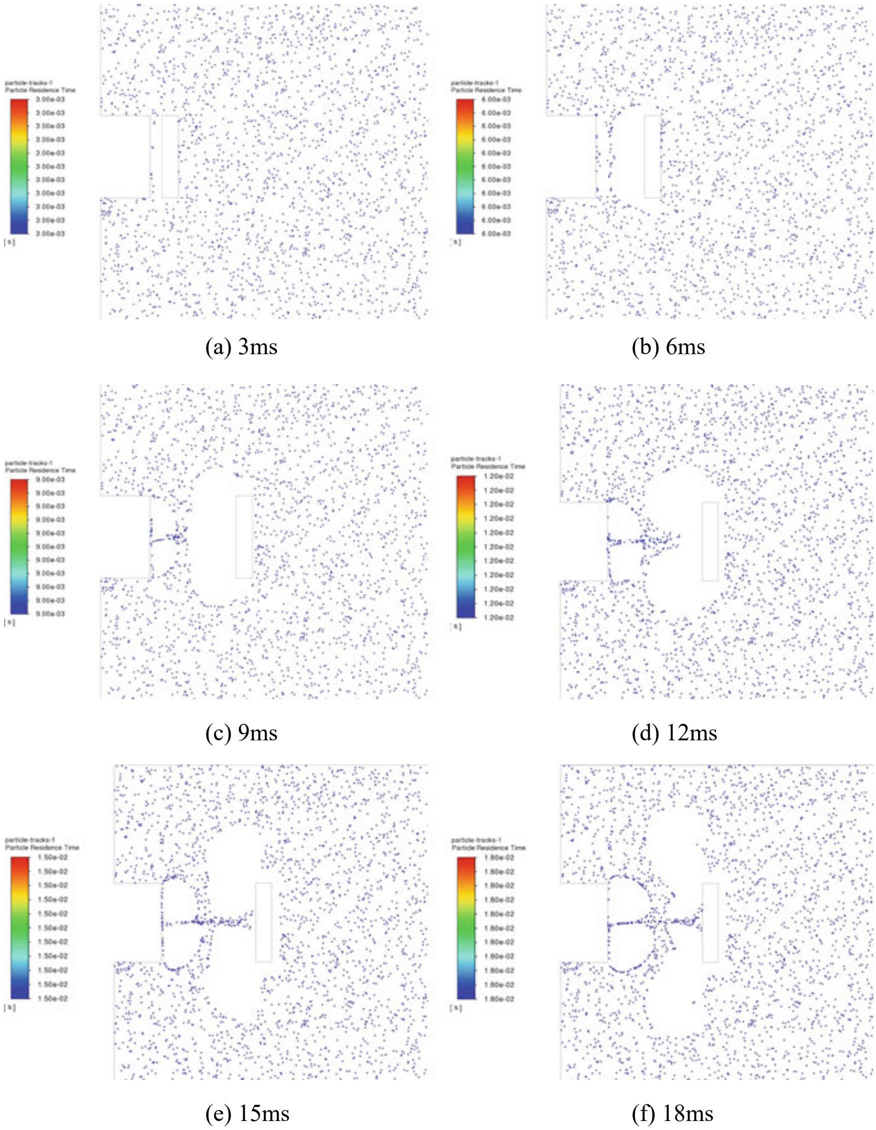


Fig. 3 Metal particle trajectory

4 Conclusion

In this paper, the motion of metal particles in the turbulent state of insulating oil is investigated by constructing a two-dimensional flat plate electrode translation model. According to the solid–liquid two-phase flow, the Eulerian method is used to describe the continuous-phase insulating oil and the Lagrangian method to describe the discrete metal particles, and the kinetic equations are constructed respectively and coupled. The velocity distribution of the insulating oil and the trajectory of the metal particles are obtained by simulation when the flat plate is moving, and it is found that the metal particles form a "small bridge" under the influence of fluid.

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