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Variation of Discharge Characteristics With Temperature in Moving Transformer Oil Contaminated by Metallic Particles

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ABSTRACT During the operation of power transformers, the insulating oil is actually in a moving state due to the effects of various cooling systems. Therefore, the investigation on insulation characters of moving transformer oil is necessary. In this paper, the influences of temperature on partial discharge (PD) and breakdown characteristics of moving transformer oil contaminated by metallic particles were experimentally studied at first. It was found that the PD magnitude and frequency first decreased and then became higher when the temperature increased from 40 °C to 80 °C, and a minimum point appeared between 70 °C and 80 °C. On the contrary, the dependence of breakdown voltage on temperature showed an opposite tendency. In order to explain the experimental results, a simulation model involving multiple forces was constructed to obtain the movement trajectory of particles. The increase of oil temperature leaded to the decrease of dynamic viscosity of transformer oil, so the forces acting on particles and their movement characters changed. As the temperature increased, the collision frequency between particles and electrodes first decreased and then became higher, and there was a minimum point between 70 °C and 80 °C. This changing tendency was in accordance with the dependence of PD parameters on the oil temperature. In terms of the above results, the effects of temperature on PD frequency and breakdown voltage were discussed.

INDEX TERMS Temperature, partial discharge, breakdown, moving transformer oil, metallic particles.

I. INTRODUCTION

Power transformers, serve as an electrical energy transfer device, play an extremely important role in power system. Hence, their safety operation is crucial to the power network. In fact, the reliability of transformers is mainly determined by its insulating components. It has been found that a lot of transformer failures result from insulation failures [1].

At present, mineral oil impregnated paper is widely used in transformers as insulating mediums [2], [3]. The former serves not only as an electrical insulation but also as a coolant. However, it is often contaminated by gas bubbles [4], fibers [5], [6] and metallic particles [7] during the processes of manufacturing, installing, operation and maintaining. These particles may lead to the local electric field distortion and induce partial discharges (PDs), which deteriorate the insulation performance of the whole device and even cause transformer failures. Moreover, it was found that the metallic particles had much more threat to transformer insulation in comparison with the others [8].

As for the effect of metallic particles on insulation performance of transformer oil, many efforts have been paid. Tobazéon [9] constructed a simulation model with regard to the conducting particle movement in insulating oil. In terms of simulations and experiments, the dependence of current pulse waveform on it was investigated. It was found that when a particle approached an electrode with opposite polarity, a steep pulse would appear. Li *et al.* [10] studied PD characteristics in transformer oil in the presence of metallic particles. As the voltage amplitude increased, the moving trajectory of particles changed, leading to the variation of PD pattern. Wang *et al.* [11] simulated the movement path of conducting particles in transformer oil at the combined

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voltage of AC and DC. It was found that particles easily collided with electrodes as DC component increased, and the breakdown voltage became lower. Carraz *et al.* [8] compared the breakdown voltage of transformer oil contaminated by metallic particles under impulse and AC voltage. When the particles were fixed, impulse breakdown voltage was much higher than AC one with free particles. Based on the results, it was inferred that the breakdown may result from a micro-discharge between particles and electrodes.

In summary, the above researches indicate that the PD and breakdown characteristics of insulating oil in the presence of metallic particles depend on their movement. If the moving trajectories of particles change, these characteristics will correspondingly vary. However, in the above researches, the insulating oil was assumed to keep stationary. Actually, due to the effects of various cooling systems, transformer oil is actually in a flow state. In this case, the movement behavior of metallic particles is different from that when the oil keeps static, leading to the change of PD and breakdown characteristics.

In recent years, several researchers realized this fact. Li *et al.* [12] investigated the influences of temperature and oil flow speed on PD properties in the transformer oil, which were induced by metallic particles, bubbles and metal intrusion. But, because of the lack of particle movement analysis, the discharge mechanism still kept confused. Our research team constructed a simulation model by considering multiple forces acting on particles [13], [14]. With the help of it, their moving trajectories in flow transformer oil were investigated, and the discharge characteristics were explained.

Due to the load fluctuation or overheating fault, the oil in field transformers may be at different temperatures. As its dynamic viscosity depends on temperature, the forces acting on particles will show distinct, leading to a change of insulation characters. In this paper, the influence of temperature on PD parameters and breakdown voltage of moving transformer oil in the presence of metallic particles was firstly investigated. Then, a simulation model was constructed to obtain moving characters of particles at different temperatures. In term of these, the experimental results were discussed.

II. EXPERIMENTAL SETUP

An experimental platform was constructed to simulate the oil circulation in transformers, as Fig. 1. An oil pump was used to force oil flow, and the flow rate was measured by an ultrasonic flowmeter. The mineral oil was heated by a heater, and the temperature was detected by a temperature sensor. A PID controller was employed to regulate the heater so that a setting temperature could be reached. In the main oil channel, two parallel plate electrodes were placed with a distance of 10 mm. Both plates were in the shape of cylinder and made of brass, with a radius of 100 mm and a thickness of 10 mm. Besides, a corrugated pipe was used to connect oil channels, which reduced the risk of channel rupture as oil temperature varied.

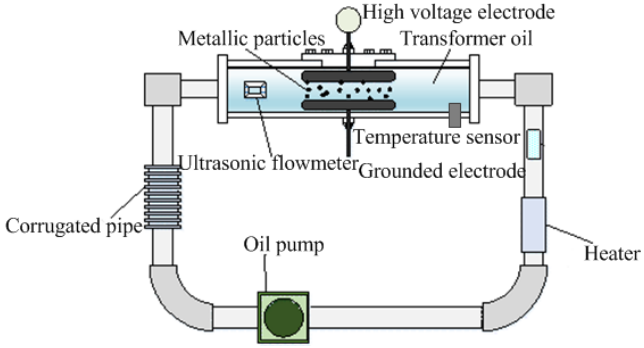

FIGURE 1. Oil circulation setup.

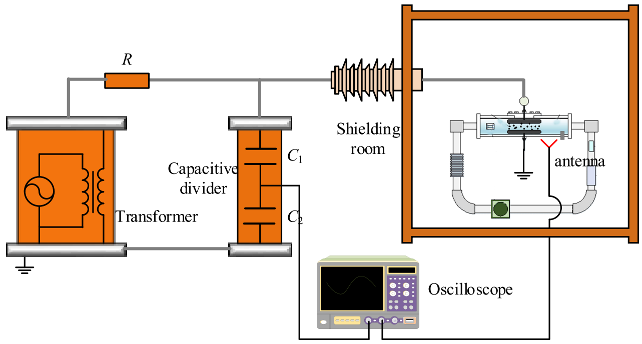

FIGURE 2. PD measurement system.

Fig. 2 shows an experimental system about PD measurement. The oil circulation setup was placed in a shielding room so that the electromagnetic interference from external environment could be eliminated. A micro-strip patch antenna, with an effective working bandwidth of 340∼440 MHz and a central frequency of 390 MHz, was employed to obtain ultra-high frequency (UHF) signals of PD, which were collected by an oscilloscope (Tektronix DPO7104). R equal to 10 kΩ served as a protection resistor. C_1, with value of 1000 pF, was the high voltage component of a capacitance divider, whereas C_2 equal to 1.005 μF, was the low voltage component.

Before each test, the mineral oil (Karamay #25) was carefully degased and dried. After the channel was filled with oil in the presence of particles, the pump began to work for a long period so that the particles dispersed uniformly. Meanwhile, the heater regulated the oil temperature towards a setting value. Then PD and breakdown experiments were conducted.

As for power transformers in operation, the maximum diameter of particles could exceed 100 μm within natural contamination oils [7], [15]. Large particles usually pose a more serious threat to oil insulation than smaller ones, so the diameter of particles was set to be 150 μm. Moreover, particles larger than 100 μm in diameter could exceed 1000 per liter (about 10^{-2} g/L) within contamination transformer oil [7], [15], [16]. We added 1.0 g particles into one liter oil, and the concentration was actually in the magnitude level of 10^{-2} g/L across parallel electrodes after a long period of circulation. Besides, the oil flow rate was set to be 0.3 m/s, because the maximum rate generally does not exceed 0.5 m/s

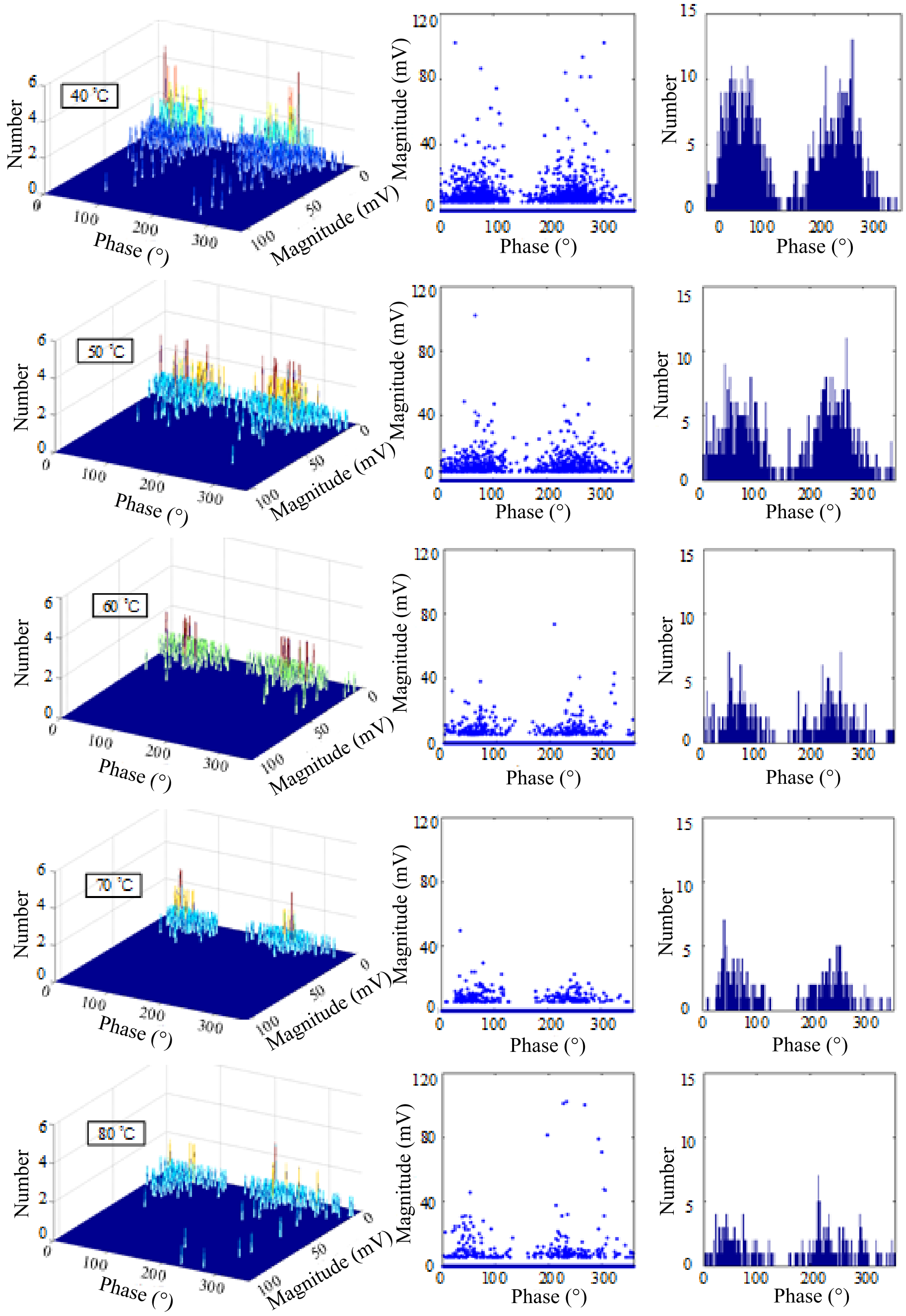

FIGURE 3. **PD patterns at different temperatures.**

in power transformers [7]. During the experiments, the oil temperature could range from 40 °C to 80 °C.

III. EXPERIMENTAL RESULTS

A. PD CHARACTERISTICS

The partial discharge inception voltage (PDIV) was firstly measured, and it was always below 13.5 kV when the oil temperature varied, so an AC voltage with a peak value of 15 kV and frequency of 50 Hz was applied to the high-voltage electrode to ensure the occurrence of PD. The sampling rate of oscilloscope was set to be 100 MS/s in order to obtain UHF signals. Due to the limitation of memory size, PD parameters during 50 continuous cycles were recorded, as Fig. 3. Here, $\varphi - q - n$, $\varphi - q$, $\varphi - n$ (φ discharge phase, q discharge magnitude, n discharge number) patterns were presented.

It was found from the results that the PD magnitude, as well as the PD number, tended to decrease as the temperature became higher. Besides, discharges easily took place at the peak value of applied voltage, i.e. at 90° and 270°. Moreover, in order to clearly analyze the effect of temperature variation on PD parameters, the changing tendencies of PD magnitude, PD frequency with temperature are depicted according to PD patterns, as Fig. 4. The average PD magnitude firstly decreased and then increased when the temperature ranged from 40 °C to 80 °C. As for the change of discharge frequency with temperature, a similar tendency was observed, and the oil temperature corresponding to the minimum PD magnitude and frequency was 73 °C.

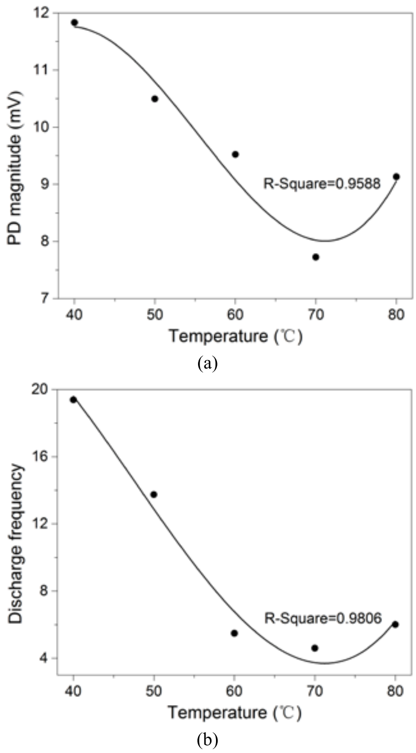

FIGURE 4. The change of PD parameters with oil temperature. (a) Average discharge magnitude, (b) Discharge frequency.

B. BREAKDOWN VOLTAGE

An AC voltage was applied to the high-voltage electrode, and rose with the rate of 2 kV/s until a breakdown occurred. The experiment was repeated for 6 times, with an interval time of 2 min for each one. Fig. 5 shows the change of breakdown voltage with oil temperature. As the temperature increased, the breakdown voltage firstly increased and then decreased, and a maximum point appeared at 70 °C. The changing rule was opposite to that in Fig. 4.

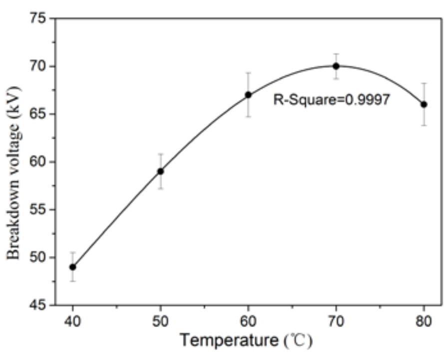

FIGURE 5. The change of average breakdown voltage with the temperature in contaminated oil.

The breakdown voltages of moving transformer oil without particles were measured for comparison, as Fig. 6. As the oil temperature became higher, the average breakdown voltage monotonously increased. It is due to the reduction of the relative concentration of water content in the oil [17], [18]. When the temperature increased, the absolute water content almost remained unchanged, but the saturated water absorption of the oil became stronger. Under the same experimental conditions, e.g. temperature and oil flow rate, the breakdown field of oil without particles was much higher than with their addition. In detail, for the former case, the breakdown field ranged from 9.5 kV/mm to 13.4 kV/mm, but the maximum one was 6.9 kV/mm for the latter case.

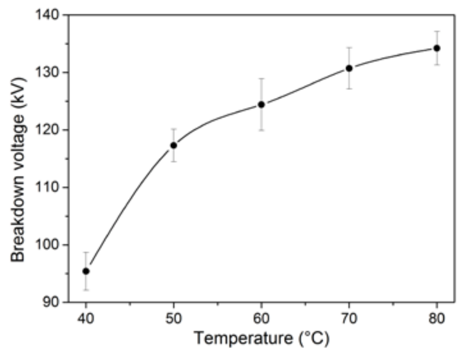

FIGURE 6. The change of average breakdown voltage with the temperature in pure oil.

IV. DISCUSSIONS

When there were no particles in transformer oil, the PDIV and breakdown voltage were higher than with contamination. This indicated that the introduction of metallic particles drastically reduce the insulation performance of the oil. Moreover, PD and breakdown characters intimately depended on the movement of contaminated particles [9]–[11]. Focusing on the oil temperature variation, its viscosity changed and so did the forces acting on particles. Therefore, the moving trajectory would be affected, leading to differences of PD and breakdown characters at various temperatures. By considering these, a physical model involving fluid and electric field was constructed to simulate the moving trajectory, and used to analyze the effect of particles on the discharge characters of oil when the oil temperature varied.

A. SIMULATION MODEL

In the presence of electric field, metallic particles mainly bore nine types of forces [19], i.e. electric field force (F_e), buoyant force (F_{bu}), gravity force (F_g), oil flow traction force (F_t), Magnus lift force (F_m), additional mass inertia force (F_a), besset force (F_{be}), pressure gradient force (F_p) and saffman force (F_s) in the moving transformer oil. Because the latter five types of forces were much smaller (in the magnitude level of $10^{-7} \sim 10^{-8}$ N), only the former four were considered ($10^{-5} \sim 10^{-6}$ N), as Fig. 7.

$$F_e = 0.832qE \text{ [20]} \tag{1}$$

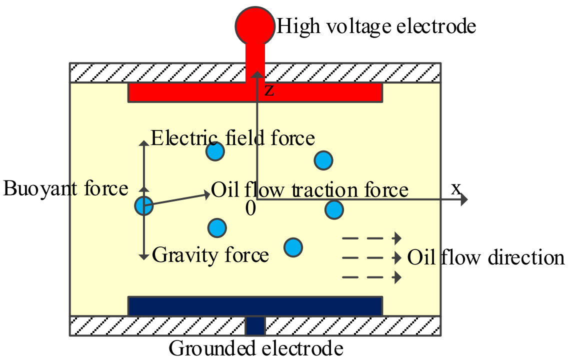

FIGURE 7. Simulation model of particle movement.

where q indicates the total charge quantity distributed on the particle surface, E is the applied filed. In our experiments, spherical particles were used, so q could be expressed as [21]

$$q = \frac{2}{3}\pi^3 \varepsilon_r \varepsilon_0 r_p^2 E \tag{2}$$

where ε_r is the relative permittivity of oil, equal to 2.25, ε_0 is the vacuum permittivity, and r_p indicates the particle radius, is 75μm. The polarity of q was consistent to the electrode which the particle instantaneously contacted.

The buoyant and gravity forces could be expressed as follows

$$F_{bu} = \frac{4}{3}\pi r_p^3 \rho_o g \tag{3}$$

$$F_g = \frac{4}{3}\pi r_p^3 \rho_p g \tag{4}$$

where ρ_o is the oil density (850 kg/m^3), ρ_p is the particle density (7850 kg/m^3), and g indicates the gravitational acceleration. All parameters except the viscosity of the fluid are listed in Table 1.

TABLE 1. The parameters used for simulation.

Parameter	ε_r	ρ_o	r_p	ρ_p
Value	2.25	850 kg/m^3	75μm	7850 kg/m^3

The oil flow traction force is the combination of friction force between particles and moving oil and shape resistance due to the pressure difference around particles, which, according to Stokes's Law, is expressed as [22]

$$F_t = 6u_o \pi r_p \left(v_o - v_p\right) \tag{5}$$

where u_o is the dynamic viscosity of the fluid, v_o and v_p are the oil flow rate and the particle velocity, respectively. u_o equals to the product of kinematic viscosity (η) and density of the fluid. When the oil temperature varied, the density almost kept unchanged, so there was a linear relationship between u_o and η. Table 2 shows the value of viscosity at different temperatures.

TABLE 2. The kinematic viscosity of mineral oil (Karamay #25) at different temperatures.

T(°C)	40	50	60	70	80
η(×10^{-6} m^2/s)	9.96	8.28	7.00	6.00	5.21
u_o(Pa·s)	8.47	7.04	5.95	5.10	4.43

Because more than one particle cruised between electrodes, their interaction should be examined. We consider two cases, two particles charged with the different and same polarity, and the electric field forces acting on them for each case was calculated whereby to speculate all circumstances in the experiments. In the first case, one particle with negative charges was placed at the middle between electrodes, and the other carrying positive charges move freely along symmetric axis, while the only different condition was charge polarity in the second case. Fig. 8a shows the change of electric field force acting on each particle when the free one departed from the grounded electrode and moved towards the fixed one. It is found that the electric field force of each particle was initially identical, which equaled to 8.1×10^{-6} N. Subsequently, when their spacing was less than 0.04 mm, the forces deviated from each other and the difference exceeded 10%. Fig. 8b shows the change of electric field force induced by the movement

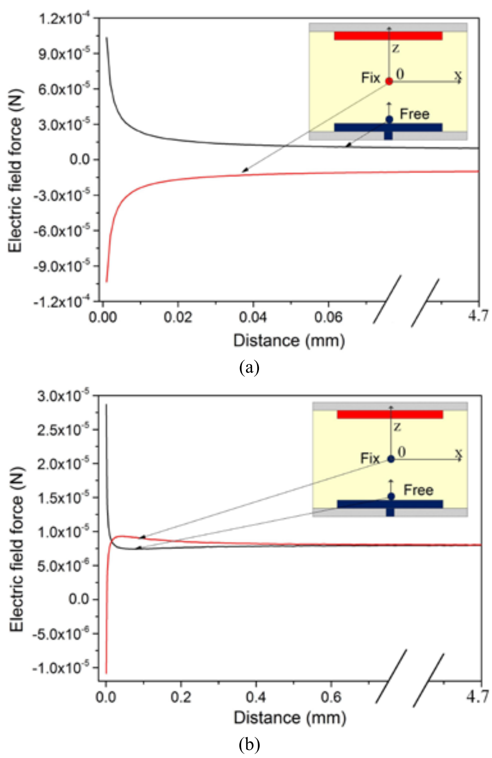

FIGURE 8. The change of electric field force acting on two particles with different locations. (a) With the different polarity, (b) With the same polarity.

of two particles with the same charge polarity. When their spacing was larger than 0.4 mm, the magnitude of electric field force acting on each one was uniform, equaling to 8.1×10^{-6} N. Besides, with a single particle in the main oil channel, the force acting on it was also 8.1×10^{-6} N. In terms of the above calculations, it is inferred that the interaction between particles could be neglected if their spacing exceeded 0.4 mm.

Look back the sizes of experimental device, the oil volume across parallel electrodes was 3.14×10^5 mm^3, whereas the effective volume within which the interaction between particles should be taken into account was 0.45 mm^3 (corresponding to the radius of particle plus 0.4 mm). And there were about 200 particles in the main oil channel with electric field application. Therefore, the probability of particles interacting was so low that could be ignored.

Based on the above analysis, the movement of particles in flow oil could be expressed as

$$m_p \frac{d\overrightarrow{v_p}}{dt} = \overrightarrow{F_e} + \overrightarrow{F_{bu}} + \overrightarrow{F_g} + \overrightarrow{F_t} \quad (6)$$

where m_p indicates the particle mass. In order to solve equation (6), an initial condition about particle velocity was needed. After a long period of circulation, the initial velocity of particles was assumed to be identical to that of oil along x-direction at the inlet of main oil channel due to the effect of oil flow traction force.

Besides, E was calculated in terms of Poisson equation, as follows

$$\overrightarrow{E} = -\nabla\varphi \quad (7)$$

where φ is the electric potential between electrodes. The potential of high voltage electrode was $15\sin(wt)$ kV, $w = 100\pi$, while the other one was always grounded. The COMSOL software was employed to achieve the simulation.

B. EFFECT OF TEMPERATURE ON PARTICLE MOVEMENT

Because the interaction between particles could be neglected, their number was largely reduced in the simulation. 6 particles with different initial locations were placed at the inlet of main oil channel, and their coordinate was #1(-10 cm, 0.5 cm), #2(-10 cm, 0.4 cm), #3(-10 cm, 0.2 cm), #4(-10 cm, 0), #5(−10cm, −0.2 cm), #6(−10 cm, −0.4 cm), respectively. Fig. 9 shows the moving trajectory of metallic particles during one second at different oil temperatures. It was found that the particles oscillated in the z-direction, while they moved forward along x-direction. Regardless of the initial location of particles, they would contact with electrodes after a short period.

According to equation (5), the direction of F_t was determined by the difference between oil flow velocity and particle moving velocity. As the temperature increased, the dynamic viscosity of the fluid became smaller, leading to the decrease of z-component of F_t. Therefore, on one hand, the particles tended to collide with electrodes during a shorter period due to the effect of gravity force minus F_t in the z-direction. On the other hand, the oscillation amplitude of particles became higher as temperature increased. It meant that when particles passed the main oil channel, the frequency of their collision with electrodes would decrease. Hence, the temperature variation may bring two opposite effects on the interaction between particles and electrode. Fig. 10 shows the collision number between particle #4 and the grounded electrode during one second after it entered the main channel with electric field application at different oil temperatures. As the

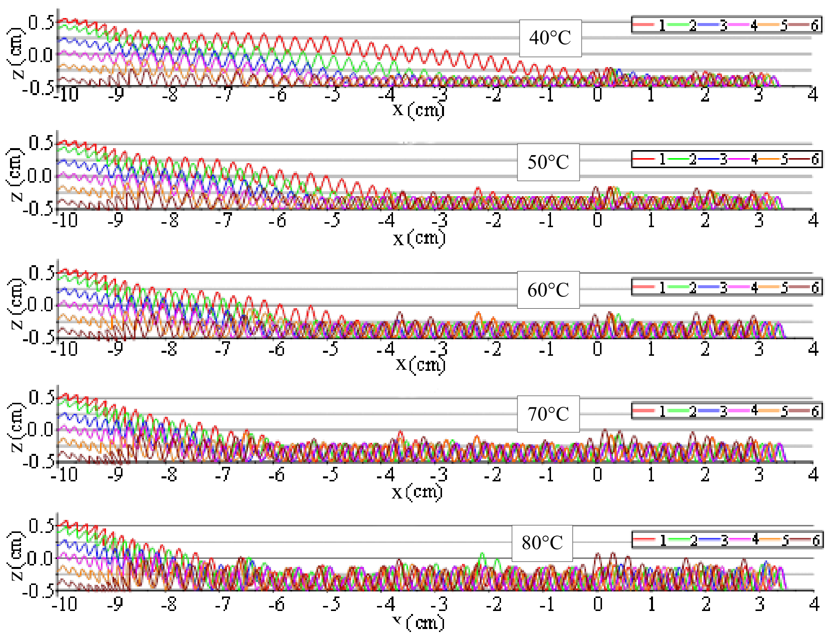

FIGURE 9. Moving trajectory of metallic particles during one second at different oil temperatures.

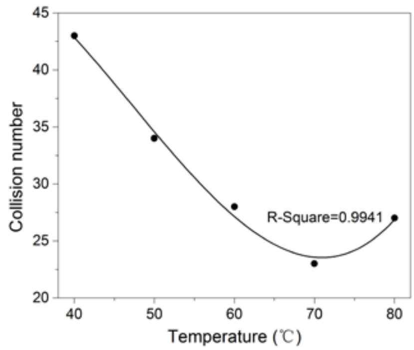

FIGURE 10. The change of collision number between particle #4 and grounded electrode with oil temperature.

temperature increased, the collision number firstly decreased, and then increased. It was attributed to the two opposite effects. When the oil temperature was below 73 °C, the latter effect dominated, and otherwise the former was prevailing. For particles at other initial locations, the similar changing tendency was also observed.

C. THE INFLUENCE OF PARTICLE MOVEMENT ON PD AND BREAKDOWN CHARACTERISTICS OF MOVING TRANSFORMER OIL

By comparing the PDIV and breakdown voltage of transformer oil with and without particle contamination, it is inferred that the addition of particles degraded oil insulation performance. Here, the change of electric field distribution across electrodes with particle location was calculated, as Fig. 11. An extreme case was considered, in which the potential of high voltage electrode was at peak value and kept unchanged for simplicity. Initially, the particle located at the high voltage electrode and had an equipotential with respect to it. Once the particle left the electrode, positive charges would present, leading to a potential difference between them. The average electric field gradually increased with the distance, and it kept the maximum value of 1.5×10^3 V/mm until the particle nearly contacted with the grounded electrode. On the other hand, the average field between particle and grounded electrode always equaled to the background field (1.5×10^3 V/mm) until their spacing was less than 1 mm. After the particle further approached the grounded electrode, the field would increase. And when the spacing was below 0.02 mm, the magnitude level of field exceeded 10^4 V/mm, which facilitated the localized breakdown of insulating oil [23], [24]. Due to AC voltage application, its magnitude was uncertain when a localized breakdown took place. And maybe a smaller spacing was needed to achieve so that the breakdown could occur because the carried charges were proportional to voltage magnitude. Anyway, in terms of spacing in the level of 0.02 mm or smaller, we roughly held that the localized breakdown was ignited if particles collided with electrodes. It was realized by charge transfer in our simulation.

Therefore, each collision between particles and electrodes represented a PD in Fig. 9. The change of PD frequency in Fig. 4b was in accordance with the change of collision number relative to the oil temperature in Fig. 10, which validated the simulation analysis. It is that the oil flow traction force varied as the temperature increased, bringing about two opposite effects, so a minimum value appeared. Note that there was a slight discrepancy of the temperature corresponding to the minimum discharge frequency and the minimum collision number. It was due to the fact that the exact number of particles within the main oil channel was difficult to obtain. In addition, the variation of discharge magnitude did not only depend on the collision number. Here, we gave the inference. As the oil temperature increased, particles easily arrived at electrodes. Due to the existence of discharge time lag, a localized breakdown across a shorter spacing would take place, leading to the decrease of PD magnitude. Subsequently, larger PDs appeared as the temperature became higher.

Because the PDIV was much smaller than the breakdown voltage of transformer oil in the presence of metallic particles, a localized breakdown did not directly lead to the complete breakdown of oil gap. However, it is found from Fig. 4 and 5 that the dependence of PD magnitude and frequency on temperature was opposite to that of breakdown voltage, so there was an intimate relationship between them. In terms of these,

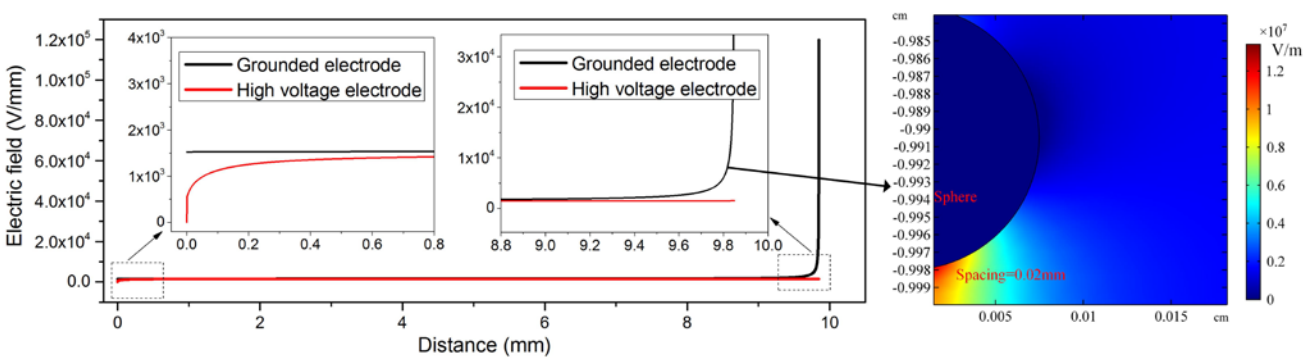

FIGURE 11. The average electric field of high-voltage and grounded electrodes with respect to a sphere at different locations.

it is inferred that the complete breakdown of transformer oil may be initiated by PD induced by particles, as Fig. 12.

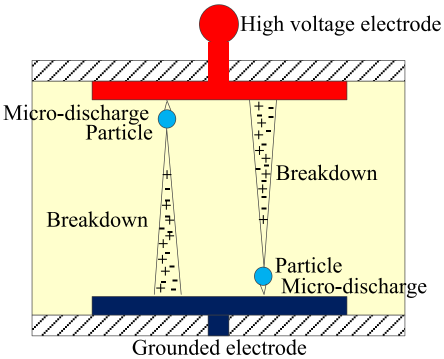

FIGURE 12. Oil breakdown initiated by micro-discharge.

When the oil temperature rose, the PD magnitude and frequency were firstly reduced due to the increase of collision frequency between particles and electrodes, and hence the breakdown probability became lower, leading to the increase of breakdown voltage, as Fig. 5. Moreover, after the discharge magnitude and frequency increased with the temperature, the probability of breakdown initiated by particles became higher, so the breakdown voltage diminished.

V. CONCLUSIONS

In this paper, the influences of temperature on PD and breakdown characteristics in moving transformer oil contaminated by metallic particles were experimentally investigated. In order to analyze the results, a simulation model was established to obtain the movement trajectory of particles. The conclusion could be summarized as follows:

(I) In the moving transformer oil contaminated by metallic particles, the PD magnitude and frequency firstly decreased and then became higher when the oil temperature increased from 40 °C to 80 °C, and a minimum point appeared between 70 °C and 80 °C. However, the dependence of breakdown voltage on temperature showed an opposite tendency.

(II) It is found from simulation results that as the temperature increased, the dynamic viscosity of transformer oil became smaller, and the oil flow traction force changed, bringing two opposite effects on particle movement. In detail, the particles collided with electrodes during a shorter period as the temperature increased. On the contrary, the frequency of their collision with electrodes would decrease due to the increase of particle oscillation amplitude with temperature.

(III) As the oil temperature increased, the collision frequency between particles and electrodes firstly decreased and then became higher, and there was a minimum point between 70 °C and 80 °C. In terms of this, the dependence of PD characters on the temperature could be well explained. In addition, PDs may initiate the complete breakdown, leading to the identical relationships between PD parameters, as well as the breakdown voltage, and the temperature.

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