

Article

Research on the Movement Characteristics and Local Accumulation Mechanism of Rubber Particles in Converter Transformer Mineral Oil

Wenlong Liao ¹, Xin Yang ¹, Yueping Yang ¹, Jiazhao Lian ², Zhenyu Wang ¹ and Zefeng Yang ^{2,*} ¹ State Grid Sichuan Electric Power Research Institute, Chengdu 610041, China; liaowenlong5415@163.com (W.L.)² Electrical Engineering College, Southwest Jiaotong University, Chengdu 611756, China

* Correspondence: yangzefeng@foxmail.com; Tel.: +86-15308185691

Abstract

Rubber particles shed from aging seals in converter transformers can distort local electric fields and degrade insulation. As a critical but understudied impurity in converter transformers, the migration and accumulation mechanisms of rubber particles remain unclear. This study investigates the movement and accumulation behaviors of nitrile butadiene rubber (NBR) particles under a DC electric field. High-speed camera observations were conducted under DC voltages up to 6 kV to capture the migration of 100–200 μm NBR particles under parallel-plate and sphere-plate electrodes. A multiphysics model was developed to simulate field gradients and particle trajectories. Results show that particles form dynamic bridges via reciprocating migration in uniform fields, whereas they exhibit staged movement under non-uniform fields. A dielectrophoretic (DEP) potential well model reveals that high-gradient regions (e.g., electrode edges) form steep wells that trap particles when their kinetic energy falls below the well depth. Quantitative analysis indicates that particles with a radius below the critical value (e.g., 150 μm) are prone to local accumulation under applied voltages above 3.5 kV. Above this critical value, accumulation is suppressed, depending on the voltage and oil velocity conditions. These findings clarify the critical criteria for rubber particle accumulation, supporting insulation design in converter transformers.

Keywords: converter transformer; rubber particles; movement characteristics; accumulation mechanism; potential energy



Academic Editor: Kambiz Vafai

Received: 24 June 2026

Revised: 27 July 2026

Accepted: 29 July 2026

Published: 30 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

As the core hub equipment of the ultra-high voltage direct current (UHVDC) transmission system, the operational reliability of the converter transformer is directly related to the safety and stability of the power grid [1,2]. In actual operation, the valve-side winding of the converter transformer is subjected to severe AC/DC composite electric fields for a long period, which imposes extremely high requirements on the oil-paper composite insulation structure on the valve side [3,4]. Insulating oil, as the key medium for internal insulation and heat dissipation, not only serves the functions of electric field homogenization and heat transfer but also acts as the main carrier for solid impurities. During manufacturing, transportation, and long-term operation, transformer oil is highly susceptible to solid particle contamination [5,6]. Since the dielectric constant of solid impurity particles is generally higher than that of transformer oil, they undergo polarization under the electric

field and directionally migrate toward regions with high electric field intensity [7]. These microparticles not only cause severe local electric field distortion but also easily induce partial discharge or even electrical breakdown, significantly degrading the insulation performance of the transformer oil [8–10]. Especially under a DC electric field, due to the significant space charge effect and the continuous unidirectional electric field force driving the microparticles, their charged migration and local accumulation behaviors are more severe than those in AC systems [11–14]. Insulation failures caused by particle contamination account for a significant proportion of the total failures, which has become a prominent bottleneck restricting the safe operation of converter transformers [15,16].

In recent years, domestic and foreign scholars have carried out extensive research on solid particles in transformer oil. S. Birlasekaran [17,18] observed the collision and electrophoretic motion of metal particles under AC electric fields using high-speed photography and established a particle charge dynamics model. L. Dascalescu et al. [19] systematically studied the dielectrophoresis phenomenon in non-uniform electric fields and quantified the influence of dielectrophoretic forces on particle trajectories. Tang Ju et al. [20] conducted a multi-physics coupling analysis on charged metal particles with an average diameter of 150 μm in an AC electric field to achieve an accurate simulation of motion trajectories, specifically investigating the impact of variables such as oil flow rate, oil gap field strength, particle size, initial conditions, and rotational effects. Li et al. [21] systematically investigated the regulation mechanism of electric field type, field strength, and particle concentration on the trajectories of solid particles ranging from 1 to 100 μm in oil flow. Li et al. [22] restored the entire motion trajectory of cellulose impurities under DC voltage by establishing a simulation model and pointed out that a single motion cycle of a particle is divided into three stages: “lifting”, “ascending”, and “descending”. Meng et al. [23] pointed out that the interaction forces between particles significantly affect their accumulation behavior, and the development process of particle chains is accompanied by dynamic changes of extension and rupture. Dong et al. [24] established a TR-PIV system to observe and analyze the micro-dynamic processes of cellulose particle migration, aggregation, and bridging.

Existing studies on impurity-induced bridging in electrode gaps mainly focus on conventional particles like metals and cellulose [17–24]. However, under long-term thermal-oxidative aging and mechanical stress, internal seals in converter transformers prone to degrade and shed micrometer-sized nitrile butadiene rubber (NBR) particles [25–27]. Unlike highly conductive metals, NBR is a non-conductive dielectric with a much smaller relative permittivity contrast against transformer oil. It also exhibits a higher volume resistivity than hydrophilic cellulose fibers. These distinct polarization and charge relaxation properties mean the motion and accumulation laws of NBR particles remain unclear. Under DC electric fields, polarized NBR particles tend to accumulate in high-gradient regions driven by dielectrophoretic forces [7], distorting local electric fields and threatening insulation safety [9]. Therefore, elucidating the transport dynamics and stable accumulation thresholds of rubber particles is crucial for accurately assessing the insulation risks in converter transformers.

To address the above issues, this paper takes NBR particles in mineral oil as the research object to investigate their movement characteristics and local accumulation mechanisms. First, a DC observation platform was established, and high-speed photography was utilized to acquire the dynamic migration characteristics of particles under uniform and non-uniform electric fields. Second, a multi-physics coupling model was established to reveal the mechanical causes of lateral particle deflection and local accumulation, providing supplementary explanations for the experiments. Finally, based on the concept of potential wells, a dielectrophoretic (DEP) potential energy model was constructed, and

the accumulation criterion was established by comparatively analyzing the particle kinetic energy and the potential well depth. This paper aims to elucidate the local accumulation mechanism of rubber particles from the perspective of micro-mechanics and energy competition, providing theoretical support for suppressing particle contamination inside converter transformers and enhancing equipment reliability.

2. Materials and Methods

2.1. Experimental Platform

The DC experimental platform is shown in Figure 1a. A ZGF series DC high-voltage generator is selected, capable of outputting a maximum DC voltage of 120 kV. The control panel allows for direct reading of the current output high voltage and the leakage current flowing through the tested sample. A transparent cubic test oil cup with a side length of 75 mm is used, equipped with an adjustable knob internally to facilitate the replacement of different electrode configurations according to test requirements. The connection between the electrodes and the oil cup is sealed with polytetrafluoroethylene (PTFE) material to ensure good insulation and sealing performance of the apparatus. Considering the extremely low magnitude of leakage current in mineral oil, which is difficult for the DC high-voltage generator to measure accurately, a Keithley 6517B electrometer manufactured by Tektronix is selected to monitor the variation of the leakage current. The current measurement resolution of this instrument reaches 10 aA (10×10^{-18} A), with an overall measurement range from 10 aA to 20 mA. The electrodes utilized in the test oil cup include parallel-plate and sphere-plate configurations. The plate electrode has a diameter of 25 mm, and the sphere electrode has a diameter of 13 mm. Both are made of brass, with an inter-electrode gap of 5 mm.

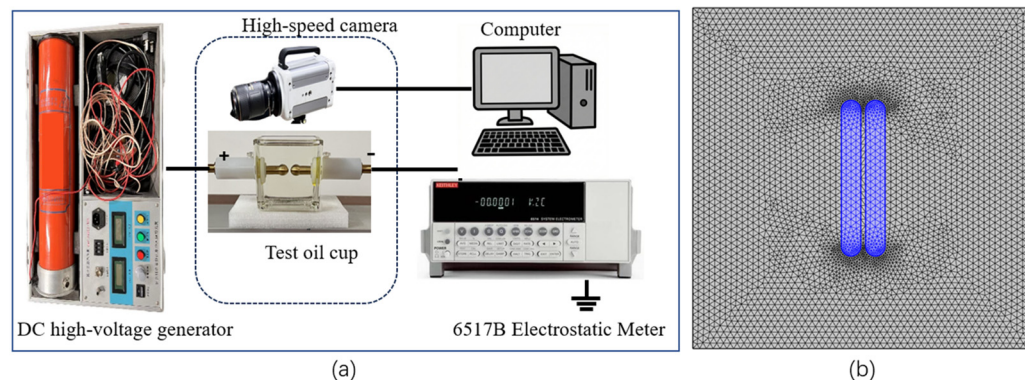


Figure 1. Experimental platform and numerical simulation model: (a) schematic of the experimental setup; (b) mesh generation of the simulation model.

2.2. Experimental Method

Kunlun KI25X transformer mineral oil (PetroChina Company Limited, Beijing, China) is used in the experiment. A ZY series high-efficiency vacuum oil purifier (Chongqing Zhongneng Oil Purifier Manufacturing Co., Ltd., Chongqing, China) is employed to filter the mineral oil. The heating temperature during filtration is set to 60 °C, and each filtration session lasts for 7 h. The average breakdown voltage of the filtered mineral oil is tested to be 64.2 kV, which meets the requirements of the IEC 60296: 2020 standard [28]. Nitrile butadiene rubber (NBR) is selected as the main source material for rubber impurity particles. Since the size of impurity particles in transformer oil is typically at the micrometer level, a file is used to generate friction on an NBR pad to obtain NBR particles, and a standard laboratory test sieve (Xinxiang Dahan Vibration Machinery Co., Ltd., Xinxiang, China) is employed to control the particle radius range between 100 and 200 μm [29].

Initially, 290 mL of mineral oil is added into the test oil cup (parallel-plate electrodes) as the base oil sample. Subsequently, 0.029 g of NBR particles is added to reach a concentration level of 0.1 g/L (corresponding to Class 12 of the ISO 4406: 2021 [30] particulate contamination classification). During the experiment, a stirrer is used to thoroughly mix the particle-containing oil sample. After stirring, the oil sample is left to stand until the bubbles completely dissipate. A stepped DC voltage is then applied, starting from 0.5 kV and increasing to 6.0 kV in increments of 0.5 kV every 20 s, followed by a constant hold phase at 6.0 kV after 240 s. At the maximum applied voltage of 6 kV, the peak electric field intensities for the parallel-plate and sphere-plate configurations reach approximately 17 kV/cm and 55 kV/cm in the finite element simulation, respectively. Each voltage level is maintained for 20 s before proceeding to the next level. Throughout the step-up voltage application process, a high-speed camera (FASTCAM Nova S6, Photron Limited, Tokyo, Japan) is used to continuously record the inter-electrode gap region with a resolution of 1024×1024 and a frame rate of 50 fps (20 ms temporal resolution, given the maximum particle velocity of ~ 2 mm/s, the maximum frame-to-frame displacement is only ~ 40 μm (2–3 pixels), which is optimal for tracking), capturing the motion trajectories of rubber particles under the DC electric field in real-time. The entire pressurization process involves measuring the leakage current in the insulating oil using the 6517B electrometer (Keithley Instruments, Solon, OH, USA). The electrodes are then replaced with sphere-plate electrodes, and the above experiments are repeated.

While this study is limited to a single concentration of 0.1 g/L, its primary focus is to reveal the fundamental transport mechanisms of individual impurity particles under the competition between fluid kinetic energy and dielectrophoretic potential barriers. Future work will systematically investigate how particle concentration influences the transition from such individual trajectories to collective network bridging.

2.3. Simulation

Particle dynamics simulations in oil under different electrode configurations are conducted in COMSOL Multiphysics (Version 6.2). The model utilizes electrode geometries that strictly match the actual experimental setup defined in Section 2.1: copper plate electrodes with a diameter of 25 mm, and a sphere electrode with a diameter of 13 mm, both with an inter-electrode gap of 5 mm, as shown in Figure 1b. Specific material parameters are as shown in Table 1.

Table 1. Material parameters used in the simulation.

Symbol	Physical Significance	Unit	Value
ε_m	Relative permittivity of mineral oil	/	2.2
ε_p	Relative permittivity of rubber particles	/	4
ε_0	Permittivity of vacuum	F/m	8.854×10^{-12}
μ_{oil}	Dynamic viscosity of mineral oil	Pa·s	0.00853
σ_m	Electrical conductivity of mineral oil	S/m	10^{-13}
σ_p	Electrical conductivity of rubber particles	S/m	10^{-14}
ρ_0	Density of mineral oil	kg/m ³	885
ρ_p	Density of rubber particles	kg/m ³	1150
r_p	Particle radius	μm	100~200

The simulation couples three physics interfaces in COMSOL Multiphysics: Electric Currents, Turbulent Flow, and Particle Tracing for Fluid Flow. First, the Electric Currents interface computes the electric potential and field distributions using charge conservation, Ohm's law, and Gauss's law, where the high-voltage electrode is set to a potential boundary under constant direct current or sinusoidal alternating current, the counterpart electrode

is grounded, and outer boundaries are electrically insulated. Second, the Turbulent Flow interface determines the oil velocity field governed by the incompressible continuity and Navier–Stokes equations, treating the electrodes and cup walls as no-slip boundaries with the fluid initially at rest. Finally, the Particle Tracing interface tracks individual rubber particles using Newton’s second law under a Lagrangian framework, integrating Coulomb, dielectrophoretic, drag, and buoyancy-gravity forces. Particles are released with zero initial velocity, and the electrode surfaces are designated as freeze boundaries to simulate particle attachment.

3. Results and Discussion

The internal insulation structure of a converter transformer is highly complex. Non-uniform electric field regions easily form at locations such as electrode edges and winding ends, whereas areas like the inter-plate gap approximate uniform electric field regions. The uniformity of the electric field directly determines the stress state and motion trajectory of rubber particles, acting as the core factor influencing particle migration, deflection, and local accumulation. To accurately reveal the motion laws of rubber particles under a DC electric field, comparative experiments using parallel-plate electrodes (simulating a uniform electric field) and sphere-plate electrodes (simulating a non-uniform electric field) were conducted respectively in this study to systematically analyze the differences in particle motion characteristics under the two typical electric field environments.

3.1. Motion Characteristics of Rubber Particles in Oil

3.1.1. Motion Characteristics Analysis of Rubber Particles Under a Uniform Electric Field

As shown in Figure 2a, the observation area for the parallel-plate electrodes is divided into three regions: ①, ②, and ③. In stage b, the particles in region ① settle slowly 0.08 ± 0.01 mm/s, as indicated by the black arrows. Meanwhile, the particles in region ②, near the top of the electrode, are attracted towards the electrode end, exhibiting a faster velocity (0.128 ± 0.04 mm/s) compared to region ①, as shown by the yellow arrows. The particles in region ③ migrate towards both plate electrodes (0.263 ± 0.04 mm/s). In stage c, the particles in the top region of the electrode acquire the same polarity charge as the electrode and are ejected from it, beginning to migrate towards region ① on the left side of the electrode (0.096 ± 0.02 mm/s), as indicated by the yellow-blue arrows in the figure.

As the voltage continues to increase, in stage d, the particles in region ② continuously migrate to region ①, ultimately resulting in the collective movement of particles in region ① towards region ②. In stage e, as the particles continuously migrate towards the electrode ends, they collide with charged ions and other particles in the oil, leading to charge redistribution. When the particles re-enter the vicinity of the left electrode top, they are attracted back to the electrode surface, where the electrode charges the particles. The particles then enter the electrode gap and are trapped, forming a rubber particle bridge within the gap, eventually appearing as shown in stage f.

Within the parallel-plate electrode gap, the rubber impurity particles initially exhibit reciprocating migration between the two poles, which is consistent with existing research findings on non-metallic impurity particles. As the voltage rises, a large number of particles enter the electrode gap and gradually form chain-like connections, ultimately developing into a rubber impurity particle bridge. Unlike the relatively stable bridge structures formed by other impurity particles, the rubber impurity particle bridge exhibits strong dynamic variation characteristics in a uniform electric field, and the bridge structure stability is poor, thereby potentially inducing discharges at different locations. In the experiment, it was measured that the leakage current of the mineral oil containing rubber particles spiked and then decayed to a stable value.

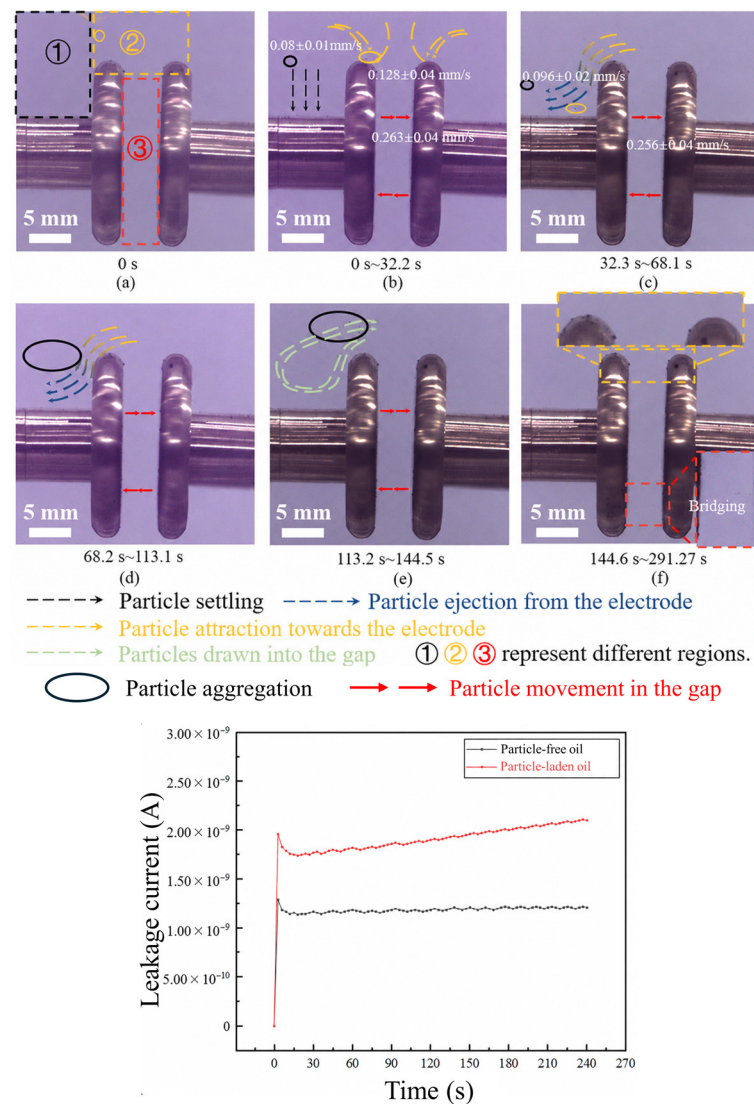


Figure 2. Experimental trajectories and migration stages, and the corresponding leakage current evolution of NBR particles under plate-plate electrodes. Tested for five replicate trials ($n = 5$). Stages (a–e) occur during the step-up voltage phase, whereas stage (f) (144.6 s–291.27 s) spans the transition into the constant 6.0 kV hold phase that begins at 240 s.

To quantitatively evaluate the macroscopic electrical response during this process, the leakage current of both the particle-laden oil (0.1 g/L) and a particle-free mineral oil control sample were continuously recorded using a Keithley 6517B electrometer. As directly correlated in the leakage current plot of Figure 2 (under the uniform plate-plate field), the pure oil stabilizes at approximately 1.15×10^{-9} A. In contrast, the particle-laden oil exhibits distinct transient spikes (corresponding to the dynamic formation and rupture of particle bridges) and settles at a significantly elevated steady-state value between 1.70×10^{-9} A and 2.00×10^{-9} A. This confirms that particles continuously migrate back and forth without being permanently trapped, generating a sustained convection current component. The analysis suggests that the particles continuously migrate back and forth driven by the electric field force, forming charge transport and generating a convection current component, which maintains the leakage current at a stable value.

3.1.2. Motion Characteristics Analysis of Rubber Particles Under a Non-Uniform Electric Field

As shown in Figure 3a, the observation area for the sphere-plate electrodes is divided into regions ①, ②, ③, and ④. In stage b, noticeable particle motion begins at 3.11 s. By 18.04 s, the particles within the sphere-plate gap collectively exhibit an upward migration. At the end of this stage, the upward-moving particles enter the upper region and divert: particles closer to the sphere electrode migrate towards the top of the sphere electrode, while those closer to the plate electrode deflect towards the upper end of the plate electrode. Simultaneously, particles in the right region of the plate electrode also move towards its end, indicating that the upper end of the plate electrode has become an important local convergence zone for particles. After an initial spike to 2.80×10^{-9} A induced by intense particle migration, the leakage current rapidly decreases over time, dropping to approximately 1.30×10^{-9} A at 240 s (approaching the pure oil baseline). This macroscopic current decay is the direct electrical manifestation of dielectrophoretic (DEP) trapping: as freely suspended particles are increasingly captured and permanently trapped in the high-gradient regions near the sphere/plate electrodes, the number of active charge carriers plummets, causing the convection current to deplete.

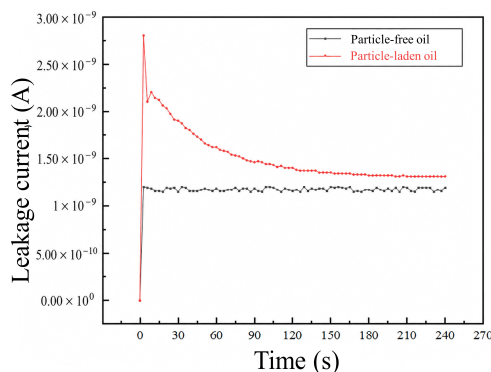
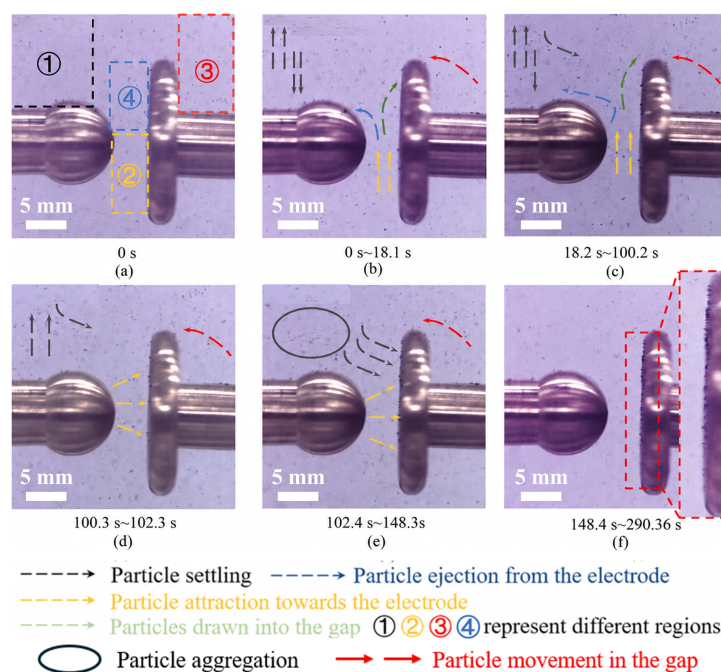


Figure 3. Experimental trajectories and migration stages, and the corresponding leakage current evolution of NBR particles under sphere-plate electrodes. Tested for five replicate trials ($n = 5$). Stages (a–e) occur during the step-up voltage phase, whereas stage (f) (148.4 s–290.36 s) spans the transition into the constant 6.0 kV hold phase that begins at 240 s.

3.1.3. Particle Motion Simulation Results

To reveal the underlying mechanism of rubber particle trajectories under a DC electric field, particle dynamics simulations under different electrode configurations were conducted using the finite element simulation software COMSOL Multiphysics (version 6.2). The computational domain was set to precisely match the 75 mm cubic test oil cup used in the experiment. The simulation coupled three physics interfaces: Electric Currents, Turbulent Flow, and Particle Tracing for Fluid Flow.

First, the Electric Currents interface computed the electric potential and field distributions. The high-voltage electrode was set to a constant DC potential, the counterpart electrode was grounded, and the outer boundaries of the 75 mm oil domain (side walls, top, and bottom) were set as electrically insulated. Second, the Turbulent Flow interface determined the oil velocity field, treating the electrodes and the cup walls as no-slip boundaries with the fluid initially at rest. Finally, the Particle Tracing interface tracked individual rubber particles using Newton's second law, integrating Coulomb, dielectrophoretic, drag, and buoyancy-gravity forces. Particles were released with zero initial velocity, and the electrode surfaces were designated as freeze boundaries to simulate particle attachment.

To ensure calculation accuracy and reproducibility, a mesh convergence study was performed. The mesh elements were progressively refined, particularly within the high-gradient regions near the electrode edges, until the relative changes in the maximum electric field intensity and fluid velocity were both less than 1%. The simulation strictly replicates the electrode geometric parameters, material properties, and boundary conditions of the experimental platform, providing verification and supplementary explanation for the experimental phenomena at a mechanistic level. It should be noted as a caveat that the comparison between the simulated trajectories and experimental observations is primarily qualitative and mechanistic. Experimental velocity estimations were extracted manually frame-by-frame from high-speed camera recordings. While effective for isolated particles, this manual tracking becomes highly challenging and prone to errors in regions with high particle density (such as near the electrodes) due to severe particle overlap.

As shown in Figure 4a,b, the particle motion trajectories are overlaid with the electric field intensity and gradient for the parallel-plate electrodes, respectively. The electric field distribution in the central region of the electrodes is relatively uniform with a small gradient. Due to contact charging with the plates, particles primarily migrate directionally along the electric field direction driven by the electric field force, presenting straight trajectories, which is consistent with the characteristics of reciprocating migration within the gap observed in the experiment [31]. Conversely, in the electrode end regions, the edge effect leads to severe electric field distortion, resulting in significantly elevated field intensity and gradients. Influenced by the large gradient, uncharged particles at the ends of the plates undergo noticeable deflection driven by the dielectrophoretic force and converge towards the edges; particles far from the plates undergo sedimentation mainly influenced by their own gravity. The results show that regions with large electric field gradients precisely correspond to locations where trajectories significantly deflect, indicating that the dielectrophoretic force generated by the non-uniform electric field is the primary force driving neutral particles to move laterally and converge locally.

Figure 5a,b present the overlaid results of particle motion trajectories with electric field intensity distribution and field intensity gradient under the sphere-plate electrode configuration, respectively. For the sphere-plate structure, due to the curvature effect of the sphere electrode, the electric field lines significantly converge on its surface, resulting in a more intense and broader concentration band of electric field gradients in the region facing the sphere and plate. In highly non-uniform electric fields, particles in the initial stage are not only prone to upward migration influenced by electrohydrodynamic (EHD)

oil flow, but also, under the strong coupling action of dielectrophoretic force and electric field force, they are more susceptible to deflection and accelerate towards local high field intensity regions (such as the surface of the plate electrode). The aforementioned simulation results explain from a mechanical perspective the underlying causes for the differences in particle motion trajectories across various regions under different degrees of electric field uniformity.

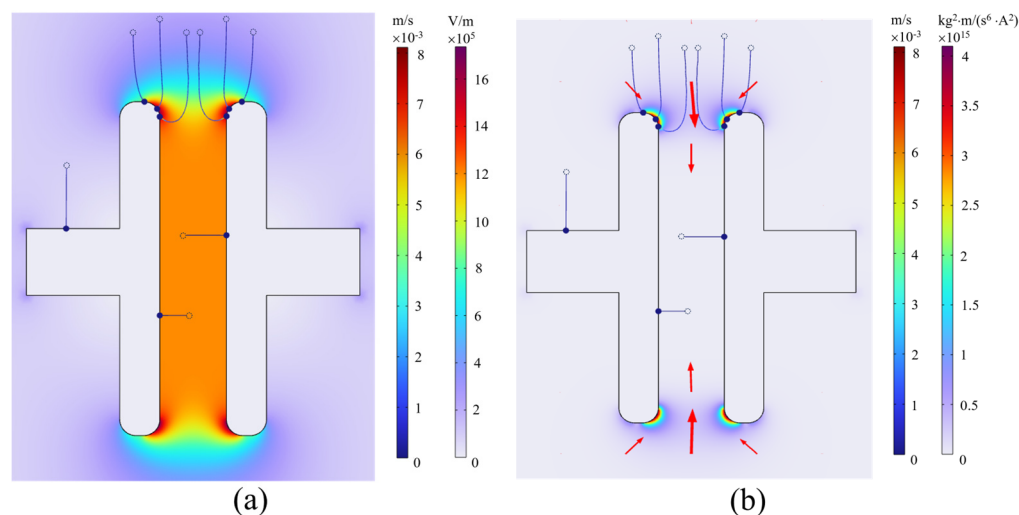


Figure 4. Simulated trajectories and field distributions of NBR particles under plate-plate electrodes: (a) Distribution of electric field strength (right color scale) and fluid velocity (left color scale) with simulated particle trajectories; (b) Distribution of electrokinetic force parameter (right color scale) and fluid velocity (left color scale) with particle motion (indicated by red arrows).

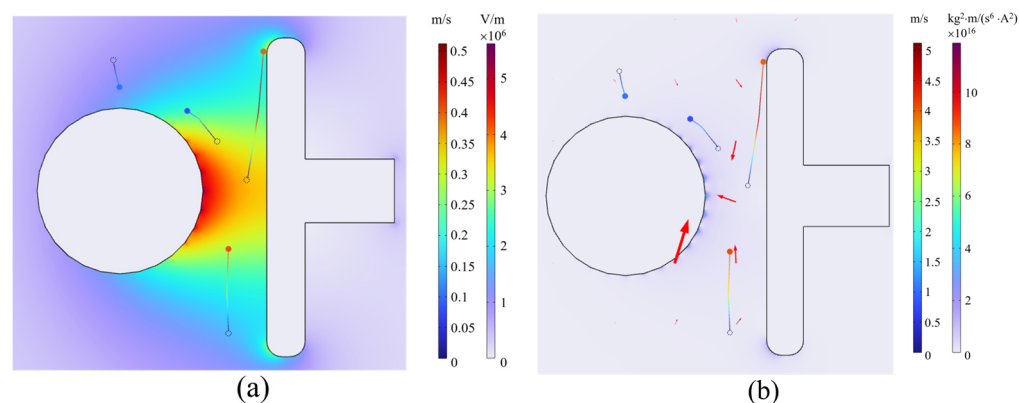


Figure 5. Simulated trajectories and field distributions of NBR particles under sphere-plate electrodes: (a) Distribution of electric field strength (right color scale) and fluid velocity (left color scale) with simulated particle trajectories; (b) Distribution of electrokinetic force parameter (right color scale) and fluid velocity (left color scale) with particle motion (indicated by red arrows).

3.2. Local Accumulation Characteristics of Rubber Particles in Oil

During experimental observations, it was found that rubber particles exhibit a distinct acceleration region as they approach the plate electrode. As shown in Figure 6, rubber particles exhibit a distinct acceleration region as they approach the plate electrode. To quantitatively determine this boundary, we applied a kinematic thresholding criterion based on the particle trajectories extracted from the high-speed videos. The boundary of this “acceleration region” is defined as the spatial location where the particle’s lateral acceleration towards the electrode suddenly exceeds a threshold of 0.02 m/s^2 . Based on this quantitative criterion, the effective physical action boundary is demarcated at an average

distance of $d_0 = 3.62$ mm from the plate end (indicated by the white curve). Within this specific range, the particles begin to experience significant lateral acceleration and are swiftly trapped by the plate. This acceleration region precisely corresponds to the local high field intensity distortion zone at the edge of the plate electrode.

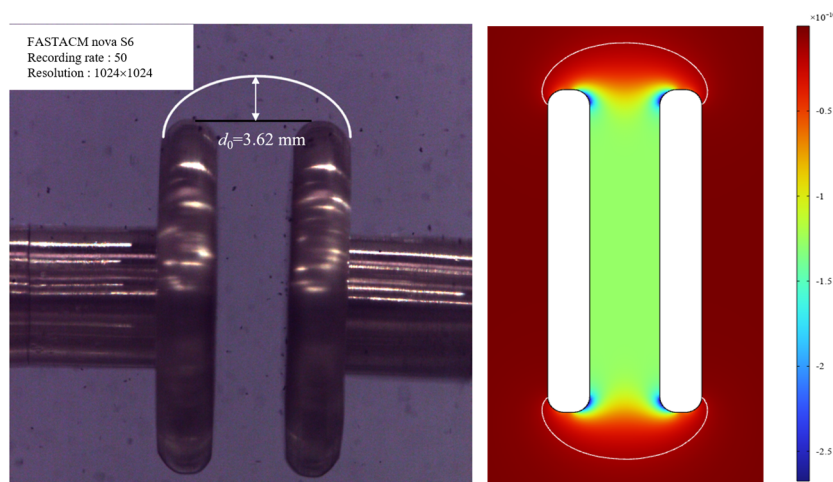


Figure 6. Demarcation of the significant particle acceleration region near the plate electrode.

3.2.1. Force Analysis of Rubber Particles in Oil

The motion of rubber particles in the transformer oil gap is the result of multiple forces acting collectively. In stationary or slowly flowing oil, the main forces influencing particle motion include the electric field force, dielectrophoretic force, viscous drag force, as well as gravity and buoyancy [32].

When a rubber particle moves in mineral oil and contacts the electrode surface, or collides and exchanges charge with other charged particles, its surface may acquire a certain net charge [31]. At this time, the particle will be subjected to the Coulomb force in an external electric field, which is macroscopically manifested as the electric field force. The electric field force exerted on a rubber impurity particle with radius r is:

$$F_e = qE \quad (1)$$

$$q = \frac{2}{3}\pi^3\epsilon_m\epsilon_0r^2E \quad (2)$$

where Equation (2) represents the theoretical saturation charge based on classical contact charging models [19,32]. Although NBR has a very low bulk conductivity, when it physically contacts the highly conductive electrode under a strong DC field, rapid charge transfer occurs via surface states and local emission. On the appropriate charging timescale, the surface of the NBR particle acts as an effective charge carrier. Therefore, treating NBR as an effectively conductive particle at the interface provides a conservative, upper-bound estimate for the maximum charge it can acquire, which fundamentally underlies the electric field force driving the reciprocating migration.

Rubber particles suspended in insulating oil are constantly subjected to gravity and buoyancy. Gravity originates from the particle's own mass, pointing vertically downwards; buoyancy originates from the resultant hydrostatic pressure of the insulating oil displaced by the particle's volume, pointing vertically upwards. The resultant force of gravity and buoyancy on a rubber particle is:

$$F_g - F_b = m_0g\frac{\rho_1 - \rho_2}{\rho_1} \quad (3)$$

When rubber particles are placed in mineral oil, due to the differences in dielectric and conductive properties between the particles and the surrounding oil medium, the external electric field induces electric dipole moments inside the particles and at their interfaces. If the electric field is spatially non-uniform, the polarization effect on both sides of the particle is no longer symmetrical, thus forming a macroscopic net force known as the dielectrophoretic (DEP) force. The DEP force exerted on the particle is:

$$F_{DEP} = 2\pi r^3 \varepsilon_0 \varepsilon_m K_{CM} \nabla |E|^2 \quad (4)$$

where KCM is the Clausius–Mossotti (CM) polarization factor, and its expression is:

$$K_{CM} = \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \quad (5)$$

It is essential to clarify the timescale regime for the application of this permittivity-based CM factor under a nominal DC field. For an infinitely steady DC field, the DEP force is typically governed by the Maxwell–Wagner interfacial polarization based on conductivities. However, the interfacial charge relaxation time τ_{MW} for the NBR-oil system is estimated as: $\tau_{MW} = \frac{\varepsilon_0(\varepsilon_p + 2\varepsilon_m)}{\sigma_p + 2\sigma_m} = 354$ s. In our experimental protocol, the voltage is applied in transient steps, and the critical dynamic behaviors—such as the rapid lateral acceleration and trapping of particles near the electrode edges—occur on a time scale (milliseconds to seconds) that is orders of magnitude shorter than the relaxation time ($t \ll \tau_{MW}$). Within this short transient timescale, the resistive interfacial polarization cannot fully establish, and the polarization response is heavily dominated by the permittivities. Therefore, calculating the CM factor based on relative permittivities is physically justified for the dynamic trapping process. Because insulating oil possesses a certain viscosity, when a particle moves relative to the oil, its surface experiences drag caused by viscous shear action, known as the liquid viscous drag. The viscous drag exerted on the particle is:

$$\begin{cases} F_D = \frac{1}{\tau_p} m_0 (u - v) \\ \tau_p = \frac{\rho_p d_p^2}{18\mu} \end{cases} \quad (6)$$

where E is the electric field intensity; ε_m , ε_0 and ε_p are the relative dielectric constant of the oil medium, vacuum dielectric constant, and particle dielectric constant, respectively; ρ_1 , ρ_2 and ρ_p are the density of the insulating oil, density of the particle, and particle concentration, respectively; μ is the viscosity of the oil medium; d_p is the diameter of the rubber particle; g is the gravitational acceleration; u is the flow velocity of the insulating oil; v is the motion velocity of the particle.

3.2.2. Accumulation Conditions of Rubber Particles

In a non-uniform electric field, the difference in dielectric constant between neutral rubber particles and transformer insulating oil triggers a polarization effect, and their motion is primarily driven by the resulting dielectrophoretic force. Its corresponding equivalent dielectrophoretic potential energy can be obtained by integrating the dielectrophoretic force along the spatial path:

$$U_{DEP} = - \int F_{DEP} \cdot dl = -2\pi r^3 \varepsilon_0 \varepsilon_m K_{CM} |E|^2 \quad (7)$$

To further reveal the physical essence of this phenomenon, the electric field distributions and dielectrophoretic potential energy surfaces of different electrode structures were calculated. As shown in Figure 7a–c and Table 2, since the relative dielectric constant of

rubber particles is greater than that of transformer oil, the particles exhibit positive dielectrophoresis characteristics and are always subjected to a traction force pointing towards the direction of the maximum electric field intensity gradient. In high field intensity regions such as the right-angle ends of the plate electrode, the dielectrophoretic potential energy drops exponentially, forming extremely steep local potential energy minimum regions, namely “dielectrophoretic potential wells”. By comparison, it can be seen that due to edge effects and electric field singularities, steep needle-like deep potential wells form at the edges of the parallel plates; deep and narrow potential wells similarly form on one side of the sphere-plate configuration; whereas the potential well depth is relatively shallow for the sphere-sphere electrodes due to the smooth change in surface curvature. This indicates that the fundamental reason particles are easily trapped in high field intensity regions lies in the physical binding effect of the potential well [33]. To provide a physically motivated definition for the “effective” potential well boundary, we correlate the theoretical potential energy landscape directly with the experimental observations. As identified in Figure 6, particles begin to experience significant lateral trapping when they cross the acceleration-region boundary at $d_0 = 3.62$ mm. Beyond this spatial limit, the dielectrophoretic force decays to a level where it is overtaken by fluid kinetic fluctuations, rendering the potential well ineffective. Computationally, this specific physical boundary corresponds to the equipotential contour where the absolute value of the potential energy decays to approximately 5% of the maximum depth at the bottom of the well. Therefore, we define this experimentally calibrated 5% decay point as the escape boundary. The effective dielectrophoretic potential energy depth can thus be expressed as:

$$\Delta U_{DEP} = |U_{DEP_{\max}} - 0.05 \cdot U_{DEP_{\max}}| = 0.95 \cdot U_{DEP_{\max}} \quad (8)$$

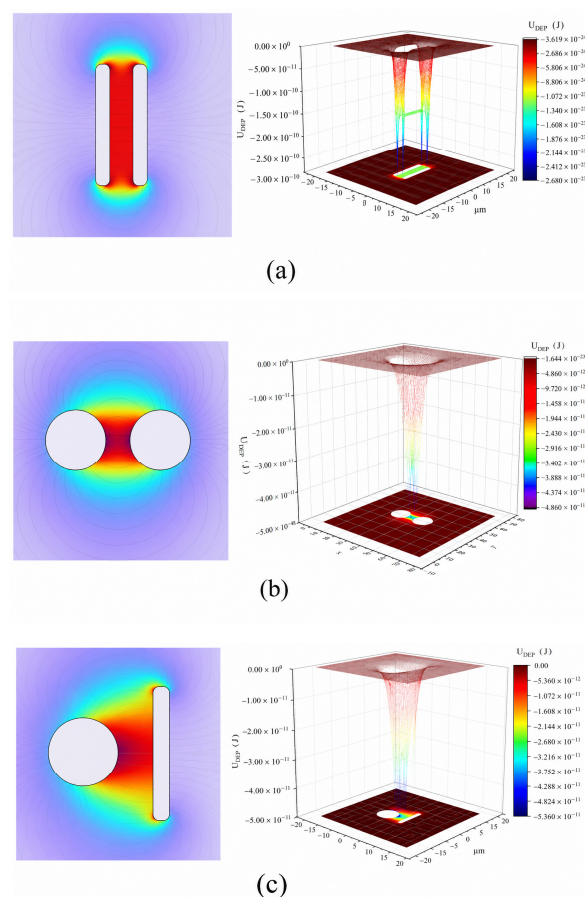


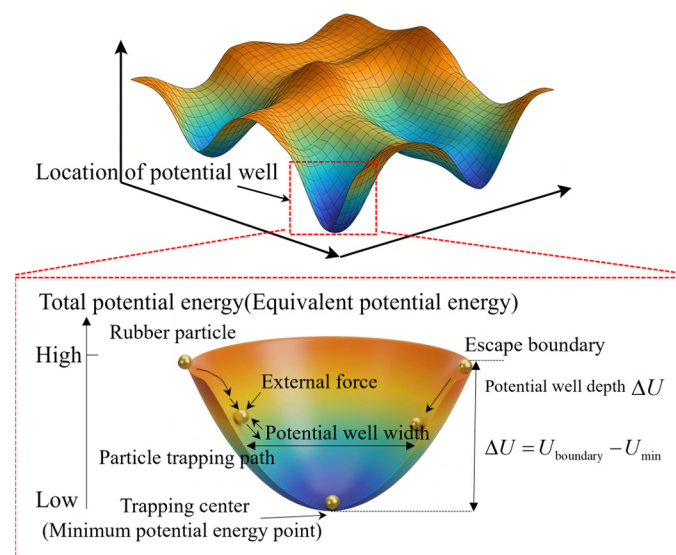
Figure 7. Electric field distributions and DEP potential energy surfaces under different electrode configurations. (a) Plate-plate electrode, (b) sphere-sphere electrode, (c) sphere-plate electrode.

Table 2. Maximum DEP potential well depths under different electrode configurations.

Electrode Configurations	ΔU_{DEP}
Plate-Plate	2.68×10^{-10}
Sphere-Sphere	4.86×10^{-11}
Sphere-Plate	5.94×10^{-11}

Introducing the concept of potential wells, as shown in Figure 8, the complex dynamic force process of particles under multi-physical fields is transformed into a spatial static energy competition problem. When a particle passes through a high field intensity distortion zone, if its initial kinetic energy E_k is insufficient to overcome the effective dielectrophoretic potential well depth ΔU_{eff} in that local region, the particle's weak kinetic energy will be engulfed by the potential energy, and ultimately, it will be unable to escape the potential barrier constraint and thus accumulate. Hence, the critical criterion for local particle accumulation is proposed as follows:

$$E_k < \Delta U_{\text{eff}} \quad (9)$$

**Figure 8.** Schematic diagram of the particle trapping mechanism in a potential well.

3.2.3. Effect of Oil Velocity on Local Accumulation

In an actually operating forced oil circulation transformer, the oil flow enters from the bottom and exits from the top, serving the purposes of circulating heat dissipation and insulation. As shown in Figure 9, the oil flow velocity is mainly concentrated in the longitudinal oil ducts on both sides of the high and low-voltage windings. However, in most areas in the middle of the windings, the insulating oil in the horizontal oil ducts hardly flows due to the small difference in oil flow pressure on both sides.

Since the relaxation time of rubber microparticles in transformer oil is extremely short and the Stokes number is much less than 1 ($Stk \approx 4.07 \times 10^{-4} \ll 1$), the particles possess extremely strong fluid followability [34]. In this overdamped regime, a particle does not overcome potential barriers via ballistic kinetic energy conservation. Instead, its passage is driven by the continuous viscous drag work supplied by the local fluid. Therefore, while the velocity of a particle as it approaches a potential well can be approximated by the local oil flow scouring velocity (v_f), in this macroscopic model, the term E_k is utilized not as the ballistic inertia of the particle itself, but as an equivalent energetic proxy representing the cumulative drag work (W_{drag}) continuously supplied by the surrounding fluid, namely:

$$E_k = \frac{1}{2}mv_f^2 \quad (10)$$

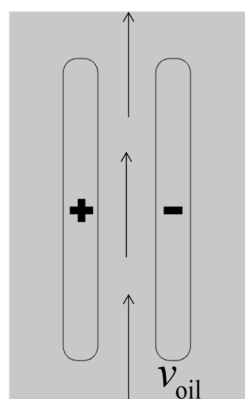


Figure 9. Simplified model of longitudinal oil ducts in HV and LV windings.

Consequently, the escape criterion fundamentally reflects a competition between the fluid drag-work and the dielectrophoretic trapping barrier. To suppress stable particle accumulation and enable escape, the equivalent fluid driving energy (cumulative drag work) of the particle must be greater than or equal to the effective dielectrophoretic potential well depth in that region. Therefore, the required critical escape oil flow velocity condition is:

$$v_f \geq \sqrt{2\Delta U_{\text{eff}}/m} \quad (11)$$

The results show, as illustrated in Figure 10, that the flow velocity in the main oil duct of the transformer (typically 1.0~2.0 m/s, which are representative illustrative values rather than directly measured from our experimental setup) far exceeds this critical flow velocity threshold, allowing particles to pass safely without being trapped. However, in flow field dead zones such as the edges of plate electrodes, the representative oil velocity often plummets to below 100 mm/s. When the applied voltage exceeds a certain threshold (e.g., 3.5 kV), the potential well deepens sharply, causing the critical flow velocity required for particle escape to rapidly breach the upper limit of the dead zone flow velocity. At this point, the dielectrophoretic potential well dominates absolutely, and passing particles are forcibly stripped from the oil flow and trapped in the potential well, triggering local accumulation. The actual oil velocity within the insulation dead zone being lower than the critical escape velocity necessary to suppress particle accumulation is the fundamental cause for the induction of persistent local accumulation inside the transformer.

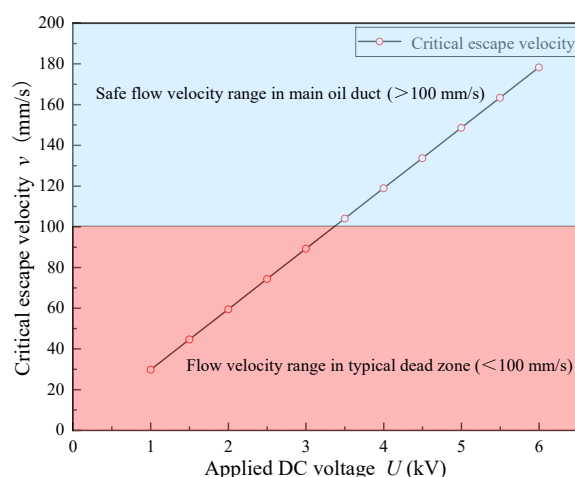


Figure 10. Critical accumulation flow velocity of rubber particles under different voltages.

3.2.4. Effect of Particle Size on Local Accumulation

In the actual insulation system of a transformer, the end of the plate electrode acts as a typical solid wall. Its flow field, subjected to viscous friction, satisfies the no-slip boundary condition. The velocity of the oil flow immediately adjacent to the wall is zero and increases approximately linearly along the normal distance from the wall, forming a distinct velocity boundary layer. When particles of different sizes remain near the wall, their effective action mass center height is exactly equal to their radius r [35]. Therefore, the local effective scouring flow velocity intercepted by a particle within the boundary layer is linearly proportional to its radius, namely:

$$v_f = S \cdot r \quad (12)$$

where S is the near-wall velocity shear rate.

Substituting this effective flow velocity into the scouring kinetic energy equation yields:

$$E_k = \frac{1}{2} \left(\frac{4}{3} \pi r^3 \rho \right) (S \cdot r)^2 = \frac{2}{3} \pi \rho S^2 r^5 \quad (13)$$

The fluid kinetic energy of the particle is proportional to the fifth power of the radius (r^5); whereas the dielectrophoretic potential well depth is only proportional to the third power of the radius (r^3) [36]. This nonlinear difference in power scale leads to a situation where, within the boundary layer, the growth rate of the particle's fluid kinetic energy with increasing particle size is significantly faster than that of the potential well depth.

To quantitatively evaluate this competition, the maximum potential well depth baseline under the 6 kV applied voltage condition was extracted. By setting a typical near-wall velocity shear rate of $S = 1200 \text{ s}^{-1}$, the energy evolution data for a particle size range of 10–290 μm was calculated [37]. Calculations demonstrate, as shown in Figure 11, that when the particle size is relatively small (e.g., 10–50 μm), because they are completely submerged in the bottom stagnation zone with extremely low flow velocity, the fluid kinetic energy they acquire is minuscule and far from sufficient to overcome the dielectrophoretic potential barrier. Therefore, they are highly prone to sinking deeply into the dead zone to form persistent deposition. As the particle size increases (e.g., breaking through the 150 μm critical point), larger particles intercept the higher flow velocities of the upper oil layers. Their kinetic energy overtakes the potential energy with an overwhelming advantage, allowing them to escape with the flow. Interestingly, the derived theoretical critical radius of 150 μm falls perfectly within the size range of the rubber particles (100–200 μm) employed in our experiments. For smaller particles with $<150 \mu\text{m}$, the dielectrophoretic trapping force dominates over the fluid hydrodynamic drag, physically binding them within the steep local potential wells to act as seeds that initiate the initial bridging behavior captured in the high-speed videos. Conversely, larger particles $>150 \mu\text{m}$ easily overcome the trapping threshold due to the more pronounced size-scaling effect of the fluid drag. This elegantly explains the size-dependent selective accumulation and why the aggregate structure does not grow indefinitely under the flowing oil. Ultimately, this evolutionary pattern reveals that micrometer-scale impurity particles of small sizes inherently pose a higher risk of local accumulation compared to large-sized particles, providing a basis for formulating standards for online oil purification in transformers.

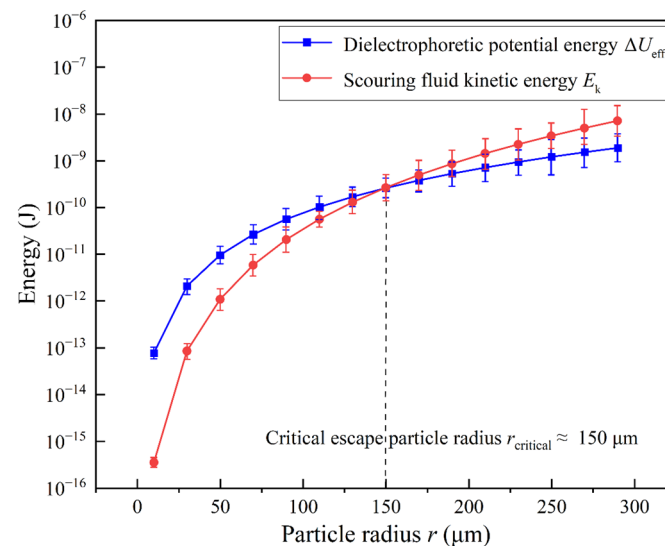


Figure 11. Evolution curves of particle kinetic energy and potential well depth with particle size (The analytical curves are calculated by extracting the maximum potential well depth baseline under the 6 kV condition and setting a typical near-wall shear rate of $S = 1200 \text{ s}^{-1}$ for a particle size range of 10 to 290 μm).

4. Conclusions

Through a combination of experimental observation and simulation modeling, this paper thoroughly investigates the motion characteristics and accumulation behaviors of rubber particles in transformer oil under DC electric fields. The main conclusions are as follows:

- (1) The dominant mechanism of DC electric field non-uniformity on particle accumulation evolution was elucidated. Under a uniform electric field, the particles mainly undergo migration driven by the Coulomb force, manifesting as reciprocating migration between the poles and gradually evolving into dynamic, unstable particle bridges. In a non-uniform electric field, the electric field distribution varies across different spatial regions, and particles in different regions exhibit staged motion characteristics. The enhanced electric field gradients and dielectrophoretic effects are the critical conditions that compel particles to directionally converge towards high field intensity regions and ultimately evolve into local accumulations.
- (2) The local accumulation mechanism of rubber particles in oil was clarified. Local potential wells are easily formed in high field intensity gradient regions such as electrode edges in non-uniform electric fields, exerting a significant binding effect on particles. This promotes the gradual transition of particles from free migration to local accumulation. Based on the potential well concept, an energy criterion for the stable local accumulation of particles was proposed: when the kinetic energy of the particle is insufficient to overcome the effective potential well depth in that region, the particle undergoes stable accumulation.
- (3) The influences of oil flow velocity and particle size on the accumulation risk were analyzed. The oil flow direction, oil velocity, and particle size all impact the particle accumulation characteristics. Controlling the oil flow direction and increasing the oil velocity can effectively suppress the local accumulation of particles. Small-sized particles are more prone to local accumulation. The main reason is that the particle kinetic energy increases with the fifth power of the radius, while the potential energy increases with the third power of the radius. The difference in their growth rates makes it difficult for particles of minute sizes to acquire sufficient kinetic energy to

break free from the potential barrier, resulting in a higher risk of local accumulation than large-sized particles.

Author Contributions: Conceptualization, W.L.; methodology, X.Y.; software, Y.Y.; validation, J.L.; formal analysis, W.L.; investigation, Z.W.; funding acquisition, Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Major Special Project of State Grid Sichuan Electric Power Company, grant number 521997240002.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Authors Wenlong Liao, Xin Yang, Yueping Yang, and Zhenyu Wang were employed by the company State Grid Sichuan Electric Power Research Institute. The remaining authors, Jiazhao Lian and Zefeng Yang, declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UHVDC	Ultra-high voltage direct current
NBR	Nitrile Butadiene Rubber
DEP	Dielectrophoretic
EHD	Electrohydrodynamic
PTFE	Polytetrafluoroethylene
C-M	Clausius–Mossotti

References

1. Wang, K.; Wang, F.; Li, J.; Zhao, Q.; Wen, G.; Zhang, T. Effect of Metal Particles on the Electrical Properties of Mineral and Natural Ester Oils. *IEEE Trans. Dielectr. Electr. Insul.* **2018**, *25*, 1621–1627. [\[CrossRef\]](#)
2. Ma, S.; Yang, D.; Liang, B.; Jin, Y. Impact of Metal Particle Size on Partial Discharge Characteristics of Moving Metal Particles in Transformer Oil. *Chem. Phys. Lett.* **2019**, *731*, 136577. [\[CrossRef\]](#)
3. Ding, M.; Xie, Z.; Li, Q.; Wang, J.; Zhang, Y.; Dai, C.; Zhao, R.; Liu, X. Partial Discharge Behavior of Oil-Paper Insulation in Converter Transformers Under Complex Electrical and Thermal Stresses. *IEEE Trans. Dielectr. Electr. Insul.* **2026**, *33*, 633–641. [\[CrossRef\]](#)
4. Wang, Q.; Bai, B.; Chen, D.; Fu, T.; Ma, Q. Study of Insulation Material Properties Subjected to Nonlinear AC–DC Composite Electric Field for Converter Transformer. *IEEE Trans. Magn.* **2019**, *55*, 8400604. [\[CrossRef\]](#)
5. Cai, W.; Zhang, C.; Zhang, M.; Tang, J. Discharge Characteristics and Mechanism of Conductive Metal Particles in Function of the Oil Flow under AC Voltages. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 268–278. [\[CrossRef\]](#)
6. Li, Y.; Zhang, Q.; Ding, Y.; Zhao, Y. Effect of Cellulose Impurities on Partial Discharges in Oil-Pressboard Insulation under DC Voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 2271–2273. [\[CrossRef\]](#)
7. Tang, J.; Ma, S.; Li, X.; Zhang, Y.; Pan, C.; Su, J. Impact of Velocity on Partial Discharge Characteristics of Moving Metal Particles in Transformer Oil Using UHF Technique. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 2207–2212. [\[CrossRef\]](#)
8. Pan, C.; Tang, J.; Tao, X.; Zhang, Y.; Ma, S. Partial Discharge and Breakdown Characteristics of Moving Transformer Oil Contaminated by Metallic Particles. *IEEE Trans. Dielectr. Electr. Insul.* **2018**, *25*, 1774–1784. [\[CrossRef\]](#)
9. Zhang, R.; Zhang, Q.; Guo, C.; He, X.; Wu, Z.; Wen, T. Bubbles in Transformer Oil: Dynamic Behavior, Internal Discharge, and Triggered Liquid Breakdown. *IEEE Trans. Dielectr. Electr. Insul.* **2022**, *29*, 86–94. [\[CrossRef\]](#)
10. Mahmud, S.; Chen, G.; Golosnoy, I.O.; Wilson, G.; Jarman, P. Experimental Studies of Influence of DC and AC Electric Fields on Bridging in Contaminated Transformer Oil. *IEEE Trans. Dielectr. Electr. Insul.* **2015**, *22*, 152–160. [\[CrossRef\]](#)
11. Sha, Y.; Zhou, Y.; Li, J.; Wang, J. Partial Discharge Characteristics in Oil-Paper Insulation under Combined AC-DC Voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2014**, *21*, 1529–1539. [\[CrossRef\]](#)
12. He, D.; Gong, W.; Xu, Z.; Geng, P.; Liu, H.; Li, Q. Effect of the DC Electric Field Polarity and Amplitude on Partial Discharge of Oil-Paper Insulated Under Wedge-Shaped Electrodes. *IEEE Trans. Dielectr. Electr. Insul.* **2022**, *29*, 599–606. [\[CrossRef\]](#)
13. Gao, C.; Qi, B.; Li, C. Effect of Interface Charge on Partial Discharge Characteristics of Oil-Pressboard Insulation in Non-Uniform AC/DC Combined Electric Field Under Different Temperatures. *CSEE J. Power Energy Syst.* **2026**, *12*, 1598–1607. [\[CrossRef\]](#)

14. Li, J.; Han, X.; Liu, Z.; Yao, X.; Li, Y. PD Characteristics of Oil-Pressboard Insulation under AC and DC Mixed Voltage. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 444–450. [[CrossRef](#)]
15. Krause, C. Power Transformer Insulation—History, Technology and Design. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1941–1947. [[CrossRef](#)]
16. Meng, X.; Guo, R.; Hou, J.; Wang, H.; Li, J. Simulation Research on the Force and Motion of Solid Particles in Transformer Oil under DC Voltage. *Energy Rep.* **2022**, *8*, 967–972. [[CrossRef](#)]
17. Birlasekaran, S. The Measurement of Charge on Single Particles in Transformer Oil. *IEEE Trans. Electr. Insul.* **1991**, *26*, 1094–1103. [[CrossRef](#)]
18. Birlasekaran, S. The Movement of a Conducting Particle in Transformer Oil in AC Fields. *IEEE Trans. Electr. Insul.* **1993**, *28*, 9–17. [[CrossRef](#)]
19. Dascalescu, L.; Mihailescu, M.; Tobazeon, R. Modeling of Conductive Particle Behavior in Insulating Fluids Affected by DC Electric Fields. *IEEE Trans. Ind. Appl.* **1998**, *34*, 66–74. [[CrossRef](#)]
20. Tang, J.; Ma, S.; Zhang, M.; Liu, Z.; Li, X. Motion Characteristics of a Charged Metal Particle in Insulating Oil under Flow State. *IEEJ Trans. Electr. Electron. Eng.* **2017**, *12*, 484–490. [[CrossRef](#)]
21. Li, B.; Huang, L.; Wang, Y.; Li, Y.; Wei, C.; Lu, Y. Experimental Study on The Motion Law of Solid Particles in Oil under Electric Field. In *2019 IEEE 20th International Conference on Dielectric Liquids (ICDL)*; IEEE: New York, NY, USA, 2019; pp. 1–4. [[CrossRef](#)]
22. Li, Y.; Yang, S.; Li, R.; Yuan, H.; Zhou, K.; Akram, S. Migration and Bridging Characteristics of Cellulose Impurities in Oil-Paper Insulation. *IEEE Trans. Dielectr. Electr. Insul.* **2024**, *31*, 801–808. [[CrossRef](#)]
23. Meng, X.; Guo, R.; Wang, H.; Han, X.; Zhang, X.; Li, J. Behavior Characteristics of Cellulose Particles in Insulating Oil Gaps under a DC Electric Filed. *IEEE Trans. Dielectr. Electr. Insul.* **2024**, *31*, 3350–3359. [[CrossRef](#)]
24. Dong, Z.; Zhang, Z.; Xue, Z.; Zhong, J.; Cheng, J.; Deng, J. Investigation of the Microscopic Dynamical Behavior and Bridging Mechanism of Cellulose Particles in Insulating Oil. *IEEE Trans. Dielectr. Electr. Insul.* **2024**, *31*, 1926–1935. [[CrossRef](#)]
25. Liao, Y.; Wei, W.; Yang, Z.; Liao, W.; Lian, J.; Jiang, K.; Yong, J.; Wu, G. Rubber Particles Motion in Mineral Oil under AC Voltage by Schlieren Imaging and Numerical Simulation. *IEEE Trans. Dielectr. Electr. Insul.* **2024**, *32*, 1508–1517. [[CrossRef](#)]
26. Naidu Vangapandu, D.; Mishra, P.; Sarathi, R.; Tariq Nazir, M.; Paramane, A.; Mondal, M. Performance Evaluation of Transformer Mineral Oil Aged Silicone Rubber/BN Nanocomposites. *IEEE Trans. Dielectr. Electr. Insul.* **2024**, *31*, 3424–3433. [[CrossRef](#)]
27. Wen, X.; Yuan, X.; Lan, L.; Hao, L.; Li, S.; Zheng, Z.; Kang, J. Effect of Transformer Oil on Room Temperature Vulcanized Silicone Rubber. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 2337–2343. [[CrossRef](#)]
28. IEC 60296:2020; Fluids for Electrotechnical Applications—Mineral Insulating Oils for Electrical Equipment. International Electrotechnical Commission: Geneva, Switzerland, 2020.
29. Yao, Y.; Su, Z.; Pan, C.; Xia, S.; Yu, M.; Tang, J. Distributed Characteristics of Free Metallic Particles in Flowing Transformer Oil Under DC and AC Voltages. *IEEE Trans. Dielectr. Electr. Insul.* **2023**, *30*, 1441–1450. [[CrossRef](#)]
30. ISO 4406:2021; Hydraulic Fluid Power—Fluids—Method for Coding the Level of Contamination by Solid Particles. International Organization for Standardization: Geneva, Switzerland, 2021.
31. Dong, Z.; Zhang, Z.; Jiang, P.; Pan, X.; Zhong, J.; Deng, J. Measurement Method of Collisional Charge and Charging Characteristics for Micrometer-Sized Particles in Insulating Oil. *IEEE Trans. Instrum. Meas.* **2023**, *72*, 1–13. [[CrossRef](#)]
32. Mahmud, S.; Golosnoy, I.O.; Chen, G.; Wilson, G.; Jarman, P. Numerical Simulation of Charging and Discharging of Particles in Contaminated Transformer Oil. In *2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP)*; IEEE: New York, NY, USA, 2017; pp. 588–591. [[CrossRef](#)]
33. Liu, L.; Zhang, X.; Ren, B. Influence of Potential Well Depth on the Dynamic Characteristics of the Bistable Electromagnetic Vibration Energy Harvester. In *2016 IEEE International Conference on Power and Renewable Energy (ICPRE)*; IEEE: New York, NY, USA, 2016; pp. 513–517. [[CrossRef](#)]
34. Melling, A. Tracer Particles and Seeding for Particle Image Velocimetry. *Meas. Sci. Technol.* **1997**, *8*, 1406. [[CrossRef](#)]
35. Schlichting (Deceased), H.; Gersten, K. *Boundary-Layer Theory*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 29–33.
36. Pohl, H.A.; Pohl, H. *Dielectrophoresis: The Behavior of Neutral Matter in Nonuniform Electric Fields*; The University of Chicago: Chicago, IL, USA, 1978.
37. Barsotti, R.; Vahey, M.; Wartena, R.; Chiang, Y.-M.; Voldman, J.; Stellacci, F. Assembly of Metal Nanoparticles into Nanogaps. *Small* **2007**, *3*, 488–499. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.