

Analysis and Simulation of Key Factors for Electrostatic Purification of Waste Hydraulic Oil Based on COMSOL

Dajun Liu¹, Xu Liu², Jiahao Cao¹, Luyang Liu¹

¹School of Mechanical Engineering, Anhui University of Technology, Ma'anshan 243032, Anhui, China

²School of Computer Science and Technology, Anhui University of Technology, Ma'anshan 243032, Anhui, China

Corresponding author: Dajun Liu (e-mail: 13721220131@163.com)

ABSTRACT Waste hydraulic oil, categorized as waste mineral oil, is listed in the National Hazardous Waste List of China, and improper disposal can cause serious pollution to soil and water environments. As a low-consumable purification technology, electrostatic oil purification enables efficient regeneration and resource-oriented treatment of waste hydraulic oil. Focusing on the electrostatic purification process, this study analyzes key influencing factors including electric field intensity, electrode structure, purification time, and flow rate based on theoretical models, and explains the migration process and action mechanism of pollutant particles under coupled electric-field and flow-field conditions. COMSOL Multiphysics is used for modeling and simulation to compare oil-purification device schemes with different electrode combinations. The results show that the wire-cylinder electrode combined with a roll-type dust collector satisfies the requirements of high-efficiency pollutant adsorption and reasonable electric-field gradient distribution. A purification device with a conical bottom enhances fluid velocity and energy transfer, facilitating rapid pollutant distribution and concentrated deposition. The findings provide technical references for electrostatic regeneration of waste hydraulic oil and treatment of similar pollutants.

INDEX TERMS waste hydraulic oil, COMSOL simulation, electrostatic purification, electric field distribution, electrode structure

I. INTRODUCTION

As an important medium for mechanical equipment, hydraulic oil plays the roles of lubrication, cooling, sealing and anticorrosion in the transmission and control of mechanical equipment, and directly affects the stability and service life of mechanical equipment[1]. Hydraulic oil is a non-renewable resource. During its service life, it may be affected by temperature differences, light exposure, oxidation and shear force, resulting in the ingress of moisture and mechanical impurity particles into the oil, as well as the generation of various pollutants such as oxides, colloids and asphaltenes. These pollutants will degrade the performance of the oil, cause problems such as wear and blockage, and bring potential risks including flammability, corrosion and environmental pollution[2-3]. Therefore, researching oil purification technology and developing efficient and green oil purification technologies are of great significance.

At present, mainstream oil purification technologies mainly include charge polymerization oil purification, centrifugal oil purification, electrostatic oil purification, multi-mechanism composite oil purification, and bionics-based renal-type oil purification. Charge polymerization oil purification is a high-efficiency oil purification device based on electrostatic physical effects and particle aggregation mecha-

nisms. It achieves deep removal of suspended contaminants in waste oil through the three-step synergistic process of “charge assignment - particle aggregation - targeted separation”, and is suitable for purifying complex systems with fine impurities such as waste hydraulic oil[4]. In contrast, centrifugal oil purification separates moisture and large particulate impurities by means of centrifugal force generated by high-speed rotation, delivering remarkable performance in removing large particulate pollutants[5]. Electrostatic oil purification mainly relies on particle polarization and adsorption under an electric field, boasting higher efficiency in eliminating fine particles[6]. Ye et al.[7] pointed out in their research that the efficiency of filter elements is one of the key factors affecting the overall performance of electrostatic oil purification. Moreover, increasing the movement speed along with the rise of particle concentration can greatly improve the oil purification efficiency. Meanwhile, many scholars have proposed centrifugal-electrostatic composite oil purifiers, whose technological process follows the sequence of coarse filtration, oil-water separation, centrifugal separation and electrostatic trapping. The composite oil purification process achieves a better overall purification effect[8]. In addition, the renal-type oil purifier draws on the separation principle of the human kidney, realizes micron-

level precision oil purification by utilizing electric field Coulomb force, maintains the stability of additives, and is applicable to various lubricating oils and hydraulic oils[9]. In summary, although different oil purification technologies have their respective advantages, they still have shortcomings in terms of efficiency, applicability and energy consumption. In particular, in-depth research is still required on fine particle removal and optimal device design.

Based on this, targeting the pollution characteristics of waste hydraulic oil, this paper takes the electrostatic oil purification technology as the core research focus. It comprehensively considers the influences of major factors including external electric field intensity, dust collector structure type, oil purification time, and oil purification flow rate on the oil purification effect. Combined with practical engineering requirements, the advanced COMSOL Multiphysics software is adopted to conduct simulation research on electrode combination configurations and the oil purification process. This paper theoretically reveals the causes affecting the purification of waste hydraulic oil, proposes optimization approaches for the electrostatic oil purification device, and provides technical references for the electrostatic regeneration and purification of waste hydraulic oil as well as the treatment of similar pollutants.

II. ANALYSIS OF KEY PURIFICATION FACTORS

A. ELECTRIC FIELD INTENSITY

Discuss the influence of electric field strength on the electrostatic oil purification efficiency. After the pollutants in the oil are adsorbed on the dust collector, the radial force formula of pollutant particles is as follows:

$$\begin{aligned} N &= F_1 + F_2 + F_3 + F_4 - F_5 - F_6 + F_7 \\ &= K \frac{1}{r^2} + K'_4 \frac{1}{r^3} + F_4 - F_5 \end{aligned} \quad (1)$$

In Equation (1), F_1 denotes the Coulomb force, F_2 the mirror force, F_3 the gradient force, F_4 the van der Waals force, F_5 the diffusion force, F_6 the viscous force, and F_7 the electric current force. Purification is achieved when pollutant particles are adsorbed by the electrode or dust collector; however, if the adsorption force is neutralized by charge transfer at the electrode interface, particle re-entrainment may occur, where previously captured pollutants are released back into the flow field. The greater the applied voltage, the stronger the resultant force, enabling the particles to acquire sufficient kinetic energy to move back and forth between the electrodes and collide intensely with the dust collector. As the distance decreases, the gradient force, van der Waals force, and mirror force change abruptly, resulting in the particles experiencing a force greater than the adsorption force and undergoing reverse motion; the radial force is illustrated below:

$$N = -F_1 + F_2 + F_3 + F_4 - F_5 + F_7 \quad (2)$$

When $N \leq 0$ in Equation (2), the pollutant particles detach from the dust-collecting body. During the collision, the

charge quantity of some pollutant particles changes while their electrical charge remains unchanged; the radial force formula for these particles is as follows:

$$N = F_3 + F_4 - F_5 + F_7 \quad (3)$$

When the condition for axial static equilibrium is satisfied, Equation (3) can be expressed as:

$$mg - 6\pi\mu a\vec{v} - \rho_1\Delta g = -Nf \quad (4)$$

In Equation (4), it represents the average velocity of the oil liquid, and denotes the friction coefficient between particles and the dust collector. When the condition is satisfied, particles will enter the flow field along with the oil liquid. To ensure a good purification effect, an electric field with appropriate intensity and gradient is required to enhance the particle adsorption speed; an excessively strong electric field may induce charge reversal upon contact with the collector. This leads to an electrostatic repulsive force that overcomes the viscous drag and van der Waals forces, resulting in particle re-entrainment (reverse scattering), which should be avoided.

1) Electrode Structure

The structure of the dust collecting body directly affects the efficiency of electrostatic oil purification. Material selection needs to balance strong dirt holding capacity and high dielectric constant, while the layout determines the electric field gradient and particle adsorption path, thereby influencing the purification speed. The following will analyze the purification efficiency of typical structures.

2) Plate electrode

The parallel plate-electrode configuration is paired with a parallel integrated structure, where the relative dielectric constants of the two different integrated materials are ε_2 and ε_3 .

$$\begin{aligned} E_1d_1 + E_2d_2 + E_1d_3 + E_3d_4 + \dots + E_1d_{2n-1} &= V \\ \varepsilon_1E_1 &= \varepsilon_2E_2 = \varepsilon_3E_3 \end{aligned} \quad (5)$$

In Equation (5), $d_1 \dots d_{2n-1}$ denotes the thickness of the oil layer, while $d_2 \dots d_{4n-2}$ and $d_4 \dots d_{4n}$ represent the thicknesses of the two dust-collecting layers, respectively. In Equation (6), E_1 , E_2 , and E_3 denote the electric field strengths between the oil layer and the dust-collecting layers. Solving and organizing Equations (5) and (6) yields:

$$\begin{aligned} E_1 &= \frac{V}{\sum d_i + \frac{\varepsilon_1}{\varepsilon_2} \sum d_j + \frac{\varepsilon_1}{\varepsilon_3} \sum d_k} \\ &= \frac{\varepsilon_2\varepsilon'_3V}{\varepsilon_2\varepsilon'_3 \sum d_i + \varepsilon_1\varepsilon'_3 \sum d_j + \varepsilon_1\varepsilon_2 \sum d_k} \\ &= \frac{\varepsilon_2\varepsilon'_3V}{M} \end{aligned} \quad (6)$$

$$\begin{aligned}
 E_2 &= \frac{V}{\frac{\varepsilon_2}{\varepsilon_1} \sum d_i + \sum d_j + \frac{\varepsilon_2}{\varepsilon_3} \sum d_k} \\
 &= \frac{\varepsilon_1 \varepsilon_3' V}{\varepsilon_2 \varepsilon_3' \sum d_i + \varepsilon_1 \varepsilon_3' \sum d_j + \varepsilon_1 \varepsilon_2 \sum d_k} \quad (7) \\
 &= \frac{\varepsilon_1 \varepsilon_3' V}{M}
 \end{aligned}$$

$$\begin{aligned}
 E_3 &= \frac{V}{\frac{\varepsilon_3}{\varepsilon_1} \sum d_i + \frac{\varepsilon_3}{\varepsilon_2} \sum d_j + \sum d_k} \\
 &= \frac{\varepsilon_1 \varepsilon_2 V}{\varepsilon_2 \varepsilon_3' \sum d_i + \varepsilon_1 \varepsilon_3' \sum d_j + \varepsilon_1 \varepsilon_2 \sum d_k} \quad (8) \\
 &= \frac{\varepsilon_1 \varepsilon_2 V}{M}
 \end{aligned}$$

To enhance the electric field intensity gradient and increase $\Delta E/\Delta X$ within the region, the material's relative dielectric constants satisfy $\varepsilon_3 > \varepsilon_2 > \varepsilon_1$, yielding the electric field intensity order: $E_3 > E_2 > E_1$. Given that the thickness of the oil layers ($d_1, \dots, d_{2n-1}$) is relatively small, the following simplification applies:

$$\frac{\Delta E}{\Delta x} \approx \frac{dE}{dx} \quad (9)$$

As shown in the above equation, the parallel-plate electrode configuration with a parallel dust collection body features a simple structure, exhibits strong contaminant adsorption capacity, and generates a significant inter-plate electric field intensity gradient, thereby enhancing the purification efficiency of oil purification equipment.

3) Coil electrode

The loose, porous filter paper is rolled into a dust-collecting assembly and filled between the wire and cylinder electrodes. First, the electrostatic field distribution equation applicable to homogeneous oil media is established, which is then modified using the Poisson equation for the potential function V . The Poisson equation for the potential function V is as follows:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V}{\partial \varphi^2} + \frac{\partial^2 V}{\partial z^2} = \frac{-1}{\varepsilon_1} \left(\rho + \sum 4\pi \varepsilon_s P E a^2 \right) \quad (10)$$

In Equation (10): r , φ , and z are the three parameters of the cylindrical coordinate system; $4\pi \varepsilon_s P E a^2$ represents the charge density of pollutant particles under a strong electric field or induced by electrostatic effects; ρ denotes the polarization rate, determined by the relative dielectric constant between the oil and the pollutant particles, given by $\rho = 3\varepsilon_s/(\varepsilon_s + 2)$. Hydraulic oils used in industrial applications are typically mineral oils, which are non-polar liquids that rarely undergo self-dissociation. The electrical conductivity of pure hydraulic oil generally remains below 10^{-14} S/m; therefore, when solving the Poisson equation for electrostatic potential distribution, the influence of oil self-dissociation can be neglected. Contaminant particles present in industrial hydraulic oils often carry electrical

charges, while their dispersed phases typically exhibit specific charge densities, enabling oil purification through electrostatic adsorption. To investigate the macroscopic electric field distribution, this study employs the Laplace equation to simplify the Poisson equation. This simplification is justified because the volume fraction of solid particles is extremely low (0.0125), and the total space charge contributed by these particles is several orders of magnitude smaller than the charge on the electrodes, thus having a negligible impact on the overall potential gradient. After modifications, the following expression is derived:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V}{\partial \varphi^2} + \frac{\partial^2 V}{\partial z^2} = 0 \quad (11)$$

Use Bessel functions to solve equation (11). In the physical model of the electrostatic purification zone, the negative electrode is a cylindrical shell with a length significantly greater than its radius, while both positive and negative electrodes are concentric cylindrical structures. The electric field strength can be approximated as dependent solely on the x - and y -axis coordinates, i.e., $\partial^2 V/\partial z^2 \approx 0$. Consequently, equation (12) can be simplified into a two-dimensional Laplace equation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V}{\partial \varphi^2} = 0 \quad (12)$$

Equation (14) can be solved using the method of separation of variables:

$$\begin{aligned}
 V(r, \varphi) &= r^n (A_n \sin n\varphi + B_n \cos n\varphi) \\
 &+ r^{-n} (A'_n \sin n\varphi + B'_n \cos n\varphi), \quad n \neq 0 \quad (13)
 \end{aligned}$$

In the physical model for studying the electrostatic purification zone, where the applied potential is set as a constant independent of the coordinate φ , Equation (13) can be simplified as follows:

$$\frac{d}{dr} \left[r \frac{dR(r)}{dr} \right] = 0 \quad (14)$$

$$R(r) - C_0 \ln r + D_0 = 0 \quad (15)$$

$$\frac{d\Phi(\varphi)}{d\varphi} = 0, \quad \Phi(\varphi) = B_0, \quad (16)$$

$$V(r) = R(r)\Phi(\varphi) = C_1 \ln r + C_2$$

Using the boundary conditions: $r = R_1$, $V = V_0$; $r = R_2$, $V = 0$, the equations (14), (15), and (16) are solved as follows:

$$V(r) = \frac{-V_0}{\ln \left(\frac{R_1}{R_2} \right)} \ln \left(\frac{R_2}{r} \right) \quad (17)$$

$$E_r = -\frac{\partial V}{\partial r} = \frac{+V_0}{\ln \left(\frac{R_1}{R_2} \right)} \cdot \frac{1}{r} \quad (18)$$

Since pollutant particles possess a certain charge density, hydraulic oil also exhibits a corresponding charge density. During the electrostatic adsorption process, the influence of hydraulic oil's charge density on the electric potential must

be considered. The Poisson equation can be rewritten as follows:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dV}{dr} \right) = \frac{-1}{\varepsilon_1} \left(\rho + \sum 4\pi\varepsilon_s P E a^2 \right) \quad (19)$$

$$K_1 = \frac{-1}{\varepsilon_1} \left(\rho' + \sum 4\pi\varepsilon_s P E a^2 \right) \rho' = \frac{\rho}{E}, \quad E = -\frac{dV}{dr} \quad (20)$$

Substitute equation 20 into equation 19 to obtain $d^2V/dr^2 = -K_1 dV/dr$. order $dV/dr = y$, $dy/dr + K_1 y = 0$, from: $r = R_1$, $V = V_0$, $r = R_2$, $V = 0$. The boundary conditions of:

$$V = \frac{V_0}{e^{-K_1 R_2} - e^{-K_1 R_1}} (e^{-K_1 R_2} - e^{-K_1 r}) \quad (21)$$

As shown in Equation (21), the electric potential exhibits an exponential radial distribution. The use of loose, porous filter paper as the dust collection material distorts the electric field between electrodes, primarily manifested in the non-uniform, porous, and anisotropic material with high dielectric constant employed in the cylindrical dust collector. When immersed in hydraulic oil, the material's relative dielectric constant is expressed tensorially. The electric field intensity within the collector shows a discontinuous distribution, with a dielectric penetration phenomenon occurring at the interface between the hydraulic oil and the layered filter paper. The equivalent dielectric constant at this interface is jointly determined by the distinct dielectric properties of both the oil and filter paper. The radial electric field gradient at the interface directly influences the purification efficiency and accuracy of the oil purification system. The mathematical relationship between the voltage and charge in the cylindrical dust collector can be derived from Gauss's law:

$$U_i = \frac{\rho}{2\pi\varepsilon_1} \ln \frac{r_{i+1}}{r_i} \quad (22)$$

Equation (23) represents the number of dielectric layers arranged radially outward from the center.

$$\begin{aligned} V_a &= \sum_{i=1}^n U_i \\ &= \frac{\rho}{2\pi\varepsilon_1} \ln \frac{r_2}{r_1} + \frac{\rho}{2\pi\varepsilon_2} \ln \frac{r_3}{r_2} + \frac{\rho}{2\pi\varepsilon_1} \ln \frac{r_4}{r_3} \\ &\quad + \dots + \frac{\rho}{2\pi\varepsilon_1} \ln \frac{r_n}{r_{n-1}} \\ &= \frac{\rho}{2\pi} \left[\frac{1}{\varepsilon_1} \left(\ln \frac{r_2}{r_1} + \ln \frac{r_4}{r_3} + \dots + \ln \frac{r_n}{r_{n-2}} \right) \right. \\ &\quad \left. + \frac{1}{\varepsilon_2} \left(\ln \frac{r_3}{r_2} + \ln \frac{r_5}{r_4} + \dots + \ln \frac{r_n}{r_{n-1}} \right) \right] \\ &= \frac{\rho}{2\pi} \left[\frac{1}{\varepsilon_1} \sum_i \ln \frac{r_{i+1}}{r_i} + \frac{1}{\varepsilon_2} \sum_j \ln \frac{r_{j+1}}{r_j} \right] \end{aligned} \quad (23)$$

$$\rho = \frac{2\pi V_0}{\frac{1}{\varepsilon_1} \sum_i \ln \frac{r_{i+1}}{r_i} + \frac{1}{\varepsilon_2} \sum_j \ln \frac{r_{j+1}}{r_j}} \quad (24)$$

$$E_1 = \frac{\rho}{2\pi\varepsilon_1 r} = \frac{V_0}{r \left(\sum_i \ln \frac{r_{i+1}}{r_i} + \frac{\varepsilon_1}{\varepsilon_2} \sum_j \ln \frac{r_{j+1}}{r_j} \right)} \quad (25)$$

$$E_2 = \frac{\rho}{2\pi\varepsilon_2 r} = \frac{V_0}{r \left(\frac{\varepsilon_2}{\varepsilon_1} \sum_i \ln \frac{r_{i+1}}{r_i} + \sum_j \ln \frac{r_{j+1}}{r_j} \right)} \quad (26)$$

From Equations (23), (24), (25), and (26), the increment of the electric field and the electric field gradient in the r -direction at the interface between the hydraulic oil and the layered filter paper within the drum-shaped dust collection body can be derived as follows:

$$\Delta E = E_2 - E_1 = \frac{V_0(\varepsilon_2 - \varepsilon_1)}{r \left(\varepsilon_2 \sum_i \ln \frac{r_{i+1}}{r_i} + \varepsilon_1 \sum_j \ln \frac{r_{j+1}}{r_j} \right)} \quad (27)$$

$$\text{grad} E = \frac{dE}{dr} \approx \frac{\Delta E}{\Delta r} \quad (28)$$

The optimized configuration of the wire-cylinder electrode and the cylindrical dust collection structure generates a high-gradient electric field, significantly enhancing the capture of fine contaminants. Moreover, this design offers high accommodation capacity, thereby enhancing the purification efficiency of the oil purifier. The electric field gradient at the interface between the hydraulic oil and the layered filter paper within the drum-shaped dust collection structure depends on ε_1 and ε_2 . When $\varepsilon_2 > \varepsilon_1$, the gradient direction aligns with the electric field intensity direction, indicating strong adsorption capability of the dust collection structure. To optimize purification efficiency, materials with a high dielectric constant should be selected.

4) clarification time

Let the concentration of contaminant particles in the hydraulic oil before electrostatic degreasing be N_0 , the instantaneous contaminant particle concentration during the electrostatic degreasing process be N , the hydraulic oil flow rate be Q , and the hydraulic system tank volume be V . The following first-order linear differential equation can be established:

$$\frac{dN}{dt} = -\frac{KQN}{V} + n \quad (29)$$

In Equation (29): n represents the ground pollution concentration generated per unit time. The solution to Equation (29) is:

$$N = N_0 e^{-\frac{KQ}{V}t} + \frac{nV}{KQ} \left(1 - e^{-\frac{KQ}{V}t} \right) \quad (30)$$

Since the value of n in Equation (30) is generally very small, it can be neglected, yielding:

$$\Delta N = N_0 e^{-\frac{KQ}{V}t} = N_0 e^{-kf v} \quad (31)$$

In Equation (31): $f = S/Q$ represents the dust collection rate per unit area. Equation (31) indicates that when the purification time is sufficiently long, dN/dT approaches zero; theoretically, the purification time is proportional to the effectiveness of electrostatic purification. During electrostatic adsorption, pollutant particles and water continuously fill the dust collection medium, generating an ion current that produces electrostatic repulsion. Therefore, the purification duration must be strictly controlled and should be

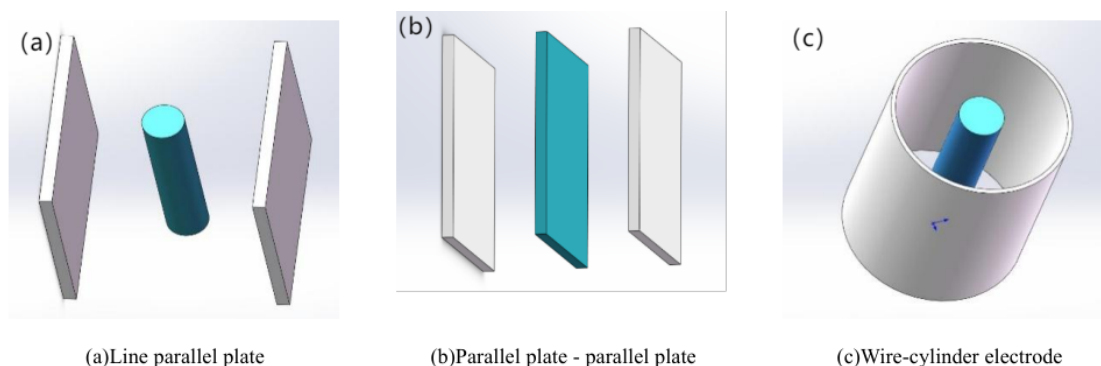


FIGURE 1. Electrode combination form of dust collector: (a) line-parallel plate; (b) parallel plate-parallel plate; (c) wire-barrel.

shorter than the time threshold at which the electrophoretic adsorption effect is canceled by electrostatic repulsion. Exceeding this limit results in significant repulsive forces exerted by the ion current on the adsorbed particles, leading to a decrease in purification efficiency.

III. MODELING AND SIMULATION OF THE PURIFICATION PROCESS

A. ELECTRODE CONFIGURATION OF THE INTEGRATED ASSEMBLY

When designing the dust collection assembly, the configuration of electrodes must be considered to ensure a uniform and stable electric field gradient. Figure 1 illustrates several commonly used electrode configuration schemes.

Using the COMSOL Multiphysics software, the positive electrode was set to 10 kV, with the material's relative dielectric constants specified as 2.5 for the positive electrode, 5 for the negative electrode, and 3 for the flow field. A steady-state electrostatic field was selected as the physical model, satisfying the charge conservation and zero charge conditions. The initial potential was set to 0 V, with a 10 kV potential applied to the positive electrode surface and the negative electrode grounded. To ensure accuracy and reduce computational load, the entire electrode domain was meshed with a fine resolution, and the calculations were performed using the ES template. The simulation results of the potential under three different electrode configurations are shown in Figure 2.

As shown in Figure 2(a), the potential distribution is uneven: the equipotential lines exhibit an elliptical shape with rapidly increasing dimensions, and the potential decreases initially rapidly before slowing down until it finally drops to zero, resulting in an electric field strength of zero outside the model. Figure 2(b) demonstrates an equally elliptical potential distribution, but with a faster increase rate compared to the parallel-plate configuration; the potential also decreases initially rapidly but not completely to zero, indicating a potential difference outside the model and posing safety hazards. Figure 2(c) shows a uniform potential distribution with circular equipotential lines that expand

uniformly in size, ultimately reaching zero potential and an electric field strength of zero outside the model. In summary, all three configuration types exhibit a “rapid initial followed by gradual decline” pattern in potential reduction. Among these, the parallel-plate configuration poses safety risks, while the line-cylinder configuration demonstrates the most uniform potential distribution with a final potential of zero, offering the best overall performance. Based on this analysis, further simulations of the electric field distributions for all three configurations were conducted, yielding the following results.

As shown in Figure 3: The line-cylinder combination exhibits a uniform electric field distribution, with electric field lines of equal intensity arranged in concentric circles and densely distributed, resulting in a gradual electric field gradient; the line-plate combination shows an uneven distribution, with rapid decline in electric field strength and localized regions where the field intensity is zero; the parallel plate combination demonstrates a relatively uniform distribution, with an electric field gradient approaching zero. Calculations further indicate that neither the line-cylinder nor the parallel plate combination contains regions of zero electric field strength, allowing particles to acquire kinetic energy regardless of their position. In contrast, the line-plate combination experiences excessive gradients, leading to ineffective capture of certain particles. Therefore, the line-cylinder configuration is the more appropriate theoretical model.

B. SIMULATION OF THE OPERATION OF THE OIL PURIFIER

Based on the above analysis, the final electrode configuration was determined as a wire-cylinder combination. This configuration was employed to investigate the fluid dynamics within different configurations of oil cleaners. Simulations were conducted using COMSOL Multiphysics 6.0, with the multiphase flow mixture model ($k-\varepsilon$) selected as the physical model. Material properties were specified as outlined in Table 1:

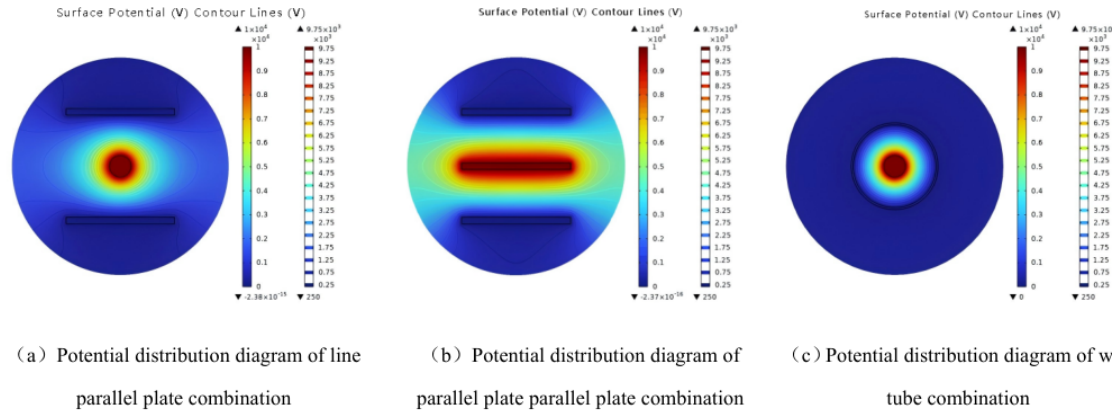


FIGURE 2. Potential distribution diagram of different combinations: (a) line-parallel plate; (b) parallel plate-parallel plate; (c) wire-barrel.

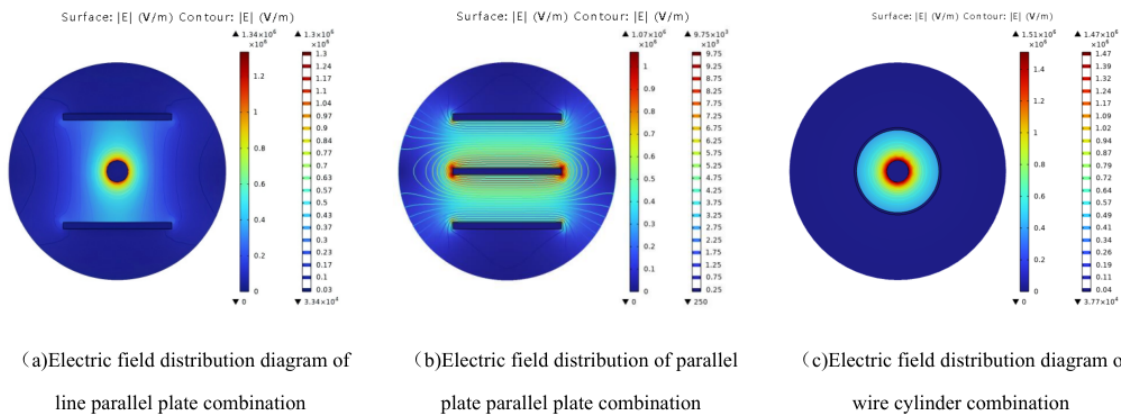


FIGURE 3. Electric field distribution of different combinations: (a) line-parallel plate; (b) parallel plate-parallel plate; (c) wire-barrel.

TABLE 1. Material property settings

name	Material properties
positive electrode	Relative permittivity: 2.5
negative pole	Relative permittivity: 5
Hydraulic oil	Relative permittivity: 2; Dynamic viscosity: 0.26 Pa·s; density: 850 kg/s
granule	Relative permittivity: 5; density: 7800 kg/s

The mixture model uses the following k - ε configuration: the dispersed phase consists of solid particles; the slip model employs the Hadamard-Rybczynski scheme; the turbulence model type is selected as RANS, with the k - ε turbulence model applied; all other parameters remain at their default settings. The mathematical expression for the Hadamard-Rybczynski slip model is as follows:

$$W_b = \frac{2R^2g(\rho_b - \rho_0)}{3\mu_0} \frac{\mu_0 + \mu_b}{2\mu_0 + 3\mu_b} \quad (32)$$

As shown in equation (32): R is the bubble radius, g is the gravitational acceleration, ρ_b and ρ_0 are the densities

of the bubble and the surrounding fluid, μ_b and μ_0 are the viscosities of the bubble and the surrounding liquid, and W_B is the final bubble velocity. In this calculation, the continuous phase is hydraulic oil (mat3), while the dispersed phase consists of particles (mat4); all properties are retrieved from the material library. The particle diameter is set to 1×10^{-5} m, the mixture model is Krieger, length limits are automatic, and all initial values are set to 0—for velocity, pressure, and particle volume fraction. Boundary conditions are specified as follows: the inlet employs a velocity boundary with a velocity of 2 m/s in the y -

direction and a dispersed phase volume fraction of 0.0125; turbulence is modeled using the $k-\varepsilon$ model (intensity 0.05, length geometrically determined). The outlet uses a pressure boundary set to 0 with no reflux, and the dispersed phase outlet is designated as the dispersed phase boundary. To balance accuracy and computational efficiency, a refined mesh was generated, and the contribution term was set

to the mixture model. The output step size range (0, 0.1, 20) was specified according to the aforementioned research nodes to observe the filling process of the mixed fluid field. Based on the linear-cylinder electrode assembly design, two electrostatic oil purification devices—one with a conical base and one without—were developed, as illustrated in Figure 4.



FIGURE 4. Three-dimensional model of simulated electrostatic oil purifier: (a) with conical bottom; (b) without conical bottom.

The study compared the mixed flow velocity, solid particle flow velocity, and particle volume fraction of two electrostatic oil purification devices. The values for the device with a conical bottom are shown in Figures 5, 7, and 9, respectively; the corresponding data for the device

without a conical bottom are presented in Figures 6, 8, and 10. The study time points were set at 0, 1, 5, and 20 seconds, with 0 seconds representing the initial state; significant changes were observed in all parameters between 0 and 1 second, and stability was achieved by 20 seconds.

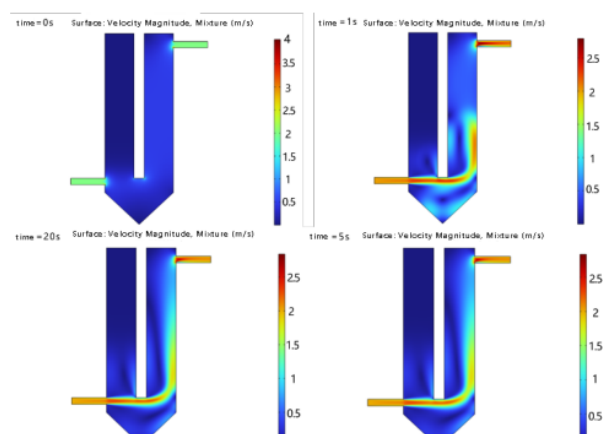


FIGURE 5. Mixture flow velocity of cone bottom electrostatic oil purifier.

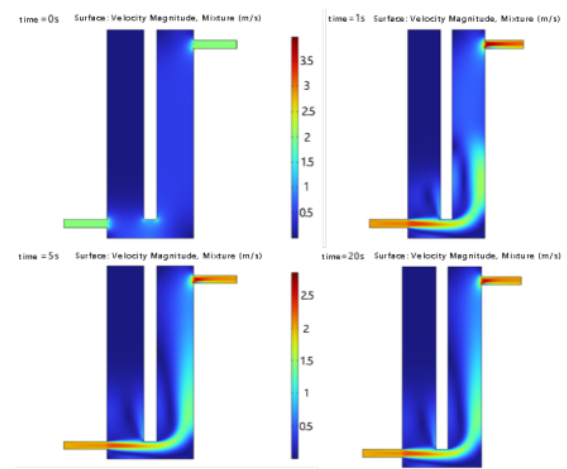


FIGURE 6. Mixture flow velocity without cone bottom electrostatic oil purifier.

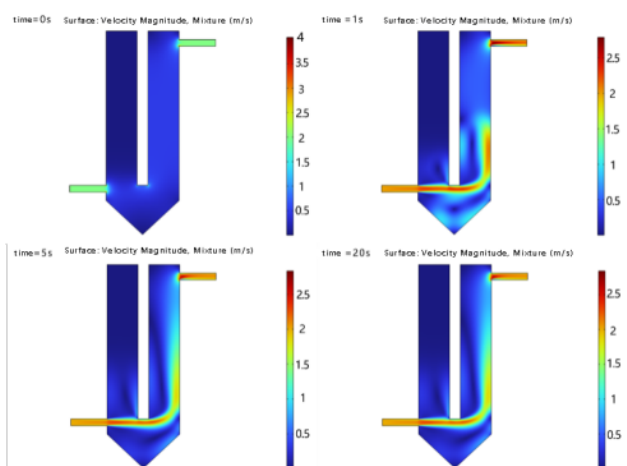


FIGURE 7. Solid particle flow velocity of electrostatic oil purifier with conical bottom.

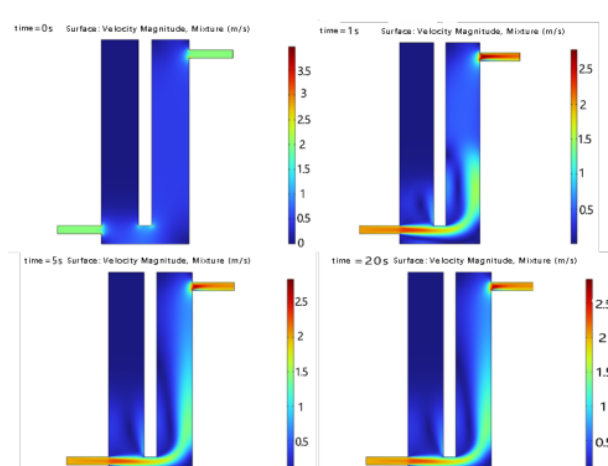


FIGURE 8. Solid particle flow velocity without cone bottom electrostatic oil purifier.

As shown in Figures 5 and 6, regardless of whether a conical bottom structure is installed, the inlet and outlet velocities at the initial moment are set to 0.2 m/s to maintain a stable flow field and prevent turbulence. Although the particle density is 7800 kg/m^3 , the influence of the electrostatic field and pressure gradient on fine particles remains dominant, but gravity is correctly accounted for in the force balance model to ensure simulation accuracy. However, the two devices exhibit distinct differences during flow field evolution. In the device with the conical bottom structure, the horizontal velocity first increases and then decreases while remaining stable; the vertical velocity peaks near the right wall, generating vortices in the triangular region. In contrast, the velocity distribution under the no-conical-bottom configuration shows similar characteristics but overall lower velocities compared to the conical bottom case. The figures demonstrate that the conical bottom structure effectively enhances fluid velocity and energy transfer, accelerating fluid coverage across the container volume,

whereas the left half region remains low-velocity due to the absence of an outlet.

Figures 7 and 8 further demonstrate that the velocity distribution of solid particles aligns with the flow pattern of the mixed fluid. This is because the gravitational and force acting on the particles are negligible compared to the pressure gradient force, allowing the particles to move with the fluid without significant settling. As shown in Figure 9, at 1 second, the particles are primarily concentrated in the inlet horizontal zone, the left half-zone, and the triangular zone. The distribution in the left half-zone results from the diffusion effect of fluid entering the container from the outlet; in the triangular zone and the right wall region, dispersion and vortex motion are induced by the fluid interacting with the wall surfaces. By 5 seconds, the particles gradually concentrate in the triangular zone and the right half-zone, with some beginning to diffuse into the left half-zone, although the particle concentrations in the right half-zone and the triangular zone remain consistently higher.

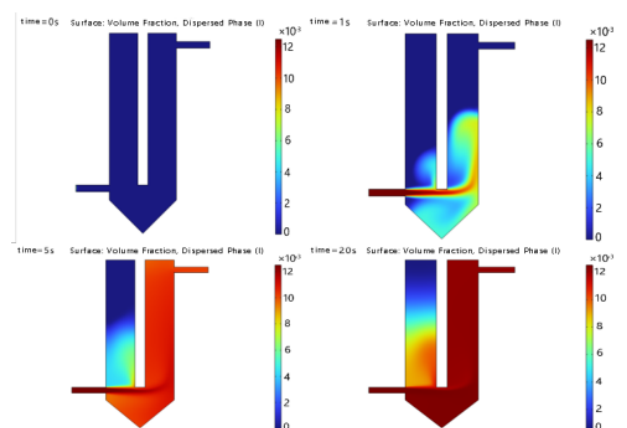


FIGURE 9. Volume fraction of solid particles in electrostatic oil purifier with conical bottom.

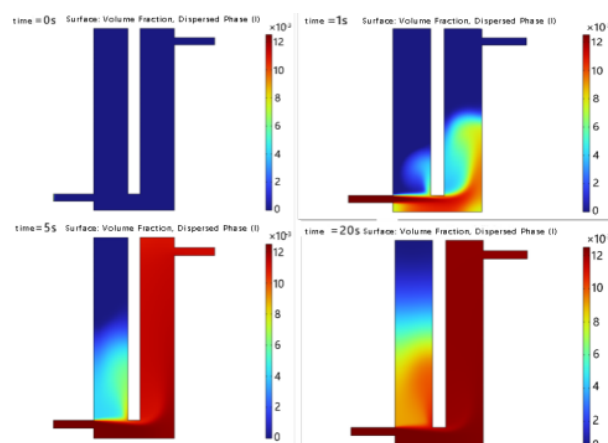


FIGURE 10. Volume fraction of solid particles without cone bottom electrostatic oil purifier.

Figure 10 shows the conditions at 1 second and 5 seconds

in the absence of a conical base: At 1 second, the particles are similarly located in the horizontal inlet zone and the left half-region, primarily concentrated in the bottom area. This is because the fluid in the horizontal direction encounters the right wall, changes direction vertically, and rapidly impacts the bottom, causing particle deposition. At 5 seconds, the particles are mainly concentrated in the bottom and right half-region, then gradually diffuse to the left; ultimately, the lower region remains larger than the right and left regions, while concentrations in other areas are nearly uniform.

As shown in the figure, within the same time frame, the particle concentration is significantly higher without the conical base device compared to with it, demonstrating superior purification efficiency in the short term. However, since the conical base device increases flow velocity and kinetic energy, accelerating pollutant movement and migration, the purification efficiency shows no difference after 20 seconds until reaching steady state. The triangular zone of the conical base device allows solid particles to accumulate in an inverted triangular pattern, and the small discharge outlets arranged beneath it facilitate concentrated pollutant discharge, resulting in better long-term operational performance and engineering applicability. Thus, the conical base electrostatic oil purification device—characterized by

rapid flow velocity, efficient energy transfer, and effective pollutant dispersion—achieves oil purification as rapidly as (or even better than) the device without a conical base. Additionally, this design facilitates subsequent centralized pollutant sedimentation and simplifies discharge port installation, enabling efficient pollutant treatment.

IV. ANALYSIS OF PURIFICATION RESULTS

Building on the previous simulations of key factors such as electric fields and electrodes, this paper further conducts a comparative evaluation of the electrostatic purification effectiveness of waste hydraulic oil from various industrial systems through actual oil purification tests. The experimental samples were obtained from four typical oil systems shown in Figure 11: 1. Brushing machine system; 2. Steam turbine system; 3. Hydraulic system; and 4. Lubrication system. These systems represent waste oils with varying degrees of contamination and operating conditions. The study primarily compares the particle counts before and after purification (Table 2), calculates the purification efficiency for each system (Figures 12 and Table 3), and analyzes changes in physicochemical parameters and metal content (Table 4).

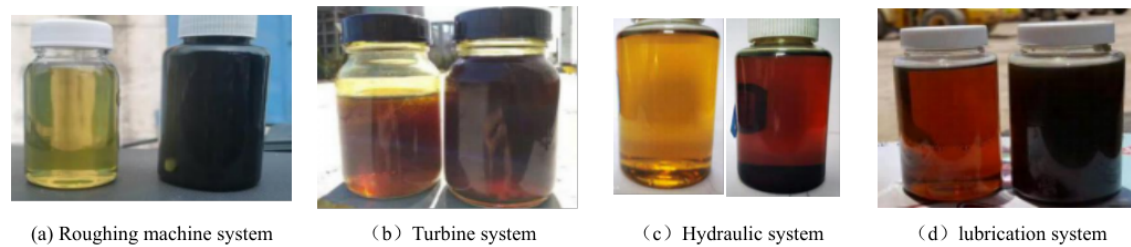


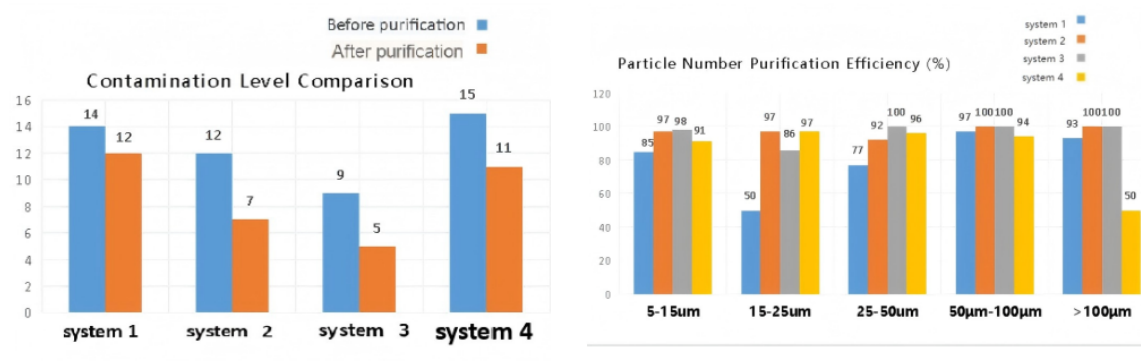
FIGURE 11. Four typical fluid system oil samples.

TABLE 2. Number of particles before and after purification

Particle size range (um)	System 1		System 2		System 3		System 4	
	Before purification	After purification	Before purification	After purification	Before purification	After purification	Before purification	After purification
5–15	4157670	616960	713765	22410	122525	1850	5659800	515880
15–25	51675	25650	12215	425	1100	150	433080	10950
25–50	8055	1890	2025	155	550	0	74100	2610
50–100	7535	245	150	0	100	0	3930	240
>100	798	55	60	0	0	0	480	240

TABLE 3. Comparison of purification efficiency

system number	Change rate of particle number (%)				
	5–15 μ m	15–25 μ m	25–50 μ m	50–100 μ m	>100 μ m
1	85	50	77	97	93
2	97	97	92	100	100
3	98	86	100	100	100
4	91	97	96	94	50
average value	93	83	91	98	86

**FIGURE 12.** Comparison of purification efficiency.

The electrostatic purification technology demonstrates significant removal efficacy for particles of all size fractions, with System 2 and System 3 exhibiting the optimal overall performance. The purification efficiency across all particle size ranges generally exceeds 92%, particularly outstanding for removing fine particles between 5–15 μ m (efficiency > 96%), confirming the high capture capacity of the wire-cylinder electrode configuration derived from simulation results for minute particles.

The primary physicochemical parameters of the oil samples before and after purification are shown in Table 4. Analysis revealed that the kinematic viscosity (at 40°C) remained unchanged in all systems, indicating that the

electrostatic purification process did not adversely affect the fundamental physical properties of the oil. The moisture content in all systems stabilized at 0.03% post-purification, demonstrating effective dewatering capability. The NAS contamination levels generally decreased after purification, with System 2 and System 3 showing particularly significant improvements—reducing from Level 12 to Level 7 and from Level 9 to Level 5, respectively—with enhanced water separation performance observed in certain systems. Major metal elements such as Fe and Cu, primarily derived from mechanical wear, exhibited reduced concentrations post-purification, with notable Fe removal effects in System 1 and System 4.

TABLE 4. Comparison of purification efficiency

system number	1		2		3		4	
	Before purification	After purification	Before purification	After purification	Before purification	After purification	Before purification	After purification
Kinematic viscosity 40°C	5	5	36	36	46	46	150	150
Total acid value	0.085	0.11	0.34	1.28	0.49	0.52	1.03	1.12
water content%	0.04	0.03	0.09	0.03	0.03	0.03	0.03	0.03
Water separability 54°C	7	7	15	10	5	10	10	10
NAS Grade	14	12	12	7	9	5	15	11
>5um	4157670	616960	713765	22410	122525	1850	5659800	515880
>15 μm	51675	25650	12215	425	1100	150	433080	10950
>25 μm	8055	1890	2025	155	550	0	74100	2610
>50 μm	7535	245	150	0	100	0	3930	240
>100 μm	798	55	60	0	0	0	480	240
Fe mg/kg	48	4	7	2	1	1	101	31
Cu mg/kg	61	15	2	1	1	1	1	1
Ba mg/kg	183	168	3010	4000	1	1	1	1
Ca mg/kg	2	2	87	7	62	53	79	101
Zn mg/kg	2	3	500	15	539	559	520	545

The experimental results demonstrate that the device yields a purification efficiency exceeding 96%. Specifically, the experimental observation of concentrated pollutant discharge aligns with the simulated deposition patterns in the triangular zone of the conical bottom structure. The agreement between the experimental removal rates and the simulated particle trajectories provides necessary validation for the vortex-driven capture mechanism identified in the COMSOL model.

V. CONCLUSION

(1) The migration of oil pollutant particles is influenced by a combination of pressure gradient forces, electrostatic attraction forces, and Coulomb forces. The intensity and gradient of the electric field must be appropriately balanced between these forces. Insufficient electric field intensity or gradient results in inadequate driving force, whereas excessive intensity may induce charge exchange or cause particle suspension, thereby compromising purification efficiency.

(2) Simulation using COMSOL software demonstrates that the wire-cylinder electrode combined with the drum dust collector forms a high-gradient electric field, combining the advantages of simple structure and strong contaminant capture capacity. It generates a uniformly graded and rationally distributed electric field within the oil, enabling efficient capture of fine particles ranging from 5 to 15 μm , with a purification efficiency exceeding 96%.

(3) The wire-cylinder electrode generates a uniformly distributed electric potential field, with equipotential lines arranged in a circular pattern. The potential attenuation characteristics facilitate particle movement. Simulation results show that the purification efficiency of the device without a conical base is higher in the short term, while the device with a conical base increases particle velocity; the efficiency difference between the two devices under stable operating conditions is minimal. The conical base promotes particle aggregation in the triangular region, making it suitable for the design of small-diameter discharge pipes.

AUTHOR CONTRIBUTIONS

Conceptualization – Dajun Liu, Xu Liu, Jiahao Cao and Luyang Liu; methodology – Dajun Liu, Xu Liu, Jiahao Cao and Luyang Liu; investigation – Dajun Liu, Xu Liu, Jiahao Cao and Luyang Liu; writing-original draft preparation – Dajun Liu, Xu Liu, Jiahao Cao and Luyang Liu. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

ACKNOWLEDGEMENTS

Not applicable.

REFERENCES

- [1] Z. Yan, F. Zhan, W. Zhou, G. Ding, B. Yue, Z. Wu, and Y. Shao, "Experimental investigation and modeling of oil retention of R454B-PVE oil mixture in suction pipes of air conditioners," *International Journal of Refrigeration*, vol. 187, 2026, 106922.
- [2] Z. Mou, J. Yao, L. Wang, Y. He, B. Zhao, Z. Wang, Y. Li, W. Tang, Z. Jiang, and B. Wang, "Immature polymeric nanoparticles as promising lubricant additives enable robust oil-based lubrication and efficient waste-to-resource conversion," *Tribology International*, vol. 219, 2026, 111791.
- [3] B. O. Ceylan and S. Memis, "Fuzzy parameterized fuzzy soft matrices-based failure mode and effects analysis (FPFS-FMEA) with ship lubricating oil system risk assessment," *Ocean Engineering*, vol. 342, Part 4, 2025, 123049.
- [4] V. K. Singh, A. Chatterjee, P. Maiti, P. Parmar, S. Mukherjee, and B. C. Meikap, "Pyrolysis of used lubricating oil using industrial waste-based catalyst for energy efficient fuel generation: A comprehensive review," *Fuel*, vol. 391, 2025, 134751.
- [5] Y. Yang, C. Chang, T. Liu, Y. Feng, Y. Wang, J. Jin, K. Cui, P. Xie, and X. Wu, "Effect of liquid properties on filtration performance of filters for lubricating oil separation from natural gas," *Chemical Engineering Research and Design*, vol. 216, 2025, pp. 282–292.
- [6] X. Zhang, J. Wu, Y. Liu, Z. Zhang, C. Hu, and Y. Lu, "Preferential adsorption control: Ca-based LDO for regenerating used lubricating oil," *Progress in Natural Science: Materials International*, vol. 34, no. 1, 2024, pp. 155–161.
- [7] X. H. Ye, J. F. Wang, W. D. Shi, et al., "Liquid-solid two-phase purification performance of ship electrostatic oil purifier[J]," *Journal of Coastal Research*, vol. 94, no. 1, p. 60, 2019.
- [8] R. Rafie, Mohammed, I. A. R. Ibrahim, A. H. Taha, and G. McKay, "Waste lubricating oil treatment by extraction and adsorption," *Chemical Engineering Journal*, vol. 220, 2013, pp. 343–351.
- [9] T. F. Guerin, "Environmental liability and life-cycle management of used lubricating oils," *Journal of Hazardous Materials*, vol. 160, no. 2–3, 2008, pp. 256–264.
- [10] D. K. Singh, J. Kurien, and A. Villayamore, "Study and analysis of wind turbine gearbox lubrication failure and its mitigation process," *Materials Today: Proceedings*, vol. 44, Part 6, 2021, pp. 3976–3983.
- [11] M. Yu, H. Ma, and Q. Wang, "Research and Recycling Advancement of used Oil in China and All Over the World," *Procedia Environmental Sciences*, vol. 16, 2012, pp. 239–243.
- [12] Q. Liu, H. Hou, Y. Wang, M. Deng, T. Li, Y. Jia, and E. Hu, "Towards low-carbon heavy oil recovery: multi-source renewable energy integration and multi-objective optimization," *Fuel*, vol. 424, 2026, 139324.
- [13] YIN Ping, "Design of electrostatic oil purification system for metallurgical hydraulic lubrication station[J]," *Metallurgical Equipment*, 2024, no. 4, p. 38.
- [14] S. Zhang, K. Chen, H. Yan, Y. Dai, Z. Yue, J. Yan, X. Wei, H. Tian, and C. Xiao, "Construction of biomimetic 'solid-bridge' structure reinforced FEP porous membrane and its application in high-temperature waste oil purification," *Journal of Environmental Chemical Engineering*, vol. 14, no. 3, 2026, 122588.
- [15] A. Mishra, H. Siddiqi, M. Sonowal, A. Chatterjee, P. Maiti, and B. C. Meikap, "A cumulative study on pyrolysis of waste motor oil exploring the design and development of a fixed-bed laboratory scale setup with emphasis on process parameter optimization, COMSOL simulation and preliminary risk assessment," *Process Safety and Environmental Protection*, vol. 185, 2024, pp. 1219–1231.