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RESEARCH NOTE

Dehydration of emulsified lubricating oil by three fields: swirl centrifugal field, pulse electric field and vacuum temperature field

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Abstract Lubricating oil can be easily polluted by water and emulsified, thereby negatively affecting the lubricating property. Meanwhile, wasted lubricating oil, a complex composition, presents high water content and exists with emulsion. A single technological method is difficult to be satisfied for efficient demulsification and dehydration of emulsified lubricating oil. In this paper, it is proposed that the swirl centrifugal field made by hydrocyclone, pulse electric field, and vacuum temperature field are coupled to achieve the oil's dehydration. Based on the theories, it is reasonable to use three fields for oil's demulsification. In the experiment of three-field dehydrating, the demulsification device is divided into two parts, namely, the coupled unit of pulse electric field and hydrocyclone, and the vacuum heating unit. The structure and size of the device were optimized through numerical simulation. With two modes of single field and three-field, the experiments were carried out. Results indicated that the use of three-field was more energy efficient and faster compared with the traditional vacuum heating method only.

Keywords Dehydration · Swirl centrifugal field · Pulse electric field · Vacuum temperature field · Emulsified lubricating oil

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Introduction

Lubricating oil, the second largest petroleum product, is widely used in machinery, electric power, transportation, and chemical industry [1]. Lubricating oil is prone to pollution during storage, transportation, filling and usage, and is then converted into emulsified oil [2]. The emulsified oil affects the physical and chemical properties of the lubricating oil, thereby leading to a decreased level of oiliness and lubrication failure [3]. The dehydration and purification treatment of emulsified lubricating oil is important in prolonging the service life, recovering the usability of the oil, reducing the generation of waste oil and ensuring the safe operation of the equipment [4]. In addition, the annual quantity of waste lubricating oil is high, of which 40–45 % can be reused through regeneration treatment [5]. The dehydration treatment is the first step in the regeneration technology of waste lubricating oil [6].

Common dehydration methods of emulsified lubricating oil include sedimentation, centrifugation, vacuum heating, etc. Nevertheless, these methods present several limitations as follows: (1) sedimentation, low demulsification efficiency; (2) centrifugation, easily causes too much loss of oil additives; (3) vacuum heating, high energy consumption; (4) filtration, limited processing ability; and (5) chemical methods, the oil can be easily polluted by the chemical demulsifier [7]. Over the recent years, several new demulsification methods have been developed, such as pulse electric field method [8], ultrasonic method [9], microwave method [10], and biological methods [11]. For emulsified lubricating oils polluted by water, the use of a single physical technique, such as vacuum heating, for rapid and efficient demulsification is difficult. Only the optimal combination of two or more unit operations can ensure successful dehydration of emulsified oil, but this strategy is difficult to employ for conventional technologies [12]. So this technology of coupling or integrated fields is the main technique used in the development of demulsification for emulsified oil.

This article mainly discusses the integration or coupling of three common physical fields, namely, hydrocyclone, pulse electric, and vacuum temperature fields, to achieve fast and efficient dehydration of emulsified lubricating oil.

Theories

Pulse electric field demulsification

Pulse electric field demulsification is a new dehydration method based on conventional electric field dehydration. The pulse electric field induces droplets in oils to generate repeating tensile deformation, intensifies the interface vibration of droplets, reduces the intensity of the interfacial film, and then accelerates mutual coalescence between droplets [13]. At present, research on pulse electric field dehydration mainly focuses on the determination of the optimal demulsification electric field conditions, such as electric field intensity and electric field frequency [14, 15]. The rise and fall of pulse voltage are crucial in ensuring the coalescence of droplets in oil. These parameters are determined by circuit resistance and coalescence device capacitance. The recommended frequency f_p in this method is in the following range [16]:

$$\frac{1}{2\pi\tau_{\mathrm{M-W}}} < f_p < \frac{1}{2\pi\tau_{\mathrm{P-Srise}}} \tag{1}$$

where $\tau_{\mathrm{M-W}}$ is the relaxation time and $\tau_{\mathrm{P-Srise}}$ is the pulse boost time constant. In addition, the field intensity can be estimated as [17]:

$$E_0 = \frac{V_p}{0.577L_e} \tag{2}$$

where V_p is the voltage between electrodes and L_e is the distance between electrodes.

When the telescopic deformation dynamics of oil droplets subjected to the pulse electric field is determined, the intensity and frequency of the optimal demulsification pulse electric field are associated with the system parameters of the emulsified oil, such as oil viscosity, interfacial tension, relative dielectric constant of the medium, and grain size of the droplet [18].

Swirl centrifugal field dehydration

Hydrocyclone, producing swirl centrifugal field, utilizes density difference between oil and water. When the liquid mixture flows into the hydrocyclone along the tangential direction from the entrance, the mixture generates high-speed revolution. Under the action of centrifugal force, the droplets gather near the wall, move toward the underflow exit, and are finally expelled. As the oil moves toward the hydrocyclone's central axis, a centronucleus is formed, flows to the entrance direction, and is expelled from the overflow port [19]. Oil–water is separated through this process. In hydrocyclone, the oil droplets are subjected to viscous shear stress, Reynolds shear stress, and Magnus force [20]. Numerical simulation is used to study oil/water separation properties because the flow field is comparatively complex [21]. Based on large eddy simulation theory, the movement locus of the droplets in the hydrocyclone can be obtained with the following formula. The separation efficiency of hydrocyclone can be effectively estimated by analyzing the movement locus [22].

$$\left(1+\frac{1}{2k}\right)\frac{d\vec{U}_d}{dt} = \frac{3C_d}{4kD_d}\left(\vec{U}_f-\vec{U}_d\right)\left|\vec{U}_f-\vec{U}_d\right| + \frac{1}{k}\frac{d\vec{U}_f}{dt} + \frac{1}{2k}\frac{d\vec{U}_f}{dt} \tag{3}$$

$$\frac{d\vec{X}_d}{dt} = \vec{U}_d \tag{4}$$

where C_D is the drag coefficient, k is the density ratio, $\vec{U}_d$ is the droplet velocity, $\vec{U}_f$ is the fluent velocity, D_d is the hydrocyclone diameter and $\vec{X}_d$ is the droplet coordinate.

Vacuum heating dehydration

The working principle of a vacuum dehydration device involves the heating of the oil–water mixture to a specific temperature under a negative pressure condition. Oil–water vacuum distillation separation is achieved because of the differences in boiling points. The evaporation diffusion equation of water in oil is shown as follows [23]:

$$N = \frac{D_{AB}}{zRT}\ln\frac{1}{1-\frac{P_{AB}}{P}} \tag{5}$$

where D_{AB} is the diffusion coefficient of component A in component B, z is the distance in the diffusion direction, R is the perfect gas constant, T is the thermodynamic temperature, and P is the pressure.

The vacuum filter oil machine is the representative vacuum dehydration equipment. Vacuum dehydration can be used to remove free water, emulsified water, and dissolved water. In addition, the emulsified oil can be dehydrated through this method without consuming oil additives. However, this method consumes a large amount of heating energy, requires high cost, and yields poor dehydration effect for the emulsified oil with high water contents.

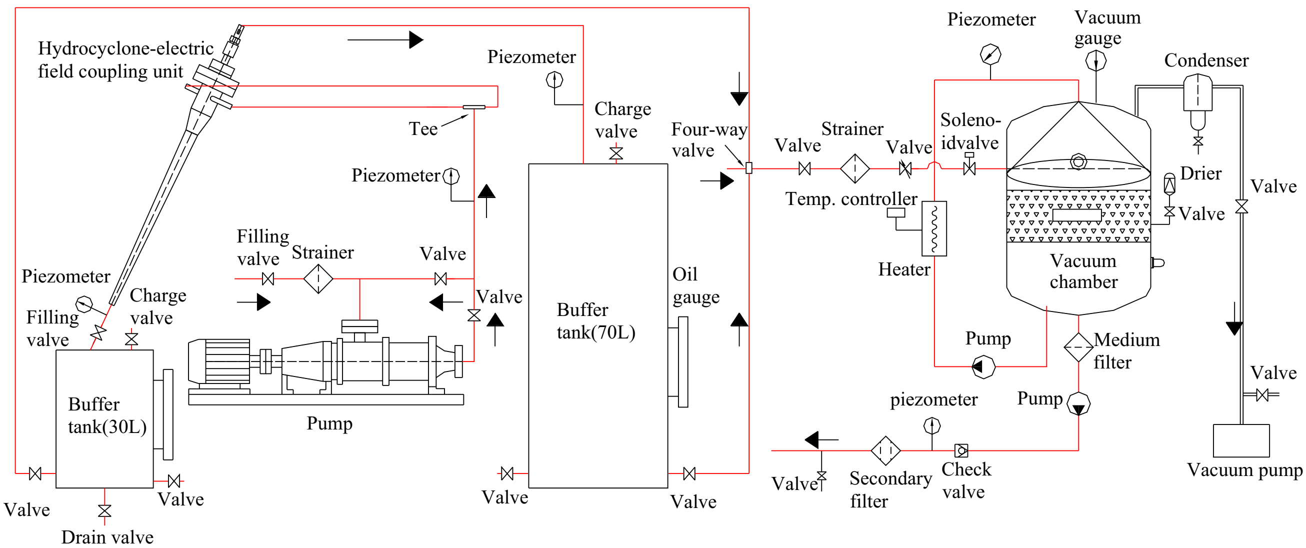


Fig. 1 Diagram of technological process of three-field coupling dehydration

Technological process of three-field dehydration

The technological process of three-field dehydration for the emulsified lubricating oil was designed, shown as Fig. 1. The dehydration process mainly consists of two parts, namely, the hydrocyclone with a set of copper electrodes fixed on the parallel part of the entrance and the back-end vacuum heating dehydration portion. Under the effect of screw pump, solid impurities (such as metal particles and sand) in oil can be filtered through the strainer. The emulsion droplets from the strainer coalesce and increase in size because the pulse electric field is fused in the hydrocyclone, and the oil–water separation is rapidly accomplished under the effect of the swirl centrifugal field. The oil from the overflow port of hydrocyclone contains a small amount of water, which is difficult to be removed using the pulse electric and hydrocyclone fields only. After being heated, the oil flows into the vacuum tank. Under the action of nitrogen blowing, the water vapor in the oil is then fully released and the oil is protected from oxidation. After entering the condenser, water vapor condenses into water. In addition, the system sets the inner circulation function to increase the time of the oil to flow through the vacuum tank and to deeply purify the oil.

Experiment setup

Test device

Based on the dehydration principle of swirl centrifugal field, pulse electric field and vacuum temperature field, the three-field dehydration device was produced, as shown in Fig. 2.

Fig. 2 Test device of three-field for emulsified oil’s dehydration

The relevant operation performance parameters of the device are shown in Table 1.

Electric field–swirl centrifugal field coupling unit

When the gravity field is replaced with swirl centrifugal field made by hydrocyclone, the unit couples with the hydrocyclone and high-voltage pulse electric fields. As such, the high-voltage pulse electric field is used to coalescence small emulsion droplets within a short time, and

Table 1 Relevant operation performance parameters of the device

Nominal flow rate	Inlet pressure of hydrocyclone	Total power of pump	Heating power	Pulse voltage/frequency
20 L/min	0.6 MPa	4.5 kW	20 kW	9 kV/60 Hz

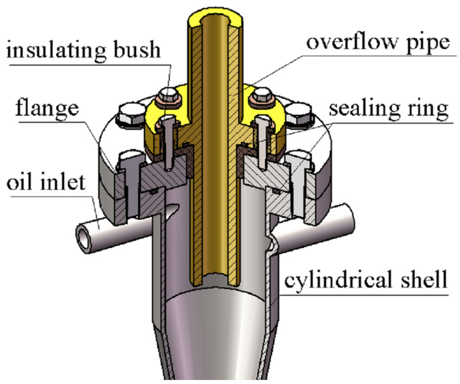


Fig. 3 Coupling unit of electric field–Swirl centrifugal field

the hydrocyclone field is used to separate the settled and coalesced droplets within a short time. Through this process, the efficiency of demulsification of oil can be improved and lubricating oil can be efficiently and rapidly dehydrated [24].

In device, the main unit is the hydrocyclone with a double cone section, and the tangential double-inlet was designed to stabilize the flow field (shown as in Fig. 3) [25]. The overflow port was designed to be bigger than that of the deoiling hydrocyclone because the latter was classified as a dehydration type. Thus, the oil phase can rapidly flow out. In addition, the cone vertex angle of hydrocyclone was increased to accelerate oil discharge. The overflow pipe had an elongation quantity in the straight pipe of the hydrocyclone and was made up of copper. The overflow pipe, which was insulated with the tube body through the insulating material, was used as the positive pole of the high-voltage electric field, whereas the straight pipe of hydrocyclone was used as the negative pole. Thus, a high-voltage electric field is formed in the straight pipe of hydrocyclone.

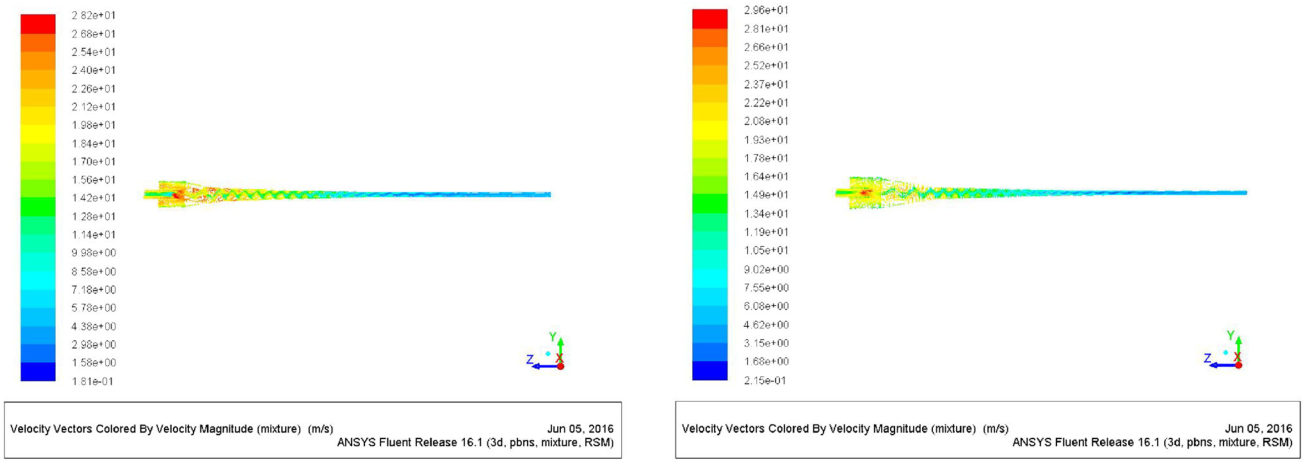
With regard to the selection and design of the hydrocyclone, the nominal diameter is set as $d_0 = 26$ mm. Based on the common design principle of hydrocyclone, the inner diameter of the straight pipe is set as $d_1 = 55$ mm. The overflow pipe has an elongation quantity in the straight pipe of hydrocyclone, which disturbs the flow field. Thus, the inner diameter of the straight pipe is increased to $d_1 = 70$ mm. The software ANSYS was used for numerical simulation of hydrocyclone to investigate the design rationality of the two kinds of pipe diameters, and the velocity and residence time of water particle are shown in Figs. 4, 5.

From Fig. 5, the hydrocyclone with a diameter of $d_1 = 55$ mm contain more water particles flowing from the overflow port, whereas the hydrocyclone with a diameter of $d_1 = 70$ mm present a small amount of water particles being expelled from the overflow port and water particles staying in underflow pipe for a longer time. This finding indicates that the pipe with a diameter of 70 mm exhibits a better separation effect. Therefore, the straight pipe of hydrocyclone must have an inner diameter of $d_1 = 70$ mm.

Vacuum demulsification dehydration unit

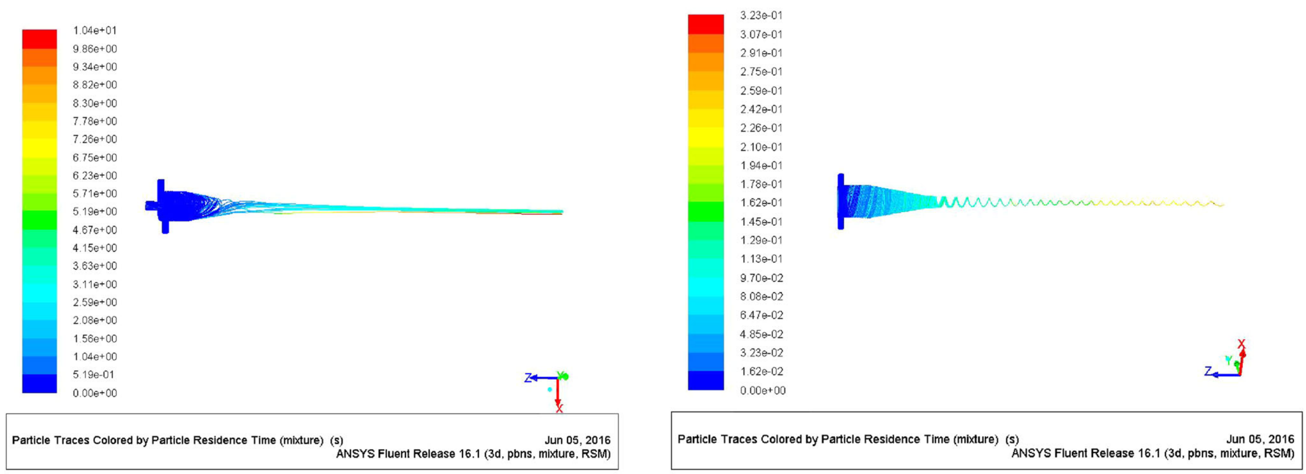
As shown in Fig. 1, after the emulsified oil flows through the electric field–hydrocyclone field coupling unit, most water flows out from the underflow pipe, whereas the oil with a small amount of water flows from the overflow pipe and then into the vacuum heating unit under negative pressure. The unit adopts the efficient vacuum separation tower and the appropriative oil atomizer. Compared with traditional models, the vacuum heating unit presents higher separation efficiency and separation degree, thereby considerably improving the vacuum separation effect.

In Fig. 1, the emulsified oil, which flows from the overflow pipe and then into the strainer through the filling valve, thereby filtering bulky mechanical impurities. The emulsified oil then flows into the vacuum separation chamber through the oil-taking control valve and the oil-taking solenoid valve. After the pressure is increased by the oil circulating pump, the emulsified oil is heated by the heater and the temperature gradually increases. After stabilizing temperature using the temperature controller, an oil mist cover is formed because of the positive pressure at the top of the vacuum chamber by the atomizer. This mist can prevent the rise of oil bubbles in the vacuum separation chamber and can avoid the injection of the vacuum pump of oil during the operation. Thus, antifoaming is automatically prevented. After atomization, the oil reenters the efficient separation tower, in which an oil film is again formed. The developed area of the oil film significantly increases. The water in the oil rapidly transforms from liquid into vapor. When nitrogen is at the bottom of the vacuum separation chamber, the water vapor in oil is removed and expelled from the top. Under the oil drain pump, the pressure of oil after dehydration changes from negative to positive, and the oil flows from the oil discharge outlet through the check valve and the fine filter. After one or more circulations, clean oil is generated.



(a) $d_1 = 55$ mm **(b)** $d_1 = 70$ mm

Fig. 4 ANSYS numerical velocity results of the two kinds of pipe diameters



(a) $d_1 = 55$ mm **(b)** $d_1 = 70$ mm

Fig. 5 ANSYS numerical particle residence time results of the two kinds of pipe diameters

Experiment sample

The 46# turbine oil, composed of base oil and a certain proportion of additives, is widely applied in power plant steam turbine, water turbine generator, etc. A BF-03 type kinematic viscosity tester and the BF-18A type density tester, produced by Dalian Northern Analysis Instrument Limited Company, were used to measure the kinematic viscosity (v) and the density (ρ) of the 46# turbine oil at 20 °C. Its physical property parameters are shown in Table 2. A certain amount of water was poured into the 46# turbine oil and the emulsified oil with a water content of 15 %, which was selected as the experimental oil sample, was formed after having been mixed fully. The emulsified oil's parameters are also given in Table 2. Kinematic viscosity of emulsified oil is much lower than that of original oil, which shows that performance of lubrication of emulsified oil happens to weaken dramatically. Additionally, the water content of oil sampled was measured with a trace moisture tester SYD-2122C (method of Karl Fischer titration) in the laboratory.

Results and discussion

In the experiment, the emulsified 46# turbine oil with a water content of 15 % was selected as the experimental oil sample and divided into several groups. The device was used to conduct the dehydration treatment of the emulsified oil in two modes.

Table 2 Parameters of the 46# turbine oil with different status at 20 °C

Status	Original oil	Emulsified oil (water content 15 %)
Density ρ ($kg.m^{-3}$)	895	912
Viscosity v ($m^2.s^{-1}$)	280×10^{-6}	100×10^{-6}

The first mode involved pretreatment by applying the pulse electric field–hydrocyclone field coupling unit. Subsequently, circulatory deep dehydration was performed through the vacuum heating unit. Particularly, at the beginning of experiment, vacuum pump worked until the pressure of vacuum chamber attained −0.08 Mpa. And then, the emulsified 46# turbine oil injected into the hydrocyclone with high speed by the action of the screw pump. So the main part of oil flew into the large tank (70 L) through the overflow pipe of hydrocyclone, and the other part of oil flew into the small tank (30 L) through the underflow pipe. Meanwhile, the output of high-voltage pulsed power supply was 8000 v and 800 Hz. In addition, sampling and sending oil into vacuum chamber could be carried out by two valves installed in the 70 L tank. At last, the oil was drawn out the vacuum chamber by a pump installed behind the medium filter (shown in Fig. 1). The de-emulsifying oil was sampled by opening the valve in the end of system. The detail of experiment above needed to operate two times for other group of emulsified oil.

The second mode involved no pretreatment, where the emulsified oil directly flows into the vacuum heating unit to conduct dehydration. Some steps of experiment were similar to the first mode. First of all, vacuum pump also worked until the pressure of vacuum chamber attained −0.08 Mpa and the four-way valve was opened. The emulsified 46# turbine oil directly flew into the vacuum chamber instead of the hydrocyclone. Hence, the de-emulsifying oil was also drawn out the vacuum chamber by the pump. The detail of experiment above also needed to repeat two times.

The oil water contents of the overflow port of hydrocyclone and the oil drainage port of vacuum heating unit were determined in the first test mode to investigate the processing capacity and effectiveness of the pulse electric field–hydrocyclone field coupling unit and the device. Moreover, the unit energy consumption and the unit time consumption of the device in the two test modes were then compared.

In the two test modes, the experiment was conducted three times and the unit energy and time consumption were compared, as shown in Table 3. W_v is the unit energy consumption of the vacuum treatment, W_m is the unit energy consumption of the multi-field coupling treatment, t_v is the unit time consumption of the vacuum treatment, and t_m is the unit time consumption of the multi-field coupling treatment.

In Table 3, the initial water content of the experimental emulsified oil sample is 15 %. After the treatment of the pulse electric field–hydrocyclone field coupling unit, the water content ranges from 5 to 6 %. This finding indicates that the unit exhibits a good demulsification dehydration effect, and the pretreatment for the emulsified oil with high water content is active and effective. The oil water content of the oil drainage port of the vacuum device is lower than 150 ppm. Regardless, if the three-field coupling demulsification–dehydration or the traditional vacuum heating dehydration was used, the oil moisture content is maintained at low levels after the treatment with the vacuum heating unit. However, in the two test modes, when the oil moisture contents are equal after the treatment, both unit energy and unit time consumption significantly differ from each other. The unit energy and unit time consumption of the three-field coupling dehydration mode are reduced by 80 and 80.7 %, respectively, compared with those of the single vacuum heating dehydration mode. Table 3 shows that the three-field coupling demulsification and dehydration device exhibit the same effect as the single vacuum heating dehydration unit in the treatment effect of the emulsified oil. Nevertheless, the former is superior in terms of unit energy and unit time consumption. The pulse electric field–hydrocyclone field coupling unit presents an evident effect in the treatment of emulsified lubricating oil and has a large contribution in reducing the subsequent processing time of the vacuum heating unit.

Table 3 Results of device test with two different modes

Terms	Rate of water in the overflow of hydrocyclone (%)	Rate of water in the outlet of device (ppm)	$\frac{W_v - W_m}{W_E} \times 100\,\%$	$\frac{t_v - t_m}{t_v} \times 100\,\%$
First time	5.5	120	80	80.4
Second time	6.3	145	78	78.5
Third time	5.8	135	83	83.4
Mean values	5.9	133	80	80.7

Conclusion

High-voltage pulse electric field, which has a simple structure, can be used to rapidly polarize and coalesce emulsion droplets in oil. Instead of the use of gravity field for the droplet settling, the hydrocyclone field can be used to rapidly and efficiently separate oil and big emulsion droplets, thereby considerably shortening the dehydration time. The vacuum heating field can dehydrate tiny emulsion droplets in oil. At present, vacuum heating is the only physical method that can be used to achieve a high dehydration degree of the emulsified oil. When the high-voltage pulse electric field, swirl centrifugal field by hydrocyclone, and vacuum heating field are integrated, the original single treatment process can be modified and a new demulsification and dehydration technology of emulsified lubricating oil is achieved. The electric field–hydrocyclone field coupling unit is important in improving the treatment efficiency of the whole device. Compared with single vacuum heating dehydration, the use of the three-field dehydration device is superior in terms of energy consumption and processing time.

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