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Review Article

Research Progress on Monitoring and Separating Suspension Particles for Lubricating Oil

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Lubricant failure or irrational lubrication is the root cause of industrial equipment failure. By monitoring the distribution of the suspended particles in lubricants, it is possible to discover hidden lubrication problems. After taking the lubricating oil samples of industrial equipment, the oil monitoring technology is used to analyze the particle size distribution and the type and content of the abrasive particles by electrical, magnetic, and optical monitoring techniques. It is necessary to separate the suspended particles in oils with impurities by some method to eliminate potential safety hazards and ensure the reuse efficiency of the lubricant. In this paper, the principles, advantages, and disadvantages of several important oil monitoring methods are described, and new developments in various methods are analyzed. Several typical methods for separation of the suspended particles in purified oils were introduced. The advantages and disadvantages of each process were summarized. The development direction of lubricant monitoring technology was pointed out, and guidance was provided for the separation and online monitoring of the suspended particles in lubricants. Finally, compared with similar review papers, this paper specifically figured out that ultrasonic separation method has the advantages of real time, high efficiency, and no pollution and has important application value for micron-scale particle separation of large precision machines.

1. Introduction

Lubricants are mainly used in machinery and vehicles to reduce the friction between their parts. It reduces noise and plays a role in cooling. In some heavy industries and manufacturing industries, the economic losses caused by maintenance and downtime are as high as 50% of the operating costs [1]. The survey data from Shell of the United States showed that [2] about 35% of diesel engine operation failures and 38.5% of gear failures are due to wear, and almost 40% of rolling bearing failures are due to improper lubrication. The degree of wear and tear of the mechanical components can be inferred by the detection and study of the particle size and composition of the particles in the lubricant to control the wear rate, extend the service life of the equipment, and avoid catastrophic accidents. Lubricant quality testing and dynamic analysis have become one of the important means for the diagnosis and health assessment of mechanical equipment. People are constantly striving to find more accurate methods, especially for various power mechanical systems that need long-term nonstop operation. The traditional method of lubricating oil testing is laboratory analysis after sampling. Laboratory analysis can provide comprehensive information on the wear of equipment components. The test results have a certain degree of accuracy. However, with too high technology, strict environment, and long testing time, it is susceptible to uncertainties, even for an experienced engineering analyst. The test results are still relatively discrete. And this offline laboratory test cannot provide real-time information on the health of the machine equipment. The lag in laboratory testing information has increased the risk of accidents in operating equipment. Research shows that [3], whether it is the production of equipment parts of wear particles or other pollution-generated particles, with the size of the particles in the 20–30 μm maximum impact on the device, less than 1 μm particles have little effect on the wear and tear, and particles larger than 100 μm can be collected and removed by magnetic plug inspection.

Therefore, solid particles with a particle size of 1–60 μm suspended in lubricating oil become the focus of monitoring.

Some online lubricating oil monitoring devices have been developed abroad, and real-time diagnosis of mechanical equipment becomes possible. Hager [4], Flanagan et al. [5], Wu et al. [6], and Martin et al. [7] used acoustic emission detection techniques to judge the quality of lubricants by reflecting the amplitude changes of sound waves, but this method is susceptible to mechanical background noise and lube oil temperature changes. Khandaker et al. [8], Keller and Saba [9], and Flanagan et al. [10] used a capacitive sensor to detect changes in the dielectric constant of lubricating oils, and the test results were often affected by changes in oil properties and oil ambient temperatures. It becomes very complicated, and the measurement of the dielectric constant cannot determine the size and concentration of the particles. Flynn and Whittington [11] further improved the resistive capacitive sensing method, which can not only detect iron particles but also nonferrous metal particles; however, only particles with a particle diameter greater than 100 μm can be detected, and particles smaller than 100 μm cannot be detected. In 1995, Liu et al. [12] confirmed that scatter counting optical methods can detect particles in lubricating oil, but the accuracy of the measurement is affected by the optical properties of the particles. Reintles et al. [13] studied the relationship between lubricating oil and particulate vibration and judged the wear status of the device by comparing with the vibration spectrum. The judgment result depends on the vibration spectrum of the previous study. Peng et al. [14] used the real-time measurement of lubricant wear debris for quantitative assessment of wear, developed an online particle counter to quantitatively assess equipment wear, and considered the total amount of debris as the quality loss of the test sample during the assessment process, but ignoring the contaminants and combustion products in the lubricant exaggerated the degree of wear. Iwai et al. [15] used a series of expansion and expansion methods to separate out 9.9 μm particles, but focused only on fluids with flow rates which are slower than 200 mL/min. Yilmaz and Morton [16] used oil fragment magnetic field sensors with seven channels arranged in parallel to monitor metal fragments in lubricants and successfully separated particles with particle sizes of 75 μm–105 μm and 125 μm–150 μm in different flow rates. The output detection is 7 times larger than the single channel, and the particle size is monitored. Du and Zhe [17] proposed a new asymmetric sharpening edge method to monitor high-flux particle concentration. This method has low sensitivity to oil flow and can separate particles of 9.94 μm. The method needs to arrange a series of sharp corners, and the monitoring structure is more complicated. Fan et al. [18] used frequency division multiplexing techniques to use multiple channel impedance-pulsed sensor shunts, but each frequency must correspond to a single channel. In recent years, the ultrasonic standing wave particle separation techniques [19–24] appeared. With the use of ultrasound standing wave field to move the transverse acoustic radiation generated by the suspended particles in fluids, to move the micron-sized suspended particles in continuous fluids, to achieve particle continuous separation mode using the Coulter counting method, to separate metal particles, and to meet the real-time and nondisruptive requirements of online monitoring, Zhe et al. [25–27] have preliminary applied ultrasonic separation technology to the suspended particles in lubricating oil separation and online monitoring. Ren et al. [28] used a curved interdigital transducer to produce a stronger and more concentrated surface acoustic wave, reducing the energy loss of the surface acoustic wave during propagation. At the same time, this technique has achieved experimental success in the separation of polystyrene particles/polyamide (about 5 μm) [29] and cells in the blood (10–100 μm) [30] in liquids, but the effect of viscous on acoustic radiation is not considered, and only two particle sizes need to be separated. Our research team has also begun to study the role of aerosol particles in the microfluidic channel between the acoustic radiation force and the particles [31–34]. Zhu et al. [35] studied a single attribute sensor such as a wear sensor and a monitoring sensor [36] for online lubricating oil condition monitoring.

A variety of special function oil sensors provided the conditions for comprehensive monitoring. The above works present new ideas and methods for the researches on monitoring and separating lubrication oil theory. The aim of the paper is to analyze the progress of traditional and advanced monitoring and separating methods at present. Combined with the research results of this research group, the research focus and direction of the oil separation work are proposed which provide a guidance for corresponding research workers.

2. Main Monitoring Methods for the Suspended Particles in Lubricants

At present, the most widely used and effective oil monitoring technologies are lubricant's physical and chemical index analysis [37, 38] and wear particle analysis [39]. The physical and chemical index analysis of lubricants is to monitor the lubrication status of the equipment by monitoring the degree of changes in the physicochemical properties of the oil due to the loss of additives and the decay of the base oil. According to the different oil indicators, this method mainly includes atomic spectroscopy and infrared spectroscopy methods. The wear particle analysis method monitors the service life of lubricating oil and diagnosis equipment failure by changing the parameters such as the appearance, size, quantity, and color of wear particles carried in the lubricating oil, thereby determining the degree of contamination of the lubricating oil. Finally, the purpose of monitoring the equipment friction and fault diagnosis is achieved. Based on the different physical parameters of the monitored particles, this method mainly includes particle counting method, ferrography method, and magnetic plug and magnetic detection methods. The common lubricating oil monitoring methods and their advantages and disadvantages are shown in Table 1.

From the literature analysis, the online monitoring of lubricants and the real-time diagnostics of equipment health are gradually changing from qualitative to quantitative, the indirect analysis of the quality of lubricants to the accurate measurement of debris particles, and static detection to dynamic monitoring of large flows. From the perspective of

Table 1: Main monitoring methods for the suspended particles in lubricants.

Project	Monitoring principle	Advantages	Disadvantages
Particle counting method [40]	When the light path illuminates the sample, the light path is blocked, and the photoelectric receiver receives the change of the photoelectric intensity, which is converted into a voltage pulse signal. The number of particles of different sizes is recorded through different voltage valves.	The particle counter is simple to operate and has a fast counting speed. It is suitable for on-site monitoring.	Particles smaller than 100 μm in diameter cannot be monitored, and the particles cannot be qualitatively analyzed.
Atomic spectroscopy [41]	The content of this element is calculated by detecting the number of photons consistent with the characteristic frequency.	Easy to operate and no need for on-site treatment of lubricants.	Cannot detect the suspended particles larger than 10 μm.
Infrared spectroscopy method [42]	Based on the characteristic absorption peaks, numbers, and relative intensities of different substances, the presence of particles in the oil sample was deduced and its molecular structure was determined.	It can analyze oil degradation and pollution status quickly and efficiently.	Insensitive to metal particles, unable to analyze wear particle size and morphology, and no qualitative analysis.
Ferrography method [43]	A high-gradient magnetic field device was designed to separate the metal from the oil sample and to deposit it on a transparent substrate in order of size and then qualitatively and quantitatively analyze the abrasive particles.	Abrasive particle detection range size is from 1 to 1000 μm. It can perform the quantitative and qualitative analysis of abrasive particles at the same time.	The analysis is slow, and the analysis results strongly depend on the experience of the engineer.
Magnetic plug and magnetic detection methods [44, 45]	The metal's magnetic principle is used to analyze the morphology, number, and size of the captured metal abrasive particles.	Can detect larger abrasive particles (100–1000 μm).	Cannot detect aerosols below 100 μm.

the development of the method, the appearance of the new method mainly follows two different paths. One is to improve the existing methods, and the other is to propose new concepts or principles. The key issue in the development of online monitoring technology for lubricating oils is the accurate determination of the suspended particles in lubricating oil, which facilitates the capture of real-time information on the operation of machinery. The measurement accuracy depends on the collection and analysis of particles. The manipulation of these suspended particles can be based on other relatively mature technologies, combined with the characteristics of lubricating oil and the suspended particles, and theoretically researched and experimentally verified, forming a new online monitoring theory and method.

3. Separation Method for Lubricating Oil

In the aerospace and mechanical fields, foreign particles in the engine oil can cause engine wear and reduce the life of the engine and even cause major accidents. This problem requires more efficient removal or detection of foreign particles in the oil. According to the different purification methods, the traditional method of purifying oil is mainly divided into physical methods, chemical methods, and conjunction methods [46]. The physical methods mainly include sedimentation [47], filtration [48], distillation [49], and centrifugation [50]. The chemical method is mainly sulfuric acid-bearing clay refining technology [51]. The conjunction methods mainly refer to combing the advantages of integrated physical methods and chemical methods, which can reduce pollution and increase efficiency [52].

3.1. Sulfuric Acid-Bearing Clay Refining and Separation. Sulfuric acid-bearing clay refining technology [53–55] regenerates waste oils with deeper deterioration, which can remove oxygenates, sulfur compounds, and nitrogen compounds in waste oils, and gums, asphaltenes, and asphalt are produced during use. The oil quality after regeneration is improved, reaching the standard of the base oil, but this technology produces a large amount of SO_2, acid slag, acid water, and white clay slag during the regeneration of waste lubricating oil and brings about serious environmental pollution. In response to solve these problems, the IFP process [56] is used by means of adding propane to purify oil before the acidification of sulfuric acid, thus reducing the amount of sulfuric acid and clay and decreasing the production cost and environmental pressure. The white clay high-temperature refining process has disadvantages such as large amount of white clay, low oil recovery rate, severe equipment corrosion, and harsh operating conditions. In view of the problem of waste clay soil pollution, hydrogenation supplement refining technology came into being, replacing the original sulfuric acid-bearing clay refining process and has become the current mainstream process for the regeneration of waste lubricants. The use of hydrogenation supplement refining technology has advantages such as high oil recovery rate and good product quality in waste lubricant regeneration, but this technology requires harsh operating conditions, huge equipment investment, and a suitable source of hydrogen; thus, its application is limited. Currently, the waste lubricant regeneration technologies mainly used is modified sulfuric acid clay technology [57], such as recycling acid slag and changing the feed rate of sulfuric acid. Meanwhile, the refining of lubricating oils from waste lubricating oil was examined, utilizing a novel blend of solvent extraction and activated alumina adsorbent [58], which has confirmed that solvent mixture can give good efficiency with the highest percent.

3.2. Vacuum Distillation. Decompression distillation method [59–62] removes water by decompression distillation firstly and obtains a certain amount of lube oil fraction through a metal element-containing additive whose boiling point is generally higher than that of a lube oil fraction, such as light oil and pitch, but its flash point, viscosity, and acid value are still noncompliant. Therefore, a second step is required for refining. NMP or furfural is used to remove undesirable components such as colloids and acidic oxides; thereby, better-quality base oil is extracted. However, this method requires high degree of operating vacuum and high temperature in the rectification process, and the oil is prone to cracking, resulting in equipment corrosion caused by refined additives. Though many variables have been studied in this research, such other variables as mixing, pressure, settling time, and temperature will affect the purification results. Further research is required to take this process to the compensation.

3.3. Centrifugation Separating Method. Centrifugation is a method of extracting the pure oil by separating the suspended particles in the lubricant by a centrifugal separator [63–65]. It uses a liquid separation aid having a density higher than the density of the oil to attract and combine the suspended particles. As shown in Figure 1, the contaminated oil is supplied to a rotary centrifuge separation chamber. The central outlet of the purified oil separation chamber is discharged, and the liquid separation aid and the separated particles are discharged through the outlet of the outer separation chamber located radially at the middle outlet. Figure 1 shows a mathematical model of a tube centrifuge. "r" is the radius of the area that determines the settling velocity. "r_1" and "r_2" are the radius of the liquid layer surface in the cylinder and the cylinder's inner wall, respectively. The liquid phase can be continuously introduced into the inlet of the bottom. The rotation of the cylinder causes the liquid phases to rotate at the same angular velocity, and the fluid is uniform in the axial direction and the outer layer is formed. A layer next to the cylinder and the inner layer is a "liquid phase surface" that is not in contact with air. Under the action of the acceleration of the centrifuge, the movement of the input material is constrained, and the particles suspended in the continuous liquid phase are dispersed under the strong shearing force and lose the focused state. However, its main weakness that lies in the separation effect has a close relation with the radius of the centrifuge rotor and the composition of the solvent and the particles; thus, it is mainly suitable for offline separation.

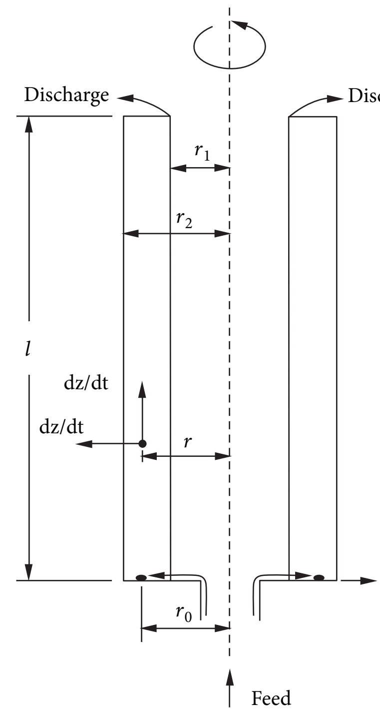


Figure 1: Schematic diagram of tube centrifuge [64].

3.4. Membrane Separation. Membrane separation technology [66–68] uses selective permeation membrane as the separation medium. Under the action of the driving force on both sides of the membrane, the components on the raw material side can selectively permeate the membrane to achieve the concentration, separation, and purification of lubricating oil. Its specific processing technology is shown in Figure 2. Membrane separation technology [69] is widely used in advanced water quality and water reuse. Owing to the large lubricating viscosity of impurities, the amount of particle passing through the membrane is very small. In the application process, ultrafiltration is usually used to remove the water-soluble salts produced from the consumption of the same additives, colloidal particles, asphaltenes, and carbon black in waste lubricating oils. In recent years, polymer organic membranes developed by Miyagi et al. [70] can reduce 14% of polar substances and 32% of oxides in waste lubricating oils, effectively improving the quality of oil products. Bart Van der Bruggen [71] used drone membrane technology to remove the content of metal particles, cleaner than the US national base oil standards. In addition, increasing the temperature and adding organic solvents, supercritical fluid technology, and so on are often used in reducing the viscosity of the lubricating oil, thereby increase the amount of membrane filtration of waste lubricants. Although the membrane treatment technology has the advantages of less pollution, simple operation, and low energy consumption, blockage and inefficient separation are usually caused by large viscosity of waste lubricants and low filtration amount.

Traditional separation method can only remove the impurity particles in oil to a certain degree. However, for large-scale precision machines (such as vehicle engines and fighter jets), the impurity particles in the engine oil are

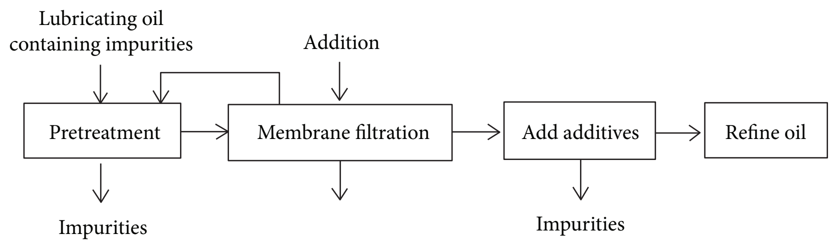


Figure 2: Membrane separation process.

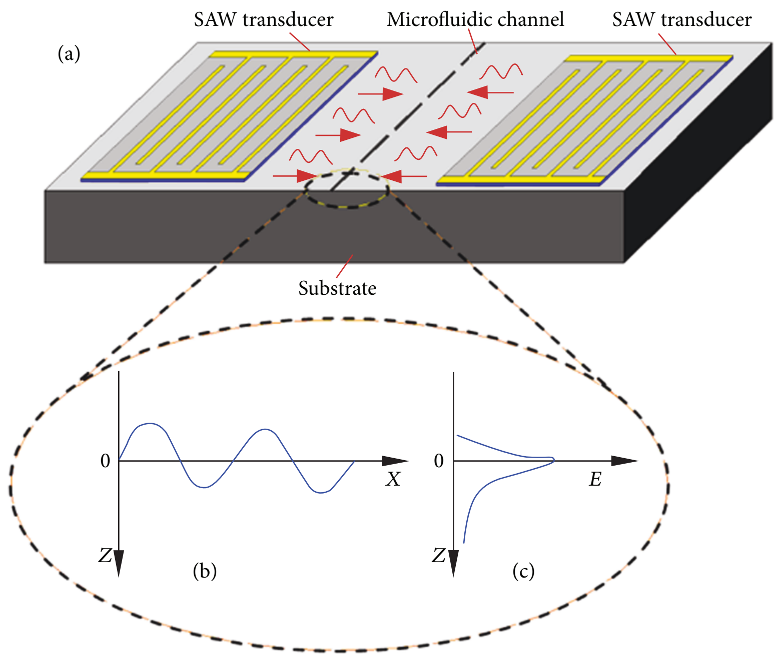


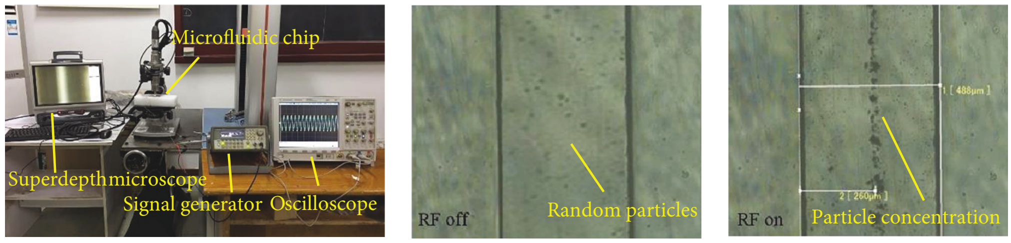
Figure 3: Schematic diagram of ultrasonic separation method.

required to be within several micrometers; thus, traditional separation methods are difficult to purify lubricating oil in a real sense. Ultrasonic separation or aggregation techniques have quite possibility to obtain higher selective, accurate, and reliable analytical results. Therefore, it is of great significance for oil sample to employ pretreatment techniques such as separation or aggregation.

3.5. Ultrasonic Separation Technology. Compared with the traditional purifying method, the ultrasonic separation technology has broad application prospects in this field for its advantages of continuous, high efficiency, low contact, and low pollution. However, the ultrasonic separation technology cannot be applied without the microfluidic chip and the theory of acoustic radiation force; thus, it is necessary to develop a transducer that can generate an ultrasonic field. In order to prepare a transducer capable of generating a qualified surface acoustic wave standing wave field and separating micronsized particles in the oil, our team conducted related research and experiments [31–34].

The theory that particles can be moved by the acoustic radiation force in the ultrasonic field was firstly proposed by King [72] who calculated the acoustic radiation forces and related conditions of rigid spheres in fluids. This theory was later promoted by Yosioka and Kawasima [73] for elastic spheres. At present, ultrasonic separation technology has been widely used in biomedical [74–76] and chemical industry fields [77–79], and with the increasing influence of biomedical and microchemical technologies [80] on human society, this technology will appear huge potential application value.

Figure 3 shows a schematic diagram of a device for separating particles using acoustic surface standing waves and a working mechanism in our research group [31–34]. Two identical interdigital (IDT) electrodes are mounted on a piezoelectric substrate. The width of the microfluidic channel is equal to half of a wavelength. The microfluidic channel is installed between two IDTs so that only one node of surface acoustic wave (SAW) field is formed inside the microfluidic channel. The oil containing the foreign particles is then fed into the pipe from one end using a pressure transmitter or a peristaltic pump. The particles are evenly distributed in the channel when the SAW is not excited. When the same RF signal is applied to a pair of IDTs, two columns of the SAWs with the same amplitude and frequency but opposite propagation directions are generated. In the microchannel region, when two wave arrays are superimposed, a single-node acoustic surface standing wave field is



(a) Standing wave-generating device (b) Before applying SSAW (c) After applying SSAW

Figure 4: Particle concentration experiment device and result graph [31].

generated. The particles in the standing wave field will be concentrated by the ultrasonic radiation force to the node, to separate the impurities. The experimental setup that is shown in Figures 4(a)–4(c) demonstrates particle concentration effects of particles observed before and after the application of voltage using ultra-well-depth microscopes, respectively, providing technical platform for online monitoring of lubricating oil.

Compared with the traditional method, the method of separating the foreign particles by the acoustic radiation force received by the particles in the ultrasonic standing wave field has its unique advantages such as the suspended particles in the fluid which can be separated easily, continuously, and efficiently and has the characteristics of no contact and low pollution. In addition, the engine oil due to a high degree of cleanliness has a protective function for the operation of large-scale equipment (automobiles, airplanes, etc.) engines; thus, it must be replaced on schedule. Ultrasonic separation technology can not only test the quality of lubricant oil, timely check the content of impurity particles in the lubricant, but also can replace the replaced lubricant for secondary cleaning and reuse, and the cleaned lubricant can fully meet the use of skill requirements. This will not only reduce the wear and tear on the mechanical equipment of the impurity particles, extend the working time of the equipment, but also reduce waste, protect the environment, reduce pollution, and greatly improve social and economic benefits.

4. Outlook and Challenges

In recent years, with the development of microfabrication processes and the development of a variety of separating methods for the suspended particles, particle separation technology has achieved breakthroughs in terms of separation accuracy and application range. Ultrasonic standing wave separation methods perform in both biological and industrial fields. Great potentials for application prospects of the key techniques for monitoring and separating suspension particles for lubricating oil are as follows.

(i) Traditional physical and chemical separating methods for oil are generally cost-effective and environment-friendly due to their destroying original oil quality and affection online operation, which can be used as supplement and comparison method to separate smaller wear debris.

(ii) The wideband IDT has the advantages of small power loss, more accurate positioning, and stronger propagation capability and can be used to generate a variety of frequency-adjustable standing waves. Therefore, designing and fabricating an IDT integrated with the substrate can improve the separation efficiency of particles with different particle sizes in the microfluidic channel and provide guarantees for the separation of smaller particles.

(iii) Due to the large perturbation of tiny particles in viscous fluids, the forces experienced by particles in different flow regimes vary greatly. The forces and motion models of particles in viscous fluids need to be refined, so as to accurately and comprehensively analyze the particles. The force and motion state in the microfluidic channel are of great significance for achieving the aggregation and separation of microparticles.

(iv) Develop a highly integrated, low-energy, and low-cost aerosol particle control device to establish a mechanism that can be used on a large scale in industrial production, which will greatly increase the service life of the engine and will have important implications for environmental protection.

5. Conclusion

The conventional methods for separating the suspended solids from lubricating oils are reviewed in this paper. However, due to the shortcomings of these conventional methods, it is more popular at home and in abroad to use ultrasonic separation methods for particle separation. Based on the abovementioned several common methods for separation of particles, the future methods for separation of particles are prospected. And especially the efficiency improvement and the achievement on separation of smaller particles are prospected, which will provide a monitoring basis for online monitoring of lubricants. With its environment-friendly characteristics, it will be widely used in a large-scale production of impurities in engine oil.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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