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A NEW TECHNOLOGY FOR OIL MANAGEMENT: ELECTROSTATIC OIL CLEANER

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Abstract

Anybody knows that contamination in oil is always harmful to hydraulic and lubricating systems. Contaminants inevitably exist in the oils of hydraulic and lubrication systems and cause tribological problems. In order to prevent such tribological problems due to contaminants, various oil cleaners have been developed and applied to hydraulic and lubricating systems. They have greatly contributed to improving the reliability of the systems. Since sophisticated hydraulic systems with proportional valves or servo valves, which are sensitive to oil contamination, became popular, fine filters like 3 micron or 1 micron are additionally used. However contamination problems have been revived. The authors have investigated the causes of hydraulic and lubricating problems and found that polymerized oil oxidation products were as harmful as solid particles. They are of molecular size and cannot be removed by mechanical filtration. The authors have developed electrostatic oil cleaners, which can remove not only micron size particulate contaminants but also polymerized oil oxidation products.

This paper discusses the principle of electrostatic oil cleaning technology and demonstrates performance of it.

NOMENCLATURE

$1/\kappa$	double layer thickness, Debye length
ε	dielectric constant
K	Boltzmann constant
T	absolute temperature
e	charge of electron
n	concentration of ion
z	valence of ion
Φ_s	surface electric charge
R	a radius of a spherical particle
m	mass
Q	Total electric charge
E	Strength of electric field
F_i	inertia (= - $mV_{p'}$)
F_r	Stokes drag force (- $6\pi RmV_p$)
F_c	Coulombic force (QE)
η	viscosity (poise, g/cm・ sec)
ρ_P	density of a particle (g/cm^3)
ρ_L	density of oil (g/cm^3)
g	acceleration of gravity (cm/s^2)

β	$3\varepsilon_1(\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + 2\varepsilon_1)$
ε_1	relative dielectric constant of oil
ε_2	relative dielectric constant of a particle
V_u	the net upward velocity of a particle
V_1	settling velocity of a particle
V_2	upward flow velocity of oil
$\nabla\|E\|^2$	gradient of electric field

INTRODUCTION:

Hydraulic systems generate large forces with relatively small size and are excellent to handle heavy objects with an accurate control. However contaminants in oils are pains in the neck for hydraulic systems. The majority of users of hydraulic systems are in industries. Oil cleaning is a subordinate item to them. The management is not interested in oil cleanliness but care about uptime and reliability of the hydraulic systems. They pay attention to oil cleaning only when hydraulic systems are in trouble. In the past, contamination control specialists have paid most attention to particulate contaminants of micron size and little attention to polymerized oil oxidation products. In order to prevent hydraulic problems due to oil contamination, almost all hydraulic systems incorporate mechanical filters in the main stream of oil, either at the pressure side or at the return side. However hydraulic problems due to oil contamination still exist. Modern hydraulic systems are used for motion control that requires accurate and precise motions. Such systems use servo valves and proportional valves, which are very sensitive to contamination of oils. Therefore use of fine by-pass mechanical filters has been recommended in addition to the in-line filters. However contamination problems not only still exist but also are rather increasing by using fine filters. The authors have investigated the causes of hydraulic problems and found that polymerized oil oxidation products are taking important roles in hydraulic problems *1) – 3)*. The authors also have found that mechanical filters generate static electricity when oil passes through filter media and that the static electricity accumulated in either a filter or oil causes spark discharges and accelerates oil oxidation, as the temperature of spark discharges is high in the range of several thousand to over ten thousand degree C *4) - 6)*. Oils will deteriorate by such high temperatures and oil deterioration leads to cause hydraulic system failures. The management, who is responsible for both the past and the current investment, does not allow any downtime of production machinery, as their capability is evaluated by the “Return on Assets (ROA)” ratio. In order to comply with such requirements of the management, we have to offer an advanced technology for protecting the assets. This paper discusses a technology of electrostatic oil cleaner, which uses static electricity.

PARTICLES IN OIL

OIL AND PARTICLES

Oils circulating in hydraulic systems have contaminants. Any materials have their own work functions. Although the whole system is electrically neutral, electric charge appears by the difference of two work functions if any, when they contact. Therefore some contaminants suspending oil will be charged positive or negative. However if there is no difference in work functions between oil and some contaminants, electric charge will not appear and such contaminants will remain neutral.

CHARGED PARTICLES

The general motion of particles in a uniform electric field may be schematically shown in Figure 1.

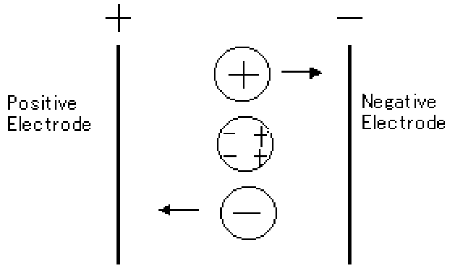


Figure 1 General Motion of Particles In a Uniform Electric Field

By the nature of electricity, which appears by potential contact difference, electric charge will be on the surface and may form the electrical double layer at the interface with oil. Provided that a particulate contaminant is a sphere, the double layer thickness ($1/\kappa$) will be expressed by the following Poisson-Boltzmann equation *7)*.

$$1/\kappa = (\varepsilon KT/8\pi e^2 nz^2)^{1/2} \quad ....(1)$$

The unit of the double layer thickness is Debye length. As mineral oils and the majority of synthetic lubricants are basically dielectric, concentration of ion n is very low for oil and $1/\kappa$ becomes large and κ small. This means that the thickness of the electrical double layer on a sphere is large in oil. Then we have to discuss the density of electric charge on a spherical surface. The density σ can be expressed as follows

$$\sigma = (\varepsilon\Phi_s / 4\pi R)(1 + \kappa R) \quad ... \quad (2)$$

The total electric charge Q of a spherical particle with a radius R becomes as follows equation,

$$Q = 4\pi R^2\sigma \quad ... \quad (3)$$

By introducing the equation (2) into the equation (3),

$$Q = R\varepsilon\Phi_s (1 + \kappa R) \quad ... (4)$$

As κ is very small, the equation (4) can be rewritten as follows:

$$Q = R\varepsilon\Phi_s \quad ... \quad (5)$$

MOTION OF CHARGED PARTICLES

A suspending particle can make free motion in oil. The motion of a spherical particle in an electric field will be expressed as follows:

$$F_i + F_r + F_c = 0 \quad .... \quad (6)$$

The equation (6) can be rewritten as

$$mV_{p'} + 6\pi R\eta V_p - QE = 0 \quad .... (7)$$

As the inertia F_i is initially zero,

$$mV_{p'} = 0,$$

therefore

$$V_p = QE / 6\pi R\eta \; .... (8)$$

By introducing the equation (5), the equation (8) can be given as follows:

$$V_p = R\varepsilon\Phi_s E / 6\pi R\eta \quad .... \quad (9)$$

If $\varepsilon\Phi_s$ is replaced by α (constant),

$$V_p = \alpha E / 6\pi\eta \quad .... \quad (10)$$

The equation (10) means that the migration velocity V_p of a charged spherical particle is proportional to the intensity of the electric field and that it is constant regardless of the particle size, when the intensity of the electric field is fixed.

SETTLING VELOCITY OF A SPHERICAL PARTICLE

Any materials on earth are under the influence of gravity. When a spherical particle is suspending in oil, the settling force will work on it. The settling velocity V_1 of a particle is given by the following equation.

$$V_1 = 2 (\rho_P - \rho_L) gR^2 / 9\eta \quad .... \quad (11)$$

In the case of electrostatic oil cleaner, contaminated oil will be introduced into the electric field from a lower inlet of a cleaning chamber and flow upward slowly at the velocity V_2 in the cleaning chamber. Taking the settling velocity V_1 of a particle into account, the net upward velocity V_u of a spherical particle can be given as follows:

$$V_u = V_2 - V_1 \quad .... \quad (12)$$

Provided that the material of particles is same, the net upward velocity V_u of a small one will be larger than that of a large one by the equations (11) and (12). In accordance with the equation (10), the migration velocity V_p of particles is constant regardless of the size of particles in the electric field. As the migration of particles is schematically shown by the vectors in Figure 2, a large particle can easily hit the electrode rather than small one, provided that an only particle exists in an electric field. However there are a large number of particles suspending in oil.

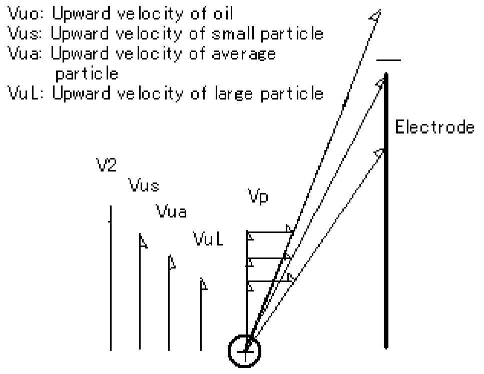


Figure 2 Schematic Figure Showing the Motion of a Positively Charged Particle in a Uniform Electric Field

Some of them are charged either positive or negative and the other neutral electrically. Charged particles will move toward the electrodes having the opposite polarity. Such motion is known as electrophoresis. When charged particles come close, if they have the same polarity, they will reject each other by Coulomb force but they will draw each other and agglomerate, if they have the opposite polarity.

MOTION OF NEUTRAL PARTICLES

In a uniform electric field, neutral particles will be polarized but cannot move because they are drawn by the equal forces from both the positive electrode and the negative electrode. In order to make them move, the electric field must be deformed to make non-uniform. In the non-uniform electric field, a gradient force will work on a neutral particle and make it move toward the strongest field region. When two neutral particles come close, they will also agglomerate by the gradient force, which work between them as shown in Figure 3. These phenomena are known as dielectrophoresis.

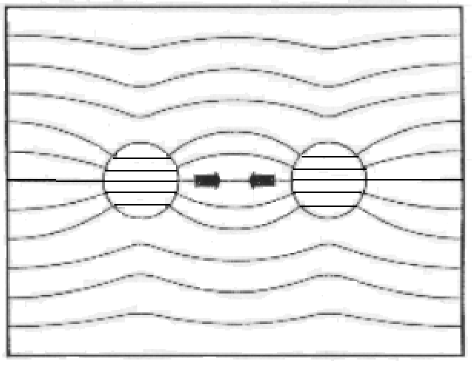


Figure 3 Gradient Force Working on Neutral Particles

Provided that the neutral particle is a sphere, the force (F_e) working on it in a non-uniform electric field can be expressed as follows *8)*:

$$F_e = \text{(volume) x (polarizability) x (local field) x (field gradient)}$$

$$= (4\pi R^3/3)\,\beta\,E\,(\nabla\cdot\ E)$$

$$= 1/2\,(4\pi R^3/3)\,\beta\,(\nabla|E|^2)$$

$$= 2\pi R^3\varepsilon_1[(\varepsilon_2-\varepsilon_1)/(\varepsilon_2+2\varepsilon_1)](\nabla|E|)^2 \quad \text{. . . . (13)}$$

The equation (13) shows that the dielectrophoresis is in proportion to the third power of the radius of a spherical particle, the difference of the relative dielectric constant between a particle and oil and the square of the electric field strength.

As the relative dielectric constant of a metallic particle is much larger than that of oil, the force working on a metallic particle is large from the equation (13) and the metallic particle will be easily drawn to the region where the intensity of the electric field is strong. Dielectrophoresis is effective with relatively high field strengths. As the dielectric constant of oil is about 2 and the relative dielectric constant of polymerized resin is larger than that of oil 8), the dielectrophoresis can remove polymerized oil oxidation products.

PRINCIPLE OF ELECTROSTATIC OIL CLEANING TECHNOLOGY

Oil cleaners must remove any harmful contaminants to hydraulic systems and should not select them by either the kinds or the sizes. As electrostatic oil cleaners use the electrical characteristics of particles and the field force, they can remove any kinds of particles of either the charged ones or neutral ones.

The electrophoresis, which works in a uniform electric field, is useful to remove charged particles and the dielectrophoresis, which works in a non-uniform electric field, is useful to remove neutral particles. In order to comply with the requirements for electrostatic oil cleaner to remove any and all kinds of contaminants, it is imperative to reproduce the phenomena of both electrophoresis and dielectrophoresis in a cleaning chamber. The schematic configuration of the electrodes and the dielectric media is shown in Figure 4.

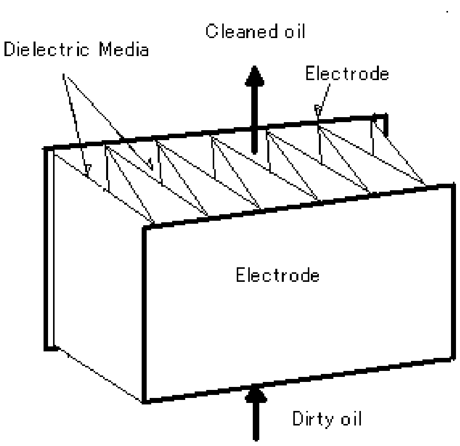


Figure 4 Schematic Configuration of Electrode and Dielectric Media

The parallel electrodes produce uniform electric field and the pleated dielectric media deform the electric field at the sharp edges. By this configuration, electrostatic oil cleaners can remove any kinds and sizes of contaminants from oil, as long as they are insoluble in oil.

EXPERIMENTAL

It is important to verify that the theory can work to the real oils. 200 liters of anti-wear type hydraulic oil with Zinc base additives was taken from an injection-molding machine. The oil was used for 3 years. The injection molding machine had in-line filters but had no by-pass filter. No special contamination control was implemented to the machine. The 200-liter oil was cleaned by a batch test stand of an electrostatic oil cleaner having a 720 lit/h pump. The contamination level was measured by an automatic particle count. The rest results are shown in Figure 5.

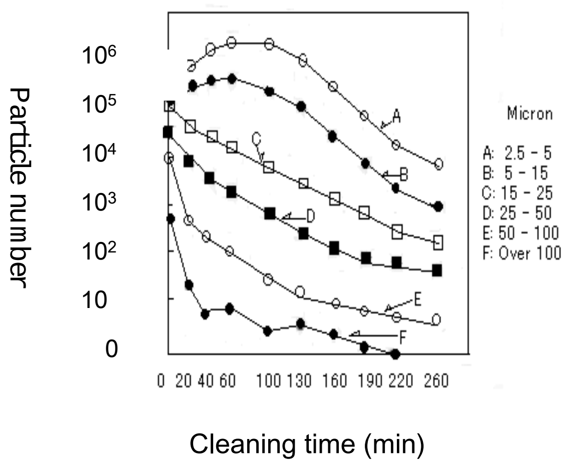


Figure 5 Change of Particle Numbers During Cleaning by an Electrostatic Oil Cleaner

RESULTS AND DISCUSSION

The figure shows that the number of particles smaller than 15 micron increases at the early stage of oil cleaning. The smaller the particle sizes, the higher the increasing rate. The figure also shows that the number of particles larger than 25 micron decreases in the process of oil cleaning and that the larger the particle size group, the sharper the declination angle. This is one of the most interesting features of electrostatic oil cleaning. As the equation (1) indicates, the thickness of electrical double layers on particles at the interface with oil is very large and makes agglomeration of particles difficult in oil without the electric field. However particles agglomerate in the electric field easily, as the electrophoresis makes the charged particles move to meet with the oppositely charged particles and the dielectrophoresis makes neutral particles draw each other by the gradient force. The fact that the number of small particles increases at the early stage of cleaning indicates that there are so many small particles which cannot be counted by particle count and that those small particles are agglomerated by the influence of the electric charge as shown in Figure 3 whether they are neutral or charged electrically. The reason why large particles are easily removed by electrostatic oil cleaning can be explained by the Figure 2 and the equation (13). Because of these specific features, electrostatic oil cleaners can remove even submicron particles, which cannot be removed by mechanical oil cleaners, as long as they are insoluble in oil.

INFLUENCE OF ELECTRIC FIELD ON OIL

When oil passes through filter media, oil will be electrified 5). As oil is dielectric, charge will be accumulated in oil, although oil has a small quantity of charge relaxation additives. As the temperature of spark discharges is higher than ten thousand degree C locally 4), no additives can protect oils. Therefore it is very important to verify that electrostatic oil cleaning does not cause any damage to oils.

CHARGE OF OIL

When oil comes into a uniform electric field, which is produced by a pair of parallel electrodes, electrons will be ejected from a negative electrode. As oil is dielectric, the ejected electrons will not go to the other electrode and stay in the oil, when the distance between two electrodes is not too narrow. Then the oil will be electrified as shown in Figure 6. This may cause damage to oil when the electric charge is accumulated and discharged with sparks. In order to use electrostatic technology for oil cleaning, it is important to solve this problem.

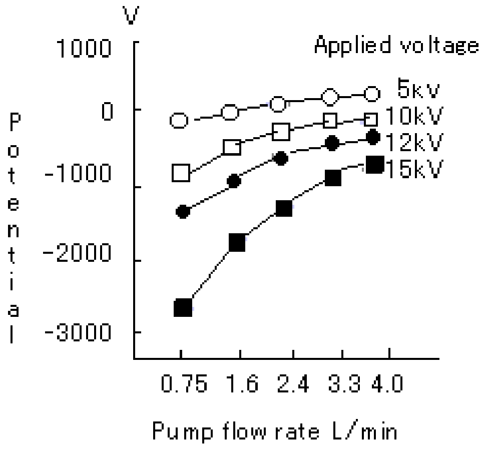
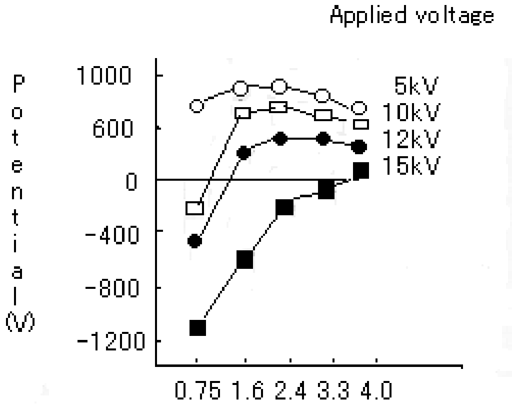


Figure 6 Electrification of Oil in Electric

Field

HOW TO AVOID OIL ELECTRIFICATION

In view that the objective of oil management is primarily to protect machines and to protect oils for it, no oil cleaners should cause damages to oils. By using the pleated dielectric media, the electric field will be deformed and the ejected electrons will be directed to the sharp points of the pleats. Then the oil will not be electrified in a certain combination of the pump flow rate and the applied potential as shown in Figure 7. This finding was a key of making electrostatic oil cleaners to serve for oil management.



Pump Flow Rate

Figure 7 Oil will not be Electrified with Pleated Collectors in Combination of Applied Voltage and Pump Flow Rate

COMPATIBILITY WITH OIL ADDITIVES

Hydraulic oils become good products with base oil and necessary additives. Almost all additives except ant-foam agent are soluble in hydraulic oils 9), 10).

OIL SOLUBLE ADDITIVES

Individual molecule of oil soluble additives makes free motion in oil. Therefore electrostatic force, which is a field force, cannot remove oil soluble molecules. Oil insoluble fractions are polymers having large molecular weight 11), 12) and contaminants in oil. They cannot make free motion but are vibrating in oil while suspending in oil. Therefore electrostatic oil cleaners can remove such oil insoluble fractions and contaminants.

ANTI-FOAM ADDITIVES

The typical anti-foam additives are silicone polymers of intermediate molecular weight, which are sometime called silicone oils 9). The surface tension of such anti-foam additives is about 20 dyne/cm, while that of lubricants in the range of 30 to 35 dyne/cm 10). A cluster of anti-foam additives having low surface tension spreads on the oil film on an air bubble having larger surface tension than the anti-foam additives and break it 10). Because of the low surface tension, anti-foam additives can be easily captured by cellulose (the surface tension is about 40 dyne/cm), synthetic fibers (the surface tension in the range of 30 to 50 dyne/cm) 13), and metal (the surface tension of steel about 1720 dyne/cm) 14).

CONCLUSION

1 Hydraulic problems are caused not only by micron size particulate contaminants but also by polymerized oil oxidation products.
2 Fine mechanical filters generate static electricity during filtration and spark discharges of it may cause deterioration of oil.
3 Electrostatic oil cleaners were discussed as a new tool for oil management, which would not damage oil.
4 Electrostatic oil cleaners can remove any size of oil insoluble contaminants by agglomeration.
5 Electrostatic oil cleaners do not remove oil soluble additives.

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