Fundamental Investigation of Charge Injection Type of Electrostatic Oil Filter (Effects of Mechanical Factors on Filtration Speed)*

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Abstract

This paper deals with the effects of mechanical factors on the filtration speed of a charge injection type of electrostatic oil filter. The new filter has been proposed by Yanada and his coworkers and it has been demonstrated that the filtration speed can be increased to a great or some degree by injecting charges into oils, but the experimental condition was limited. In this paper, the effects of the number of the projections, the electrode spacing, the applied voltage and the oil temperature on the filtration speed are examined using a simple filter model and various types of oil. In order to discuss the effects of those mechanical factors on the filtration speed, numerical simulation of electrostatic field between electrodes is done and the oil flow caused between the electrodes due to ion drag phenomenon, called the ion drag flow in the paper, is observed using a charge coupled device (CCD) camera and is analyzed using a particle image velocimetry (PIV) technique. The experiments and numerical simulation make clear the effects of the mechanical factors on the filtration speed. An optimal electrode configuration and operating condition are found out.

Keywords: Electrostatic Filter, Lubricating Oil, Charge Injection, Mechanical Factor, Ion Drag Flow, Electrostatic Field Simulation, Reuse

1. Introduction

An electrostatic oil filter can remove submicrometer-sized contaminants such as the oxidation products of additives from oils. By virtue of this characteristic, it has contributed to lengthening the lives of lubricating oils and to decreasing waste oil as well as failures of machines including hydraulic systems^{(1),(2)}. However, the filtration speed of electrostatic oil filters is slow and it usually takes a long time for a contaminated oil to be purified.

Yanada and his coworkers^{(3),(4)} have proposed a new type of electrostatic oil filter, named charge injection type of electrostatic oil filter. The new filter uses one or more set(s) of an emitter electrode with many sharp projections and two smooth plate electrodes. The application of a high DC voltage between the emitter and smooth electrodes enables electric charges with the same polarity as that of the emitter electrode to be injected from the tips of the sharp projections into oils. If the electric charges injected can be adsorbed on the surfaces of the contaminants, the magnitude of Coulomb force exerted on them becomes larger and the contaminants may be easily removed from oils.

Previous investigations^{(3),(4)} have demonstrated that the filtration speed can be increased to a great or some degree by injecting electric charges and that the degree of the increase in the filtration speed largely depends on the type of oil. In addition, chemical

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analyses of the oil into which electric charges were injected have confirmed that the charge injection has no bad influence on the oil at all. However, the filtration experiments were conducted under limited experimental conditions. In order to find out a better electrode configuration and appropriate operating conditions of the filter, the effects of such mechanical factors as the electrode configuration, the magnitude of the applied voltage and the oil temperature on the filtration speed need to be investigated.

Electric field plays an important role in the filter performance. The electric field strength at the tips of emitter projections affects the quantity of charges injected; the average electric field strength between the electrodes has an influence on the magnitude of Coulomb force exerted on contaminant particles. In order to evaluate the variation of those electric field strengths due to the alteration of the electrode configuration and operating conditions, numerical simulations of the electrostatic field are carried out.

As was shown in a previous paper⁽⁴⁾, the filtration speed was decreased by injecting charges for two test oils of all the fourteen test oils. Taking into account the fact that the particles were relatively weakly captured on the smooth electrodes in the two oils, it was deduced that part of the particles captured on the smooth electrodes may be detached by the flow generated by ion drag phenomenon, called the ion drag flow in the paper, and that the decrease in the filtration speed under the charge injection in the two oils may result from the ion drag flow. Thus, charge injection makes a positive contribution to the increase in the filtration speed but, at the same time, may make a negative one to that for some cases due to the effect of the ion drag flow. Therefore, in order to discuss the effects of the mechanical factors on the filtration speed, the ion drag flow needs to be examined under various conditions. In this paper, the behavior of the particles captured on the smooth electrode is observed, and the observation of the ion drag flow is made using a two-dimensional filter model.

As written above, this paper treats the effects of the mechanical factors on the filtration speed of a charge injection type of electrostatic oil filter. Filtration experiments are conducted under various conditions of the mechanical factors. In order to discuss the effects of the mechanical factors, the numerical simulation of the electrostatic field between the electrodes and the observation of the ion drag flow are done. An optimal electrode configuration and operating condition are proposed.

The organization of the paper is as follows. Section 2 describes the experimental apparatus and method. The method of numerical simulation of electrostatic field is given in Section 3. The experimental results, simulation results and discussion are given in Section 4. Finally, the conclusion is described in Section 5.

Nomenclature

E_{av}	: average electric field strength
E_{max}	: maximum electric field strength
n	: number of projections
p	: pressure generated by ion drag pump
r	: percentage of powder concentration at time t to the initial powder concentration
$r_{t=0.25h}$	: r at $t=0.25$ hour
s	: electrode spacing
t	: time
T	: oil temperature
$\bar{u}$	: magnitude of ion drag flow
V	: applied voltage
μ	: viscosity
σ	: conductivity

2. Experimental apparatus and method

2.1 Filter model

In the same way as the previous works^{(3),(4)}, a simple filter model consisting of only electrodes was used for filtration experiments. As was written in (4), such configuration of electrostatic filter cannot remove conductive contaminants like metallic wear debris. In this investigation, in order to examine the effects of mechanical factors on the filtration speed, such a simple filter model was used again. For oils in which conductive contaminants are hardly included, even such a simple filter configuration is enough to purify the oils.

Figure 1 shows a schematic of electrodes that consist of one emitter electrode with sharp triangular projections on its both sides and two plate electrodes. The emitter and the two smooth electrodes are made of stainless steel plates with the dimensions of $100 \times 200\text{mm}$. Isosceles triangular projections were machined by laser beam and the length of the base of them is 2mm . The averaged radius of curvature of the tips of the projections is $25\mu\text{m}$. The three electrodes are inserted in parallel in the casing made of polycarbonate; the emitter electrode is located in the middle of two smooth electrodes. The distance between the surfaces of the emitter and the smooth electrodes is 9.5mm . In order to examine the effects of the electrode spacing, s , and the number, n , of the projections on the filtration speed, emitter electrodes with different heights ($h=3.5, 4.5, 5.5, 6.5\text{mm}$) and numbers ($n=40, 84, 166, 312$) of the projections were made. The heights of the projections, $h=3.5, 4.5, 5.5, 6.5\text{mm}$, correspond to the electrode spacing of $s=6, 5, 4, 3\text{mm}$, respectively. It was not possible to machine 312 projections on one emitter electrode and, therefore, in order to make the emitter of $n=312$, two plates with 156 triangular projections bent to one side were put on back to back with each other. In order to evaluate the effect of charge injection, a smooth plate electrode was also used instead of the emitter electrode. The plate electrode with no projections is written as $n=0$.

Fig.1 Schematic of electrodes

2.2 Test oils

Seven types of artificially contaminated hydraulic fluids and multipurpose oils were used for filtration experiments. The oils were selected from the fourteen oils used in a previous work⁽⁴⁾. A test powder (JIS 1st kind, class 11, Kanto loam, median diameter = $1.6 - 2.3 \mu\text{m}$)⁽⁵⁾ was mixed into the oils at a concentration of 1g/L . The volume of test oil was 1.5L . In Table 1, the values of the conductivity and viscosity of the test oils at a temperature of 313K (40°C) are shown. The word “polarity” written in Table 1 means the electrification polarity of the powders mixed in the oils. The powders were charged positive in Oils 1 to 6. In Oil 7, most powders were charged positive and the rest negative.

Table 1. Physical properties of test oils at 313K and electrification polarity of powders
(σ : conductivity, μ : viscosity)

Oil no.	Maker, brand name, viscosity grade	σ (S/m)	μ (mPa·s)	Polarity
1	Nippon Oil Corp., Super Hyrando, 22	1.35×10^{-10}	19.4	+
2	Nippon Oil Corp., Super Hyrando, 32	1.35×10^{-10}	27.4	+
3	Nippon Oil Corp., Super Hyrando 46	1.24×10^{-10}	39.4	+
4	Cosmo Oil Co. Ltd., Hydro HV, 32	3.18×10^{-9}	28.6	+
5	Nippon Oil Corp., Super Mulpus, 10	5.31×10^{-12}	9.82	+
6	Cosmo Oil Co. Ltd., Cosmo Allpus, 32	4.71×10^{-13}	27.1	+
7	Japan Energy Corp., Hydflux 32	1.29×10^{-11}	26.3	+/-

2.3 Filtration experiment

A schematic of the experimental apparatus used is shown in Fig.2. Contaminated oil in reservoir ① is fed into the filter model ⑤ by a gear pump ③ and then returns to the reservoir. The oil in the reservoir is stirred by a magnetic stirrer ② to avoid the gravitational sedimentation of the powders. A DC voltage is applied by a high DC power supply ⑥. The magnitude of the applied voltage was changed from 8kV up to 14kV in order to examine the effect of the applied voltage. The polarity of the applied DC voltage can be changed. The flow rate was adjusted to 3×10^{-6} m³/s by an inverter ④. The temperature of the oil was controlled during the experiment by using a heater ⑦ and a thermoregulator ⑧.

The standard experimental conditions are as follows: the applied voltage $V = +10$ kV, the oil temperature $T = 40^\circ\text{C}$, the number of the projections $n = 166$, and the electrode spacing $s = 4$ mm. When examining the effect of one of these four factors on the filtration speed, the values of the other three factors were kept at the standard values. About 20×10^{-6} m³ of oil was sampled from the reservoir at specified times during the filtration experiment to evaluate the variation of the concentration of the powders in oil with time. The mass concentration of the powders included in the sampled oil was measured by filtering it together with enough volume of hexan, a solvent, using membrane filters having a pore size of $0.8 \mu\text{m}^{(6)}$.

Fig.2 Schematic of apparatus used for filtration experiment

2.4 Observation of ion drag flow

Coulomb forces are exerted not only on charged particles but on oil itself because excess charges (ions) exist in the oil due to charge injection. When the excess charges move towards the smooth electrodes by the action of electric field, they drag neutral molecules and a flow is generated from the projection tips towards the smooth electrodes. This phenomenon is called the ion dragging. As stated in the introduction, the flow may have an influence on the filter performance and is investigated in the present paper.

The experimental apparatus used for the observation of the ion drag flow is shown in Fig.3. Almost all the devices are the same as those of the experimental apparatus of the filtration experiment, except for the filter model and a few additional devices. A smaller filter model was used in this observation. In order to make the observation easy, approximately two-dimensional emitter electrodes were used as shown in Fig.4. The dimensions of the electrodes are 38mm×100mm×0.3mm. The emitter electrodes are made of stainless steel and the rectangular projections were machined by laser beam. A transparent electrode was used as the smooth electrode for a light sheet to be penetrated into the filter model, and is made of glass of which one surface is coated by a conductive material (SnO₂). Emitter electrodes with different heights, $h=6.5, 5.5, 4.5$ and 3.5 mm, of the projection were made and the heights correspond to the electrode spacing of $s=3, 4, 5$ and 6 mm, respectively.

Porous plastic particles, of which specific gravity is 1.02 and of which size ranges from 75 to 150 μm , were mixed into test oils to visualize the ion drag flow. It was confirmed that the plastic particles were hardly charged in all the test oils and that the particle motion represented the motion of oil. The motions of the particles were observed by a CCD camera (Fig.3) and the flow field was analyzed by a PIV technique.

The standard experimental conditions for observation are $V=+10\text{kV}$, $s=5\text{mm}$, $T=40^\circ\text{C}$. When examining the effect of one of the three factors on the ion drag flow, the values of the other two factors were kept at the standard values.

In addition to the observation of the ion drag flow, the detachment of particles captured on the smooth electrode was observed by replacing the CCD camera ⑩ with a microscope and by replacing the computer ⑪ with a TV monitor. In this observation, artificially contaminated oils, into which the test powder (Kanto loam) was mixed, were used.

Fig.3 Schematic of apparatus used to observe ion drag flow

Fig.4 Schematic of two-dimensional emitter electrode

3. Numerical simulation of electrostatic field

Electrostatic fields in the filter model were numerically analyzed using ANSYS software. Charges are injected from the emitter projections and move together with neutral molecules towards the smooth electrodes. Therefore, the field is never static. In order for the electric field to be simulated accurately, the flow field has to be solved together. The actual maximum electric field strength at the tips of the projections should be significantly smaller than the value of the electrostatic field due to the injected charges with the same polarity as the emitter's one. The actual average electric field strength between the electrodes should be different to some degree from that of the electrostatic field. However, the simulation of the electrostatic field should be helpful in comparing the electric field strength among different electrode configurations or among different magnitudes of the applied voltage.

Figure 5 shows a unit volume in which only one projection is included and was used for the numerical simulation of the electrostatic field. Periodic boundary condition was applied to the surfaces a, b, c, d. An electric potential ranging from 8 to 14 kV was given to the emitter surface and zero volt to the smooth electrode surface. The size of the unit volume was changed corresponding to the number of the projections: 40, 84, 166 and 312. The height of the projection was varied within the range of 3.5mm to 6.5mm corresponding to the electrode spacing of 6mm to 3 mm. Figure 6 shows an example of meshing for finite element in the vicinity of the projection tip.

Fig.5 Example of unit volume for numerical simulation of electrostatic field

Fig.6 Example of meshing for finite element in the vicinity of projection tip

4. Results and discussion

4.1 Observations of particle detachment and ion drag flow

Behaviors of particles in artificially contaminated test oils were observed using a microscope and a TV monitor. The observations showed the following: (1) The detachment of the particles captured on the smooth electrode does not take place when the thickness of the layer of the particles is thin but part of the particles on the smooth electrode starts to be detached as the thickness of the particle layer is increased. (2) The detachment of particles takes place not only for charge injection but also for no charge injection. (3) Part of the particles on the particle layer surface is detached by the ion drag flow. (4) Vortices are formed above and below the projections as shown later. (5) It appears that the particles are only rotating between the electrodes and are not efficiently captured on the smooth electrode when the ion drag flow is relatively large.

The observation results indicate that the ion drag flow tends to promote the detachment of the particles and to hinder the capture of particles. Therefore, when the effects of the mechanical factors on the filtration speed are discussed, the relations between the ion drag flow and the mechanical factors need to be examined.

Figure 7 shows an example of a pattern of the ion drag flow measured. It can be seen that a flow is generated near the tip of the projection and moves towards the smooth electrode and that twin vortices are formed above and below the projection. The maximum flow velocity was observed on the projection line but it could not be measured well because of a relatively high velocity under some conditions. Therefore, the mean value of the magnitude of the flow velocity in the two square areas shown in Fig.7, where the velocity fluctuation was relatively small, was used as the measure of the magnitude of the ion drag flow.

4.2 Effect of number of projections

Figure 8 shows an example of the result of the filtration experiment, which was obtained using Oil 1 for different numbers of the projections. The ordinate of Fig.8 stands for the percentage, r , of the powder concentration at time t to the initial powder concentration and the abscissa the filtration time, t . As can be seen from Fig.8, the powder concentration is decreased at a faster speed with increasing number of the projections. In the present paper, the filtration speed was evaluated using the value of r at $t=0.25h$, expressed as $r_{t=0.25h}$, of which lower value indicates a faster filtration speed.

The effect of the number of the projections on the filtration speed was examined using Oils 1, 2, 3 and 5 and the experimental results are shown in Fig.9. As can be seen from Fig.9, a larger number of the projections can bring a faster filtration speed. For Oil 5, the filtration speed was significantly increased even at $n=40$ but tended to be saturated at larger numbers of the projections. As indicated by Fig.9, the effect of the number of the

projections is somewhat different among the oils.

Fig.7 Example of ion drag flow generated between electrodes
(Oil 6, $s=5\text{mm}$, $V=+10\text{kV}$, $T=40^\circ\text{C}$)

Fig.8 Variation of powder concentration with time at different numbers of projections
(Oil 1, $V=+10\text{kV}$, $s=4\text{mm}$, $T=40^\circ\text{C}$)

Fig.9 Effect of number of projections on filtration speed ($V=+10\text{kV}$, $s=4\text{mm}$, $T=40^\circ\text{C}$)

Figure 10 shows simulation results of the maximum and average electric field strengths calculated under different number of the projections. The maximum electric field strength, E_{max} , appears at the tip of the projection and is decreased to some degree with increasing number of the projections. This is because the degree of the electric field

concentration at the projection tips is relaxed by increased number of the projections. The decrease in the maximum electric field strength decreases to some degree the quantity of the injected charges from one projection but the total quantity of the charges injected from all the projections may be increased. The average electric field strength, E_{av} , was evaluated on the plane at 2mm distance from the smooth electrode surface. As can be seen from Fig.10, the increase in the number of the projections brings about the increase in the average electric field strength, which results in stronger Coulomb forces exerted on particles. Taking the simulation results shown in Fig.10 into account, the filtration speed can be increased by the increase in the number of the projections resulting from augmented quantity of charges injected and average electric field strength. However, it is difficult to machine a large number of the projections in a limited area of an emitter electrode. About 150 to 200 projections are appropriate for the size of the emitter electrodes used, which is equal to the number density of 0.375 to 0.5 projections/cm² on one side.

Fig.10 Effect of number of projections on maximum and average electric field strengths ($s=4\text{mm}$, $V=+10\text{kV}$)

4.3 Effect of electrode spacing

Figure 11 shows experimental results of filtration obtained at different electrode spacings using the same four oils as those in Fig.9. As can be seen from Fig.11, the filtration speed was increased with decreasing electrode spacing. It is considered that the increase in the filtration speed mainly results from the increase in the quantity of the electric charges injected from the projection tips, which is caused by greater electric field strengths at the tips of the projections at smaller electrode spacings. This can be confirmed by the numerical simulation results of the electrostatic field shown in Fig.12. Both the maximum and average electric field strengths are increased with decreasing electrode spacing and these augment the quantity of charges injected and the Coulomb forces exerted on the particles.

Figure 13 shows the effect of the electrode spacing on the magnitude of the ion drag flow. The decrease in the electrode spacing brings about increases in the maximum and average electric field strengths. However, the magnitude of the ion drag flow was decreased with decreasing electrode spacing as shown in Fig.13. It is considered that some distance is necessary for the oils (fluid in general) to be accelerated by the Coulomb force (a body force in general) and that the magnitude of the ion drag flow is decreased under smaller electrode spacings regardless of greater Coulomb forces.

Smaller electrode spacing is better to increase the quantity of the injected charges as well as the electric field strength between the electrodes and, at the same time, to suppress the undesirable effect of the ion drag flow. However, too small electrode spacing may cause discharges at the projection tips. In addition, a filter element has to be inserted between the

electrodes to capture conductive contaminants. Taking these into consideration, it seems that $s=4$ to 5mm is appropriate.

Fig.11 Effect of electrode spacing on filtration speed ($V=+10\text{kV}$, $n=166$, $T=40^\circ\text{C}$)

Fig.12 Effect of electrode spacing on maximum and average electric field strengths ($n=166$, $V=+10\text{kV}$)

Fig.13 Effect of electrode spacing on ion drag flow ($V=+10\text{kV}$, $T=40^\circ\text{C}$)

4.4 Effect of applied voltage

Figure 14 shows the effect of the magnitude of the applied voltage on the filtration speed and was obtained using Oils 3, 4, 5 and 6. The open symbols stand for no charge injection and the solid symbols for charge injection. As shown in Fig.14, the filtration speed was increased with the increase in the applied voltage but was apt to be saturated at the applied voltages higher than 10kV, especially for the case of charge injection.

Figure 15 shows the numerical simulation results of the electrostatic field under different applied voltages. The maximum and average electric field strengths are increased in proportion to the applied voltage. As consequence, the quantity of the charges injected and the Coulomb forces exerted on the particles are augmented and the filtration speed can become faster at greater applied voltages.

Fig.14 Effect of applied voltage on filtration speed ($s=4\text{mm}$, $n=166$, $T=40^\circ\text{C}$)

Fig.15 Effect of applied voltage on maximum and average electric field strengths ($n=166$, $s=4\text{mm}$)

On the other hand, the increased electric field strength and electric charges injected make the ion drag flow towards the smooth electrodes stronger, which may hinder the capture of the particles and may detach part of the particles on the smooth electrodes, as described in Section 4.1. The effect of the applied voltage on the magnitude of the ion drag flow is shown in Fig.16. The magnitude of the ion drag flow was increased with increasing applied voltage for all three oils. The result seems to correspond to the result shown in Fig.14; namely, the filtration speed increases with the increase in the magnitude of the applied voltage but is apt to be saturated at high applied voltages. It is considered that a greater ion drag flow at a higher applied voltage prevents particles from being captured on

the smooth electrode and/or may detach part of the particles on the smooth electrodes. Taking the results shown in Figs.14, 15 and 16 into consideration, the applied voltage of 10kV can be optimal. Such a lower voltage is helpful in reducing the cost of the high DC power supply.

Fig.16 Effect of applied voltage on ion drag flow ($s=5\text{mm}$, $T=40^\circ\text{C}$)

4.5 Effect of oil temperature

Figure 17 shows the effect of the oil temperature on the filtration speed. The filtration speed was increased to some degree with increasing oil temperature for the case of no charge injection. This may be due to decreased oil viscosity. However, the filtration speed was increased relatively largely for the case of charge injection when the temperature was increased from 40°C to 50°C . The increased filtration speed by charge injection at relatively low temperatures ($\leq 50^\circ\text{C}$) enables the charge injection type of electrostatic oil filter to be operated at relatively lower temperatures. This characteristic can save the electric power used to heat up oils.

Fig.17 Effect of oil temperature on filtration speed ($s=4\text{mm}$, $n=166$, $V=+10\text{kV}$)

The filtration speed at a further increased temperature (60°C), however, was apt to be saturated for Oil 7 and was decreased to some degree for Oils 5 and 6. As in the previous paper⁽⁴⁾, the pressure generated by an ion drag pump was measured for Oils 5, 6, 7 at different temperatures to estimate the variation of the quantity of the charges injected with temperature. The relation between the generated pressure, which can be an index of the

quantity of the injected charges, and the temperature is shown in Fig.18. A schematic of the ion drag pump used is shown in Fig.18 and the pressure was measured under no bulk flow condition. It can be seen from Fig.18 that the quantity of the injected charges is augmented with temperature slightly for Oil 5 and relatively largely for Oils 6 and 7.

Similar tendencies were observed also for the ion drag flow as shown in Fig.19. The magnitude of the ion drag flow was slightly increased for Oil 5 and relatively largely increased for Oil 6 with temperature. The saturation of or the decrease in the filtration speed at 60°C may be attributed to the increased ion drag flow. The optimal temperature to speed up the filtration may be around 50°C but would be changed by the viscosity grade of oil.

Fig.18 Relation between pressure generated by ion drag pump and temperature ($V = +16\text{kV}$, distance between electrodes=4mm, no bulk flow)

Fig.19 Effect of oil temperature on ion drag flow ($s=5\text{mm}$, $V=10\text{kV}$)

5. Conclusions

The effects of some mechanical factors on the filtration speed of a charge injection type of electrostatic oil filter were examined. Numerical simulations of electrostatic field were carried out to discuss the effect of the mechanical factors. An ion drag flow generated from the tips of the projections towards the smooth electrode was observed using a CCD camera and was analyzed by a PIV technique.

It has been shown that the filtration speed is increased with increasing number of the projections, applied voltage and oil temperature and with decreasing electrode spacing but is apt to be saturated at higher applied voltages and temperatures. Observations have shown

that the magnitude of the ion drag flow is increased with increasing applied voltage and electrode spacing and that part of the particles on the smooth electrodes is detached by the ion drag flow. It is considered that a strong ion drag flow hinders the capture of contaminants, detaches part of the contaminants on the smooth electrodes and may be the primary cause of the saturation tendency of the filtration speed seen, e.g., at higher applied voltages or oil temperatures.

Based on the experimental and numerical simulation results, optimal electrode configuration and operating conditions for the model of charge injection type of electrostatic oil filter used have been obtained as follows: the number density of the projections is 0.375 to 0.5 projections/cm² on one side, the electrode spacing is 4 to 5mm and the applied voltage is about 10kV, and an optimal oil temperature can be 50°C but the selection should be based on the viscosity grade of oil.

In this investigation, a simple filter model consisting of electrodes alone was used. In order to capture both non-conductive and conductive contaminants, a filter element has to be inserted between the emitter and smooth electrodes. An optimal configuration and arrangement of the filter element needs to be found out. In addition, detailed analyses of ion drag flow field in the filter are necessary to reduce its undesirable effect on the filter performance.

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