研究論文

Measurement and Numerical Simulation of Flow and Electric Fields
in Charge Injection Type of Electrostatic Oil Filter*

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This paper presents experimental and numerical simulation results of the flow and electric fields in a two-dimensional model of charge injection type of electrostatic oil filter. A previous work has shown that flow is generated from the tips of the projections of the emitter electrode towards the smooth electrodes because of ion drag phenomenon and that the flow may detach part of the contaminant particles captured on the smooth electrodes and may be the principal cause of the saturation of the filtration speed at higher applied voltages and oil temperatures. In order to minimize the bad influence of the ion drag flow on the filter performance, it is important to be able to predict the flow in filters of various configurations by numerical simulation. Numerical simulation results of the flow field are compared to experimental results. In addition, electric potential distribution is measured and is compared between experiment and simulation. It is shown that the flow fields obtained by numerical simulation agree relatively well with measured ones. It is expected that the numerical simulation contributes to designing a filter with a better performance.

Key words : Filter, Contamination, Electrostatic oil filter, Charge injection, Ion drag flow, Electric field, Measurement, Numerical simulation

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 systems¹⁾. 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^{2),3)} 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, especially 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. It has been

demonstrated using many types of oil that the filtration speed is increased to a great or some degree^{2),3)}.

A previous investigation⁴⁾ has made clear the effects of mechanical factors such as the applied voltage and electrode spacing on the filtration speed and has shown that the filtration speed is apt to be saturated at higher applied voltages and oil temperatures. Observation of the flow field in a two-dimensional filter model using a PIV technique has shown that flow is generated from the tips of the sharp projections by the ion drag phenomenon and may detach the contaminant particles from the surface of the smooth electrodes and that the ion drag flow may be the primary cause of the saturation of the filtration speed⁴⁾. However, in the previous investigation, the ion drag flow was not fully examined and only electrostatic field simulations were made to discuss the effects of the mechanical factors. If the flow field as well as the electric field in an electrostatic oil filter can be predicted by numerical simulation, it will be helpful in designing an electrostatic oil filter with a better performance.

The ion drag phenomenon has been applied to ion drag pumps, heat transfer enhancement, etc. Numerical simulations of ion drag flow in dielectric liquids have been made^{5),8)} but comparison between measured and simulated flow fields has hardly been done so far⁶⁾. The fundamental equations that describe the flow and electric fields have established since long ago. However, the injected charge density, which has to be given as a boundary condition in numerical simulations, cannot be theoretically known. In

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addition, it is known that at high electric fields, the ionic mobility does not obey the Walden's law and becomes significantly larger than that predicted by the law⁹⁾. In order to numerically simulate the ion drag flow field in dielectric liquids, it is important to find out the dependences of the injected charge density and the ionic mobility on the electric field strength for each dielectric liquid. If those dependences can be obtained using a simple electrode configuration, flow and electric fields in a complicated three-dimensional filter configuration will be able to be predicted.

In this paper, the ion drag flow field and the electric field are examined in detail under various conditions using a two-dimensional filter configuration. Numerical simulation results are compared with measured ones and the possibility of the prediction of the flow and electric fields by numerical simulation is discussed.

The organization of the paper is as follows. Nomenclature used in this paper is listed in Section 2. Section 3 describes the experimental apparatus and method. The method of numerical simulation of flow field and electric field is given in Section 4. The experimental results, simulation results and discussion are given in Section 5. Finally, the conclusion is described in Section 6.

2. Nomenclature

D_i	: ion diffusivity
E	: electric field
E_{static}	: magnitude of electrostatic field strength
$E_{staticmax}$	: maximum value of E_{static}
E_{thres}	: threshold of electric field strength
f_x, f_y	: x and y components of Coulomb force
J	: current density
k	: proportional constant
n	: exponent
p	: pressure
q	: charge density
q_{in}	: injected charge density
s	: electrode spacing
T	: oil temperature
u, v	: x and y components of flow velocity
$\bar{u}$	: magnitude of ion drag flow
V	: applied voltage
V	: velocity
x, y	: x and y coordinates
ε	: permittivity
μ	: viscosity
μ_i	: ionic mobility
ϕ	: electric potential

ρ	: mass density
σ	: conductivity

3. Experimental Apparatus and Method

3.1 Test Oils

Two types of hydraulic fluids and one type of multipurpose oil were used for flow field observation. In Table 1, the values of the conductivity and viscosity of the test oils at 313K (40°C) are shown. Porous plastic particles, of which specific gravity is 1.02 and of which size ranges from 75 to 150 μm , were mixed into the 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.

Table 1 Physical Properties of Test Oils at 313K

Oil No.	σ [S/m]	μ [mPa · s]
1	1.24×10^{-10}	39.4
2	4.71×10^{-13}	27.1
3	5.31×10^{-12}	9.9

3.2 Observation of Flow Pattern

A schematic of the experimental apparatus used is shown in Fig. 1. A test oil in reservoir ① was fed into the filter model ⑤ by a gear pump ③, of which delivery flow rate can be adjusted by an inverter ④, until the oil temperature in the filter model was reached a specified value. The temperature of the oil was controlled by using a heater ⑦ and a thermoregulator ⑧. The oil in the reservoir was stirred by a magnetic stirrer ② to avoid the gravitational sedimentation of the plastic particles. A DC voltage was applied by a high DC power supply ⑥.

In order to make the observation easy, approximately two-dimensional emitter electrodes were used as shown in Fig. 2. The emitter electrodes were made of stainless steel and the rectangular projections were machined by laser beam. A transparent electrode made of glass of which surface is coated by a conductive material (SnO_2) was used as the smooth electrode for a light sheet ⑨ to be penetrated into the filter model. Emitter electrodes with different heights, $h=5.5, 4.5$ and 3.5mm , of the projection were made and the heights correspond to the electrode spacing of $s=4, 5$ and 6mm , respectively. The motions of the particles were observed by a CCD camera ⑩ and the flow field was analyzed by a PIV technique using a computer ⑪. When measuring the flow pattern, the pump ③ was stopped.

The effects of the magnitude and polarity of the applied voltage, the electrode spacing, and the oil temperature on the

ion drag flow were examined. The magnitude of the applied voltage was varied from 8kV to 14kV under the conditions of $s=5\text{mm}$ and $T=313\text{K}$. When examining the effect of the electrode spacing, the magnitude of the applied voltage and the oil temperature were kept at 10kV and 313K, respectively. The oil temperature was varied from 313K to 333K under the conditions of $s=5\text{mm}$ and $V=-10\text{kV}$.

Fig. 1 Schematic of Apparatus Used to Observe Ion Drag Flow

Fig. 2 Schematic of Two-Dimensional Emitter Electrode

3.3 Measurement of Electric Potential Distribution

In order to make clear the electric field between the electrodes, it is important to measure the electric potential distribution. Figure 3 shows a schematic of the apparatus used to measure the electric potential distribution. Because it takes a long time for the measured value at one point to be settled, the potential was measured only along the projection center line. A probe (6), which is made of stainless steel wire of 0.3mm in diameter and is covered by a ceramic hollow tube of 1mm in outer diameter, was inserted between the electrodes and was moved along the center line. The stainless steel wire sticks out of the ceramic tube by 0.3mm

as shown in Fig. 3. The probe was connected to a circular plate (5) made of stainless steel. The electric potential of the circular plate was measured by using a surface potential meter (3) through a non-contacting probe (4). A DC voltage was supplied by a high voltage power supply (2). The electric potential distribution was measured under different applied voltages and electrode spacings.

Fig. 3 Schematic of Apparatus Used to Measure Electric Potential Distribution

4. Numerical Simulation

In the simulations, two-dimensional, incompressible, steady, laminar flows are assumed. Because of relatively high viscosities of oils and relatively low flow velocities, the assumption of laminar flow is appropriate. Figure 4 shows the unit area to be analyzed. Taking the symmetry of the configuration into account, only a half of the observation area shown in Fig. 2 was used for simulation. Followings are the basic equations that describe the flow field and electric field :

Continuity equation :

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Navier-Stokes' equation :

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + f_x \quad (2)$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + f_y \quad (3)$$

Charge conservation law :

$$\nabla \cdot \mathbf{j} = 0 \quad (4)$$

Current density :

$$\mathbf{j} = q\mu\mathbf{E} + q\mathbf{V} - D\text{grad}q + \sigma\mathbf{E} \quad (5)$$

Gauss' law :

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = -\frac{q}{\epsilon} \quad (6)$$

Coulomb force :

$$f_x = -\frac{q}{\rho} \frac{\partial \phi}{\partial x}, \quad f_y = -\frac{q}{\rho} \frac{\partial \phi}{\partial y} \quad (7)$$

All the equations were discretized by a finite volume method and SIMPLE algorithm was used to solve the discretized equations. The boundary conditions are given to the surfaces ① to ⑤ as follows :

$$\textcircled{1} \quad \frac{\partial u}{\partial y} = 0, \quad v = 0, \quad \frac{\partial q}{\partial y} = 0, \quad \frac{\partial \phi}{\partial y} = 0 \quad (8)$$

$$\textcircled{2} \quad u = 0, \quad v = 0, \quad q = q_{inS}, \quad \phi = 0 \quad (9)$$

$$\textcircled{3} \quad v = 0, \quad \frac{\partial u}{\partial y} = 0, \quad \frac{\partial q}{\partial y} = 0, \quad \frac{\partial \phi}{\partial y} = 0 \quad (10)$$

$$\textcircled{4}\textcircled{5} \quad u = 0, \quad v = 0, \quad q = q_{inE}, \quad \phi = V \quad (11)$$

where q_{inS} and q_{inE} stand for the charge density injected from the smooth and emitter electrodes, respectively and have opposite signs each other.

Fig. 4 Simulation Area

As was written in the introduction, in the numerical simulation of the ion drag flow, the injected charge density has to be given as a boundary condition but it cannot be theoretically known. In addition, it has not been known how the ionic mobility depends on the electric field. In this investigation, the dependences of the injected charge density and the ionic mobility on the electric field strength were determined by comparing the measured flow fields with simulated ones :

It was assumed that the injected charge density q_{in} depends on the electrostatic field strength and the following equation was used:

$$q_{in} = k (E_{static} - E_{thres})^n \text{sgn}(V) \quad (12)$$

where E_{static} stands for the magnitude of the electrostatic field strength on the electrode surface where the charges are injected. E_{thres} stands for the threshold magnitude of the electric field strength below which no charges are injected. On the electrode surfaces where $E_{static} < E_{thres}$, a zero is given to q_{in} . $\text{sgn}(V)$ is the signum function and takes a value of +1 for $V > 0$ and -1 for $V < 0$. If $V > 0$, then $q_{inE} \geq 0$ and $q_{inS} \leq 0$,

and if $V < 0$, then $q_{inE} \leq 0$ and $q_{inS} \geq 0$.

E_{thres} was determined experimentally by observing the motion of oil. When the applied voltage is increased, oil near the tip of the projection starts to move at a certain voltage. By making an electrostatic field numerical simulation using the value of the applied voltage, the value of E_{thres} can be obtained as the magnitude of the electric field strength at the projection tip. The exponent, n , was varied from 1 to 3 in simulations and it was found that $n=1$ is most appropriate within the scope of the present experimental conditions. The proportional constant, k , was also determined by comparing numerically simulated flow fields with measured ones.

The values of E_{thres} and k depend on the type of oil, the polarity of the applied voltage and the oil temperature. Those values obtained are shown in Table 2.

Table 2 Values of E_{thres} and k for Test Oils

Oil No.		Negative			Positive		
		313K	323K	333K	313K	323K	333K
1	E_{thres} [V/m]	0.22×10^6	0.22×10^6	0.21×10^6	0.16×10^6	0.15×10^6	0.16×10^6
	k [C/Vm ²]	8.29×10^{-10}	8.32×10^{-10}	8.37×10^{-10}	5.27×10^{-10}	—	—
2	E_{thres} [V/m]	0.12×10^6	0.12×10^6	0.13×10^6	0.21×10^6	0.18×10^6	0.17×10^6
	k [C/Vm ²]	3.74×10^{-10}	3.76×10^{-10}	3.77×10^{-10}	3.00×10^{-10}	—	—
3	E_{thres} [V/m]	0.17×10^6	0.14×10^6	0.15×10^6	0.17×10^6	0.17×10^6	0.16×10^6
	k [C/Vm ²]	4.65×10^{-10}	4.62×10^{-10}	4.69×10^{-10}	2.61×10^{-10}	—	—

In the same way as the injected charge density, the value of the ionic mobility was determined through the comparison between measured flow fields and simulated ones. It was found that for the electrode configuration shown in Fig. 2, the value of the ionic mobility hardly affects the ion drag flow field, and the value predicted by the Walden's law ($\mu\mu_i = \text{const.}$) was used.

Figures 5 and 6 show the electrostatic field strength distribution at $V=10\text{kV}$. The injected charge density distributions on the electrode surfaces were calculated by Eq. (12) with $n=1$ into which the distributions of E_{static} were substituted, and were assigned as boundary conditions. For the electrode configuration used, the effect of the charges injected from the electrode surfaces except for the projection tip area is very small and the boundary condition of the charge injection can be approximated with a good accuracy by $q_{in} = k (E_{staticmax} - E_{thres})$ only on the surface AB shown in Fig. 4, where $E_{staticmax}$ stands for the maximum value of E_{static} which

appears on the corner A of the projection tip. For this approximation, the value of k becomes slightly larger than that shown in Table 2.

Fig. 5 Distribution of Electrostatic Field Strength on Projection ($y=0.15\text{mm}$, $V=10\text{kV}$, $s=5\text{mm}$)

Fig. 6 Distributions of Electrostatic Field Strength in y -Direction on Smooth and Emitter Electrodes ($V=10\text{kV}$, $s=5\text{mm}$)

5. Results and Discussion

Examples of flow field obtained from experiment and simulation under different electrode spacings are shown in Fig. 7. As can be seen from Fig. 7, vortices are formed above and below (not shown) the projection. The forms of the vortices are somewhat different between simulation and experiment but are relatively similar. In the experimental flow fields (upper figures in Fig. 7), a small vortex is formed for $s=4\text{mm}$ whereas a larger one is formed for $s=6\text{mm}$. This tendency of the experimental flow field was obtained also from the simulation as shown in the lower figures of Fig. 7.

Examples of the flow field obtained at the applied voltages of -10kV and -14kV are shown in Fig. 8. As can be seen from the figures, the size of the vortex and the magnitude of the flow velocity are increased with increasing magnitude of the applied voltage. Such a tendency of the flow field was obtained in both experiment and simulation.

Fig. 7 Comparison of Flow Fields at Different Electrode Spacings (Oil 1, $V=-10\text{kV}$, $s=4\text{mm}$ (left) and 6mm (right), $T=313\text{K}$)

In order to evaluate the agreement between simulation and experiment, the velocity distribution in a slender rectangular region, shown in Fig. 7, 0.5mm above the projection, is compared in Fig. 9 under different electrode spacings. It can be seen from Fig. 9 that the maximum velocity is almost the same between the simulation and experiment but that the velocity distribution curves in the experiment are not smooth unlike those in the simulation. The ion drag flow pattern was sometimes fluctuated with time and the electrode configuration is not exactly two-dimensional. Uncertainties are included in the values of the injected charge density and ionic mobility used in the simulation. It is considered that those may be the primary causes of the difference between the experimental and simulation results.

Figures 10 to 13 show the effects of the applied voltage, the electrode spacing and the temperature on the magnitude of

Fig. 8 Comparison of Flow Fields at Different Applied Voltages (Oil 2, $V=-10\text{kV}$ (left) and -14kV (right), $s=5\text{mm}$, $T=313\text{K}$)

Fig. 9 Comparison of Velocity Distribution between Experiment and Simulation for Oil 1

the ion drag flow, respectively. In addition, comparisons between the experimental and simulation results are made. As described above, the flow was sometimes fluctuated and the measurement along or near the projection line was not easy partly because of relatively high velocity. Therefore, the comparisons were done in a square area shown in Fig. 8 where the velocity fluctuation was relatively small for all the test oils.

Figures 10 to 13 show that the magnitude of the ion drag flow velocity increases with the increases in the magnitude of the applied voltage (Figs. 10, 11), the electrode spacing (Fig. 12) and in the oil temperature (Fig. 13). As was discussed in a previous paper⁴⁾, the increase in the applied voltage increases not only the electric field strength on the projection surface but that between the electrodes. The former effect brings about the increase in the injected charges and the latter effect contributes to the increase in the Coulomb force exerted on the oil. The increase in the electrode spacing makes the electric field strength on the projection surface as well as that between the electrodes decreased. These bring about a decrease in the Coulomb force exerted on the oil. However, the increased distance between the electrodes can contribute to accelerating the oil and hence to the increase in the flow velocity. Higher oil temperature yields an increase in the injected charges for the test oils, which was confirmed by measuring the pressure generated by an ion drag pump as in the previous papers^{3), 4)}. Such a characteristic makes the ion drag flow large together with the effect of decreased oil viscosity at increased temperatures.

As can be seen from Figs. 10 to 13, the tendency for the flow velocity to be varied with those mechanical factors in the simulation is almost the same as that in the experiment, but the magnitude of the flow velocity is somewhat different.

The polarity of the charge injection also affects the ion drag flow as shown in Figs. 10 and 11. For Oil 3, the

Fig. 10 Effect of Negative Applied Voltage on Ion Drag Flow ($s=5\text{mm}$, $T=313\text{K}$)

Fig. 11 Effect of Positive Applied Voltage on Ion Drag Flow ($s=5\text{mm}$, $T=313\text{K}$)

magnitude of the flow velocity is much larger for negative charge injection than for positive one. For the other two test oils, the magnitude of the ion drag flow was almost the same for both polarities. It has been shown that usually, negative charges are more easily injected than positive ones³⁾. It has been pointed out that the ion drag flow may prevent contaminant particles from being captured on the smooth electrodes⁴⁾. Therefore, when in particular injecting negative charges, some measures to minimize the bad influence of the ion drag flow have to be taken. This is the subject for a future study.

The results of the measurement and simulation of the electric potential distribution for different applied voltages for Oil 2 are shown in Fig. 14. The potential is monotonously decreased from the projection tip to the smooth electrode for the simulation while bumps appear between the electrodes in the measured potential distribution curves. Such difference may arise from inappropriate values of the injected charge density and ionic mobility. The elucidation of the cause of the difference is also the subject for a future study. Similar potential distributions to Fig. 14 were obtained for the other test oils.

Fig. 12 Effect of Electrode Spacing on Ion Drag Flow ($V = -10\text{kV}$; $T = 313\text{K}$)

Fig. 13 Effect of Temperature on Ion Drag Flow ($V = -10\text{kV}$; $s = 5\text{mm}$)

Simulated distributions of the electric field strength averaged on the planes parallel to the smooth electrode along the projection line for $V = 10\text{kV}$ and 14kV are shown in Fig. 15. The electric field strength becomes lower at and near the projection tip under charge injection than that for the electrostatic field due to the injected charges with the same polarity as the emitter electrode, while higher electric field strengths are yielded near the smooth electrode under charge injection. The latter characteristic can contribute to increasing the Coulomb force acting on contaminant particles.

6. Conclusions

In this paper, ion drag flow field and electric field in a two-dimensional model of charge injection type of electrostatic oil filter were examined by experiment and numerical simulation. Though the simulated potential distribution did not agree well with measured one, the ion drag flow fields obtained by numerical simulation agreed relatively well with the measured ones. In this investigation, a simple two-dimensional filter model without a filter element was used. In order to capture conductive contaminants, a filter element has to be inserted between the electrodes. The insertion of

Fig. 14 Effect of Applied Voltage on Electric Potential Distribution (Oil 2, $s = 5\text{mm}$, $T = 313\text{K}$)

Fig. 15 Simulated Distributions of Electric Field Strength Averaged on Planes Parallel to Smooth Electrode (Oil 2, $s = 5\text{mm}$, $T = 313\text{K}$)

the filter element will change the flow and electric fields. The simulation accuracy is not very high at present but the numerical simulation may contribute to designing a filter with a better performance. Investigation needs to be continued to improve the simulation accuracy. In addition, the effect of a filter element needs to be investigated.

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References

- 1) Sasaki, A., Sasaoka, M., Tobisu, T., Uchiyama, S., Sasaki, T.: The Use of Electrostatic Liquid Cleaning for Contamination Control of Hydraulic Oil, Lubric. Engng, 44-3, 251/256 (1988)
- 2) Yanada, H., Masuoka, T., Yoshida, Y.: Fundamental

- Investigation of Charge-Injection Type of Electrostatic Oil Filter, The 1st Int. Conf. Manufacturing, Machine Design and Tribology 2005, Seoul, Korea (2005), CD-ROM
- 3) Yanada, H., Tran, K. D. : Fundamental Investigation of Charge Injection Type of Electrostatic Oil Filter, J. Advanced Mechanical Design, Systems, and Manufacturing, 2-1, 119/132 (2008)
- 4) Tran, K. D., Yanada, H. : Fundamental Investigation of Charge Injection Type of Electrostatic Oil Filter (Effects of Mechanical Factors on Filtration Speed), J. Advanced Mechanical Design, Systems, and Manufacturing, 2-6, 971/984 (2008)
- 5) Hasegawa, M., Yabe, A., Nariai, H. : Numerical Analysis of Electro-Hydrodynamical Enhancement Mechanism of Forced Convection Heat Transfer in Duct Flow, Trans, JSME, Ser. B, 64-620, 1196/1201 (1998) (in Japanese)
- 6) Eto, M. and Kagawa, Y. : Numerical Simulation of EHD Flow and Effect Estimation of The Thin Plastic Plate on Charge Injection Enhancement, J. Inst. Electrostat. Jpn., 24-6, 338/342 (2000) (in Japanese)
- 7) Vázquez, P., A., Chacón Vera, E., Castellanos, A., Chacón Rebollo, T. : Numerical Calculations of Two-Dimensional EHD Plumes with Finite Element and Particle Methods, 2003 Annu. Rep. Conf. Electr. Insul. Dielectr. Phenom., 706/709 (2003)
- 8) Darabi, J., Rhodes, C. : CFD Modelling of An Ion-Drag Micropump, Sensors and Actuators A, 127-1, 94/103 (2006)
- 9) Felici, N. J. : D.C. Conduction in Liquid Dielectrics-A Survey of Recent Progress (Part I), Direct Current, 2-3, 90/99 (1972)