流動帯電液体の探極測定

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Probe Method of Measuring for Charged Oil which is Streaming

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Abstruct

This paper presents experimental results of the measurement of electrical potential and leakage current to a spherical probe in a charged (ionized) oil inside a tank on the basis of a linear relationship between the probe potential and leakage current. Effect of the probe size on the potential-current relations are examined.

1. Introduction

Good insulating liquid is electrified when it flows through a pipe. The charges generated in the flow may be carried to a tank and sometimes cause an accident. The charge accumulated inside a tank and the potential in the charged oil are determined mainly by so-called streaming current.[1]

The charge accumulation in a tank can be found by use of an spherical probe. Its electric potential can be used to measure the accurate potential in the charged oil and the charge density. In the measurement of the probe potential in the charged oil the current leaks through the insulation of the probe support.

According to our experiment, the relationship between the probe potential and the leakage current is linear as the insulation of the probe support is varied.[2]

Based on this linear relation the probe potential in the absence of leakage current can be found and also the true potential of the charged oil in a tank with constant flow rate. In this experiment, spheres of different radii also used to obtain a similar relationship. From these results we discovered that the leakage current at a same probe potential is proportional to the radius.

2. Experimental Apparatus

The experimental apparatus consists of a steel cylindrical test tank (recieving tank) for the potential measurement, an auxiliary tank of the same size for the oil circulation and a pump and a pipeline for the charge generation by flowing. Schematic representation of apparatus is shown in Fig. 1.

The oil level in the test tank was kept constant. The insulation of the test tank to the ground was varied from zero to the maximun of about $10^{11}\,\Omega$ by use of ceramic insulators and paraffin blocks.

Steel spheres of various radii were used as probes. The sphere was attached to one end of a polyethylene covered wire.

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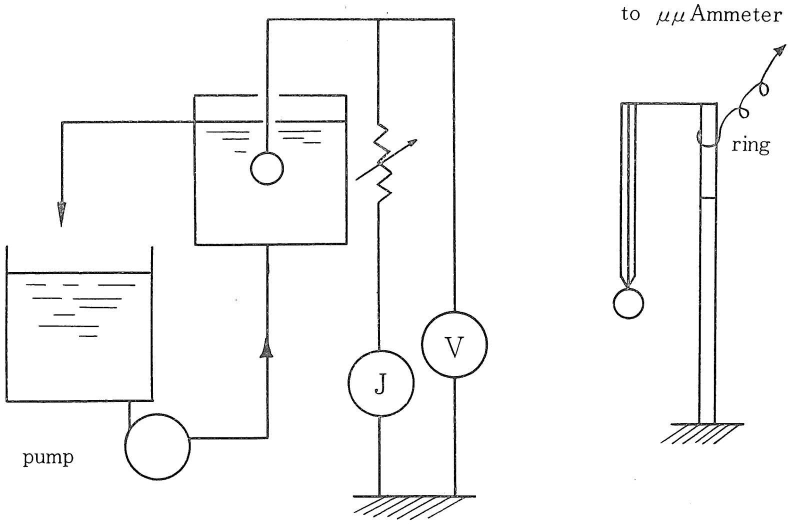

Fig. 1 (a) (b)

Fig.1. Schematic representation of apparatus. [2]

The potential measurement was made by using a R. I. electrometer. For current measurement we used a vibrating reed electrometer and a vacuum tube electrometer.

A clock pump was used to circulate the oil. This pump is able to transport the oil of 50 liters per minute. In a poly vinyl pipe of 2.5 cm, i.d., the oil flows at the maximum velocity of 1.7 m/sec, and streaming current generated was up to 10^{-8} A.

3. Experimental Methods and Results

(3.1) Relation between the leakage current and the probe potential in the charged oil.

When the insulation resistance of the probe support was varied by moving the conducting rings (contact maker) attached to the teflon rods in Fig. 1.(b), the probe potential as well as the leakage current changed. An ammeter connected to this ring indicates the leakage current flowing on the rod surface alone. But the current flowing inside the rod was considered to be much smaller, and therfore the reading of the ammeter is taken as the value of the leakage current.

The plot of the probe potential V against the leakage current J shows a straight line [2] (henceforth, this line is called V-J characteristic line).

Fig. 2 shows the V-J characteristic lines obtained by using four spherical probes of different radii in the test tank which was either grounded or insulated.

When extrapolated to zero leakage current, respective set of lines converge to one value on the ordinate. This value V_0 is considered as the true potential at the location of the probe in the charged oil.

Under the different insulation conditions of the test tank, the V-J characteristic lines for the same radius are parallel. The horizontal dotted lines indicate the wall potentials of the test tank under the different insulating conditions.

These values must be equal to the potential drop in the tank insulation due to the leakage current flowing through the tank wall.

If the streaming current is kept constant above potential drop decreases as the probe leakage current J increases, and the potential of the insulated tank does not remain constant, but decreases slightly.

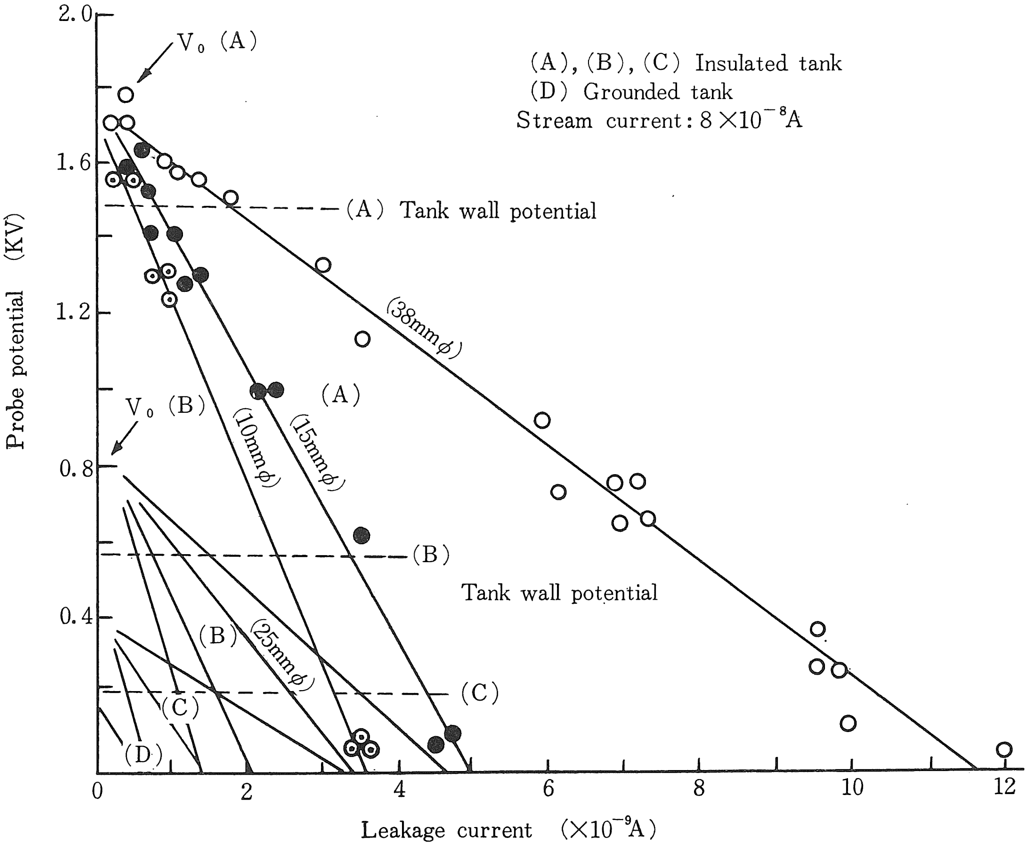

Fig.2. Probe potential vs. leakage current.

(3.2) Distribution of V_0 in the test tank

Figure 3 shows the radial distributions of the potential in the charged oil as a function of distance from the tank axis.

(3.3) Relationship between the inclination of the V-J characteristic line and the size of the probe.

If the streaming current is constant the inclination of the V-J characteristic line is inversely proportional to the probe radius. Figure 4 shows this relationship.

4. Consideration and Discussion

Assume that the leakage current to the probe from the charged oil obeys Ohm's law. Then leakage current density i is written as

$$i=kE,\quad E=-\text{grad } V \tag{1}$$

Where k is the conductivity in the charged oil. V and E are the potential and the electric field in the charged oil respectively. Divergence of the leakage current density is written as

$$\text{div } i=-\frac{\partial\rho}{\partial t} \tag{2}$$

where ρ is the charge density in oil.

In this experiment, since a circulating oil system was taken, the oil level in the test tank is kept constant and the streaming current flows constantly into the test tank as far as the pumping does not be stopped. Then the normal quantity of the charges in the oil should remain constant. Since $-\partial\rho/\partial t$ in Eq. (2) is considered as zero, substitution of Eq. (1) to Eq. (2) yields

$$\text{div grad } kV=0 \tag{3}$$

This equation corresponds with the following electro-static field equation.

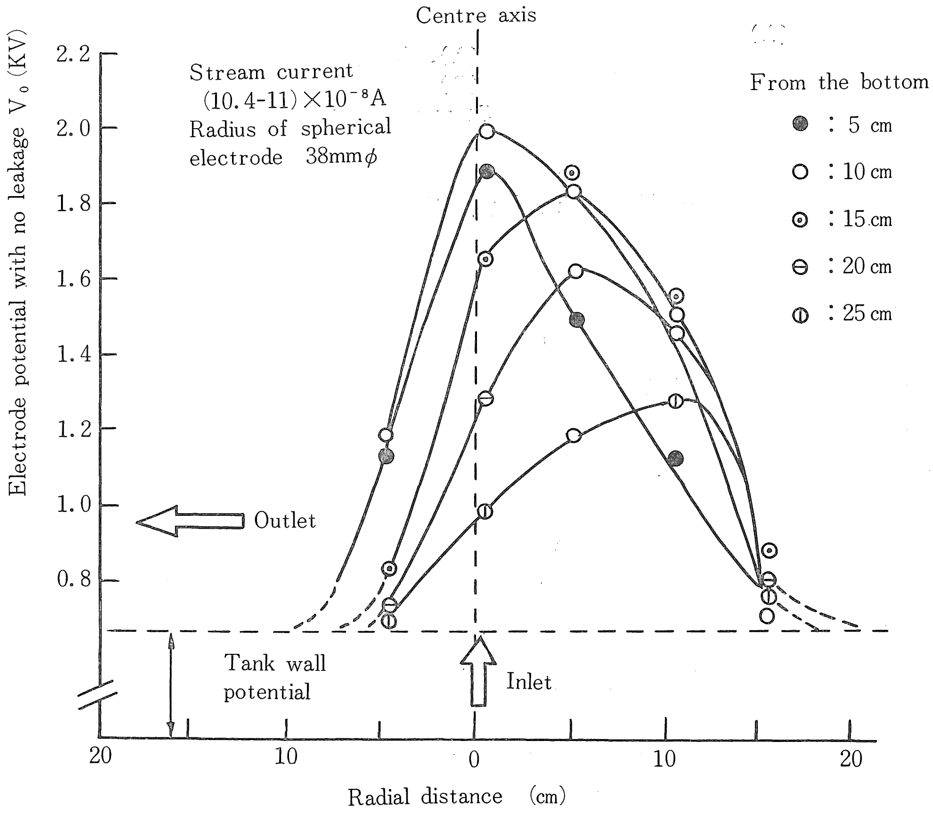

Fig.3. Radial distribution of V in the mail tank.

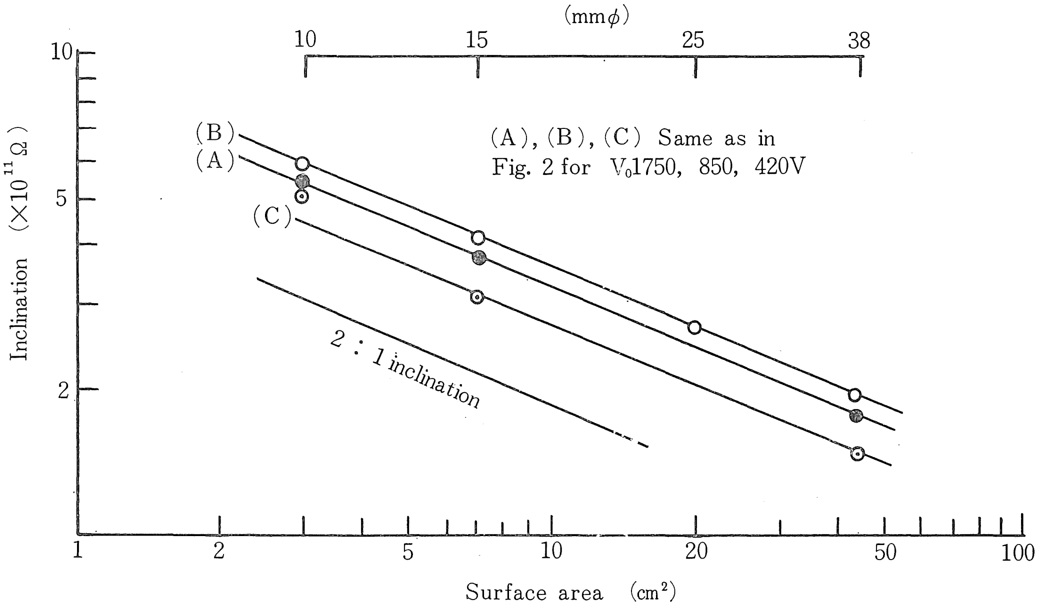

Fig. 4. Inclination of V-J characteristic lines vs. spherical surface area.

$$\mathrm{div}\ \mathrm{grad}\ \varepsilon V = 0 \qquad (4)$$

Then according to the culculation for electrostasic field, the probe potential and the electric field near the probe in charged oil are culculated as follows.

(4.1) Equation of the electric field near a spherical probe.

(a) Earthed probe

The electric field in the vicinity of an earthed spherical probe of radius r_P immersed in the charged oil can be culculated easily. In this case, the probe potential is zero. Let the charges in the oil be q_i $(i=1,2,\ldots)$, and their distances from the probe center be f_i $(i=1,2,\ldots)$. Then the electric field near the probe is equal to that obtained when the charge $-q_i r_P/f_i$ is placed at a distance $r_P{}^2/f_i$ from the centre. The electric field at a point of p on the sphere is written as

$$E_{r=r_p} = \frac{1}{4\pi\varepsilon r_p} \sum_i \frac{q_i(f_i{}^2-r_i{}^2)}{r_i{}^3}$$

$$(i=1,2,\cdots) \quad (\mathrm{V/m}) \qquad (5)$$

Where ε is permitivity of the oil and r_i is a distance from a point of p to q_i.

(b) Totally isolated probe

The electric field near the probe is equal to that obtained when the charge $\sum_i q_i \cdot r_P/f_i$ is placed at the sphere centre and $-q_i \cdot r_P/f_i$ at a distance $r^2{}_P/f_i$ from the centre.

$$E_{r=r_p} = \frac{1}{4\pi\varepsilon r_p} \sum_i \frac{q_i(f_i{}^2-r_i{}^2)}{r_i{}^3} - \frac{V_0}{r_p}$$

$$(i=1,2,\cdots) \quad (\mathrm{V/m}) \qquad (6)$$

where v_0 is the probe potential of zero leakage current. The charge at the centre essentially determines the sphere potential which is given as $\sum_i q_i/4\pi\varepsilon f_i$ $(i=1,2,\ldots)$. This value is equal to v_0.

The first term of the right side of Eq. (6) represents the electric field pointing from the oill to the probe and the second term represents the electric field which points away from the probe to the oil.

(c) Isolated probe

When a probe is not totally isolated, its potential becomes V, the electric field near the probe will be written as

$$E_{r=r_p} = \frac{1}{4\pi\varepsilon r_p} \frac{p_i(f_i{}^2-r_i{}^2)}{r_i{}^3} - \frac{V}{r_p}$$

$$(i=1,2,\cdots) \quad (\mathrm{V/m}) \qquad (7)$$

In this case the leakage current to the probe is generated.

(4.2) Leakage current to the probe from the charged oil.

For a constant value of the streaming current, the relationship between the leakage current and the spherical probe potential is linear as the insulation resistance is varied. Thus, the probe potential V and the leakage current J are related as follow;

$$J=GV \qquad (\mathrm{A}) \qquad (8)$$

Where G is conductance in charged oil. Assume that when the insulation resistance of the probe support is varied under the constant streaming current, the probe potential V_1 becomes V_2 and the leakage current J_1 becomes J_2. Then the variation of the electric field between the sphere potentials will be written as $\varDelta V/r_P$ by Eq. (3) and the leakage current variation $\varDelta J$ will be regarded as the result of the variation in the electric field $\varDelta E(\varDelta V/r_P)$.

Let the variation of the leakage current density $\varDelta i$, which is culculated as $\varDelta J/4\pi r_P{}^2$. Then, from Eq. (8)
we have a following relation as

$$\varDelta i = k\varDelta E \qquad (\mathrm{A/m}) \qquad (9)$$

Where, $$k = (4\pi r_p)^{-1}.\ G \qquad (\mho/\mathrm{m}) \qquad (10)$$

Figure 5 shows some of the experimental values shown in Fig, 2, expressed in terms of Eq. (9). Under a constant streaming current into the test tank, all the data points from various radii and different insulation conditions for the test tank seem to lie on a straight line, thus verifying Eq. (9).

It is evident that both G and k are the constants and the relationship between them

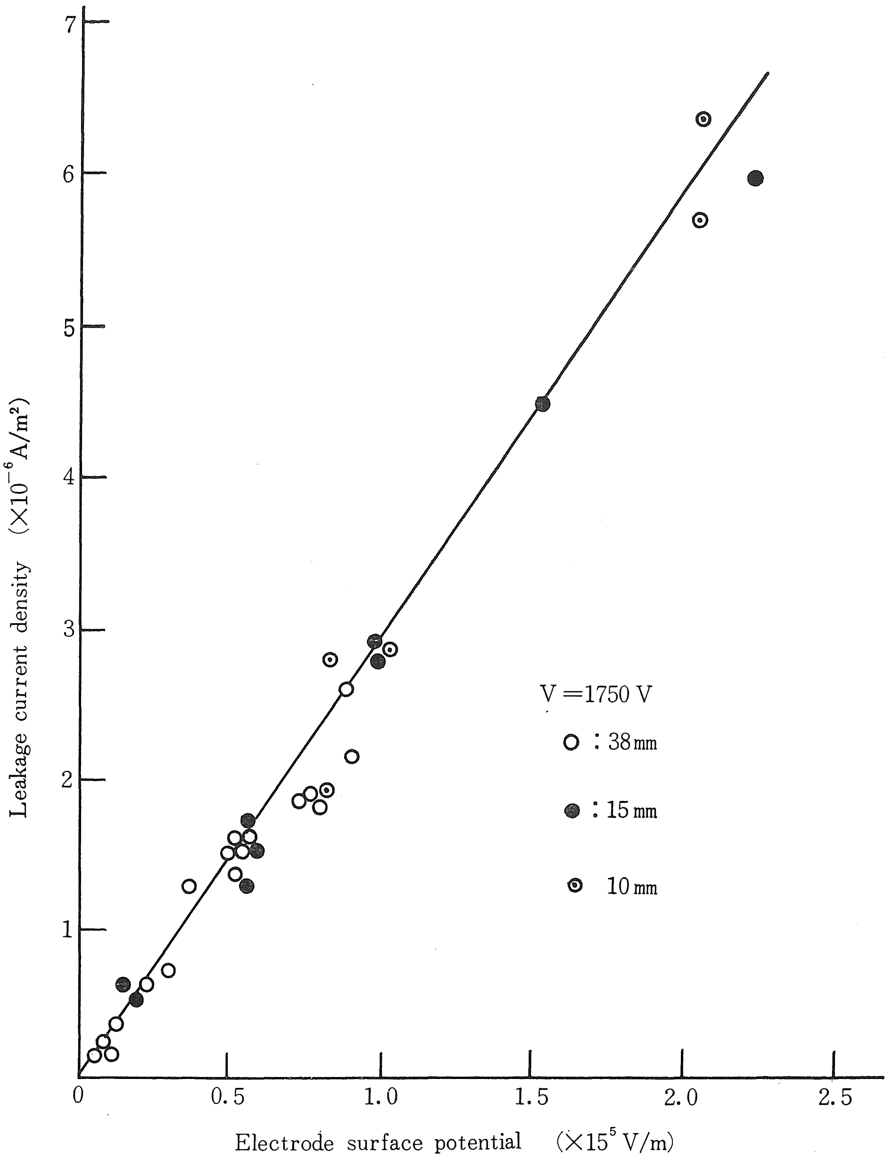

Fig.5. Leakage current density vs. electrode surface potential generating leakage.

is shown in Eq. (10). Then from Eq. (8) and Eq. (10), we can find that, for a same value of potentials obtained from various radii, respective leakage currents are generated proportionally to the radii of the probes.

(4.3) Conductivity in charged (ionized) oil

Conductivity in charged oil near the probe is determined from Eq. (10) as follows.

$$k=(4\pi r_p \cdot \Delta V/\Delta J)^{-1}=(4\pi r_p \gamma)^{-1} \ (\mho/m) \qquad (11)$$

Where γ is $\Delta V/\Delta J$ and it is determined from the inclination of V-J characteristic line. γ has a dimension of an eletric resistance.

If γ were due mainly to the contact resistance on the spherical surface, then it is inversely proportional to the square of the radius. But experimental results show that it is inversely proportional to the radius. Thus, γ is considered as the resistance of the charged (ionized) oil near the probe.

(4.4) Potential V_0

When the probe is not present, let the total charge of the oil filling the sphere volume be 3q. The potential at the sphere center will be V_0 plus $\Delta V = 3q/8\pi\varepsilon r_P$. Using experimental value of $1.3\times 10^{-6}\mathrm{cm}$[2] as the average charge density, 1 cm as the sphere radius and 2.3 as the permitivity of the oil, we obtained 0.8 V as ΔV.

Although the boundary problems should be taken into account, V_0 can be considered as the potential of the oil in the absence of the probe.

The true potential of the oil should be independent of the sphere radius, but according to the above arguments, the value of ΔV depends upon the radius r_P. For example, the difference in ΔV between the spheres of radii of 10mm and 15mm is about 1V. Therefore, strictly speaking, the extraporation of the V-J lines for various values of the radius shoud not converge to the same value on the vertical axis in Fig. 2.

But, as long as radii are not too different, the extraporated values should agree within the experimental error.

(4.5) Influence of liquid stream on the probe measuring

In this experiment the oil near the probe is flowing from the oil entrance to the upper part inside the test tank with the velocity of about 1.7 m/sec.

Since the dynamic viscosity of the oil is about 4 cst, Reynold number becomes 1.6×10^{-4}, and therefore the resistance factor C_D of the sphere against the liquid stream is determined 0.5[3].

As is well known, the surface of electric field of the sphere of radius r_P which is falling in the liquid is given by Dorn's equation.

$$E_d = -\varepsilon F\zeta/k\eta \qquad (\mathrm{V/m}) \qquad (11)$$

Where ε and k are permitivity and conductance of the liquid respectively, and ζ is a potential of the interface, η is the coefficient of the liquid visconsity and F is the reactive force of the sphere and its value is given by the following epuation

$$F = C_d(\pi r_p{}^2)\rho U^2/2 \qquad (12)$$

where ρ is the mass density of the oil and U is the velocity of the oil near the probe. Using $10^{-11}\mho/\mathrm{m}$ for k, 3.2 cp $(3.2\times 10^{-3}$ kg/m.sec) for η, 800 kg for η and 0.03 V for ζ[4], we have $Ed \fallingdotseq 0.2$ (V/m), and $F = 7\times 10^{-1}$ (N) for this probe of 38 mmϕ

In this case, the potental of the probe by Dorn's effect becomes 4 mV and the probe has charge of 1.7×10^{-14} C by this effect. As is shown in Fig. 2. the potential difference of the probe from the earth is about 90 V, above value of 4 mV is negligible small compared with 90 V. A charge of q $(1.7\times 10^{-14}\mathrm{C})$ above mentioned distributes the sphere surface and the sphere surface density becomes $2\times 10^{-12}\mathrm{C/m^2}$. The other side, the charge density of the oil near the probe is order of $10^{-14}\ \mathrm{C/m^3}$[2] and therefore, q above mentioned does not affect the measuring value of the conductivity in the oil. As is pointed by Klinkenberg et al.[5], the electric current density kE_d generated dy Dorn's effect becomes equal to that of qU and therefore the probe leakage current is not affected by this effect.

Then the probe measuring in the streaming oil is considered as a useful method in these experiments.

5. Conclusion

The potential of the spherical probe in the charged oil depends upon the size of the probe, its support, the insulating condition of the tank and charge condition of the oil.

The potential thus measured is not the same as the potential of the oil at the location of the probe. However, from the probe potential, the true potential can be deduced.

Conductivity of the charged liquid which is flowing can also be determined by this probe measuring, and an accurate determination of the ionic density can be made based on the accurate value of the transport rate of ions. This transport rate may be obtained from the charges in the inclination of the V-J characteristic lines for various streaming currents.

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