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Dielectrophoretic Filtration of Liquids. II. Conducting Liquids

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Abstract

The authors' earlier work is extended to dielectrophoretic filtration of conducting liquids by means of highly nonhomogeneous electric fields. The efficiency of the process is shown to be high for metallic impurities, but decreases for insulating impurities as liquid conductivity increases. Means for improving it in the latter case are described.

1. INTRODUCTION

The first paper of the present series (*1*) dealt with liquid filtration by means of dielectrophoretic forces (*2*). Such a force is exerted on a neutral body placed in a nonhomogeneous electric field and equals $F = p\nabla E$, where p is the induced dipole of the body and E the local electric field. For moderately strong fields the relation between E and p is linear and the force is proportional to ∇E^2. The proportionality factor—depending on the properties of the body and the medium (in our case, a fluid)—may be either positive, in which case the force is oriented in the direction of increase of the field, or negative, in which case it is oriented in the direction of decrease.

The mechanism of dielectrophoretic filtration may be described as follows. As the liquid, which contains very small impurity particles (~50 μm), flows in a nonhomogeneous field, the impurities migrate in the direction of increase of the field and are trapped on stationary collecting bodies, while the filtrate flows on and is collected outside the field region. An apparatus based on this principle is shown schematically in Fig. 1. The field region contains a cylindrical outer electrode and coaxial inner one, between which a voltage is applied. The collecting bodies are glass beads, 6 mm in diameter. The performance of this apparatus with liquids of very low electric conductivity was analyzed in detail in Ref. *1*, and very good yields (ratios of trapped material to total amount of impurities in the liquid) were obtained with different kinds of impurities (minerals, ceramics, plastics, and metals).

On the other hand, it was established that trapping becomes more and more unlikely as the relaxation time τ of the system decreases. [$\tau = (\varepsilon_2 + 2\varepsilon_1)/(\sigma_2 + 2\sigma_1)$, where ε_1 and ε_2 are the dielectric constants of the liquid and impurities, respectively, and σ_1 and σ_2 are their electric conductivities.] (See Section 2 below.) Since τ decreases, *inter alia*, with increasing σ_1, we extend our earlier work here to liquids with higher conductivity and study the performance of the apparatus under these conditions, including a detailed theoretical analysis. In the last section a new version of the apparatus, adapted for conducting liquids, is presented.

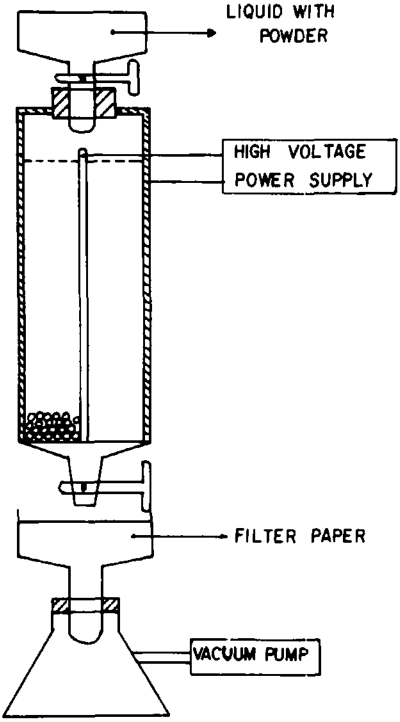

FIG. 1. Schematic view of conventional filtration apparatus.

2. THEORETICAL

The dielectrophoretic force exerted on a small spherical particle of radius R by a suddenly applied dc field E is given by

$$F = 2\pi R^3 \varepsilon_1 \left[\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_1 + 2\varepsilon_1} + 3 \frac{\varepsilon_1 \sigma_2 - \varepsilon_2 \sigma_1}{(\varepsilon_2 + 2\varepsilon_1)(\sigma_2 + 2\sigma_1)} \times (1 - e^{-t/\tau}) \right] \nabla E^2 \tag{1}$$

At $t = 0$, the force equals

$$F(t = 0) = 2\pi R^3 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \nabla E^2 \tag{2}$$

while at $t \to \infty$ it equals

$$F(t \to \infty) = 2\pi R^3 \varepsilon_1 \frac{\sigma_2 - \sigma_1}{\sigma_2 + 2\sigma_1} \nabla E^2 \tag{3}$$

(Note that the positive force is defined in the direction of increase of the field.)

At the inlet of the apparatus, a particle is subjected to the $t = 0$ limit of F, and the force varies along the path according to Eq. (1). If the transit time is very large compared to τ, this is equivalent to $t \to \infty$, and the final force is given by Eq. (3). Accordingly, we write

$$F(t = 0) = 2\pi R^3 \varepsilon_1 g_0 \nabla E^2 \tag{4}$$

and

$$F(t \gg \tau) = 2\pi R^3 \varepsilon_1 g_\infty \nabla E^2 \tag{5}$$

where $g_0 = (\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + 2\varepsilon_1)$ and $g_\infty = (\sigma_2 - \sigma_1)/(\sigma_2 + 2\sigma_1)$.

Regarding the role of the glass-ball matrix (dielectric constant ε_b) in disturbing the field, it was shown (*1, 3*) that given $\varepsilon_1 < \varepsilon_b$ the gradient is larger at contact points of the balls and smaller in the gaps between them.

If $\varepsilon_2 > \varepsilon_1$ and $\sigma_2 > \sigma_1$, both g_0 and g_∞ are positive and so is the force irrespective of the time variable; thus the particles are attracted to the matrix and trapped. In the reverse case (both g_0 and $g_\infty < 0$), the particles tend to drift away into the gaps in the matrix and trapping is prevented.

In fact, there is always, even in the absence of field, some trapping which we call the mechanical trapping. The trapping discussed above was in addition to the mechanical trapping which is set as zero in our measurements.

In this paper we are concerned with conducting liquids, $\sigma_1 > \sigma_2$, i.e., $g_\infty < 0$. For filtration to be possible in these circumstances, it is thus necessary that $g_0 > 0$ or $\varepsilon_2 > \varepsilon_1$, a condition complied with throughout our experiments.

With $g_0 > 0$ and $g_\infty < 0$, the force is positive for $t = 0$ and later goes through a change of sign at time t_0. The latter is obtained by setting $F(t_0) = 0$ in Eq. (1), namely,

$$t_0 = \tau \ln \frac{3(\varepsilon_1\sigma_2 - \varepsilon_2\sigma_1)}{(\sigma_2 - \sigma_1)(\varepsilon_2 + 2\varepsilon_1)} \tag{6}$$

If $\sigma_2 < \sigma_1$, but the two values are close (for example, $\sigma_2/\sigma_1 \simeq 0.9$), t_0 may be much larger than τ. If, however, $\sigma_2 \ll \sigma_1$ such that $\varepsilon_1\sigma_2 \ll \varepsilon_2\sigma_1$, t_0 equals

$$t_0 \simeq \tau \ln \frac{3\varepsilon_2}{\varepsilon_2 + 2\varepsilon_1} \tag{7}$$

In general, we shall see that t_0 is slightly smaller than τ, but of the same order of magnitude. Note also that if $\varepsilon_2 \gg 2\varepsilon_1$, $t_0 \simeq \tau$, and if $\varepsilon_2 = 2\varepsilon_1$, $t_0 \simeq 0.4\tau$.

We thus see that, denoting the total velocity of the particle by v, the dielectrophoretic force is positive over a path segment $L_1 = vt_0$, along which the particle is attracted by the matrix. The probability of actual trapping in this segment is substantial, although very difficult to determine. It depends on many parameters. The most important are the density differential between the impurities and the liquid, and the friction between them and the matrix. It should also be borne in mind that the dielectrophoretic force may be very small away from the inner electrode. By contrast, beyond t_0, along the rest of the path $L_2 = L - L_1$ (L being the total length of the apparatus), the probability of trapping is low, as the particle is repelled by the matrix. In other words, the closer L_1 to L, the more favorable the conditions for filtration. The situation was demonstrated by us in Ref. *1* on a mixture of kerosene and ilmenite, with very high yields under relatively low voltages (~4 kV).

It is now also clear why our apparatus becomes less efficient (i.e., the yield decreases as liquid conductivity increases): the relaxation time τ and inversion time t_0 decrease and consequently L_1 decreases while L_2 increases. Eventually, with $L_1 \ll L_2$, the yield may drop below the mechanical trapping level.

All the above refers to insulating impurities. For metallic impurities ε_2, $\sigma_2 \to \infty$, and Eqs. (4) and (5) reduce to the single expression

$$F_{\text{met}} = 2\pi R^3 \varepsilon_1 \nabla E^2 \tag{8}$$

It is seen that the force is always oriented throughout in the direction of increase of the field. Conditions for filtration are always favorable ($g_0 = g_\infty > 0$) and the yield is not affected by the conductivity of the liquid.

3. EXPERIMENTAL RESULTS

As in previous works (*1, 3, 4*) we use the same liquid as before—kerosene (heating oil) with its conductivity (originally 10^{-10}–$10^{-11}\ \Omega^{-1}\mathrm{m}^{-1}$) progressively increased through admixture of polar liquids such as dichloromethane (CH_2Cl_2) and isopropanol, in such percentages as to stay within the requirements $\varepsilon_2 > \varepsilon_1$ and $\varepsilon_1 < \varepsilon_b$. The variation of the dielectric constant (moderate) and conductivity (steep) with the percentage of polar admixture is shown in Figs. 2 and 3, respectively.

We have worked with two types of impurities: insulating and metallic. The insulating impurity used was PVC (dielectric constant of the order of 4.5), percentage 1%, and the metallic impurity was copper (0.18%). These low concentrations were adopted in order to avoid short-circuits by bridging, and to present a case for filtration of dilute suspensions.

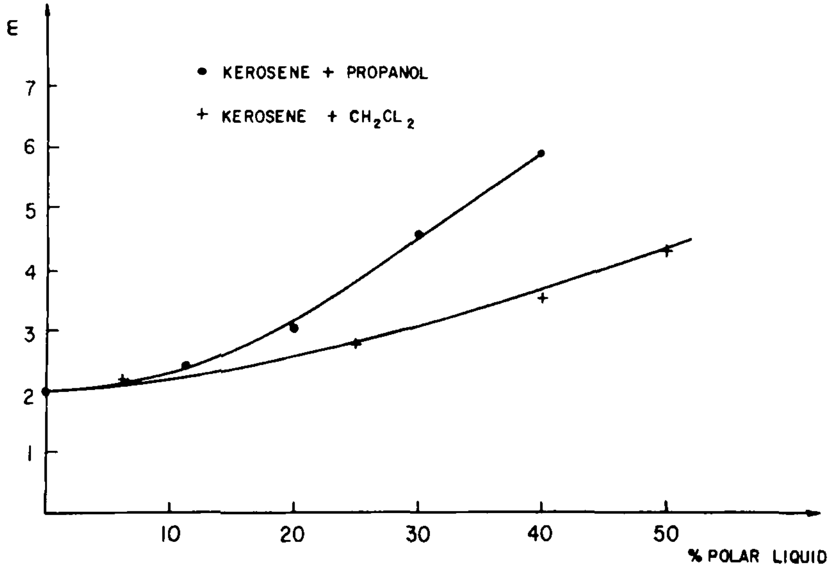

FIG. 2. Dielectric constant of the kerosene-polar liquid mixtures versus polar-liquid concentration.

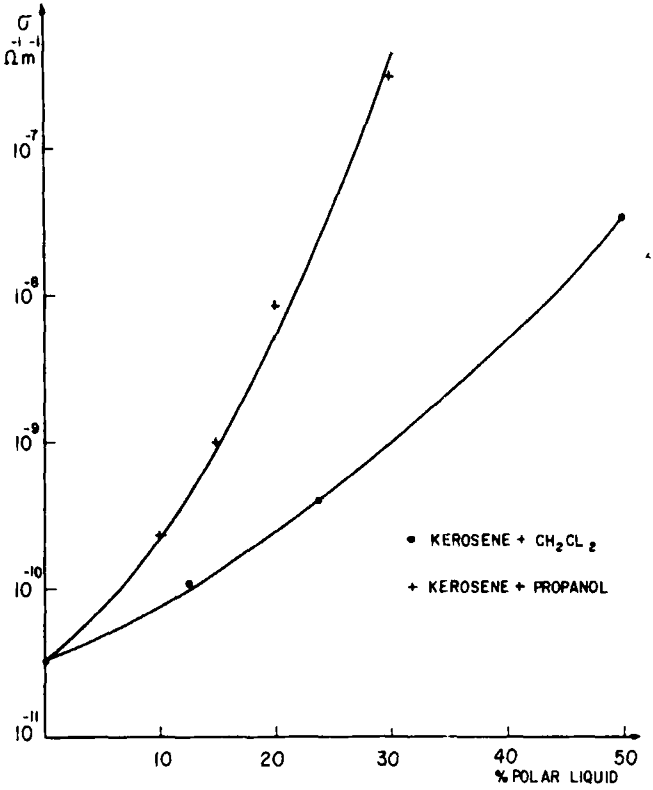

FIG. 3. Electric conductivity of kerosene-polar liquid mixtures versus polar-liquid concentration.

Results (yields as function of applied voltage, Figs. 4 and 5) are in agreement with the theoretical analysis in the preceding section:

(a) For the metallic impurity no change of the yield was observed over a range of variation of σ_l by three orders of magnitude. (The scatter of the experimental points is due to measurement errors.)

(b) By contrast, for the PVC the yield is seen to vary significantly with σ_l. As the dielectric constant of the kerosene–isopropanol mixture varies only moderately in the chosen concentration range, the variation of the yield cannot be attributed to the change in g_0. As explained above, the length L_l decreases as σ_l increases, and the apparatus is less efficient.

(c) It is remarkable that for the 15% mixture we have a decrease of the yield as the voltage increases, below the level of its mechanical

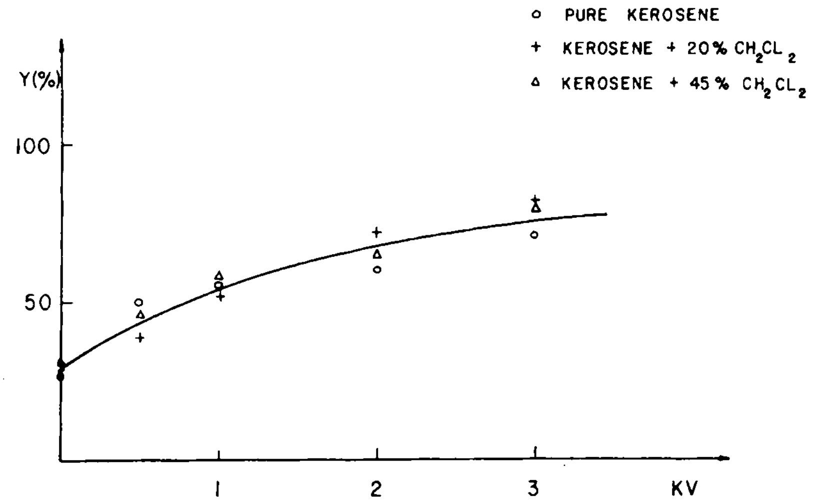

FIG. 4. Yield versus applied dc potential for copper particles.

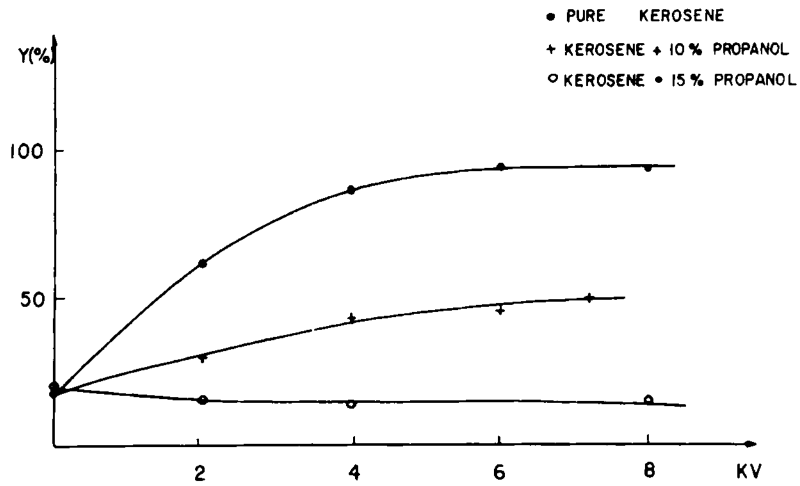

FIG. 5. Yield versus applied dc potential for PVC particles in conventional apparatus.

counterpart. The reason is that in this case L_1 is so small (~1 mm) that $L_2 \simeq L$. During the crossing of the apparatus, the particles are repelled by the beads and consequently the total yield is smaller than the mechanical yield.

In terms of relaxation time, the picture is as follows. Assuming $\sigma_2 \ll \sigma_1$ we get for pure kerosene $\tau \simeq 2$ s and $t_0 \simeq 1$ s, and since $v \simeq 2$ cm/s we have $L_1 = 2$ cm and $L_2 = 25$ cm; yet the yields observed were very good (~98%). The conclusion is that apparently σ_1 and σ_2 are of the same order of magnitude. For the 10% mixture $\tau = 0.17$ s, and taking $\sigma_2 \simeq 5 \times 10^{-11}$, $\sigma_1 = 2 \times 10^{-10}\,\Omega^{-1}\,\mathrm{m}^{-1}$, we have $t_0 \simeq 0.5\tau$. L_1 is already small and the dielectric yield at 7 kV is about 30%, by no means negligible. For the 15% mixture, however, τ decreases to 10^{-2} s, far too short for dielectric trapping.

4. NEW VERSION OF FILTRATION APPARATUS

In the light of the above, there is no advantage, when $\sigma_2 \ll \sigma_1$ in increasing the length of the apparatus. The answer lies, rather, in creating a repetitive pattern of the force as per Eq. (4) at $t = 0$. This was realized by us in a three-stage apparatus (Fig. 6) where three active field zones 1, 2, 3 alternate with

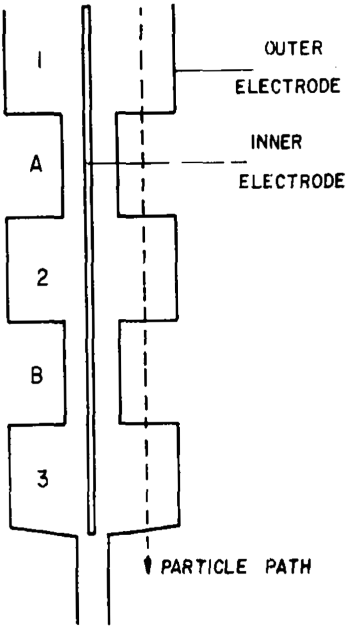

FIG. 6. Multistage filtration apparatus for conducting liquids. (Active field regions 1, 2, 3 filled with glass balls; zero field regions A and B empty.)

two zero-field zones A, B, all of which are crossed successively by the particle. As the stages are shorter (one-third, in this case) than the original apparatus, the operation is not equivalent to multiple repetition of the process in the original device. On the other hand, since the overall length and the flow rate are the same, the transit time also remains the same but the trapping probability is tripled by recurrence of the $t = 0$ conditions, and the repulsion probability is reduced. Thus an increase in the total yield can be expected with the same material. (Generally, the higher the conductivity of the liquid, the greater should be the number of stages and the shorter each stage.)

The results are given in Fig. 7. For pure kerosene, the yield-voltage is almost identical with that of Fig. 5, confirming that $\sigma_2 \simeq \sigma_1$. The improvement in performance is especially marked for the 15% mixture: the dielectric field is now positive, and the yield is 50% for 8 kV.

A similar improvement was obtained for MgO ($\varepsilon \simeq 9$) in a mixture of kerosene and dichloromethane ($\sigma_1 \simeq 10^{-8}\ \Omega^{-1}\,\mathrm{m}^{-1}$): at 6 kV the yield was 32% in the original apparatus and 80% in the three-stage. The fact that the yield was larger for MgO than for PVC (compare Fig. 3) is essentially due to the higher value of g_0 in the former.

CONCLUSION

The experiments in dielectrophoretic filtration were in complete agreement with the theoretical analysis presented above. While for insulating impurities the yield decreases as liquid conductivity increases, in the case of metallic

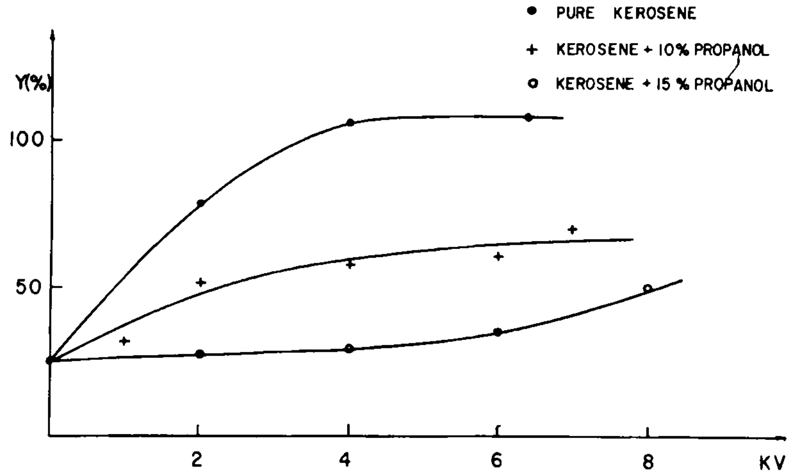

FIG. 7. Yield versus applied dc potential for PVC particles in three-stage apparatus. (Compare Fig. 5.)

impurities it is independent of the latter. In the light of the results, a more efficient multistage device was designed and satisfactory yields were obtained for $\sigma_1 \simeq 10^{-7}\ \Omega^{-1}\text{m}^{-1}$.

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