Selecting a Working Fluid to Increase the Efficiency and Flow Rate of an EHD Pump

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Abstract—**The ultimate flow rate and velocity of an electrohydrodynamic (EHD) pump with a given length and depth are determined by the material properties of the working fluid. High dielectric constant and low viscosity lead to high flow velocities, while low conductivity and mobility promote high efficiency. A fundamental model of EHD pumping is formulated to account for the material properties of the working fluid, and is applied to several experimental pumps reported earlier, with generally good agreement. An example of the use of this model to select a working fluid for a typical pump suggests several new liquids suitable for EHD pumping.**

INTRODUCTION

An ELECTROHYDRODYNAMIC (EHD) pump uses electric fields acting on electric charges embedded in a fluid to move that fluid. The electric fields can be generated with a variety of electrode configurations, including transverse mesh electrodes and longitudinal traveling-wave electrodes. The charges can be injected directly by sharp points or induced by applying fields across conductivity gradients. A number of these pumps have been described in the literature, either to study the basic mechanism of EHD pumping or to apply them to practical problems such as the cooling of high-voltage equipment. In all of this previous work, the experimenters have been concerned primarily with a single working fluid, selected for convenience or because the pump was intended to move a specific liquid. Many of these pumps operated at relatively low flow rates and efficiencies, which suggests that such pumps may be inherently slow and inefficient.

In the present paper, we examine the effect of the working fluid on the flow rate and efficiency to determine the ultimate performance which can be expected, using a simplified model of an EHD pump in which the complicating effects of channel geometry, electrode structure, charge injection and flow stability are neglected. This model is expected to overestimate the performance, so it should be taken as an upper limit to what could be achieved in practice. It is, however, capable of guiding our choice for a working fluid, since all available fluids can be compared under the same assumed operating conditions. The model will be compared with the results reported on several earlier pumps, and then used in an example to illustrate how a working fluid could be selected for a typical EHD pump.

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FUNDAMENTAL LIMITS ON PUMP PERFORMANCE

The basic EHD pump is arranged as shown in Fig. 1, with two parallel plates confining the fluid flow to a rectangular slot of width w and height d. (Symbols are defined in the Nomenclature at the end of the paper.) The section has a cross sectional area $A = wd$ and a length L which separates the two electrodes responsible for the internal electric field. Neglecting space charge effects for the moment, the electric field, which will then be uniform between the electrodes, has a magnitude

$$E \approx V/L \tag{1}$$

where V is the voltage drop between the electrodes. The charges, on which the electric force is acting, transmit this force to the fluid, either because they are bound to the fluid, or because they exert a steady drag force on the fluid as they move through it [3]. As a result, the fluid moves at a steady velocity U, which is assumed to be uniform across the cross section of the duct.

The charges are numerous enough so that they can be considered as a charge distribution with a uniform density of ρ. The total electric force pulling all of the charge in the direction of the electric field is then

$$F \approx \rho E \cdot \text{volume} = \rho EAL \approx \rho AV. \tag{2}$$

Injecting large amounts of charge into a medium is not always possible, however, since each additional unipolar charge decreases the electric field. When the field becomes too low, charge can no longer be removed from the electrodes, since the charge already present in the channel repels it, and the pump reaches its space charge limit. We will not consider this limit in detail here, but the limiting value of charge is easy to

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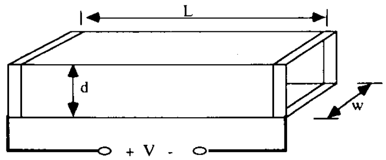

Fig. 1. Geometry of basic EHD pump.

estimate from Gauss' law,

$$\frac{dE}{dx} \approx \frac{E}{L} \approx \frac{\rho}{\epsilon} \tag{3}$$

which gives the space charge limit as

$$\rho_{\mathrm{scl}} = \frac{\epsilon E}{L}. \tag{4}$$

In many pumps, there are several stages of electrodes, or even traveling-wave electrodes which extend along the entire length of the channel. These cases can also be covered if each stage or half-wavelength of the pump is represented by the model of Fig. 1. In these cases, we would assume that the charge and the electric field both reverse, so that the pumping force is consistent from one section to the next.

Maximum Velocities

The velocity of the fluid which flows through the pump has been assumed so far, as if its source was some other remote mechanism. This may be the case if the EHD pump is only used as a booster pump, but a more likely situation would require the EHD pump to produce the flow velocity by itself. This is the case that we will consider here. Actually, the pump will often be called on to force the fluid into an external pressure head, but we will also neglect this possibility for now, and concentrate on finding the flow velocity produced by an EHD pump which extends over the entire length of the channel, so that the viscous drag of the walls and the forward thrust of the electric field operate over the same region.

In fluid flows, it is usually more convenient to work in terms of pressure, which is given by

$$p = F/A = \rho E L \tag{5}$$

using (2). This pressure will rise with the charge density, which is limited by space charge repulsion to approximately

$$\rho \approx \epsilon E/L \tag{6}$$

as before. Thus the maximum pressure that can reasonably be expected in the pump is

$$p \approx \epsilon E^2. \tag{7}$$

The flow velocity generated by this pressure depends on the nature of the flow, which can be either laminar or turbulent.

The average velocity of a laminar flow in a wide slot between two planes is [2]

$$U = \frac{d^2 \rho E}{12\eta} \approx \frac{\epsilon E^2 d^2}{12\eta L} \tag{8}$$

using the space charge limit. If the flow is turbulent, its velocity can be determined by the pressure–flow relation

$$p = \frac{2L}{R_H}\frac{\gamma U^2}{2} f(\mathrm{Re}) \tag{9}$$

where γ is the mass density of the fluid in kg/m^3. The function f is the friction factor, which depends on the flow conditions, as expressed by the Reynolds number,

$$\mathrm{Re} = \frac{\gamma R_H U}{2\eta} \tag{10}$$

where η is the viscosity and R_H is the hydraulic radius of the channel. For a wide channel, $R_H = d/2$. When the flow is well into turbulence, the friction factor becomes more or less constant, with a value near

$$f \approx 0.008 \tag{11}$$

depending on the roughness of the walls. Since we are dealing with a first pass at pump design, we will use this constant value to estimate the turbulent velocity as

$$U = E\sqrt{\frac{\epsilon}{2\gamma(L/d)f}} \tag{12}$$

when the space charge limit of the electric pressure is used. In the turbulent regime, the velocity is proportional to the first power of the electric field, not the square as in laminar flow. This is related to the increased drag generated by the turbulence. As in the laminar regime, the velocity decreases with the aspect ratio L/d, but it is independent of the absolute size.

We now have two expressions for the velocity of the fluid; one for laminar flow and one for turbulent. In practice, the lower velocity of the two is the one that actually occurs, with the transition from laminar to turbulent occurring at a Reynolds' number near 2000.

Efficiency

We define the efficiency (eff) as the ratio of useful power to input power:

$$\mathrm{eff} = \frac{P_{\mathrm{output}}}{P_{\mathrm{input}}}. \tag{13}$$

On the electrical side of this energy converter, the voltage source must supply a current related to the current density inside the pump. The basic definition of current density for unipolar charge motion is

$$J = \rho u + \sigma E \tag{14}$$

where u is the velocity of the charges and σ is the bipolar conductivity.

The first term represents the motion of the net space charges, which are always free to move inside the fluid. In a stationary fluid, the electric force applied to the charges tends to pull them through the fluid at a velocity that depends on the strength of the electric field, or

$$u = \mu E. \tag{15}$$

The force still acts if the fluid is moving, so the charge velocity relative to the fluid should be added to the convective motion imparted by the fluid flow, giving a net charge velocity of

$$u = U + \mu E. \tag{16}$$

The second term in (14) represents an additional mechanism for electric current flow within the pump. This is ordinary bipolar conduction, in which charge carriers are produced not by injection from electrodes, but by dissociation of molecules within the pump fluid. This process always creates equal numbers of positive and negative charges, so it does not affect the net force on the fluid, but it does furnish a current path which leads to additional input power requirements for the pump. The current carried by this process is given (at "low" field strengths) by

$$J = \sigma E \tag{17}$$

where σ is the conductivity of the fluid. Combining all of the current flow mechanisms gives the total input current as

$$i = JA = \rho UA + \rho\mu EA + \sigma EA \tag{18}$$

where $A = wd$ is the cross-sectional area of the flow channel.

The electrical input power to the pump is the product of voltage and current, or

$$P_{\text{elec}} = \rho UAV + \rho\mu AEV + \sigma AEV. \tag{19}$$

There is some question as to what constitutes the useful output of the pump. If the pump were working against an external pressure load (as most pumps do), we could identify the useful output as the product of pressure drop and flow rate. It makes more sense to use an EHD pump as a distributed device, however, because the pressure head is relatively low. In the normal configuration for an EHD pump, it therefore occupies most or all of the total length of a closed circuit. In such a case, there is little or no "external" load, since the useful output of the pump consists entirely of the work done to overcome the viscous losses inside the pumping channel itself. Thus all of the mechanical work is useful and the only sources of loss in the pump are those related to electrical current flow, giving an efficiency of

$$\text{eff} = \frac{P_{\text{input}}(\mu = \sigma = 0)}{P_{\text{input}}} = \frac{1}{1+\alpha} \tag{20}$$

where α is the loss coefficient,

$$\alpha = \frac{\mu E}{U} + \frac{\sigma E}{\rho U}. \tag{21}$$

Under this definition, the efficiency is 100 percent when the mobility and conductivity vanish, so that the fluid is forced to move at the same speed as the charges. This efficiency may not be reached in practice, due to additional effects such as secondary flows and electroconvection, so it represents the best that can be hoped for in an EHD pump.

TABLE I
COMPONENTS OF THE LOSS COEFFICIENT IN LAMINAR AND TURBULENT REGIMES

Regime	Conductivity	Mobility
Laminar	$\alpha = \frac{12\eta\sigma}{\epsilon^2 E^2}\left(\frac{L}{d}\right)^2$	$+\frac{12\eta\mu}{\epsilon EL}\left(\frac{L}{d}\right)^2$
Turbulent	$\alpha = \frac{2\sigma L}{\epsilon E}\sqrt{\frac{L}{d}\frac{f\gamma}{\epsilon}}$	$+2\mu\sqrt{\frac{L}{d}\frac{f\gamma}{\epsilon}}$

The loss coefficient contains two terms. The term $\mu E/U_0$ is the ratio between the mobility velocity and the fluid velocity. Clearly, the fluid velocity should be large compared to the mobility velocity if inefficient operation is to be avoided. Thus we are seeking to design a pump in which

$$U > \mu E. \tag{22}$$

The second term can be rewritten using the space charge limit (4) as

$$\frac{\sigma E}{\rho U} = \frac{(L/U)}{(\epsilon/\sigma)} \tag{23}$$

is the ratio of two characteristic times. The first is the mechanical transit time for the channel, while the second is the charge relaxation time of the fluid. For high efficiency, the ratio should be low, which means that the fluid must pass from one electrode to the other before the charge has time to flow backward. Just as for the mobility losses, this requires a high-speed flow,

$$U > \sigma L/\epsilon. \tag{24}$$

The effects of operating parameters on the loss coefficient are more complex than for the velocity, because there are two contributors to the loss, and they behave differently in the laminar and turbulent regimes. The expressions for the mobility and conductivity contributions in the space charge limit are shown in Table I.

Both laminar flow and conductive losses are predominant at low velocities, so the efficiency is likely to be characterized by the upper left element of the array. In this term, the loss increases as the aspect ratio L/d is made larger, so long thin channels tend to have low efficiency as well as low speeds. The conductivity term is independent of the size scale, but the mobility loss decreases with size L, so larger laminar channels are more efficient than small ones of the same aspect ratio.

At the extreme of high speeds, turbulence and mobility are most important, so the loss is described by the lower right element, which also increases with aspect ratio, but at a much slower rate. This term is independent of the size scale, but the conductivity term does increase with size, so larger channels will be less efficient in the turbulent regime than smaller ones with the same aspect ratio.

Operating Regimes

At this point, we have formulated several fundamental restrictions on the EHD pump. The velocity must be high

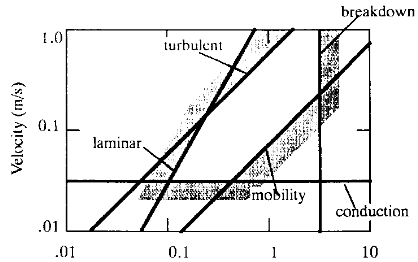

Fig. 2. Combined operating regime plot.

TABLE II
SUMMARY OF SOME EHD PUMPS[a]

Reference	Stuetzer	Krawinkel	Sharbaugh	Melcher	Kervin	Seyed-Yagoobi
Fluid	kerosene	acetone	trans. oil	Aroclor	Sun 4	Sun 4
κ	2	21	(2.0)	5.7	2.54	2.5
σ nS/m)	(<0.001)	5000	0.00033	1	0.122	0.122
μ (m2/V·s)	(2.2E-8)	(6.8E-8)	(1.1E-9)	(1.3E-9)	(0.57E-9)	(0.57E-9)
η (mPa·s)	0.92	0.293	(18)	15	35	35
γ (kg/m^3)	728	780	(728)	1380	880	880
L (mm)	1.2	0.8	5.	430	30	15
d (mm)	0.6	20	60	25	22	16
E (MV/m)	(16.6)	3	4	(0.023)	0.3	0.53
U (m/s)	(2.1)	7.8	0.05	0.03	0.08	0.02

[a] (Values in parentheses are estimates).

enough to avoid conduction and mobility losses, but it cannot exceed the limits set by viscosity, turbulence, and electric breakdown. If all of these constraints are shown simultaneously on a single plot, the possible operating range appears immediately, as in Fig. 2.

The lower limits in this figure represent the flow velocities needed to transport the fluid between the electrodes before the charge decays due to conduction (24) or mobility (22). At higher electric fields, higher velocities are needed, since charge mobility causes them to move faster. The upper limits on the figure represent the velocities obtainable with ideal laminar (8) or turbulent (10) flow, whichever is appropriate for the fluid and operating conditions. The limitation to electric field from breakdown will depend on the particular fluid and is discussed in a later section. Only the clear section in this figure represents a combination of electric field and flow velocity which can possibly meet the design criteria. Of course, there are many additional effects, such as secondary flows and electroconvective instability, which will also degrade the performance. As a result, the open area in this plot should be considered as a necessary but not sufficient condition for a successful EHD pump. The plot is very useful, however, for eliminating many combinations from consideration.

Comparison with Earlier Experimental Results

EHD pumps have been constructed for many years, but until now no systematic comparison of these pumps has been made based on how close they come to the limits imposed by the physical considerations already discussed. In fact, many of the data needed to assess the efficiency and flow rates are lacking in the published literature. Nonetheless, it is useful to compare the pumps of several different laboratories to determine whether there is still room for improvement, and whether the model presented represents a useful guide to understanding and designing EHD pumps.

A selection of such pumping experiments is summarized in Table II. The values in parenthesis are not given directly in the paper cited but are estimates based on physical reasoning. Mobilities and conductivities are estimated as described in the Appendix, while the electric fields and velocities are estimated from the voltages, geometry, and flow rates.

The earliest reported pump was an ion drag pump [14] with kerosene as a working fluid. The operating regime plot for this pump is shown in Fig. 3(a). The operation actually achieved is denoted by the $\times$ in the figure. This point lies above the turbulent transition indicated by the intersection of the two heavy black lines and is at a velocity high enough to avoid significant losses caused by mobility. Conductive losses are also negligible, but this is not apparent from the figure because the velocity needed to overcome conductive losses is less than 1 mm/s. Thus the first pump with serious studies reported appears to have operated at fairly high efficiencies. Stuetzer actually reported low efficiencies ($\approx$ 20 percent), but he based this figure on the mechanical work delivered to an external flow circuit, rather than on a distributed pump. This was consistent with this experiment but indicates that redesign of the pump could lead to significant increases in efficiency.

A later ion drag pump, described by Krawinkel [7] used acetone as a working fluid (Fig. 3(b)). His velocity was also in the turbulent regime, even though the electric field was not as large. This is due partly to the lower viscosity of acetone but also to the relatively high dielectric constant. The electric

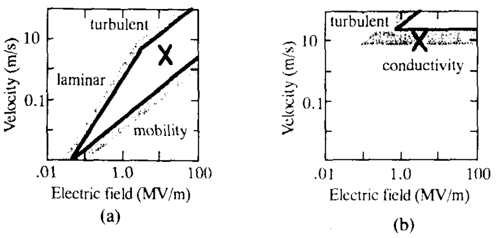

Fig. 3. Operating regimes for two ion drag pumps. (a) Steutzer [14]. (b) Krawinkel [7].

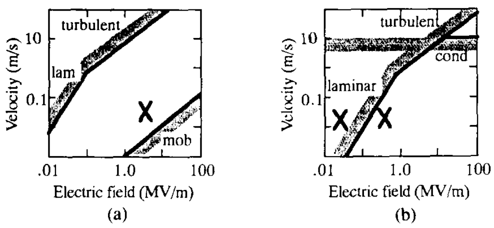

Fig. 4. Operating regimes for ion drag and interfacial pump. (a) Sharbaugh and Walker [13]. (b) Melcher [8].

force is proportional to the dielectric constant, so it is always advantageous to use as large a dielectric constant as possible. High dielectric constants are usually associated with high conductivities, so this pump, while producing high velocities, is not expected to offer the highest efficiency. From the figure, the predicted efficiency can be estimated as 30 percent.

In fact, Krawinkel reported efficiencies around 50 percent—somewhat higher than predicted by the model. These efficiencies were based on direct measurements of the electrical input currents, but the mechanical output was inferred from measurements of stagnation pressure, which may not have been accurate. On the other hand, he did not measure the conductivity of his acetone, and Fig. 3 is based on handbook values. There is good evidence, however (Sharbaugh and Barker [12]) that conductivity in polar liquids results mainly from the dissociation of water as an impurity, so actual values may depend on the detailed purification process used. In addition, the application of a strong electric field will remove impurities from an insulating liquid, and the conductivity of pumped liquids usually drops as operation continues (Seyed-Yagoobi *et al.* [11]). Thus Krawinkel may have actually achieved high flow rates with high efficiency.

The latest ion drag pump, described by Sharbaugh and Walker [13], involves the application of EHD pumping to transformer cooling. Their pump used Shell XSL-916 transformer oil, which is similar to decane (on which the material constants are based). The operating regime plot for the pump was plotted as Fig. 4(a).

As in the previous pumps, the flow is turbulent. Because transformer oil has low conductivity and mobility, the operation is expected to be efficient. Along with the low mobility, however, goes a high viscosity (Walden's rule), so the flow is not expected to be as fast as for acetone. In fact, the actual velocities were considerably slower than predicted, but this resulted from the configuration of the pump, which used a relatively short pump moving fluid through a long external

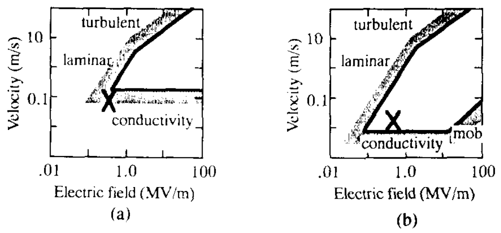

Fig. 5. Operating regimes for two thermal induction pumps. (a) Kervin *et al.* [5]. (b) Seyed-Yagoobi *et al.* [11].

circuit with considerable pressure drop. The flow is naturally slower under these conditions, since the model assumes that the pump does not have to drive an external load.

A different kind of EHD pump was introduced by Melcher [8]. Instead of injecting charge carriers from an sharp electrode, he induced separation of charges already present in a poorly insulating fluid. In its basic form, the charges collect at an interface, which is typically between the liquid and a insulating gas. Melcher's first pump used Monsanto Aroclor 1232 and had the operating regime shown in Fig. 4(b). The electric field here is difficult to estimate, because the field geometry in this pump was quite a bit different from that assumed in the model. Instead of a uniform field directed in the flow direction, the field was directed principally across the flow direction, with only a small component in the direction of flow. Two operating points are shown on this figure, corresponding to the electric field along the flow and across the flow. Both give velocities in the laminar regime, and they bracket the expected flow velocity. The conductive efficiency line is much higher than the actual operating velocity, suggesting that this pump must have been very inefficient.

The last type of EHD pump is related to the induction pump just described, but it does not localize the charge at a free surface. Instead, a thermal gradient is established within the liquid, which serves to localize the charge at the corresponding conductivity gradient. Because a fluid with a nonuniform temperature distribution occurs naturally in many heat transfer processes, this type of pump has always seemed attractive for circulating fluids that carry heat. This pump was also introduced by Melcher [9] and has been pursued for several years at the University of Illinois, primarily as a means to cool underground cables by circulating the insulating oil. All of these pumps were based on Sun #4 cable oil and involved fairly large pumped volumes. A typical one (Kervin *et al.* [5]) is shown in Fig. 5(a). This pump achieved velocities near 10 cm/s, which is approximately equal to the efficient operation speed for conductivity limitations.

The last example we will consider is the recent work by Seyed-Yagoobi *et al.* [11] describing a thermal induction pump suitable for cooling a transformer. The pump used the same oil as the previous pump, Sun #4, but a different electrode arrangement. The corresponding operating regime plot is shown in Fig. 5(b). The flow is slower here, but more efficient, as the operating point lies above the efficiency lines. This increase in efficiency was obtained even though the velocity was decreased below the limiting value by the additional loading imposed by the nonpumped regions of the flow channel.

TABLE III
FLUIDS WITH EFFICIENCY >20 PERCENT, SORTED BY VELOCITY

Fluid	Maximum Velocity (m/s)	Efficiency (Percent)
Methanol (deionized)	6.62	64
Ethanol (deionized)	6.02	98
Ethanol	6.02	49
Nitrobenzene (deionized)	5.60	100
Acetone (deionized)	5.46	98
Ethylene chloride	3.00	45
Ethyl ether	2.67	96
Disec butyl sebacate	2.30	97
Anisole	2.19	99
Aroclor 1232	2.14	91
Bromobenzene	2.00	90
Chloroform	1.93	45
Kerosene	1.83	99
n-hexane	1.79	97
Toluene	1.75	98
Triacetin	1.75	34
Xylene	1.73	99
Benzene	1.67	98
Ethylene bromide	1.57	25
Freon R113	1.30	97
Carbon tetrachloride	1.24	98
Shell XSL-916	0.90	100
Sun #4 cable oil	0.53	92
Corn oil	0.38	95

In all of these pumps, the model presented above has given reasonable agreement with the results actually reported, even though the model is approximate, and the pumps are different in construction and operation. This indicates that the model would be useful as a screening device in a new design, since it gives an overall view of the various physical constraints that must be faced in an EHD pump.

AN EXAMPLE OF WORKING FLUID SELECTION

In most designs for which EHD pumps are practical as the sole source of pressure, the pump must extend along the entire length of the flow channel. Hence the geometry of the pump is determined by the size and shape of the channel into which is fits. At the same time, the flow requirements are usually known, at least in terms of velocities to be reached in the channel. There are two questions to be answered at the start of the design: Can the required velocities be reached? Can the efficiency be high?

The first question can be answered by considering the velocities that can be reached when electric breakdown occurs. The velocity will be given either by the turbulent or the laminar expression presented above, whichever is less. The efficiency can then be calculated using the material constants of the fluid. These material constants were collected or estimated for approximately 50 fluids of possible interest in EHD pumping (see the Appendix). For each of these fluids, the turbulent and laminar velocities were calculated at the assumed breakdown field of 1 MV/m. The smaller of these was selected, and the efficiency at this velocity was then calculated. Table III presents the results of these calculations, assuming an aspect ratio of unity and a size of 1 cm. Only those fluids with an efficiency greater than 20 percent are listed.

There are several noteworthy aspects of this list. The velocities (flow rates) to be expected vary by orders of magnitude for the different working fluids. Those at the top of the list have high dielectric constants and low viscosities, so this combination should always be sought if high-speed pumping is desired. The fluids with very slow flow rates all have lower dielectric constants or much higher viscosities. Viscosity is an especially important property, since it varies over a wide range in the fluids that might be considered.

The ultimate efficiencies for many of the fluids are quite high. These fluids all have low conductivities, as might be expected. An especially interesting group is the liquids prepared by the Laboratoire de Electrostatique in Grenoble (Felici 1964), in connection with their research into working fluids for EHD generators. These fluids (nitrobenzene, ethanol, propanol, and acetone) all have relatively high dielectric constants, but they normally have conductivities too large to allow efficient operation. To circumvent this difficulty, the Grenoble group has worked out a deionizing process for these liquids, based on standard ion exchange resins which have been modified to work with nonaqueous liquids.

There are also several common fluids which are high on this list, such as ethanol and ethyl ether, but which have not yet been tried in EHD pumps. Since they offer both high velocities and high efficiencies, they may be more suitable working fluids and should be considered when appropriate.

Both the velocities and efficiencies on this list may seem high by comparison to the results achieved in most EHD pumps, but it should be kept in mind that they were obtained under the assumption that secondary effects such as electroconvection and adverse pressure loads were absent. If the pump is not designed to eliminate such effects, the performance will be degraded. In addition, the pump is assumed to operate at a uniform field near the breakdown limit (1 MV/m). Many practical pumps involve nonuniform field distributions which greatly decrease the flow rate because the electric force is proportional to the square of the field. Lower velocities in turn decrease the efficiency, because the charges have more time to flow back to the electrodes. Thus the pump should be designed to keep the electric field uniform throughout the pump, and close to the breakdown limit, if high flow rates and efficiencies are desired.

NOMENCLATURE

d	Depth, m.
E	Electric field, V/m.
F	Net force, N.
f	Friction factor.
i	Current, A.
J	Current density, A/m^2.
L	Length, m.
P	Power, W.
p	Pressure, Pa.
Re	Reynolds number.
R_H	Hydraulic radius, m.
u	Charge velocity, m/s.
U	Fluid velocity, m/s.
V	Voltage, V.
γ	Mass density, kg/m^3.
ϵ	Permittivity, F/m.

TABLE IV
FLUID PROPERTIES

Fluid	κ	σ (S/m)	μ ($m^2/V \cdot s$)	η (mPa·s)	γ (Mg/m^3)
Acetic acid	6.1	1.0E-06	(1.7E-08)	1.15	1.05
Acetone	21.0	5.0E-06	(6.8E-08)	0.29	0.78
Acetone (deionized)	21.0	1.0E-09	(6.8E-08)	0.29	0.78
Acetophenone	17.4	5.0E-07	(1.3E-08)	1.60	1.03
Aniline	6.7	1.0E-07	(4.5E-09)	4.40	1.03
Anisole	4.3	1.0E-11	(1.5E-08)	1.32	1.00
Aroclor 1232	5.7	1.0E-09	(1.3E-09)	15.00	1.38
Benzene	2.2	5.0E-15	(3.1E-08)	0.65	0.87
Benzonitrile	25.0	5.0E-06	(1.6E-08)	1.24	1.00
Benzyl alcohol	13.1	2.0E-04	(3.4E-09)	5.80	1.04
Bromobenzene	5.4	1.0E-09	(2.0E-08)	1.00	1.50
Butanol	17.7	1.0E-06	(6.9E-09)	2.90	0.81
Carbon tetrachloride	2.2	5.0E-16	(2.1E-08)	0.96	1.59
Chlorobenzene	5.6	1.0E-07	(2.5E-08)	0.80	1.11
Chloroform	4.9	1.0E-08	(3.4E-08)	0.58	1.46
Corn oil	3.1	5.0E-11	(3.3E-10)	60.00	0.90
Disecbutyl sebacate	4.6	2.5E-10	(3.3E-09)	6.00	0.96
Ethanol	25.8	1.4E-07	(1.7E-08)	1.20	0.79
Ethanol (deionized)	25.8	3.0E-09	(1.7E-08)	1.20	0.79
Ethyl ether	4.6	3.0E-11	(9.0E-08)	0.22	0.71
Ethylene bromide	4.9	2.0E-08	(1.2E-08)	1.70	2.18
Ethylene chloride	10.1	3.3E-08	(2.5E-08)	0.80	1.24
Ethylene glycol	41.2	1.0E-04	(1.2E-09)	16.20	1.10
Formamide	84.0	2.0E-04	(6.1E-09)	3.30	1.13
Formic acid	57.0	5.0E-03	(1.1E-08)	1.80	1.22
Freon R113	2.4	1.0E-14	(3.5E-08)	0.57	1.56
Glycerol	15.3	9.0E-06	(2.1E-11)	950.	1.26
Kerosene	2.2	(1.6E-14)	(2.2E-08)	0.92	0.73
Methanol	31.2	3.3E-05	(3.4E-08)	0.60	0.79
Methanol (deionized)	31.2	1.0E-07	(3.4E-08)	0.60	0.79
n-hexane	1.9	1.0E-17	(6.1E-08)	0.33	0.66
Nitrobenzene	34.0	1.0E-06	(9.9E-09)	2.03	1.20
Nitrobenzene (deionized)	34.0	5.0E-12	(9.9E-09)	2.03	1.20
Nitromethane	37.4	1.0E-06	(3.2E-08)	0.62	1.13
o-cresol	5.7	1.0E-07	(4.5E-09)	4.49	1.03
o-toluidine	6.0	5.0E-05	(4.6E-09)	4.39	1.00
Phenol	11.0	1.0E-06	(2.5E-09)	8.00	1.07
Propanol	22.2	1.0E-06	(8.9E-09)	2.25	0.80
Pyridine	12.4	5.0E-06	(2.1E-08)	0.97	0.98
Shell XSL-916	2.2	3.0E-13	(1.1E-09)	18.00	0.73
Sun #4 cable oil	2.5	1.0E-10	(5.7E-10)	35.00	0.88
Toluene	2.4	1.0E-12	(3.4E-08)	0.59	0.86
Triacetin	6.6	2.0E-08	(7.1E-10)	28.00	1.16
Water	80.0	1.0E-04	(2.0E-08)	1.00	1.00
Xylene	2.4	1.0E-13	(2.5E-08)	0.80	0.88

[a] Values in parentheses are estimates.

η Dynamic viscosity, Pa · s.
κ Dielectric constant.
μ Mobility, $m^2/V \cdot s$.
ρ Charge density, C/m^3.
σ Electrical conductivity, S/m.

APPENDIX
FLUID PROPERTIES

Before a fluid can be evaluated for use in an EHD pump, several of its physical properties must be known. Some properties, such as density, viscosity, and dielectric constant are usually available in standard handbooks and manufacturers' literature, but some of the electrical properties are harder to locate, and in many cases have not been reported at all. Some of these are given (or estimated) in Table IV.

The mobility, for example, plays a crucial role in the efficiency of the pump, but tabulated values are available only for the more common liquids and gases. Fortunately, the experimental work carried out on mobility has led to a generally useful relation between the viscosity of a fluid and its mobility, known as Walden's rule. Like any rule, it is not completely accurate, but it rarely errs by an order of magnitude, so it should be useful for preliminary selection of fluid candidates. For positive ions, which are slightly less mobile, and therefore better candidates for pumping, the relation is given by Adamczewski [1] as

$$\mu = \frac{2 \times 10^{11}}{\eta} \quad m^2/V \cdot s \qquad (A.1)$$

in SI units.

Electrical conductivity is another electrical property for which it is hard to obtain accurate figures. Those that are available tend to vary widely in different reports, especially for the good insulators. This is not a fault of the investigators, but an inherent property of good insulators. There are so few charge carriers available that even minute traces of impurities can change their number by a significant fraction, so the measurements reflect the purity of the sample more than an inherent property of the material. In practice, this can be quite disconcerting, since practical devices cannot always guarantee high purities. This problem was examined in some detail by Sharbaugh and Barker [13], who found that the chief impurity was water, whose dissociation produced the bipolar carriers associated with conductivity. By comparing simultaneous measurements of dielectric constant and conductivity for a large number of liquids, they developed an empirical formula for the conductivity of normally pure liquids,

$$\sigma = \sqrt{c_w}\,10^{-2.34}\,10^{20.8/\kappa} \quad \text{S/m} \qquad \text{(A.2)}$$

where κ is the dielectric constant and c_w is the concentration of water, in mol/L. This relation is valid, within a factor of 10, for most liquids if a concentration of 10^{-4} mol/L is assumed. Some liquids, however, had conductivity 100 times (or 1/100) that predicted. Since conductivity range they considered covered 11 orders of magnitude, these results are really quite consistent, although they should be used cautiously if they predict that a pump is within a factor of 100 of the minimum efficiency velocity determined by conductivity.

One additional group of exceptions is the highly purified high dielectric constant liquids prepared by Felici [4] and his associates at Grenoble. The conductivity of these liquids was as much as six orders of magnitude less than standard purity. Low conductivity in a high dielectric constant is both rare and valuable, since it increases the electric pressure (via increased permittivity, $\epsilon = \kappa\epsilon_0$), while reducing ohmic losses.

Another electrical property that is hard to specify is the breakdown strength of a liquid. Like the conductivity, it depends strongly on the purity of the material. Technical grade liquids often specify a minimum value, but the values reached in practice may be higher, depending on the uniformity of the field as well as the quality of the liquid. Fortunately, breakdown values are confined to a relatively narrow range compared to mobility and conductivity, with typical values ranging from 3 to 15 MV/m. These values may be difficult to reach in practice, so a conservative value of 1 MV/m was assumed.

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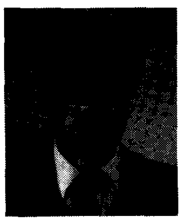

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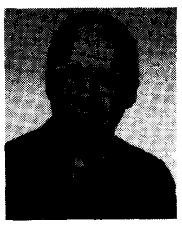

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