Dielectrophoretic transients effects on liquid stability

D S PARMAR and BIMLA LABROO

Department of Physics, University of Kashmir, Srinagar 190 006, India

Abstract. Effects of dielectrophoretic transients on stability of n-pentane and methyl methacrylate have been experimentally studied. Dielectrophoretic transients have been found to demonstrate anomalous effects in methyl methacrylate. The effects are observed both on the application of electric field and its subsequent turning off to zero and are equal in magnitude and direction during both the operations. Results have been explained on the basis of the body forces acting on the dielectric in presence of a non-uniform electric field and a temperature gradient. Heater surface thermodynamics has been studied under controlled temperature and electric field gradients. A striking feature of the experiment is the application of a high voltage directly on the heater surface making the body force calculations more realistic.

Keywords. Dielectrophoretic transients; liquid stability; n-pentane; methyl methacrylate.

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1. Introduction

"Dielectrophoresis" which results from the effect of non-uniform electric fields in matter, is defined as the motion of the matter caused by polarization effects. The matter tends to polarize in the field and a dipole of the medium experiences a force towards higher field strength. Even on reversal of the polarity of the field, the dipole experiences force in the same direction. The effect is, therefore, independent of polarity of the field and depends on its non-uniformity only. Thus in dielectrophoresis, one way motion of the medium takes place both in d.c. and a.c. electric fields. "Electrophoresis" on the other hand results from the electrostatic attraction of charged particles towards electrodes. The electrophoretic forces, therefore, depend on the polarity of the electrodes and hence are electric field direction dependent.

It has been reported by Parmar and Jalaluddin (1973a, b, c) that a critical electric field is required for initiation of nucleation in a liquid. They also observed a pre-nucleation relaxation phenomenon (Parmar and Jalaluddin 1977) in liquids at subcritical fields. It was assumed that the dielectrophoretic forces result in electrohydrodynamic motion (Pohl 1958; Parmar and Jalaluddin 1974) producing non-uniformity in the applied electric field. The effect of climbing up electrodes of the dielectric liquids in stationary fields (the Sumoto effect, Sumoto 1946), pumping action of strong divergent electric field (Pickard 1965) and the "electroconvection" effects (Krasucki 1966) have been explained as due to strong electric stresses on liquids in non-uniform fields. According to the theory of liquid hydrodynamics under electric fields (Landau and Lifshitz 1960), application of an electric field to an insulating liquid should enhance convection from the heater surface. The phenomenon of electroconvection has thus been invoked as a

possible way to promote heat transfer from a warm surface to a surrounding cold fluid bath. However, many experiments (Allen 1959; Senftleben and Schnabel 1962; Coelho and Venderschueren 1977) have demonstrated that the forced heat transfer due to electroconvection has not been successful. It has been suggested that the space charge effects not accounted in the elementary theory of electroconvection may be of dominating importance stabilizing the liquid in contact with heater and thus impede the heat exchange process. The effects of these charges on liquid motion and development of internal pressures inside electrically stressed insulating liquids due to these charges have clearly been demonstrated by many workers (Mirza *et al* 1970). This paper investigated the effects of dielectrophoretic forces on the liquid stability in order to find possible answers to the above mentioned experimentally observed effects. The phenomenon has been probed during dielectrophoretic transients where the effects are expected to be much more predominant. The effectiveness of the dielectrophoretic transients has been improved considerably by the introduction of (i) non-uniformity of the applied electric field; and (ii) gradient in the dielectric permittivity of the liquid system used. In order to conserve the physical picture of the electroconvection theory and to make the body force calculations more realistic, high voltage has been applied directly on the heater surface. With a view to clearly identify the contributions of the dielectric and the conductivity forces in the liquid, two types of molecular systems, namely the non-polar *n*-pentane and the polar methyl methacrylate, have been studied. The theory of dielectrophoretic transients effects on liquid stability is given in § 2, in which surface force has been calculated to demonstrate the relative contributions of the dielectric and the conducting terms. The experimental details and results are given in § § 3 and 4 respectively. The results are discussed in § 5 on the basis of the theory derived in § 2. In the present work, the role of electrophoretic and the dielectrophoretic forces has been clearly demonstrated. Quantitative evaluation of the contribution of the electrophoretic forces has been made and the exact nature and origin of space charges predicted.

2. Theory of dielectrophoretic transients effects in insulating and weakly conducting liquids

Dielectrophoretic effects in a liquid result from heating which produces non-uniformity $\nabla \sigma$ in the electrical conductivity σ and $\nabla \varepsilon$ in the dielectric permittivity ε. If $\nabla \sigma$ is non-zero in the liquid bulk, free charge builds up which can be acted upon by the electric field. If $\nabla \varepsilon$ is non-zero and if the electric field is non-uniform, polarization forces cause liquid motion resulting in destabilization of an otherwise gravitationally stable liquid system. The thermal convection due to buoyancy increases. The matter tends to become polarised and higher dielectric permittivity regions move in the regions of higher field strength.

In the present discussions we consider a spherical heater surface surrounded by a liquid, as shown in figure 1. There is a temperature gradient ΔT from the heater surface (hs) towards the outer surface of the liquid.

We consider a small region of the surface of the dielectric in contact with the hs and assume the properties of the liquid and the electric field there as uniform. In presence of extraneous charge q per unit volume, the volume force in presence of dielectric
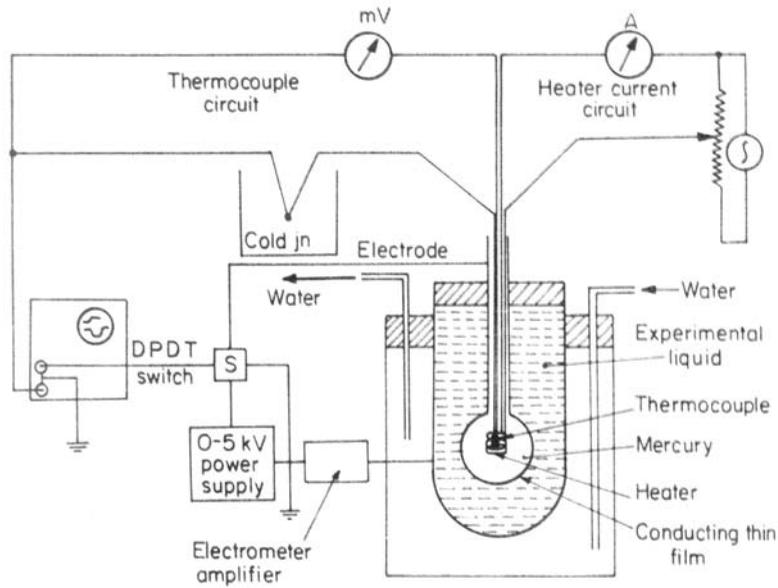
Figure 1. Block diagram of the experimental set up.

permittivity and electric field gradients can be written as (Landau and Lifshitz 1960):

$$\mathbf{F}_V = qE - \tfrac{1}{2}\varepsilon_0 E^2 \,\mathrm{grad}\,\varepsilon + \frac{\varepsilon_0}{2}\,\mathrm{grad}\left(E^2 \frac{\partial \varepsilon}{\partial \rho}\,\rho \right), \tag{1}$$

where ε and ε_0 are respectively the dielectric permittivity of the medium and the free space, ρ is the medium density and E is the electric field.

The first term in (1) represents the force on the free charge q per unit volume and the second term is effective in the presence of gradient in ε. The third term is due to electrostriction and as a gradient leads to no resultant total force on the dielectric. The force in (1) localized on the HS leads to specific surface force F_s (Daba 1980):

$$\mathbf{F}_s = qE - \tfrac{1}{2}\left(\varepsilon - \varepsilon_0 - \frac{\partial \varepsilon}{\partial \rho}\,\rho \right) E^2\,\mathbf{n} \tag{2}$$

where $\mathbf{n}$ is a unit vector on the HS directed towards the surrounding liquid and q now is the surface charge density. Introduction of the force $\mathbf{F}_s$ in momentum equation results in destabilization of the liquid in contact with HS which can be represented by the Nusselt correlation (Kronig and Ahsmann 1949):

$$\mathrm{Nu} = f(\mathrm{Gr} \cdot \mathrm{Pr}) + g(\mathrm{El} \cdot \mathrm{Pr}) \tag{3}$$

where Nu, Gr and Pr are respectively the well known dimensionless Nusselt, Grashof and Prandtl numbers, El is the electric field influence number.

Nu in (3) is given as a sum of two functions f and g of products $\mathrm{Gr} \cdot \mathrm{Pr}$ and $\mathrm{El} \cdot \mathrm{Pr}$. The second function g in (3) appears only in presence of electric field and represents the change in Nu due to electric field. Thus the change $\Delta\,\mathrm{Nu}$ in Nu due to electric field is

given by

$$\Delta \mathrm{Nu} = g(\mathrm{El} \cdot \mathrm{Pr}), \tag{4}$$

where Pr is given by

$$\mathrm{Pr} = C_p \eta / \lambda, \tag{5}$$

and El by

$$\mathrm{El} = \rho(\partial\varepsilon/\partial\rho)d^2 \,\Delta T E^2 / \eta^2. \tag{6}$$

In (5) and (6) C_p, η and λ are respectively the specific heat at constant pressure, the dynamic viscosity and thermal conductivity of the liquid and d is the diameter of the heater. $\Delta \mathrm{Nu}$ is thus a measure of the effect of electric field on liquid motion.

3. Experimental technique

The experimental arrangement, shown in figure 1, consists of (i) a spherical glass bulb heater assembly, (ii) a constant temperature bath system, (iii) an arrangement for application of high voltage to the heater, and (iv) a set up for oscillographic recording of the heater surface thermodynamics. The spherical glass heater (diameter 1·2 cm, wall thickness 0·05 cm) coated with a thin ($\sim$ 1 μm), conducting and transparent tin oxide film acts as an electrode to apply electric field directly on the HS. The centre of the heater bulb is kept at the axis of the outer cylindrical glass container of the experimental liquid. Uniformity of the HS temperature could be attained by filling the glass bulb with mercury. A glass insulated nichrome wire dipped in mercury, is used as heater filament. A Cu-Co thermocouple, dipped in mercury, is used to sense the heater surface temperature. The thermo e.m.f. and its variation is measured on an oscilloscope screen. The outer temperature of the experimental liquid is maintained up to 0·2°C using an ultra thermostat. A voltage of 0–5 kV was applied to the HS from a high voltage power supply through a double-pole-double-throw (DPDT) switch. Outer surface of the experimental liquid container is earthed through the circulating liquid bath in order to keep symmetrical field geometry. Transient currents were measured using an electrometer amplifier by connecting it between the inner surface of the experimental liquid container and one of the electrodes of the HV supply.

The heater is switched on at a surface heat flux of $\approx$ 20 kW/m^2 and simultaneously a constant temperature bath is circulated at a known temperature of 10–50 K lower than the HS temperature. A steady state is reached in about 10 min when the power input to the heater balances the natural convection heat exchange from the HS to the surrounding cold liquid bath. The position of the lower beam of the oscilloscope is adjusted to the thermo e.m.f. value corresponding to the heater surface temperature (HST). When the voltage is applied to the HS through the DPDT switch, change in HST is observed and measured as a function of time on the oscilloscope screen. A steady state in HST is attained in presence of voltage on the heater surface. Now the HS is earthed with the help of DPDT switch and changes in its temperature are similarly recorded.

A typical dual trace oscillogram characterising the processes of the application of electric field (upper trace) and the rate of change of HST (lower trace) for n-pentane (99·5 %) is shown in figure 2. Whereas a small initial rise in the upper trace corresponds to the instant of application of electric field, a small initial fall indicates the instant of switching off of the electric field to zero.
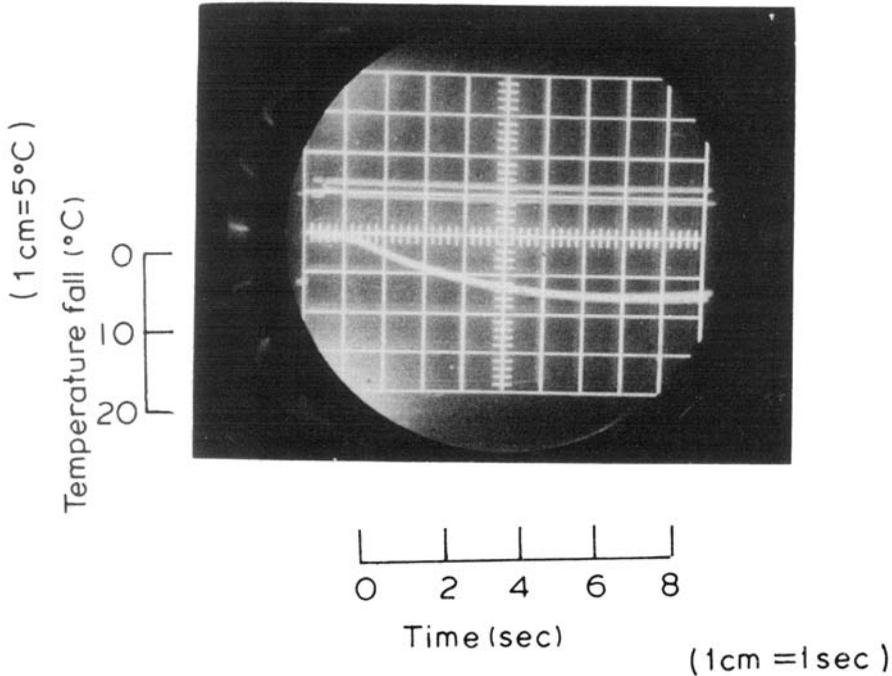
Figure 2. Dual trace oscillograms characterising the transient effects on the application of electric field and its switching off to zero. Effects during both the transients are equal.

In figure 2, the HST falls exponentially (lower trace) from its initial value of 325·5 K to 318 K at $\Delta T = 29$ K for *n*-pentane on the application of 2 kV (indicated by a small rise in the upper trace) and attains the initial zero field value after this (not shown in the oscillogram) in presence of the voltage. Now when the HS is earthed (indicated by a small fall in the upper trace) for the same ΔT, as shown in figure 2, the HST falls again in exactly the same way from its steady state (obtained in presence of 2 kV on HS). Similar "fast" transient followed by a "slower" transient is observed in this case also. This is demonstrated in figure 2 by the overlap of both the oscillograms (lower traces) in the above two cases. This shows not only the repeatability of the observations but also that the dielectrophoretic effects are exactly equal both on the application of the field and its switching off to zero from equilibrium. The HST changes are rapid in the initial transient and saturate in about 5 sec of the electric field application or its subsequent switching off to zero demonstrating the fact that the electroconvection is the result of dielectrophoretic transients.

3.1 *Calculation of heater surface temperature*

The steady state temperature gradient from mercury to the liquid surrounding the bulb is shown in figure 3. Assuming that the heat is transferred across the stagnant mercury film solely due to conduction (Bennet and Myers 1974), one obtains:
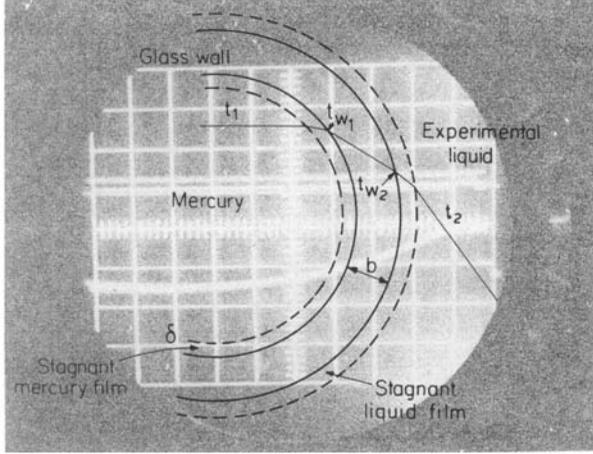
$$t_1 - t_{w1} = \frac{\delta}{A K_1} Q, \tag{7}$$

Figure 3. Geometry of HS in contact with the experimental liquid.

$$t_{w1} - t_{w2} = \frac{b}{AK} Q, \tag{8}$$

where t_1 is the bulk temperature of mercury, t_{w1} the inner wall temperature of the glass bulb, t_{w2} the outer wall temperature of the glass bulb, K_1 the thermal conductivity of mercury, K the thermal conductivity of laboratory pyrex glass, A the mean surface area of the glass bulb, b the mean wall thickness of the glass bulb, δ the thickness of the stagnant mercury film, Q the heat input in steady state.
From (7) and (8),

$$t_1 - t_{w2} = \frac{Q}{A}\left(\frac{\delta}{K_1} + \frac{b}{K}\right). \tag{9}$$

But since $\delta \ll b$ and $K_1 \gg K$, therefore $\dfrac{\delta}{K_1} \ll \dfrac{b}{K}$, thus

$$t_{w2} = t_1 - \frac{Qb}{AK}$$

$$= t_1 - \theta, \text{ where } \theta = \frac{Qb}{AK} \tag{10}$$

θ is the measure of the temperature drop across the wall.

3.2 *Constants of heater bulb*

The diameter of the bulb was measured using slide calipers for different orientations of the bulb. The mean diameter is $1 \cdot 2$ cm. Area of the bulb surface has been calculated from

$$A = 4\pi r^2 - \pi r_1^2, \tag{11}$$

where A is the area of the bulb surface, r the radius of the bulb and r_1 the outer radius of

the glass tube of the bulb. In the experiment, $r = 0.6$ cm, $r_1 = 0.375$ cm, $b = 0.05$ cm, thus $A = 4.08$ cm^2 and heater constant $b/A = 0.0122$ cm^{-1}.

3.3 *Temperature drop across the wall of the heater bulb*

The temperature drop across the wall of the heater bulb, θ calculated from (10), is:

$$\theta = Qb/AK = \frac{0.238\, I^2\, Rb}{AK}$$

where I is the current in the heater ($\approx$ 1 A), R the resistance of the heater (1.5 ohm), $Q = 0.238\, I^2 R = 0.238 \times 1.5 \times I^2 = 0.357\, I^2$. Thus

$$\theta = \frac{4.355 \times 10^{-2} \times I^2}{K}. \tag{12}$$

Substituting the value of $I = 1$ A, and $K = 10.74 \times 10^{-3}$ W cm^{-1} °C^{-1}, $\theta \approx 4$°C.

The HST was determined from (10) and (12) by substituting the values of heater currents. The thermal conductivity of pyrex glass and its temperature variation was obtained from literature (Washburn 1929). Considering the thermal conductivity of mercury to be ≈ 0.0839 W cm^{-1} °C^{-1}, the response time for the mercury temperature changes is $\approx 10^{-2}$ sec for the amount of mercury and the power levels in the heater used. Obviously this time is two orders of magnitude smaller than the "fast" transient time and thus the response time of mercury has been neglected in the rate of fall of temperature calculations.

4. Experimental results

The liquids used in the present investigations were high purity (99.9 %) analar grade *n*-pentane (distilled twice more for further purification) and methyl methacrylate (95 %).

The HST obtained as described in §3 at different ΔT and applied voltages for *n*-pentane are shown in figure 4 as a function of time. The instant of application of electric field corresponds to zero on the time axis. The HST attains a saturation in a transient of about 5 sec depending on ΔT and the applied voltage. At the same ΔT, the fall in HST increases with the applied voltage, *e.g.*, at $\Delta T = 12.5$ K, the maximum fall in HST is 5.2 K at 2 kV and 6.2 K at 2.5 kV. The HST always falls on the application of electric field for all ΔT values shown in figure 4.

The results for methyl methacrylate (95 %) are shown in figure 5, where HST has been plotted at different ΔT as function of applied voltage. In this case only the minimum values of HST attained on the application of an electric field are shown. In figure 5a, the HST being in equilibrium at 86.2°C with $\Delta T = 73.5$ K begins to fall on the application of a voltage up to 2 kV and attains a minimum at 83.5°C. On further increasing the applied voltage, the HST increases to saturate at 97.6°C for an applied voltages of ≈ 3.5 kV. At $\Delta T = 83.5$ K (figure 5b), HST does not change on the application of voltage up to 2 kV and maintains its equilibrium value of 97.5°C. On further increasing the applied voltages, HST increases and saturates at 106.5°C beyond 3 kV. At higher temperatures, $\Delta T = 106.5$ K, HST increases for all values of applied electric field (figure 5c) to attain a saturation at 125°C beyond applied voltages ≈ 1 kV.
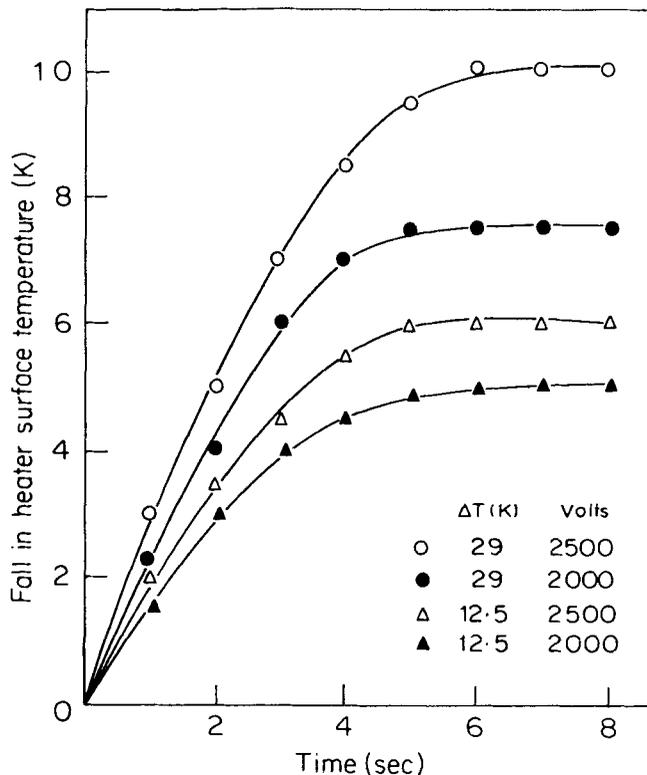
Figure 4. Rate of HST fall at various values of applied voltage and ΔT for *n*-pentane.

Dielectrophoretic transients effects in both the liquids, normal in *n*-pentane and anomalous in methyl methacrylate, are independent of polarity of the applied voltage.

4.1 *Transient current measurements*

In order to obtain the role of electrical conductivity of liquid, transient currents were measured with the help of an electrometer amplifier connected in series with the liquid-HS system, as shown in figure 1, at different applied voltages to the HS. The results for *n*-pentane and methyl methacrylate are shown in figure 6 at different temperatures. For *n*-pentane the transient currents are relatively low ($\approx 10^{-15}$ A) and increase only slightly with voltage and increase in the temperature of the liquid. In methyl methacrylate, the transient currents are larger ($\approx 10^{-13}$ A) and increase with temperature in comparison to *n*-pentane. Although the transient currents are almost steady for lower applied voltages, they start increasing beyond 1·5 kV at $\Delta T = 73\cdot5$ K and 83·5 K giving anomalous current variation. At higher temperatures (*e.g.* $\Delta T = 106\cdot5$ K), the transient current increases with applied voltage. Although transient currents demonstrate time dependence, in figure 6, only the maximum values of current have been given. The transient current increases for about 5 sec of the field application and then falls to lower values (unable to be measured by the present experiment) in about 50 sec. The transient times are of the order of the space charge relaxation time $\tau_\sigma = \varepsilon_0\varepsilon/\sigma \approx 30$ sec, where σ is the electrical conductivity of the liquid $\approx 7 \times 10^{-13}$ mho m^{-1}, considering the

transient current levels. However, the "fast" transient time in the present situation of temperature, dielectric permittivity and electric field gradients is determined from the thermal diffusivity k ($\approx 5 \times 10^{-4}$ m^2/sec) of the liquid. The temperature difference ΔT would vanish for 1 cm^2 ($= 10^{-4}$ m^2) area in a time ≈ 5 sec giving rise to increase in HST beyond this time.

5. Discussions

The dielectrophoretic effects and coupled dynamics of the liquid in each transient depends on the relative magnitude of the forces qE and $[\varepsilon - \varepsilon_0 - (\partial \varepsilon / \partial \rho)\rho]E^2/2$ in (4).
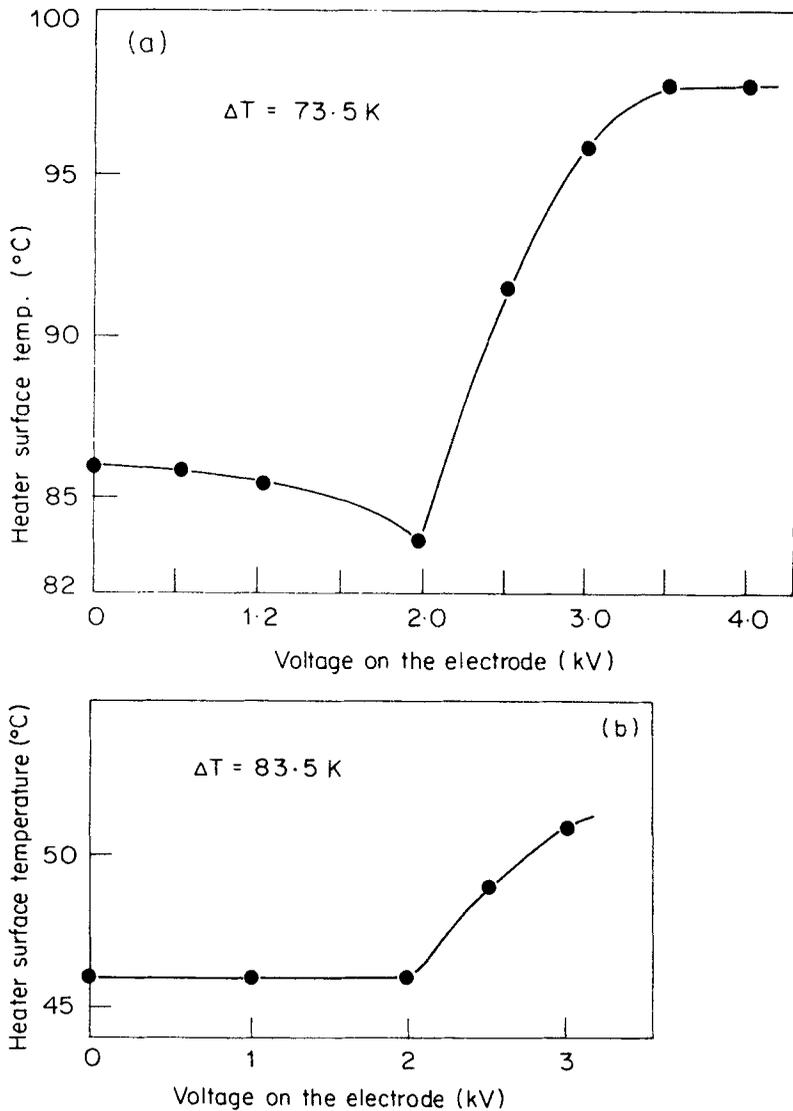

Figure 5. HST changes at different applied voltages and ΔT for methyl methacrylate ΔT equals $a = 73.5$ K, $b = 83.5$ K
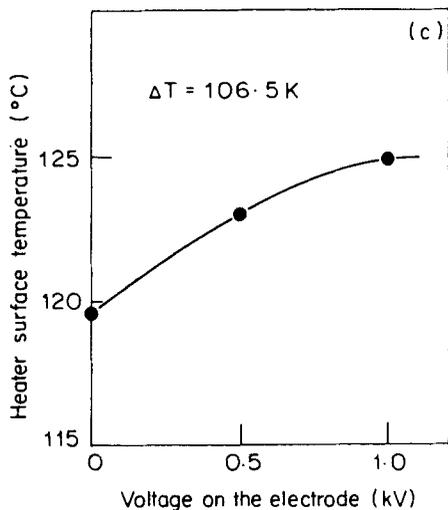
Figure 5c. HST change at different applied voltages and ΔT for methyl methacrylate. ΔT equals 106·5 K.
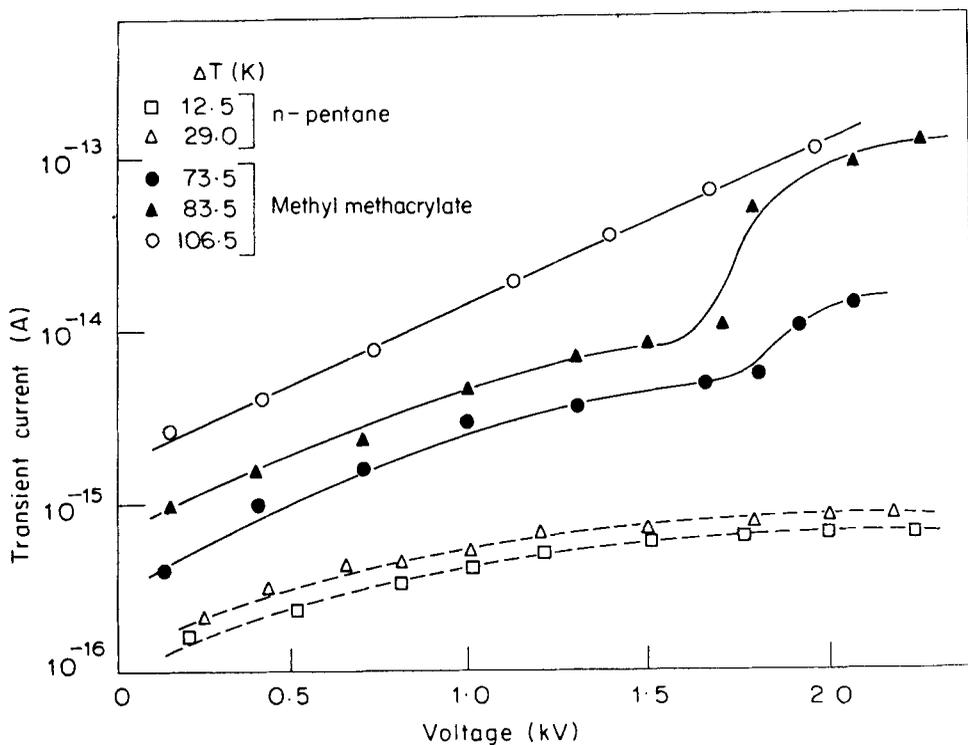

Figure 6. Transient currents for *n*-pentane and methyl methacrylate at various temperatures and applied voltages.

Three situations can often arise as a result of these forces depending on the gradients in conductivity, temperature (hence the dielectric permittivity) and the electric field in the test liquid for the range of applied voltages:

(i) If the liquid surrounding the heater remains non-conducting in the range of applied voltages or has a negligible electrical conductivity, either $qE = 0$, or $qE < [\varepsilon - \varepsilon_0 - (\partial\varepsilon/\partial\rho)\rho]E^2/2$. The dielectrophoretic forces, from (4), would force the liquid to move from regions of higher electric fields to lower ones. In the present set up, liquid at higher temperature in contact with the HS would move away from it towards the lower temperature regions. The HST in turn would fall on the application of electric field.

(ii) In case the electrical conductivity of the liquid is non-zero and if $qE \neq 0$ but $= [\varepsilon - \varepsilon_0 - (\partial\varepsilon/\partial\rho)\rho]E^2/2$, the net surface force due to electric field on HS is zero from (4). The electric field does not contribute towards surface forces and the coupled motion of the liquid from HS. The HST does not change on the application of electric field.

(iii) If the electrical conductivity of the liquid is non-zero and if $qE > [\varepsilon - \varepsilon_0 - (\partial\varepsilon/\partial\rho)\rho]E^2/2$, the electric field forces the liquid to move towards HS to raise its temperature. This situation can arise due to the formation of space charges in the liquid. The electrostatic force on these charges does not allow the liquid to move away from HS. HST in turn increases on the application of electric field unlike in the above two cases.

5.1 *n-Pentane*

The fall in HST on application of electric field for *n*-pentane, as shown in figure 4, corresponds to the situation described under (i) above. Using the data in table 1 for *n*-pentane, the value of $[\varepsilon - \varepsilon_0 - (\partial\varepsilon/\partial\rho)\rho]E^2/2$ is obtained to be 2·77 dynes for applied voltages $\approx 1\,kV$. For measured transient currents $\approx 5 \times 10^{-16}\,A$ for *n*-pentane, as shown in figure 6, the qE forces are computed to be ≈ 0.5 dynes for $q \approx 5 \times 10^3$ SI giving $qE < [\varepsilon - \varepsilon_0 - (\partial\varepsilon/\partial\rho)\rho]E^2/2$ for applied voltages $\approx 5\,kV$.

5.2 *Methyl methacrylate*

The situation in methyl methacrylate, however, is different but can be explained on the basis of the situations (i), (ii) and (iii) mentioned earlier. The magnitude of the dielectric and the conductivity terms in (2) are given in table 2 for methyl methacrylate. The dielectric and conductivity contributions have been calculated at different ΔT and applied voltages using the data in table 1 and the transient current measurements of figure 6. In this case, at $\Delta T = 73.5$ K, as shown in figure 5a, the HST begins to fall on the application of voltages up to about 2 kV in accordance with condition (i) above. The HST starts increasing on further increase in the applied voltage. On the basis of the data

Table 1. Physical constants for *n*-pentane and methyl methacrylate.

Liquid	b.p. (K)	ρ (kg m^{-3})	ε	$(d\varepsilon/dT)$ (K^{-1})	$(d\varepsilon/d\rho)$ (kg^{-1} m^3) $\times 10^{-4}$
n-pentane	309·1	650	1·844	0·0016	2·7
Methyl methacrylate	373·5	910	2·840	0·0014	3·3

Table 2. Dielectric and conductivity terms for methyl methacrylate at different applied voltages and ΔT.

V (kV)	$F_d = \left(\varepsilon - \varepsilon_0 - \dfrac{\partial \varepsilon}{\partial \rho}\rho\right)E^2/2$ (dynes)	Transient current ($\times 10^{15}$ A)	q ($\times 10^{-5}$ SI)	$qE = F_c$ (dynes)	ΔT (K)
1·5	2·10	1	0·67	1·01	73·5
2·0	3·04	8	2·25	4·50	73·5
1·5	2·04	50	1·37	2·06	83·5
2·0	3·00	100	2·60	5·20	83·5
1·0	2·96	100	2·30	4·60	106·5

in table 1 for methyl methacrylate, the dielectric term $F_d = [\varepsilon - \varepsilon_0 - (\partial \varepsilon/\partial \rho)\rho]E^2/2$, in (2), increases from 2·1 dynes to 3·04 dynes for increase in voltage from 1·5 kV to 2 kV. The corresponding conductivity term $F_c = qE$ increases from 1·01 dynes to 4·5 dynes for the same values of applied voltages considering the transient current variation from $1·2 \times 10^{-15}$ A at 1·5 kV to 8×10^{-15} A at 2 kV from figure 6. These transient current variations correspond to variation in charge densities in bulk liquid from $6·7 \times 10^4$ SI at 1·5 kV to $2·25 \times 10^5$ SI at 2 kV. Thus beyond 2 kV of applied voltages $F_c > F_d$ and the HST increases on the application of electric field in accordance with condition (iii) above. The charge densities are two orders of magnitude higher in comparison to n-pentane. The increase in charge density is due to large polarisation effects in methyl methacrylate possessing two methyl groups in each molecule of the monomer.

The stability of HST at $\Delta T = 83·5$ K (figure 5b) below 2 kV of applied voltage is explained by comparing F_d and F_c in the force equation (2), *e.g.* at V = 1·5 kV, the F_d term is 2·04 dynes whereas $F_c = 2·06$ dynes from transient current values of 5×10^{-14} A from figure 6. The two terms, being nearly equal, do not contribute towards dielectrophoretic forces and the HST remains steady till 2 kV, a voltage beyond which the HST starts increasing on application of the field. This happens again due to dominance of the conducting term $qE(F_c) = 5·9$ dynes, calculated from transient current $\approx 10^{-13}$ A from figure 6, in comparison to the term $F_d = 3$ dynes in accordance with condition (iii).

At $\Delta T = 106·5$ K (figure 5c), HST increases on application of electric field in accordance with situation (iii) above. This is evident from higher values of transient current in figure 6 at this temperature. From the data in table 1, the F_d term in this case is 2·96 dynes and the F_c term is 4·6 dynes for the applied voltages. The $qE = F_c$ term being larger, HST increases on the application of electric field.

5.3 *Gravitational pull and steady equilibrium*

In addition to the body forces in (2) due to electric field, the liquid also experiences gravitational forces due to buoyancy. The gravitational force F_g per unit volume of the heated liquid surrounding the heater is

$$F_g = \frac{4\pi}{3} R^3 \text{ grad} \cdot \rho \cdot E, \tag{13}$$

where grad ρ is the density gradient due to the temperature gradient from HS towards the bulk liquid. This gravitational force tries to inhibit heat transfer from the lower half of the bulb and enhance heat transfer from the upper half. The two effects being almost equal, the net effect due to gravitational force on the over-all heat exchange from HS is negligible and the resultant force on HS is due to the electric field only. Thus in the present calculations the effect of gravitational forces has been neglected in comparison to dielectrophoretic forces.

Although the consideration of the conductivity term in (2) helps in explaining the experimental results on the anomalous transient effects in methyl methacrylate, measurements on its conductivity before and after the experiments do not indicate degradation of the liquid due to electric field application or due to its heating. Therefore, the origin of space charges in liquid beyond voltages of 2 kV at lower temperatures might be the result of the minute impurities in the liquid. However, the exact nature of impurities could not be ascertained in these experiments.

In the range of applied voltages and temperatures where the liquid behaves as a non-conductor, correlation of ΔNu with Nu for n-pentane and methyl methacrylate at fields $\approx 10^6$ V/m in the present experiment is shown in figure 7 for various values of El $\cdot$ Pr from (5) and (6) calculated from data in table 1. Nu has been calculated from (Kronig and Ahsmann 1949):

$$\text{Nu} = \frac{Q}{\pi d \lambda \Delta T}.$$

The general observation of complex fluid motion suggests that the natural convection patterns are completely destroyed by the dielectrophoretic effects so that Nu correlation in figure (7b) is quite appropriate in the present case. Also the use of thin conducting film on an electrode has reduced the thermal capacity of the heater system considerably, making the instantaneous temperature measurements more realistic and accurate. In calculating the values of ΔNu and El $\cdot$ Pr, the material constants have been taken at the temperature of the HS since the stability conditions are destroyed by the electric field in the neighbourhood of the HS.
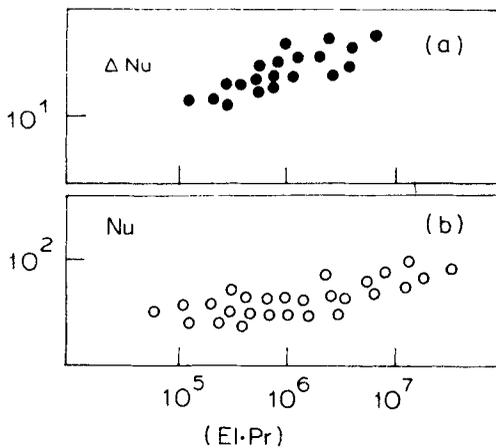

Figure 7. Correlation of **a.** ΔNu and **b.** Nu with El $\cdot$ Pr.

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