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Electroconvective specific heat transfer properties of some selected liquids

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ABSTRACT. The electroconvective specific heat transfer coefficient has been measured in selected liquids (methanol, kerosene, silicon oil and ethanol) using a single platinum wire (diameter = 0.025 mm) mounted along the axis of a copper cylinder (diameter = 53 mm). The heat transfer coefficient has been evaluated under the influence of ac and dc fields. An ac field always causes an enhancement in heat transfer coefficient. A dc field causes an inhibition in heat transfer in methanol. A similar trend is noted in kerosene, but the heat transfer coefficient increases again as the field is increased. An enhancement in heat transfer coefficient is noted in silicon oil, and a similar trend is noted in ethanol, but the heat transfer coefficient decreases again as the field is increased further. The effect of cylinder orientation on convection is studied. The efficiency of convection has been evaluated for various liquids using an empirical relationship. The efficiency obtained in a dc field is found to be higher than the ac field. Similar trend is also noted for electric Nusselt number.

RESUMEN. Se midió el coeficiente del calor específico de transferencia electroconvectiva en algunos líquidos (metanol, querosén, aceite de silicón y etanol) utilizando un alambre de platino (diámetro = 0.025 mm) montado a lo largo del eje de un cilindro de cobre (diámetro = 53 mm). Se evaluó el coeficiente de transferencia de calor bajo la influencia de campos de corriente alterna (ca) y directa (cd). Un campo ca produce siempre un incremento en dicho coeficiente, mientras que un campo cd produce una inhibición del mismo en etanol. Se observa un patrón similar en el querosén, pero en este caso el coeficiente de transferencia de calor aumenta una vez más al aumentar más el campo. En el aceite de silicón, se observa un incremento del coeficiente de transferencia de calor, similar a lo observado en el etanol, pero el coeficiente de transferencia de calor decrece al aumentar más el campo. Se estudia también el efecto de la orientación del cilindro en la convección. Se evaluó la eficiencia de la convección en varios líquidos utilizando una relación empírica. La eficiencia obtenida en un campo cd resultó ser mayor que en un campo ca. El mismo comportamiento se observó también respecto del número de Nusselt eléctrico.

PACS: 44.25

1. INTRODUCTION

The application of an electric field to transport processes offers several advantages. Among them are the increase of transport rates through the electric field induced motion. Although the augmentation of heat transfer in liquids has been observed in the experiment of Kronig and Ahsman [1–3] nearly 50 years ago, very little is understood about its enhancement mechanisms.

Not until recently has the problem received a considerable renewed interest motivated by a desire to develop compact direct-contact liquid heat exchangers for space applications, and to resolve some technical difficulties related to traditional mechanical agitations as commonly found in numerous chemical engineering processes. As a result, a number of studies have been conducted in the past few years in an effort to understand the phenomena [4–7]. Allen [7] has demonstrated in his small scale experiment that the heat transfer from heated bodies to insulating liquids are influenced both by an ac and dc field. A dc field causes an inhibition in heat transfer, while an ac field always enhances it. According to Allen, the enhancement with dc fields reported by previous workers may be due to the ripples present in the dc fields used by them. Bonjour *et al.* [8] have reported an enhancement of heat transfer with dc as well as ac fields, and have shown that the effect also depend on the conductivity of the liquid. Care and Swan [9] have shown some transient effects in heat transfer as a result of the electric stresses. Gangwar [10, 11] has shown an enhancement of heat transfer due to electric field in soya bean oil.

From the foregoing, it can be seen that there is a need for a more broad based experimental investigation in order to understand the exact mechanism behind the heat transfer. The present work has been undertaken to investigate the effects of both ac and dc electric fields on heat transferred from an electrically heated platinum wire embedded in ethanol, methanol, kerosene and silicon oil, each in a cylindrical container maintained inside a constant temperature bath. The effect of cylinder orientation on the convective heat transfer has been investigated. The electric Nusselt number for various liquids has been evaluated under the influence of ac and dc fields. Additionally, the efficiency of electroconvection has been evaluated using an empirical relationship and the results for ac and dc fields are presented here.

In the experiments reported here, we have chosen commonly used inexpensive liquids (methanol, ethanol, kerosene and silicon oil), the choice is mainly based on their practical applications in many technical fields. Typical examples in the field of energy conversion systems, as in the device heat pipes. Alcohol is used as the working fluid and the device can transport heat fluxes many times that which can be conducted by solid metal bars of equal cross section. The device is also used to transport heat fluxes in gravity free environment. Kerosene oil is used in gas turbines, jet aircraft, etc. Silicon oil is used as a lubricating agent in many devices such as high-vacuum equipment, laser systems, computers, etc. In order to select the optimum regimes for the construction of these equipments and to determine the most effective heat transfer conditions and characteristics, it is necessary to know how electric fields influence the processes of momentum and thermal energy transfer in such systems.

2. EXPERIMENTAL SET-UP

2.1. The equipment

A diagram of the experimental set-up is shown in Fig. 1. The characteristics of the various

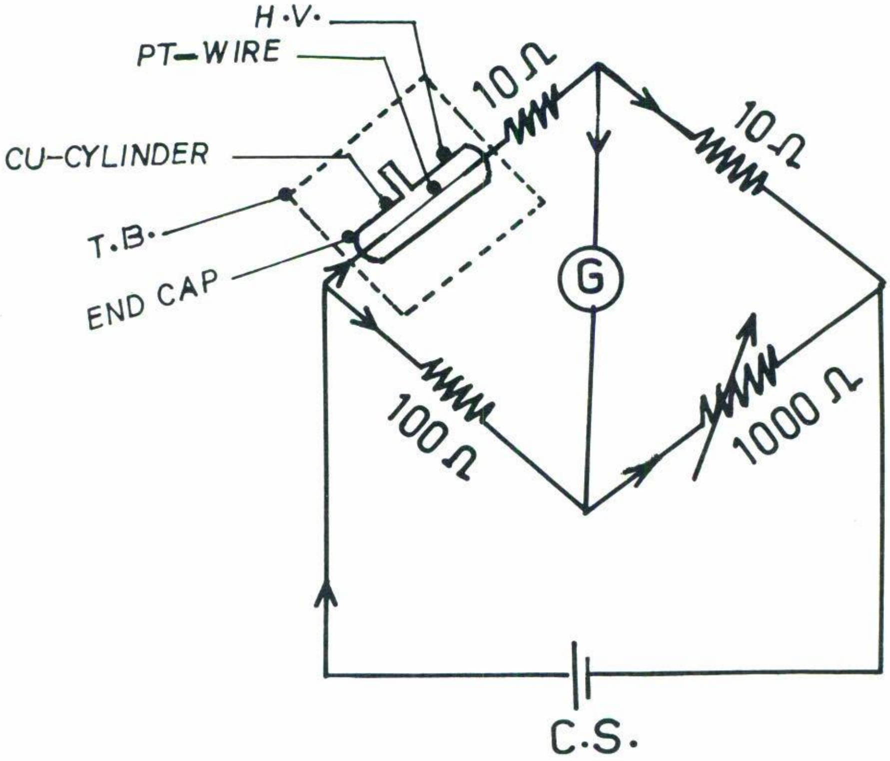

FIGURE 1. Experimental set up used for the determination of the electroconvective heat transfer coefficients in liquids. In the diagram, H.V. = High voltage, Pt = platinum, Cu = copper, T.B. = Temperature bath, C.S. = Current source, G = Galvanometer.

equipments used in this set up are as follows. The hot wire cell was an electrically insulated cell. The breakdown voltage was above 20 kV. The cell was vacuum sealed, the ultimate vacuum was about 10^{-6} torr. The range of the temperature bath was 0–80°C and the temperature was controlled by an electronic thermostat with an accuracy of ±0.05°C. The range of the current source was 0–1.0 A and the open circuit voltage was 10 V. The resolution was 10 μA while the accuracy was ±0.25%. The dc high voltage range was 0–20 kV, with a maximum current of 1 mA. The voltage stability was 0.02%, while the regulation was ±0.05% for no load to full load condition. The ac high voltage range was 0–15 kV, with an accuracy of ±2% in the range 10 Hz to 200 KHz. The resolution of the digital voltmeter was 1μv, the accuracy was ±0.25% ±1 digit, and the stability was within ±1 digit. The input impedance was 10 M ohm at 10 V range and the display was of $5\frac{1}{2}$ digit. The accuracy of the ammeter was ±0.25% corresponding to the response of 20 Hz to 20 KHz. The Wheatstone bridge was composed of high quality decade resistance box and was suitable for ac and dc measurements. The accuracy of adjustment was better than 0.1% and the normal continuous loading of each step was 0.5 W. A galvanometer was used as an indicator and the sensitivity was 25 mm/μA.

TABLE I. Physical properties of methanol, ethanol, kerosene and silicon oil at 20°C.

Liquid	Boiling (°C)	Density (gm/cm^3)	Kinematic viscosity, $\nu \times 10^2$ (cm^2/s)	Thermal conductivity, k (Cal/cm °C sec)	Purity (%)
Methanol	64–65	0.810	0.737	0.0004832	95
Ethanol	77–79	0.7893	1.52	0.0003995	99
Kerosene	180–230	0.82	—	0.0003572	95
Silicon oil	140–177	0.96	105.6	0.00037	100

2.2. Method of calibration

The equipments used to calibrate the platinum wire as a platinum resistance thermometer were as follows: a hot wire cell, constant temperature bath, constant current source, Wheatstone bridge, standard resistor, digital resistance box, digital multimeters and galvanometer. The hot wire cell was constructed from a copper cylinder (diameter = 53 mm, length = 180 mm) with a fine platinum wire (diameter = 0.025 mm) stretched along its axis. The calibration was carried out in presence of methanol, ethanol, kerosene and silicon oil. Some of the physical properties of these fluids and their chemical purities are listed in Table I. The hot wire cell in series with a standard resistor was placed in one arm of the Wheatstone bridge and was then immersed inside a constant temperature bath. The bath temperature was adjusted to a particular value T_1 and was kept constant to within ±0.05°C. The bridge was kept balanced. The heating current was supplied from the constant current source. The bridge was rebalanced. The current through the platinum wire was obtained by measuring the voltage across the standard resistor. The resistance of the wire was then obtained by measuring the voltage across it. Thus the heat loss $Q_1 = i_1^2 R_1$ was obtained for a particular wire current i_1 and resistance R_1. The procedure was repeated for different heating currents and corresponding heat loss $Q_2, Q_3, \ldots$ etc. were calculated. The Q was plotted against R and a straight line was obtained. The straight line was extrapolated and the value of the resistance at zero current was calculated. Thus the resistance of the platinum wire at a particular bath temperature T_1 was obtained. The procedure was repeated for different bath temperature and the corresponding resistances were calculated. By this way a calibration data was obtained and the calibration of the wire was carried out using the relation $R = A + BT_w$, where R is the resistance and T_w is the temperature of the wire. The values of the constants were obtained from the calibration data.

2.3. Method of measurement

A hot wire cell was used to furnish the heat transfer data. The cell was placed in one arm of a Wheatstone bridge and was then immersed inside a constant temperature bath. This cell could be positioned at any angle between the vertical and horizontal orientations. Electric fields in the cell were created by an applied electrical potential (dc or ac) between the central wire and the surrounding cylinder. The heat transfer coefficient was obtained by measuring the voltage across the platinum wire and a standard resistor in series with it. The bridge was kept balanced for any experimental situation. If I is the current flowing through the wire in the absence of any electric field and ΔI is the current necessary to keep the bridge balanced in the presence of any electric field, then the rate of heat transfer is given by

$$Q_{\mathrm{el}} = \left[2I(\Delta I) + (\Delta I)^2\right]R,$$

where R is the resistance of the wire. The heat transfer coefficients are obtained using the relations

$$q_{\mathrm{el}} = \frac{Q_{\mathrm{el}}}{A} \quad \text{and} \quad h_{\mathrm{el}} = \frac{Q_{\mathrm{el}}}{AT_{\mathrm{d}}},$$

where q_{el} is the electroconvective specific heat transfer coefficient, h_{el} is the electroconvective heat transfer coefficient, A is the surface area of the wire and T_{d} the temperature difference between the wire and the surrounding medium. The details of this experimental arrangement have been described elsewhere [12–16].

3. EXPERIMENTAL RESULTS

Figure 2 shows the results of the electroconvective specific heat transfer coefficient for methanol. The results of the ac and dc fields are shown in the same plot. An ac field always causes an enhancement in heat transfer coefficient. The heat transfer coefficient increases gradually as the field is increased, and no indication of saturation is noted. An inhibition in heat transfer coefficient is always noted under the influence of the dc field. The results for kerosene is presented in Fig. 3. In the case of an ac field, a slight inhibition in heat transfer is noted at lower range (~ 0–800 V). The heat transfer coefficient then increases almost linearly as the field is increased. An inhibition in heat transfer coefficient is also noted in a dc field, and the inhibition produced in a dc field is much higher than the ac field. The heat transfer coefficient then increases linearly as the field is increased. The results for silicon oil is presented in Fig. 4. At lower region (~ 0–2 kV) an inhibition in heat transfer coefficient is noted under the influence of dc and ac field, the inhibition produced in a dc field is much higher than the ac field. In the case of a dc field the heat transfer coefficient increases almost linearly as the field is increased and then approaches towards a saturation value at higher electric fields. However, in the case of an ac field, the heat transfer coefficient increases linearly with an increase in electric field and no indication of saturation is noted at all. Figure 5 shows the results for ethanol. In the case of a dc field, the heat transfer coefficient increases very rapidly as the field is increased gradually, reaches a saturation value and then decreases again as the field is increased further. In the case of an ac field and at lower region (~ 0–80 V), the magnitude of he heat transfer coefficient is almost zero. It then increases gradually as the field is increased, approaches a saturation value and then decreases again as the field is increased further. The magnitude of the convection under the influence of dc field is found to be much higher than the ac field.

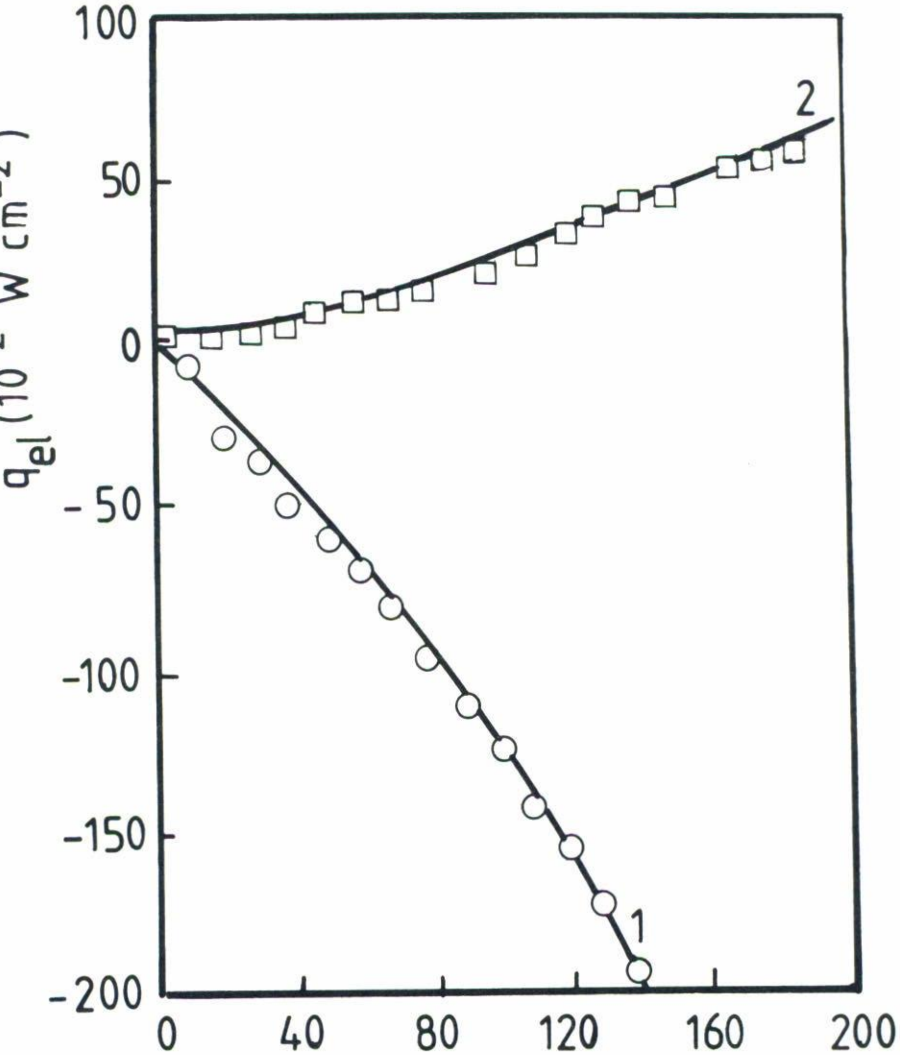

FIGURE 2. Plots of electro-convective specific heat transfer coefficient as a function of dc and ac voltage for methanol. *Horizontal Cylinder*: 1. dc voltage, $T_d = 13.47°C$; 2. ac voltage, $T_d = 13.20°C$.

The effect of inclination to the horizontal for the convective specific heat transfer coefficient of various liquids was also studied. The results for methanol, kerosene, silicon oil and ethanol are presented in Figs. 6a, b, c and d respectively. The convective specific heat transfer coefficient is found to remain almost constant for inclination to the horizontal up to about 50°, but the heat transfer coefficient increases rapidly as the axis of the cylinder approaches the vertical position. An overall 50% increase in heat transfer coefficient is noted in most of the cases. When a heated cylinder is inclined at an angle $\theta \neq 0$ to the horizontal, there is an axial component of heat flow and a thickening of the boundary layer,

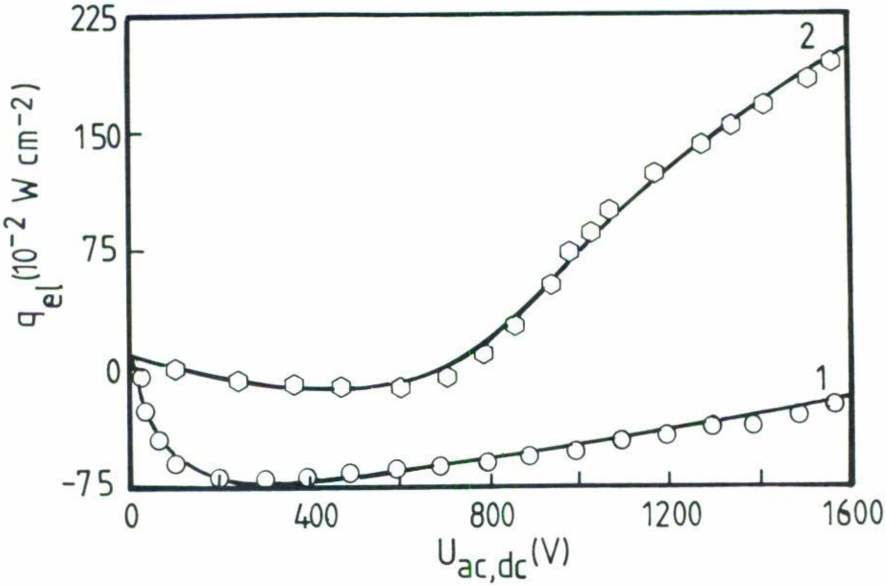

FIGURE 3. Plots of electro-convective specific heat transfer coefficients as a function of dc and ac voltage for kerosene. *Horizontal Cylinder*: 1. dc voltage, $T_d = 13.34°C$; 2. ac voltage, $T_d = 16.51°C$.

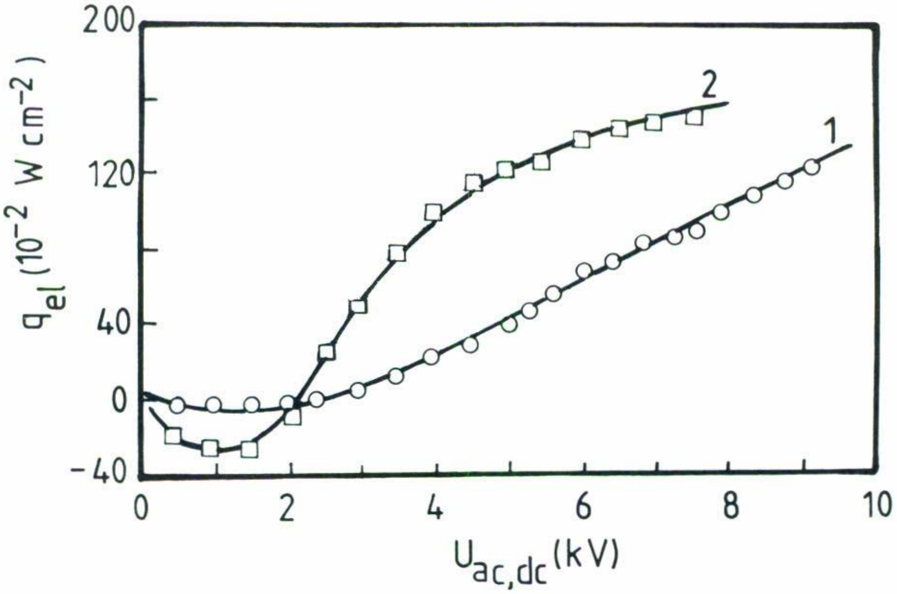

FIGURE 4. Plots of electro-convective specific heat transfer coefficients as a function of dc and ac voltage for silicon oil. *Horizontal Cylinder*: 1. ac voltage, $T_d = 11.27°C$; 2. dc voltage, $T_d = 11.51°C$.

leading to a decrease in convective heat transfer, as indicated previously [17]. The boundary layer thickness is reduced in the presence of an electric field, leading to an enhanced heat transfer coefficient, the maximum enhancement occurring at $\theta = 90°$ inclination.

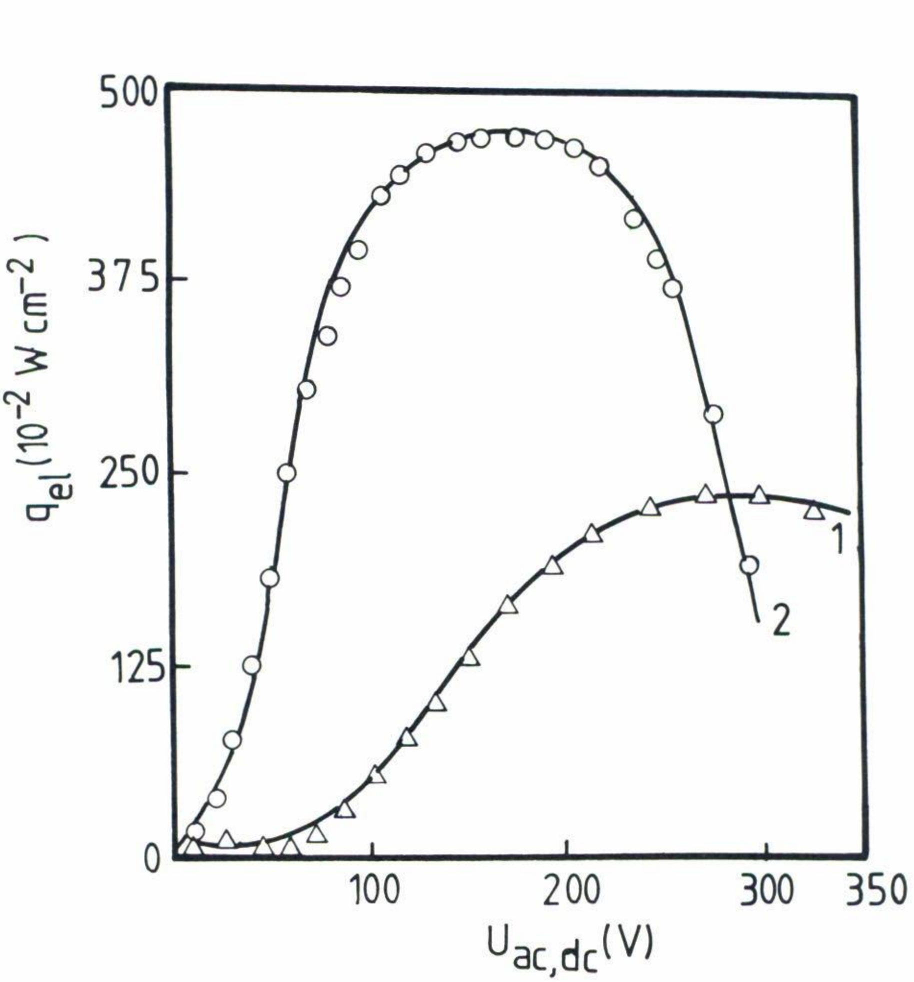

FIGURE 5. Plots of electro-convective specific heat transfer coefficients as a function of dc and ac voltage for ethanol. *Horizontal Cylinder*: 1. ac voltage, $T_d = 6.29°C$; 2. dc voltage, $T_d = 6.43°C$.

The efficiency of electroconvection for various liquids (methanol, kerosene, silicon oil and ethanol) was evaluated under the influence of ac and dc fields and the results are presented in Tables II, III, IV and V, respectively. Likewise, the electric Nusselt number for various liquids are evaluated under the influence of ac and dc fields and the results are presented in the same tables.

The efficiency of electroconvection is defined by the relation

$$\gamma_{el} = \frac{h_{el}}{h_{el} + h_f}, \tag{1}$$

where h_{el} is the electroconvective heat transfer coefficient and h_f is the free convective heat transfer coefficient. The efficiency of free convection is defined as the transformation of the rate of electrical power supplied to the system into the rate of kinetic energy generation of convective motion [18]. Thus the measurement of heat transfer coefficient in presence of electric field represents a useful conversion of additional electrical energy into the rate

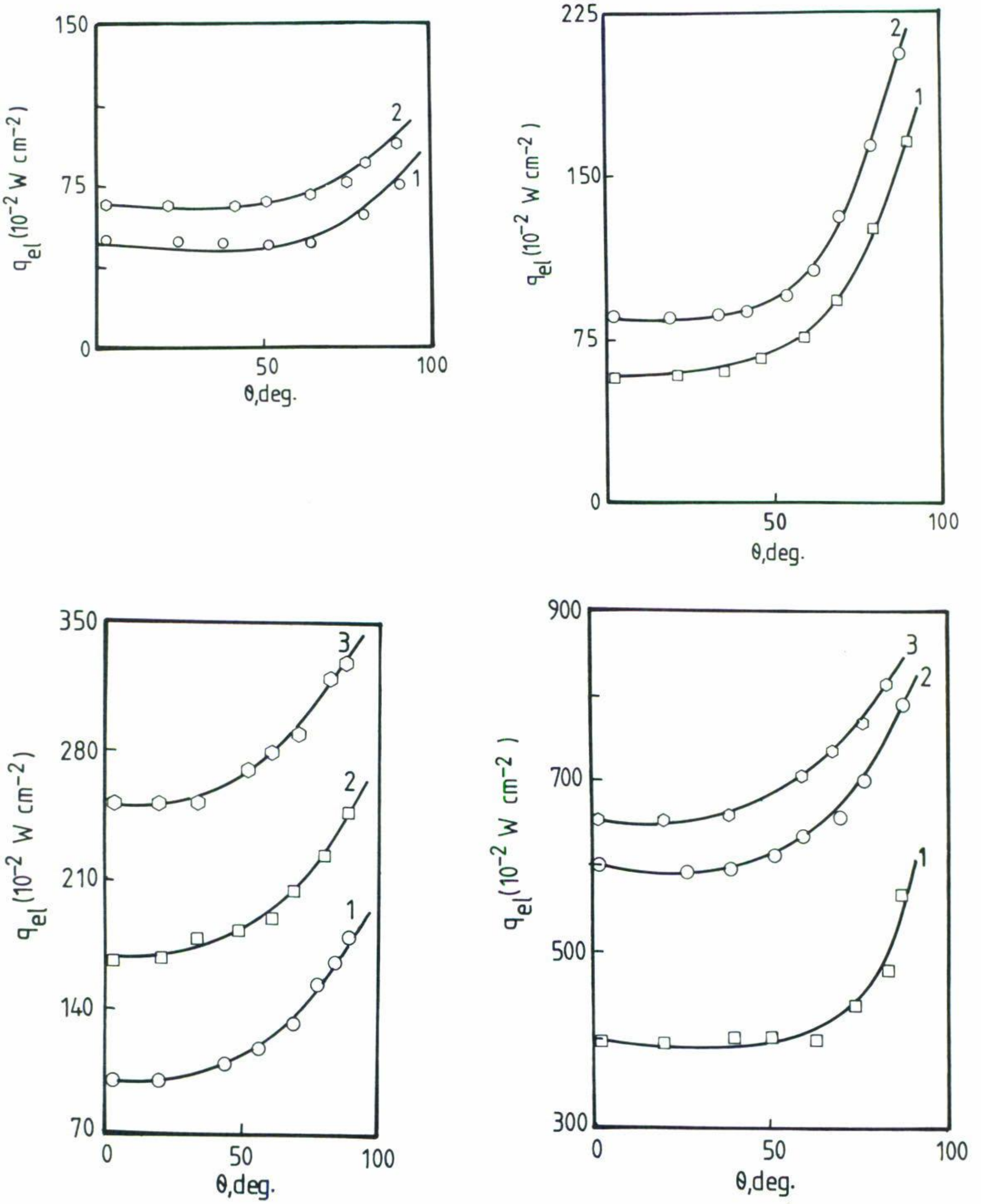

FIGURE 6. Effect of inclination to the horizontal of a cylinder containing liquid on the electroconvective specific heat transfer. (a) *Methanol*: $T_d = 15.0$°C. 1. $U = 150$ V ac; 2. $U = 180$ V ac. (b) *Kerosene*: 1. $T_d = 12.0$°C, $U = 1.0$ kV ac; 2. $T_d = 15.0$°C, $U = 1.0$ kV ac. (c) *Silicon Oil*: $T_d = 12.0$°C. 1. $U = 5.0$ kV ac; 2. $U = 7.0$ kV ac; 3. $U = 5.0$ kV dc. (d) *Ethanol*: 1. $T_d = 6.0$°C, $U = 100$ V dc; 2. $T_d = 8.0$°C, $U = 100$ V dc; 3. $T_d = 10.0$°C, $U = 100$ V dc.

TABLE II. Calculated efficiency of convection and Nusselt number for methanol as a function of electric fields. Horizontal cylinder: 1. (γ_{ac}, Nu_{ac}), T_d = 13.47°C; 2. (γ_{dc}, Nu_{dc}), T_d = 13.20°C.

E_s (V/cm) × 10^3	$-\gamma_{dc}$ (%)	γ_{ac} (%)	$-Nu_{dc}$	Nu_{ac}
0	0	0	0	0
1.04	1.21	0	11.18	0
2.08	9.14	0.28	78.52	2.62
3.12	11.32	0.68	95.29	6.55
4.16	15.50	1.63	125.75	15.71
5.20	19.59	2.95	153.57	28.80
6.24	23.78	3.72	180.00	36.67
7.28	28.63	3.97	208.60	39.28
8.32	36.12	4.73	248.64	47.14
9.36	44.46	5.60	288.45	56.31
10.40	53.44	6.21	326.39	62.85
11.44	64.96	7.17	369.06	73.33
12.48	74.31	8.11	400.12	83.81
13.52	91.09	9.45	446.76	99.52
14.56	—	10.38	—	109.99
15.60	—	10.71	—	113.92
16.64	—	12.12	—	130.95
17.68	—	12.65	—	137.49
18.72	—	12.97	—	141.42
19.76	—	13.38	—	146.66
20.80	—	13.79	—	151.90

E_s = electric field intensity at the surface of the platinum wire.

of generation of kinetic energy of convective motion. In the definition of γ_{el} [Eq. (1)], a positive value of γ_{el} implies an enhancement of free convection by electroconvection, while a negative value implies a suppression of the free convection by electroconvection. The absence of electroconvection is indicated by a zero value of γ_{el}. In the case of methanol (Table II), the efficiency of electroconvection decreases gradually with an increase in dc field. Clearly, a negative value of γ_{el} implies a suppression of the free convection by electroconvection. However, in the case of an ac field a positive value of γ_{el} is noted. The efficiency of electroconvection increases gradually with an increase in electric field and then approaches towards a saturation value. Table III shows the results for kerosene. In a dc field, the efficiency of electroconvection decreases at first and then increases again as the field is increased further. In an ac field, the efficiency of electroconvection is virtually positive, the efficiency increases with an increase in electric field and appears to reach a saturation value. Table IV shows the results for silicon oil. An increase in efficiency is noted with an increase in electric field (dc) and then appears to reach a saturation value. A similar trend is noted in an ac field. However, the efficiency obtained in a dc field is found to be higher than the ac field. The result for ethanol is presented in Table V. The efficiency of electroconvection increases with an increase in electric field, reaches a

TABLE III. Calculated efficiency of convection and Nusselt number for kerosene as a function of electric fields. Horizontal cylinder: 1. ($\gamma_{\mathrm{dc}}, Nu_{\mathrm{dc}}$), $T_{\mathrm{d}} = 18.78°\mathrm{C}$; 2. ($\gamma_{\mathrm{ac}}, Nu_{\mathrm{ac}}$), $T_{\mathrm{d}} = 17.23°\mathrm{C}$.

E_s (V/cm) × 10^3	$-\gamma_{\mathrm{dc}}$ (%)	γ_{ac} (%)	$-Nu_{\mathrm{dc}}$	Nu_{ac}
5.20	8.36	0	70.82	0
10.40	18.24	0	141.65	0
15.60	21.57	0	162.90	0
20.80	22.72	−0.56	169.98	− 3.54
26.00	23.89	−0.84	177.06	− 5.31
31.20	25.08	−1.13	184.14	− 7.08
36.40	24.48	−1.24	180.60	− 7.79
41.60	23.89	−1.41	177.06	− 8.85
46.80	22.72	−1.69	169.98	− 10.62
52.00	21.57	−1.81	162.90	− 11.33
57.20	20.99	−1.99	159.35	− 12.39
62.40	19.88	+1.10	152.27	+ 7.08
67.60	19.33	5.52	148.73	37.19
72.80	18.78	11.78	145.19	84.99
78.00	18.24	18.21	141.65	141.65
83.20	17.97	23.76	139.88	198.31
88.40	17.70	28.89	138.11	258.51
93.60	17.17	31.86	134.57	297.46
98.80	16.90	35.76	132.80	354.12
104.00	16.64	37.97	131.02	389.53
109.20	16.21	40.64	127.48	435.57
114.40	15.09	43.08	120.40	481.60
119.60	14.58	45.17	116.89	524.10
124.80	14.08	46.15	113.32	545.34
130.00	13.08	47.57	106.24	577.22
135.20	12.11	48.76	99.15	605.56
140.40	11.62	50.18	95.61	640.96
145.60	11.14	51.40	92.07	672.83
150.80	10.20	—	84.99	—
156.60	9.27	—	77.91	—
161.20	8.36	—	70.82	—

saturation value and then decreases again as the field is increased further. The result for ac field is similar to that of dc field. However, the efficiency obtained in a dc field is found to be much higher than the ac field.

The electric Nusselt number is calculated by using the relationship

$$Nu_{\mathrm{el}} = \frac{h_{\mathrm{el}} D}{\lambda}, \tag{2}$$

where h_{el} is the electroconvective heat transfer coefficient, D is the diameter of the cylinder

TABLE IV. Calculated efficiency of convection and Nusselt number for silicon oil as a function of electric fields. Horizontal cylinder: 1. ($\gamma_{\mathrm{dc}}, Nu_{\mathrm{dc}}$), $T_{\mathrm{d}} = 13.81°\mathrm{C}$; 2. ($\gamma_{\mathrm{ac}}, Nu_{\mathrm{ac}}$), $T_{\mathrm{d}} = 14.45°\mathrm{C}$.

E_s (V/cm) $\times 10^5$	γ_{dc} (%)	γ_{ac} (%)	Nu_{dc}	Nu_{ac}
0	0	0	0	0
0.26	6.31	0	35.59	0
0.52	9.97	0	58.53	0
1.04	14.65	0	90.70	0
1.56	32.86	0	258.52	0
2.08	41.31	1.84	371.89	13.68
2.60	47.76	3.62	482.96	27.35
3.12	53.51	6.98	608.02	54.70
3.64	57.75	11.06	722.03	88.89
4.16	60.26	15.46	801.21	133.33
4.68	61.63	18.38	848.69	164.10
5.20	63.03	20.68	900.62	190.08
5.72	63.99	23.23	938.78	220.51
6.24	64.75	26.66	970.23	264.95
6.74	65.50	28.50	1002.90	290.59
7.28	66.47	30.60	1047.10	321.36
7.80	66.90	33.21	1067.60	362.38
8.32	67.55	35.24	1099.90	396.57
8.84	67.77	36.40	1111.0	417.08
9.36	68.73	37.51	1161.10	437.59
10.40	69.36	40.97	1195.80	505.97

and λ is the thermal conductivity of the fluid. The fluid properties were evaluated at the film temperature given by

$$T_{\mathrm{f}} = \frac{T_{\mathrm{w}} + T_{\infty}}{2}, \tag{3}$$

where T_{w} is the temperature of the wire and T_{∞} is the temperature of the surrounding medium. The electric Nusselt number for various liquids (methanol, kerosene, silicon oil and ethanol) are presented in the last two columns of Tables II, III, IV and V, respectively. As seen in the tables, a zero value of Nu_{el} implies an absence of convection. A positive value of Nu_{el} implies that heat flows from the wire, while a negative value means that heat flows into the wire. The behaviour of Nu_{el} is found to be similar to that of γ_{el}.

4. DISCUSSION

When a voltage difference is applied across a fluid, the fluid will be acted on by the three different types of electrical forces [19], such as Coulomb or the electrophoretic force

$$\mathbf{F}_{\mathrm{e}} = \rho_{\mathrm{s}} \mathbf{E}_r, \tag{4}$$

TABLE V. Calculated efficiency of convection and Nusselt number for ethanol as a function of electric fields. Horizontal cylinder: 1. $(\gamma_{\mathrm{dc}}, Nu_{\mathrm{dc}})$, $T_{\mathrm{d}} = 6.43$°C; 2. $(\gamma_{\mathrm{ac}}, Nu_{\mathrm{ac}})$, $T_{\mathrm{d}} = 6.29$°C.

E_s (V/cm) $\times 10^3$	γ_{dc} (%)	γ_{ac} (%)	Nu_{dc}	Nu_{ac}
0	0	0	0	0
1.04	0.82	0	8.61	0
2.08	15.45	0	188.55	0
3.12	27.94	0	400.14	0
4.16	37.81	0	627.26	0
5.20	47.50	0.74	933.46	6.3
6.24	55.19	1.47	1270.80	12.67
7.28	59.98	4.26	1546.50	37.99
8.32	62.42	10.60	1714.00	101.32
9.36	64.49	16.16	1874.20	164.64
10.40	65.99	20.13	2000.22	215.30
11.44	68.05	27.04	2196.50	316.62
12.48	68.65	31.48	2259.10	392.61
13.52	69.29	35.42	2328.60	468.60
14.56	69.51	39.48	2352.10	557.25
15.60	69.59	42.57	2360.80	633.24
16.64	69.72	45.80	2376.0	721.89
17.68	69.72	48.29	2376.40	797.88
18.72	69.72	50.92	2376.40	886.54
19.76	69.73	51.80	2376.80	918.20
20.80	69.73	54.25	2376.80	1013.20
21.84	69.53	54.86	2354.90	1038.20
22.88	68.86	55.90	2282.30	1082.80
23.92	68.23	56.60	2216.30	1114.50
24.96	67.15	57.96	2109.10	1139.80
26.00	65.71	57.77	1977.40	1165.20
27.04	64.65	57.96	1887.10	1177.80
28.08	61.47	58.21	1446.40	1187.30
29.12	58.50	58.22	1454.80	1190.50
30.16	51.06	58.22	1076.50	1190.50
31.20	48.35	58.09	965.79	1184.20
32.24	—	57.96	—	1177.80
33.28	—	57.69	—	1165.20
34.32	—	56.95	—	1130.30

where ρ_s is the net space charge density and $\mathbf{E}_r$ is the electric field intensity; the dielectrophoretic force

$$\mathbf{F}_{\mathrm{d}} = -\left(\tfrac{1}{2}\mathbf{E}_r^2\right)\nabla\varepsilon, \tag{5}$$

where ε is the permittivity of the fluid; and the electrostrictive force

$$\mathbf{F}_s = \nabla\left[\left(\tfrac{1}{2}\mathbf{E}_r^2\right)\left(\frac{\partial\varepsilon}{\partial\rho}\right)\rho\right], \tag{6}$$

where ρ is the fluid density. In electrohydrodynamic systems the electrodynamic equations comprise Maxwell's relations and appropriate constitutive relations. For a single known species of charge carrier the constitutive relation for current in a dc system takes the following postulate form:

$$\mathbf{j} = \rho_s b\mathbf{E}_r + \rho_s\mathbf{u} + D_c\nabla\rho_s\,, \tag{7}$$

where, except in ultra pure liquids in which free electrons may occur, charge carriers are thought to exist as positive or negative ions [20, 21]. The first term represents the current which results from the drift of ions relative to surrounding host fluid molecules, b being the ion mobility, while the other terms account for the convective transport and diffusion of ions respectively. The quantity D_c is the ion diffusion coefficient and except in regions very close to the electrodes ($\mathbf{u} \to 0$) the diffusion term is small compared with other two terms and can be neglected. From the foregoing it is clear that as a body force the electrophoretic component, rather than acting on all the constituents of the medium, operates on individual ions which then transfer momentum to surrounding molecules as they are driven through the host medium.

In the absence of an applied electric field the free convective heat transfer coefficient remains constant. The behaviour of the convective heat transfer coefficient under the influence of dc and ac fields is the result of the combined effect of the dielectrophoretic and electrophoretic forces. The dielectrophoretic force is the result of the polarization of the liquid that occurs when it is subjected to a non uniform field. It is independent of the polarity of the field but always has a tendency to drag the medium towards the maximum intensity of the field [10, 22]. The presence of free charges in the liquid medium, on the other hand is responsible for the electrophoretic force and hence depends on the polarity of the field [22, 23].

In the present investigation, natural convection is first established in the liquid by passing a heating current through the wire. The relative motion between the hot and the cold volumes of the liquid gives rise to the streaming potential and, therefore, the applied electric field retards the natural convection electrophoretically, resulting in the inhibition of heat transfer. Parallel to the electrophoretic force is the dielectrophoretic force, since the field inside the cylinder is non uniform; moreover, there is a dielectric gradient in the liquid. The dielectrophoretic force therefore forces the hot volume of the liquid away from the wire surface, thereby dragging the cold volume towards the surface of the curve, resulting in the setting up of electroconvetion [1–5, 10] in addition to the natural convection already present in the liquid. Thus the electrophoretic and dielectrophoreic forces act in opposite directions [1–4]. The net circulatory force caused by the inhomogeneous dielectric can be written as

$$\nabla\times\mathbf{f} = \frac{1}{8\pi}\nabla\varepsilon\times\nabla\mathbf{E}_r^2 + \nabla\rho_s\times\mathbf{E}_r, \tag{8}$$

where $\mathbf{f}$ is the electric body force per unit volume.

The enhancement of the heat transfer coefficient is due to the dominance of the dielectrophoretic forces over the electrophoretic forces, while in the saturation region, an energy balance is attained due to Joule heating, which develop gradually as the field is increased. Joule heating is also responsible for the reduction of heat transfer as noted in the experiment. The electric field intensity inside the cylinder is estimated as

$$\mathbf{E}_r = 0.13\,U/r \quad (\mathrm{V\ cm^{-1}}), \tag{9}$$

where r is the radial distance from the centre of the wire and U is the voltage applied to the cylinder. The maximum conduction current (i_c) flowing through the cylinders at maximum electric field strength was recorded as 9.5, 2.30, 0.0 and 0.0 mA for methanol, ethanol and kerosene and silicon oil respectively. An estimate of the Joule heating near the immediate vicinity of the platinum wire gives a very significant figure for methanol as well as for ethanol. For example, in the case of ethanol, an estimate of the Joule heating near the immediate vicinity of the platinum wire (0.005 cm from the surface) and at maximum voltage ($U = 300$ V) gives $Q_j = 200.0$ W, while the convective heat loss is $Q_\mathrm{el} = 0.22$ W. On the other hand, maximum convective heat loss is $Q_\mathrm{el} = 0.55$ W, corresponding to $U = 160$ V, while $Q_j = 0$ since $i_\mathrm{c} = 0$ at $U = 160$ V. Therefore, the reduction in convective heat transfer at higher electric field, as observed in the experiment, is due to Joule heating.

5. CONCLUSION

Electroconvective specific heat transfer coefficient (q_el) has been measured in various liquids (methanol, kerosene, silicon oil and ethanol) under the influence of dc and ac fields. An ac field always causes an enhancement in heat transfer coefficient in methanol, kerosene, silicon oil and ethanol. At lower region, a slight inhibition is noted in kerosene and silicon oil. The increase in heat transfer is gradual and no indication of saturation is noted except in ethanol. A dc field always causes an inhibition in heat transfer in methanol. An inhibition in heat transfer is noted in kerosene, but the heat transfer coefficient increases linearly as the field is increased further. An inhibition in heat transfer is also noted in silicon oil, but the heat transfer coefficient increases again with an increase in electric field and then approaches towards a saturation value. In the case of ethanol, a rapid increase in heat transfer is noted as the field is increased. It then reaches a saturation value and then decreases again as the field is increased further. It is to be noted that although ethanol and methanol belonging to the same family, a difference in behaviour of the heat transfer is noted in a dc field. The difference is attributed to Joule heating. It has been observed that the conductivity of the methanol was about four and half times higher than the ethanol. As a result, Joule heating in methanol will be much higher than the ethanol. Hence different results were noted in a dc field.

The electric Nusselt number (Nu_el) for various liquids has been calculated under the influence of ac and dc fields. The Nusselt number for dc field is found to be higher than the ac field. Likewise, the efficiency of electroconvection (γ_el) has been calculated under the influence of ac and dc fields. The efficiency obtained in a dc field is found to be higher than the ac field. The behaviour of Nu_el is also found to be similar to that of γ_el.

The uncertainty of experimental parameters such as current and voltage was within ±1%, while the uncertainty in the heat transfer coefficients were within 5%. The uncertainty in Nu_{el} was 4%, while that of γ_{el} was 3%.

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