Convective Specific Heat Transfer in Gases in Presence of Non-Uniform Electric Field

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Electroconvective specific heat transfer coefficient has been measured in gaseous air, argon, nitrogen, oxygen, freon-12 and freon-22, from a single platinum wire (diameter = 0.025mm) mounted along the axis of a copper cylinder (diameter = 53mm). The measurements have been carried out as a function of electric field and pressure in the earth's gravitational field. The measurements reveal a complicated development of heat convections which appear to be strongly interacting. The heat convection is found to exist over the range of the Nusselt number extending from 74 to 6360. The efficiency of heat convection has been evaluated for various gases using an empirical relation. The efficiency obtained in a DC field is found to be higher than in a AC field. The effect of applied frequency on the efficiency of the process is also studied.

I. Introduction

Natural convection of heat in a fluid often shows itself to be a relatively inefficient means of thermal transfer with many industrial processes using mixed convection or other outside body forces to make flows more turbulent. Therefore, the idea of imposing such constraints on thermal flows has the aim of enhancing mixing and thus heat transfer within the fluid. In particular, the use of electrical forces to this end is referred to as electro-tliermohydrodynamics (ETHD). Work on this subject dates back to the mid-1930s with Senftleben's experiments using gases[1-3] and then those of Ahsmann and Kronig[4] in 1950 on liquids. Senftleben presented an analysis of heat transfer from a heated wire mounted along the axis of a cylinder. An increase in heat transfer coefficient was observed under the influence of a non-uniform electric field. The effect was first discovered by Senftleben and is called the electroconvectional heat transfer and depends on the various transport properties of the fluid as well as the electric field. Senftleben[2] assumed that the enhanced heat transfer in the presence of electric field is due to electrostrictive forces which alters the convection currents. The presence of electric field induces a dipole moment in a spherically symmetric molecule. In the case of a molecule possessing a permanent dipole moment, it will tend to align with the field. Since at constant pressure electric susceptibility is temperature dependent, it turns out that a cold fluid in a non-uniform field would experience more forces than a hot fluid in the same region. As a result, a pressure gradient is developed which forces the cold fluid to replace the hot fluid, thereby generating a circulating current, which is the cause of increased lieat transfer.

Kronig and Schwarts[5] rnade a quantitative interpretation of the above phenomena using the theory of similarity. Subsequently, interpretations were also given by Senftleben and Bultmann[6], Senftleben and Lange-Hahn[7] and more recently by Lykoudis and Yu[8]. The experimental studies of electroconvectional Beat transfer from horizontal cylinders were also dealt with by Ahsman and Kronig[4,9], De Haan[10], Arajs and Legvold[11] and Schnurmann and Lardge[12]. So far, no investigations on quantitative aspects of electroconvectional heat loses have been made using different geometries such as inclined or vertical cylinders. The present work has been undertaken to characterize the heat transfer argumentation in polar (Air, N_2, O_2, Freon-12 and Freon-2) and non-polar (Argon) gases using a simple geometry of a cylindrical container subject to a non-uniform electric field. The convective specific heat transfer coefficient has been investigated under the influence of DC and AC electric fields, with particular choice given to higher field strength and pressures maintained inside the cylinder. The electric Nusselt numbers for various gases were evaluated at constant pressure. Likewise, Nusselt number for various gases were also evaluated as a function of pressure with constant electric field. Additionally, the heat transfer coefficient has been studied with different geometries such as horizontal or vertical cylinders. An attempt has been made to evaluate the efficiency for electroconvection using an empirical relation and the result for air is presented here. The effect of applied frequency on efficiency is also studied.

II. Experimental arrangement

The detailed experimental arrangement used in this investigation has been described elsewhere[13–17]. Refs. 16 and 17 report the recent work carried out by us.

A brief description of the equipment is furnished here. The heat transfer coefficient was determined from a hot wire cell, made of a copper cylinder (diameter = 53mm), with a fine platinum wire (diameter = 0.025 mm) stretched along its axis. This cell was placed into 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 the horizontal orientations. Electric fields in the cell were created by an applied electrical potential (DC or AC) between the body of the cylinder and the central wire which was grounded. The heat transfer coefficient was obtained by calibrating the wire as a platinum resistance thermometer and then measuring the voltage across it and a standard resistor in series with it. The bridge was kept balanced for any experimental situation. The rate of heat transferred is given by

$$Q_{el} = (2II_{el} + I_{el}^2)R \ , \tag{1}$$

where I is the current flowing through the wire in the absence of any electric field and I_{el} is the current necessary to keep the bridge balanced in the presence of any electric field.

The convective specific heat transfer coefficient is obtained using the relation

$$q_{el} = \frac{Q_{ei}}{A} \ , \tag{2}$$

and the convective heat transfer coefficient is given by

$$h_{el} = \frac{Q_{el}}{AT_d} \ , \tag{3}$$

where A is the surface area of the wire and T_d is the temperature difference between the wire and the surrounding medium.

The frequency dependence of the electroconvective heat transfer was carried out by connecting the input of an audio oscillator to a solid-state amplifier, the output of which was connected to a high-voltage transformer through a step-up transformer. The output of the high-voltage transformer was directly applied to the body of the cylinder. The frequency was varied from 20 Hz to 1000 Hz and measurements made accordingly.

III. Results

The results of the electroconvective specific heat transfer coefficient obtained under difference pressure conditions are illustrated in Fig. 1(a) to Fig.1(f). The results of the AC and DC fields are also shown in the same plot. As seen in the figures, an absence of convection is observed for electric field less than the critical electric field. The critical electric field is found to depend on the various transport properties of the fluid (such as thermal conductivity, the electric dipole moment, the molecular weight, the viscosity and the polarizability of the fluid) as well as the pressure maintained inside the cylinder. When the applied electric field is greater than the critical electric field, the heat transfer coefficient increases gradually, reaches a saturation value and then decreases as the field is further increased. In some cases, the heat transfer coefficient reduces to zero and becomes negative as may be seen in Figs. 1(a), (c), (d) and (e). In most of the cases, a Gaussian distribution of heat transfer profile is observed under the influence of AC and DC fields.

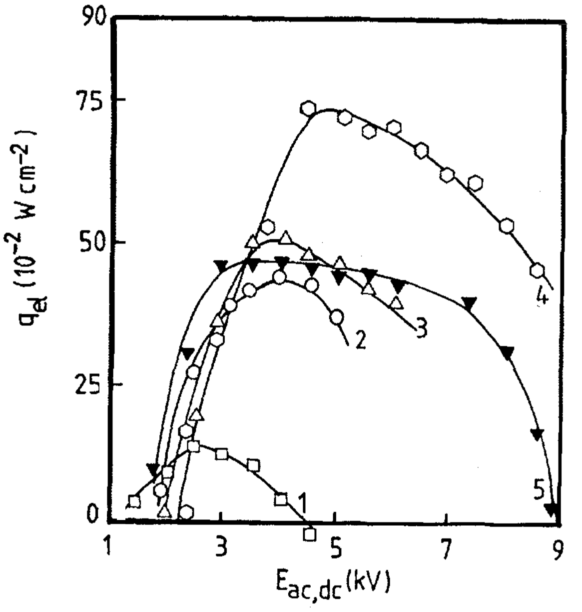

Figure 1a: Electroconvective specific heat transfer in gases as a function of AC and DC field in vertical cylinder.

(a) - AIR: 1. DC field, T_d = 10.0°C, p = 29.7 cm Hg; 2. DC field, T_d = 9.17°C, p = 41.8 cm Hg; 3. DC field, T_d = 9.0°C, p = 49.4 cm Hg; 4. DC field, T_d = 8.23°C, p = 76 cm Hg; 5. AC field, T_d = 7.17°C, *p* = 76 cm Hg.

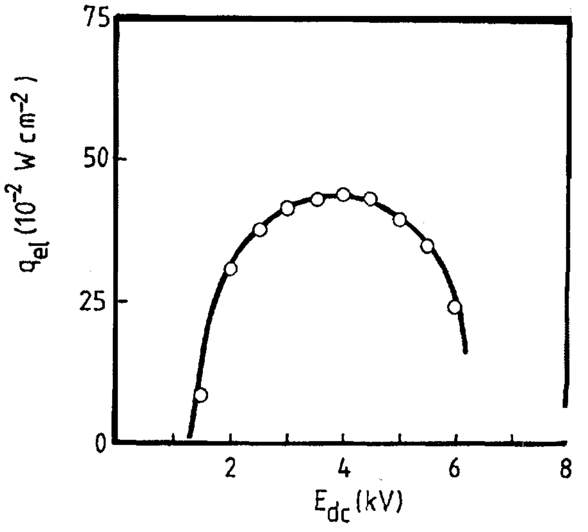

Figure 1b: Electroconvective specific heat transfer in gases as a function of AC and DC field in vertical cylinder. ARGON: 1. DC field, T_d = 9.74°C, p = 73.5 cm Hg.

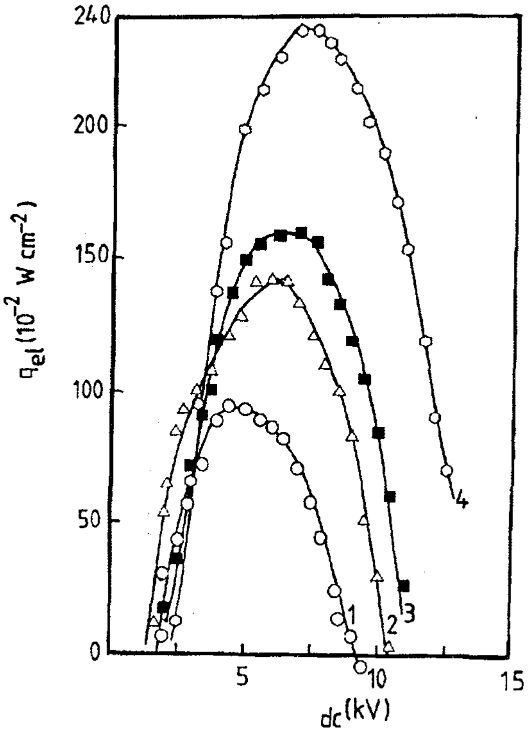

Figure 1c: Electroconvective specific heat transfer in gases as a function of AC and DC field in vertical cylinder. OXYGEN: 1. DC field, T_d = 4.17°C, p =42 cm Hg; 2. AC field, T_d = 4.0°C, p = 54 cm Hg; **3.** DC field, T_d = 4.0°C, p = 54 cm Hg; 4. DC field, T_d = 4.1°C, p = 69 cm Hg.

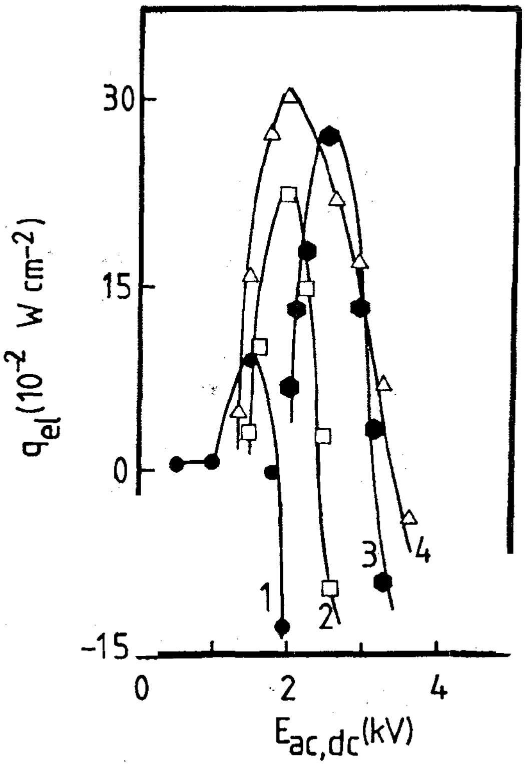

Figure 1d: Electroconvective specific heat transfer in gases as a function of AC and DC field in vertical cylinder. NITROGEN: 1. DC field, T_d = 6.0°C, *p* = 26.1 cm Hg; 2. DC field, T_d = 6.0°C, p = *36* cm Hg; **3.** DC field, T_d = 5.0°C, p = 50 cm Hg; 4. AC field, T_d = 5.0°C, p = 50 cm Hg.

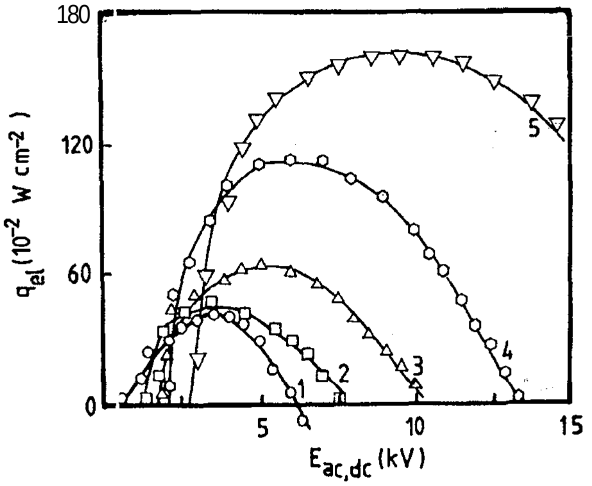

Figure 1e: Electroconvective specific heat transfer **in** gases as a function of AC and DC field in vertical cylinder. FREON-12: 1. AC field, T_d = 11.03°C, p = 15.7 cm Hg; 2. DC field, T_d = 13.40°C, p = 15.7 cm Hg; 3. AC field, T_d = 16.08°C, p = 29.4 cm Hg; 4. DC field, T_d = 14.41°C, p = 29.4 cm Hg; 5. DC field, T_d = 22.54°C, p = 40 cm Hg.

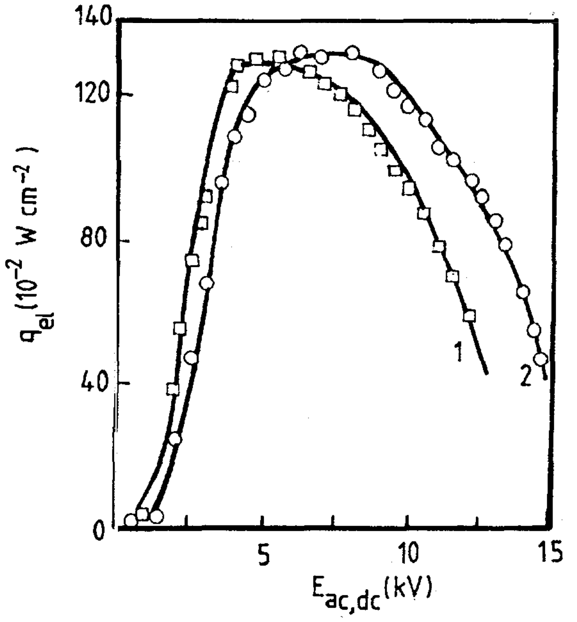

Figure 1f: **Electroconvective** specific heat transfer in gases as a function of AC and DC field in vertical cylinder. FREON-22: 1 AC field, T_d = 8.51°C, p = 34.1 cm Hg; 2. DC field, T_d = 8.05°C, p = 34.9 cm Hg.

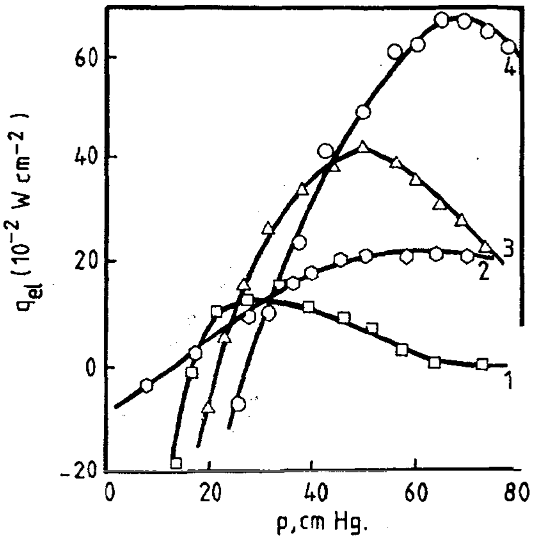

Figure 2a: Electroconvective specific heat transfer in gases as a function of AC and DC field in (vertical cylinder). AIR: 1. E=2.0 kV dc, T_d = 9.56°C; 2. E=3.0 kV dc, T_d = 9.63°C; 3. E=4.0 kV dc, T_d = 9.17°C; 4. E=2.0 kV dc, T_d = 9.38°C.

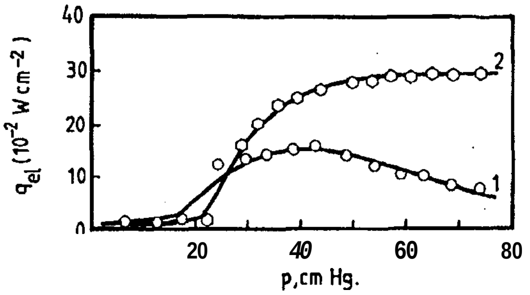

Figure 2b: Electroconvective specific heat transfer in gases as a function of AC and DC field in (vertical cylinder). (b) - ARGON: 1. E=1.0 kV dc, T_d = 10.84°C; 2. E=2.0 kV dc, T_d = 10.81°C.

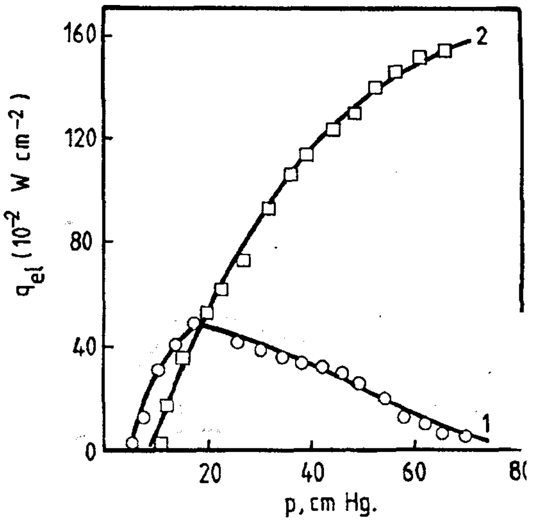

Figure 2c: Electroconvective specific heat transfer in gases as a function of AC and DC field in (vertical cylinder). OXYGEN: 1. E=2.0 kV dc, T_d = 10.0°C; 2. E=3.0 kV dc, T_d = 10.2°C.

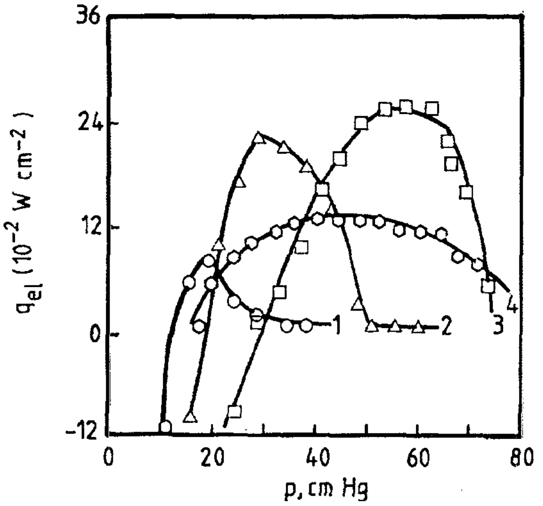

Figure 2d: Electroconvective specific heat transfer in gases as a function of AC and DC field in (vertical cylinder). NITROGEN: 1. E=1.0 kV dc, T_d = 7.0°C; 2. E=1.5 kV dc, T_d = 6.17°C; 3. E=2.0 kV dc, T_d = 7.0°C; 4. E=1.5 kV dc, T_d = 6.17°C.

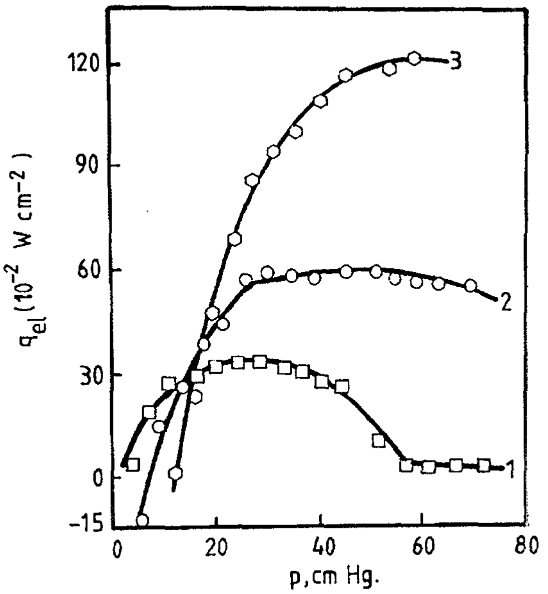

Figure 2e: Electroconvective specific heat transfer in gases as a function of AC and DC field in (vertical cylinder). FREON-12: 1. E=3.0 kV dc, T_d = 18.70°C; 2. E=4.0 kV dc, T_d = 17.15°C; 3. E=7.0 kV dc, T_d = 17.64°C.

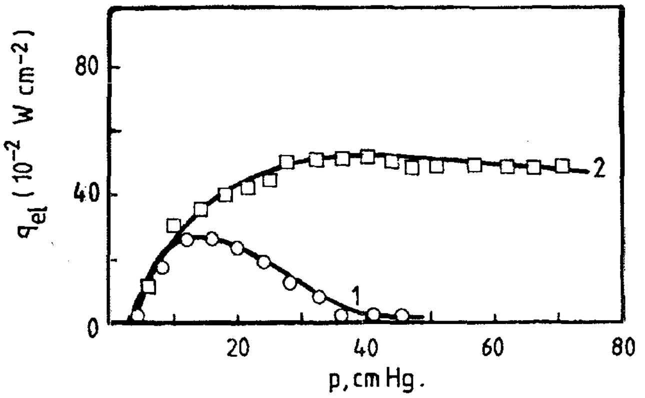

Figure 2f: Electroconvective specific heat transfer in gases as a function of AC and DC field in (vertical cylinder). FREON-22: 1. E=2.0 kV dc, T_d = 19.26°C; 2. E=3.0 kV dc, T_d = 20.11°C.

The results of the electroconvective specific heat transfer coefficient obtained under different electric field conditions are presented in Figs. 2a-f. At low gas pressure, a negative value of heat transfer coefficient is observed in most of the cases, implying a suppression of the free convection by electroconvection. As the pressure is increased gradually, the convective heat transfer coefficient increases, reaches a saturation value and then decreases on further increase in pressure. At higher pressure, the convective heat transfer coefficient disappears completely, as may be seen in Fig. 2a (curves 1,2), Fig. 2c (curves 1,2), Fig. 2d (curve I), Fig. 2e (curves 1,2) and Fig. 2f (curve 1).

In Table I, the electric Nusselt numbers for different gases are shown under different pressure conditions, while Table II presents the results obtained under different electric field conditions. The efficiency for electroconvection of air is presented in Table III, while Table IV represents the result for argon at different applied frequency.

IV. Discussion

On a more fundamental level, we may distinguish between three types of electrical force acting on a fluid once a voltage difference is aplied across it: the Coulomb or the electrophoretic force

$$F_e = qE \,, \tag{4}$$

TABLE I. Nusselt number of various gases as a function of electric field in a vertical cylinder. Air: p=76 cm Hg, T_f = 28°C; Argon: p=73.5 cm Hg, T_f = 29°C; Oxygen: p=54 cm Hg, T_f = 28°C; Nitrogen: p=50 cm Hg, T_f = 27°C; Freon-12: p=29.4 cm Hg, T_f = 30°C; Freon-22: p=24.2 cm Hg, T_f = 28°C

E_s(V/cm) 10^5(DC)	AIR p=76 cm Hg	ARGON p=73.5 cm Hg	OXYGEN p=42 cm Hg	NITROGEN p=50 cm Hg	FREON-12 p=29.4 cm Hg	FREON-22 p=24.2 cm Hg
	Nu_{el}	Nu_{el}	Nu_{el}	Nu_{el}	Nu_{el}	Nu_{el}
0.52	0	0	0	0	0	0
1.04	0	0	0	0	0	0
1.56	0	238	0	608	139	0
2.08	0	921	636	1014	445	1576
2.60	336	1114	1391	912	1613	1936
3.12	691	1233	2783	557	2504	2386
3.64	834	1248	3578	101	3116	2723
4.16	1058	1278	4770	0	3784	2996
4.68	1474	1278	5367	-	3979	3196
5.20	1434	1174	5963	-	4174	3286
5.76	1403	1040	6162	-	4257	3376
6.24	1424	713	6281	-	4257	3511
6.76	1352		6360	-	4285	3601
7.28	1271	-	6360	-	4257	3601
7.80	1261		6181	-	4035	3601
8.32	1078		5963	-	3896	3623
8.84	915	-	5367	-	3617	3665
9.36	-	-	4770	-	3562	3669
9.88			4174	-	3478	3669
10.40			3379	-	3089	3665
10.92	-	-	2385	-	2643	3601
11.44			1073	-	2365	3421
11.96			0		1809	3241
12.48	-	-			1391	3061
13.00	-	-			1113	2926
13.52			-		139	-
					139	-

TABLE II. Nusselt number of various gases as a function of pressure in a vertical cylinder. DC field. Air: $E_{DC} = 3.12 \times 10^5$(V/cm), $T_f = 28°C$; Argon:$E_{DC} = 2.08 \times 10^5$(V/cm), $T_f = 28.5°C$; Oxygen: $E_{DC} = 3.12 \times 10^5$(V/cm), $T_f = 27.5°C$; Nitrogen: $E_{DC} = 2.08 \times 10^5$(V/cm), $T_f = 27.5°C$; Freon-12: $E_{DC} = 3.12 \times 10^5$(V/cm), $T_f = 31.0°C$; Freon-22: $E_{DC} = 3.12 \times 10^5$(V/cm), $T_f = 31.0°C$.

	AIR $E_s = 3.12 \times 10^5$ (V/cm)	ARGON $E_s = 2.08 \times 10^5$ (V/cm)	OXYGEN $E_s = 2.08 \times 10^5$ (V/cm)	NITROGEN $E_s = 3.12 \times 10^5$ (V/cm)	FREON-12 $E_s = 3.12 \times 10^5$ (V/cm)	FREON-22 $E_s = 3.12 \times 10^5$ (V/cm)
p(cm Hg)	Nu_{el}	Nu_{el}	Nu_{el}	Nu_{el}	Nu_{el}	Nu_{el}
5	-		-	-	-	0
7.5	-	-	-	-	0	450
10	-	-	-	0	557	675
12.5	-	-	-	338	863	720
15	-		-	596	1113	787
17.5	-	-	-	795	1391	923
20	0	0	-	994	1614	990
22.5	104	74	-	1193	1809	1035
25	203	223	-	1371	1976	1103
27.5	356	371	-	1550	2059	1125
30	458	446	0	1690	2115	1148
32.5	559	594	152	1888	2143	1170
35	610	669	253	2087	2115	1170
37.5	661	713	355	2186	2087	1170
40	732	743	507	2286	2115	1170
42.5	763	802	578	2425	2143	1148
45	813	817	659	2485	2115	1125
47.5	854	832	760	2624	2170	1125
50	864	847	821	2703	2170	1103
52.5	844	862	862	2787	2115	1103
55	793	877	862	2882	2143	1103
57.5	762	877	862	2942	2115	1103
60	712	891	841	3021	2115	1080
62.5	661	891	811	3061	2087	1058
65.0	610	891	730	3081	2087	1058
67.5	559	891	659	3140	2087	1058
70	508	891	507	3180	2031	1080
72.5	458	-	[illegible]		2003	-

TABLE III. The efficiency of electroconvection in air in a horizontal and vertical cylinder under influence of DC and **AC** field. $T_d = 9.0°C$, p = 76 cm Hg.

E(V/cm)10^5	γ_{DC} (%)	γ_{AC} (%)	γ_{DC} (%)
	V.C	V.C	H.C
0.52	0	0	0
1.04	0	0	0
1.56	0	0	0
2.08	0	23	0
2.60	17	35	13
3.12	39	43	22
3.64	49	43	37
4.16	56	42	46
4.68	58	42	47
5.20	59	42	48
5.72	58	41	46
6.24	58	40	45
6.76	57	40	41
7.28	56	40	40
7.80	53	40	36
8.32	51	33	34
8.84	48	21	27
9.36	-	2	-

TABLE IV. The efficiency of electroconvection in argon in a vertical cylinder under influence of AC field of various frequencies. $T_d = 9.66°C$, p = 73.5 cm Hg, E = 3.12 x 10^5V.

E(V/cm)10^5	Freq (Hz)	y (%)
3.12	40	45
	70	44
	100	43
	200	40
	400	38
	600	39
	800	38

where q is the charge density and E is the electric field intensity; the dielectric force

$$F_d = -(E^2/2)\nabla\epsilon \ , \qquad (5)$$

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

$$F_e = \nabla[(E^2/2)(\delta\epsilon/\delta\rho)] \ , \qquad (6)$$

where ρ is the fluid density. It is usual to include the electrostrictive term with the pressure. Thus the dominant body force in the gases arises from the electrophoretic force and the electrostrictive force.

In EHD 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 a DC system assumes the form

$$j = qbE + qu + D_c\nabla q \ , \qquad (7)$$

where, except in ultra-pure liquids in which free electrons may occur, charge carriers are thought to exist as positive or negative ions[18,19]. 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. D_c is the ion diffusion coefficient and except in regions very close to the electrons ($u \rightarrow 0$) the diffusion term is small compared with the 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 only on individual ions which then transfer momentum to surrounding molecules as they are driven through the host medium.

In Fig. 1, convective specific heat transfer coefficient for various gases are plotted as a function of electric field. At very low field strength, the induced dipole moment is small, resulting in the weak electrophoretic force and hence no convection is observed. As the field is increased gradually, dipolar interaction increases and this in turn increases the electrophoretic force and hence enhances the convection. In the saturation region, an energy balance is obtained due to Joule heating which developes gradually as the field is increased and is responsible for the reduction of heat transfer as observed in each case. The electric field intensity inside the cylinder is estimated as

$$E_r = (0.13/r)E(Vcm)\ , \tag{8}$$

where r is the radial distance from the centre of the wire and E is the voltage applied to the cylinder. The maximum conduction current following through the cylinder of maximum electric field strength and pressure was recorded as 100, 190, 200, 300, 200 and 150 μA for air, argon N_2, O_2, Freon-12 and Freon-22, respectively. An estimate of Joule heating near the immediate vicinity of the platinum wire gives a very significant figure, implying the fact that Joule heating is responsible for the reduction of heat transfer as observed in the experiment.

Figs. 2a-f show the results of the electroconvective specific heat transfer coefficient for air, argon, nitrogen, oxygen, Freon-12 and Freon-22, plotted as a function of pressure with a fixed electric field. The enhancement in heat transfer coefficient observed in each case is the dominance of the electrophoretic force over the electrostrictive force. In the saturation region, electrophoretic force is balanced by the electrostrictive force, while the reduction in heat transfer coefficient is due to the dominance of the electrostrictive force over the electrophoretic force. As the pressure is increased, electrostrictive force also increases and this in turn reduces the r.m.s. velocity of the convection. At elevated pressure, the r.m.s. velocity of the convection disappears completely, leading to a zero value of heat transfer coefficient as observed in several cases.

In Table I, the electric Nusselt number for various gases has been calculated using the relation

$$Nu_{el} = \frac{h_{el}D}{K}\ , \tag{9}$$

where h_{el} is the electroconvective heat transfer coefficient, D is the diameter of the cylinder and K is the thermal conductivity of the fluid and the values were taken from Ref. 20. The fluid properties were evaluated at the film temperature given by

$$T_f = \frac{T_\omega + T_\infty}{2}\ , \tag{10}$$

where T_ω is the temperature of the wire and T_∞ is the temperature of the surrounding medium. As seen in that Table for any particular case, the Nusselt number increases with an increase in electric field, reaches a maximum value and then decreases as the field is further increased and becomes zero as may be seen in oxygen and nitrogen. A zero value of Nusselt number implies absence of electroconvection, while a positive value implies that the heat flows from the wire to the surrounding medium. In Table II, the Nusselt number has been plotted for various gases as a function of pressure, while the electric field was kept constant. Again, the electric Nusselt number increases with an increase in pressure, reaches a maximum value and then decreases, as may be seen in air, nitrogen, Feon-12 and Freon-22.

The efficiency for electro-convection has been calculated using the relation

$$\gamma_{el} = \frac{h_{el}}{h_{el} + h_f}\ , \tag{11}$$

where h_{el} is the electroconvective heat transfer coefficient and h_f is the free convective heat transfer coefficient. The result for air is presented in Table III, where the efficiency for convection has been calculated as a function of AC and DC fields. The general trend observed in this case is found to be exactly similar to that obtained for the electric Nusselt number (Table I). However, the efficiency obtained in a DC field is found to be higher than the AC field. Likewise, the efficiency obtained in a vertical cylinder is found to be higher than the horizontal cylinder. The efficiency for electroconvection for argon is shown in Table IV, where the efficiency has been calculated as a function of the frequency of the applied electric field. As seen in the tables, the efficiency decreases gradually as the frequency is increased and reaches a stationary value.

V. Conclusion

The electroconvective specific heat transfer coefficient has been measured in polar and nonpolar gases. The enhancement in heat transfer coefficient in polar gases is found to be higher than the non-polar gases. Similarly, the enhancement in heat transfer coefficient in a DC field is found to be higher than the AC field. The enhancement in heat transfer coefficient with an increase in electric field is due to the increase in electrophoretic force, while the reduction in heat transfer coefficient is attributed to Joule heating. Likewise, the enhancement of heat transfer coefficient with an increase in pressure is due to the dominance of the electrophoretic force over the electrostrictive force, while the reduction in heat transfer coefficient is due to the reduction in r.m.s. velocity of the convection.

The Nusselt number for various gases is found to increase with an increase in elecric field, reach a maximum value and then decrease as the field is further increased. Similar effect is also noticed when the pressure of the gas is increased. The efficiency for electroconvection is found to increase with an increase in electric field. At higher electric field, efficiency reaches its maximum value and then decreases as the field is further increased. Efficiency obtained in a DC field is found to be higher than in the AC field. Similarly, the efficiency obtained in a vertical cylinder is found to be higher than in the horizontal cylinder, but a decrease in efficiency is noticed when the frequency of the applied field is increased.

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