EFFECT OF THE ELECTRIC FIELD FREQUENCY ON HEAT EXCHANGE IN FREE CONVECTION

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The effect of the electric field frequency on intensification of free-convection heat exchange is investigated.

Systematic investigations of heat exchange in an electric field have been in progress during the past few decades. Most of the researchers were interested in the intensifying effect of the field strength, which reached 20 MV/m or more [1], on the heat exchange, while the effect of the frequency on natural convection was not investigated. The present article represents a continuation of the series of investigations in progress at the A. M. Kirov Kazan Chemical Engineering Institute concerning the effect of electromagnetic fields on heat exchange and the thermophysical characteristics of materials in a wide frequency range.

The following coolants were used: acetone, methyl ethyl ketone, n-propyl alcohol, chlorobenzene, and benzene, whose basic thermal and electrophysical characteristics differ considerably from each other, while they are widely used in chemical technology. A horizontal steel tube with a length of 260 mm and an outside diameter of 5 mm, heated by dc current, provided the heat-exchange surface. An electric field was created between this tube and a coaxial solid cylinder with a diameter of 130 mm. The quantities measured in the experiments were the temperatures of the liquid and of the heat-exchange tube, the electric power released by the tube, and the frequency and the potential difference between the electrodes. The field strength at the tube surface was calculated by using the well-known expression for coaxial cylinders.

Processing of the results of experiments performed without an electric field has shown that the experimental data are described by I. N. Mikheeva's well-known equation [2].

Experiments where an alternating electric field was applied were performed in the 0.01-100 Hz range. A sinusoidal voltage source was used at frequencies of 5-100 Hz, and a bipolar square pulsed voltage source was used at frequencies below 5 Hz. The experiments were performed at both increasing and decreasing field frequencies.

No effect of the electric field was observed in experiments with a nonpolar liquid (benzene) for E = 0-200 kV/m.

Figure 1 shows the experimental results for polar liquids and $q = 10\ kW/m^2$ and $t_l = 20°C$. A sharp increase in the heat-transfer coefficient, by a factor of 1.5-5, was observed at certain frequencies. The heat-transfer coefficient increases with the field strength at all frequencies, while the peak values of α_E/α_0 are shifted to the region of high frequencies. It is noteworthy that, within frequency ranges where peak values of α_E/α_0 are reached, the electric field intensifies the heat exchange even when the field effect does not manifest itself at other frequencies due to low strength. Thus, in the case of acetone and methyl ethyl ketone, for E = 37 kV/m, the relative heat-transfer coefficient increases markedly at frequencies from 0.1 to 1.0 Hz, while the field effect is absent at frequencies above 5 Hz.

In the opinion of many authors, the main cause of the intensifying effect of an electric field of moderate strength and low frequency is the development of electroconvection, which is caused by ponderomotive forces. We have, therefore, estimated the ponderomotive forces acting in the thermal boundary layer. We have analyzed each term in the equation of ponderomotive forces given in [3] in application to our experimental conditions.

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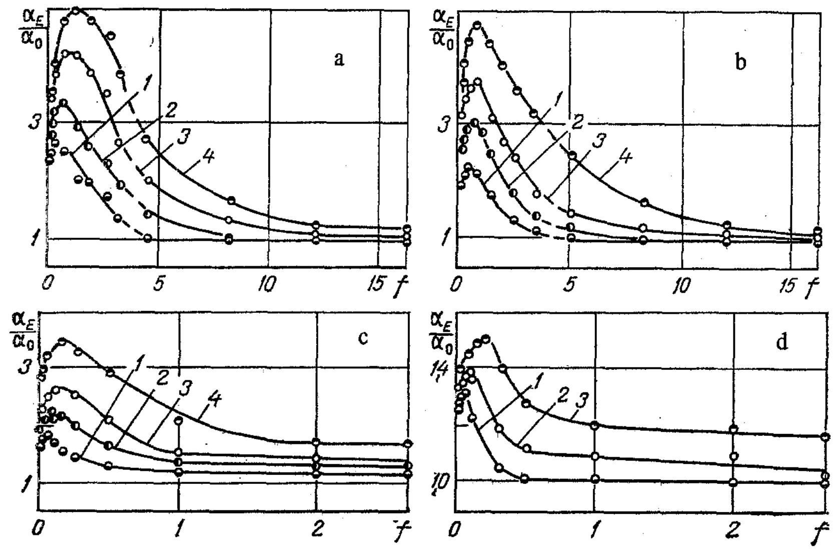

Fig. 1. Relative heat-transfer coefficient as a function of the electric field frequency f (Hz). a) Acetone; b) methyl ethyl ketone; c) n-propyl alcohol; d) chlorobenzene. a, b: 1) E = 37 kV/m, 2) 49, 3) 61, 4) 74; c: 1) E = 61 kV/m, 2) 74, 3) 86, 4) 110; d: 1) E = 98 kV/m, 2) 123, 3) 147.

There are different opinions about how to account for the $\rho_e E$ component. As was done in [1], we also calculated the product $\omega\tau_r$. For acetone, methyl ethyl ketone, n-propyl alcohol, and chlorobenzene,

$$\omega\tau_r \ll 1, \tag{1}$$

while for benzene

$$\omega\tau_r \gg 1 \tag{2}$$

throughout the investigated frequency range. Therefore, in accordance with [1], $\rho_e E$ should be taken into account for the polar liquids which we used, while for benzene this component is negligibly small. Since relationship (1) holds, the Coulomb force is independent of the field frequency and can be determined by means of the equation [1]

$$\vec{F}_c = -\varepsilon_0\varepsilon(\beta_\varepsilon + \beta_\sigma)\vec{E}(\vec{E}\,\mathrm{grad}\,T). \tag{3}$$

The second and the third terms of $\vec{F}_E$ are estimated by means of the relationships [1, 4]

$$\vec{F}_\varepsilon = \frac{1}{2}\varepsilon_0\varepsilon\beta_\varepsilon E^2\,\mathrm{grad}\,T, \tag{4}$$

$$\vec{F}_{str} = -\frac{1}{2}\varepsilon_0 E^2\rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)\left[\frac{2}{\varepsilon-1}\left(\frac{\partial\varepsilon}{\partial T}\right)+\beta\right]\mathrm{grad}\,T. \tag{5}$$

The coefficient β_σ was calculated on the basis of our measurements of the electrical conductivity of liquids at different temperatures, while the values of $\partial\varepsilon/\partial T$ and β_ε were determined by using the data from [5].

The forces considered here that act on a liquid in the boundary layer are proportional to the square of the field strength. In an alternating electric field, they pulsate at double the field frequency, since

$$E^2(\tau) = E_m^2\sin\omega\tau = \frac{1}{2}E_m^2(1-\cos\omega\tau), \tag{6}$$

while their mean value, averaged over a period, remains constant. The polarization $\vec{F}_\varepsilon$ and the striction $\vec{F}_{str}$ components of ponderomotive forces have a direction coinciding with the temperature gradient, while the direction of the Coulomb component is opposite to this

TABLE 1. Ratios of Forces and of Heat-Transfer Coefficients for Different Electric Field Strengths

Liquid	E, kV/m	F_E/F_0	$\alpha_{E\,\max}/\alpha_0$
Acetone	37	0,5	2,6
	49	0,9	3,3
	61	1,4	4,3
	74	2,1	5,0
Methyl ethyl ketone	37	0,6	2,5
	49	1,1	3,1
	61	1,7	3,6
	74	2,5	4,7
n-Propyl alcohol	61	1,6	1,8
	74	2,4	2,2
	86	3,3	2,6
	110	5,4	3,5
Chlorobenzene	74	0,2	1,1
	98	0,3	1,3
	123	0,5	1,4
	147	0,8	1,5
Benzene	74	0,01	1,0
	123	0,03	1,0
	147	0,04	1,0

TABLE 2. Calculated and Measured Frequencies (Hz)

Liquid	f_0	$f_{E\max}$	$f_{F\max}$
Acetone	2,6	0,3—1,0	0,6—2,0
Methyl ethyl ketone	2,3	0,2—0,5	0,1—1,0
n-Propyl alcohol	1,1	0,05—0,15	0,1—0,3
Chlorobenzene	1,9	0,05—0,23	0,1—0,46

gradient. The value of F_E is compared to Archimedes' force F_0 (Table 1) in order to estimate the effect of ponderomotive forces on the convection mechanism.

It is evident from Table 1 that the value of F_E is of the same order as the buoyancy in polar liquids, while it is much smaller (by one to two orders of magnitude) for benzene. This may have been the reason why the effect of an electric field on heat exchange was not observed in experiments with benzene.

According to the opinion expressed in [1], the sharp increase in the heat-transfer coefficient at certain frequencies occurs due to resonance vibrations of the heat-releasing wire. In connection with this, we estimated the natural oscillation frequency of the heat-releasing tube. It was equal to 370 Hz in an air ambient. Thus, the natural oscillation frequency of the tube lies outside our range of electric field frequencies and exceeds by a factor of three to four orders of magnitude the frequencies at which peak values of the heat-transfer coefficient are observed. Therefore, we can neglect the effect of tube vibrations on the heat exchange.

In order to broaden our concepts regarding the causes of the sharp increase in α_E at certain electric field frequencies, we estimated the characteristic vibration frequency f_0 of the liquid in the boundary layer in the absence of a field. As was shown by Gebhart and others [6, 7], as external disturbances act on the boundary layer, they are amplified at certain frequencies, and damped at other. The frequency at which the greatest amplification occurs has been referred to as the characteristic frequency in [7]. The results of calculations of the characteristic frequency based on the relationship [7]

$$f_0 = \frac{0.315\,\mathrm{Pr}^{-0.065}}{2\pi}\sqrt[3]{\frac{(g\beta\Delta T)^2}{\nu}} \qquad (7)$$

are given in Table 2. This table also provides the field frequency $f_{E\,\max}$ at which peak values of α_E are observed and the ponderomotive force pulsation frequency $f_{F\,\max}$, which is equal to double the $f_{E\,\max}$ value.

The frequencies $f_{F\,max}$ at which peak values of the heat-transfer coefficient are observed are close to the liquid vibration frequencies in the boundary layer in the absence of a field. Moreover, the relationships $\alpha_E/\alpha_0 = \varphi(f)$ have the form of resonance curves. This suggests that the sharp increase in α_E occurs as a result of resonance phenomena, when the vibration frequency of the forces is close to the characteristic frequency. A certain discrepancy between these frequencies is probably due to the fact that, as was mentioned by Gebhart [7], amplification of disturbances in the boundary layer occurs in a certain frequency range, rather than at a single frequency. Moreover, the characteristic frequency was calculated by using an approximate relationship.

The use of resonance phenomena for heat exchange intensification ensures maximum effectiveness for minimal power consumption and a low electric field strength.

NOTATION

E, electric field strength (V/m); F, force density (N/m^3); f, frequency (Hz); g, acceleration due to gravity (m/sec^2); q, thermal flux density (W/m^2); T, temperature (°K); α, heat-transfer coefficient ($W/m^2 \cdot K$); β, thermal dilation ($°K^{-1}$); β_e and β_σ, thermal coefficient of permittivity and thermal coefficient of electrical conductivity, respectively ($°K^{-1}$); ε, relative permittivity; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ (F/m), electric constant; ν, kinematic viscosity coefficient (m^2/sec); ρ, density (kg/m^3); ρ_e, electric charge density (C/m^3); τ, time (sec); $\tau_r = \varepsilon_0\varepsilon/\sigma$, electric relaxation time (sec); ω, angular frequency, (sec^{-1}). The subscripts pertain to the following: 0, quantities in the absence of an electric field; E, quantities in an electric field; m, amplitude values of a quantity; max, peak values of a quantity.

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