HEAT TRANSFER IN FORCED CONVECTION IN HIGH-FREQUENCY ELECTROMAGNETIC FIELDS

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The effect of electromagnetic fields of frequency $3.85 \cdot 10^5$ and $6.66 \cdot 10^5$ Hz on heat transfer was investigated. The effect of the field depends on its strength and the fluid flow regime.

In plant for induction hardening, soldering, smelting, and ultrasonic treatment of metals and in some chemical technology processes, heat transfer takes place in conditions complicated by the effect of electromagnetic fields with frequency from hundreds of Hz to tens of hundreds of kHz. The circuits of powerful radio-receiving and transmitting stations and high-frequency plasma generators also require continuous cooling. In heat calculations for the various parts of such equipment the effect of the field on the heat transfer is usually ignored. This is due to the fact that the effect of high-frequency electromagnetic fields on heat transfer has received little study so far. It has been established, however, that heat transfer in low-frequency constant and alternating electric fields is more intense than in ordinary conditions.

Experimental investigations of the effect of high-frequency electromagnetic fields on various kinds of heat transfer have been carried out in the laboratories of the Heat Engineering Department of the Kazan Chemical Technology Institute. An appreciable intensification of heat transfer in the case of boiling [1] and natural convection [2] in an electromagnetic field of frequency $6.5 \cdot 10^5$ Hz was discovered. The field effect was found to depend on the field strength and the properties of the liquid.

In the present work the effect of high-frequency electromagnetic fields of $3.85 \cdot 10^5$ and $6.66 \cdot 10^5$ Hz on heat transfer accompanying forced convection of distilled water in an annular gap was investigated for the first time. Water was selected as the working medium because the greatest intensification of heat transfer in boiling and natural convection in an electromagnetic field of frequency $6.5 \cdot 10^5$ Hz was observed when water was used. In addition, water is widely used as a coolant in engineering.

TABLE 1. Experimental Conditions

No. of expt.	$q \cdot 10^{-3}$, W/m^2	U, V	E_z, V/m	E_n, V/m	H_φ, A/m	Material of heat-emitting tube
1	46,3	80,5	5,7	470	11567	Brass
2	32,0	66,0	4,8	383	9630	
3	26,2	60,0	4,3	348	8716	
4	12,9	42,0	3,0	242	6079	
5	9,8	36,0	2,6	207	5326	
6	21,6	79,0	2,7	460	11628	Copper
7	16,1	69,5	2,3	407	10046	
8	49,2	83,0	5,9	482	11944	Brass
9	46,9	81,0	5,8	470	11673	
10	34,9	69,5	5,0	407	10060	
11	33,0	67,5	4,8	395	9792	
12	21,6	79,0	2,7	460	11628	Copper
13	16,4	70,0	2,3	407	10125	

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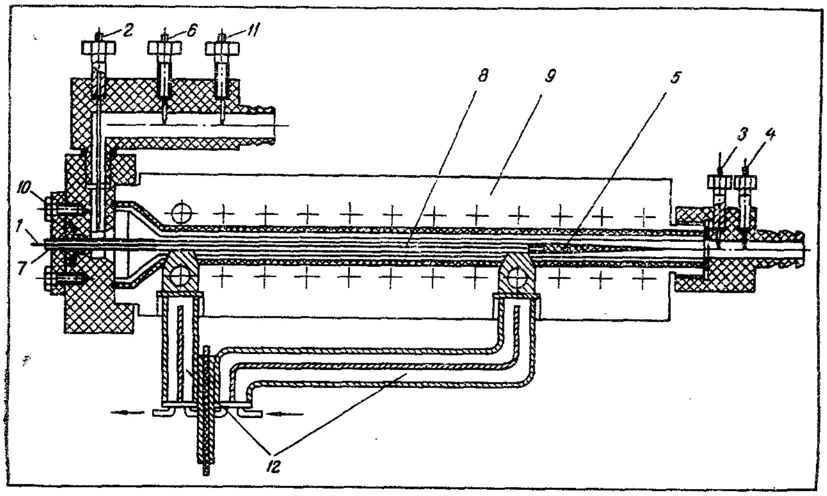

Fig. 1. Diagram of test assembly: 1-4, 6, 11) Chromel–Copel thermocouples; 5) nosepiece; 7) cylindrical textolite tube; 8) heat-emitting tube; 9) textolite housing; 10) end sealing cap; 12) current supply bars.

The test section (Fig. 1) was an annular channel formed by a heating tube and the cylindrical surface of a textolite housing. To exclude the effect of extraneous fields on the investigated process, the current supply bars and the conductors of the measuring circuit and the section were enclosed, separately and as a whole, in grounded electromagnetic screens. For the same purpose the nonconducting parts of the assembly were made of stable dielectric materials.

As a heating surface we used seamless copper and brass tubes 260 mm long with external diameter 5.91 mm, which were rigidly attached along the axis of the test assembly.

The electromagnetic field around the heat-emitting tube and its heating were produced by the passage of high-frequency current through it from a standard LZ-13 vacuum-tube oscillator. Owing to the skin effect the heat was produced in a thin surface layer of the heater, determined by the depth of penetration of the current.

This method of heating ensured uniformity of the temperature within the tube and on its surface. Hence, for the temperature of the heating surface in the calculations we used the temperature within the tube, averaged over its length.

The temperatures of the tube and water were measured with Chromel–Copel thermocouples 1, 2, 3, 4, 6, and 11, two of which (2 and 3) (Fig. 1) were connected up in a differential arrangement.

The heat-transfer coefficient was calculated from the equation

$$\alpha_{\text{hf}} = \frac{q}{\Delta t_{\text{av}}}, \tag{1}$$

where Δt_{av} is the average logarithmic difference of temperatures of the wall and flow of water. The heat flux density was determined as

TABLE 2. Experimental Conditions

No. of experiment	$q \cdot 10^{-3}$, W/m^2	t_L, °C	Material of heat-emitting tube
1	46,3	20	Brass
2	21,6	20	Copper
3	46,9	40	Brass
4	21,6	40	Copper
5	19,3	20	Brass
6	18,8	20	Copper
7	29,4	40	Brass
8	33,4	40	Copper

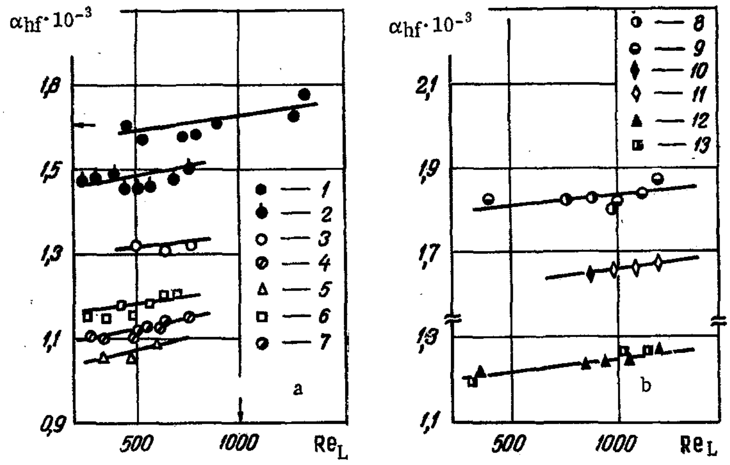

Fig. 2. Heat-transfer coefficient in high-frequency field α_{hf}(W/m$^2\cdot$deg) as function of Re_L. Experimental conditions given in Table 1: a) f = 3.85 · 10^5 Hz, t_L = 20°C; b) f = 3.85 · 10^5 Hz, t_L = 40°C. Arrow denotes change of scale.

$$q = \frac{c_p G \Delt t_L}{\pi d l}. \tag{2}$$

To check the value of q we carried out additional experiments by the method described in [1]. To assess the effect of the high-frequency electromagnetic field on the heat transfer we carried out experiments in which the tubes were heated by current of industrial frequency 50 Hz (ordinary heating).

From an analysis of the results obtained in the case of laminar flow of the liquid and ordinary heating, we were able to represent them by means of the dimensionless relation

$$Nu_L = 0.22 Re_L^{0.33} Pr_L^{0.43} Gr_L^{0.1} \left(\frac{Pr_L}{Pr_w}\right)^{0.25}, \tag{3}$$

which differs from the known equation [3] only in the numerical factor in front of Re_L. The probable reason for this difference is that in the path of the water entering the annular gap there were a current supply bar and a nosepiece, which distorted the flow velocity field to some extent.

A comparison of the obtained heat-transfer coefficients in a high-frequency field with the values calculated from (3) enabled us to determine the degree of intensification of heat transfer in the field.

Figure 2 shows the results of some experiments in the form of a plot of the heat-transfer coefficient in the high-frequency field (α_{hf}) against the Reynolds number Re_L.

Figure 2 shows that for equal Re_L, t_L, and f the field effect increases with increase in heat load, i.e., with increase in the strength of the electric (E) and magnetic (H) fields, since q, like E and H, is a function of the current I and the voltage drop U on the tube [4, 5].

The results of comparing the heat-transfer coefficients in high-frequency fields with the heat-transfer coefficient in the case of tubes heated by a current of 50 Hz are shown in coordinates $\log(\alpha_{hf}/\alpha_0)$ and $\log(Re_L)$ in Fig. 3. The heat-transfer coefficient α_0 was calculated from the dimensionless equation (3) for the same experimental conditions, i.e., for the same Re_L, t_L, and t_w as in the experiments in the high-frequency field.

The graphs show that heat transfer is more than twice as intense in high-frequency electromagnetic fields. This effect is attained when the strength of the high-frequency electric field is 2-3 orders less than in the case where constant or low-frequency alternating electric fields are applied [6-9]. Figure 3 also shows that the relative heat-transfer coefficient decreases with increase in Reynolds number and increases with increase in the water temperature.

In the case of transition and turbulent flow of the liquid no appreciable intensification of heat transfer was observed either in a field of 3.85 · 10^5 Hz or in a field of 6.66 · 10^5 Hz. The intensification was probably within the limits of experimental error.

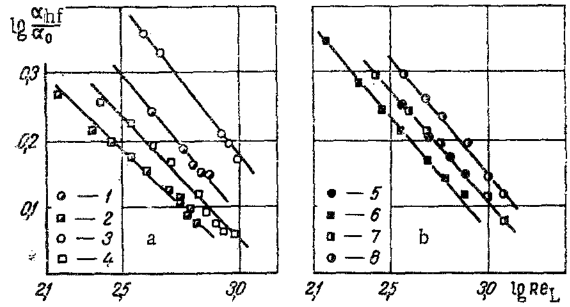

Fig. 3. Relative heat-transfer coefficient as function of Reynolds number. Experimental conditions given in Table 2. a) $f = 3.85 \cdot 10^5$ Hz; b) $f = 6.66 \cdot 10^5$ Hz.

Other investigators [6-10] have observed a reduction of the field effect with increase in Re_L. Most of them believe that the reduction of the field effect is due to the intensification of the heat transfer by ordinary turbulence, which with increase in Re_L can mask the field effect.

A system of equations of hydrodynamics and electromagnetism, providing the necessary basis for description of heat transfer between a wall and a moving dielectric medium in an alternating electromagnetic field [11], shows that convective heat transfer in an electromagnetic field is affected not only by the thermophysical, but also by the electrical and magnetic properties of the medium.

In our experimental conditions the electromagnetic force ($\bar{F}_{em}$) with which the field acts on an element of volume of the flowing liquid in the electromagnetic field is given by the equation [4]

$$\bar{F}_{em} = \sigma\bar{E} + [\bar{J}\,\bar{B}] - \frac{1}{2}(E^2\nabla\varepsilon + H^2\nabla\mu) + \frac{1}{2}\nabla\left(E^2\rho\frac{\partial\varepsilon}{\partial\rho} + H^2\rho\frac{\partial\mu}{\partial\rho}\right). \tag{4}$$

The force $\bar{F}_{em}$, calculated from (4), is 2-3 orders less than the hydrodynamic force.

In [12] an effect of a high-frequency field ($3 \cdot 10^5$-10^6 Hz) on the structure of water, i.e., on its properties, was discovered.

In our experiments the water was subjected to the action of an electromagnetic field in the same frequency range. In view of this we can expect changes in some properties of the liquid. The effect will probably be greatest in the wall layer, where the strengths of the electric and magnetic fields are greatest. We have no information, however, about these properties. Hence, it was impossible to correlate the experimental data by the similarity method.

In view of this we represented the results of measurements of the heat-transfer coefficients for a laminar flow of water by the empirical relation

$$\frac{\alpha_{hf}}{\alpha_0} = 0.84 Re_L^{-0.32} q^{0.15} t_L^{0.35}. \tag{5}$$

The deviation of the experimental points from the curve given by Eq. (5) was ±7.5%.

Equation (5) can be put in a more convenient form for practical use if the heat flux density is replaced by the voltage drop on the tube, which is known from the experimental conditions [1],

$$q^{0.5} = kU. \tag{6}$$

Equation (5) can then be written in the form

$$\frac{\alpha_{hf}}{\alpha_0} = 0.84 k^{0.3} U^{0.3} Re_L^{-0.32} t_L^{0.35}. \tag{7}$$

From the conducted investigation we can draw the following conclusions.

1. Intensification of heat transfer occurs at relatively low field strengths. In our case a significant increase in heat-transfer coefficient was obtained when the strength of the high-frequency electric field was 2-3 orders less than that of constant or low-frequency electric fields.

2. The effect of a high-frequency field depends on its strength, the liquid flow regime, and the temperature of the liquid.

3. In the case of laminar flow the effect of fields of the same strength decreases with increase in Reynolds number and increases with increase in water temperature. In the case of transition and turbulent flow (up to $Re_L = 17,600$) there is no appreciable intensification of heat flow in the field.

4. An analysis of the experimental results showed that the intensifying effect of a high-frequency field is due mainly to electromagnetic forces. There are no grounds, however, for complete rejection of the possible effect of a high-frequency field on the physical properties of a liquid.

5. In addition, the results of investigations indicate not only the need to take into account the effect of the high-frequency field on heat transfer in the calculation of particular types of plant, but also that high-frequency electromagnetic fields might be used to intensify heat transfer in some cases.

NOTATION

c_p, specific heat at constant pressure; G, water flow rate; Δt_L, difference in water temperature at inlet and outlet of test section; d, external diameter of heat-emitting tube; l, length of working section of heat-emitting tube; t_L, average temperature of liquid; t_w, mean temperature of wall of heat-emitting tube; f, frequency of electromagnetic field; ρ, density; σ, charge bulk density; ε, dielectric constant; μ, magnetic permeability; B, magnetic induction; J, current density.

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