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CONVECTIVE HEAT-TRANSFER ENHANCEMENT BY ELECTRIC FIELDS

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Abstract—A general problem is formulated of electroconvective heat transfer and the problems of this kind are classified according to motive force types and to nonuniformity of electrophysical parameters. Typical cases of nonuniformities are considered, namely, thermal, mechanical and those due to the electric field itself. A qualitative theory is developed covering all the flow patterns which correlates experimental data on electroconvective heat transfer in homogeneous and disperse media and on corona discharge in gases. Experimental data agree with theoretical predictions.

NOMENCLATURE

γ, volumetric density of the medium [kg/m^3];
η, ν, dynamic and kinematic viscosities, respectively [N.s/m^2, m^2/s];
λ, thermal conductivity [W/m deg];
a, thermal diffusivity [m^2/s];
c_p, specific heat at constant pressure [J/kg.deg];
Pr, $= \nu/a$, Prandtl number;
ε, absolute dielectric constant [F/m];
σ, specific electrical conductivity [Ω^{-1} m^{-1}];
τ, $= \varepsilon/\sigma$, relaxation time [s];
t_0, characteristic time of induction change in external electric field;
β, volumetric expansion coefficient [deg^{-1}];
β_ε, $= -\frac{1}{\varepsilon}\frac{d\varepsilon}{dT}$, $\beta_\sigma = \frac{1}{\sigma}\frac{d\sigma}{dT}$, $\beta_\tau = -\frac{1}{\tau}\frac{d\tau}{dT}$, temperature coefficients of dielectric permittivity, specific electric conductivity and relaxation time [deg^{-1}];
k, ionic mobility with the sign of corona electrode [m^2/V.s];
r, radial coordinate [m];
δ, δ_T, thicknesses of velocity and thermal boundary layers [m];
l, characteristic dimension (corona wire length) [m];
d, $= 2r_s$, internal diameter of cylindrical (spherical) condenser [m];
P, pressure [N/m^2];
$\mathbf{v}$, T, velocity and absolute temperature distributions [m/s; °K];
ρ, volumetric density of free charges [k/m^3];
$\mathbf{j}$, electric current density vector [A/m^2];
φ, electric field potential [V];
$\mathbf{E}$, electric intensity [V/m];
I, total discharge current through a medium [A];
i, discharge current per unit length of corona wire [A/m];
θ, u, deviations of temperature and electric potential from equilibrium disturbances [°K, V];
q_0, specific heat flux without electric field [W/m];
α_E, α_0, heat-transfer coefficients with and without electric field [W/m^2.deg].

Subscripts
0, refers to equilibrium distributions, characteristic values;
s, refers to internal plates of cylindrical (spherical) condenser;
f, refers to a medium;
w, refers to the heat-transfer surface;
E, refers to an electric field.

INTRODUCTION

VARIOUS hypotheses have been set forth [1, 2] concerning the nature of phenomena involved in heat transfer in electric fields, among which that on the electric fields to increase molecular heat conduction. However, study of dielectric fluids in the field of different strengths has revealed their motion which has left no doubt that it is the electric convection that intensifies the effect of an electric field on heat transfer.

Electric convection and, mainly, its contribution to convective heat transfer is treated in quite a number of works, mostly experimental [3–9]. Nevertheless, its mechanism remains unclear as yet in many respects. Difficulties with the solution of many practical problems and understanding of the physical nature of electroconvective phenomena arise due to electrization of the fluid when in contact with the electrodes forming the field. Up to now this question remains problematic [10].

It will be shown below that formation of a free space charge $\rho = \nabla\mathbf{D} \neq 0$ under the action of an electric field is closely connected with nonuniformity of the fundamental, in this respect, parameter $\tau = \varepsilon/\sigma$ which is the relaxation time of electric effects in the medium. Since dielectric permittivity ε and electrical conductivity σ which affect this parameter depend essentially on temperature, this, when assuming no other nonuniformities, may be used to find a temperature distribution of the density of a free charge and electric forces in the medium. The hydrodynamic effects involved will be referred to as electrothermal, thus emphasizing two conditions indispensable for their onset: availability of an external electric field and of thermal nonuniformities.

The above difficulties appear in the case when nonuniformities of τ are due to the electric field itself which causes electric concentration, ionization, electrochemical phenomena in the vicinity of an electrode. In these cases before investigating electrohydrodynamic phenomena study should be made of the physical mechanism of charge formation in fluid. The exception is unipolar conduction, when the charge carriers of the same sign prevail in the fluid, and the Coulomb force can be found directly by the current density $\mathbf{j}$ and charge-carrier mobility k.

In view of the above, we studied the types of electroconvective heat transfer in homogeneous and disperse heat-transfer fluids (emulsions and suspensions) as well as in case of unipolar conductivity, particularly, with corona gas discharge.

2. GENERAL STATEMENT

Fluid is considered viscous and incompressible; the fields of physical quantities are assumed, as it is customary in mechanics of continua, to be averaged over finite volumes containing a great number both of molecules and of disperse particles as far as emulsions and suspensions are concerned. It is fairly evident in the latter case that the particle concentration should be sufficiently large while the size of particles is small.

For the above approximation, convective heat transfer in an electric field is described by the system of equations for electric convection in homogeneous fluids:

$$\gamma\left[\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\nabla)\mathbf{v}\right] = -\nabla P+\mathbf{f}_1+\mathbf{f}_2+\gamma\mathbf{g}+\eta\nabla^2\mathbf{v}; \quad \nabla\mathbf{v} = 0;$$

$$\frac{\partial T}{\partial t}+\mathbf{v}\nabla T = a\nabla^2 T+\sigma E^2/c_p\gamma; \quad \mathbf{j} = \sigma\mathbf{E}+\rho\mathbf{v}+\frac{\partial(\varepsilon\mathbf{E})}{\partial t};$$

$$\nabla\mathbf{j} = 0; \quad \rho = \nabla(\varepsilon\mathbf{E}); \quad \mathbf{E} = -\nabla\varphi; \tag{2.1}$$

$$\mathbf{f}_1 = \rho\mathbf{E}; \quad \mathbf{f}_2 = -\tfrac{1}{2}\mathrm{E}^2\nabla\varepsilon; \quad P = p-\frac{E^2}{2}\gamma\left(\frac{\partial\varepsilon}{\partial\gamma}\right)_T$$

closed for the unknown functions $\mathbf{v}$, P, T, φ, ρ, $\mathbf{j}$, $\mathbf{E}$, $\mathbf{f} = \mathbf{f}_1+\mathbf{f}_2$. For each specific problem it is indispensable that the fluid properties $(\gamma, \varepsilon, \tau) \to F(T, P, \mathbf{E})$ and appropriate boundary conditions should also be given.

An important class of solutions to system (2.1) are steady-state solutions in case of vanishing time derivatives, particularly in the electric field equations. This means bias currents are negligible compared, for example, to continuous conduction currents

$$\left|\frac{\partial(\varepsilon\mathbf{E})}{\partial t}\right| \Big/ \left|\sigma\mathbf{E}\right| \sim \tau/t_0 \ll 1 \tag{2.2}$$

where t_0 is the characteristic time.

Inequality (2.2) becomes the stronger, the less τ is, i.e. the greater electric conductivity. However, we shall also set an upper limit to the value of σ by the requirement of a negligible contribution to Joule heat to the heat conduction equation:

$$(\sigma E^2/c_p\gamma)/a|\nabla^2 T| \sim \sigma E^2 l^2/\lambda\theta_s \ll 1 \tag{2.3}$$

where θ_s is the characteristic temperature difference. Inequalities (2.2) and (2.3) impose a two-side restriction on the electrical conductivity

$$\varepsilon/t_0 \ll \sigma \ll \lambda\theta_s/E^2 l^2. \tag{2.4}$$

We shall call heat-transfer fluids that meet conditions (2.4) low-conductivity ones. In a d.c. field, among such turn to be a transformer oil, kerosene and many others for which $\tau \lesssim 10^{-1}$ s and which in practice are viewed as insulators.

The inequality reverse to (2.2)

$$\tau/t_0 \gg 1 \tag{2.5}$$

indicates that the electroconductive properties of the fluid may be neglected. Hence, condition (2.5) points out a particular class of ideal dielectrics, for which $\sigma = 0$, $\rho = 0$. In an a.c. field (50 counts/s) the above fluids cannot be considered low-conductivity ones and should be referred to dielectrics.

Consideration of two classes of fluids is expedient mainly in view of the fact that when $\tau/t_0 \gg 1$ electric convection and its intensifying effect on heat transfer are caused by the force $\mathbf{f}_2 = -1/2E^2\nabla\varepsilon$. Taking into account that convection can be excited only by vortex forces (rot $\mathbf{f} \neq 0$) [4, 11, 12] the conclusion is drawn that if heat transfer appears to be enhanced (when $E \leqslant$ 10 kV3 cm) only in a nonuniform field ($\nabla\varepsilon \times \nabla E^2 \neq 0$), this is due to the action of $\mathbf{f}_2$.

In low-conductivity fluids besides $\mathbf{f}_2$ the purely Coulomb force $\mathbf{f}_1 = \rho\mathbf{E}$ acts which in most cases dominates over $\mathbf{f}_2$. Density of free charges is unambiguously related with the relaxation time gradient τ. Indeed, after substituting current density $\mathbf{j}$ into the continuity equation $\nabla\mathbf{j} = 0$ and accounting of the Ostrogradsky–Gauss theorem we obtain:

$$\sigma\mathbf{E}\nabla\tau+\rho+\tau\mathbf{v}\nabla\rho+\tau\frac{\partial\rho}{\partial t} = 0. \tag{2.6}$$

Assuming τ = const and multiplying equation (2.6) by ρ, after integration over the fluid volume enclosed by impermeable walls, we find

$$\int \rho^2\,\mathrm{d}V = \int \rho^2(0)\,\mathrm{d}V.\,l^{-2t/\tau} \tag{2.7}$$

where $\rho(0)$ is the space charge distribution at the moment when the field is imposed at $t = 0$.

Formula (2.7) implies that if the fluid is electrically charged, the field is imposed, i.e. $\rho(0) \neq 0$, its charge disappears in the field at $t \to \infty$, $\rho \to 0$. But if the field is imposed on a neutral fluid, as it actually happens in practice, then $\rho \equiv 0$. Thus, when τ = const, equation (2.6) implies also the reverse situation: if $\nabla\tau \neq 0$, then $\rho \not\equiv 0$. Hence, nonuniformity with respect to τ is the necessary and sufficient condition for free space charges to emerge in the medium under the electric field.

Thus, for analysis and solution of equations (2.1) it may be useful to consider separately ideal and low-conductivity fluids. It should be taken into account that according to equations (2.6) and (2.7) the charge density ρ and force $\mathbf{f}_1$ are caused by nonuniformity with respect to τ while force $\mathbf{f}_2$, with respect to ε. Further classification of the problems and investigation of the heat transfer fluid nonuniformities (thermal, mechanic or those due to the field itself) are necessary.

3. ELECTROTHERMAL HEAT CONDUCTION

Consider convective heat transfer in homogeneous fluids, when to a first approximation one may restrict account of electrohydrodynamic effects only to those which are due to temperature nonuniformities. In this case density of electric body forces can be expressed in terms of distributions of electric potentials φ and temperature T:

$$\mathbf{f}_1 = \rho\mathbf{E} = \nabla\varphi \,.\, \nabla[\varepsilon(T)\nabla\varphi], \tag{3.1}$$

$$\mathbf{f}_2 = -\tfrac{1}{2}E^2\nabla\varepsilon = \tfrac{1}{2}\varepsilon\beta_\varepsilon(\nabla\varphi)^2\nabla T. \tag{3.2}$$

It seems useful to further consider the problems in two aspects on the basis of electrohydrostatic stability, when heat-transfer enhancement can be related with electrothermal convection arising at mechanical equilibrium, and from the boundary layer viewpoint.

In the former case electric force $\mathbf{f} = \mathbf{f}_1 + \mathbf{f}_2$ is expanded into a power series of temperature disturbances $\theta = T - T_0$ and of electric potential $U = \varphi - \varphi_0$ near equilibrium

$$\mathbf{f}' = \mathbf{f} - \mathbf{f}_0 = \left(\frac{\partial \mathbf{f}}{\partial \varphi}\right)_0 u + \left(\frac{\partial \mathbf{f}}{\partial T}\right)_0 \theta + \ldots \tag{3.3}$$

where the expansion coefficients in a general case are operators affecting θ and u, respectively. For a linear approximation, when $\tau/t_0 \ll 1$, expansion (3.3) assumes the form:

$$\mathbf{f}_1' = \varepsilon_0\beta_\varepsilon\beta_\tau\mathbf{E}_0(\mathbf{A}_0\mathbf{E}_0)\theta - \varepsilon_0\beta_\varepsilon\mathbf{E}_0(\mathbf{E}_0\nabla\theta) + \varepsilon_0\beta_\tau(\mathbf{A}_0\mathbf{E}_0)\nabla u + \varepsilon_0\beta_\varepsilon\mathbf{E}_0(\mathbf{A}_0\nabla u) - \varepsilon_0\mathbf{E}_0\nabla^2 u \tag{3.4}$$

$$\mathbf{f}_2' = \tfrac{1}{2}\varepsilon_0\beta_\varepsilon E_0^2\nabla\theta - \tfrac{1}{2}\varepsilon_0\beta_\varepsilon^2 E_0^2\mathbf{A}_0\theta - \varepsilon_0\beta_\varepsilon\mathbf{A}_0(\mathbf{E}_0\nabla u). \tag{3.5}$$

Equilibrium distributions of electric potential ($\nabla\varphi_0 = -\mathbf{E}_0$), temperature ($\nabla T_0 = \mathbf{A}_0$), and of other quantities are assumed to be known from the solution of the electrohydrostatic problem.

The following approximation to $\mathbf{f}' = \mathbf{f}_1' + \mathbf{f}_2'$ turns to be cubic with respect to small parameters (temperature coefficients)

$$\beta_\varepsilon = -\frac{1}{\varepsilon}\frac{d\varepsilon}{dT},\ \beta_\sigma = \frac{1}{\sigma}\frac{d\sigma}{dT},\ \beta_\tau = -\frac{1}{\tau}\frac{d\tau}{dT} = \beta_\varepsilon + \beta_\sigma. \tag{3.6}$$

Therefore, as in the case of thermogravitational convection, a linear approximation of disturbance (motive) force $\mathbf{f}'$ seems to be sufficient even in the general nonlinear theory of electrothermal convection.

Linearized equations of motion, heat conduction and electric potential ($\operatorname{div} \mathbf{j} = 0$)

$$\sigma_0\beta_\varepsilon(\mathbf{A}_0\nabla u - \mathbf{E}_0\nabla\theta) + \sigma_0\nabla^2 u - \varepsilon_0\beta_\tau^2(\mathbf{E}_0\mathbf{A}_0)(\mathbf{A}_0\mathbf{v}) = 0 \tag{3.7}$$

together with equations (3.4), (3.5) and the suitable boundary conditions constitute a closed system of equations describing electrothermal convection and its contribution to heat transfer at mechanical equilibrium.

In case of ideal dielectrics such a problem is essentially simpler because $\mathbf{f}_1' = 0$ and the field equation ($\nabla\mathbf{D} = 0$) contains no convective term

$$-\beta_\varepsilon(\mathbf{A}_0\nabla u - \mathbf{E}_0\nabla\theta) + \nabla^2 u = 0. \tag{3.8}$$

The most interesting recent researches [13, 14] in the field considered deal with solution of the boundary-value problems (though in a somewhat different mathematical form) for the simplest model, i.e. a plane horizontal condenser at constant (different) temperatures and potentials on its plates. Thus, on an electronic computer an exact solution to the problem [14] for dielectrics has been obtained and it has been shown that the electric field causes instability (monotonous) at quite appreciale strengths ($E \gtrsim 10^2$ kV/cm). This indicates a negligible contribution of forces $\mathbf{f}_2'$ to heat-transfer enhancement observed experimentally.

The case of low-conductivity fluids so far remains disputable [13, 14]. Mathematical difficulties make it necessary to thoroughly analyze the formulated equations, primarily the expressions for motive forces, (3.4) and (3.5). Such an analysis has revealed [12] that in all practically important cases we can confine ourselves to the first two terms and the last one in equation (3.4) and the first two terms in equation (3.5). The only exception is the problem of electrothermal convection in a plane condenser with $\tau/t_0 \gg 1$, which may however be omitted from consideration at all because its solution is known [14]. Equation (3.7) can also be simplified as [12]:

$$-\beta_\sigma\mathbf{E}_0\nabla\theta + \nabla^2 u = 0. \tag{3.9}$$

Then, the sum of the second and last terms in equation (3.4) is $-\varepsilon_0\beta_\tau\mathbf{E}_0(\mathbf{E}_0\nabla\theta)$.

With regard for the above, we formulate the following dimensionless system of equations for the case of electrothermal convection in classical symmetry condensers when $\tau/t_0 \ll 1$

$$\begin{aligned} Pr^{-1}\left[\frac{\partial\mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v}\right] = \\ -\nabla P + K_\sigma^{(n)}\,.\,\theta\,.\,r^{-3n}\,.\,\mathbf{e} - Et\,.\,(\mathbf{e}\nabla\theta)\,.\,\mathbf{e}\,.\,r^{-2n} \\ + Ra\,.\,\theta\,.\,\mathbf{k} + \nabla^2\mathbf{v}; \quad \nabla\mathbf{v} = 0 \\ \frac{\partial\theta}{\partial t} + \frac{A_s r_s}{\theta_m}\,.\,\frac{\mathbf{ev}}{r^n} + \mathbf{v}\nabla\theta = \nabla^2\theta. \end{aligned} \tag{3.10}$$

Here $n = 0, 1, 2$ for plane, cylindrical and spherical symmetries, respectively; $\mathbf{e}$ is the unit vector which, as follows from the electrohydrostatic equation, is common for the equilibrium vectors $\mathbf{E}_0 = \mathbf{e}E_0$, $\nabla T_0 = \mathbf{e}A_0$. The subscript s means equilibrium on the surface of the internal condenser at $n = 1, 2$. $\theta_m = A_s r_s$ is assumed to be a temperature scale if $T_0 \neq$ const (which is possible when $n = 0$, $\mathbf{e} \to \mathbf{k}$ as well as when $n = 1, 2$; but $Ra = 0$). $\theta_m = \theta_s$ if $T_0 =$ const.

Besides Rayleigh and Prandtl numbers, the system of equations (3.10) contains two more similarity numbers for thermoelectroconvective phenomena

$$Et = \frac{\varepsilon_0 \beta_\tau \theta_m r_s^2 E_s^2}{\gamma_0 . \nu . a} . \left(\frac{\sigma_s}{\sigma_0}\right)^2 \quad (3.11)$$

$$K_\sigma^{(n)} = \frac{\varepsilon_0 \beta_\varepsilon \theta_m r_s^2 E_s^2}{\gamma_0 \nu a} . \left(\frac{\sigma_s}{\sigma_0}\right)^2 \times [(\beta_\varepsilon + 2\beta_\sigma) A_s r_s + n r^{n-1}]. \quad (3.12)$$

They characterize the contribution of purely Coulomb force $\mathbf{f}_1'$ and pondermotive force $\mathbf{f}_2'$ to heat-transfer enhancement, while

$$Et/K_\sigma^{(n)} \sim \mathbf{f}_1'/\mathbf{f}_2' \gtrsim \beta_\tau/\beta_\varepsilon \gg 1 \quad (3.13)$$

since usually $\beta_\tau/\beta_\varepsilon \sim 10^2 \div 10^3$.

Substitution of $Et = 0(\rho = 0)$ into system (3.10) and replacement of

$$K_\sigma^{(n)} \to -K_\varepsilon^{(n)} = -\frac{\varepsilon_0 \beta_\varepsilon \theta_m r_s^2 E_s^2}{\gamma_0 \nu a} . \left(\frac{\varepsilon_s}{\varepsilon_0}\right)^2 . (\beta_\varepsilon A_s r_s - n r^{n-1}) \quad (3.14)$$

give the system describing electrothermal convection in ideal liquid dielectrics. The generalized parameters (3.11), (3.12) and (3.14) are weak functions of the coordinates in terms of equilibrium quantities. For the Boussinesque approximation they may, however, be assumed constant and equal to some volume averaged values. The boundary conditions for θ and $\mathbf{v}$ for the system of equations (3.10) coincide with those for natural convection.

The advantage of the electrothermal convection problem in the form of equation (3.10) is not only its simplicity against the initial equations but also the fact that individual problems are directly reduced to the case of natural convection with a modified Rayleigh number.

It is significant that in ideal dielectrics ($\rho = 0$) the motive force $\mathbf{f}_2'$ is proportional to the temperature disturbance as well as the Archimedian force. That is why the onset of instability is monotonous [15] and electrothermal convection has much in common with natural convection. According to equation (3.13) for low-conductivity fluids the system of equations (3.10) may incorporate only the term with Et. The motive force $\mathbf{f}_1'$ in this case contains a temperature disturbance derivative with respect to the coordinates in the direction of the electric field that results in oscillatory instability. It can be shown by the energy method [16, 17] that such disturbances develop whose frequencies exceed a certain critical value

$$\omega^2 \geqslant Pr \int \left(\left|\nabla^3 \theta^2 + \left| Ra \frac{\partial \theta}{\partial x} \right|^2 \mathrm{d}V \right/ \int \left| \nabla \theta \right|^2 \mathrm{d}V. \quad (3.15)$$

On the one hand, this proves the possibility of existence of internal thermoelectroconvective waves and, on the other hand, indicates that local heat transfer in the case considered (T/r = const) is unsteady, which has been verified experimentally [18]. Here, the extent to which the electric field affects convective heat transfer both in uniform and in nonuniform fields can be estimated by:

$$q_\sigma = Et/Ra = \varepsilon \beta_\tau E^2/\gamma l \beta g,$$

e.g. for transformer oil ($\varepsilon \approx 2 \times 10^{-11}$, $\beta_\tau \sim 10^{-1}\,\mathrm{deg}^{-1}$, $E \sim 10^5$ V/m, $l \sim 10^{-1}$ m) $q_\sigma \approx 1$ if $E \approx 1$ kV/cm. This implies that at natural convection with the strengths considered the enhancing effect of the field on heat transfer becomes appreciable. This conclusion agrees with numerous experimental results and, hence, thermal nonuniformities in homogeneous fluids at $\tau/t_0 \ll 1$ are very important for heat transfer.

Since in ideal dielectrics this effect should be lower by some orders and in uniform fields should vanish we, before considering the boundary-layer heat transfer, shall analyze the case of low-conductivity fluids (2.4) which is primarily interesting for correlation of experimental data as well as for their application to engineering practice.

The main ideas of the boundary-layer approach with reference to heat transfer from an electrically heated charged vertical plate have been developed in [19]. We consider ordinary boundary-layer equations [20] with the difference that a heat transfer surface in a horizontal flow ($0X$) is at the same time an electrode which generates an electric field $E = \mathbf{k}E_z$, $E_z = E =$ const normal to the surface. The entrainment of electric charges by a fluid flow may be very essential in this case. Therefore, we shall have to use initial equations (2.1) which in a steady-state case, with regard for equation (2.6) assume the form:

$$\gamma(\mathbf{v}\nabla)\mathbf{v} = -\nabla P + \rho \mathbf{E} - \tfrac{1}{2}E^2 \nabla \varepsilon + \tfrac{1}{2}\nabla\left[E^2 \gamma \left(\frac{\partial \varepsilon}{\partial \gamma}\right)_T\right] - \gamma \beta \mathbf{g} \theta + \eta \nabla^2 \mathbf{v};$$

$$\nabla \mathbf{v} = 0; \ \mathbf{v}\nabla\theta = a\nabla^2\theta; \ \rho + \tau \mathbf{v}\nabla\rho = -\varepsilon\beta_\tau \mathbf{E}\nabla\theta. \quad (3.16)$$

The field strength E is given, $\mathbf{v}$, P, θ, ρ; $\theta = T - T_\infty$ are unknown where T_∞ = const is the temperature at infinity.

Within a thin boundary layer the field is considered uniform, while outside it the fluid is homogeneous. Thus, the force $\mathbf{f}_2$ may be written as $E^2\nabla\varepsilon = \nabla(\varepsilon E^2)$. From equation (3.16) it follows that

$$\gamma\left(V_x \frac{\partial V_x}{\partial x} + V_z \frac{\partial V_x}{\partial z}\right) = -\frac{\partial \mathscr{P}}{\partial x} + \eta\left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial z^2}\right);$$

$$\gamma\left(V_x \frac{\partial V_z}{\partial x} + V_z \frac{\partial V_z}{\partial z}\right) = -\frac{\partial \mathscr{P}}{\partial z} + \rho E + \gamma\beta g\theta + \eta\left(\frac{\partial^2 V_z}{\partial x^2} + \frac{\partial^2 V_z}{\partial z^2}\right); \quad (3.17)$$

$$V_x \frac{\partial \theta}{\partial x} + V_z \frac{\partial \theta}{\partial z} = a\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial z^2}\right); \quad \frac{\partial V_x}{\partial x} + \frac{\partial V_z}{\partial z} = 0;$$

$$\rho + \tau\left(V_x \frac{\partial \rho}{\partial x} + V_z \frac{\partial \rho}{\partial z}\right) = -\varepsilon\beta_\tau E \frac{\partial \theta}{\partial z},$$

where

$$\mathscr{P} \equiv p + \frac{E^2}{2}\left(\varepsilon - \gamma \frac{\partial \varepsilon}{\partial \gamma}\right).$$

The usual procedure of comparisons and estimations of the terms in equations (3.17) used in the boundary-layer theory with the assumption that the boundary-layer thickness δ is much less than the characteristic dimension l in the flow direction leads to the equation:

$$\frac{\partial \mathscr{P}}{\partial z} = \rho E + \gamma \beta g \theta, \quad (3.18)$$

whereas in the ordinary boundary-layer theory

$$\frac{\partial \mathscr{P}}{\partial z} = 0.$$

Integrating equation (3.18) from z to ∞ gives:

$$\mathscr{P}(x, z) = -\int_z^\infty (\rho E + \gamma \beta g \theta)\,dz + \mathscr{P}(x, \infty), \quad (3.19)$$

where $\mathscr{P}(x, \infty)$ is the potential flow pressure to be determined from the Bernoulli equation

$$\mathscr{P}(x, \infty) = -\gamma u^2/2 \quad (3.20)$$

u is the velocity in the potential flow due to either the external hydrodynamic pressure or relative motion of the body itself in the fluid.

With regard for equations (3.19) and (3.20) the boundary-layer equations assume the form:

$$V_x \frac{\partial V_x}{\partial x} + V_z \frac{\partial V_z}{\partial z} = \frac{\partial}{\partial x}\left(\frac{w^2}{2}\right) + \nu \frac{\partial^2 V_x}{\partial z^2},$$

$$V_x \frac{\partial \theta}{\partial x} + V_z \frac{\partial \theta}{\partial z} = a \frac{\partial^2 \theta}{\partial z^2}, \quad \frac{\partial V_x}{\partial x} + \frac{\partial V_z}{\partial z} = 0 \quad (3.21)$$

$$\rho + \tau\left(V_x \frac{\partial \rho}{\partial x} + V_z \frac{\partial \rho}{\partial z}\right) = -\varepsilon \beta_\tau \mathrm{E} \frac{\partial \theta}{\partial z}$$

where

$$w = \left\{\frac{2}{\gamma}\int_z^\infty (\rho E + \gamma \beta g \theta)\,dz + u^2\right\}^{1/2}. \quad (3.22)$$

The first summand in the braces is a correction to the potential flow velocity caused by the body forces within the boundary layer. These forces, though normal to the flow, change the velocity in the main stream because of their dependence on the longitudinal coordinate x. Thus, w is the total velocity in the potential flow.

As in the case of forced motion we may introduce the Reynolds number (Re_E), as the characteristic quantity, containing a certain effective value derived from expression (3.22). Introduction of scale units from the relevant formulas of the boundary-layer theory and transition to a dimensionless form in equations (3.21) shows that one of the main conclusions of the theory that the boundary layer thickness is inversely proportional to the square root of Re_E approximately holds although the body forces are taken into account. Hence, heat transfer in a laminar boundary layer in the presence of an electric field may be approximated, as usual, by dimensionless equation [21]:

$$Nu_E = F(Pr) Re_E^{0.5} \quad (3.23)$$

where $F(Pr)$ is a function of the Prandtl number depending on particular conditions of the problem; usually $F(Pr) \sim Pr^{1/3}$.

The effective velocity should naturally incorporate the mean longitudinal component of the true velocity, for which either the mean over the bulk layer total velocity $\bar{w}$ or its order $w \sim w_0$ may be assumed. Both definitions will coincide to within a numerical factor, so the choice of this or that scale is of no practical importance.

Taking notice that the integrand in equation (3.22) is positive ($\theta = T - T_\infty > 0$, $\rho E \approx -\varepsilon\beta_\tau(\mathbf{E}\nabla\theta)\mathbf{E} > 0$), we may write:

$$\bar{w}^2 = \frac{2}{\gamma}(\bar{\rho}E + \gamma\beta g\bar{\theta})\delta_T + u^2(x) \quad (3.24)$$

where the bar means averaging over $0 \leqslant z \leqslant \delta_T$ (when $z > \delta_T, \rho, \theta = 0$), $\delta_T = f(Pr)\delta$ is the thermal boundary-layer thickness, f is the Prandtl number function ($f \sim F^{-1} \sim Pr^{-1/3}$).

The value of the mean charge density from expression (3.24) is found from the averaged continuity equation

$$\bar{\rho} + \tau \frac{d}{dx}(\bar{\rho}\bar{V}_x) = \varepsilon\beta_\tau E\theta_s/\delta_T \quad (3.25)$$

where $\theta_s = \theta(x, 0) = T_w - T_\infty$. The derivative in the l.h.s. of equation (3.25) is positive because convective charge transfer in the boundary layer should involve reduction of its mean density. Then, replacing $(d/dx)(\bar{\rho}\bar{V}_x) \to \bar{\rho}\bar{V}_x/l$, which corresponds to the linear approximation of the dependence of $(\bar{\rho}\bar{V}_x)$ on x and also $\bar{V}_x = \bar{w}$, and taking into account $\delta \sim lRe_E^{-1/2}$, we finally obtain:

$$\bar{\rho} = \frac{\varepsilon\beta_\tau E\theta_s\sqrt{(Re_E)}}{f(Pr).l[1 + f(Pr)\tau\nu Re_E/l^2]}. \quad (3.26)$$

$$Re_E = Re_E^{(m)} = l^2/f\tau\nu \quad (3.27)$$

the charge density $\bar{\rho}$ reaches its maximum

$$\bar{\rho}^{\max} = \frac{\beta_\tau E\theta_s}{2}\sqrt{\left(\frac{\varepsilon\sigma}{\nu}\right)}(f\sqrt{f})^{-1} \quad (3.28)$$

The presence of the maximum is accounted for by the fact that at small Re_E the temperature gradients and $\bar{\rho}$ are small too. At large Re_E the density of a charge starts to decrease due to its entrainment by a convective flow. Relations (3.27) and (3.28) determine the conditions under which the maximum field effect on heat transfer in the boundary layer should be expected.

Taking into account expressions (3.24) and (3.26), we define the order of the Reynolds number:

$$Re_E = \left(\frac{Gr_E}{1 + f\tau\nu Re_E/l^2} + \frac{f.Gr}{\sqrt{(Re_E)}} + Re\right)^{1/2} \quad (3.29)$$

where

$$Gr_E = \varepsilon\beta_\tau\theta_s l^2 E^2/\gamma\nu^2, \quad (3.30)$$

$$Gr = \beta g\theta_s l^3/\nu^2 \quad (3.31)$$

The knowledge of the effective Reynolds number allows, according to equation (3.23), approximation of the dependence of the Nusselt number on the generalized parameters entering into equation (3.29). Equation (3.29) expresses the general laws and peculiarities of a complicated process of heat transfer at mixed convection.

Expression (3.29) is rather complicated, therefore, to illustrate the effectiveness of the above formulas we shall restrict consideration to some special cases. In the absence of gravitational and electric convections ($Gr_E = 0, Gr = 0$), certain regular features of heat transfer at forced motion become apparent. In the conditions of gravitational convection alone, relation (3.23) with account of equation (3.29) assumes the form:

$$Nu = F(Pr)Gr^{0.2}.$$

Such regularity is observed in the case of heat transfer in horizontal layers with high Grashof numbers $Gr \geqslant 10^6$ [22]. It is quite understandable, for only in the case of sufficiently intensive convection we can speak of a boundary layer.

For purely electrothermal convection $Gr_E \neq 0$, $Gr = 0$, $Re = 0$, Re_E is determined by:

$$Re_E^2(1 + f\tau\nu Re_E/l^2) = Gr_E.$$

Here two subcases are also possible:

$$f\tau\nu Re_E/l^2 \ll 1; \quad Re_E = Gr_E^{1/2};$$

$$f\tau\nu Re_E/l^2 \gg 1; \quad Re_E = \left(\frac{l^2}{f\tau\nu}\right)^{1/3} Gr_E^{1/3}$$

for which

$$Nu_E = F(Pr)Gr_E^{1/4}, \tag{3.32}$$

$$Nu_E = F(Pr).(l^2/f\tau\nu)^{1/6}Gr_E^{1/6}. \tag{3.33}$$

In a general case

$$Nu_E = F(Pr).(l^2/f\tau\nu)^n Gr_E^m \tag{3.34}$$

where $0 < n < 1/6$; $1/6 < m < 1/4$. Analytical solutions [19] also lead to the relations similar to expressions (3.32) and (3.33).

Figure 1 is a plot of the dimensionless experimental correlation [23] for heat transfer from a vertical cylinder (inner plates of a cylindrical condenser) to various fluids in an a.c. electric field. The experimental values fall near the straight line within 20 per cent (cylinder length l is a characteristic dimension):

$$Nu_f = 3.85.(Gr_{E,f}.Pr_f)^{0.18} \times (l^2/\tau_f\nu_f)^{0.13}.(Pr_f/Pr_w)^{0.75}.$$

This relation agrees well with formula (3.34). It may thus be calculated that general formula (3.34) is a realistic description of heat transfer at developed electrothermal convection of weakly conducting fluids ($\tau/t_0 \ll 1$) and may be taken as a correlation for experimental data.

4. CONVECTIVE HEAT TRANSFER AT ELECTROCONDUCTIVE CONVECTION

Electroconductive convection implies electric convection, whose origin is not attributed to thermal nonuniformities of a heat agent. If in these cases the temperature dependence of medium properties is neglected in the motion equations, then like in the case with forced motion, the electrohydrodynamic problem has no connection with the thermal one and is formulated as:

$$\gamma(\mathbf{v}\nabla)\mathbf{v} = -\nabla P + \mathbf{f} + \eta\nabla^2\mathbf{v}; \quad \nabla\mathbf{v} = 0; \quad \mathbf{v}|_r = 0,$$

where $\mathbf{f} \neq \mathbf{f}(T)$ is assumed to be known. Reducing this system to a dimensionless form:

$$(\mathbf{v}, \nabla_1)\mathbf{v}_1 = -\nabla_1 P_1 + \frac{f_0\gamma l^3}{\eta^2}\mathbf{f}_1 + \nabla_1^2\mathbf{v}_1;$$

$$\nabla_1\mathbf{v}_1 = 0; \quad \mathbf{v}_1|_r = 0$$

where f_0 is the characteristic external force gives:

$$\mathbf{v} = v_0\mathbf{v}_1 = \frac{\eta}{l\gamma}\mathbf{v}_1\left(\frac{f_0\gamma l^3}{\eta^2}, \mathbf{r}_1\right). \tag{4.1}$$

Now consider two limit flow modes

$$|\gamma(\mathbf{v}\nabla)\mathbf{v}| \ll \eta|\nabla^2\mathbf{v}| \quad \text{(laminar flow)}$$

$$|\gamma(\mathbf{v}\nabla)\mathbf{v}| \gg \eta|\nabla^2\mathbf{v}| \quad \text{(turbulent flow).}$$

The solution of equation (4.1) should not depend on density γ in the first case and on viscosity η in the second, which is possible if it is expressed as:

$$\mathbf{v} = \frac{\eta}{\gamma l}.\left(\frac{f_0 l^3\gamma}{\eta^2}\right)^m \mathbf{F}(\mathbf{r}_1) \tag{4.2}$$

where for the above cases $m = 1$ and $m = 0.5$, respectively. This allows the assumption that as convection is developing, m diminishes remaining within $0.5 < m < 1$.

It can be seen from expression (4.2) that the dimensionless complex

$$Re_E = \left(\frac{f_0 l^3}{\gamma\nu^2}\right)^m \tag{4.3}$$

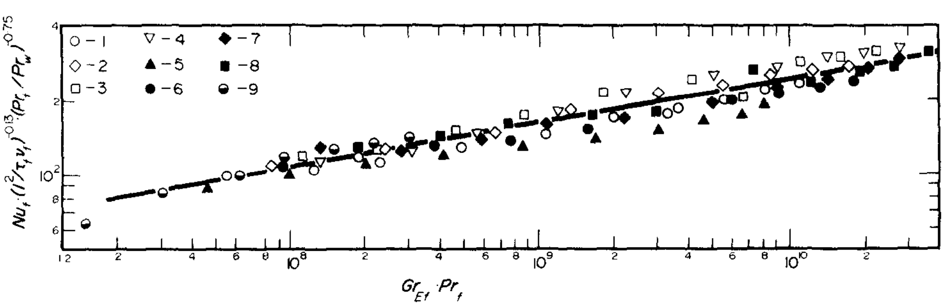

FIG. 1. Heat transfer from a vertical cylinder to fluid at free convection in an electric field. 1–10, transformer oil; 11–14, benzene; 15, dichlorethane. 15, 8 mm dia; 1–14, 1.5 mm dia; 1–14, $T_f = 30°$; 1–5, $T_f = 40°$; 15, $T_f = 50°$; 6–10, $T_f = 79°C$; 1, 6, 11 and 15, $\theta_s = 10$ deg; 2, 7 and 12, $\theta_s = 20$ deg; 3, 8 and 13, $\theta_s = 30$ deg; 4, 9 and 14, $\theta_s = 40$ deg; 5, 10, $\theta_s = 50$ deg.

characterizes liquid motion intensity and acts as the Reynolds number. And here, like in the previous section, the Nusselt number may be approximated by relation (3.23).

We shall now consider particular cases of application of the formulas obtained. Let a nonuniform system, whose closed phase is a dielectric liquid (transformer oil, kerosene, etc.) and the disperse phase is liquid particles in emulsions or solid particles in suspensions, be in an external electric field. As has been pointed out in the general statement of the problem, such a system can be regarded as uniform from the hydrodynamic point of view, but from the viewpoint of origin of free space charges ($\rho \neq 0$) in it the particle kinetics should be applied to.

If a particle does not contact an electrode, it polarizes but remains electrically neutral. If it contacts an electrode, it charges, and in a steady case its electric charge according to equation (2.6) becomes equal to:

$$q = \int \rho \, \mathrm{d}V = \int \mathbf{j}\nabla\tau \, \mathrm{d}V = (\tau_2 - \tau_1) . \varphi j_n \, \mathrm{d}s,$$

or, because of the normal component of the current density being continuous on the particle surface:

$$q = j_n . s . (\tau_2 - \tau_1) = \varepsilon_2 \bar{E} . s\left(1 - \frac{\tau_1}{\tau_2}\right). \quad (4.4)$$

This formula shows that the particles will gain the same charge as the electrode in contact with it (j) provided that their relaxation time τ_1 is less than the ambient relaxation time τ_2. On the other hand, just in this case we should expect a hydrodynamically unstable distribution of the mean density of a space charge ($\nabla\rho . \mathbf{E} < 0$). That is why, to intensify convective heat transfer the disperse phase should have a sufficiently small value of τ. Otherwise ($\tau_1 > \tau_2$) heat transfer suppression should be observed due to hydrostatic liquid stabilization by Coulomb forces ($\nabla\rho . \mathbf{E} > 0$).

To define the form of relation (3.23), we should first find the characteristic value of force f_0, namely,

$$f_0 = \rho_0 E \quad (4.5)$$

where ρ_0 is the order of charge density which may be found from formula (4.4)

$$\rho_0 = qn = \varepsilon_2 \bar{E} sn\left(1 - \frac{\tau_1}{\tau_2}\right)$$

where n is the particle concentration in the vicinity of the heat-liberating electrode equal to:

$$n = C/V_1$$

where C is the volume concentration of particles, V_1 is the volume of a particle. Taking into account that $s \sim r^2$, $V_1 \sim r^3$ (r is the characteristic size of a particle), the dependence of the Nusselt number of Re_E is approximated in accordance with equations (3.23), (4.3) and (4.5) as follows:

$$Nu_E = F(Pr) . \left[\frac{\varepsilon E^2 l^3}{\gamma v^2} \frac{C}{r}\left(1 - \frac{\tau_1}{\tau_2}\right)\right]^{0{\cdot}5-0{\cdot}25} . \quad (4.6)$$

When $\tau_1/\tau_2 \ll 1$ and also in case of sufficiently great concentrations this formula is reduced.

In [24] an experimental investigation of heat transfer to dielectric liquid emulsions in uniform fields is described, and the data are generalized by the following criterial relationship

$$Nu_E = 5{\cdot}8\left(\frac{\varepsilon E^2 l^2}{\gamma v^2} Pr\right)^{0{\cdot}26} \quad (4.7)$$

which is in good agreement with theoretically predicted formula (4.6). The exponent in formula (4.7) being closer to its lower limit signifies that vigorous mixing takes place in emulsions which can easily be observed [24].

Experimental data on suspensions are generalized by [25]:

$$Nu_E = 0{\cdot}4\left(\frac{\varepsilon E^2 l^2}{\gamma v^2}\right)^{0{\cdot}36} . \left(\frac{Pr_f}{Pr_s}\right)^{0{\cdot}25} \quad (4.8)$$

where the exponent equal to 0·36 is also within the theoretically predicted limits, but it is greater than in emulsions which indicates less intensive electrohydrodynamic effects.

Finally, consider the case of unipolar conductivity when, as has already been noted, the Coulomb force equal j/k. With account of expressions (3.23) and (4.3):

$$Nu_E = F(Pr) . \left(\frac{j_0 l^3}{k\gamma v^2}\right)^{0{\cdot}5-0{\cdot}25} . \quad (4.9)$$

A typical example of unipolar conductivity is the corona discharge in gases. In order to check relation (4.9), heat transfer from a corona displaying wire to various gases (air, carbon dioxide, argon, helium) has been investigated experimentally in a wide range of pressure variation, which essentially affects ion mobility k and gas density γ. The experimental technique is described in [26]. The experimental results are presented in Fig. 2 where the solid line is described by the generalized relation:

$$Y \approx 0{\cdot}06 X^{-0{\cdot}007 \log X + 0{\cdot}5}$$

where $Y = ((\alpha_E/\alpha_0) + (BI/q_0) - 1)$, $X = id^2/k\gamma v^2$, $d_{0,E}$ is the coefficient of heat transfer within and without the field, q_0 is the specific heat flux at $E = 0$; $I = il$ is the total discharge current; l, d is the length and the diameter of the corona displaying wire; B is the coefficient taking into account Joule heating of a gas by the corona discharge [26]. In the case under consideration theoretical predictions and experimental data have also shown satisfactory agreement.

As a result of investigation, a general problem of electroconvective heat transfer has been formulated. In the formulation aspect classification of problems has been made according to the character of electroconvective motive forces, and of nonuniformities of the relaxation time of electric phenomena in the medium that unambiguously define the distribution of charge density in low-conductivity fluids in the presence of electric fields, and thus a common approach to the problem considered has been suggested.

The following typical nonuniformities have been considered: thermal, mechanical and those caused by an electric field itself (unipolar conductivity). The main

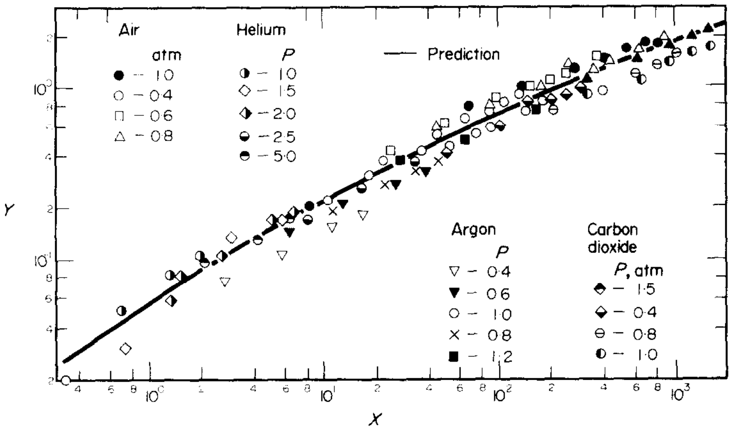

FIG. 2. Generalized relationship for heat transfer in gases affected by corona discharge.

attention is paid to the problems of electrothermal convective heat transfer because heat transfer itself is due to thermal nonuniformities.

Peculiarities and regularities of the process which, as it turned out, depend essentially on the type of the fluid and the character of the external field, have been found theoretically. A thorough theory has been worked out for all of the analyzed nonuniformities which, in spite of its relative simplicity, embraces practically all the flow regimes and permits generalization of vast experimental material on convective heat transfer in the presence of electric fields in uniform media, disperse systems (emulsions, suspensions) as well as in gases during a corona discharge. The results obtained make it possible to draw a conclusion that the physical concepts of the mechanism of electrohydrodynamic phenomena in heat transfer which are fundamentals of the theoretical models suggested provide a correct picture of their character and, hence, may be accepted as a basis for further investigations and can also be used in engineering computations.

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AMELIORATION DE LA CONVECTION THERMIQUE PAR LES CHAMPS ELECTRIQUES

Résumé—On a formulé un problème général de transfert de chaleur électroconvectif; les problèmes de cette nature sont classés suivant le type des forces actives et la nonuniformité des paramètres électriques. Des cas types de nonuniformité, sont considérés, à savoir: thermiques, mécaniques et ceux dûs au champ électrique même. Une théorie qualitative est développée qui recouvre toutes les configurations d'écoulements et qui approxime les données expérimentales sur le transfert de chaleur électroconvectif dans les milieux homogènes et dispersés, et sur la décharge dans les gaz avec effet de couronne. Les données expérimentales sont en bon accord avec les prévisions théoriques.

DIE ERHÖHUNG DES KONVEKTIVEN WÄRMEÜBERGANGS DURCH ELEKTRISCHE FELDER

Zusammenfassung—Das elektrokonvektive Wärmeübergangsproblem wird in allgemeiner Form beschrieben und entsprechend den treibenden Kräften sowie der Ungleichförmigkeit der elektrophysikalischen Parameter klassifiziert. Einige typische Fälle von Ungleichförmigkeiten werden betrachtet, nämlich thermische, mechanische und solche, die auf das elektrische Feld selbst zurückzuführen sind. Es wird eine qualitative Theorie entwickelt, die alle Strömungszustände berücksichtigt und Daten des elektrokonvektiven Wärmeübergangs in homogenen und dispersen Medien sowie bei Koronaentladungen in Gasen korreliert. Die Versuchsergebnisse stimmen mit den theoretischen Voraussagen überein.

ИНТЕНСИФИКАЦИЯ КОНВЕКТИВНОГО ТЕПЛООБМЕНА ПОД ВОЗДЕЙСТВИЕМ ЭЛЕКТРИЧЕСКИХ ПОЛЕЙ

Аннотация — Сформулирована общая задача электроконвективного теплообмена и проведена классификация задач по характеру движущих сил электроконвекции и неоднородностей среды по электрофизическим параметрам. Рассмотрены типичные случаи неоднородностей: термические, механические и обусловленные самим электрическим полем; разработана качественная теория, охватывающая все режимы течения и позволяющая обобщить экспериментальные данные по электроконвективному теплообмену в гомогенных и дисперсных средах, а также при коронном разряде в газах. Опытные данные согласуются с теоретическими выводами.