

HEAT TRANSFER IN EMULSIONS OF POOR CONDUCTORS UNDER ELECTRIC FIELD

B. R. LAZARENKO, I. A. KOZHUKHAR and M. K. BOLOGA
 Institute of Applied Physics, Moldavian Academy of Sciences, Kishinev, U.S.S.R.

(Received 26 July 1970 and in revised form 20 May 1973)

Abstract—The results of investigation are presented of hydrodynamic and heat-transfer processes in dielectric emulsions with disperse phase of higher conductivity under electric field. The dependence of the heat-transfer coefficient on the field strength, temperature driving force, temperature and concentration of emulsions is shown. The accumulation mechanism of space charge which causes EHD-disturbances of the field is analysed. A one-dimensional problem is considered whose solution shows charge distribution in the field of a plane capacitor and reveals the presence of similarity region of heat-transfer processes in case of emulsions with high concentrations. The results on heat transfer under the electric field effect are treated in terms of similarity numbers.

NOMENCLATURE

- l, h , characteristic dimension of a heat-transfer surface and distance between the electrodes [m];
- U , potential difference between the electrodes [V];
- E , electric field strength [$V \cdot m^{-1}$];
- ϵ_0 , electric constant, $\epsilon_0 \simeq 8.85 \cdot 10^{-12} F \cdot m^{-1}$;
- ϵ , dielectric permeability;
- σ , electrical conductivity [$\Omega^{-1} \cdot m^{-1}$];
- $\beta_\sigma, \beta_\epsilon$, temperature coefficients of electrical conductivity and dielectric permeability [deg^{-1}];
- k , charge carrier mobility [$m^2 \cdot s^{-1} \cdot V^{-1}$];
- ρ^+, ρ^- , density of positive and negative charges [$C \cdot m^{-3}$];
- q^+, q^- , mean particle charge [C];
- V^+, V^- , regular motion velocity of charged particles [$m \cdot s^{-1}$];
- γ , density [$kg \cdot m^{-3}$];
- ν , kinematic viscosity [$m^2 \cdot s^{-1}$];
- φ , bulk concentration of the disperse phase;
- α_E , heat-transfer coefficient in an electric field [$W \cdot m^{-2} \cdot deg^{-1}$];
- t_f , fluid temperature [$^{\circ}C$];
- Δt , temperature driving force [deg].

investigations are carried on with models similar to capacitors of various shapes (plane, cylindrical) with one plate, normally earthed, serving as a heat-transfer surface, the other connected to a high-voltage source.

The results of different investigators [1-8] allow a conclusion that the enhancing effect of an electric field on heat transfer is a consequence of electrohydrodynamic effects due to electric forces.

The density of forces of an electric field is shown to be expressed as

$$\mathbf{f} = \rho \mathbf{E} - \frac{\epsilon_0}{2} E^2 \nabla \epsilon + \frac{\epsilon_0}{2} \nabla \left(E^2 \frac{\partial \epsilon}{\partial \gamma} \gamma \right), \quad (1)$$

where the first term in the r.h.s. is the force affecting free electric charges; the second and the third terms are ponderomotive forces depending on $\nabla \epsilon$, $\partial \epsilon / \partial \gamma$ and ∇E^2 .

Electric forces (1) have been analysed and conditions have been found for convection to arise in electric and gravitational fields by the present authors [9]. Unstable mechanical equilibrium, for example, occurs when [10]

$$E \uparrow \downarrow \nabla \rho, \quad \nabla \epsilon \uparrow \downarrow \nabla E^2, \quad \nabla \gamma \uparrow \downarrow g. \quad (2)$$

As has been demonstrated by experiments [11], in this case electrothermal convection only arises when the field strength exceeds certain critical values.

It should be emphasised that the force ρE [2, 11] is dominating practically always in the process of electroconvection, and in these cases the other terms in (1) are negligible.

Nonhomogeneity of the fluid with respect to the parameter $\tau = \epsilon_0 \epsilon / \sigma$ is the necessary condition for charge ρ to be formed due to external electric field effect [10, 12].

1. INTRODUCTION

IN RECENT years the possibility of considerable intensification of heat-transfer processes by the electric field effect attracts ever-growing attention. Dielectric liquids with the specific resistance of about $10^6 \Omega \cdot m$ and above are used in this case; the field strength ranges from a few kilovolts per cm up to disruptive values. Experimental

Let us demonstrate the validity of the statement, making use of the known relations of electrodynamics. The law of Ostrogradsky–Gauss in a differential form and the law of charge conservation will be expressed as

$$\nabla \mathbf{D} = \varepsilon_0 \mathbf{E} \nabla \varepsilon + \varepsilon_0 \varepsilon \nabla \mathbf{E} = \rho; \quad (3)$$

$$\nabla \mathbf{j} = \sigma \nabla \mathbf{E} + \mathbf{E} \nabla \sigma = 0, \quad (4)$$

respectively. From equations (3) and (4) we obtain

$$\rho = \sigma \mathbf{E} \nabla \tau, \quad (5)$$

which implies that a space charge is formed in a fluid nonuniform with respect to electrophysical parameters ($\nabla \tau \neq 0$), in the external electric field.

Nonhomogeneity of the fluid with respect to τ may in its turn be caused by different reasons. Nonuniformity of the temperature field may result in nonuniformity of the fluid with respect to τ because the temperature effect on the electrophysical parameters of dielectric liquids is rather strong [13]; nonuniform Joule heating in a nonuniform field can also cause similar effects.

Let us consider forming of a space charge in a thermal boundary layer. If a heat-transfer surface in a fluid flow serves as an electrode, characterised by the current density j , then according to (5) a space charge

$$\rho = j \frac{d\tau}{dz} = \sigma E \frac{d\tau}{dz}$$

arises in the boundary layer where the axis z is normal to the surface. Since the boundary layer $dt/dz \neq 0$, then, as follows from the above formula, a unipolar charge appears within this layer, the density of the charge increasing with variations of τ and the electric field strength. The density of this charge decreases as its distance from the heat-transfer surface increases, and thus the condition for electroconvection to arise is satisfied throughout ($\nabla \rho \uparrow \downarrow \mathbf{E}$).

Usually, when studying convective heat transfer in an electric field, it is chiefly thermal nonuniformities (electrothermal convection), that the nature of the charge is related to. However, as experiments on electric potential distribution show, in a liquid which is in a capacitor field [14] accumulation of charges is also possible in a thermally uniform medium. In these cases nonuniformity with respect to τ may be caused either by the field itself,* or by mechanical nonuniformity of the fluid (as, for example, in emulsions and suspensions) [15].

*It is known that in powerful electric fields the dependence of electric conductivity and dielectric permeability of the medium on the strength becomes essential. Hence, an external nonuniform field can lead to corresponding nonuniformity of the medium with respect to the parameter τ , that is to electroconvection (electric wind in gases and dielectric liquids) [16].

A conclusion can be drawn from what has been said that study of electroconvection should necessarily involve determination of the space charge and the mechanisms of formation of the charge may be different.

A general aspect of composing differential equations governing convection and heat transfer in an electric field is considered in [1, 10, 12, 17]. This equation system differs from that governing convective heat transfer in a gravitational field by a force term (1) in the Navier–Stokes equation, the Joule heat term in the heat-conduction equation and is supplemented with the equations of electrodynamics. A solution of the problem is probably possible in particular cases with certain assumptions, but the general solution meets insuperable difficulties. In this respect the similarity theory methods are of great importance.

Reduction of convective heat-transfer equations in an electric field to a non-dimensional form results in a set of generalised similarity parameters which allowed the means of correlation of the experimental data to be found. Here we shall mention only some of the similarity numbers and explain their physical meaning. $\Pi_1 = \varepsilon_0 \varepsilon E^2 l^2 / \gamma v^2$ is the ratio of the Coulomb force to the viscosity force (analogue of the Galileo number). Π_1 is usually multiplied by one of the $\Delta \sigma / \sigma \sim \beta_0 \Delta t$ and $\Delta \varepsilon / \varepsilon \sim \beta_\varepsilon \Delta t$ simplexes (or by their sum), expressing nonuniformity of the fluid with respect to electrical conductivity and dielectric constant; as a result, complexes are obtained, similar to the Grashof number.

$\Pi_2 = \sigma l^2 / \varepsilon_0 \varepsilon v$ is a measure of proportion of the relaxation time of the mechanical disturbances to that of the electric field (charge) in the fluid [8, 15], that is Π_2 expresses a certain relation between the rate of change of mechanical conditions in the fluid and the rate of space charge formation due to these changes. Depending on the magnitude of this relation, accumulation of the charge in the medium may be either partial (when $\Pi_2 \ll 1$) or complete, up to saturation (when $\Pi_2 \gg 1$).

$\Pi_3 = \varepsilon_0 \varepsilon E l / k \gamma v$ is a measure of proportion of the forces due to “apparent viscosity” in an electric field and viscosity of the fluid [18].

The most important thing from the said above is that the necessary condition for electroconvection to start is nonuniformity of the medium with respect to the parameter τ . This nonuniformity may be of quite different nature, namely, thermal, mechanical, caused by the electric field itself, etc., and in practice we most frequently observe the net effect resulted from many of the mentioned effects.

As is known, study of such cases requires the technique based on separate investigation of each of the effects (if possible). Electrothermal convection as well as convection and heat transfer in case of corona discharges in gases are studied fairly well to date. As far

as electromechanical convection is concerned (convection, caused by mechanical nonuniformity of the medium might obviously be called so), such a problem was actually not considered. However, use of disperse materials as a working fluid either in heat transfer or in other processes, based on EHD-effects (particularly the EHD energy transformation), seems to be most promising.

2. EXPERIMENTAL RESULTS ON HEAT TRANSFER IN EMULSIONS

With the view to increase the EHD-effect the present authors have suggested [15] to use dielectric emulsions as heat-transfer fluids with a disperse phase* of higher conductivity. Heat-transfer rate in such fluids may be increased by the electric field effect, so that it will be of an order larger compared with that in case of free convection in large volume.

The effect of uniform and nonuniform electric fields on convective heat transfer was studied. Heat transfer of a disc (the case of a uniform field) and a cylinder (a nonuniform field) was investigated on the models of plane [8] and cylindrical [15] capacitors, respectively, with one of the plates being a heat-transfer surface. In the case of a cylindrical capacitor the inner electrode was a heat-transfer surface. The conditions of heat transfer in an infinite volume were provided by the second plate which was either permeable (a mesh) or placed at a quite large distance. The experimental technique also provided variations of almost all of the parameters involved in the similarity numbers. The experiments were made under stationary conditions, the error being within 10 per cent.

Let us consider some experimental relationships and the supposed mechanism of the field effect.

Heat-transfer coefficient α_E increases with the applied voltage (Fig. 1), and the field effect may be expressed by a power relation with a constant exponent of 0.5: $\alpha_E \sim U^{0.5}$.

The temperature driving force Δt does not actually affect the heat-transfer coefficient to emulsion, since nonuniformity of the medium caused by the temperature gradient obviously makes no essential contribution to the nonhomogeneity of the two-phase fluid existing at the moment.

The temperature t_f of the emulsion equally affects heat transfer, viscosity of the heat-transfer fluid and concentration of the disperse phase due to changes in the solubility and droplet dimensions as a result of surface tension change. Therefore, in every particular case dependence of α_E on t_f at $\varphi < 2$ per cent has a

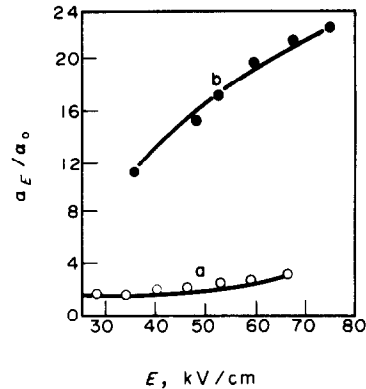


FIG. 1. Plot of the relative coefficient in kerosene (a) and aniline-kerosene emulsion (b) vs the electric field strength. The heat-transfer surface is a cylinder with the diameter of 3 mm; $\varphi = 8.4$ volume per cent; $t_f = 20^\circ\text{C}$, $\Delta t = 20$ deg.

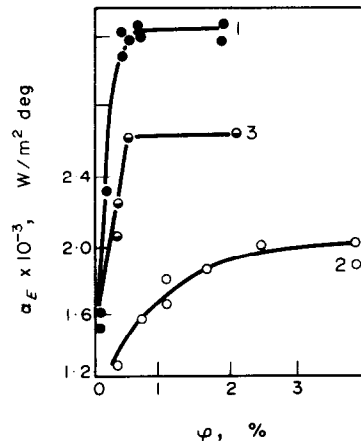


FIG. 2. Plot of the heat-transfer coefficient vs concentration of the disperse phase. $U = 25$ kV, $h = 20$ mm, $t_f = 30^\circ\text{C}$, $\Delta t = 20$ deg. 1. Alcohol-kerosene; 2. Alcohol-transformer oil; 3. Castor oil-kerosene.

special form. For example, in alcohol-transformer oil emulsions α_E increases with t_f , and here changes in the viscosity are probably controlling, but in alcohol-kerosene emulsions, α_E decreases. The latter fact is probably a consequence of a considerable increase in solubility of alcohol in kerosene with temperature, resulted in a decrease of the disperse phase concentration as it is verified experimentally.

Of the greatest interest is the relation between heat transfer and concentration of a disperse phase shown in Fig. 2. First increase of φ increases α_E , then (at

*To save space we shall use only the word "emulsion" in what follows.

$\varphi > 1-2$ per cent) the heat-transfer coefficient remains actually constant, and in case of sufficiently large concentrations some reduction of the heat-transfer rate is possible. Such dependence of α_E on φ may probably be attributed to the fact that as the concentration increases, the number of drops intensifying charge formation in the heat-transfer carriers grows. However, with large φ the forces causing EHD-effects are probably stabilised. A more detailed consideration of the charge-forming mechanism in emulsions in uniform electric fields is given below.

Visual observations, photography and high-speed photography of the behaviour of emulsions in the field of a plane capacitor give us the following picture of the EHD-processes. A drop of the higher conductivity phase, when on the electrode, gets certain charge due to electric contact, then it is separated from the electrode by the electrostatic repulsive force, and moves to the opposite electrode. A similar process occurs on the latter. Two cases should be noted here. In a dilute emulsion, when interaction of drops is hardly possible, each of them oscillates between the electrodes independently (Fig. 3a). But in a concentrated emulsion interaction of drops is observed (Fig. 3b) resulted in redistribution of charges among the drops, or in their mutual neutralisation and convective agitation of the fluid in the form of cellular motion.

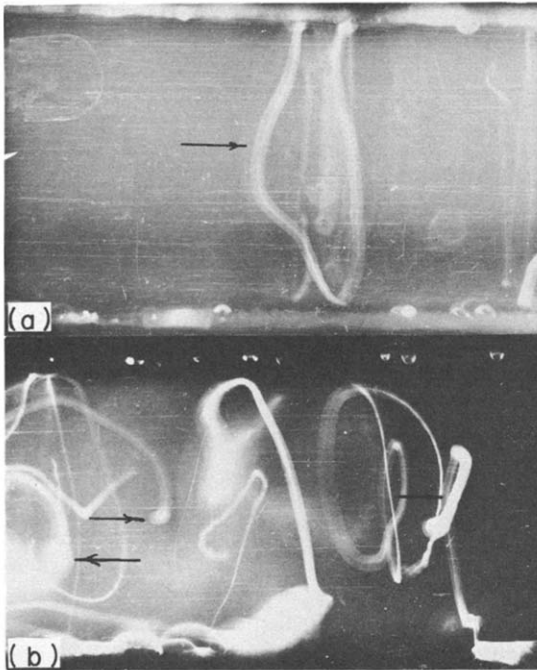


FIG. 3. Motion of ethyl alcohol drops in transformer oil. $U = 6$ kV, $h = 1$ cm. (a) The trajectory of a drop (indicated by an arrow) oscillating between the electrodes; (b) The trajectory of interacting particles.

The described behaviour of EHD-flows should be a consequence of formation of space charges because drops of the higher conductivity phase, leaving the electrode, form a "cloud" of the like charge; but those, which came from the opposite electrode at sufficiently high concentration of the disperse phase are partially or completely neutralised, having met oppositely charged drops. From the above said it follows that positively charged drops are generally in excess near the positive electrode, and an excess of negatively charged drops may be found near the negative one. Such distribution of charges is mechanically unstable, and thus, satisfies the condition for electroconvection to arise. It is noteworthy that the slower the particle motion, the more clearly its trajectory is displayed. There are reasons to suppose that the sections in Fig. 3 indicated by arrows show motion of partially or completely neutralised drops.

3. STATEMENT OF THE PROBLEM

The problem is to compose, on the basis of the statements of mechanics and electrophysics, a system of equations governing electrohydrodynamics and heat transfer in emulsions.

The theory of hydrodynamics and heat transfer in multiphase fluids is being developed in several directions [19,20]. Two of them may probably be most acceptable here. The first is consideration of a mixture as a single-phase fluid with mean parameters. In this case the problem can be expressed by an ordinary equation system, if the Coulomb term ρE is included into the equation of motion, and the system is supplemented with equations of electrodynamics. The second direction implies the account for relative velocities of the phases, and the problem is formulated for each of the phases with account for coefficients of their interaction [19]; here the Coulomb term should be included into the equation of motion only for a more conductive phase as a charge-carrier. In each of the mentioned cases the system should be supplemented with the equation of charge conservation, the Poisson equation and the equation relating the potential and the strength of the field.

We shall consider below emulsions as a homogeneous incompressible fluid with mean parameters. The disperse phase is composed by spherical particles of equal size and mass, carrying equal charges of a positive (q^+) or negative (q^-) sign or neutral. The bulk concentration (φ) of the disperse phase is assumed sufficiently small so that the following inequality may be written

$$\varphi \ll 1. \quad (6)$$

Let n with the appropriate superscripts designate the

concentration of particles: n^+ , n^- , n^0 , n and φ are related by

$$n = n^+ + n^- + n^0, \quad (7)$$

$$\varphi = \frac{4}{3}\pi r^3 n. \quad (8)$$

Electroconvection of emulsion is ensured by force ρE , where

$$\rho = \rho^+ + \rho^-, \quad (9)$$

$$\rho^\pm = n^\pm q^\pm. \quad (10)$$

Equation (10) is a general form of two equations for drops of different signs. Such a form of similar equations will be used in the subsequent text.

The charge received by a conducting spherical drop in electric contact with a flat electrode, is defined by [21]

$$q^\pm \approx \pm 3\pi\epsilon_0 \epsilon r^2 E_c, \quad (11)$$

where E_c is the field strength at the plate surface far from the drop, r is the drop radius.

Viscous drag of the main phase to the motion of the drop is determined from the Stokes formula. Velocity V_n of the charged drop relative to the closed phase is found from the condition of equal Coulomb forces and viscous drag:

$$V_n = \frac{qE}{6\pi\eta r}. \quad (12)$$

Parameters of the emulsion can be found experimentally or from the available predicted relations. For example, viscosity can be found from the Einstein formula [22]

$$\eta = \eta_2(1 + 2.5\varphi). \quad (13)$$

Dielectric constant of the mixture [23] can be found from

$$\epsilon = \epsilon_2 + \varphi \frac{3(\epsilon_1 - \epsilon_2)\epsilon_2}{\epsilon_1 + 2\epsilon_2} \quad (14)$$

etc.

On the basis of the above physical assumptions the equations of energy (without Joule heat) and continuity are to be written as

$$\mathbf{v}\nabla\vartheta = \frac{\lambda}{c\gamma} \nabla^2\vartheta_1 \quad (15)$$

$$\nabla\mathbf{v} = 0. \quad (16)$$

In the equation of motion the force $g\beta\vartheta$ is neglected and the Coulomb force $(1/\gamma)\rho E$ is included

$$(\mathbf{v}\nabla)\mathbf{v} = -\frac{1}{\gamma} \nabla p + \frac{1}{\gamma} \rho \mathbf{E} + \nu \nabla^2 \mathbf{v}. \quad (17)$$

Let us add equations of electrodynamics to the system (15)–(17). Before this we write the law of conservation of charged particles:

$$\nabla(n^\pm \mathbf{W}^\pm) = -An^+n^-|\mathbf{W}^+ - \mathbf{W}^-|, \quad (18)$$

where A is the effective cross-section of drop collision. The l.h.s. of the equation defines the flow of particles of a certain sign via a unit volume surface, the r.h.s. is the number of collisions of particles of opposite charges, that is, the number of recombinations in this volume per unit time. \mathbf{W}^\pm is the particle velocity relative to a fixed co-ordinate system

$$\mathbf{W}^\pm = \mathbf{v} + \frac{q^\pm \mathbf{E}}{6\pi\eta r}, \quad (19)$$

where \mathbf{v} is the closed phase velocity.

The above equation implies

$$|\mathbf{W}^+ - \mathbf{W}^-| = \frac{qE}{3\pi\eta r}. \quad (20)$$

Upon multiplying the l.h.s. of (18) by q^\pm and the r.h.s. by $q^\pm = q^+q^-/q^\mp$ with account for (10) and (20) we obtain

$$\nabla(\rho^\pm \mathbf{W}^\pm) = \pm A\rho^+\rho^- \frac{E}{3\pi\eta r}. \quad (21)$$

When deriving equation (21) collisions of charged particles with neutral ones were not taken into account, as this does not lead to any change of the rate of charge neutralisation if A is a constant value. Indeed, if upon collision of charged particles with neutral ones the number of the former increased by m times, the mean charge of a particle decreased by m times also that as follows from equation (10) will generally cause no changes in equation (21).

Particularly, equation (21) implies that

$$\nabla(\rho^+ \mathbf{W}^+) + \nabla(\rho^- \mathbf{W}^-) = \nabla\mathbf{j} = 0, \quad (22)$$

which corresponds to the conventional form of the law of charge conservation.

The Poisson equation

$$\rho^+ + \rho^- = -\epsilon_0 \epsilon \cdot \nabla^2 U. \quad (23)$$

The equation relating potential U and strength E of the field

$$E = -\nabla U. \quad (24)$$

So, as a result of the present analysis we obtained a system of equations, which, provided the adopted assumptions hold, describes convective heat transfer in emulsions of dielectric fluids with a more conductive disperse phase in an electric field. Substitution of (9)

into (17) and (19) into (21) and certain manipulations yield

$$\left. \begin{aligned} v\nabla\vartheta &= \frac{\lambda}{c\gamma} \nabla^2\vartheta, \\ \nabla v &= 0, \\ (v\nabla)v &= -\frac{1}{\gamma} \nabla p + \frac{1}{\gamma} \mathbf{E}\varepsilon_0\varepsilon \nabla E + v\nabla^2 v, \\ v\nabla\rho^\pm + \nabla\left(\rho^\pm \frac{q^\pm \mathbf{E}}{6\pi\eta r}\right) &= \pm A\rho^+\rho^- \frac{E}{3\pi\eta r}, \\ q^\pm &= \pm 3\pi\varepsilon_0 e r^2 E_c, \\ \rho^+ + \rho^- &= \varepsilon_0\varepsilon \nabla E, \\ \mathbf{E} &= -\nabla U. \end{aligned} \right\} (25)$$

This system consists of nine equations (two vectors) with nine unknown quantities ($\vartheta, v, p, \rho^+, \rho^-, \mathbf{E}, q^+, q^-, U$), which is soluble in principle.

4. A SPECIAL CASE OF CONCENTRATION DISTRIBUTION OF CHARGED PARTICLES OF EMULSION IN THE FIELD OF A FLAT CAPACITOR

Although the solution of this problem does not give all the general quantitative relations between quantities under the real conditions of interest, still it permits certain useful conclusions.

Let us assume that the space between the plates is filled with a disperse material; the conducting particles of $2N$ concentration, receiving charges of the same absolute values at the electrodes, move towards each other with a constant velocity. The closed phase is assumed to be at rest ($v = 0$). Collision of particles of opposite signs implies their recombination. The coordinate origin is placed at the positive electrode, the direction of the Ox axis coincides with that of the electric field.

With the above assumptions equation (18) in a one-dimensional case can be written as

$$\left. \begin{aligned} \frac{dn^+}{dx} &= -Bn^+n^-, \\ \frac{dn^-}{dx} &= Bn^+n^-, \end{aligned} \right\} (26)$$

where $B = 2A$.

Let (26) satisfy the boundary conditions

$$n^+|_{x=0} = n^-|_{x=h} = N. \tag{27}$$

Then the solution of system (26) yields

$$n^+ + n^- = C, \tag{28}$$

$$\frac{1}{BC} \ln \frac{(n^- - C)N}{n^-(N - C)} = h - x. \tag{29}$$

From (29), at $x = 0$ with account for (27) and (28) we obtain

$$\frac{ye^y}{1 + e^y} = Z, \tag{30}$$

where

$$y = \frac{CBh}{2}, \quad Z = \frac{NBh}{2}.$$

The integration constant is found from the plot of function (30). The appropriate concentration distribution of charged particles between the plates of the flat capacitor

$$\frac{n^+ - n^-}{N} = f(x) \tag{31}$$

and the relation between the concentration of charged particles at the electrodes and the emulsion concentration

$$\frac{n^+ - n^-}{N} = f(N) \tag{32}$$

are plotted in Figs. 4 and 5, respectively.

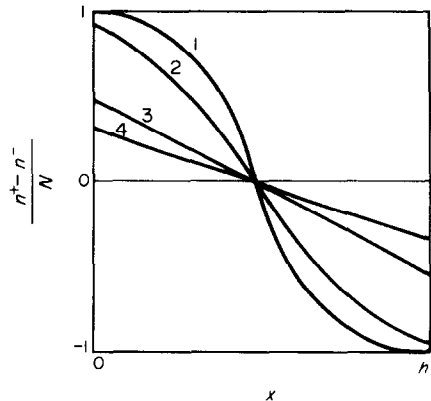


FIG. 4. Density distribution of charged particles in the field of a plane capacitor. $B = 10^{-9} \text{ m}^2$, $h = 1 \text{ cm}$, 1-4, $N = 10^{12}$; 5×10^{11} ; 10^{11} and $5 \times 10^{10} \text{ m}^{-3}$, respectively. The notations as in Fig. 2.

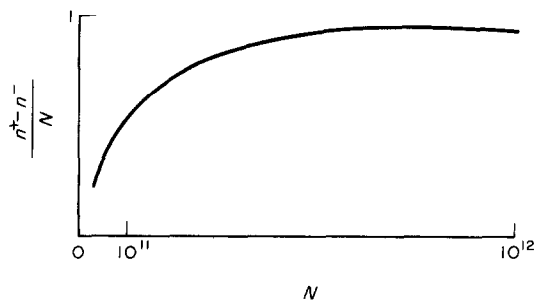


FIG. 5. Relation $(n^+ - n^-)/N = f(N)$ at $B = 10^{-9} \text{ m}^2$, $h = 1 \text{ cm}$.

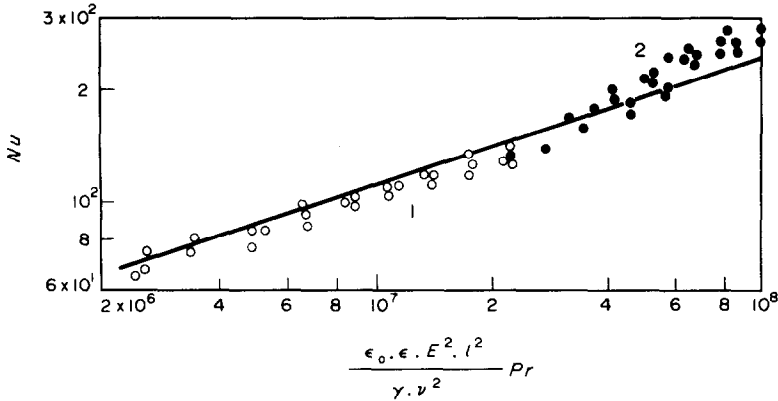


FIG. 6. Heat transfer to emulsions with disperse phase of a higher conductivity in a weakly nonuniform electric field. The heat-transfer surface is a cylinder with the diameter of 3 mm. 1. Aniline-transformer oil; 2. Aniline-kerosene.

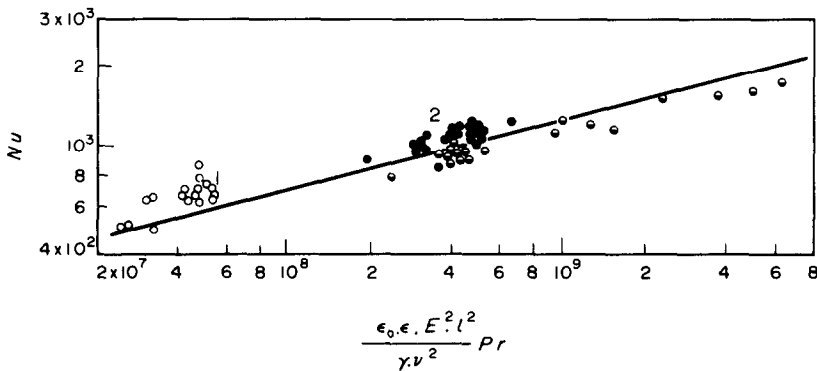


Fig. 7. Heat transfer in a uniform electric field. The heat-transfer surface is a flat disc. The notations as in Fig. 2.

The above example illustrates within the assumptions adopted the processes in emulsions placed in the field of a capacitor, and the obtained results show that:

(a) Under the effect of an electric field a space charge (Fig. 4) is formed (mostly in the vicinity of the electrode) in emulsions of dielectric fluids with a disperse phase of higher conductivity.

(b) As the particle concentration increases, the relation $n^+ - n^-/N = f(N)$ (Fig. 5) asymptotically approaches the straight line $n^+ - n^-/N = 1$ that indicates stabilisation of the charge density and of the Coulomb force, and, hence, similarity of heat-transfer regime at large N ; the relation between α_E and φ (Fig. 2) is similar.

(c) The process of charge formation in homogeneous fluids is obviously similar, if the fluids contain admixtures in the form of dust particles, drops and other solids, which can be recharged at the electrodes.

5. GENERALISED RELATIONS

The data on heat transfer to emulsions in a similarity case ($\varphi > 2$ per cent) are fairly well approximated by a dimensionless relation of the form

$$Nu = C \left(\frac{\epsilon_0 \epsilon_2 E^2 l^2}{\gamma v^2} Pr \right)^n, \quad (33)$$

which shows the intensifying effect of both weakly nonuniform (Fig. 6) and uniform (Fig. 7) d.c. electric fields. Here ϵ_2 is the relative dielectric constant of the closed phase; E is the predicted strength of the electric field at the heat-transfer surface; γ , v and Pr are parameters of the emulsion; $v = \eta/\gamma$, where η is calculated from formula (13).

For a cylinder with the diameter l , $C = 0.45$, $n = 0.34$. The formula is derived for $Pr = 2 \times 10^6 - 10^8$,

$$E = \frac{U}{r_1 \ln \frac{r_1}{r_2}},$$

r_1 is the cylinder radius, r_2 is the radius of a high-voltage cylindrical (mesh) electrode coaxial with the heat-transfer surface.

For a flat disc with the diameter l , $C = 11.0$, $n = 0.22$. The formula is derived for $\prod_I = 2 \times 10^7 - 9 \times 10^9$, $E = U/h$.

6. CONCLUSIONS

So, use of emulsions with a disperse phase of higher conductivity makes it possible to increase considerably electrohydrodynamic perturbation of the heat-transfer fluid, thus ensuring essential intensification of heat transfer. The behaviour of the disperse phase shows that the particles obtain a charge at the electrodes and as far as they move, they become neutralised, in particular, when colliding with charge carriers of the opposite sign. As a result a space charge is formed, mostly in the vicinity of the electrodes, whose density with growth of the concentration of the emulsion tends to a certain constant value, defining the area of similarity heat transfer. The account for the proportion between the Coulomb and viscous forces in terms of similarity numbers leads to a simple relation which satisfactorily approximates the experimental results and may be proposed for calculations.

REFERENCES

1. G. A. Ostroumov, Isothermal self-motion of fluids in an electric field, *Elektron. Obrabot. Mater.* No. 2, 32-44 (1970).
2. R. A. Moss and J. Grey, Intensification of heat transfer affected by d.c. and a.c. electric fields, *Advances in Heat Transfer*, pp. 426-453. Izd. Mir. Moscow (1970).
3. N. F. Baboi, M. K. Bologna and K. N. Semenov, An effect of electric fields on heat transfer in liquids and gases, *Elektron. Obrabot. Mater.* No. 1, 57-71 (1965).
4. K. N. Semenov, F. P. Grosu and M. K. Bologna, An effect of a corona discharge on heat transfer under natural convection conditions of air, *Inzh.-Fiz. Zh.* 15, 922-930 (1967).
5. M. K. Bologna, Yu. T. Burbulya and I. A. Kozhukhar, Heat transfer with natural convection of dielectric fluids in an electric field, *Heat and Mass Transfer*, Vol. 1, pp. 699-703. Energiya, Moscow (1968).
6. N. F. Baboi and M. K. Bologna, Boiling heat transfer in organic fluids, in *Heat and Mass Transfer—II. Heat and Mass Transfer with Physical and Chemical Conversions*, pp. 197-204. Nauka i Tekhnika, Moscow (1968).
7. M. K. Bologna, Yu. T. Burbulya and E. L. Khlolina, An experimental study of an effect of electric fields on heat transfer in slits, *Elektron. Obrabot. Mater.* No. 5, 51-58 (1969).
8. I. A. Kozhukhar and M. K. Bologna, Heat transfer to organic fluids solutions in a uniform electric field, *Elektron. Obrabot. Mater.* No. 3, 60-62 (1969).
9. F. P. Grosu and M. K. Bologna, Forces providing electrothermal convection of poor-conducting fluids, *Elektron. Obrabot. Mater.* No. 2, 59-66 (1970).
10. F. P. Grosu and M. K. Bologna, On conditions for electric convection to arise, *Elektron. Obrabot. Mater.* No. 6, 58-63 (1968).
11. Yu. T. Burbulya, M. K. Bologna and I. A. Kozhukhar, A dependence of heat transfer of a vertical cylinder on a heat flux direction in an electric field, *Izv. AN Mold. SSR, ser. Fiz-Matem. Nauk* No. 6, 39-43 (1967).
12. F. P. Grosu and M. K. Bologna, On contribution of electric convection to a heat-transfer process, *Izv. AN Mold. SSR, ser. Fiz-Matem. Nauk* No. 2, 44-48 (1968).
13. G. I. Skanavi, *Physics of Dielectrics (Region of Weak Fields)*, pp. 216-220, 241-245. GITL, Moscow (1949).
14. P. K. Mitskevich and L. S. Kazatskaya, Investigation of potential distribution in liquid dielectrics using the Kerr effect method, *Elektron. Obrabot. Mater.* No. 2, 71-74 (1968).
15. I. A. Kozhukhar and M. K. Bologna, Heat transfer in dielectric fluid emulsions affected by an electric field, *Elektron. Obrabot. Mater.* No. 1, 51-55 (1968).
16. V. I. Arabadzhi, On an electric wind from a point, *Zh. Tekh. Fiz.* 20(8), 967-969 (1950).
17. A. M. Mkhitarian, V. Ya. Fridland, G. N. Boyarsky and V. A. Kasiyanov, Experimental investigation of electrohydrodynamic effect on aerodynamic characteristics of a profile, *Some Problems of Aerodynamics and Electrohydrodynamics*, Vol. 2, pp. 115-124. Kiev (1966).
18. I. A. Kozhukhar, M. K. Bologna and R. S. Luvishchuk, Heat transfer from a plate to dichloride ethane-transformer oil mixture in an electric field, *Izv. AN Mold. SSR, ser. Fiz-Tekh. i Matem. Nauk* No. 1, 89-91 (1970).
19. D. F. Fainzullaev, A laminar motion of multiphase media in pipe-lines, *Izd. FAN, Uzbeksk. SSR*, 5-8 (1966).
20. A. N. Kraiko and L. E. Sternin, To the theory of double-velocity continuum flows with solid and liquid particles, *Prikl. Matem. i Mekh.* 29(3), 418-429 (1965).
21. O. A. Mezdryakov, V. N. Demidovich and V. A. Suslov, An ionization-mechanical detector of ionizing radiations, *Atom. Energiya* 20(5), 442-444 (1968).
22. W. Clayton, *Theory of Emulsions and Their Technical Treatment*, edited by G. G. Samner. London (1954).
23. L. D. Landau and E. M. Lifshits, *Electrodynamics of Continua*, p. 69. GIFML, Moscow (1959).