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EXPERIMENTAL INVESTIGATION OF THE ELECTRICAL CONDUCTIVITY OF A TWO-PHASE STREAM

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We consider the question of the effective electrical conductivity of a bubbling stream, for which a computation relation is proposed. We give the results of the experiment.

Two-phase streams of an electrically conductive liquid with bubbles of a gas which is not electrically conductive (bubbling streams) appear to have come into widespread use in the liquid-metal MHD generators of self-contained power installations [1-3].

To perform the calculations for an MHD channel with a bubbling stream of working substance, we must know the variation of the electrical conductivity as a function of the amount of the gaseous phase per unit volume. Literature [4-6] contains some well-developed methods for calculating the coefficients of generalized conductivity of heterogeneous structures in which the concentrations of the components present are expressed by functions $C_i = f_i(x, y, z)$.

The distinguishing feature of bubbling streams is the interaction of the interface between the phases with turbulent pulsations of the carrying phase. The problem of determining the conductivities in a bubbling stream is complicated further by the fact that the gas bubbles may be in chaotic motion in the stream, may have arbitrary shape, and may be deformed, pulsate, break up, and coagulate. The result is that the stream parameters become nonstationary; e.g., the concentration of bubbles is expressed by the function $C = C(x, y, z, t)$, and we must obtain a space—time average. Furthermore, bubbling streams

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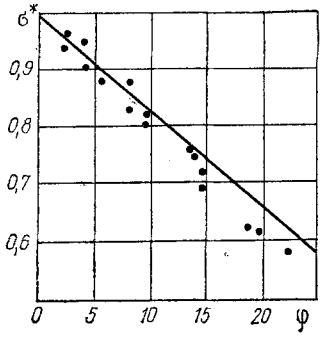

Fig. 1. Reduced electrical conductivity of the bubbling stream as a function of the volumetric gas content, %.

may, as is known [7], reconstruct their structure with an increase in the amount of gaseous phase per unit volume. If the bubbling regime of flow is replaced, e.g., by a dispersed regime (drops of electrically conductive liquid in a nonconductive gas), the function $\sigma^* = \sigma(\varphi)$ has a discontinuity at $\varphi = \varphi_{cr} < 1$. The loss of electrical-conduction properties by the bubbling stream is due to the loss of stability in the liquid films penetrating the stream and is a consequence of a hydrodynamic crisis [8]. Therefore, the discontinuity of the function $\sigma^* = \sigma(\varphi)$ is characterized not by an exact but by a most probable value of φ_{cr}.

It should be noted that the model of an infinitely conductive cluster used by the authors of [6] to explain a similar conductivity jump in heterogeneous structures does not take account of hysteresis in the hydrodynamic and, consequently, the electrical-conductivity properties of a two-phase stream as the gas content varies.

In what follows, we shall consider bubbling streams in which the turbulent pulsations of the carrying phase are regular and periodic.

Suppose that the domain V of the bubbling stream is a rectangular parallelepiped with edges $a < l \ll h$. We assume that for every V_0, consisting of a volume $V_1(t)$ of the liquid phase and $V_2(t)$ of the gaseous phase and satisfying the inequality $r^3 \ll V_0 \ll V$, the average volumetric gas content φ will be constant, i.e.,

$$\varphi = \frac{1}{tV_0} \int_0^t dt \int_0^{V_0} \varphi(x, y, z)\, dV = \text{const}. \tag{1}$$

Here $\varphi(x, y, z)$ is a unit function, equal to $\varphi(x, y, z) = 1$, if $x, y, z \in V_2(t)$ and $\varphi(x, y, z) = 0$ if $x, y, z \in V_1(t)$, but $V_0 = V_1(t) + V_2(t)$. Physically this means that the fluctuations in gas content, bubble concentration, and bubble radii will not be many times as great as the corresponding average values of φ, C, r.

If Eq. (1) is satisfied for small Weber numbers [9], we can regard the bubbling stream as monodisperse, with a uniform distribution of spherical gas bubbles throughout the stream.

The condition of densest packing of the parallelepiped V with spherical bubbles determines the value of the limiting permissible gas content in the bubbling stream

$$\varphi_{\text{sph. max}} = \frac{Vg}{V} = \frac{4}{3}\pi r^3 \frac{\frac{a}{2r}\,\frac{l}{2r}\,\frac{h}{2r}}{alh} = \frac{\pi}{6}. \tag{2}$$

The number of bubbles situated along the edges of the parallelepiped can be found from the corresponding expressions

$$n_a = aC_L \quad n_l = lC_L, \quad n_h = hC_L. \tag{3}$$

Now suppose that the faces of the parallelepiped formed by edges l and h are subjected to some potential difference and that these faces themselves are equipotential surfaces. To find the electrical resistance of the bubbling stream, we subdivide the volume of the parallelepiped by equipotential planes into layers of thickness 2r. Making use of Dirichlet's "principle of cells" and taking account of the above assumptions, we can easily show that some of these layers will contain gas bubbles ("bubble layers"), while others will not ("liquid layers"). The number of bubble layers will be equal to n_a, while the number of liquid layers will be $-a/2r - n_a$.

The electrical conductivity of a bubble layer can easily be determined if each spherical cavity formed by the gas bubbles in this layer is replaced by a cylindrical hole of the same radius

$$r_{bub} = \frac{2r}{\sigma lh\,(1 - \pi r^2 C_L^2)}. \tag{4}$$

Such a replacement is based on the assumption that the electrical conductivity of a bubble layer with spherical inclusions will be the same as that of a bubble layer with cylindrical inclusions.

The electrical conductivity of a liquid layer will be equal to

$$r_{liq} = \frac{2r}{\sigma lh}, \tag{5}$$

and the electrical resistance of the parallelepiped will be determined by adding the expressions (4) and (5) for all the layers; its value will be

$$R = \frac{a}{\sigma lh}\left(1 + \frac{2\pi r^3 C_L^3}{1 - \pi r^2 C_L^2}\right). \tag{6}$$

On the other hand, this same resistance can be found by using the effective electrical resistance of a bubbling stream, i.e.,

$$R = \frac{a}{\sigma_{el} h}. \tag{7}$$

Equating the right sides of the expressions (6) and (7) and writing the expression for σ_{el}, we obtain

$$\sigma_{el} = \frac{\sigma}{1 + \dfrac{2\pi r^3 C}{1 - \pi r^2 C^{2/3}}}. \tag{8}$$

Taking account of the fact that in the case when the inclusions are cylindrical, the quantities C and φ_{cyl} are related by the equation

$$\varphi_{cyl} = 2\pi r^3 C,$$

we find from the expression (8) that

$$\sigma^* = \frac{\sigma_{el}}{\sigma} = \frac{1}{1 + \dfrac{\varphi_{cyl}}{1 - \left(\dfrac{\pi}{4}\varphi_{cyl}^2\right)^{1/3}}} \tag{9}$$

It should be noted that when the spherical bubbles are replaced by cylindrical bubbles, the gas content in the stream is increased from φ_{sph} to φ_{cyl}. For an equal concentration of inclusions, these quantities are related by the formula

$$\varphi_{cyl} = \frac{3}{2}\varphi_{sph}.$$

Substituting the last expression into (9), we can revert to the original gas content of the two-phase stream and obtain the desired function

$$\sigma^* = \frac{1}{1 + \dfrac{3}{2}\dfrac{\varphi_{sph}}{1 - \left(\dfrac{9\pi}{16}\varphi_{sph}^2\right)^{1/3}}}. \tag{10}$$

The expression (10) remains valid in the passage to the liquid phase as a limit, i.e., as $\varphi_{sph} \to 0$, $\sigma^* \to 1$. Furthermore, it follows formally from it that for the critical value of gas content,

$$\varphi_{sph.cr} = \frac{4\sqrt{\pi}}{3\pi} > \varphi_{sph.max}$$

the electrical conductivity of the stream becomes zero, which qualitatively reflects the above-mentioned property of the bubbling stream.

The last inequality can easily be explained if we take note of the fact that in a two-phase stream packed as densely as possible with spherical (or cylindrical) bubbles, there remains a space filled with electrically conductive liquid. Consequently, for $\varphi_{sph.max}$ the bubbling stream is still capable of conducting electricity. The actual loss of electrical-conductivity properties in a bubbling stream must be attributed to a gas-content value such that the liquid films lose stability and the structure of the bubbling stream is reconstructed.

It should also be noted that for values of $\varphi_{sph} \ll 4/3\sqrt{\pi}$ the expression (10) becomes the simple formula

$$\sigma^* = \frac{1}{1 + \frac{3}{2}\varphi_{sph}}. \tag{11}$$

In order to explain the validity of formula (10), we verified it experimentally.

Into a vertically placed rectangular channel made of plastic, with copper electrodes glued onto two opposite walls, we poured water with an electrical conductivity of $\sigma = 0.5$ $(\Omega \cdot m)^{-1}$. In the lower part of the channel we set up a special block with a perforated sheet having holes of diameter $8 \cdot 10^{-4}$ m. The block was fed from a compressor, by means of a reducer having coarse and fine adjustments, with air whose flow rate could be regulated. When air was bubbled into the liquid, we obtained a bubbling structure similating a two-phase stream. On the free surface of the water in the channel we placed a floating partition, whose level during the time the air was blown in determined the gas content of the air bubbles in the water. For different values of air flow rate determining the gas content φ, we measured the electrical resistance of the water in the channel by means of a Ts4341 tester. The error in the gas-content measurements based on the level of the partition did not exceed 10% for values of $\varphi \leq 25\%$. For larger values of φ the accuracy of the measurement of this quantity was lower because of the severe fluctuations of the partition. The error in the measurement of the electrical resistance was no more than 5% and was determined by the capabilities of the measuring instrument.

In the experiment we found a slight gas-content gradient with respect to the height of the channel, due to the expansion of the bubbles as they floated upward.

The processed results of the series of measurements made in the experiment are shown in Fig. 1. The figure also shows the function $\sigma^* = f(\varphi)$ calculated from formula (10). A comparison of the calculated and experimental values of σ^* shows that for $\varphi \leq 25\%$ the difference between them is no more than 7%, which is within the limits of experimental error.

NOTATION

σ, σ_{el}, $\sigma^* = \sigma_{el}/\sigma$, electrical conductivity of the liquid phase, effective electrical conductivity, and effective electrical conductivity ratio of the bubbling stream, respectively; t, time interval used in averaging; V and V_g, volume of the parallelepiped and of gas bubbles, respectively; C and C_L, volumetric and linear concentrations of gas inclusions, respectively, $C = C_L^3$; r_{bub} and r_{liq}, electrical resistances of the bubble layer and the liquid layer, respectively; R, electrical resistance of the bubbling stream in the volume of the parallelepiped. Subscripts: sph and cyl, packing of the stream with spherical and cylindrical gas inclusions; max and cr, maximum and critical values, respectively.

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THERMAL CONDUCTIVITY OF LIQUID PROPIONATES AT HIGH TEMPERATURE AND PRESSURE

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Experimental data on thermal conductivity of octyl- and heptylpropionate over a wide range of temperature and pressure are presented.

Special and complex apparatus is required to perform experiments at high pressure and temperature. In recent years nonstationary methods have been employed widely, in particular, the technique of the spherical and cylindrical regular regime bicalorimeter [1-3]. These methods do not consider the temperature dependence of thermophysical properties, which differ little from stationary values over the duration of the experiment (at high temperature), and moreover, do not permit determination of the temperature dependence of thermal conductivity from a single experiment. In this connection, monotonic heating techniques are more promising for studies over a wide temperature and pressure range. They are convenient because measurements over a wide temperature range do not require multiple reestablishments of a stationary state, and because they do permit determination of the thermal conductivity temperature dependence $\lambda = F(T)$ in a single experiment over a temperature range which is infinite in principle.

The present study, which is a continuation of previous investigations [4-11], is dedicated to experimental determination of the thermal conductivity of liquid propionates (octyl- and heptylpropionate). The specimens studied were chemically pure, with chromatographic analysis revealing a content of not less than 99.20% of the desired substance.

The temperature range studied extended from room temperature to 600°K at pressures up to 147 MPa. Measurements were performed by the continuous heating method in a newly developed variant of the cylindrical bicalorimeter. The theory behind the method, the experimental technique used, and the construction of the device were described in detail in [9, 11, 12].

The main component of the experimental equipment is a cylindrical bicalorimeter consisting of two coaxially arranged cylinders. The gap between the cylinders is filled with the liquid to be studied.

The experimental thermal conductivity determination reduces to measurement of the time delay of the core temperature relative to the temperature of the block. Measurements were performed at various heating rates, which permitted variation of the temperature differential across the liquid layer over the range 3-8°K. The absence of convection was verified by measurements performed at different heating rates. In calculating the thermal conductivity, all the corrections intrinsic to this technique [11] were applied. No correction for radiation was provided in view of the absence of data on absorption spectra of the materials studied. Maximum relative measurement error is estimated to be ±2%. Reproducibility of

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