EFFECT OF STRUCTURE FORMATION IN A CONSTANT ELECTRIC FIELD ON THE THERMAL CONDUCTIVITY OF A SUSPENSION OF AEROSIL IN CETANE

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This article presents the results of an experimental determination of the effective thermal conductivity of a suspension of Aerosil in cetane as a function of the electric field intensity, the activator content, and the concentration of particles by weight.

In the investigation of electrorheological suspensions, until recently, the main attention was devoted to their mechanical and electrophysical properties [1, 2]. It was found that thermal effects influence the rheological characteristics, primarily the plastic component of flow and the effective viscosity, the conductivity in an electric field, the dielectric permittivity, and the tangent of the angle of dielectric loss of electrorheological suspensions. Our observations showed that the particles of a suspension in an electric field form various structures whose geometry and strength are determined, other things being equal (same nature and properties of the solid phase, same form and concentration of the activator adsorbed on it), by the intensity of the external electric field. Thus, electrorheological suspensions constitute systems with a variable structure that can be regulated over a wide range. It may be assumed a priori that the transfer of matter (heat, mass, momentum, charge) by such a system will also be determined by the characteristics of the electric field applied to it. Until recently, no information on the thermal conductivity of electrorheological suspensions was available. Such information has not only theoretical, but also great practical, value, particularly in the use of an electrorheological effect for holding parts in place during mechanical treatment, when it is necessary to know the rate of heat transfer through a film of the suspension.

In order to investigate the thermal properties, we selected suspensions of A-175 Aerosil in cetane; the mechanical and electrical properties of such suspensions were investigated earlier [3, 4]. Activators from the gaseous phase – water or diethylamine – were adsorbed onto the surface of the Aerosil, which had been dried in advance. The suspension was made uniform by ultrasonic treatment of the mixture of aerosil and cetane (UZDN-1 generator, frequency 15 khz).

The investigation was carried out by the nonstationary plane-layer method [5]. We constructed a special measuring cell which made it possible to fix a uniform parallel-plane layer of the suspension being investigated by applying a constant electric field in a direction normal to the isothermal source of heat.

The experimental apparatus consisted of the measuring cell, a single-point electron potentiometer, a thermostat, and a high-voltage source. The scheme of the measuring cell is shown in Fig. 1. A thick-bottomed cylindrical cuvette 4 made of polymethylmethacrylate was used as a standard material with a known thermal activity. A copper – constantan thermocouple 7 was caulked at the center of the polished bottom of the cuvette, and a thin layer of nickel 3, serving as the zero electrode, was chemically deposited over its entire surface. The other electrode was a thin-walled hollow copper cylinder 1 connected to the thermostat. A second copper – constantan thermocouple 8 was soldered to the surface of the cylinder to check that the temperature remained constant; the external surface of the cylinder was covered with silver in order to keep the copper from corroding. The diameter of the heater cylinder 1 was less than the

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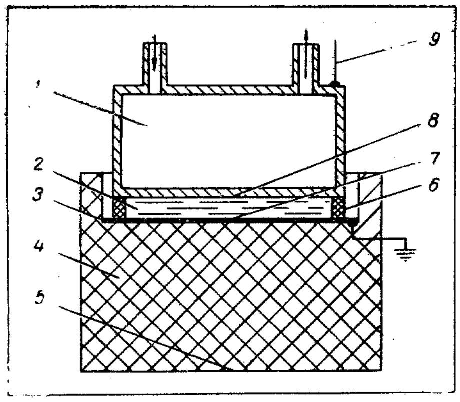

Fig. 1

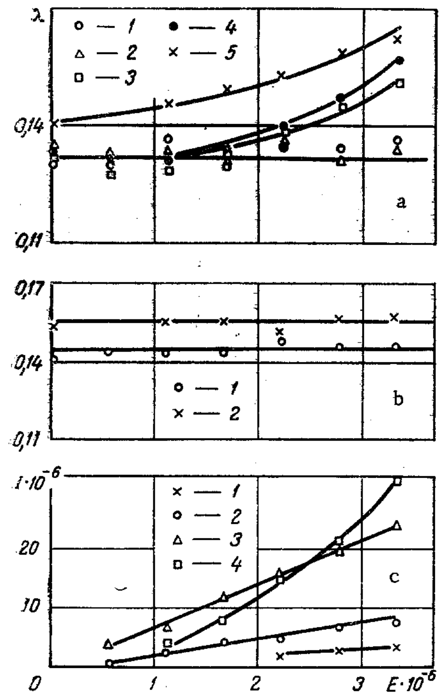

Fig. 2

Fig. 1. Scheme of the experimental cell.

Fig. 2. Effective thermal conductivity λ_{eff} (W/m · deg) (a, b) and electrical conductivity I (c) of 3% suspensions of Aerosil in cetane as functions of the intensity of a constant electric field E (V/m) for the following activator content values. a) Water: 1) 0%; 2) 2.7%; 3) 5.2%; 4) 7.7%; 5) 9.8%; b) diethylamine: 1) 4.8%; 2) 6.7%; c) water: 1) 5.2%; 2) 7.7%; 3) 9.8%; diethylamine: 4) 6.7%.

diameter of the cuvette 3, and the gap between the two electrodes was kept uniform by means of three supporting legs 6 of equal height (0.9 mm).

The method used in conducting the experiment was the following. The suspension under investigation 2 is poured into the cuvette 4, the heater 1 is put in, the lower electrode is grounded, making it possible to record the readings of the differential thermocouple (junctions 7, 5) with no induction and no distortion. The upper electrode is connected through a contact 9 to a VS-23 regulated high-voltage source. In the experiments in which an electric field is applied, the given intensity is maintained for 1 min; in addition, the thermostatted liquid is poured into the copper heating cylinder 1, and at the same time the potentiometer paper drive is turned on in order to record the thermograms.

The experiment is continued until a stationary condition is reached; in our case this means ~60 sec. We then remove the electric field and measure the temperature of the heater.

The resulting thermogram of the process of heating the suspension makes it possible to determine all the necessary parameters for calculating the thermal conductivity, which is not a true, but an effective, characteristic [5]. The thermal-conductivity measurements were made for suspensions with dispersed-phase concentrations of 0-8%, various values of activator content, and electric field intensities of (0-3.3) $\cdot 10^6$ V/m.

Figure 2 shows the results of our investigation of the thermal conductivity of suspensions of Aerosil in cetane for various values of electric field intensity. As can be seen in Fig. 2a, the nature of the λ_{eff} vs E curve depends on the type and amount of activator used. For suspensions with no activator (Fig. 2a, curve 1) the electric field does not change the effective thermal conductivity, and the same is observed when there is a low moisture content (Fig. 2a, curve 2). In the region of low intensities, increasing the amount of moisture adsorbed on the Aerosil has almost no effect on the curve of λ_{eff} vs E. However, for field intensities higher than $1.5 \cdot 10^6$ V/m we observe a considerable increase in λ_{eff}, especially for suspensions with a high moisture content (Fig. 2a, curves 3, 4, 5). In suspensions for which the activator is diethylamine, the effective thermal conductivity increases slightly with field intensity for the Aerosil-particle concentration investigated (Fig. 2b).

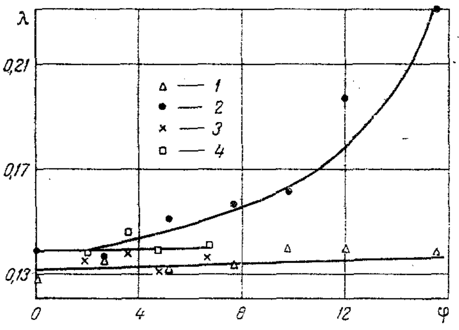

Fig. 3

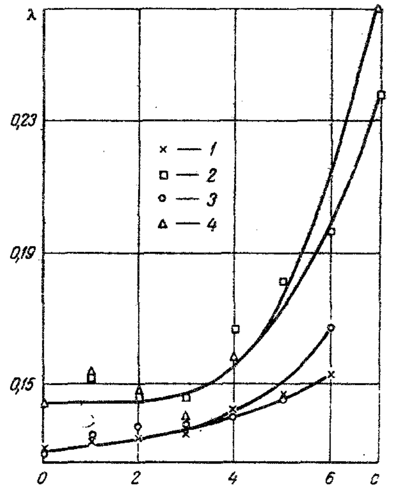

Fig. 4

Fig. 3. Effective thermal conductivity λ_{eff} of 3% suspensions of Aerosil in cetane as a function of the activator content φ (%): 1, 2) water vapor; 3, 4) diethylamine; for 1, 3 there is no external field, for 2, 4 there is an external field with an intensity of $3.33 \cdot 10^6$ V/m.

Fig. 4. Effective thermal conductivity λ_{eff} of suspension of Aerosil in cetane as a function of 6, the concentration of particles by weight (%): 1, 3) with no field; 2, 4) in a field with intensity $3.33 \cdot 10^6$ V/m. Diethylamine content: 1, 2) 3.6%; 3, 4) 6.7%.

The increase in field intensity is accompanied by the appearance of a conductance current through the suspension. For moist Aerosil, the increase in current through the cell takes place simultaneously with an increase in effective thermal conductivity, whereas in suspensions with diethylamine this relationship is less noticeable (Fig. 2c).

From the foregoing it is clear that the effect of the electric field on the effective thermal conductivity of the suspensions investigated is closely related to the behavior of the activators. The variation of λ_{eff} as a function of the amount of adsorbed water or diethylamine shows that in the absence of an electric field an increase in the water content (Fig. 3, curve 1) and the diethylamine content (Fig. 3, curve 3) of the Aerosil does not produce any appreciable effect on the value of the effective thermal conductivity of the suspensions. It should be taken into account that the diameter of the Aerosil particles does not exceed 0.05 μ and that the particles are spherical and nonporous. In the suspension, a solvate envelope is formed around each particle or aggregate, thus resulting in a system of a set of fine particles separated by thick layers of medium. As in the case of systems with high porosity, under our conditions the heat flux is propagated preferentially in the dispersion medium, and the influence of the particles is leveled out [6].

As was shown earlier [1], an increase in the effective viscosity of the suspensions in the electric field is connected with the formation of interelectrode bridges consisting of Aerosil particles. When the concentration of the solid phase is sufficiently high, a network or framework of dispersed particles is formed in the interelectrode gap. If the activator content is low, the forces acting on the particles in the electric field are also small, so that the number of bridges crossing from one electrode to the other is small, and the strength of the contacts between the particles is low. In this case the effective viscosity of the suspensions is almost identical with their viscosity outside of the electric field, as is the case with their effective thermal conductivity (Fig. 2, curves 1, 2). Increasing the amount of activator to some limit increases the strength of the bridges (and, accordingly, the effective viscosity of the suspensions); beyond this limit, any further increase in the activator content results in a decrease in the strength of the bridges [7].

Increasing the water-vapor content in the suspensions of Aerosil and cetane results in an increase in the effective thermal conductivity when the electric fields are of high intensity (Fig. 3, curve 2). The forces of interaction between the particles are high; when the structures are formed, the layers of dispersion medium are squeezed out, and direct contacts of particles with one another and with the electrodes are established. The increase in conductance current indicates the formation of solid bridges from one electrode to the other, and since the transfer of charge in our case takes place by way of the adsorption envelopes of the particles, we can speak of the formation of conductance channels passing through the contacting adsorption layers. The increase in effective thermal conductivity under these conditions means that the structures oriented in the direction of the field have less thermal resistance than the original suspension.

It is known that adsorption layers of water have high thermal conductivity [6]. Apparently the limiting factor in the transfer of heat along the bridges is constituted by the contacts between particles. The increase in the thickness of the adsorption layers of water improves the thermal contact between the particles, the effective thermal conductivity increases, although the mechanical strength of the structure decreases [3,7].

In the case of diethylamine adsorption the effective thermal conductivity depends only slightly on the amount of diethylamine present (Fig. 3, curve 4), while the effective viscosity increases sharply [3]. It may be assumed that the adsorption layer of diethylamine has high thermal resistance (in comparison with water), and this in turn may be attributed to a difference in the structure of the adsorption envelopes. In particular, the ordered structure of the adsorption layer of water can extend to a greater distance from the surface of the particle than that of a diethylamine layer.

We determined the variation of the effective thermal conductivity of the suspensions as a function of particle concentration. In the region of low activator content the variation of λ_{eff} in the concentration range of 1-8% was very low, both with and without an electric field. In suspensions with a fairly high activator content the effective thermal conductivity without a field increases when the particle concentration increases (Fig. 4, curves 1, 3). In strong electric fields, in the case of suspensions with low concentrations, electroconvection may occur. If there are not enough particles to form bridges crossing the gap, or if the forces of interaction between the particles are small and cannot overcome the effect of the thin layers of medium forcing the particles apart (this happens when the activator content is low), the transfer of charge through the gap is carried out by a displacement of particles, together with the liquid they entrain, from one electrode to the other. In our case the convective transfer of heat in low-concentration suspensions leads to an increase of λ_{eff} in strong fields (Fig. 4, initial segment of curves 2, 4).

An increase in the concentration of Aerosil particles makes the system gel-like, so that any movement of liquid in the gap becomes impossible, but the number of bridges is still large, and therefore the value of λ_{eff} decreases somewhat (Fig. 4, curves 2, 4 in the $c = 2$-3% range). Any further increase in the particle concentration brings an increase in the effective thermal conductivity in the electric field because the density of the structural network in the interelectrode gap is increased (Fig. 4).

NOTATION

λ_{eff} is the effective thermal conductivity, W/m·deg;
E is the electric field intensity, V/m;
φ is the activator content, wt. %;
c is the particle concentration, wt. %.

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