HEAT CONDUCTIVITY OF CONCENTRATED SUSPENSIONS

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According to the representation formulated in [1, 2], ordered rotation of suspension particles under the action of an external field results in intensification of the heat (mass, charge) transfer. Since the suspension as a whole remains fixed, the observer perceives this as a change in its effective heat conductivity which meanwhile becomes tensorial in nature. Intensification of heat transfer in magnetic suspensions subjected to a rotating field was observed in experiments [3, 4]. A unique interpretation of these observations as a result of internal rotation meets difficulties associated with the possibility of the origination of macroscopic suspension motion in the rotating field, although all possible measures for its exclusion where taken in [4]. According to the theoretical result [5], more than a tenfold increment in the effective heat conductivity is possible because of internal rotation. However, the theoretical model [5], being cellular, is based on replacement of the real system by some analog so that the degree of approximation to reality is unknown in the exact sense. This can be judged by examining the resulting particular result for the heat conductivity of a suspension of spherical particles at rest. We deal here with the classical object of the theory of generalized conductivity of heterogeneous media [6].

Historically, the Maxwell formula derived in 1872 for electrical conductivity and extended later [7] to heat conductivity because the electrothermal analogy

$$\lambda = \lambda_0[1 + 3\varphi(K - 1)/(2 + K + \varphi\ (1 - K))] \qquad (1)$$

is the first and simplest, in form, result on this question (λ, λ_0, λ_1 are the heat conductivities of the composite, carrying medium, and particles, and $K = \lambda_1/\lambda_0$, φ is the bulk fraction of particles).

The results [5] for a suspension at rest agree with that presented above. An opinion, based on assumptions made in the derivation of (1) that the applicability of the formula is limited to small concentrations is prevalent ([6, 8-11], for example) in the literature. In this connection, a large number of alternative theories has been formulated that explicitly takes account of the mutual thermal influence of the particles [9, 11, 12] and results in more complex expressions. However, we have not succeeded in detecting any experimental proofs of the boundedness of the Maxwell formula in practice. Analysis of known experiments and our results shows that the test data have no substantial systematic deviation from Maxwell theory in the whole range of concentrations studied up to $\varphi = 0.58$. There are no advantages, in practice, of the later and more complex theoretical results we relied upon with the intention of improving the Maxwell theory, over it. Moreover, the Maxwell formula is obtained in [5] without a concentration constraint, just a chaotic particle distribution over the suspension volume is assumed.

Suspensions of spherical particles of carbonyl iron of 1 μm diameter, suspended in aviation hydraulic oil AMG-10 opacified in order to impart sedimentation stability were the object of experiments we performed by the methodology in [13]. The particle concentration varied between 0 and 0.4 in 0.05 steps. Data from [14-16] on the heat conductivity of metallic and vitreous spherical particles of different disperseness impregnated in a resin matrix, were also utilized.

It is possible to pass to the limit $K \to \infty$ in (1)

$$\lambda = \lambda_0(1 + 2\varphi)/(1 - \varphi). \qquad (2)$$

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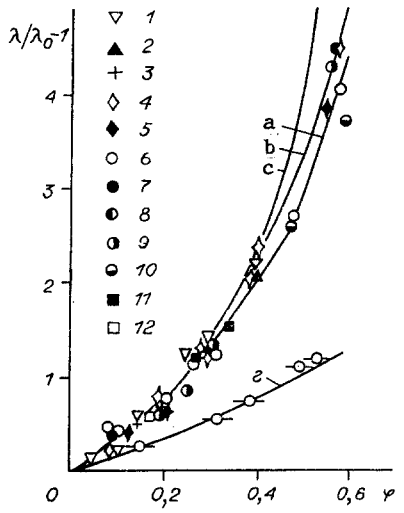

Fig. 1

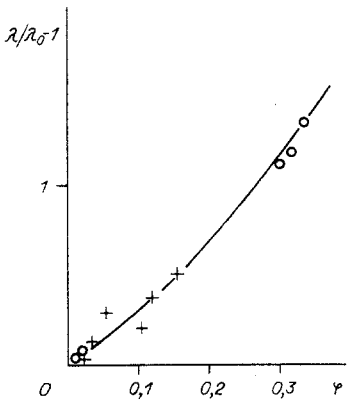

Fig. 2

for any metallic particles in nonmetallic matrices for all achievable concentrations. For comparison we take the formulas from [9, 11] which take the following form in the limit being considered

$$\lambda = \lambda_0\left[1 + \frac{7\beta^2 + 22\beta + 7}{7\beta + 5}\varphi\right],\ \beta = \frac{7 + 17\varphi}{7(1-\varphi)}; \tag{3}$$

$$\lambda = \lambda_0 \frac{1 + 2\varphi - 0{,}409\varphi^{7/3} - 2{,}133\varphi^{10/3}}{1 - \varphi - 0{,}409\varphi^{7/3} - 0{,}906\varphi^{10/3}}. \tag{4}$$

Comparison of theory and experiment is represented in Fig. 1 for composites containing metallic (1-12) and vitreous (13) globes (1, 2 are data of the authors for 2% and 5% thickening agent content; 3 are data of [14]; 4-12 of [16]; 13 of [15]; 1-3, 7-13 were obtained at room temperature; 4-6 at a 200-K temperature). The material (diameter) of the particles is: 1, 2 carbonyl iron (1 μm); 3 Al (1.2 mm); 4, 11 Cu (100 μm); 5, 12 Cu (11 μm); 6, 8 Ag (48 μm); 7 stainless steel (98 μm); 9 Ag (27 μm); 10 Au (37 μm); 13 glass (132 μm). The line a-c are graphs of the functions (2)-(4).

As we see, up to the concentration $\varphi \approx 0.4$ all the theories under consideration yield similar results. Later, the curve according to (4) departs upward from the experimental data; the curves according to (2) and (3) are, as before, cloase to each other (the difference is 13% for $\varphi = 0.6$) and lie among the experimental points. The whole preference can be given to the Maxwell formula: the points are grouped around the appropriate curve without noticeable systematic deviation to either side. The line d in Fig. 1 is constructed according to (1) for K = 4 and describes the data of the experiments [15] well for the glass balls in epoxy resin.

The Maxwell formula yields the result represented by the lines in Fig. 2 for magnetite colloids in organic fluids ($\lambda_0 = 0.13$, $\lambda_1 = 6.26$). Upon its comparison with experiment, the difference in concentration of the solid substance in the colloid φ and the magnetic substance concentration φ_m, cited sometimes in the papers as determined by the magnitude of the saturation magnetization of the colloid referred to the saturation magnetization of the magnetite, should be taken into account. This is associated with the formation of a nonmagnetic layer on the particle surface because of chemical deposition of surfactants utilized for colloid stabilization. The thickness of the nonmagnetic layer can be taken equal to the constant of the magnetite crystalline lattice $\delta = 8$ Å. By taking the typical magnetic diameter of a colloid partricle at $d_m = 100$ Å we find the relationship between the concentrations of the solid and magnetic substances: $\varphi = \varphi_m(1+2\delta/d_m)^3 = 1.56\varphi_m$. In the limit of small magnetite concentrations $\lambda = \lambda_0(1 + 2.82\,\varphi)$ according to the Maxwell formula. At the same time, the dependence $\lambda = \lambda_0(1 + 4.5\,\varphi_m)$ is derived from the experiments of a number of authors in [17], which taking account of the above-mentioned relationship between φ and φ_m goes over into $\lambda = \lambda_0(1 + 2.88\,\varphi)$, which agrees with 3% accuracy with the Maxwell value. Data [18] (crosses) and intrinsic data from [19] (light circles in [19]) are represented for illustration in Fig. 2.

It seems to us that the Maxwell formula is applicable to concentrations differing only slightly from compact stacking, when numerous contacts can occur between particles. In its turn, this result can be considered as a definite confirmation of the applicability of the theory of heat transfer by internal rotation [5] for large particle concentrations.

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