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N. A. FUKS and S. S. YANKOVSKII

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Abstract

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N. A. FUKS and S. S. YANKOVSKII

ON THERMOPHORESIS IN AN AEROSOL FLOW

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The question of the magnitude of the force acting on aerosol particles in a nonuniformly heated medium has been solved theoretically for two limiting cases: very large and very small values of the ratio d/λ, where d is the particle size and λ is the mean free path of the gas molecules. When $d \ll \lambda$, the presence of the particle does not disturb the distribution of molecular velocities, the temperature gradient inside the particle is small, and it may be neglected. The force acting on the particle is caused by the fact that the mean velocities of the gas molecules bombarding the particle from different sides are somewhat different. The resulting force, independent of the nature of the particle (if one neglects the small effect due to differences in the value of the accommodation coefficient of the molecules and takes it equal to unity), is, in the case of a spherical particle of diameter d,

$$F = -\frac{\pi d^2 p \lambda G}{8T}, \tag{1}$$

where p is the gas pressure, T the absolute temperature, and G the temperature gradient in the gas ([1], [2]).

In the case $d \gg \lambda$, the principal role is played by the temperature gradient at the surface of the particle, which, as Maxwell pointed out, causes the gas to slip along the surface. The resulting force, due to friction between the particle and the gas, is, according to Epstein ([3]),

$$F = -\frac{9\pi\beta\eta^2 dG}{2\gamma T}, \tag{2}$$

where η is the viscosity and γ the density of the gas, $\beta = \chi_a/(2\chi_a + \chi_i)$, and χ_a and χ_i are the thermal conductivities of the gas and the particle.

Equating F to the resistance of the medium, we obtain for the thermophoretic velocity, i.e., the motion of the particle in the field of a temperature gradient, for $d \gg \lambda$ the expression

$$V = -\frac{3\beta\nu G}{2T}, \tag{3}$$

where ν is the kinematic viscosity of the gas. For $d \ll \lambda$ the resistance of the medium is equal to $-\pi/3\varkappa\gamma\bar{c}d^2V$, where $\bar{c}$ is the mean absolute velocity of the gas molecules and $\varkappa$ is a coefficient having values from 1.0 to 1.44 ([4]). Consequently,

$$V = -\frac{3p\lambda G}{8\varkappa\gamma\bar{c}T}. \tag{4}$$

Putting $p = \pi/8 \cdot \gamma(\bar{c})^2$, $\eta = \vartheta\gamma\bar{c}\lambda$ (ϑ is a numerical coefficient from 0.3 to 0.5), we obtain:

$$V = -\frac{3\pi\nu G}{64\vartheta\varkappa T}. \tag{5}$$

Thus, in both limiting cases the thermophoretic velocity does not depend on the particle size. Since in most cases $\beta \ll 1$, except for particles made of very poor heat conductors, the thermophoretic velocity for $d \ll \lambda$ should be considerably greater than for $d \gg \lambda$. For the case $d \simeq \lambda$ the theory of the phenomenon is very complicated; there are no works in this direction.

An experimental study of thermophoresis was carried out in a Millikan condenser, in which the upper plate had a higher temperature than the lower one ([5,6]), i.e., in a stationary medium. The thermophoretic velocity of droplets of nonvolatile organic liquids with $d = 0.8$—$4.0\,\mu$ was measured, and good agreement with formula (3) was obtained; moreover, for droplets with $d < 1\,\mu$ it was necessary to introduce Cunningham' s correction factor into it.

Thermophoretic deposition of aerosols from a flow is of very great practical importance, since dust deposits formed during the motion of hot dust-laden gases on the walls of coolers, boiler tubes, etc., usually have very low thermal conductivity and are difficult to remove. The operation of one of the most important instruments for aerosol research—the thermoprecipitator—is also based on thermophoresis in a flow. In this instrument the aerosol is drawn through a plane-parallel slit between massive metal blocks, midway between which a heated metal wire or strip is stretched perpendicular to the streamlines. The aerosol is deposited, in the form of narrow bands, on transparent substrates placed on the surfaces of the blocks.

In investigating the operation of the instrument on a number of polydisperse aerosols, we found that at the front edge of the bands (facing upstream) the finest particles are deposited preferentially, and at the rear edge the coarsest ones. In passing from the front to the rear edge, the dispersion composition of the deposit changes continuously in such a way that the ratio of the number of particles belonging to neighboring fractions changes in favor of the coarser fraction (see Fig.

1). This phenomenon was observed over the entire particle-dispersion interval we studied, from 0.05 to 6 μ, on aerosols obtained by pulverizing a NaCl solution or ink followed by drying of the droplets, or by blowing air over quartz powder, and on PbO smoke obtained by sublimation of galena in an air jet. Deposition conditions: transverse section of the slit 0.6×9 mm, nickel-wire thickness 0.2 mm, heating current 1.2—1.5 a, suction rate 5–10 ml/sec, which corresponds to an average linear velocity of 2–4 cm/sec. The aerosol was drawn directly into the slit, without a transition confuser, and moved vertically upward. Deposition was carried out either on cover glasses (for optical microscopy) or on grids with a collodion film (for electron microscopy). Let us also note that, at the indicated flow velocity, particles up to 20—30 μ should have been drawn into the instrument, whereas the maximum particle size in the deposits was 6—7 μ. However, the rapid decrease in the deposition efficiency in the thermoprecipitator with increasing particle size, beginning at $d \simeq 5\,\mu$, is well known.

The phenomenon described, indicating that the thermophoretic velocity in a flow decreases continuously as the particle size increases even in the range of applicability of formula (3), could not have gone unnoticed by the numerous investigators who have worked with this instrument; however, strange as it may seem, in the literature one can find only passing remarks that the size distribution of particles in the thermoprecipitator deposit is not entirely uniform. The same contradiction with Epstein' s theory was found in a recently published work by Shadt and Keidel ([7]), who studied the deposition in a thermoprecipitator of aerosols with sharply differing thermal conductivities and found that the influence of the latter on deposition is considerably smaller than follows from formula (3). Since, for thermophoresis in a stationary medium, the formula is confirmed by experiment, the cause of these contradictions may be

there can be only certain effects connected with the flow of the aerosol. Let us briefly consider some of them.

The inertia of the particles hinders their deposition. However, the magnitude characterizing the inertia-caused deviation of the particle trajectories—the "inertial path" of the particles ([8])—for example, for NaCl particles of size 4 μ is, in our experiments, 1-2 μ; with dimensions of the temperature-gradient region of several hundred microns, such a deviation is insignificant. Rotation of the particles, caused by the velocity gradient of the flow Γ, hinders the creation of a temperature gradient inside the particles. The maximum value of Γ in our experiments was of the order of 1000 sec^{-1}, which corresponds ([9]) to a rotation period ~ 0.01 sec., whereas the time of thermal relaxation of NaCl particles with $d = 4\,\mu$ is $3 \cdot 10^{-7}$ sec. ([10]). Brownian rotation of the particles has an even smaller value. When a particle moves parallel to a wall at a short distance from it, at small Reynolds numbers there arises a repulsive force from the wall $F = {}^{9}/_{64} \cdot \pi\gamma d^2 V^2$ ([11]). This force, caused in the case considered by sedimentation of the particles, for the NaCl particles indicated above is equal to $8 \cdot 10^{-13}$ dyn. Meanwhile, under ordinary operating conditions of a thermoprecipitator, G has a value of the order of 5000 deg/cm, and the thermophoretic force, according to formula

Fig. 1. Electron-microscope images of the deposit of a NaCl aerosol in the thermoprecipitator. *a*—at the front edge, *b*—in the middle of the deposit, *v*—at the rear edge

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(2), is of the order of 10^{-8} dyn. Thus, none of the effects considered explains the phenomenon described above. It also contradicts the experiments of Ya. I. Kogan and R. S. Repina ([12]), who, when aerosols were drawn from below upward through a vertical capillary, i.e., in the absence of thermophoresis, observed deposition of them on the capillary walls that increased rapidly with increasing particle size (beginning with $d = 0.5\,\mu$).

State Scientific-Research
Institute of Non-Ferrous Metals

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Note: Figure translations are in progress. See original paper for figures.