



Thermophoretic motion of slightly deformed aerosol spheres

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ABSTRACT

The thermophoretic motion of a slightly deformed aerosol sphere in a uniformly prescribed but arbitrarily oriented temperature gradient is analyzed in the steady limit of negligible Peclet and Reynolds numbers. The Knudsen number is assumed to be small so that the fluid flow is described by a continuum model with a temperature jump, a thermal slip, and a frictional slip at the surface of the particle. The energy and momentum equations governing the system are solved asymptotically using a method of perturbed expansions. To the second order in the small parameter characterizing the deformation of the aerosol particle from the spherical shape, the thermal and hydrodynamic problems are formulated for the general case, and explicit expressions for the thermophoretic velocity of the particle are obtained for the special cases of prolate and oblate spheroids. The agreement between our asymptotic results for a thermophoretic spheroid and the relevant exact or numerical solutions in the literature is quite good, even if the particle deformation from the spherical shape is not very small. Depending on the values of the relative thermal and surface properties of the aerosol spheroid, its thermophoretic mobility normalized by the corresponding value for a spherical particle with equal equatorial radius is not necessarily a monotonic function of the aspect ratio of the spheroid.

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1. Introduction

Small particles suspended in a nonisothermal gas acquire a mean velocity relative to the gas in the direction opposite to the temperature gradient. This phenomenon, known as thermophoresis, was first described in 1870 by Tyndall, who observed the removal of dust particles from air in the vicinity of hot surfaces (Davis & Schweiger, 2002; Waldmann & Schmitt, 1966). Deposition by thermophoresis is of considerable practical importance in many industrial applications when hot gases containing small suspended particles flow over cool surfaces. For example, thermophoresis can be effective in removing or collecting small particles from laminar gas streams in air cleaning and aerosol sampling devices (Friedlander, 1977; Sasse, Nazaroff, & Gadgil, 1994). The phenomenon has also been cited as an origin for the deposition of particulate matter on surfaces of heat exchangers causing scale formation with the attendant reduction of the heat-transfer coefficient (Montassier, Boulaud, & Renoux, 1991) and supporting the development of systems for filterless removal of combustion aerosol particles (Messerer, Niessner, & Pöschl, 2004). Convincing evidence has been provided that, in the modified chemical vapor deposition process for the manufacture of high-quality optical fibers, thermophoresis is the primary mechanism responsible for the deposition of aerosol particles (soot) onto the inner walls of the containing tube (Balsara & Subramanian, 1987). On the other hand, deposition of contaminant particles by thermophoresis on wafers in clean rooms

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during manufacturing steps can be a major cause of loss of product yields in the microelectronics industry (Ye et al., 1991). In the area of nuclear safety, knowledge of thermophoresis is required to calculate the deposition rates of radioactive aerosol particles released in reactor accident situations where large temperature gradients exist (Williams & Loyalka, 1991).

The thermophoretic effect can be explained in part by appealing to the kinetic theory of gases (Kennard, 1938). The higher-energy gas molecules in the hot regions impinge on the particle with greater momenta than molecules coming from the cold regions, thus leading to the migration of the particle in the direction of decreasing temperature. It is convenient to express the thermophoretic velocity of a spherical particle in a constant temperature gradient ∇T_∞ as

$$\mathbf{U} = -M_T \nabla T_\infty, \quad (1)$$

where the negative sign indicates that the particle motion is in the direction opposite to the temperature gradient. The thermophoretic mobility M_T depends on the magnitude of the Knudsen number, l/a , where l is the mean free path of the gas molecules and a is a characteristic linear dimension of the particle.

In the regime of small Knudsen number ($l/a \leq 0.1$), the fluid flow may be described by a continuum model and the thermophoretic force arises from a thermal slip along the particle surface due to the existence of a tangential temperature gradient at the surface. Utilizing the gas kinetic theory, Maxwell (1879) predicted that a tangential temperature gradient $\nabla_s T$ at a gas–solid surface would cause a thin layer of gas (known as the Knudsen layer) adjacent to the surface to move (as a thermoosmotic flow), with the relative velocity at the outer edge of the layer being

$$\mathbf{v}^{(s)} = C_s \frac{\mu}{\rho T} \nabla_s T, \quad (2)$$

where μ is the fluid viscosity, ρ is the fluid density, and T is the local-gas absolute temperature. The thermal slip coefficient C_s was found to be $3/4$ by Maxwell on the assumption that the distribution function in the bulk of the gas held all the way to the solid surface. Note that the thermal slip velocity $\mathbf{v}^{(s)}$ is directed toward the high temperature side and ρT in Eq. (2) is a constant for an ideal gas at constant pressure.

By using the Maxwellian thermal slip velocity in Eq. (2), which gives the coupling between temperature and velocity fields, as well as the effects of temperature jump and frictional slip at the particle surface and solving the equation of continuum fluid motion incorporating with the heat conduction in the gas and particle at low Reynolds and Peclet numbers, Brock (1962) derived an expression for the thermophoretic mobility of a suspended aerosol sphere of radius a as

$$M_T = \frac{2C_s \mu (k + k_p C_t l/a)}{\rho T_0 (1 + 2C_m l/a) (2k + k_p + 2k_p C_t l/a)}. \quad (3)$$

Here k and k_p are the thermal conductivities of the gas and particle, respectively, T_0 is the bulk-gas absolute temperature at the particle center in the absence of the particle (or the mean gas temperature in the vicinity of the particle), and C_t and C_m are the dimensionless coefficients on the order of unity accounting for the temperature jump and frictional slip, respectively, at the particle surface and must be determined experimentally for each gas–solid system. In an analysis carried out on the basis of the linear BGK equation, Yamamoto and Ishihara (1988) obtained numerical solutions for the thermophoretic force on an aerosol sphere over a wide range of Knudsen numbers which agree well with Eq. (3) for the case of small l/a .

Satisfactory agreement of the prediction by Eq. (3) with experiments (Li & Davis, 1995; Schadt & Cadle, 1961) has been obtained. Derjaguin, Rabinovich, Storozhilova, and Shcherbina (1976) presented the experimental data of the thermophoretic mobility for a variety of aerosols, which are in good agreement with Eq. (3) with $C_m = 0$, $C_s = 3/2$ and a suitable selection of the coefficient C_t . A set of kinetic-theory values for complete thermal and momentum accommodations appear to be $C_s = 1.17$, $C_t = 2.18$ and $C_m = 1.14$ (Talbot, Cheng, Schefer, & Willis, 1980). Recently, kinetic-theory values of these slip and jump coefficients have been obtained accurately under various conditions (Cercignani, 2000; Ivchenko, Loyalka, & Tompson, 2007; Sone, 2002). According to Eqs. (1) and (3), particles with large thermal conductivity and small Knudsen number (say, $k_p/k = 100$ and $l/a = 0.01$) will migrate by thermophoresis at velocities of $10\text{--}50 \mu\text{m/s}$ in temperature gradients of order 100K/cm , such gradients are easily attainable in thermal boundary layers.

Usually, aerosol particles are not spherical and it is interesting to examine the effect of particle shape on thermophoresis (Dahneke, 1973; Laucks, Roll, Schweiger, & Davis, 2000). Direct measurements of the thermophoretic force on nonspherical aerosol particles consisting of aggregates of polystyrene latex spheres were made over a wide range of Knudsen numbers using an electrodynamic balance mounted in a vacuum chamber (Zheng & Davis, 2001). On the other hand, the thermophoretic motion of a long circular cylinder in the direction normal to its axis has been analyzed with the consideration of the effects of temperature jump, thermal slip, and frictional slip at the particle surface (Keh & Tu, 2001). Earlier, the axisymmetric thermophoresis of a spheroidal particle along its axis of revolution without temperature jump and frictional slip at its surface was also analytically studied (Leong, 1984; Williams, 1986). This analysis has been generalized to a spheroid (Keh & Ou, 2004) and a particle departing slightly in shape from a sphere (Mohan & Brenner, 2006) with an arbitrary orientation relative to the imposed temperature gradient. Although the thermophoretic motion of a general axisymmetric particle with the effects of temperature jump, thermal slip and frictional slip along its axis of revolution was numerically examined to some extent by using a boundary collocation method (Keh & Chang, 2009), the problem of thermophoresis of particles of a general shape with the jump/slip conditions at the particle surface in an

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