Universal Journal of Physics and Application 2(5): 251-256, 2014
DOI: 10.13189/ujpa.2014.020503 http://www.hrpub.org

Influence of motion of environment on thermo - , photo - and diffusiophoresis of a solid aerosol particle of the spheroidal form

N.V. Malay, N.N. Mironova*, E.R.Shchukin

Belgorod State University, Belgorod, 308015 Russia

*Corresponding Author: mironovanadya@mail.ru

Abstract In Stokes approach, the theoretical description of stationary motion of a large solid aerosol particle of the spheroidal form in external fields of temperature and concentration of gradients, on which powerful electromagnetic radiation in a binary gas mixture falls down, is carried out. At motion consideration it was supposed, that the average temperature of a surface of a particle slightly differs from the temperature of the gaseous environment surrounding it. In the course of the gasdynamics equations solution analytical expressions for force and speed of thermo -, photo-, and diffusion-phoresis taking into account influence of movement of environment are obtained.

Keywords spheroid; thermophoresis; photophoresis; diffusiophoresis.

1 Introduction

In a modern science and the technique, in areas of chemical technologies, hydrometeorology, preservations of the environment etc. multiphase mixes are widely applied. The disperse mixtures, consisting of two phases one of which is a particle and the other one is the viscous environment (gas or a liquid), hold the greatest interest today. Gas (liquid), with the particles suspended in it is called aerosol and the particles are called aerosol particles. Hydro - and aerosol particles can make considerable impact on a course of physical and physical - chemical processes of a various types in disperse systems (for example, processes of mass - and heat exchange). The size of particles of a disperse phase lies in a very wide limits: from macroscopic ($\sim 500mkm$) to molecular ($\sim 10nm$) values; a concentration of particles varies accordingly - from one particle to highly concentrated systems ($> 10^{10}\quad^{-3}$). Nowadays, with development of nano-technologies and nano-materials, the essential prospect is represented by application of ultradisperse (nano-) particles, for example, in nano-electronics and nano-mechanics, etc.

The forces of the various nature can effect on the particles of disperse systems causing their ordered movement concerning the centre of inertia of the viscous environment. For example, the sedimentation occurs in the field of the gravitational force. In gaseous environments with non-uniform distribution of temperature there can be ordered movement of the particles which is caused, for example, by externally set gradients of temperature and concentration that is called thermophoresis and diffusiophoresis [1]. If movement is caused at the expense of internal sources of heat non-uniformly distributed in particle volume such movement is called photophoretic [2-4].

Average distance between aerosol particles of a considerable part of aerodisperse systems meeting in practice is much greater than a characteristic size of particles. In such systems the account of influence of an aerosol on development of physical process can be carried out, basing on knowledge of laws of dynamics of movement and heat - and mass exchange with infinite environment of separate aerosol particles. Mathematical modeling of evolution of aerosol systems and the solution of such important question as purposeful influence on aerosols is impossible without knowledge of laws of this type of behavior.

Many particles that can be found in industrial devices and nature, have the form of a surface different from spherical, for example, spheroidal (ellipsoid of rotation). Therefore studying of laws of motion of separate particles in gaseous (liquid) both homogeneous, and non- homogeneous environments is the important actual problem representing considerable theoretical and practical interest.

2 Materials and Methods

2.1. Problem of formulation. The large solid particle of the spheroidal form suspended in a binary gas mixture with temperature T_∞, density ρ_g and viscosity μ_g is considered. Let in this binary gas mixture by means of external sources a small gradient of temperature ∇T and concentration ∇C_1 is sustained. Here $C_1 + C_2 = 1$, $C_1 = n_1/n_g$, $C_2 = n_2/n_g$, $n_g = n_1 + n_2$, $\rho_g = \rho_1 + \rho_2$, $\rho_1 = m_1 n_1$, $\rho_2 = m_2 n_2$, m_1, n_1 and m_2, n_2 - mass and concentration of the first and second components of the binary gas mixture. In the researches on the theory of thermo -, the photo -, and diffusiophoresis of large solid aerosol particles of the spheroidal form at small relative temperature drops, which were [5] published until the present time, the simultaneous influence of the environment movement (i.e. convective terms in the heat conductivity and diffusion equations) and surface heating on thermo -, photo-, and diffusiophoresis, and which represents theoretical and practical interest, was not considered. In the given article the estimation of this influence is evaluated.

At the theoretical description of the thermo -, photo-, and the diffusiophoretic particle movement process we will assume, that due to a small time of thermal and diffusion relaxation process, the thermal and mass transfer process in the system of a particle, the gaseous environment takes place quasi-stationary. The particle movement occurs at small Peclet and Reynolds numbers, and at small relative temperature drops in its vicinity, i.e. when $(T_s - T_\infty)/T_\infty \ll 1$, T_s - is an average temperature of the particle surface, T_∞ - is the temperature of the gaseous environment far from it. At fulfillment of this condition it is possible to consider coefficients of heat conductivity, dynamic and kinematic viscosity as constant [13], and the gas as the continuous environment. The problem is solved by a hydrodynamic method, the equations of hydrodynamics with corresponding boundary conditions are solved and it is considered, that a phase transition is absent, and the particle is homogeneous over its composition.

Let's assume also, that at some moment of time the flat monochromatic wave of intensity I_0 falls on the particle. Energy of electromagnetic radiation, being absorbed in the particle volume, will be transformed to thermal energy. Non-uniformly in its volume is the local distribution of the heat sources arisen by this way, which can be described by some function q_p called the volume density of internal sources of heat [12].

The description of thermo -, photo-, and diffusiophoretic particle motions we will carry out in spheroidal system of co-ordinates $(\varepsilon, \eta, \varphi)$ with the beginning in the spheroid center, i.e. we chose the beginning of the motionless system of co-ordinates in an instant position of the center of the particle. Curvilinear co-ordinates $\varepsilon, \eta, \varphi$ are connected with the Cartesian co-ordinates by the following relations [6]:

$$x = c\cosh\varepsilon\sin\eta\cos\varphi, y = c\cosh\varepsilon\sin\eta\sin\varphi,$$

$$z = c\sinh\varepsilon\cos\eta, \qquad (1)$$

$$x = c\sinh\varepsilon\sin\eta\cos\varphi,\ y = c\sinh\varepsilon\sin\eta\sin\varphi,$$

$$z = c\cosh\varepsilon\cos\eta, \qquad (2)$$

where $c = \sqrt{a^2 - b^2}$ in case of the oblate spheroid ($a > b$, formulae (1)), and $c = \sqrt{b^2 - a^2}$ - in case of the prolate ($a < b$, formulae (2)); and b - semi-axes of the spheroid. At that the position of the Cartesian system of co-ordinates is fixed concerning the particle so that the axis coincides with the axis of symmetry of the spheroid.

Within the limits of the formulated assumptions the distribution of speed U_g, pressure P_g, temperatures T_g and T_p, and a relative concentration of the first component of the binary gas mixture C_1 are described by the following system of the equations [7]:

$$\nabla P_g = \mu_g \triangle \mathbf{U}_g,\ div\mathbf{U}_g = 0,$$

$$\rho_g c_{pg}(U_g\nabla)T_g = \lambda_g \triangle T_g,\ \triangle T_p = -\frac{q_p}{\lambda_p}, \qquad (3)$$

$$(U_g\nabla)C_1 = D_{12}\triangle C_1.$$

The system of equations (3) was solved with the following boundary conditions [5]:

$$\varepsilon = \varepsilon_0 : \qquad U_\varepsilon = -\frac{cU\cosh\varepsilon}{H_\varepsilon}\cos\eta,$$

$$U_\eta = \frac{cU\sinh\varepsilon}{H_\varepsilon}\sin\eta - K_{TS}\frac{\nu_g}{T_g}(\nabla T_g\cdot\mathbf{e}_\eta) - K_{DS}D_{12}(\nabla C_1\cdot\mathbf{e}_\eta),$$

$$T_g = T_p,\ \lambda_g\frac{\partial T_g}{\partial\varepsilon} = \lambda_p\frac{\partial T_p}{\partial\varepsilon},\ \frac{\partial C_1}{\partial\varepsilon} = 0. \qquad (4)$$

$$\varepsilon \to \infty : \qquad T_g \to T_\infty + |\nabla T_g|\cdot c\sinh\varepsilon\cos\eta,$$

$$C_1 \to C_\infty + |\nabla C_1|\cdot c\sinh\varepsilon\cos\eta$$

$$P_g \to P_\infty;\ U_g \to 0, \qquad (5)$$

$$\varepsilon \to 0 \qquad T_p \neq \infty \qquad (6)$$

here $\mathbf{e}_\eta$, $\mathbf{e}_\varepsilon$ are unit vectors of spheroidal system of co-ordinates; U_ε, U_η - components of the mass speed of the gas U_g, $U = |\mathbf{U}|$ - characteristic speed of the particle movement; λ_g, λ_p - coefficients of the heat conductivity of the gas and the particle respectively; ν_g, μ_g - kinematic and dynamic viscosity; $H_\varepsilon = c\sqrt{\cosh^2\varepsilon - \sin^2\eta}$ - Lamé coefficient; K_{TS} and K_{DS} - coefficients of thermal and diffusion slips which are determined by methods of the kinetic theory of gases. For example, at accommodation coefficients of a tangential impulse and the energy, equal to unity, the gaskinetic coefficient (in case of a spherical particle) $K_{TS} \approx 1,152$, $K_{DS} \approx 0,3$ [1, 8]. $\varepsilon = \varepsilon_0$ - the co-ordinate surface corresponding to a surface of the particle.

2.2. Distribution of temperature and relative concentration out of and in the particle. Let us make equations (3) and boundary conditions (4) - (6) dimensionless, having entered dimensionless temperature and speed as follows: $t_k = T_k/T_\infty, V_g = U_g/U, (k = g, p)$.

In the problem except Reynolds's and the Peclet dimensionless numbers there are two more controllable small parameters $\xi_1 = a|\nabla T_g|/T_\infty \ll 1$, $\xi_2 = a|\nabla C_1| \ll 1$, characterizing relative temperature drop and concentration over the size of a particle. For pure thermophoresis the characteristic speed U is of the order of magnitude $U \sim (\mu_g/\rho_g T_\infty)|\nabla T_g|$, and for pure diffusion phoresis - $U \sim D_{12}|\nabla C_1|$. If we take this into account, the solution of the boundary problem (3) - (6) will be found in the form of expansion of corresponding physical sizes over powers of ξ_1. The small parameter ξ_2 is expressed through ξ_1, and also the Reynolds number

REFERENCES

1. Poddoskin A.B., Yushkanov A.A., Yalamov Yu.I. Theory of thermophoresis of moderately large aerosol particles. // Zhurnal Teknich Phys. 1982. V. 52, N. 11. P. 2253-2261.
2. Fucks N.A. Mechanics of aerosols. Moscow. AN USSR Publishers. 1955.
3. Hidy G.M., Brock J.R. Photophoresis and the descent of particles into the lower stratosphere // J. Geophys. Res. 1967. Vol. 12. Pp. 465-460.
4. Kutukov V.B., Schukin E.R., Yalamov Yu.I. On a photophoresis movement of an aerosol particle in the field of the optic radiation. // Zhurnal Teknich Phys. 1976. V. 46, N.3. P. 626-627.
5. Leong K.N. Thermophoresis and diffusiophoresis of large aerosol particles of different shapes // J. Aerosol Sci. 1984. Vol. 15, 4. Pp. 511-517.
6. Happel J., Brenner H. Low Reynolds number hydrodynamics. Moscow. Mir Publishers. 1976.
7. Landau L.D., Lifshits E.M. Mechanics of continuous media. Moscow. Gosud. Publish. Techn. Teoret. Lit. 1954.
8. Yalamov Yu.I., Poddoskin A.B., Yushkanov A.A. About boundary conditions of a spherical surface of small curvature at flow around by the non-uniformly heated gas.// Doklady AS USSR. 1980. V. 254, N2. P. 1047-1050.
9. Kamke E. Reference book on ordinary differential equations/ E. Kamke. - Moscow. Nauka Publishers. 1976.
10. Bakanov S.P., Deryagin B.V. // Doklady AS USSR. 1962. V. 142. N.1. P. 139-142.
11. Yalamov Yu.I., Sanasaryan A.S. // Ingen. Phys. Zhur. 1975. V. 28. N.6. P. 1061-1064.
12. Boren K., Hafmen D. Absorption and scattering of light by small particles. Moscow. Mir Publishers. 1986.
13. Breitshgaider S. Properties of gases and liquids. Engineering methods of calculations. Moscow., 1966.