Influence of Motion of Environment on Thermo-, Photo- and Diffusiophoresis of a Solid Aerosol Particle of the Spheroidal Form

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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 ($\sim 500\mu m$) to molecular ($\sim 10nm$) values; a concentration of particles varies accordingly - from one particle to highly concentrated systems ($> 10^{10} - 10^{13}$). 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]:

$$\begin{aligned} x &= c \cosh \varepsilon \sin \eta \cos \varphi, y = c \cosh \varepsilon \sin \eta \sin \varphi, \\ z &= c \sinh \varepsilon \cos \eta, \end{aligned} \quad (1)$$

$$\begin{aligned} x &= c \sinh \varepsilon \sin \eta \cos \varphi, y = c \sinh \varepsilon \sin \eta \sin \varphi, \\ z &= c \cosh \varepsilon \cos \eta, \end{aligned} \quad (2)$$

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]:

$$\begin{aligned} \nabla P_g &= \mu_g \Delta \mathbf{U}_g, \operatorname{div} \mathbf{U}_g = 0, \\ \rho_g c_{pg} (U_g \nabla) T_g &= \lambda_g \Delta T_g, \Delta T_p = -\frac{q_p}{\lambda_p}, \\ (U_g \nabla) C_1 &= D_{12} \Delta C_1. \end{aligned} \quad (3)$$

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

$$\begin{aligned} \varepsilon = \varepsilon_0 : \quad U_\varepsilon &= -\frac{cU \cosh \varepsilon}{H_\varepsilon} \cos \eta, \\ U_\eta &= \frac{cU \sinh \varepsilon}{H_\varepsilon} \sin \eta - K_{TS} \frac{\nu_g}{T_g} (\nabla T_g \cdot \mathbf{e}_\eta) - K_{DS} D_{12} (\nabla C_1 \cdot \mathbf{e}_\eta), \\ T_g &= T_p, \lambda_g \frac{\partial T_g}{\partial \varepsilon} = \lambda_p \frac{\partial T_p}{\partial \varepsilon}, \frac{\partial C_1}{\partial \varepsilon} = 0. \end{aligned} \quad (4)$$

$$\begin{aligned} \varepsilon \rightarrow \infty : \quad T_g &\rightarrow T_\infty + |\nabla T_g| \cdot c \sinh \varepsilon \cos \eta, \\ C_1 &\rightarrow C_\infty + |\nabla C_1| \cdot c \sinh \varepsilon \cos \eta \\ P_g &\rightarrow P_\infty; U_g \rightarrow 0, \\ \varepsilon \rightarrow 0 \quad T_p &\neq \infty \end{aligned} \quad (5)$$

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 diffusiophoresis - $U \sim D_{12}|\nabla C_1|$. 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

($\xi = Re = \rho_g U a / \mu_g \ll 1$) calculated by the characteristic speed of pure thermophoresis coincides with ξ_1 , which proves the expansion over the given small parameter.

$$V_g = V_{g0} + \xi_1 V_{g1} + \dots, \quad p_g = p_{g0} + \xi_1 p_{g1} + \dots$$

$$t = t_0 + \xi_1 t_1 + \dots, \quad C_1 = C_{10} + \xi_1 C_{11} + \dots \quad (7)$$

Searching the force and the speed of thermo-, photo- and diffusiophoresis, we will be limited by the corrections of the first order smallness over ξ_1 . In order to find them it is necessary to know the distribution of speed, pressure, temperatures and concentration in the spheroid vicinity. Substituting (7) in (3), leaving terms of the order ξ_1 , solving the obtained systems of the equations by the method of separation of variables, finally we obtain for zero and the first approximations

$$t_{g0}(\lambda) = 1 + \gamma \lambda_0 \operatorname{arccctg} \lambda, \quad C_{10} = C_{1\infty} \quad (8)$$

$$t_{p0}(\lambda) = 1 + (1 - \delta) \gamma \lambda_0 \operatorname{arccctg} \lambda_0 + \delta \gamma \lambda_0 \operatorname{arccctg} \lambda + \int_{\lambda_0}^{\lambda} f_0 \operatorname{arccctg} \lambda d\lambda - \operatorname{arccctg} \lambda \int_{\lambda_0}^{\lambda} f_0 d\lambda \quad (9)$$

$$t_{g1} = \cos \eta \left\{ \frac{c\lambda}{a} + \Gamma(\lambda \operatorname{arccctg} \lambda - 1) + Pr_{\infty} \frac{\gamma \lambda_0}{ac} \left\{ A_2(\operatorname{arccctg} \lambda - \frac{\lambda}{2} \operatorname{arccctg}^2 \lambda) + \frac{A_1}{2}(\operatorname{arccctg} \lambda - \lambda \operatorname{arccctg}^2 \lambda) \right\} \right\} \quad (10)$$

$$t_{p1} = \cos \eta \left\{ B\lambda + \frac{3(1 - \lambda \operatorname{arccctg} \lambda)}{4\pi c^2 \lambda_p T_{\infty}} \int_V q_p z dV - \lambda \int_{\lambda_0}^{\lambda} f_1(\lambda \operatorname{arccctg} \lambda - 1) d\lambda + (\lambda \operatorname{arccctg} \lambda - 1) \int_{\lambda_0}^{\lambda} f_1 \lambda d\lambda \right\} \quad (11)$$

$$C_{11} = \cos \eta \left\{ \frac{c\lambda}{a} - \frac{c(1 + \lambda_0^2)}{((1 + \lambda_0^2) \operatorname{arccctg} \lambda_0 - \lambda_0)a} (\lambda \operatorname{arccctg} \lambda - 1) \right\} \quad (12)$$

where $\lambda = \sinh \varepsilon$, $\lambda_0 = \sinh \varepsilon_0$, $\delta = \lambda_g / \lambda_p$, $\gamma = t_s - 1$ - dimensionless parameter characterizing heating of the spheroid; $t_s = T_s / T_{\infty}$, T_s - average temperature of the spheroid surface defined by the formula

$$\frac{T_s}{T_{\infty}} = 1 + \frac{1}{4\pi c \lambda_0 \lambda_g T_{\infty}} \int_V q_p dV \quad (13)$$

Integration in the formulae (14) is carried out over the whole particle's volume.

$$f_n = -\frac{2n+1}{2\lambda_p T_{\infty}} \int_{-1}^1 c^2 q_p (\lambda^2 + x^2) P_n(x) dx,$$

$x = \cos \eta$, $P_n(x)$ - Legendre polynomials [9].

The constants entering into expressions for fields of temperatures out of and in the particle (11), (12) are determined from corresponding boundary conditions on the spheroid surface. Considering, that later the expression for the coefficient is required, let us represent its explicit form

$$\Gamma = -\frac{c(1 - \delta)}{a\Delta} + \frac{3}{4\pi c^2 \lambda_p \lambda_0 T_{\infty} (1 + \lambda_0^2) \Delta} \int_V q_p z dV +$$

$$+ Pr_{\infty} \frac{\gamma \lambda_0}{ac} \left\{ A_2(\operatorname{arccctg} \lambda_0 - \frac{1 - \delta}{2\Delta} \operatorname{arccctg}^2 \lambda_0 - \frac{\delta}{(1 + \lambda_0^2)\Delta}) + \frac{A_1}{2}(\operatorname{arccctg} \lambda_0 + \frac{\delta(\lambda_0 \operatorname{arccctg} \lambda_0 - 1)}{(1 + \lambda_0^2)\Delta}) \right\} \quad (14)$$

$$\Delta = (1 - \delta) \operatorname{arccctg} \lambda_0 + \frac{\delta \lambda_0}{1 + \lambda_0^2} - \frac{1}{\lambda_0}$$

2.3. Determination of the force and the speed of thermo-, photo-, and diffusiophoresis. A general solution of hydrodynamic equations in the spheroid coordinate system has a form [5]:

$$U_{\varepsilon}(\varepsilon, \eta) = \frac{U}{c \cosh \varepsilon H_{\varepsilon}} \cos \eta \{ \lambda A_2 + [\lambda - (1 + \lambda^2) \operatorname{arccctg} \lambda] A_1 + c^2(1 + \lambda^2) \},$$

$$U_{\eta}(\varepsilon, \eta) = -\frac{U}{c H_{\varepsilon}} \sin \eta \left\{ \frac{A_2}{\lambda} + [1 - \lambda \operatorname{arccctg} \lambda] A_1 + c^2 \lambda \right\}, \quad (15)$$

$$P_g(\varepsilon, \eta) = P_{\infty} + c \frac{\mu_g U}{H_{\varepsilon}^4} x(x^2 + \lambda^2) A_2.$$

Constants of integration A_1, A_2 , are determined from the boundary conditions of the spheroid surface, in particular,

$$A_2 = -\frac{2c^2}{\lambda_0 + (1 - \lambda_0^2) \operatorname{arccctg} \lambda_0} - 2K_{TS} \frac{c^2 \nu_g \delta}{U t_s} \frac{|\nabla T_g|}{T_{\infty}} \frac{\lambda_0 - (1 + \lambda_0^2) \operatorname{arccctg} \lambda_0}{\lambda_0 + (1 - \lambda_0^2) \operatorname{arccctg} \lambda_0} \times$$

$$\times \frac{1}{(1 + \lambda_0^2) \Delta} \left(1 + \frac{3a(1 - \lambda_0 \operatorname{arccctg} \lambda_0)}{4\pi c^3 \lambda_0 \lambda_g T_{\infty}} \int_V q_p z dV - \frac{Pr_{\infty} \gamma \lambda_0}{2(\lambda_0 + (1 - \lambda_0^2) \operatorname{arccctg} \lambda_0)} [2 \operatorname{arccctg}^2 \lambda_0 + \right.$$

$$+ 4(\lambda_0 \operatorname{arccctg} \lambda_0 - 1) + (1 - \lambda_0^2)(\lambda_0 \operatorname{arccctg} \lambda_0 - 1)^2] - \left. - 2K_{DS} D_{12} \frac{c^2 |\nabla C_1|}{U(\lambda_0 + (1 - \lambda_0^2) \operatorname{arccctg} \lambda_0)} \right) \quad (16)$$

Main force acting on the spheroid is determined by integration of the stress tensor over the surface of the aerosol particle [5, 6] and has a form:

$$F_z = 4\pi \frac{\mu_g U}{c} A_2 \quad (17)$$

Granting the explicit form of the coefficient A_2 , we obtain the general expression for the force acting on the spheroidal particle, which additively consists of the force of the environment viscous resistance F_{μ} , thermophoretic force F_{th} , photophoretic force F_{ph} proportional to the dipole moment of thermal sources density, non-uniformly distributed in the volume of the particle, force considering the influence of the environment movement, and the diffusion phoretic force F_{dh}

$$F_z = F_{\mu} + F_{th} + F_{ph} + F_{dh}, \quad (18)$$

$$F_{\mu} = -8\pi \mu_g U \frac{c}{\lambda_0 + (1 - \lambda_0^2) \operatorname{arccctg} \lambda_0},$$

$$F_{th} = -8\pi K_{TS} \frac{\mu_g \nu_g}{t_s} \frac{|\nabla T_g|}{T_{\infty}} \frac{\lambda_0 - (1 + \lambda_0^2) \operatorname{arccctg} \lambda_0}{\lambda_0 + (1 - \lambda_0^2) \operatorname{arccctg} \lambda_0} \times$$

$$\begin{aligned}
& \times \frac{c\delta}{(1+\lambda_0^2)\Delta} \left(1 - \frac{Pr_\infty \gamma \lambda_0}{2(\lambda_0 + (1-\lambda_0^2)\text{arcctg}\lambda_0)} \times \right. \\
& \quad \left. \times [\text{arcctg}^2 \lambda_0 - \lambda_0^2(\lambda_0 \text{arcctg}\lambda_0 - 1)^2] \right) \\
F_{ph} = & -8\pi K_{TS} \xi \frac{\mu_g \nu_g}{t_s} \frac{\lambda_0 - (1+\lambda_0^2)\text{arcctg}\lambda_0}{\lambda_0 + (1-\lambda_0^2)\text{arcctg}\lambda_0} \times \\
& \times \frac{c\delta}{(1+\lambda_0^2)\Delta} \left(\frac{3a(1-\lambda_0 \text{arcctg}\lambda_0)}{4\pi c^3 \lambda_0 T_\infty} \int_V q_p z dV - \right. \\
& \quad \left. - \frac{Pr_\infty \gamma \lambda_0}{2(\lambda_0 + (1-\lambda_0^2)\text{arcctg}\lambda_0)} [\text{arcctg}^2 \lambda_0 + \right. \\
& \quad \left. + 4(\lambda_0 \text{arcctg}\lambda_0 - 1) + (\lambda_0 \text{arcctg}\lambda_0 - 1)^2] \right) \\
F_{dh} = & -8\pi K_{DS} D_{12} \mu_g \frac{c|\nabla C_1|}{\lambda_0 + (1-\lambda_0^2)\text{arcctg}\lambda_0}
\end{aligned}$$

Equating the general force to zero, we obtain the general expression for the speed of the ordered movement of the oblate spheroidal particle in the external set field of the gradient of temperature and concentration

$$\begin{aligned}
U = & -\frac{b}{a} K_{TS} \frac{\nu_g \delta}{t_s} \frac{|\nabla T_g|}{T_\infty} \frac{(1 - (\lambda_0 + \frac{1}{\lambda_0})\text{arcctg}\lambda_0)}{\sqrt{1+\lambda_0^2}\Delta} \times \\
& \times \left(1 - \frac{Pr_\infty \gamma \lambda_0}{2(\lambda_0 + (1-\lambda_0^2)\text{arcctg}\lambda_0)} [\text{arcctg}^2 \lambda_0 - \right. \\
& \quad \left. - \lambda_0^2(\lambda_0 \text{arcctg}\lambda_0 - 1)^2] - \right. \\
& \quad \left. - \frac{b}{a} K_{TS} \xi \frac{\nu_g \delta}{t_s} \frac{(1 - (\lambda_0 + \frac{1}{\lambda_0})\text{arcctg}\lambda_0)}{\sqrt{1+\lambda_0^2}\Delta} \times \right. \\
& \quad \times \left(\frac{3a(1-\lambda_0 \text{arcctg}\lambda_0)}{4\pi c^3 \lambda_0 T_\infty} \int_V q_p z dV - \right. \\
& \quad \left. - \frac{Pr_\infty \gamma \lambda_0}{2(\lambda_0 + (1-\lambda_0^2)\text{arcctg}\lambda_0)} [\text{arcctg}^2 \lambda_0 + \right. \\
& \quad \left. + 4(\lambda_0 \text{arcctg}\lambda_0 - 1) + (\lambda_0 \text{arcctg}\lambda_0 - 1)^2] - K_{DS} D_{12} |\nabla C_1| \right)
\end{aligned} \quad (19)$$

In order to obtain an expression for the force and the speed of thermo-, photo-, and diffusiophoresis of the prolate spheroid, it is necessary to replace λ for $i\lambda$ in (18), (19) and c for $-i$ (i - imaginary unit).

Thus, formulas (18), (19) have the most the general character and allow to estimate the general force acting the solid aerosol particle of the spheroidal form and speed of its ordered movement in the external set field of the gradient of temperature and concentration when the non-uniformly distributed sources of heat act inside the particle. Thus, the influence of the environment movement is calculated at small relative temperature drops in its vicinity.

3 Analysis of obtained results

One can see from formulas (18), (19), that the movement of environment does not bring the contribution into the diffusion phoresis. Convective terms in the diffusion equation do not influence on the movement of a solid aerosol particle in the field of the concentration gradient. It can be of great importance in practical applications, for example, at the description of aerosol particles movement in the diffusion fields. In order the convective terms to influence on the diffusion phoresis it is necessary

to change boundary conditions for the diffusion part. It can be made in variety of ways. For example, to consider the movement not of the solid particle, but of an evaporating drop.

Movement of the environment brings the contribution both in the thermophoresis, and in the photophoresis. This contribution is proportional to the product of Prandtl number and an average temperature of the particle surface. Prandtl number for the majority of gases is of the order of unity. As the problem was solved at small relative temperature drops the movement contribution can give no more than 10 - 12 percent.

Consideration of special cases of movement of particles of the spheroidal form is of interest.

If not to consider the influence of the environment movement and internal sources of heat, then (19) transforms into expression for pure thermophoresis speed of the spheroidal particle.

$$U = -\frac{b}{a} K_{TS} \frac{\nu_g \delta}{t_s} \frac{|\nabla T_g|}{T_\infty} \frac{1 - (\lambda_0 + \frac{1}{\lambda_0})\text{arcctg}\lambda_0}{\sqrt{1+\lambda_0^2}\Delta} \quad (20)$$

coinciding with the formulae (9) of the work [5].

In case of a sphere the formula (19) transforms in expression for thermo-, photo-, diffusiophoretic speed of a solid spherical particle of radius R , considering influence of the environment movement and internal sources of heat:

$$\begin{aligned}
U(a=b=R) = & -K_{TS} \frac{\nu_g}{t_s} \frac{|\nabla T_g|}{T_\infty} \frac{2\delta}{1+2\delta} \cdot (1 - Pr_\infty \frac{\gamma}{3}) - \\
& - K_{TS} \xi \frac{\nu_g}{t_s} \frac{2\delta}{1+2\delta} \cdot \left(\frac{1}{4\pi R^2 \lambda_g T_\infty} \int_V q_p z dV + Pr_\infty \frac{\gamma}{8} \right) - \\
& - K_{DS} D_{12} |\nabla C_1|
\end{aligned} \quad (21)$$

Without influence of the environment movement and internal sources of heat we have the classical formula for the thermophoresis speed of a large spherical particle [10, 11].

$$U(a=b=R) = -K_{TS} \frac{\nu_g}{t_s} \frac{|\nabla T_g|}{T_\infty} \frac{2\delta}{1+2\delta} \quad (22)$$

To estimate, what influence renders the environment movement on the speed of thermo- and photophoresis of a spheroidal particle, it is necessary to concretize the nature of thermal sources non-uniformly distributed in its volume. As an example we will consider the most simple case when the particle absorbs radiation as a black body, i.e. the radiation absorption occurs in a thin layer in the thickness $\delta\varepsilon \ll \varepsilon_0$, adjoining to a heated up part of the particle surface. At that the density of thermal sources in a layer in the thickness $\delta\varepsilon$ is equal [12, 13] to

$$q_p(\varepsilon, \eta) = \begin{cases} -\frac{\cosh \varepsilon \cos \eta}{c(\cosh^2 \varepsilon - \sin^2 \eta)\delta\varepsilon} I_0, & \frac{\pi}{2} \leq \eta \leq \pi, \\ \varepsilon_0 - \delta\varepsilon \leq \varepsilon \leq \varepsilon_0, \\ 0, & 0 \leq \eta \leq \frac{\pi}{2} \end{cases} \quad (23)$$

where I_0 - is the intensity of falling radiation.

The expression for the speed of thermo- and photophoresis includes integrals $\int_V q_p dV$, $\int_V q_p z dV$. Substituting (23) in these integrals and accounting that $\delta\varepsilon \ll \varepsilon_0$ after integration one obtains:

$$\int_V q_p z dV = -\frac{2}{3}\pi c^3 I_0 \lambda_0^3 \left(1 + \frac{1}{\lambda_0^2}\right) \quad (24)$$

$$\int_V q_p dV = \pi c^2 I_0 \lambda_0^2 \left(1 + \frac{1}{\lambda_0^2}\right) \quad (25)$$

With accounting of (24), (25) the expression (19) has a form:

$$U = K_{TS} \nu_g \delta \left(f_{th}^* \cdot \frac{|\nabla T_g|}{T_\infty} + f_{ph}^* \cdot \xi \right) - K_{DS} D_{12} |\nabla C_1| \quad (26)$$

$$\begin{aligned} f_{th}^* &= -\frac{b}{a} \frac{1}{t_s} \frac{1 - (\lambda_0 + \frac{1}{\lambda_0}) \operatorname{arctg} \lambda_0}{\sqrt{1 + \lambda_0^2 \Delta}} \times \\ &\times (1 - Pr_\infty \frac{a I_0 (1 + \lambda_0^2)}{2 \lambda_g T_\infty} \cdot \frac{\operatorname{arctg}^2 \lambda_0 - \lambda_0^2 (\lambda_0 \operatorname{arctg} \lambda_0 - 1)^2}{4 \sqrt{1 + \lambda_0^2 (\lambda_0 + (1 - \lambda_0^2) \operatorname{arctg} \lambda_0)}}) \\ f_{ph}^* &= -\frac{b}{a} \frac{1}{t_s} \frac{1 - (\lambda_0 + \frac{1}{\lambda_0}) \operatorname{arctg} \lambda_0}{\sqrt{1 + \lambda_0^2 \Delta}} \times \\ &\times \frac{a I_0 (1 + \lambda_0^2)}{2 \lambda_g T_\infty} \cdot [\lambda_0 \operatorname{arctg} \lambda_0 - 1 - \\ &- Pr_\infty \frac{\operatorname{arctg}^2 \lambda_0 + 4 (\lambda_0 \operatorname{arctg} \lambda_0 - 1) + (\lambda_0 \operatorname{arctg} \lambda_0 - 1)^2}{4 \sqrt{1 + \lambda_0^2 (\lambda_0 + (1 - \lambda_0^2) \operatorname{arctg} \lambda_0)}}] \\ f_{th}^{**} &= -\frac{b}{a} \frac{1}{t_s} \frac{1 - (\lambda_0 + \frac{1}{\lambda_0}) \operatorname{arctg} \lambda_0}{\sqrt{1 + \lambda_0^2 \Delta}} \end{aligned}$$

In case of the sphere the expression (26) has a form:

$$\begin{aligned} U(a=b=R) &= -K_{TS} \frac{\nu_g}{t_s} \frac{|\nabla T_g|}{T_\infty} \frac{2\delta}{1+2\delta} (1 - Pr_\infty \frac{I_0 R}{12 \lambda_g T_\infty}) - \\ &- K_{TS} \xi \frac{\nu_g}{t_s} \frac{2\delta}{1+2\delta} \cdot \frac{I_0 R}{6 \lambda_g T_\infty} \left(\frac{3 Pr_\infty}{16} - 1 \right) - \\ &- K_{DS} D_{12} |\nabla C_1| \quad (27) \end{aligned}$$

To illustrate the contribution of the form-factor (the relation of semi-axes of the spheroid), the influence of the environment movement and an internal thermal release for the speed thermo- and photophoresis (26), in the picture curves connecting values $f = f_{t.ph}^* / f_{t.ph}^{**} |_{T_\infty=300K}$ with the intensity of falling radiation for particles of boride graphite ($\lambda_p = 55 W/(mK)$) with spheroidal (a curve 1 - taking into account the environment movement, a curve 2 - without movement) and spherical (a curve 3) forms of the surfaces suspended in air at $T_\infty = 300K$ and $P_g = 10^5 Pa$, for various relations of semi-axes of a spheroid are represented.

The numerical analysis has shown, that at the fixed relation of semi-axes with increase in intensity of the falling radiation the total contribution of the motion of environment and of internal thermal release leads to monotonous reduction of the thermo- and photophoresis speed, and this reduction essentially depends on equatorial radius of a spheroid a.

Quantitative research of the discussed phenomenon for solid heated particles represents quite real experimental problem.

Figure 1. Dependence of function f on the intensity of an incident radiation at the relation of semi-axes $b/a = 0, 2$ (ris.1). $I_0 - W/sm^2$

Figure 2. Dependence of function f on the intensity of an incident radiation at the relation of semi-axes $b/a = 0, 5$ (ris.2). $I_0 - W/sm^2$

Figure 3. Dependence of function f on the intensity of an incident radiation at the relation of semi-axes $b/a = 0, 7$ (ris.3). $I_0 - W/sm^2$

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