PHOTOPHORETIC, THERMOPHORETIC, AND DIFFUSOPHORETIC MOTION OF HEATED NONVOLATILE AEROSOL PARTICLES

E. R. Shchukin and N. V. Malai

UDC 533.72

The motion of heated nonvolatile particles in compressible gaseous media is investigated in the case where their surface temperature is much greater than the temperature of the surrounding medium at infinity.

Aerosol particles suspended in gas mixtures of nonuniform temperature and concentration are acted upon by forces produced by thermal and concentration stresses, which can impart an ordered motion to the particles [1-4]. The motion acquired by particles in a field of external temperature and concentration gradients is called thermodiffusophoretic motion [1, 2]. If the motion of the particles is induced by internal heat sources of electromagnetic origin, it is called photophoretic motion [3, 4].

The motion of particles for small relative temperature differences in the immediate surroundings has been investigated in sufficient detail in papers published to date on the theory of thermodiffusophoretic and photophoretic motion [1-4]. It is important from the theoretical and practical standpoint to study the laws governing the motion of particles when their mean surface temperature is much greater than the ambient temperature. The particles can be subjected to strong heating in an electromagnetic field as in, e.g., the laser sensing of clouds and fogs [5].

In the present article we formulate (in the Stokes approximation) a theory of photophoretic, thermophoretic, and diffusophoretic motion of large and moderate-size solid aerosol particles whose mean surface temperature differs significantly from the ambient temperature. We analyze the particle transport process at thermal and diffusion Peclet numbers much smaller than unity. We solve the gasdynamic equations with allowance for the compressibility of the gaseous medium and a power-law temperature dependence of the transfer coefficients. We assume that $\kappa_e \ll \kappa'$. We solve the problem in spherical coordinates with origin at the center of the representative particle.

The distribution of the fields $\mathbf{U}$, P, T_e, T', and C_{1e} are described by the system of equations

$$\frac{\partial}{\partial x_i}(\rho U_i)=0,\ \frac{\partial}{\partial x_i}P=\frac{\partial}{\partial x_j}\left\{\mu\left[\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial U_k}{\partial x_k}\right]\right\}, \tag{1}$$

$$\operatorname{div}(\varkappa_e\nabla T_e)=0,\quad \operatorname{div}(\varkappa'\nabla T')=-q_i, \tag{2}$$

$$\operatorname{div}\left(\frac{n^2 m_2 D_{m_1}}{\rho}\nabla C_{1e}\right)=0. \tag{3}$$

The system (1)-(3) is solved subject to the boundary conditions [3, 6, 7]

$$U_r=\frac{C_v^*}{R^2}\frac{\nu}{T_e}\left(\frac{\partial^2 T_e}{\partial\Theta^2}+\operatorname{ctg}\Theta\frac{\partial T_e}{\partial\Theta}\right)\Big|_{r=R}, \tag{4}$$

$$U_\theta=C_m^*\left[r\frac{\partial}{\partial r}\left(\frac{U_\theta}{r}\right)+\frac{1}{r}\frac{\partial U_r}{\partial\Theta}\right]+K_{Ts}\frac{\nu}{RT_e}\left(1+\frac{\beta_R^{*\prime}}{R}+\right.$$
$$\left.+\sigma_T\frac{\beta_R^*}{R}\right)\frac{\partial T_e}{\partial\Theta}+K_{Ds}\frac{D}{R}\left(1+\frac{\beta_{Rc}^{*\prime}}{R}+\sigma_c\frac{\beta_{Rc}^*}{R}\right)\frac{\partial C_{1e}}{\partial\Theta}-K_{Ts}\frac{\nu}{2T_e}$$
$$\left(\frac{1}{r^2}\frac{\partial^2 T_e}{\partial r\partial\Theta}+r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial T_e}{\partial\Theta}\right)\right)\times\beta_B^*-K_{Ds}\frac{D}{2}\beta_{Bc}^*\times\left(\frac{1}{r^2}\frac{\partial^2 C_{1e}}{\partial r\partial\Theta}+r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial C_{1e}}{\partial\Theta}\right)\right)\Big|_{r=R}, \tag{5}$$

State Pedagogical Institute, Tambov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 4, pp. 628-635, April, 1988. Original article submitted February 24, 1986.

0022-0841/88/5404-0437$12.50

$$T_e - T' = K_T \left.\frac{\partial T_e}{\partial r}\right|_{r=R}, \quad P|_{r\to\infty} = P_0, \quad T'|_{r\to 0} \neq \infty, \tag{6}$$

$$T_e|_{r\to\infty} = T_{e\infty} + |\nabla T_{e\infty}| \, r \cos\Theta, \quad U_r|_{r\to\infty} = (\mathbf{U}_\infty \mathbf{n}_z) \cos\Theta, \tag{7}$$

$$-\varkappa_e \frac{\partial T_e}{\partial r} + \varkappa' \frac{\partial T'}{\partial r} = -\frac{C_q^*}{R^2} \varkappa_e \left.\left(\operatorname{ctg}\Theta \frac{\partial T_e}{\partial \Theta} + \frac{\partial^2 T_e}{\partial \Theta^2}\right)\right|_{r=R}, \tag{8}$$

$$C_{1e}|_{r\to\infty} = C_{1\infty} + |\nabla C_{1\infty}| \, r\cos\Theta, \quad U_\theta|_{r\to\infty} = -(\mathbf{U}_\infty \mathbf{n}_z)\sin\Theta, \tag{9}$$

where

$$\sigma_T = \left.\left(\frac{\partial^2 T_e}{\partial r \partial \Theta}\right)\left(\frac{1}{R}\frac{\partial T_e}{\partial \Theta}\right)\right|_{r=R}^{-1}, \quad \sigma_c = \left(\frac{\partial^2 C_{1e}}{\partial r \partial \Theta}\right)\left(\frac{1}{R}\frac{\partial C_{1e}}{\partial \Theta}\right)_{r=R}^{-1}.$$

Expressions for the distributions of the fields t_e, t_i, and C_{1e} are obtained in the course of solving the system of equations (2), (3) by separation of variables:

$$t_e = t_{e0} + \frac{1}{t_{e0}^{\alpha}}\left(\sum_{n=1}^{\infty}\frac{\Gamma_n P_n}{y^{n+1}} + |\nabla t_{e\infty}| \, Ry\cos\Theta\right), \tag{10}$$

$$t_i = t_{i0} + \frac{1}{t_{i0}^{\gamma}}\left(\sum_{n=1}^{\infty}\left\{B_n y^n + \frac{y^{-(n+1)}}{2n+1}\int_1^0 f_n y^n dy - \frac{1}{2n+1}\left[y^n \int_1^y \frac{f_n}{y^{n+1}} dy - \frac{1}{y^{n+1}}\int_1^y f_n y^n dy\right]\right\} P_n\right), \tag{11}$$

$$C_{1e} = C_{1\infty} + \left(\frac{\Psi_2 \cos\Theta}{y^2} 3R|\nabla C_{1\infty}| + \sum_{n=1}^{\infty}\frac{M_n P_n}{y^{n+1}}\right)\Psi_1, \tag{12}$$

where $P_n = P_n(\cos\Theta)$ denotes the Legendre polynomials, $y = r/R$, $t_e = T_e/T_{e\infty}$

$$t_{e0} = \left(1 + \frac{\Gamma_0}{y}\right)^{\frac{1}{1+\alpha}}, \quad f_0 = -\frac{R^2}{2\varkappa_i} y^2 \frac{\gamma+1}{T_{e\infty}} \int_{-1}^{1} q_i d(\cos\Theta), \quad t_i = \frac{T'}{T_{e\infty}},$$

$$\underset{n\geqslant 1}{f_n} = -\frac{R^2}{\varkappa_i T_{e\infty}} y^2 \frac{2n+1}{2}\int_{-1}^{1} q_i P_n d(\cos\Theta), \quad \Psi_1 = \sum_{n=0}^{\infty}\Delta_n l^n, \tag{13}$$

$$t_{i0} = \left(B_0 + \frac{1}{y}\int_1^0 f_0 dy - \frac{1}{y}\int_1^y f_0 dy + \int_1^y \frac{f_0}{y} dy\right)^{\frac{1}{1+\gamma}},$$

$$\Psi_2 = \Gamma_0^3\left(\frac{1}{3l^3} + \left(\frac{\Omega_1}{2} - 1\right)\frac{1}{l^2} + (1 - 2\Omega_1 + \Omega_2)\frac{1}{l} + \ln l(-\Omega_1 + \right.$$
$$\left. + 2\Omega_2 - \Omega_3) + \sum_{n=1}^{\infty}(-\Omega_{n+1} + 2\Omega_{n+2} - \Omega_{n+3})\frac{l^n}{n}\right).$$

In Eqs. (12) and (13) the variable $l = \Gamma_0/(y + \Gamma_0)$. The values of Δ_n and Ω_n are determined by means of recursion relations, in which $\Delta_0 = \Omega_0 = 1$, $\Delta_{-1} = \Omega_{-1} = 0$:

$$\underset{n\geqslant 1}{\Delta_n} = \frac{1}{n(n+3)}\left\{(n+1)\left[2(n-1) - \frac{\omega}{1+\alpha}\right]\Delta_{n-1} + (n-2)\left[1 - n + \frac{\omega}{1+\alpha}\right]\Delta_{n-2}\right\}, \tag{14}$$

$$\underset{n\geqslant 1}{\Omega_n} = \frac{1}{n}\sum_{k=0}^{n-1}\left\{(k-2n)\Delta_{n-k} + \left[2n - k - 2 - \frac{\omega}{1+\alpha}\right]\Delta_{n-k-1}\right\}\Omega_k. \tag{15}$$

Because of the small temperature asymmetry $\kappa_e \ll \kappa'$, the coefficient D is estimated according to the relation $D = D_\infty t_{e0}^{1+\omega}$ in the determination of the field C_{1e}. This dependence is taken into account in the solution of the diffusion equation. The thermodiffusophoretic force and velocity are determined by constants Γ_1 and M_1, which are equal to

$$\Gamma_1 = |\nabla t_{e\infty}| \, Rb_3 + \frac{t_{e0}^{\alpha}}{b_2 t_{i0}^{\gamma}}\int_1^0 f_1 y dy, \quad M_1 = -3Rb_5|\nabla C_{1\infty}|, \tag{16}$$

where

$$b_4|_{y=1} = \Psi_1^I\Psi_2 + \Psi_2^I\Psi_1 - 2\Psi_1\Psi_2,\ K_{T0} = K_T|_{t_e=t_{es}},\ t_{es} = \left.\frac{T_{e0}}{T_{e\infty}}\right|_{y=1},$$

$$b_0|_{y=1} = \left[1 + \frac{K_{T1}}{R}\frac{lt_{e0}}{1+\alpha} - \frac{K_{T0}}{R}\left(\frac{\alpha l}{1+\alpha} - 2\right)\right],\quad K_{T1} = \left.\frac{dK_T}{dt_e}\right|_{t_e=t_{es}},$$

$$b_1|_{y=1} = \left[1 + \frac{K_{T1}}{R}\frac{lt_{e0}}{1+\alpha} - \frac{K_{T1}}{R}\left(1 + \frac{\alpha l}{1+\alpha}\right)\right],\quad \varkappa_{e0} = \varkappa_\infty t_{es}^{\alpha},$$

$$b_2|_{y=1} = \left(2\frac{\varkappa_{e0}}{\varkappa_{i0}} - 2\frac{\varkappa_{e0}}{\varkappa_{i0}}\frac{C_q^*}{R} + b_0\right),\quad b_5|_{y=1} = \frac{b_4}{\Psi_1^I - 2\Psi_1}, \tag{17}$$

$$b_3|_{y=1} = \frac{1}{b_2}\left(\frac{\varkappa_{e0}}{\varkappa_{i0}} + 2\frac{\varkappa_{e0}}{\varkappa_{i0}}\frac{C_q^*}{R} - b_1\right),\quad \varkappa_{i0} = \varkappa_i t_{is}^{\gamma},\quad t_{is} = \left.\frac{T_{i0}}{T_{e\infty}}\right|_{y=1},$$

$$b_6|_{y=1} = \int_1^0 f_0 dy \Big/ \left(B_0 + \int_1^0 f_0 dy\right).$$

In Eqs. (17) Ψ_1^I and Ψ_2^I are the derivatives of the functions Ψ_1 and Ψ_2 with respect to y.

The mean surface temperature t_{is} is related to the mean relative temperature t_{es} by Eq. (18), in which $\ell^{(s)} = \ell|_{y=1}$, $t_{es} = t_{e0}|_{y=1}$, $t_{is} = t_{i0}|_{y=1}$:

$$\frac{\varkappa_{e0}}{\varkappa_{i0}}\frac{l^{(s)}t_{es}}{1+\alpha} = b_6\frac{t_{is}}{1+\gamma},\quad t_{is} = t_{es}\left(1 + \frac{K_{T0}}{R}\frac{l^{(s)}}{1+\alpha}\right). \tag{18}$$

Expressions for the coordinates U_r and U_θ are obtained in the form of infinite series in Legendre and Gegenbauer polynomials, respectively. The resultant force acting on the particle is described by the first terms of these expansions:

$$U_r^* = (\mathbf{U}_\infty \mathbf{n}_z)(3U_3a_1 + U_2B_2' + B_1'a_1)\cos\Theta, \tag{19}$$

$$U_\theta^* = -(\mathbf{U}_\infty \mathbf{n}_z)(\Phi_3 + \Phi_2B_2' + \Phi_1B_1')\sin\Theta. \tag{20}$$

Inasmuch as $\kappa_e \ll \kappa'$, the values of the coefficients ν and μ are estimated in the derivation of these equations according to the relations $\nu = \nu_\infty t_{e0}^{1+\beta}$ and $\mu = \mu_\infty t_{e0}^{\beta}$.

The functions Φ_1, Φ_2, Φ_3, U_2, U_3 and a_1 in Eqs. (19) and (20) have the form

$$a_1 = \frac{1}{y^3}\sum_{n=0}^{\infty}\Theta_n l^n,\quad \Phi_1 = \left(1 + \frac{l}{2(1+\alpha)}\right)a_1 + \frac{1}{2}ya_1^I,$$

$$\Phi_2 = \left(1 + \frac{l}{2(1+\alpha)}\right)U_2a_1 + \frac{1}{2}y(U_2^Ia_1 + U_2a_1^I),$$

$$\Phi_3 = 3\left(1 + \frac{l}{2(1+\alpha)}\right)U_3a_1 + \frac{3}{2}y(U_3^Ia_1 + U_3a_1^I), \tag{21}$$

$$U_2 = \Gamma_0^2\left[\frac{1}{2l^2} + (\delta_1 - 1)\frac{1}{l} + \ln l(\delta_1 - \delta_2) + \sum_{n=1}^{\infty}(\delta_{n+2} - \delta_{n+1})\frac{l^n}{n}\right],$$

$$U_3 = \Gamma_0^3\left[\frac{1}{3l^3} + \left(\frac{\varepsilon_1}{2} - 1\right)\frac{1}{l^2} + (1 - 2\varepsilon_1 + \varepsilon_2)\frac{1}{l} + \ln l(-\varepsilon_3 + 2\varepsilon_2 - \right.$$

$$\left. -\varepsilon_1) + \sum_{n=1}^{\infty}(-\varepsilon_{n+3} + 2\varepsilon_{n+2} - \varepsilon_{n+1})\frac{l^n}{n}\right].$$

In Eqs. (21) $\ell = \Gamma_0/(y + \Gamma_0)$, a_1^I, U_2^I, U_3^I, etc., are the y-derivatives of the corresponding functions. The values of the coefficients Θ_n, δ_n, and ε_n are determined by means of recursion relations, in which $\Theta_0 = \delta_0 = \varepsilon_0 = 1$, $\Theta_{-n} = \delta_{-n} = \varepsilon_{-n} = 0$:

$$\Theta_{n \atop n\geq 1} = -\frac{1}{n(n+3)(n+5)}\{[(1-n)(3n^2 + 13n + 8) + (n+2)(n+3)\gamma_1 -$$

$$-(2+n)\gamma_2]\Theta_{n-1} + [(n-2)(n-1)(3n+5) - 2(n^2-4)\gamma_1 + (n-2)\gamma_2 + \tag{22}$$

$$+(n+3)\gamma_3]\Theta_{n-2} + [(1-n)(n-2)(n-3) + (n-3)(n-2)\gamma_1 - (n-2)\gamma_3]\Theta_{n-3}\},$$

$$\varepsilon_{n \atop n\geq 1} = -\frac{1}{n(n+2)}\sum_{k=0}^{n-1}\{[k^2+3n^2-3kn+7n-5k]\,\Theta_{n-k}+[2n+k+4-$$
$$-2(k^2+3n^2-3kn)+(2+2n-k)\gamma_1-\gamma_2]\,\Theta_{n-k-1}+ \tag{23}$$
$$+[k^2+3n^2-3kn+4k+6-9n+(4+k-2n)\gamma_1+\gamma_3]\,\Theta_{n-k-2}\}\,\varepsilon_k,$$

$$\delta_{n \atop n\geq 1} = -\frac{1}{(n+1)(n+3)}\left\{\sum_{k=0}^{n-1}[(3n^2+k^2-3kn+10n-6k+3)\,\Theta_{n-k}+\right.$$
$$+(-6n^2-2k^2+6kn-n+2k+7+(3+2n-k)\gamma_1-\gamma_2)\,\Theta_{n-k-1}+ \tag{24}$$
$$+(3n^2+k^2-3kn-9n+4k+6+(4-2n+k)\gamma_1+\gamma_3)\,\Theta_{n-k-2}]\,\delta_k-$$
$$\left.-3\,\frac{(-h)(1-h)\ldots(n-1-h)}{n!}\right\},$$

where

$$\gamma_1=\frac{\beta-1}{1+\alpha},\quad \gamma_2=2\frac{1+\beta}{1+\alpha},\quad \gamma_3=\frac{2+2\alpha-\beta}{(1+\alpha)^2},\quad h=\frac{\beta}{1+\alpha}.$$

The values of the coefficients B_1' and B_2' are determined by substituting U_θ^* and U_r^* in the boundary conditions (4) and (5). Once B_1' and B_2' have been calculated, an equation for the total force $\mathbf{F}$, acting on the particle is obtained by integrating the tensor of viscous stresses over the particle surface:

$$\mathbf{F}=\mathbf{F}_\mu+\mathbf{F}_D+\mathbf{F}_T+\mathbf{F}_q, \tag{25}$$

where

$$\mathbf{F}_\mu=6\pi R\mu_\infty f_{\mu 1}\,|\mathbf{U}_\infty|;$$
$$\mathbf{F}_T=-6\pi R\mu_\infty\nu_\infty f_{T1}\,\mathrm{grad}\,t_{e\infty};$$
$$\mathbf{F}_D=-6\pi R\mu_\infty D_\infty f_{D1}\,\mathrm{grad}\,C_{1\infty}; \tag{26}$$
$$\mathbf{F}_q=-6\pi R\mu_\infty f_{q1}\frac{\nu_\infty}{R^3\varkappa_i T_{e\infty}}\int_V \mathbf{r}q_i\,dV.$$

The coefficients $f_{\mu 1}$, f_{D1}, f_{T1}, and f_{q1} in the equations for the viscous resistance of the medium $\mathbf{F}_\mu$, the diffusophoretic force $\mathbf{F}_D$, the thermophoretic force $\mathbf{F}_T$, and the photophoretic force $\mathbf{F}_q$ can be evaluated according to the equations

$$f_{\mu 1}=\frac{U_3^{\mathrm{I}}+N_1\dfrac{C_m^*}{R}}{U_2^{\mathrm{I}}+N_2\dfrac{C_m^*}{R}}, \tag{27}$$

$$f_{D1}=\frac{2K_{Ds}t_{e0}^{1+\omega}}{a_1\left(U_2^{\mathrm{I}}+N_2\dfrac{C_m^*}{R}\right)}\left\{\left(1+\frac{\beta_{Rc}^{*\prime}}{R}+\frac{\beta_{Bc}^*}{R}\right)\frac{\psi_1^2\psi_2^{\mathrm{I}}}{2\psi_1-\psi_1^{\mathrm{I}}}\right\}, \tag{28}$$

$$f_{T1}=\frac{2t_{e0}^{\beta-\alpha}}{3a_1\left(U_2^{\mathrm{I}}+N_2\dfrac{C_m^*}{R}\right)}\left\{K_{Ts}\left[\left(1+\frac{\beta_R^{*\prime}}{R}+\frac{\beta_B^*}{R}\right)(1+b_3)+\right.\right.$$
$$\left.\left.+\left(\frac{\beta_R^*}{R}-\frac{\beta_B^*}{R}\right)\left(\left(\frac{\alpha l}{1+\alpha}-2\right)(1+b_3)+3\right)\right]+\frac{C_v^*}{R}(1+b_3)\left(N_3+N_4\frac{C_m^*}{R}\right)\right\}, \tag{29}$$

$$f_{q1}=\frac{t_{e0}^{\beta}(b_2t_{i0}^{\gamma})^{-1}}{2\pi a_1\left(U_2^{\mathrm{I}}+N_2\dfrac{C_m^*}{R}\right)}\left\{K_{Ts}\left[1+\frac{\beta_R^{*\prime}}{R}+\frac{\beta_B^{*\prime}}{R}+\right.\right.$$
$$\left.\left.+\left(\frac{\beta_R^*}{R}-\frac{\beta_B^*}{R}\right)\left(\frac{\alpha l}{1+\alpha}-2\right)\right]+\frac{C_v^*}{R}\left(N_3+N_4\frac{C_m^*}{R}\right)\right\}, \tag{30}$$

where

$$N_1|_{y=1} = -\left(2+\frac{l}{1+\alpha}\right)U_3^{\mathrm{I}} - \left(U_3^{\mathrm{II}} + 2U_3^{\mathrm{I}}\frac{a_1^{\mathrm{I}}}{a_1}\right);$$

$$N_2|_{y=1} = -\left(2+\frac{l}{1+\alpha}\right)U_2^{\mathrm{I}} - \left(U_2^{\mathrm{II}} + 2U_2^{\mathrm{I}}\frac{a_1^{\mathrm{I}}}{a_1}\right);$$

$$N_3|_{y=1} = \left(2+\frac{l}{1+\alpha}\right) + \frac{a_1^{\mathrm{I}}}{a_1}; \qquad (31)$$

$$N_4|_{y=1} = \frac{(2-l)\,l}{1+\alpha} - \left(2+\frac{l}{1+\alpha}\right)\frac{a_1^{\mathrm{I}}}{a_1} - \frac{a_1^{\mathrm{II}}}{a_1}.$$

In Eqs. (27)-(30) the quantities C_m^*, C_V^*, K_T, K_{Ts}, $\beta_R^{*'}$, β_R^*, K_{Ds}, $\beta_{Rc}^{*'}$, β_B^*, and β_{Bc}^* are evaluated at $t_{e0} = t_{es}$. In the limit $\Gamma_0 \to 0$ (small temperature differences in the vicinity of the particle) the coefficients $a_1 = 1$, $a_1^{\mathrm{I}} = -3$, $a_1^{\mathrm{II}} = 12$, $U_2 = 0{,}5$, $U_2^{\mathrm{I}} = 1$, $U_2^{\mathrm{II}} = 1$, $U_3 = 1/3$, $U_3^{\mathrm{I}} = 1$, $U_3^{\mathrm{II}} = 2$, $N_1 = 2$, $N_2 = 3$, $N_3 = -1$, $N_4 = -6$, $\psi_1 = 1$, $\psi_1^{\mathrm{I}} = 0$, $\psi_2 = 1/3$, and $\psi_2^{\mathrm{I}} = 1$.

Setting **F** equal to zero, we obtain an expression for the velocity $\mathbf{U}_p$ of ordered motion of the particle as the sum of the diffusophoretic velocity $\mathbf{U}_D$, the thermophoretic velocity $\mathbf{U}_T$, and the photophoretic velocity $\mathbf{U}_q$:

$$\mathbf{U}_p = \mathbf{U}_D + \mathbf{U}_T + \mathbf{U}_q, \qquad (32)$$

where

$$\mathbf{U}_D = -D_\infty f_{D2}\,\mathrm{grad}\,C_{1\infty}; \quad \mathbf{U}_T = -\nu_\infty \gamma_{T2}\,\mathrm{grad}\,t_{e\infty};$$

$$\mathbf{U}_q = -f_{q2}\frac{\nu_\infty}{R^3 \varkappa_i T_{e\infty}}\int_V \mathbf{r} q_i dV. \qquad (33)$$

The form of the coefficients f_{D2}, f_{T2}, and f_{q2} is analogous to the form of the coefficients f_{D1}, f_{T1}, and f_{q1}, except that the expression $[U_2^1 + N_2(C_m^*/R)]$ must be replaced by $[U_3^{\mathrm{I}} + N_1(C_m^*/R)]$ everywhere in front of the braces.

In Eqs. (26) and (33) $\mathbf{r}$ is a radius vector denoting the positions of points of the particle, and the integration is carried out over the entire volume of the particle.

The equations obtained for $\mathbf{F}_\mu$, $\mathbf{F}_D$, $\mathbf{F}_T$, $\mathbf{F}_q$, $\mathbf{U}_D$, $\mathbf{U}_T$, and $\mathbf{U}_q$ can also be used to estimate the forces acting on the particle and the velocities of its ordered motion for an arbitrary, not necessarily azimuthally symmetric distribution of the density of heat sources in the particle volume and for arbitrary relative orientations of the vectors $\nabla t_{e\infty}$ and $\nabla C_{1\infty}$.

It follows from Eqs. (26) and (33) that the direction of the photophoretic force and velocity is determined by the direction of the dipole moment of the density of heat sources $\int_V \mathbf{r} q_i dV$. If the dipole moment coordinate perpendicular to the direction of radiation transmission is not equal to zero, particles will be repulsed from (or drawn into) the radiation flow.

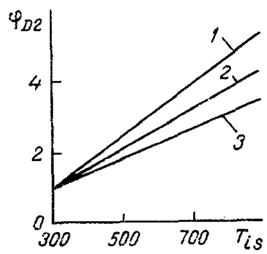

Fig. 1

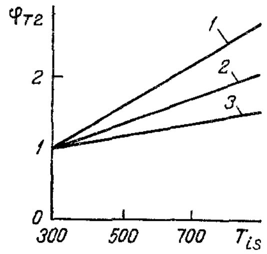

Fig. 2

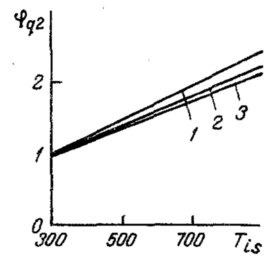

Fig. 3

Fig. 1. Coefficient φ_{D2} vs mean temperature T_{is} (K).

Fig. 2. Coefficient φ_{T2} vs mean temperature T_{is} (K).

Fig. 3. Coefficient φ_{q2} vs mean temperature T_{is} (K).

To illustrate the dependence of U_q and U_T on T_{is}, Figs. 1 and 2 show curves relating the values of the coefficients $\varphi_{T2} = f_{T2}/f_{T2}|_{T_{is}=300\text{K}}$ and $\varphi_{q2}=f_{q2}/f_{q2}|_{T_{is}=300\text{K}}$ to the values of T_{is} for large aluminum particles of radius R = 15 μm suspended in pure nitrogen at a temperature $T_{e\infty}$ = 300 K and a pressure P_0 = 1 atm. The values of $\varphi_{D2} = f_{D2}/f_{D2}|_{T_{is}=300\text{K}}$ are estimated in a vapor–air mixture with $C_{1\infty}$ = 0.05, $T_{e\infty}$ = 300 K, and P_0 = 1 atm (see Fig. 3). Curves 1-3 in Figs. 1-3 are plotted for α = β = ω = 1, 0.7, 0.5, respectively. The values of κ_{i0} are taken from [8] for $\varkappa_{io} = \varkappa'|_{T_{is}=300\text{K}}$. At $T_{e\infty}$ = 300 K the coefficients f_{D2}, f_{T2}, and f_{q2}, are equal to $f_{D2}|_{T_{is}=300\text{K}} = 1.4\cdot10^{-1}$, $f_{T2}|_{T_{is}=300\text{K}} = 2.37\cdot10^{-4}$ and $f_{q2}|_{T_{is}=300\text{K}} = 1.84\cdot10^{-1}$.

NOTATION

T_e, T', temperature of gas and particle; $\rho = \rho_1 + \rho_2$, $\rho_1 = n_1m_1$, $\rho_2 = m_2n_2$; n_1, n_2, concentrations of first and second components of gas mixture; m_1, m_2, masses of these components; $C_{1e} = n_1/n$, $n = n_1 + n_2$; U_θ, U_r, polar and radial components of mass flow velocity; C_m^*, K_{Ds}, K_{Ts}, isothermal, diffusion, and thermal slip factors; K_T, temperature-jump coefficient; n_z, unit vector in direction of z axis; q_i, density of heat sources in particle interior, which depend on spherical coordinates r, Θ (0 ≤ Θ ≤ π); $\mathbf{U}_\infty$, gas flow velocity around particle ($\mathbf{U}_\infty \| OZ$); R, particle radius; $(\nabla T_{e\infty})$, $(\nabla C_{1\infty})$, temperature and relative concentration gradients of first component of binary gas mixture; κ', κ_e, coefficients of kinematic and dynamic viscosity, diffusion, and thermal conductivity of particle and gas, respectively [$\nu = \nu_\infty t_e^\beta$, $\mu = \mu_\infty t_e^{1+\beta}$, $D = D_\infty t_e^{1+\omega}$, $\kappa' = \kappa_i t_i^\gamma$, $\kappa_e = \kappa_\infty t_e^\alpha$, where $\nu_\infty = \nu(T_{e\infty})$, $D_\infty = D(T_{e\infty})$, $\mu_\infty = \mu(T_{e\infty})$, $\kappa_\infty = \kappa_e(T_{e\infty})$]; $T_{e\infty} = T_e|_{r\to\infty, \Theta=\pm\pi/2}$, $C_{1\infty} = C_{1e}|_{r\to\infty, \Theta=\pm\pi/2}$, $P_0 = P|_{r\to\infty, \Theta=\pm\pi/2}$, unperturbed values of temperature, relative concentration, and pressure; C_m^*, C_v^*, K_{Ts}, K_{Ds}, K_T, $\beta_R^{*\prime}$, β_B^*, $\beta_{Rc}^{*\prime}$, and β_{Bc}^* are determined by methods of the kinetic theory of gases and can be taken from [1, 6, 7]; $\kappa_i = \kappa'(T_{e\infty})$; $t_e = \frac{T_e}{T_{e\infty}}$, $t_i = \frac{T'}{T_{e\infty}}$.

LITERATURE CITED

1. Yu. I. Yalamov and V. S. Galoyan, Dynamics of Droplets in Inhomogeneous Viscous Media [in Russian], Erevan (1985).
2. Yu. I. Yalamov, M. N. Gaidukov, and E. R. Shchukin, Inzh.-Fiz. Zh., 37, No. 2, 505-507 (1975).
3. E. R. Shchukin, Zh. Tekh. Fiz., 50, No. 6, 1332-1335 (1980).
4. S. P. Lin, J. Colloid Interface Sci., 51, No. 1, 66-74 (1975).
5. M. A. Kolosov, Attenuation of Laser Radiation in Hydrometeors [in Russian], Moscow (1977).
6. A. B. Poddoskin, A. A. Yushkanov, and Yu. I. Yalamov, Zh. Tekh. Fiz., 50, No. 1, 157-169 (1980).
7. I. N. Ivchanko and Yu. I. Yalamov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 59-66 (1969).
8. A. S. Okhotin, R. P. Borovikov, T. V. Nechaev, and A. S. Pushkarskii, Thermal Conductivity of Solids (Handbook) [in Russian], Moscow (1984).