PERGAMON

International Journal of Heat and Mass Transfer 42 (1999) 4055–4063

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Gas pressure on the surface of condensed phase in a resonance radiation field

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Received 30 July 1997

Abstract

The influence of resonance radiation on the pressure exerted by gas on the surface of a condensed phase is studied. The effects, which are associated with a change in the recoil pressure of molecules escaping from the surface in a radiation field, are considered. Combined manifestation of thermal and resonance effects is analyzed, as well as the influence of a change in the indicatrix of scattering of the molecules leaving a surface in a radiation field. It is shown that new components of a photophoretic force, that acts on an aerosol particle, can appear in the field of resonance radiation. In such a situation there is a resultant force even in the case of uniform heating of the particle when classical photophoresis does not occur. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Gas pressure; Resonance radiation; Photophoresis

1. Introduction

It is known that transfer phenomena in heterogeneous systems are substantially, and in a number of cases decisively, influenced by the processes occurring on the interface surface. Surface processes often prove to be a channel by means of which transfer phenomena are connected with different kinds of external influences on a system. So, resonance (in particular, laser) radiation can change the character of the interaction of gas particles with a surface [1,2], which in turn leads to a change in the permeability of porous bodies and individual capillaries relative to the gas flowing through them [3–6]. When resonance radiation affects a gas-porous body system, which was equilibrium before the exposure to radiation, a resultant mass flux can be realized in this system [7–16]. The influence of radiation on the escape of gas through capillary-porous bodies into vacuum in the absence of the sources and sinks of molecules on the walls of the pores can occur both by means of surface diffusion process and via a change in the indicatrix of scattering of molecules by the wall of a capillary due to radiation [4–6]. The second of the mechanisms mentioned above allowed one in Ref. [6] to explain the results of experiments concerning the reduction of the resultant flux of rarefied gas outgoing from a capillary into vacuum in the resonance radiation field [3] and [15] to interpret the results of experiments related to the sign of pressure drop occurring in a gas exposed to radiation with a frequency detuned from the resonance frequency of the molecules of the gas contained in two closed volumes connected by a capillary [16]. Besides the previously mentioned phenomena of radiation-induced

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PII: S0017-9310(99)00061-7

Nomenclature

E	density of energy flux
e	excitation energy of molecules
F	force acting on an aerosol particle
f	velocity distribution function of molecules
h	Planck constant
I_d	density of flux of desorbing molecules
J	radiation flux density
k	Boltzmann constant
k_p	factor of efficiency of radiation absorption by aerosol particle
L	thickness of plate
m	mass of a molecule
N	$P/(2\pi mkT_g)^{1/2}$
n	density of gas molecules
n_a	density of adsorbed molecules
P	gas pressure
P_d	recoil pressure of gas molecules
R	radius of an aerosol particle
T_g	gas temperature
T	temperature of surface
t_ν	time of relaxation of excited molecules
v	mean velocity of molecules

Greek symbols

α	sticking coefficient
α_{ab}	absorption coefficient
β_r	reflection coefficient
ε	emissivity
θ	angle between a normal to the surface and a trajectory of molecule movement
λ	thermal conductivity
μ	parameter characterizing the difference of molecule scattering by a surface from the cosine law
ν	radiation frequency
ξ_n	projection of molecule velocity on a normal to a surface
ξ_x, ξ_y, ξ_z	coordinates of molecule velocity
Σ_r	cross section of radiation transitions of molecules
τ	adsorption time

Subscripts

1	nonexcited molecules
2	excited molecules
a	adsorbed molecules
ab	radiation absorption
g	gas

mass transfer in separate channels and porous bodies, effects due to the radiation-induced change in the pressure, acting from the side of the gas on the condensed phase surface, can also be important. These problems arise, in particular, in calculation of the forces that act on aerosol particles. The detuning of the frequency of the radiation incident on the wall from the resonance frequency of molecules deforms the velocity distribution function [17] leading also to a change in the state of the gas near the wall [18]. Note that a change in the character of the occurrence of surface processes in the radiation field can lead to a change in gas pressure acting on the surface even if the velocity distribution function of molecules incident on the surface can be considered to be invariable. Further the effects are considered which are related to a change in the recoil pressure of the molecules outflowing from a surface in a radiation field [19–23].

2. Gas pressure on a wall heated by radiation in the case of different coefficients of sticking to a surface of the molecules excited and nonexcited by radiation

Consider a solid plate placed in a gas phase. Let resonance radiation with the flux density J fall on one of the sides of the plate. The plate is assumed to be thermally thin, so that the temperature can be considered constant along the thickness (this can be realized for sufficiently thin opaque bodies with high heat conductivity and also for optically transparent materials [24]). In this case, for a stationary temperature of the plane-parallel plate, placed in a gas phase, at a rather small difference between the temperature of the plate T and the surrounding gas temperature T_g, with [24] taken into account, the following expression can be written

$$J_{ab} = 2(\eta + 4\varepsilon\sigma T_g^3)(T - T_g) = 2\eta'(T - T_g), \tag{1}$$

where η' is the effective coefficient of heat transfer between the plate and the gas phase (the conditions of heat transfer for both sides of the plate are assumed to be identical), σ is the Stefan–Boltzmann constant. For transparent bodies we have: $J_{ab} = J(1-\beta_r)(1-\exp\{-\beta_{ab}L\})$, where β_r is the reflection coefficient, β_{ab} is the absorption coefficient, L is the plate thickness; for opaque bodies the following correlation can be written: $J_{ab} = J(1-\beta_r)$.

A combined influence of thermal and resonance radiation effects will be considered using as an example velocity-selective excitation of molecules by radiation in a gas phase. Suppose that radiation characterized by a frequency ν affects in the direction of the X-coordinate, which is perpendicular to the side surfaces of a transparent plate. If the resonance frequency ν_0 of the gas molecules is slightly larger than ν, only the molecules moving in the direction opposite to the direction of radiation flux will go over into an excited state due to the Doppler effect. Thus, a larger portion of excited molecules is incident on the plate surface at $X=L$ than at $X=0$ (excited molecules fall on the latter surface only after intermolecular collisions due to which they can be deactivated). Further we consider for simplicity that excited molecules do not fall on the surface $X=0$ at all. For the densities of excited and nonexcited molecules equations can be written that describe transitions of molecules from one state to another. In the two-level model approximation they have the following form [25]

$$\frac{dn_1}{dt} = (n_2 - n_1)\frac{J\Sigma}{h\nu} + \frac{n_2}{t_v}, \tag{2}$$

$$\frac{dn_2}{dt} = (n_1 - n_2)\frac{J\Sigma}{h\nu} - \frac{n_2}{t_v}, \tag{3}$$

where n_1, n_2 are the densities of nonexcited and excited molecules, respectively; t_v is the relaxation time of molecules; Σ is the cross section of radiation transitions of molecules from one state to another.

In a stationary state for $\gamma = n_2/(n_2+n_1)$ Eqs. (2) and (3) yield

$$\gamma = \frac{J\Sigma}{h\nu}t_v \Big/ \left(1 + 2\frac{J\Sigma}{h\nu}t_v\right). \tag{4}$$

In the case considered the value of Σ is nonzero if the component ξ_x of the molecular velocity falls into a certain interval of values which depends on the frequency of radiation (it is essential that in this case the value of Σ is nonzero only when $\xi_x < 0$ due to the Doppler effect).

It is known that the pressure exerted by gas on the condensed phase surface is attributable to the impacts of molecules against the surface, as well as to the recoil pressure generated on escape of molecules from the surface. Further we assume that excited molecules stick to the surface (they are adsorbed with complete deactivation and take the surface temperature) with the probability α_2 and reflect elastically (without deactivation) with the probability $1-\alpha_2$. There are analogous probabilities also for nonexcited molecules. The sticking coefficients of excited (α_2) and nonexcited (α_1) molecules are considered to be averaged over velocities and angles of incidence. We also neglect the possibility for the excitation of gas molecules on their impact against the surface. With the above assumptions taken into account the following expressions can be written for the velocity distribution functions of nonexcited (f_1^-) and excited (f_2^-) molecules escaping from the surface

$$f_1^- = (1-\alpha_1)f_1 + f_d, \tag{5}$$

$$f_2^- = (1-\alpha_2)f_2, \tag{6}$$

where f_1 and f_2 are the velocity distribution functions of nonexcited and excited molecules incident on the surface, respectively. The function f_d characterizes desorbing molecules. In the case of monomolecular adsorption and diffuse law of emission of desorbing molecules this function has the form

$$f_d = \frac{n_a}{\tau}g_f, \tag{7}$$

where g_f is determined as

$$g_f = \frac{m^2}{2\pi(kT)^2}\exp\left\{-\frac{(\xi_x^2+\xi_y^2+\xi_z^2)m}{2kT}\right\}. \tag{8}$$

Assuming the Henry law to be satisfied for adsorption, we have for n_a

$$n_a = \left|\alpha_1\int_{\xi_n<0}\xi_n f_1\,d\vec{\xi} + \alpha_2\int_{\xi_n<0}\xi_n f_2\,d\vec{\xi}\right|\tau. \tag{9}$$

We have the following expression for the pressure exerted by the gas on the surface

$$P = P^+ + P^- + P_d, \tag{10}$$

where P^+, P^- and P_d are the components of the pressure due to incident, reflecting and desorbing molecules, respectively.

It is seen from Eqs. (1–10) that the pressure exerted by the gas on the surface exposed to radiation depends on both its heating and resonance effects ($f_1 \neq f_2, \alpha_1 \neq \alpha_2$). In a general case the functions f_1, f_2 are determined by kinetic equations that take account of the transitions of gas molecules from one state to another due to radiation.

If the velocity distribution of gas molecules is approximated by the Maxwell velocity distribution, which is identical on both sides of the plate, we, taking into consideration what has been said above, have the following expressions for the difference of pressures acting on the opposite sides of the plate [20–22]

$$\Delta P = \frac{1}{2}(\alpha_1 - \alpha_2)\frac{J\Sigma}{h\nu}t_\nu\left(1 + 2\frac{J\Sigma}{h\nu}t_\nu\right)^{-1} nkT_g \times \left[\left(1 + \frac{J_{ab}}{2\eta' T_g}\right)^{1/2} - 1\right]. \tag{11}$$

It is seen from Eq. (11) that the value of ΔP will increase with an increase in J_{ab} and in the difference $\alpha_1 - \alpha_2$ and with a decrease in η'. Therefore, when the pressure and temperature of the gas on both sides of the plate are identical, the resultant force acting on the plate can appear as a result of plate heating by incident radiation and of the difference in the sticking coefficients for the opposite surfaces of the plate.

3. Influence of the spatial distribution of the molecules outgoing from a surface on recoil pressure

It is known that in the field of resonance radiation molecules can be scattered by the surface in nonequilibrium fashion [26,27]. The influence of this effect on gas flow in capillaries was considered in [6,15]. Below, the influence of change in the spatial distribution of molecules outgoing from the surface in radiation field on a normal momentum transferred by gas molecules to the surface and, correspondingly, on the gas pressure on the surface is analyzed [19–22].

The problems of nonequilibrium desorption of gas molecules from the surface are considered in [26]. The nonequilibrium desorption is understood to be the desorption of molecules, in which the distribution function of emerging molecules is not described by the Maxwell distribution function with the temperature equal to the surface temperature. It is noted that the cosine law is not usually applicable for nonequilibrium desorption and that angular distribution of desorbing molecules is proportional to $\cos^\mu \theta$, where θ is the angle between the direction of the motion of a molecule and a normal to the surface, μ is the parameter, which characterizes the difference of the spatial distribution of molecules leaving the surface from the cosine law. A similar spatial distribution of evaporating CdS molecules exposed to the influence of optical radiation was observed experimentally in [27]. It is also shown that evaporating molecules are divided into high-energy ones that emerge at small angles relative to the normal to the surface ($\mu > 1$) and low-energy ones whose angular distribution corresponds to the cosine law and the desorption mechanism can be considered to be quasi-equilibrium thermal. The probability of the escape of molecules from the surface at an angle θ to the normal in the solid angle element $d\omega$ can be presented in the form

$$dW = (\mu + 1)\frac{\cos^\mu \theta}{2\pi}\, d\omega. \tag{12}$$

With the foregoing taken into consideration, it is assumed further that the dependence of μ on the mean velocity of scattered molecules can be approximated as

$$\mu = 1 \text{ at } v = v_{1'}, \tag{13}$$

$$\mu > 1 \text{ at } v = v_{\mu'}$$

where v_1 is the mean velocity, which corresponds to the surface temperature, v_μ is the mean velocity of molecules in nonequilibrium scattering ($\mu \neq 1$) (a more exact description of the process naturally needs allowance for the distribution function in velocities and, correspondingly, in the values of μ, but further for simplicity we will limit ourselves to the approximation of the mean values of v and μ).

Suppose that all the molecules incident on the surface are adsorbed on it and that the influence of radiation on an adsorbed phase leads to a nonequilibrium desorption (the parameter μ in (12) is not equal to unity). In this case the pressure exerted by desorbing molecules on the surface can be presented in the form [19–22]

$$P_d = \int_0^{2\pi}\int_0^{\pi/2} mvI_d(\mu + 1)\frac{\cos^{\mu+1}\theta}{2\pi}\sin\theta\, d\theta\, d\phi, \tag{14}$$

where I_d is the flux density of the molecules being desorbed [19–22].

From Eq. (14) we obtain an expression for P_d:

$$P_d = \frac{\mu+1}{\mu+2}mv_\mu I_\mu + \frac{2}{3}mv_1 I_1, \tag{15}$$

where I_1 and I_μ are the densities of fluxes of the molecules being desorbed that correspond to the velocities v_1 and v_μ. The relationship between I_μ and I_1 depends, in particular, on radiation flux density, and the sum of I_μ and I_1, on the assumption of the Maxwell distribution function for gas molecules incident on the surface, is equal to $nv/4$, where v is the mean velocity of molecules in the gas phase. Under the assumption that the desorption of molecules, characterized by the inequalities $\mu > 1$ and $v_1 \neq v_\mu$, is realized only on the irradiated side of the plate, the difference in the recoil pressures of escaping molecules for the opposite sides of the plate is determined by the expression [21]

$$\Delta P_d = I_\mu m\left(\frac{\mu+1}{\mu+2}v_\mu - \frac{2}{3}v_1\right). \tag{16}$$

As it follows from Eq. (16), the value of ΔP_d increases with increasing I_μ, v_1 and μ.

The detuning of the frequency with which radiation is incident on the plate from the resonance frequency of gas molecules, which leads to velocity-selective excitation of molecules [17], can also influence the recoil pressure of the molecules that escape from the surface. In this case the effect of the detuning mentioned can manifest itself both via the dependence of the sticking coefficient of gas molecules on the direction of their motion and through the change in the indicatrix of scattering of the excited molecules. Besides, velocity-selective excitation of molecules can lead to asymmetric transfer of energy released in deactivation of excited molecules on their collisions with a wall [28,29].

4. Momentum transfer by molecules to a surface due to light-induced energy transfer

Consider the process of light-induced energy transfer using as an example a transparent plane-parallel plate [21]. As before, suppose that the plate of thickness L is exposed to resonance radiation in the direction of the X-coordinate, perpendicular to the plane of the plate, and that this radiation is characterized by the frequency ν whose value is slightly smaller than the resonance frequency ν_0 of the gas molecules; this, as noted earlier, leads to the excitation of the molecules that move oppositely to the X-axis.

Disregarding radiation heat transfer, the stationary distribution of temperature $T(x)$ along the plate thickness is determined from the equation

$$\frac{\mathrm{d}}{\mathrm{d}X}\left(\lambda\frac{\mathrm{d}T}{\mathrm{d}X}\right)=0 \tag{17}$$

under the following boundary conditions

$$-\lambda\frac{\mathrm{d}T}{\mathrm{d}X}\bigg|_{X=0}=E(0)-E_{\mathrm{s}}(0), \tag{18}$$

$$-\lambda\frac{\mathrm{d}T}{\mathrm{d}X}\bigg|_{X=L}=E_{\mathrm{s}}(L)-E(L), \tag{19}$$

where λ is the thermal conductivity (hereafter assumed to be constant); $E(0)$ and $E(L)$ are the densities of the fluxes of energy brought onto the plate surfaces $X=0$ and $X=L$ by the gas molecules incident on them; $E_{\mathrm{s}}(0)$ and $E_{\mathrm{s}}(L)$ are the densities of the fluxes of energy removed from the corresponding surfaces of the plate by emerging molecules.

The sticking coefficients of both excited and nonexcited molecules are assumed to be equal to unity for simplicity. We also consider that when excited molecules are being adsorbed, they deactivate completely, whereas the molecules incident on the surface and leaving it are described by the Maxwell velocity distribution function.

To estimate $E(0)$ and $E(L)$, we use the following simple model. Let the densities of the molecular fluxes incident on the opposite surfaces of the plate be equal to $N=P/(2\pi mkT_{\mathrm{g}})^{1/2}$, where P and T_{g} are the pressure and temperature of the gas, respectively (assumed to be constant values), m is the mass of a molecule, k is the Boltzmann constant, and the difference between $E(0)$ and $E(L)$ is only that $E(L)$ includes the excitation energy e of gas molecules because of the account taken of the above-mentioned condition of detuning of the radiation frequency from the resonance frequency of these molecules. On the assumption that $E_{\mathrm{s}}(0)=N\kappa T(0)$, $E_{\mathrm{s}}(L)=N\kappa T(L)$, $E(0)=N\kappa T_{\mathrm{g}}$, $E(L)=N(\kappa T_{\mathrm{g}}+\gamma e)$, where κ is the quantity characterized by the number of the degrees of freedom of gas molecules, Eqs. (17–19) yield the following equation for $T(X)$

$$T=T_{\mathrm{g}}+\frac{\lambda\gamma e}{\kappa(2\lambda+\kappa NL)}+\frac{\gamma eN}{2\lambda+\kappa NL}X. \tag{20}$$

It follows from Eq. (20) that under the conditions specified the temperature T will be maximum at $X=L$, i.e., on the plate surface, which is located farther away from a radiation source (with a change in the sign of detuning $\nu-\nu_0$ the temperature profile reverses).

The difference between $T(0)$ and $T(L)$ leads to the occurrence of noncompensated momentum acting on the plate. Under the above-stipulated assumptions and under the condition $(T-T_{\mathrm{g}})/T_{\mathrm{g}} < < 1$ we obtain for the difference in the pressures that act on the opposite sides of the plate the following relation

$$\Delta P=\frac{P}{4}\frac{\gamma NeL}{T_{\mathrm{g}}(\kappa NL+2\lambda)}. \tag{21}$$

It is seen from Eq. (21) that ΔP increases with increasing γ, e and decreases with increasing T_{g} and λ.

5. The force acting on an aerosol particle in the resonance radiation field

Electromagnetic radiation is known to be able to exert direct force on the aerosol particle (pressure of radiation), as well as to lead to the appearance of the forces associated with a temperature drop in the gas phase and in the particle itself. The last two factors initiate, respectively, such phenomena as thermophoresis and photophoresis of aerosol particles. But when an aerodisperse system is subjected to the influence of resonance radiation, new specific regularities can appear in momentum transfer by gas molecules to an aerosol particle due to the radiation-induced change in the character of the interaction of molecules with a condensed phase particle [30–39]. In [30] the effect of light-induced drift of aerosol particles due to the detuning of radiation frequency from the resonance frequency of gas molecules was investigated by analogy with a light-induced drift of molecules in a gas mixture [17]. In this case, specific models of the interaction of gas molecules with a surface were not considered. In [31–33] the influence of the above-mentioned frequency detuning on the speed of motion of aerosol particles was analyzed in the case of different tangential momenta transferred by excited and nonexcited gas molecules to the surface. As noted in Ref. [22], this phenomenon is related to the light-induced gas flow in channels and porous bodies. If the walls are immovable, gas moves under the action of radiation, and if the walls (aerosol particles) are not fixed, they also are set into motion in the field of radiation, which changes the tangential momentum transferred by the molecules. Works [34–39] are devoted to the discussion of the problems associated with the onset of the force, which acts on the aerosol particle in the field of radiation and which is caused by a change in the recoil pressure of the gas molecules escaping from a surface. This is directly related to the above-considered problems of the influence of resonance radiation on the pressure exerted by the gas on the condensed phase surface.

Consider a spherical aerosol particle of radius R on which radiation flux of density J is incident, with the radiation wave length being much smaller, and the mean free path much larger, than R. For the absolute value of the force acting on the particle the following expression can be written [40]

$$F = 2\pi R^2 \left| \int_0^{\pi} P_s \cos\theta \sin\theta \, d\theta \right| , \tag{22}$$

where P_s is the gas pressure on the particle surface, θ is the angle between the axis, passing through the particle centre in the direction parallel to the radiation flux, and a normal to the surface.

The value of P is determined by the momenta transmitted to the aerosol particle on impact of a gas molecule with the particle surface and by the recoil momenta of the molecules that escape from the surface. Under the assumption that the pressure and temperature of the gas that surrounds the aerosol particle are constant and that its surface is impermeable (absence of phase transitions), the contribution to the value of F will be made only by the recoil pressure P_d of the molecules that leave the particle surface. The difference in P_d for different parts of the surface for a one-component gas are usually attributed to nonuniform heating of the particle [40]. However, with resonance radiation acting on an aerodisperse system, the noted difference in the values of P_d can appear even in the case of uniform temperature distribution in the aerosol particle.

First we will consider a case of the influence of resonance radiation on the force that acts on an aerosol particle in accordance with the mechanism studied in Section 2 (uniform heating of a body and difference in the sticking coefficients of excited and nonexcited molecules). The difference in the sticking coefficients for an aerosol particle can be attributed to both the radiation field nonuniformity (e.g., for the particles whose size is much in excess of the radiation wave length and that have illuminated and shaded regions) and velocity-selective excitation of gas molecules, when only those molecules are excited which move in a definite direction. Further we consider for simplicity that the excited molecules fall only on one side of the particle and assume that the flux density of the excited molecules incident on the particle surface is a constant value (it does not depend on the angle θ). Assuming the Maxwell distribution function of the molecules incident on the particle surface with constant density and temperature, and taking into account Eqs. (11), (22) and the fact that the temperature of a uniformly heated spherical particle can be expressed in the form

$$T = T_g + \frac{k_p J}{4\eta'}, \tag{23}$$

where k_p is a factor of radiation absorption efficiency, we have for F

$$F = \frac{P}{2}\pi R^2 \frac{J\Sigma}{h\nu} t_\nu \left(1 + 2\frac{J\Sigma}{h\nu} t_\nu\right)^{-1} | \alpha_1 - \alpha_2 | \times \left[\left(1 + \frac{k_p J}{4\eta' T_g}\right)^{1/2} - 1\right]. \tag{24}$$

It follows from Eq. (24) that for F to be different from zero, the resonance and thermal effects (excitation of gas molecules and difference in the temperatures of an aerosol particle and gas) should be realized simultaneously. But if there are phase transitions on the particle surface (i.e., there is a resultant molecular flux into the particle), the force F will not be zero even in the case of the equality between the temperatures of the particle and of the gas. Only the difference in the sticking coefficients of the excited and nonexcited molecules is sufficient here. The value of F in a quasi-stationary approximation can be estimated as

$$F = \frac{P}{2}\pi R^2 \frac{J\Sigma}{h\nu} t_\nu \left(1 + 2\frac{J\Sigma}{h\nu} t_\nu\right)^{-1} | \alpha_1 - \alpha_2 | , \tag{25}$$

where α_1 and α_2 have the sense of the condensation coefficients for excited and nonexcited molecules, and the radius R of the aerosol particle depends on time and is determined by the resultant molecular flux into the particle. Note that unlike the case of an impenetrable surface, here the asymmetry of the recoil pressure is due to the molecules that fall on the particle surface and condense on it; under the above assumptions the molecules that escape (evaporate) from the surface do not make contribution to the arising force.

Note that the change in the sign of the difference $\alpha_1 - \alpha_2$ which, in particular, can be attained by detuning of the radiation frequency from the resonance frequency of gas molecules leads to a change in the direction of the force acting on the particle.

Consider the influence of the spatial distribution of molecules emerging from the surface of an aerosol particle on the force acting on this particle with $\alpha_1 = \alpha_2 = 1$ [35]. Suppose that nonequilibrium scattering of molecules ($\mu \neq 1$, $v_\mu \neq v_1$) is realized only on one of the sides of the particle; then the dependence of the fraction ε_μ of molecules, scattered in nonequilibrium manner, on the angle θ can be presented in the form

$$\varepsilon_\mu = \chi J \cos\theta, \tag{26}$$

where χ is the proportionality factor, which characterizes the probability of nonequilibrium scattering of molecules.

Taking account of the conditions mentioned, we obtain from Eq. (22) the following expression for the value of the force acting on an aerosol particle [35]

$$F = \frac{2\pi}{3} R^2 \chi J N m \left(\frac{\mu + 1}{\mu + 2} v_\mu - \frac{2}{3} v_1 \right). \tag{27}$$

It should be noted that in the case of that considered in Section 3 light-induced energy transfer connected with the deactivation of radiation-excited molecules on interaction with the surface, the source of heat released on the surface of the aerosol particle will be an asymmetric surface source also in the case of transparent aerosol particles, as well as particles which are small relative to the radiation wave length (i.e., for situations when ordinary radiative heating of particles is practically uniform).

For the absolute value of the force acting on a spherical particle exposed to radiation by its one side, with radiation being absorbed on its surface, the following expression can be written accurately to the terms of the first order of smallness [40]

$$F = \frac{\pi R^3 \mid J \mid P}{6(P v R/2 + \lambda T_g)}. \tag{28}$$

However, as noted in [40], expression (28) is applicable only for opaque particles, whose radius is much in excess of the radiation wave length. Small particles have not sharp shades, light flows around them due to diffraction [40]. In this case the asymmetry of the heat field in the particle is small, which, respectively, also means a small force of ordinary photophoresis. When energy is transferred to the particle in the process of the deactivation of radiatively excited molecules on the particle surface, expression (25) is also applicable to small, as well as transparent particles with account taken of the fact that the quantity J will be replaced by the density of the flux caused by the excitation of the molecules and their subsequent deactivation on the particle surface.

6. Conclusions

The change in the character of interaction of gas molecules with the condensed phase surface in the resonance radiation field can result in a change of the pressure exerted by the gas on the surface. In turn, this is responsible for the onset of new components of photophoretic force acting on an aerosol particle. The appearing components of the force are different from zero even in the case of uniform temperature distribution in an aerosol particle. This fact is especially important for small-radius particles with large thermal conductivity or for transparent particles when ordinary photophoresis is very small. The presence of new components of the photophoretic force enables one to control the movement of aerosol particles by exposing an aerodisperse system to resonance radiation.

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