THERMAL BLOOMING OF LIGHT BEAMS PROPAGATING IN SOLID AEROSOL

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Thermal distortions of Gaussian light beams in sub– and supersonic gas flows with suspended solid aerosol particles are investigated. It is demonstrated that under typical atmospheric conditions the effect of aureole scattering on the peak light beam intensity is less pronounced than that of thermal blooming. It is found that aerosol particle thermal inertia results in focusing of Gaussian light beams in subsonic cross flow of an aerosol medium and affects inversly in supersonic flow.

Nonlinear distortions of high–power light beams propagating in the atmospheric solid aerosol were widely studied in the literature (see, e.g., Refs. 1 and 2). In particular, it is well known that without destruction (combustion, evaporation, or explosion) of particles upon exposure of radiation, the variations in the beam intensity are due to both nonlinear refraction (thermal blooming) and scattering of radiation on thermal haloes arising around the heated particles. The two aforementioned nonlinear phenomena are engendered by the variations in the real and imaginary parts of the effective index of refraction of aerosol medium, respectively.[3,4] Previously they were considered separately (see, e.g., aureole scattering in Ref. 5 and thermal blooming in Ref. 6). Given in this paper are a comparative analysis of these effects and their joint manifestation. It is also known that aerosol particle thermal intertia may affect the character of thermal distortions of light beams[7]; therefore, this effect is discussed at length here.

We consider a light beam propagating in the positive direction along the z axis and moving relative to an air medium. Let the x axis be directed along a gas flow with suspended particles. This flow is transverse to the beam. Without regard to aureole scattering (the imaginary part of the effective index of refraction of a medium) the nonlinear self–refraction of the light beam is determined by the real part of the refractive index which in its turn is proportional to mean (averaged over a volume element containing a large number of particles) density of air. To describe nonlinear self–refraction (self–action) of the beam in this case, the equation of paraxial optics in dimensionless variables[8] can be used

$$\frac{\partial u}{\partial z} + i\,\nabla_{\perp}^2\,u = -\,i\,F\,N\,\rho_1\,u - \frac{N_\alpha}{2}\,u\,, \qquad (1)$$

where u is the complex field amplitude; $uu^*=I$ is the dimensionless radiation intensity (normalized to the characteristic intensity I_0); $F = 2\pi a^2/\lambda L$ is the Fresnel number; λ is the radiation wavelength; a is the beam radius; L is the characteristic path length; $N_\alpha = \alpha_e L$ is the extinction factor; α_e is the radiation extinction coefficient incorporating molecular and aerosol absorption and scattering; $N = (L/z_t)^2$ is the thermal blooming parameter; $z_t = a/\sqrt{\varepsilon(n_0 - 1)}$ is the length of thermal blooming; n_0 is the refractive index of air; $\varepsilon = (\alpha_m + \alpha_a)\,I_0\,a/\rho_0\,V_0\,h_0$ is the scale of perturbation of the mean (averaged over a volume element containing a large number of particles) density of air; ρ_0, V_0, and h_0 are the unperturbed density, velocity, and enthalpy of the gas flow, respectively; α_m and α_a are the coefficients of molecular and aerosol absorption,; and, ρ_1 is the function describing the perturbation of mean density ($\langle\rho\rangle/\rho_0 = 1 + \varepsilon\rho_1$). The transverse coordinates in Eq. (1) are normalized to the characteristic radius of the beam a, and the longitudinal coordinate z is normalized to L.

Equation (1) is equivalent to the corresponding equation for thermal blooming in a pure gas[8] with the only difference that the concept of mean density averaged over a volume element containing a large number of particles is used in place of the density. It can be readily shown that perturbation of the mean gas density is determined by the mean rate of the volume heat release which in its turn appears to be proportional to the radiation intensity when the time required to heat up the aerosol particles is sufficiently small. Hence the mean density perturbation function ρ_1 in this case can be found using linearized equations of gas dynamics used to determine the perturbation of the density of a gaseous medium in the case of molecular absorption.[8] Thus effects of nonlinear self–refraction of radiation in an aerosol medium and a pure absorbing gas are fully equivalent for equal absorption coefficients, if the time required to heat up the particles and the corresponding time delay of heat release are small compared to the characteristic gas–dynamical time a/V_0. Below we return to the problem of determining the mean density perturbation function ρ_1 taking into account the finite time required to heat up the particles and its effect on the character of thermal distortions of the light beam.

Let us now calculate the nonlinear aureole scattering of a light beam in a cross gas flow containing suspended absorbing particles. Analogous calculation for an optical beam switched on at $t = 0$ in a stationary aerosol medium was made in Ref. 3 and the following result was obtained for the coefficient of aureole scattering:

$$\alpha_{or} = \alpha_a\left(\frac{n_0 - 1}{T_0}\right)^2 \frac{I_0^2}{\rho_0^2\,C_p^2}\,\frac{\kappa_\alpha\,\pi\,r_0^2\,\kappa^2}{(2\pi)^2\,k}\,g(t)\,, \qquad (2)$$

$$g(t) = 9\,t_0 \int_0^\infty x\left(\frac{\sin x - x\cos x}{x^3}\exp\left(-x^2\,\frac{t}{t_0}\right)\times\right.$$

$$\times \int_0^{t/t_0} I(\tau, t) \exp(x^2 \tau)\, d\tau \Bigg)^2 dx , \quad (3)$$

where I is the dimensionless intensity normalized to I_0, κ_a is the factor which describes the efficiency of radiation absorption by an aerosol particle, χ is the thermal diffusivity, r_0 is the radius of the aerosol particle, $t_0 = r_0^2/\chi$, and $\kappa = 2\pi/\lambda$ is the wave number.

It should be noted that $t_0 \sim 5 \cdot 10^{-8}$ s (for $r_0 = 1$ μm and $\chi = 2 \cdot 10^{-5}$ m^2/s) is much smaller than the characteristic time of radiation exposure to a particle a/V_0; therefore, the limit $t/t_0 \to \infty$ must be taken in Eq. (3). In this case the integrand differs noticeably from zero only at small values of x, and hence the expression $(\sin x - x \cos x)/x^3$ can be replaced by 1/3. The result is

$$g(t) = \frac{1}{2} \int_0^{\infty} ds \left(\int_0^{\tau} I(t - \tau') \exp(-\tau' s)\, d\tau' \right)^2 . \quad (4)$$

When an optical beam is in a cross flow, the form of the function $I(t)$, which enters into Eq. (4), is determined by aerosol particle motion at the velocity V_0 through the cross section of the beam of given shape $I(x, y)$. In a stationary case in which the beam intensity is constant with time, taking into account formulas (2) and (4), the following expression for the coefficient of aureole scattering vs. transverse coordinates can readily be obtained:

$$\alpha_{or} = \frac{N_s}{L} g(x, y),\ N_s = \alpha_a \left(\frac{n_0 - 1}{T_0} \right)^2 \times$$

$$\times \frac{I_0^2}{\rho_0^2 C_p^2} \frac{\kappa_a \pi r_0^2 \kappa^2}{(2\pi)^2 x} \frac{a}{V_0} g(x, y) L , \quad (5)$$

$$g(x, y) = \frac{1}{2} \int_0^{\infty} ds \left(\int_0^{\tau} I(x - \tau', y) \exp(-\tau' s)\, d\tau' \right)^2 . \quad (6)$$

Here the variables x and y are normalized to the beam radius a.

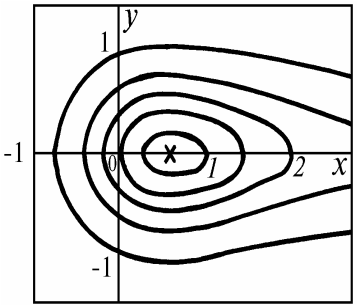

FIG. 1. Contours of the function of aureole scattering $g(x, y)$ corresponding to 10, 25, 50, 75, *and* 90% *of its maximum* $g_{max} = 0.829$ *attained at a point marked off by a cross.*

Using Eq. (6) and standard algorithms for numerical integration, the function of aureole scattering for Gaussian intensity distribution over the beam cross section $I(x, y) = \exp[-(x^2 + y^2)]$ was calculated. The result is shown in Fig. 1. The scattering is maximum for the leeside of the beam at $x = 0.61$.

In calculating the light beam propagation, the aureole scattering can be taken into account by adding the term $-(N_s/2)\, g(x, y)\, u$ to the right side of Eq. (1), and $g(x, y)$ in this case is determined from Eq. (6).

Now let us compare the two nonlinear effects of aureole scattering and thermal blooming. By following the formula (5) and expression for the thermal blooming parameter [see the text after Eq. (1)], we find the following relation between the parameters N and N_s:

$$N_s = N^2 F^2 \left(\frac{\alpha_a}{\alpha_m + \alpha_a} \right)^2 \frac{\Lambda}{\pi L} . \quad (7)$$

Here $\Lambda = 1/\nu\sigma_{or}$ is the optical path between haloes, ν is the aerosol particle concentration, $\sigma_{or} = \pi r_{or}^2$ is the cross section of a thermal halo, and $r_{or} = \sqrt{4\chi a/V_0}$ is its characteristic radius.

Let us now determine the relative contributions of aureole scattering and thermal blooming (self–refraction). Let us take $N = 1$, i.e., the path length L equals the length of thermal blooming z_t. In this case the intensity on the target changes by the order of magnitude due to thermal blooming. For the same to happen due to aureole scattering, the parameter N_s must be equal to unity. By following formula (7) and taking into account $\alpha_a^2 / (\alpha_a + \alpha_m)^2 \cong 1$, we obtain the condition for the Fresnel number $F \cong \sqrt{z_t/\Lambda}$.

Now we estimate the value of Λ. Taking the following characteristic values of the parameters: $\nu = 10$ cm^{-3}, $a/V_0 = 10^{-3}$ s, and $\chi = 2 \cdot 10^{-5}$ m^2/s, we obtain $\Lambda = 40$ cm. When the length of thermal blooming $z_t = 4$ km, we obtain the condition for the Fresnel number $F \cong 100$. Hence aureole scattering may strongly affect the beam propagation in the aerosol only for a very short–wave beam whose Fresnel number is no less than 100. Thus in the majority of cases the contribution of aureole scattering is much less than that of thermal blooming.

In spite of what has been said above, of interest is the study of a weakly pronounced effect of aureole scattering on thermal distortions of a light beam propagating through a moving aerosol medium. Such calculations were made for an optical beam in subsonic ($M = 0$ and 0.8) and supersonic ($M = 1.5$ and 2) flows ($M = V_0/c_s$ is the Mach number and c_s is the sound speed in air). The results of calculation of peak intensity variations in an initially Gaussian beam $I(x, y)|_{z=0} = \exp[-(x^2 + y^2)]$ along the path (vs. the dimensionless coordinate z) for the parameters of aureole scattering $N_s = 0$, 0.2, and 0.4 are depicted in Fig. 2. The calculations were accomplished by numerical solution of Eq. (1) with the term $-(N_a/2)\, g(x, y)\, u$ added to its right side. In this case we used the algorithm proposed in Ref. 9, whose implementation was described in Ref. 10 in detail. In supersonic regime the amount of decrease of light beam intensity due to aureole scattering turns out to be relatively larger than that in subsonic regime. This is associated with the changes in the beam shape along the propagation path.[8] In the subsonic flow the beam acquires a characteristic crescent shape with maximum intensity

being strongly displaced in the direction counter to the flow towards the region of small values of the scattering function $g(x, y)$ (see Fig. 1). In the supersonic flow the initial position of peak intensity remains practically constant, and hence it is subject to a much stronger effect of aureole scattering.

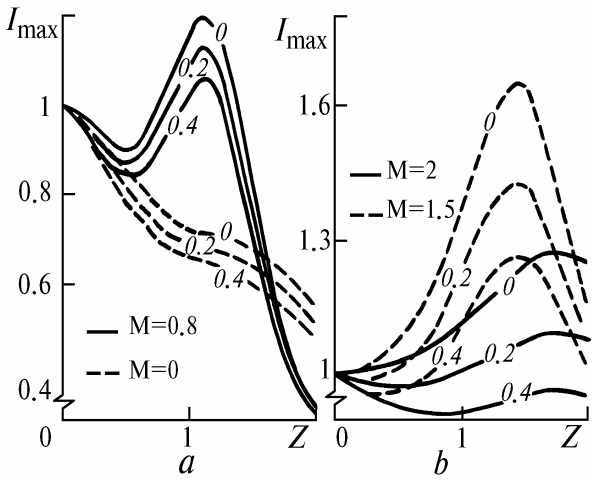

FIG. 2. Variations in the maximum intensity $I_{max} = \max\limits_{x, y}[I(x, y)]$ *along the path for different values of the aureole scattering parameter* N_s *(adjacent to the curves) and light beam in subsonic (a) and supersonic (b) flows of an aerosol medium. Calculation was made neglecting the linear mechanisms of intensity extinction for* $N_\alpha = 0$, $N = 1$, *and* $F = 5$.

Now we turn back to the problem of the influence of the finite time of particle heating on manifestation of nonlinear effects accompanying the propagation of high–power optical beams through an aerosol medium. Since, as was stated above, the contribution of aureole scattering turned out to be relatively small, we restrict our consideration to the influence of particle heating rate on thermal blooming. For simplicity and clarity, we ignore molecular absorption and restrict ourselves to the case in which the whole heat releases to gas through aerosol.

Now we determine the relation between the dimensionless heat release to gas q (normalized to the quantity $q_0 = \alpha_a I_0$) and the dimensionless intensity I. For the temperature of the particle surface T_p we have the equation

$$\frac{d(T_p - T_0)}{dt} = -\frac{3\chi^* p_0 C_p}{r_0^2 \rho^* C^*}(T_p - T_0) + \frac{3}{4}\frac{\kappa_a I_0 I(t)}{\rho^* C^* r_0}, \qquad (8)$$

where ρ^* and C^* are the density and specific heat of a particle and $I(t)$ is determined, as previously, by particle passage across the light beam. The quantity $r_0^2 \rho^* C^*/(3 \chi \rho_0 C_p) = \tau_{rel}$ is the time of particle thermal relaxation. It should be noted that the aforementioned equation is valid only when the times of establishing of a temperature field inside the particle $r_0^2/4\chi^*$ (χ^* is the thermal diffusivity of the particle material) and outside of it $r_0^2/4\chi$ are small compared to τ_{rel}. However, this condition always holds.

A heat flow to a gas is related to the temperature of aerosol particle surface by the expression $q q_0 = 4 \pi r_0 \nu (T_p - T_0) \chi \rho_0 C_p$. After transforming in Eq. (8) to dimensionless variables (by normalizing the time to the quantity a/V_0 and using dimensionless heat release q in place of $(T_p - T_0)$, we obtain

$$\frac{dq}{dt} = \frac{1}{\delta}(I - q), \qquad (9)$$

where $\delta = \tau_{rel}/(a/V_0)$.

Let us construct the solution of Eq. (9) for small δ. Assuming $I - q = \delta Y$ and neglecting the term of the order of $\delta(dY/dt)$, we obtain $Y = dI/dt$. Wherefrom, using the equality $d/dt = \partial/\partial x + \partial/\partial t$, we finally have $q(x, y) = I - \delta(dI/dt) = I(x - \delta, y, t - \delta)$ or in the stationary case $q(x, y) = I(x - \delta, y)$.

Thus the finiteness of aerosol particle heating rate in the first order is manifested in simple time delay of heat release that in its turn causes the displacement of the perturbed density field downflow by the amount δ compared to the case of molecular absorption or inertialess aerosol particles. This displacement affects thermal blooming.

The quantitative aspect of this effect is depicted in Fig. 3 where the peak intensity variations in a Gaussian beam are shown along the path with different values of the parameter δ. The calculations were made both for subsonic and supersonic velocities of cross flow of an aerosol medium. In subsonic regime the beam tangibly tends to focusing when δ increases. This effect becomes especially pronounced for $M = 0.8$. On the contrary, in supersonic regime, after the termination of the transfer of absorbed energy to a gas, some defocusing of the beam takes place. In this case the effect is much less pronounced than that in a subsonic flow.

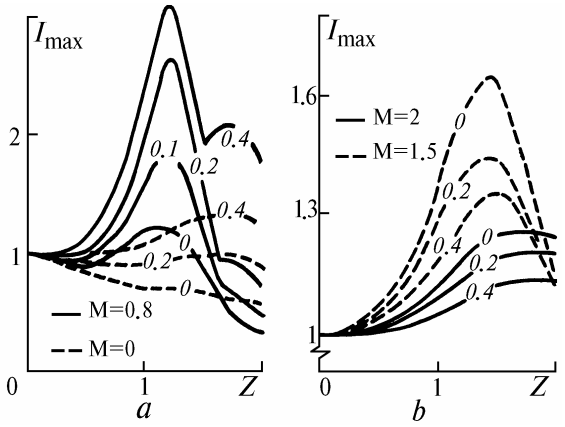

FIG. 3. Variations of maximum intensity in the light beam propagating along the path for different values of the parameter δ (adjacent to the curves) in subsonic (a) and supersonic (b) flows of an aerosol medium. Calculation was made for $N_\alpha = 0$, $N = 1$, *and* $F = 5$.

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