ε, rate of dissipation of this energy; ν_a, ν_t, ν, kinematic, turbulent, and effective viscosities, respectively; Ψ, stream function; Ψ_m, minimum flow rate in the appropriate flow; $C_{x\ell}$, C_{xd}, drag coefficients of the leading and trailing endfaces of the interceptor (normalized with respect to the velocity head of the unperturbed stream and the interceptor height h); C_{x_1}, C_{x_2}, drag coefficients of the first and second interceptors; C_x, total drag coefficient of the configuration; C_y, configuration lift coefficient; K, configuration aerodynamic quality; Re_h, Reynolds number; Ri_t, Richardson number; Re_t, turbulent Reynolds number; c_1, c_2, c_μ, σ_k, σ_ε, c_w, f_2, f_μ, constants and empirical functions governing the turbulence model. Subscripts: ∞, unperturbed flow; 1, the vortex ahead of the interceptor on the free stream side; 2, the main vortex in the wake behind the interceptor.

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THE EFFECT OF THERMAL SELF-ACTION OF A LIGHT BEAM IN A SHEAR FLOW

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The effect of thermal self-action in a shear gas flow transverse to the beam and containing a stagnation domain is investigated.

The effect of thermal blooming of a radiation beam in a moving self-absorbing medium was examined earlier for the case of a homogeneous uniform flow [1, 2]. A classification is introduced for the light beam blooming modes in the gas flow as a function of the magnitude of the stream velocity component transverse to the beam [3]. In a medium at rest and in a slow stream (the heat conducting mode and the forced convection mode) a beam with an initially Gaussian distribution is defocused, as a rule, if the index of refraction of the medium diminishes as the temperature rises (water, air and other media). At high stream velocities when pressure perturbations become substantial, focusing the beam in a gaseous medium becomes possible because of the thermal blooming.

The effect exerts extreme action on the beam in an unsteady flow (at the initial time interval after switching in the beam). For instance, the peak intensity reaches a maximum or minimum depending on just how the gasdynamic blooming mode is considered [4, 5].

The effect of thermal blooming is investigated in this paper in a shear flow when the velocity changes its magnitude in distances on the order of the beam dimension.

We direct the z coordinate along the beam, the x coordinate in the stream direction. We assume the magnitude of the stream velocity to depend only on the transverse coordinate y ($\mathbf{V} = \mathbf{i}\, U_0 U(y)$, where $\mathbf{V}$ is the velocity vector, $\mathbf{i}$ is the unit direction along the x axis, U(y) is a given function, and U_0 is the characteristic magnitude of the velocity), while

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the remaining gasdynamic quantities in the unperturbed stream are constants. We assume that the characteristic magnitude U_0 of the velocity is a value of the velocity function for y = R (i.e., U(y = R) = 1), where the value of U_0 is such that on the one hand the viscosity and heat conduction can be neglected (Pe, Re $\gg 1$, where $Pe = Ru_0/\chi$ $Re = \rho_0 U_0 R/\mu$, and ρ_0 is the density of the unperturbed medium), and pressure perturbations can be neglected on the other. In this case, according to the classification mentioned [3], we have the forced convection mode.

The density perturbation in the main approximation is described by the transport equation

$$\left(\frac{\partial}{\partial t}+U(y)\frac{\partial}{\partial x}\right)\rho_1=-g(x,\ y,\ z,\ t),$$
$$-\frac{\Delta T}{T_0}=\frac{\Delta\rho}{\rho_0}=\varepsilon\rho_1,\ \varepsilon=\frac{\alpha I_0 t_0}{\rho_0 h_0},\ h_0=c_p T_0,\ g=\frac{I}{I_0},\ t_0=\frac{R}{U_0}. \tag{1}$$

Here the time t is referred to the characteristic time t_0 of flight across the beam section by a fluid particle, the coordinates x, y are referred to the radius R, the stream velocity to U_0, the radiation intensity I to the characteristic value I_0 ($I_0 = I_{max}$ for a Gaussian beam), the density ρ to the density of the unperturbed medium ρ_0, h_0 is the gas enthalpy, c_p is the specific heat at constant pressure, and T_0 is the temperature of the unperturbed medium. Let us note that cases are considered when the beam cross section is considerably less than the characteristic length of propagation $R \ll L_z$. Longitudinal gradients of the hydrodynamic quantities along the beam can be neglected in each beam section (plane-parallel approximation), the function ρ_1 depends on the coordinate z as a parameter because the radiation intensity I varies along the beam path.

The terms containing gradients in the coordinate y are quantities of second order of smallness in ε.

By using the substitution t' = t, x' = x − Ut we easily obtain a solution of (1):

$$\rho_1(x,\ y,\ z,\ t)=-\int_0^t g(x-Ut+U\tau,\ y,\ z,\ \tau)\,d\tau. \tag{2}$$

In the case when the radiation intensity in the initial section is independent of the time (stationary distribution), the solution (2) has the form

$$\rho_1(x,\ y,\ 0,\ t)=-\frac{1}{U(y)}\int_{x-Ut}^{x} g(x',\ y,\ 0)\,dx'. \tag{3}$$

The fundamental characteristic features of the thermal blooming effect are described well by the approximate Gebhardt–Smith [6] and Livingston [7] solution for a Gaussian intensity distribution $g = \exp(-x^2 - y^2)$, which is valid in a weakly absorbing medium ($z \ll \alpha^{-1}$, α^{-1} is the characteristic length of absorption), in the geometric optics approximation ($z \ll kR^2$, $k = 2\pi/\lambda$ is the wave number) and for a small thermal blooming effect ($z \ll x_0$, $z_0 = R/\sqrt{\varepsilon(n_0 - L)/n_0}$ is the thermal blooming length, and n_0 is the refractive index of the medium:

$$I=I_{ph}/I_0=\exp\{-x^2-y^2-Nf(x,\ y,\ t)\},$$
$$N=(z/z_0)^2,\ f=\left[\frac{1}{2}\nabla_\perp^2-x\frac{\partial}{\partial x}-y\frac{\partial}{\partial y}\right]\rho_1(x,\ y,\ 0,\ t). \tag{4}$$

Taking (3) into account, the function f can be written for this solution

$$f=\frac{\exp(-y^2)}{U}\left\{\int_{x-Ut}^{x}\exp(-\tau^2)\,d\tau\left[1+\frac{U''}{2U}-\frac{U'^2}{U^2}-4y^2-3y\frac{U'}{U}\right]+\right.$$
$$\left.+\exp[-(x-Ut)^2]\left[-2x+t\left(U+3yU'-\frac{U''}{2}+\frac{U'^2}{U}\right)-t^2U'^2(x-Ut)\right]+\exp(-x^2)\,2x\right\}. \tag{5}$$

Going over to an analysis of specific kinds of shear flows, we recall that tracks with "stagnation" domains act maximally on the beam [8-10]. Let us consider the class of flows described by the velocity function $U(y) = (y + a)^n/b$, where we include the case, in the considerations, when the stream velocity diminishes to zero (as $y \to a$, $U \to 0$ — the stagnation domain). In the neighborhood of the stagnation section, as $y \to -a$ the expressions (3) and (5) take the following form

$$\rho_1 = -t\exp(-x^2-y^2)\left[1+Uxt+U^2t^2\frac{2x^2-1}{3}+O(U^3)\right], \tag{6}$$

$$f = -t\exp(-x^2-y^2)\left[-2+4x^2+4y^2+U''\frac{xt}{2}+U'^2t^2\frac{2x^2-1}{3}-U'y3xt+O(U)\right]. \tag{7}$$

Let us examine three specific kinds of velocity distributions: 1) $U = y^2$ ($n = 2$, $a = 0$, $b = 1$) is symmetric with respect to the x axis; 2) $U = y$ ($n = 1$, $a = 0$, $b = 1$) is antisymmetric; 3) $U = (y + 1)^2/4$ ($n = 2$, $a = 1$, $b = 4$) is asymmetric.

Results are represented in the figure for different velocity distributions. The thermal blooming parameter, which is a small quantity by virtue of the constaints mentioned, is taken equal to $N = 0.1$. Lines of equal values of the perturbation function of the density ρ_1 are constructed whose minimums equal $\rho_{1min} = -1, -2, -3$ for $t = 1, 2, 3$, respectively; also isochores for ρ_1 equal to 0.9, 0.75, 0.5, 0.25, and $0.1\rho_{1min}$; and the isophots for the intensities $I = 0.75I_m$, $0.5I_m$, $0.25I_m$ and $0.1I_m$, where I_m is the maximal value.

As is seen from the Fig. 1a, the density minimums in a symmetric flow are at the center of the beam for $x = 0$, $y = 0$. The intensity peak is first bifurcated and disposed near the axis of symmetry. Up to the time $t = 1$ values of the intensity peaks exceed the initial values and continue to grow with time. An intensity trough is observed in the stagnation zone. At a certain distance from the axis of symmetry local intensity maximums grow with the lapse of time, and their magnitudes can exceed the values in the near-axis beams for $t \geqq 5$. The beam as a whole is defocused, as constructions for the domains of increasing ($\Delta I > 0$ hatched) and decreasing ($\Delta I < 0$ not hatched) intensity show. The intensity in the beam is redistributed from the smaller to the greater area, is "blurred." The presence of local focusing in a shear flow is an interesting and important fact.

The distributions of the density of the medium and the beam intensity in an antisymmetric flow possess central symmetry (Fig. 1b). The density minimum is at the center, the intensity maximums at a certain distance from the center. The maximal value of the intensity grows monotonically and for $t > 2$ the magnitude of the maximums exceeds the initial value I_m. The beam as a whole is defocused since the intensity is redistributed from the smaller to the greater area. A local intensity peak appears at the center of the beam with the lapse of time.

In a nonsymmetric flow (Fig. 1c) when the stagnation zone is at a distance of the exponential radius of the beam for $y = -1$, the following distinguishing features of the thermal blooming effect are noticed. The density minimum shifts easily into the right lower corner from the center $x = 0 = y$. The intensity maximum is shifted into the left upper corner, increases monotonically with the lapse of time and at the time $t = 3$ exceeds the initial value. In addition, a local maximum appears in the lower right corner which exceeds the mentioned maximum in magnitude at the time $t > 7$, as computations showed. The location of this second peak is close to the stagnation zone. The tempo of intensity peak growth in the nonsymmetric flow is slower than in the two preceding cases because the stagnation zone is located at the edge of the beam where the intensity is not large. On the whole, the beam is defocused as in the two previous cases.

The unsteady thermal blooming mode was examined above. The solutions (3)-(5) do not permit steady stationary density and intensity distributions to be obtained since, as (6) and (7) show, the perturbations grow without limit in the stagnation domain as $t \to \infty$. This singularity requires reexamination of the scale of the perturbation ε of the characteristics of the medium and the thermal blooming parameter N (the thermal blooming length z_0).

Let $y \to -a$, $U \to 0$. Then there exists a certain scale δ in which the heat conduction of the medium plays a noticeable part, at least in the direction of the y axis. Let us introduce the new transverse coordinate Y: $y = -a + \delta Y$, $\delta \ll 1$, $Y \sim 1$, $U \sim \delta^n Y^n/b$. It follows from the heat-conduction equation that the new scale δ equals $\delta = Pe^{-1/(n+2)}$, the new perturbation build-up time in the stagnation zone is $t_T = t_0\delta^{-n} = t_0 Pe^{n/(n+2)}$, and the new perturbation scale of the medium parameters is $\varepsilon_T = \alpha I_0 t_T/(\rho_0 h_0) = \varepsilon Pe^{n/(n+2)}$. In order for small perturbation theory to be valid, the condition

$$\varepsilon_T \ll 1,\ \varepsilon \ll Pe^{-n/(n+2)} \tag{8}$$

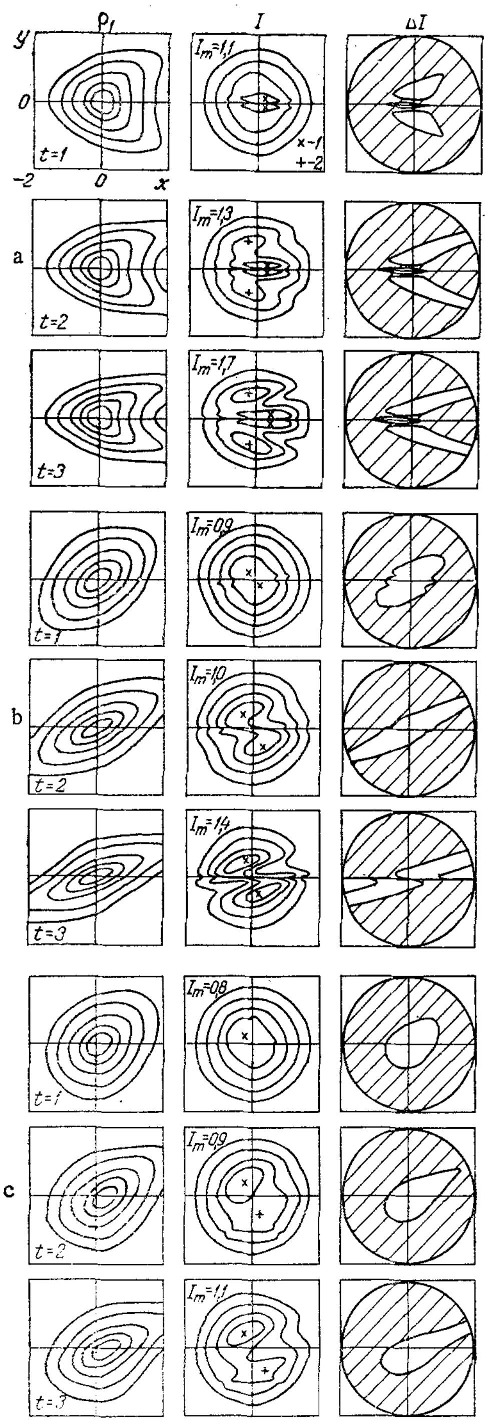

Fig. 1. Isochores, isophots, and domains of increasing and diminishing intensity of a Gaussian beam in a symmetric $U = y^2$ (a), antisymmetric $U = y$ (b) and asymmetric $U = (y + 1)^2/4$ (c) stream; $\Delta I = I - I|_{z=0}$; 1) intensity maximums; 2) local intensity maximums.

should be satisfied. We have for the principal term of the density (temperature) perturbation

$$\left(\frac{\partial}{\partial t}+\frac{Y''}{b}\frac{\partial}{\partial x}\right)\rho_1=\frac{\partial^2}{\partial Y^2}\rho_1-g(x,\ 0,\ 0). \qquad (9)$$

The boundary conditions for this equation are the asymmetry conditions (n even) or central symmetry (n odd) of the function ρ_1 as $Y \to 0$ and the condition of connection with the external solution as $Y \to \infty$:

$$\rho_1 \to -\frac{b}{Y^n} \int\limits_{x-Y^n t/b}^{x} g(x', 0, 0)\, dx'. \tag{10}$$

We obtain the following problem for the stationary limit $t \to \infty$

$$\frac{Y^n}{b} \frac{\partial}{\partial x} \rho_1 = \frac{\partial^2}{\partial Y^2} \rho_1 - g(x, 0, 0), \tag{11}$$

$$\rho_1 \to -\frac{b}{Y^n} \int\limits_{-\infty}^{x} g(x', 0, 0)\, dx' \text{ for } Y \to \infty, \tag{12}$$

$$\rho_1(x, -Y) = \rho_1(x, Y) \ (n - \text{ even }) \text{ for } Y \to 0. \tag{13}$$

Because of the diminution in the stream velocity to zero in the stagnation zone and the presence of perturbations of all the gasdynamic quantities, including the transverse velocity component v, there is the question of the influence of the transverse motion of the medium.

It follows from the continuity equation that $v \sim \varepsilon_T \delta^{n+1}$ in order of magnitude. Then, as follows from the heat-conduction equation, transverse convection can be neglected if $\varepsilon_T \ll 1$ (condition (8)). Therefore, transverse convection can be neglected within the framework of perturbation theory.

For a symmetric flow with the boundary conditions (12) and (13) taken into account the solution of (11) has the following asymptotic representation for large and small values of the coordinate Y:

$$\rho_1(x, Y) = \begin{cases} -\dfrac{F(x)}{Y^2} - \sum\limits_{k=1}^{\infty} \dfrac{i^k F(x)}{Y^{4k+2}} \prod\limits_{n=1}^{k} (4n-1)(4n-2), & Y \to \infty, \\ A(x) + \dfrac{Y^2}{2} g + \sum\limits_{k=1}^{\infty} Y^{4k} \left\{ \dfrac{\dfrac{d^k A(x)}{dx^k}}{\prod\limits_{n=1}^{k} 4n(4n-1)} + \dfrac{\dfrac{Y^2}{2} \dfrac{d^k g}{dx^k}}{\prod\limits_{n=1}^{k} (4n+2)(4n+1)} \right\}, & Y \to 0. \end{cases} \tag{14}$$

Here $F(x) = \int\limits_{-\infty}^{x} g(x', 0, 0)\, dx'$, $i^0 F(x) = F(x)$, $i^1 F(x) = \int\limits_{-\infty}^{x} F(x')\, dx'$, ... The function A(x) is arbitrary and to be determined from the condition of connection with the solution in the domain $Y \sim 1$.

The expression for the perturbed intensity (4) in the stagnation domain can be written

$$I = \exp\left(-x^2 - N_T \frac{1}{2} \frac{\partial^2 \rho_1}{\partial Y^2}\right), \quad N_T = \left(\frac{z}{z_T}\right)^2, \quad z_T = \frac{\delta R}{\sqrt{\varepsilon_T (n_0 - 1)/n_0}}, \tag{15}$$

where the new thermal blooming parameter is greater in order of magnitude than before: $N_T = N\delta^{-n-2} = N\mathrm{Pe}$, and the new length of the thermal blooming is shorter than before: $z_T = z_0 \mathrm{Pe}^{-1/2}$. Taking (14) into account, (15) shows that the beam intensity diminishes in comparison to the perturbed value in the neighborhood of the axis of symmetry and increases at the edge of the stagnation zone. Therefore, because of the stationary thermal blooming of the Gaussian beam in the shear flow, the radiation is displaced from the narrow stagnation domain whose transverse dimension is $R\delta$. Local focusing of the radiation is possible at the edge of this zone, as in the unsteady mode. The length of the thermal blooming in the stagnation zone is very much shorter than in the main part of the beam. For instance, for such widespread media as air ($\chi = 1.9 \cdot 10^{-5}$ m²/sec) and water ($\chi = 1.43 \cdot 10^{-7}$ m²/sec) for R = 0.1 m and U_0 = 1 m/sec the ratio of the blooming length in the stagnation zone and in the main part of the beam is $z_T / z_0 = 1.2 \cdot 10^{-3}$ and $1.38 \cdot 10^{-2}$, respectively. The thermal blooming parameter in the stagnation zone is $5.3 \cdot 10^3$ times greater for air and $7 \cdot 10^5$ times greater for water, while the build-up time t_T is greater than the build-up time in the main part of the beam in the case of a symmetric stream (n = 2) by 72.5 and $8.36 \cdot 10^2$ times, respectively. The transverse dimension of the stagnation domain is 0.117R in air and 0.0346R in water.

NOTATION

x, y, z, coordinates in the system coupled to the beam; t, time; U(y), a dimensionless velocity function; R, exponential beam radius; Pe, Peclet number; Re, Reynolds number; χ, gas coefficient of thermal diffusivity; μ, dynamic viscosity coefficient; ρ_1, dimensionless function of the density perturbations; ε, scale of the perturbations of the gasdynamic quantities; g, a dimensionless function of the radiation intensity distribution; α, absorption coefficient; n_0, refractive index of the unperturbed medium; and z_0, N, length and parameter of the thermal blooming.

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ENERGY DISSIPATION AND HEAT EXCHANGE IN MAGNETORHEOLOGICAL SUSPENSIONS IN A ROTATING MAGNETIC FIELD

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We present the results of experiments on the effect of the rheological properties of magnetic suspensions and the regime parameters on energy dissipation and heat transport in a rotating magnetic field.

A magnetorheological suspension is a stable suspension of noncolloidal single-domain ferromagnetic particles in a fluid dispersing medium. A rotating magnetic field causes a remagnetization of the elements of the microstructure of the suspension. There are two mechanisms: the turning of the particles themselves and flipflops of the moments of the particles from one direction of easy magnetization to the other. The latter is similar to the remagnetization of "solid" suspensions of single-domain particles, in the case when the external field strength exceeds the quantity $H_a/2$. When $H_a/2 < H < H_a$ the remagnetization has a jumplike discontinuity and is irreversible (so-called rotational hysteresis) [1].

If the rate of rotation of the external magnetizing field is small then the particles of the suspension can follow the field and rotational hysteresis does not occur. From the equation of motion of a uniaxial particle in the strong field limit ($H \gg H_a$) [2]

$$\mu_0 I_s H_a \sin 2\varphi = \alpha\eta\,(\omega_0 - d\varphi/d\tau)$$

we see that the particle can rotate with the field ($d\varphi/d\tau = 0$) up to a rotational frequency of the field given by

$$\omega_0 \leqslant \omega' = \mu_0 I_s H_a/\alpha\eta.$$

For larger frequencies the viscous forces "turn" the particle and it rotates with an angular velocity smaller than those of the field, so that there is a partial "freezing" in the fluid. Rotational hysteresis occurs under these conditions.

For a suspension of γ-ferric oxide ($I_s = 10^5$ A/m; $H_a = 6\cdot10^4$ A/m) in the hydraulic fluid AMG-10 ($\eta = 0.02$ Pa·sec) the quantity ω' is of order 10^3 sec^{-1}. However for a concentrated suspension ($C_{vol} \geqq 0.05$) ω' is much lower ($\omega' \sim 10$ sec^{-1}). This is explained by the fact

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