in the opposite direction ($A_6 > 0$), and the rotation velocity reaches a maximum at $\sigma_1 = \sigma_+$, defined by Eq. (3.2) with the plus sign. It is obvious that similar principles will hold with variation of σ_2 and fixed σ_1.

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PROPAGATION OF A CLEARING WAVE IN AN INHOMOGENEOUS COMBUSTIBLE AEROSOL

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The propagation of intense optical radiation in an aerosol is accompanied by clearing which develops due to the vaporization or (and) combustion of the aerosol particles. Induced clearing in fogs and clouds developing due to the vaporization of water drops in a powerful optical field has been the most fully studied up to now [1-4]. A decrease in the size of water particles leads to weakening of absorption, as a result of which clearing of the aerosol occurs. Peculiarities of the dynamics of clearing are due to the fact that the rate of particle combustion is not a unique function of the radiation intensity. The rate of particle combustion at a given time depends on the radiation intensity at previous times and, of course, depends on the character and type of chemical reactions taking place in the process of combustion. The dynamics of clearing in an inhomogeneous, monodisperse, combustible aerosol is analyzed in the present report.

1. It is known that the rate of heterogeneous combustion K_S of a solid particle at a temperature T below the ignition temperature T_0 can be taken as equal to zero ($T_0 \approx 1500°K$ for carbon particles with a size of 1-10 μm). At $T > T_0$ the quantity K_S is different from zero and, generally speaking, depends on T. If the radiation intensity is relatively low, then after ignition of a particle the heat released as a result of the chemical reaction of combustion will make the main positive contribution to its heat balance. Therefore, after the ignition of a particle the combustion rate can be considered as practically independent of the radiation intensity. In this case radiation plays the role of the initiator of combustion.

An elementary estimate of the time of heating a carbon particle with a characteristic size of ∿1 μm to the ignition temperature determines a value of $\sim 10^{-5}$ sec. This time is much less than the other characteristic times of the given problem (for example, the characteristic time of burnup of a particle of the same size is $\sim 10^{-3}$ sec). Therefore, one can assume that a particle ignites practically instantly when a certain radiation intensity I_0 is reached at the given point. From the heat-balance equation we get the estimate

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$$I_0 = (4\mu/a_0 k_a)(T_0 - T_\infty),$$

where T_∞ is the temperature of the ambient medium; μ is the coefficient of thermal conductivity; a_0 is the radius of the spherical particle; k_a is the coefficient of absorption. Taking the aerosol concentration as relatively low, we will assume that separate particles burn independently of each other without significantly changing the temperature of the ambient medium. Finally, we will neglect the motion of particles under the action of light pressure and wind, considering the simplest static model of the aerosol.

The square of the radius of particles burning in a diffusional mode decreases by the linear law

$$a^2(t) = a_0^2\left(1 - \frac{t}{t_0}\right), \tag{1.1}$$

where t is the time of burning of the particle; t_0 is the time of complete burnup of the particle. We note that this dependence describes well only the initial stage of particle combustion. The law of combustion of very fine particles is more complex, but as a certain approximation we will take Eq. (1.1) as valid in all stages of combustion. We need the model dependence (1.1) to illustrate the general relations obtained below.

Let the half-space $z > 0$ be filled with fuel particles for which the combustion law is given by a known function $a^2(t)$. The distribution of radiation intensity is determined by the Bouguer law

$$\partial I/\partial z + \alpha I = 0. \tag{1.2}$$

The volumetric coefficient of attenuation α is found from the well-known equation

$$\alpha = \pi a^2 k_0 N, \tag{1.3}$$

where k_0 is a dimensionless attenuation efficiency factor; N is the particle concentration. At large values of the Mie parameter $\rho = 2\pi a/\lambda$ (λ is the radiation wavelength) the quantity k_0 is practically constant and approximately equal to two [5]. For carbon particles this condition is well satisfied at $\rho > 15$. Even at $\rho = 6$ graphite and anthracite particles have $k_0 = 2.25$ [6]. Thus, the dynamics of the clearing of a system of large particles is determined mainly by the function $a^2(t)$. The concentration of the inhomogeneous aerosol will be written in the form

$$N = n_0 n(z),\ n(0) = 1, \tag{1.4}$$

where n_0 represents the aerosol concentration at $z = 0$ while the dimensionless function $n(z)$ determines the character of inhomogeneity of the aerosol. Using (1.4), we rewrite Eq. (1.3) in the form

$$\alpha = gn(z),\ g = \pi a^2 k_0 n_0.$$

For a homogeneous aerosol the quantity g coincides with the volumetric coefficient of attenuation.

We define the front of the clearing wave as the boundary separating burning particles from nonburning ones. Let the point z_0 coincide with the front of the clearing wave at the time t. Then $I(z_0) = I_0$. From Eq. (1.2) we find

$$\ln\frac{I_1}{I_0}\int_0^{z_0} g(z)\,n(z)\,dz. \tag{1.5}$$

Here I_1 is the initial intensity of the optical radiation. Each point $z \in [0, z_0]$ is set in correspondence with the time τ at which the clearing wave arrives at this point. Such a correspondence defines the function $z(\tau)$, which is unique at $\tau > 0$. The function $z(\tau)$ determines the position of the front of the clearing wave, while the derivative of this function, $v = dz/d\tau$, obviously represents the velocity of the clearing wave.

We replace the integration variable z in Eq. (1.5) by the variable τ, after which we have

$$\ln \frac{I_1}{I_0} = \int_0^t g(t-\tau)\, n(z(\tau)) \frac{dz}{d\tau}\, d\tau. \tag{1.6}$$

Here the time of combustion of a particle at the point with the coordinate z is given as the argument of the function g.

Equation (1.6) is a nonlinear integrodifferential equation for determining the function z(t). The layer of aerosol which corresponds to the intensity distribution from I_1 to I_0 ignites instantly if we neglect the small time of particle heating to the ignition temperature and take the speed of light as infinite. The thickness z_* of such a layer is determined from the equation

$$\frac{1}{g_0} \ln \frac{I_1}{I_0} = \int_0^{z_*} n(z)\, dz, \quad g_0 = \pi a_0^2 k_0 n_0. \tag{1.7}$$

The singular velocity component of the clearing wave is obviously expressed through the equation

$$v = z_* \delta(t),$$

where $\delta(t)$ is a δ function. Having isolated the singular part of the solution, we obtain the following nonlinear integrodifferential equation:

$$\ln \frac{I_1}{I_0}\left(1 - \frac{g(t)}{g_0}\right) = \int_0^t g(t-\tau)\, n(z_* + z_1(\tau)) \frac{dz_1}{d\tau} d\tau. \tag{1.8}$$

The function $z_1(t)$ determined from Eq. (1.8) is connected with the function z(t) by the simple relation

$$z_1(t) = z(t) - z_*, \quad z_1(0) = 0.$$

2. To solve Eq. (1.8) we introduce the auxiliary function

$$f(t) = n(z_* + z_1(t))\, dz_1/dt. \tag{2.1}$$

The function f(t) satisfies the relatively simple integral equation

$$\ln \frac{I_1}{I_0}\left(1 - \frac{g(t)}{g_0}\right) = \int_0^t g(t-\tau) f(\tau)\, d\tau. \tag{2.2}$$

Since the convolution of the functions f and g is written on the right side of (2.2), it is convenient to solve this equation by the method of a Laplace transform using the Borel multiplication theorem.

The function f(t) is defined as the inverse transform of the well-known transform

$$f(t) = \frac{1}{G(p)} \ln \frac{I_1}{I_0}\left(\frac{1}{p} - \frac{G(p)}{g_0}\right). \tag{2.3}$$

Here G(p) is the transform of the function g(t).

The inversion of the Laplace transform again consists in the solution of an integral equation of the first kind, but this is already a standard problem of operational calculus [7]. We will henceforth assume that the problem of inverting the Laplace transform is solved and the function f(t) has been found.

Now the determination of the function $z_1(t)$ comes down to the solution of the ordinary nonlinear differential equation (2.1). Separating the variables in this equation, we obtain

$$\int_{0}^{z_1} n(z_* + x)\,dx = \int_{0}^{t} f(t)\,dt. \tag{2.4}$$

The function $z_1(t)$ is determined from Eq. (2.4). By differentiating this function, we obtain the velocity of the clearing wave. The quantity dz_1/dt can be obtained from Eq. (2.1):

$$dz_1/dt = f(t)/n(z_* + z_1(t)). \tag{2.5}$$

In the general case the function $z_1(t)$ is found numerically. In the examples presented below an analytical solution can be obtained.

At $t \geqslant t_0$ the function $g(t)$ is reduced to zero, while the integral equation (2.2) takes the form

$$\ln\frac{I_1}{I_0} = \int_{t-t_0}^{t} g(t-\tau) f(\tau)\,d\tau. \tag{2.6}$$

The solution of Eq. (2.6) is obvious:

$$f_0 = \frac{\ln\frac{I_1}{I_0}}{\int_0^{t_0} g(t_0 - s)\,ds}. \tag{2.7}$$

Using (2.7), from Eq. (2.5) we find the velocity of the clearing wave as a function of the z coordinate at $t > t_0$:

$$\frac{dz_1}{dt} = \frac{\ln\frac{I_1}{I_0}}{n(z)\int_0^{t_0} g(t_0 - s)\,ds}, \quad z > z_* + z_1(t_0). \tag{2.8}$$

This equation allows us to determine the position of the front of the clearing wave at $t > t_0$. We have

$$\int_{z_1(t_0)}^{z_1} n(z_* + x)\,dx = \ln\frac{I_1}{I_0}\,\frac{t - t_0}{\int_0^{t_0} g(t_0 - s)\,ds}. \tag{2.9}$$

Having determined the function $z_1(t)$ from this and substituted it into (2.9), we find the quantity dz_1/dt as a function of time at $t > t_0$.

At the time $t = t_0$ the velocity of the clearing wave undergoes a jump of the first kind, generally speaking. The velocity jump is due to the violation of the analytical nature of the function $g(t)$ at $t = t_0$. We designate the velocity $v(t_0 - 0)$ as v_- and the velocity $v(t_0 + 0)$ as v_+. In accordance with Eqs. (2.1) and (2.8), the relative size of the velocity jump is expressed through the equation

$$\frac{v_-}{v_+} = \frac{f(t_0)}{\ln\frac{I_1}{I_0}} \int_0^{t_0} g(t_0 - s)\,ds. \tag{2.10}$$

We note that if the quantity z_* or the quantity $z_1(t)$ goes to ∞ at $t \leqslant t_0$, then the need for these solutions at $t > t_0$ naturally drops out.

Let the function $n(z)$ be integrable over a finite interval. Then the quantity z_* becomes infinite if

$$\frac{1}{g_0} \ln \frac{I_1}{I_0} \geqslant \int_0^\infty n(z)\, dz. \tag{2.11}$$

The quantity z_* is finite if the function $n(z)$ is not integrable over a finite interval.

3. We take the model equation (1.1) as the combustion law. In this case the function $g(t)$ has the form

$$g(t) = g_0(1 - t/t_0),\ t \leqslant t_0,\ g(t) = 0,\ t > t_0. \tag{3.1}$$

The simple equations (2.8), (2.9) can be used at $t > t_0$, so that the main task consists in the search for a solution at $t < t_0$. For this purpose we analytically extend the function $g(t)$ into the region of $t > t_0$ and in place of (3.1) we define the function

$$g(t) = g_0(1 - t/t_0),\ 0 \leqslant t < \infty. \tag{3.2}$$

The solution, obtained by the method of a Laplace transform using the function (3.2), will obviously be valid at $t < t_0$.

The transform of the function (3.2) has the simple look

$$G(p) = (g_0/p)(1 - 1/t_0 p). \tag{3.3}$$

Substituting (3.3) into Eq. (2.3), we obtain

$$f(t) = \frac{1}{g_0 t_0} \ln \frac{I_1}{I_0} e^{t/t_0}. \tag{3.4}$$

Using Eqs. (2.4) and (3.4), we find

$$\int_0^{z_1} n(z_* + x)\, dx = \frac{1}{g_0} \ln \frac{I_1}{I_0} \left(e^{t/t_0} - 1\right). \tag{3.5}$$

By substituting $f(t_0)$ and $g(t_0 - s)$ into Eq. (2.10) we can ascertain that the relative size of the velocity jump at $t = t_0$ is small and equal to $e/2$. Of course, this result has meaning if the velocity of the clearing wave is finite at $0 < t \leqslant t_0$.

Let the quantity n vary by the linear law

$$n(z) = 1 + (1/k)\, z,\ k > 0. \tag{3.6}$$

Substituting (3.6) into Eq. (3.5), we find

$$z_1(t) = k \sqrt{1 + \frac{1}{\varkappa}} \left[-1 + \sqrt{1 + \frac{1}{1+\varkappa} \left(e^{t/t_0} - 1\right)} \right],$$
$$\varkappa = k \Big/ \left(\frac{2}{g_0} \ln \frac{I_1}{I_0} \right), \quad t \leqslant t_0.$$

At $t > t_0$ we obtain

$$z_1(t) = k \left[-\sqrt{1 + \frac{1}{\varkappa}} + \sqrt{\left(\frac{z_1(t_0)}{k} + \sqrt{1 + \frac{1}{\varkappa}} \right)^2 + \frac{2}{\varkappa} \left(\frac{t}{t_0} - 1 \right)} \right].$$

From this we determine the velocity of the clearing wave:

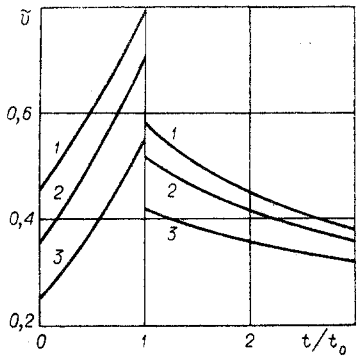

Fig. 1

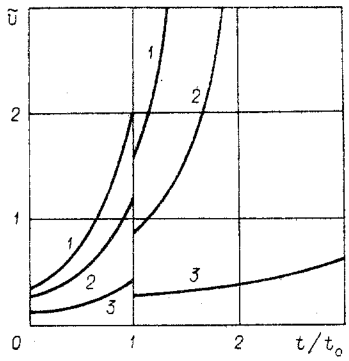

Fig. 2

$$\tilde{v} = \frac{1}{2}\frac{1}{\sqrt{\varkappa + e^{t/t_0}}} e^{t/t_0}, \quad t_0 > t > 0, \quad \tilde{v} = \frac{1}{\sqrt{\varkappa + e - 2 + 2(t/t_0)}}, \quad t > t_0. \tag{3.7}$$

In Eq. (3.7) the velocity is given in the dimensionless form

$$\tilde{v} = vt_0 \Big/ \sqrt{\frac{2k}{g_0}\ln\frac{I_1}{I_0}}.$$

This dependence is presented in Fig. 1. Curves 1-3 correspond to the values $\varkappa$ = 0.2, 1, and 3, respectively.

The aerosol becomes homogeneous as $k \to \infty$. In this case

$$v(t) = \frac{1}{g_0}\ln\frac{I_1}{I_0}\left(\delta(t) + \frac{1}{t_0}e^{t/t_0}\right), \quad t < t_0, \quad v(t) = \frac{2}{g_0 t_0}\ln\frac{I_1}{I_0}, \quad t > t_0.$$

Let us consider another example:

$$n(z) = e^{-z/\gamma}. \tag{3.8}$$

This dependence corresponds to a Boltzmann distribution of the aerosol particles. Since the function (3.8) is integrable over an infinite interval, the quantity z_* can become infinite in certain cases. In these cases the clearing of the medium is radically improved and, within the framework of the model adopted here, is determined only by the time of particle burnup.

Substituting (3.8) into Eq. (1.7) and using (2.11), we find that the quantity z_* is infinite with the condition

$$\Phi = \frac{1}{g_0\gamma}\ln\frac{I_1}{I_0} \geqslant 1.$$

If the dimensionless parameter Φ is less than one, then at the initial time a combustible layer is formed with a finite thickness $z_* = -\gamma \ln(1 - \Phi)$. We determine the position of the front of the clearing wave and its velocity by using (3.5) and (3.8). For $0 < \Phi < 1/e$ we have

$$z_1 = \gamma \ln\frac{1 - \Phi}{1 - \Phi e^{t/t_0}}, \quad 0 < t \leqslant t_0; \tag{3.9}$$

$$\tilde{v} = v/(\gamma/t_0) = \frac{\Phi e^{t/t_0}}{1 - \Phi e^{t/t_0}}, \quad 0 < t < t_0; \tag{3.10}$$

$$\tilde{v} = \frac{1}{D - \frac{t}{t_0}}, \quad D = \frac{1 - \Phi e + 2\Phi}{2\Phi}, \quad t_0 < t \leqslant Dt_0. \tag{3.11}$$

If $1/e < \Phi < 1$, then Eqs. (3.9) and (3.10) are valid up to the time $t = t_0 \ln(\Phi^{-1}) < t_0$. At this time the length of the clearing channel becomes infinite (Eq. (3.11) is not used for $1/e < \Phi < 1$). In Fig. 2 we present the dependence of $\tilde{v}$ on time expressed in units of t_0. Curves 1-3 correspond to $\Phi = 0.25$, 0.2, and 0.1, respectively.

4. Let us discuss the results obtained and the region of their applicability. If the aerosol concentration declines rapidly enough that $\int_0^\infty n(z)\,dz$ converges, then with an increase in the radiation intensity a radical clearing of the medium can be achieved through the formation of a clearing channel of infinite length at the initial time. In this case the clearing time practically coincides with the time of particle burnup. Allowance for vaporization, essential at high intensities, can only decrease this estimate. If the velocity of the clearing wave is finite at $t > 0$, the time of complete clearing of the aerosol layer is equal to the sum of the time of passage of the clearing wave through this layer and the time of burnup of a particle.

We note that for typical aerosol parameters ($a \gtrsim 10^{-6}$ m, $k_0 = 2$, $t_0 \gtrsim 10^{-3}$ sec, $n_0 \gtrsim 10^{11}$ m^{-3}) the characteristic initial velocity of the wave of clearing of an aerosol with a slowly varying concentration is $\sim 10^4$ m/sec when the quantity $\ln(I_1/I_0)$ is on the order of several units. Hence, the time of propagation of the clearing wave must be allowed for in this case even for aerosol layers with a thickness on the order of or greater than 10 m.

In the present report we have considered the simplest static model of an aerosol. If the cross section of the clearing channel is small, then in the general case allowance for the wind can significantly alter the pattern of clearing even in the central part of the channel. If the transverse component of the particle velocity is small (usually less than or on the order of 1 m/sec), however, then the pattern of clearing should be altered significantly in the central part of the channel.

Let us estimate the region of applicability of the model combustion law (1.1) to the problem of aerosol clearing. Using a general expression for the combustion rate [8], one can show that for carbon particles with a radius of $\sim 8 \cdot 10^{-6}$ m heated to a temperature of ~ 3000°K the diffusional mode of combustion is retained as the particle radius decreases by about an order of magnitude. In such a range of variation of the particle radius the value of k_0 can be taken as approximately constant and equal to two if the radiation wavelength is $\sim 10^{-6}$ m. We can show that the dynamics of the remaining part of a particle hardly affects the dynamics of clearing over a considerable time interval. Let us assume, for example, that a particle "remnant" does not burn up at all, and determine how this would affect the dynamics of clearing. In the simplest case of $n(z) = 1$ at $t > t_0$ we obtain an approximate expression for the velocity of the clearing wave,

$$v(t) \approx \frac{2}{g_0 t_0} \ln \frac{I_1}{I_0} \exp\left[-2 \frac{\alpha_0}{g_0} \frac{(t - t_0)}{t_0}\right], \quad \alpha_0 \ll g_0,$$

where α_0 is the volumetric coefficient of attenuation of the particle "remnants." The exponential factor characterizes the difference between the clearing modes being compared. The two modes will be close to each other if the exponential factor is close to one. This will occur with the condition $t \ll g_0 t_0 / 2\alpha_0$. If the radii of a particle and a "remnant" are in a ratio of 10 to 1, then this condition takes the form $t \ll 50 t_0$.

Thus, if the diffusional mode of combustion corresponds to a considerable change in the radius of a particle, then using Eq. (1.1) one can satisfactorily describe the dynamics of clearing over a considerable time interval. Estimates of the radiation intensities at which the combustion process prevails over the vaporization process are given in [9].

In the case of a polydisperse aerosol the front of the clearing wave will be smeared out, since particles of different sizes ignite at different intensities of radiation incident on them.

In other words, a traveling region of finite width separating the burning from the nonburning particles will exist in the aerosol. Within the limits of this region there are both burning and nonburning particles. The position of such a region and the velocity of its movement can be estimated on the basis of the results presented above, taking a characteristic average radius as the particle size. Such an estimate will obviously be the more precise, the narrower the range of particle sizes.

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PERTURBATION PROPAGATION IN NONLINEAR TRANSPORT PROCESSES DESCRIBED BY A TURBULENT FILTRATION EQUATION

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A parabolic quasilinear equation of the form

$$\frac{\partial u}{\partial t}-\frac{\partial}{\partial x}\left(\left|\frac{\partial u^k}{\partial x}\right|^{n-1}\frac{\partial u^k}{\partial x}\right)=0,\quad k, n>0,\quad kn>1 \tag{1}$$

describes different transport processes in the case of a power-law dependence of the transport coefficients on the transportable quantity u and its gradient $\partial u/\partial x$. In particular, for n = 1 Eq. (1) can be considered as a nonlinear heat conduction equation, for k = 1 as the momentum transport in a non-Newtonian dilatant fluid, and in the general case of k, n ≠ 1, as a turbulent filtration equation [1-3]. The essential feature of the transport processes described by (1) is the presence of the line $x = x_f(t)$ delimiting the domain with u(x, t) = 0 and the domain of localization of perturbations with u(x, t) > 0 [4]. Regularities of the motion of the front $x = x_f(t)$ in the Cauchy problem for (1) are investigated in this paper.

We shall consider an initial distribution of the transportable quantity described by the bounded finite function

$$u_0(x)\begin{cases}>0 & \text{for} \quad |x|<|x_\Phi|,\\ =0 & \text{for} \quad |x|>|x_\Phi|,\end{cases}$$

that is symmetric with respect to x to be given at the initial time t = 0, and assume that the asymptotic representation of the function $u_0(x)$ as $x \to x_\Phi + 0$, $x_\Phi < 0$ has the form

$$u_0(x) \sim U_0(x-x_\Phi)^\omega,\ \omega \geqslant 0. \tag{2}$$

Then the law of front motion $x_f = x_f(t)$ should be found from the solution of the Cauchy

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