WATER AEROSOL CLEARING UP UNDER CONDITIONS OF LATERAL WIND, THERMAL BLOOMING AND DIFRACTION DIVERGENCE OF AN OPTICAL BEAM

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Stationary clearing up of water aerosol by a laser beam at lateral movement of the medium relative to the beam is investigated. The deterioration in performance of clearing up is shown to take place under thermal blooming and diffraction of the beam. The boundaries of clearing up regions are determined (from given levels of intensity transmission in the beam center) in the space of similarity factors. The specific examples in physical variables are given in the paper.

The extensive bibliography conserning studied problem is contained in Refs. 1–6. The analytical solution of the problem in the approximation of water nature of aerosol and in the geometric–optics limit was considered in Refs. 3, 4, and 7–11. There are a lot of versions of this solution in which beam divergence, thermal blooming, etc. were considered within various ranges of accuracy. The first attempts to construct a numerical solution with due regard for diffraction and thermal blooming were made in Refs. 12–14.

A beam propagation in aerosol medium is described by a system of equations of paraxial optics and aerohydrodynamics. Let axis z be directed along beam passage, whereas axis x is directed along lateral component $V_{\perp}$ of velocity of the movement of beam or aerosol medium relative to each other (or wind velocity). In dimensionless form the optical equation with boundary conditions is as follows:

$$2F\frac{\partial u}{\partial z} + i\,\nabla_{\perp}^2 u = -\,[2i\,F\,N\,\rho_1(I;\,M;\,\mathrm{Pe}_D) + N_\mathrm{a} + N_b\,w]\,F\,u, \quad (1)$$

$$u\,\Big|_{z=0} = u_0(x,\,y,\,t)\,,\; u\,\Big|_{x,\,y\to\mp\infty} \to 0\,. \quad (2)$$

In Eq. (1) $\nabla_{\perp}^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$; u is a complex function of electromagnetic field (related to dimensionless intensity by relationship $I = uu^*$); $u_0(x,\,y,\,t)$ is a known distribution of this function at the start of path; $F = 2\pi r_0^2/\lambda L$ is Fresnel number; r_0 is an initial beam radius; λ is radiation wavelength; α is characteristic path length; $N_\mathrm{a} = \alpha_\mathrm{g}\,L$ is a parameter of molecular (gas) absorption of radiation; α_g is a linear (m^{-1}) coefficient of radiation absorption by vapor–air mixture; $N_b = bw_*L$ is a parameter of aerosol extinction; w_* is an initial characteristic water content of a medium, i.e., concentration of liquid (droplet) aerosol phase; $b = b_a + b_d$ is a specific coefficient of aerosol extinction of radiation (m^2/kg); b_a and b_d are absorption and scattering coefficients, respectively; $N = (L/L_T)^2$ is a parameter of the beam thermal blooming; $L_T = r_0/\sqrt{\varepsilon\,(n_0-1)/n_0}$ is a length of thermal blooming; $\varepsilon = b_a\,(1-\beta_m)\,w_*\,I_*\,t_a/\rho_g h_g$ is a scale of disturbance of medium density; ρ_g, $h_g = C_pT_0$, and n_0 are an initial density, enthalpy (temperature T_0, thermal capacity C_p), and refractive index of undisturbed air; β_T is a dimensionless coefficient characterising the part of absorbed energy which is spent for drop evaporation ($\beta_T = 0.3$–1.0 in dependence on initial temperature T_0, characteristic intensity I_*, and initial radius of the drop $r_{\mathrm{d}0}$); and $t_\mathrm{a} = r_0/V_{\perp}$ is a characteristic aerodynamic time (time of medium particle transit across beam). Coordinate z was related to L, coordinates x and y were related to r_0, and radiation intensity I – to characteristic value I_* The value I_* is a maximum value for originally normal (Gaussian) distribution considered below

$$I\,\Big|_{z=0} = \frac{I_\mathrm{phys}}{I_*} = I_0(x,\,y,\,t) = \exp\,(-\,(x^2+y^2)_\mathrm{phys}\,/\,r_0^2)\,f(t)\,,$$

where $f(t)$ is a temporal law of intensity changing in the initial cross section (further $f(t)$ is a step function).

The dimensionless function ρ_1 in equation (1) describes disturbance of vapor–air medium density $\Delta\rho/\rho_g = 1 + \varepsilon\rho_1(x, y, z, t)$ and it is obtained together with function of water content w from equations of aerohydrodynamics

$$\left(\frac{1}{N_t}\frac{\partial}{\partial t} + \frac{\partial}{\partial x}\right)\rho_1 = \frac{1}{\mathrm{Pe}}\,\nabla_{\perp}^2\rho_1 - \left[w + \frac{N_\mathrm{a}}{N_b}\,\frac{b}{b_a(1-\beta_T)}\right]I\,; \quad (3)$$

$$\rho_1\,\Big|_{t=0} = 0;\;\; \rho_1\,\Big|_{x\to-\infty} \to 0\,; \quad (4)$$

$$\left(\frac{1}{N_t}\frac{\partial}{\partial t} + \frac{\partial}{\partial x}\right)w = \frac{1}{\mathrm{Pe}_D}\,\nabla_{\perp}^2\,w - N_v\,w\,I\,; \quad (5)$$

$$w\,\Big|_{t=0} = w_0(x,\,y,\,z)\,; \qquad w\,\Big|_{x\to-\infty} \to w_0(x,\,y,\,z)\,. \quad (6)$$

Here $w_0(x,\,y,\,z)$ is initial distribution of the function of water content; $N_v = t_a/t_v$ is an evaporation (clearing up) parameter; $t_v = H_0/b_a\beta_T\,I_*$ is characteristic time of aerosol evaporation; H_0 is a water evaporation heat (in J/kg) ; $N_t = t_0/t_a$ is parameter of nonstationary; t_0 is characteristic duration of a pulse; $\mathrm{Pe} = \rho_\mathrm{g}C_\mathrm{p}\,V_{\perp}r_0/k_0$ is a Peclet number of gas; k_0 is a thermal conduction coefficient of undisturbed gas; $\mathrm{Pe}_D = V_{\perp}r_0/D$ is a diffusion Peclet number; and, D is a coefficient of turbulent diffusion of liquid (drop) phase. It is assumed in the present paper that Mach number $M_{\perp} = V_{\perp}/c$ (c is sonic speed in a medium) is close to zero and acoustic disturbances are small. Thermal conduction and diffusion are ignored in the paper too. It should be noted that there are some situations when drop diffusion is essential. Coefficient of turbulent diffusion amounts to $D \sim 10^{-4}$–10^{-3} $\mathrm{m}^2/\mathrm{sec}$ in laboratory artificial mist.[3,9,15] A Peclet diffusion number may be a value of unity order when $r_0 = 0.01$ m and $V_{\perp} = 0.1$ m/sec.

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Considerable long pulses $t_0 \gg t_a$, t_v ($N_t \gg 1$) for which the establishment of stationary regime of clearing up occurs will be studied in the present paper. In the other limiting case of very short pulses $t_0 \ll t_a$ ($N_t \ll 1$) the clearing up process will be essentially nonstationary; relative medium movement can be ignored, and it is necessary to substitute pulse duration t_0 for aerodynamic characteristic time t_a in the parameters of blooming N and evaporation (clearing up) N_v.

Passing to intensity I and phase φ (or to deflection angle $\vartheta = V_\perp \varphi$ by substitution $u = \sqrt{I}\exp(-iF\varphi)$) in Eq. (1), we obtain the following system:

$$\left(\frac{\partial}{\partial t}+(\vartheta, V_\perp)\right)\vartheta = N V_\perp \rho_1 + \frac{1}{4F^2} V_\perp \left\{\frac{V_\perp^2 I}{I} - \frac{(V_\perp I, V_\perp I)}{2I^2}\right\}; \quad (7)$$

$$\left(\frac{\partial}{\partial z}+(\vartheta, V_\perp)\right)\ln I + (V_\perp, \vartheta) = -N_a - N_b w\,. \quad (8)$$

The equation (7) demonstrates that in the geometric–optics limit $F \to \infty$ the error due to neglect of diffractional term amounts to $O(F^{-2})$. It should be noted that vapor–air mixture absorbs radiation several orders weaker than drop liquid phase. In view of that, we assume $N_a = 0$. First of all, we examine the influence of thermal blooming (parameter N) and diffraction (Fresnel number F) on clearing up process (at N_v, $N_b \sim 1$).

In the geometric–optics limit ($F \to \infty$) and without thermal blooming ($N = 0$) the system of equations (8) and (5) has a known analytical solution

$$I(x, y, z, t) = \frac{I_0(x, y, t)}{\{1 + [\exp(\tau_0) - 1]\exp(-E_0)\}}; \quad (9)$$

$$w(x, y, z, t) = \frac{w_0(x - t, y, z)\exp(\tau_0 - E_0)}{\{1 + [\exp(\tau_0) - 1]\exp(-E_0)\}}; \quad (10)$$

$$\tau_0 = N_b \int_0^z w_0(x, y, z')\,\mathrm{d}z'; \quad (11)$$

$$E_0 = N_v \int_0^t I_0(x - t + t', y, t')\,\mathrm{d}t', \quad (12)$$

where τ_0 is an optical thickness of nondisturbed aerosol medium; E_0 is an energy variable, i.e., energy that would have been absorbed by the moment t per unit area of aerosol medium without disturbance intensity I.

The homogeneous medium $w_0 = 1$ is considered in the present paper. In this case optical thickness at $z = 1$ coincides with extinction parameter $\tau_0 = N_b$. Energy variable for originally Gaussian stationary distribution equals

$$E_0(x, y, z, t) = N_v \int_{x-t}^{x} \exp(-x'^2 - y^2)\,\mathrm{d}x' \Big|_{t\to\infty} =$$

$$= N_v \int_{-\infty}^{x} \exp(-x'^2 - y^2)\,\mathrm{d}x'\,. \quad (13)$$

Let us take the analytical solution (9)–(13) as an initial base of investigation. The numerical solution of system (1)–(6) was obtained as in Ref. 16 using method of Fourier fast transform (FFT). The results of calculations are presented in Figs. 1–4 and in the table. Figure 1 shows change of intensity peak $I_m(z) = \max_{x,y}\{I(x, y, z)\}$ with the path z, intensity in the center $I_{00}(z) = I(x=0, y=0, z)$ (dashed line), and square of beam mean radius

$$r_c^2(z)/r_0^2 = \iint_{-\infty}^{\infty} [(x - x_c)^2 + (y - y_c)^2]\, I(x, y, z)\,\mathrm{d}x\,\mathrm{d}y\,,$$

where $x_c = \iint_{-\infty}^{\infty} x\, I\,\mathrm{d}x\,\mathrm{d}y$ and $y_c = \iint_{-\infty}^{\infty} y\, I\,\mathrm{d}x\,\mathrm{d}y$ are coordinates of center of gravity of intensity distribution. Four specific cases are presented: *1* – $N_b = 1$, $N_v = 1$, $N = 0$, and $F = 10$ corresponding to a moderate extinction and clearing up without thermal blooming and diffraction (geometric optics); *2* – $N_b = 2.5$, $N_v = 3$, $N = 0$, and $F = 10$ corresponding to strong clearing up and extinction; *3* – $N_b = 0.5$, $N_v = 1$, $N = 1$, and $F = 10$ corresponding to thermal blooming along with moderate extinction and clearing up without diffraction, and *4* – $N_b = 0.5$, $N_v = 1$, $N = 0.1$, and $F = 1$ corresponding to an influence of diffraction divergence on the medium clearing up. The intensity profiles $I(x, y=0, z=1)$ are constructed in the separate fragment in the direction longitudinal with respect to wind at the end of the beam path. The intensity peak shifts downflow (curves *1* and *2* in fragment), since clearing up is maximum in the lee area of beam. Intensity peak is higher on the curve *2* than on the curve *1* though extinction parameter $(N_b)_2 > (N_b)_1$.

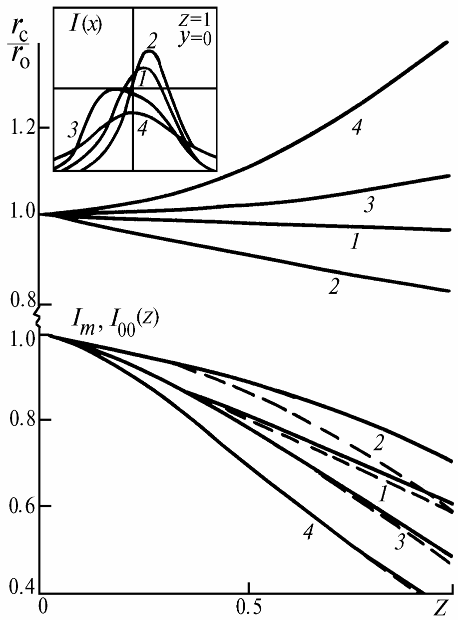

FIG. 1. Intensity profiles $I(x)|_{y=0;\ z=1}$ (fragment). Change of intensity peak I_m (solid curves), intensity in the beam center $I_{00}(z) = I(x=0, y=0, z)$ (dashed curves), and square of beam mean radius $r_0^2(z)/r_0^2$ with path.

This is explained by the fact that evaporation in the case *2* are stronger $(N_v)_2 > (N_v)_1$ and water content w in extinction integral $I \sim \exp(-N_b \int w\,\mathrm{d}z)$ is less than that in case *1* of moderate clearing up. The mean beam radius r_c decreases in case *2* as against case *1*. It attests that beam as a whole focuses at clearing up amplification. Thermal blooming (curves *3*) results in the following effects: beam expansion and decreasing of intensity peak; shifting of peak and beam as a whole towards a flow of aerosol medium. Diffraction when F~1 (curves *4*) leads to beam divergence and essential decreasing of intensity peak. Numerical results of the versions *1* and *2* within the computation error correspond to the Glickler analytical solution (9)–(13).

The table results allow the analysis of the influence of thermal blooming and diffraction within wide range of parameters $N = 0$–1 and $F = 1$–10. In decreasing of Fresnel number the essential differences from geometric–optics limit are observed at $F \le 3$. In accordance with Eqs. (7) and (8) the difference from geometric–optics limit must be less than 10% at $F > \sqrt{10} \cong 3.16$ and not more than 1% at $F > 10$. It should be noted that at $F = 10$ intensity values I are closer to analytical solution which is strictly valid at $F = \infty$, than corresponding values of water content w. At $F < 1$ diffraction divergence of beam is very large, and intensity at the end of path decreases more than twice, and there is practically no clearing up.

TABLE. Decreasing of intensity value in the beam center $I_{00} = I(x=0, y=0, z=1)$ in parameter of thermal blooming N increasing and Fresnel number F decreasing.

$N_v = 1$							
$N_b = 0.1$				$N_b = 0.5$			
$N = 0$		$F = 10$		$N = 0$		$F = 10$	
F	I_{00}	N	I_{00}	F	I_{00}	N	I_{00}
∞	0.958	0; $F=\infty$	0.958	∞	0.789	0; $F=\infty$	0.789
10	0.949	0; $F=10$	0.949	10	0.786	0; $F=10$	0.786
5	0.919	0.1	0.898	5	0.750	0.1	0.743
3	0.850	0.3	0.810	3	0.700	0.3	0.665
2	0.765	0.5	0.728	2	0.620	0.5	0.607
1	0.473	1.0	0.575	1	0.368	1.0	0.481

Increasing of thermal blooming parameter N at fixed values of other similarity factors results in noticeable decreasing of radiation transmission by medium at $N > 0.2$. Intensity at the end of path in aerosol medium is reduced by more than 40% at $N > 1$.

The use of similarity factors N, F, N_b, N_v, and others minimize a number of possible versions at change of physical parameters. Every parameter characterises one physical process (mechanism or property of medium or beam). At the same time, different specific problems in physical variables can correspond to one and the same situation in similarity factors space.

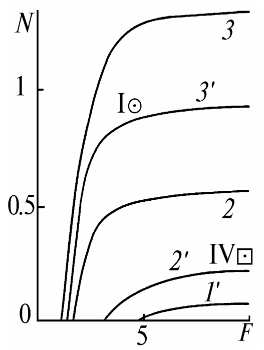

FIG. 2. Boundaries of areas of radiation transmission at the end of path in the similarity factors space ≪N–F≫ by intensity levels $I_{00} = I_{00}(z = 1) = 0.9$ (1), 0.7(2), and 0.5(3). Evaporation parameter $N_v = 1$. Extinction parameter $N_b = 0.1$ (curves 1, 2, and 3) and $N_b = 0.5$ (curves 2′ and 3′). Example I: $N_v = 1$, $N_b = 0.5$, $N = 0.915$, *and* $F = 4.74$; *Example* IV: $N_v = 1$, $N_b = 0.5$, *and* $N = 0.293$; $F \gg 1$.

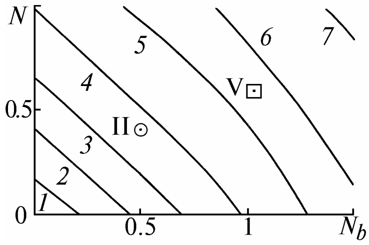

FIG. 3. Clearing up areas in coordinates ≪N–N_b≫ by intensity levels at the end of the path $I_{00} = 0.9$(1), 0.8(2), 0.7(3), 0.6(4), 0.5(5), 0.4(6), and 0.3(7). Clearing up (evaporation) parameter $N_v = 1$. Fresnel number $F = 10$. Example II: $N_v = 1$, $N_b = 0.51$, $N = 0.441$, *and* $F = 10$. *Example* V: $N_v = 1$, $N_b = 1$, $N = 0.586$, *and* $F \gg 1$.

The areas of aerosol clearing up are plotted on the ≪N–F≫ plane in Fig. 2 by the levels of transmitted radiation at the end of path $I_{00} = I_{00}(z = 1) = 0.9$, 0.7, and 0.5 (curves *1*, *2*, and *3*) at fixed parameters of extinction $N_b = 0.1$, 0.5 and evaporation $N_v = 1$. In Fig. 3 clearing up areas are constructed by levels of I_{00} in the similarity factors space ≪N–N_b≫ for fixed values of evaporation parameter and Fresnel number. Clearing up areas are placed on the left and below boundary curves *1*–*7*.

Clearing up areas in the similarity factors space ≪N_v–N_b≫ are constructed in Fig. 4 by intensity levels at the end of the path $I_{00} = 0.9$, 0.8, 0.7, 0.5, 0.3, and 0.1 (curves *1*–*6*) for $N = 1$ and $F = 10$. Given level of aerosol medium transmission is realized on the left and above curves *1*–*6*. For comparison corresponding boundaries of clearing up areas at $N = 0$ are marked by dashed line. The fact of essential extension of clearing up areas with no thermal blooming should be noted.

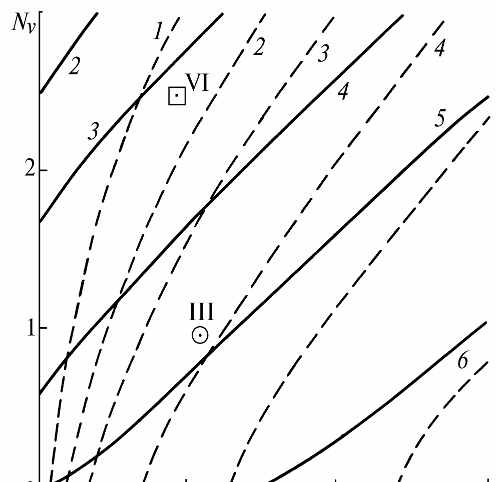

FIG. 4. Clearing up areas in the space ≪N–F≫. Parameter of thermal blooming $N = 1$ (solid curves) and $N = 0$ (dashed curves). Example III: $N_v = 1$, $N_b = 1.16$, $N = 1$, *and* $F = 10$. *Example* VI: $N_v = 2.56$, $N_b = 1$, $N = 1$, *and* $F \gg 1$.

Let us consider specific examples. Let $T_0 = 273$ K, $\rho_g = 1.225$ kg/m^3, $h_g = 2.73 \cdot 10^5$ J/kg, $\lambda = 10.6$ μm;

$I_* = 10^6$ W/m^2, $b_a = 100$ m^2/kg, $r_{d0} = 5$ μm; $b = 1.72\ b_a$ (Ref. 3, p. 144), and $H_0 = 2.5\cdot10^6$ J/kg.

Value of β_T can be estimated approximately in the following way.[17] It is known that if intensively heated the drop temperature T_d reaches maximum value T_m during a very short time interval, and then the drop is evaporated at practically constant temperature $T_d \cong T_m$ during a more long time interval. When $dT_d/dt \cong 0$ we cane[17]

$$\beta_T = j_m(T_m)\ H(T_m)\ /\ j_T(T_m)\ . \tag{14}$$

$$\frac{1}{T_m} = \frac{1}{T_{\rm boil}} - \frac{R}{\mu_v H_0} \ln\left[\frac{b_a\ r_w\ I_*\ r_{d0}\ \mu_g}{3\ r_g\ D_g\ H_0\ \mu_v}\right], \tag{15}$$

where $T_{\rm boil}$ and ρ_w are boiling temperature and water density, respectively; μ_g and μ_v are molecular weight of air and vapor (water); $H_0 = H(T_0)$; D_g is coefficient of vapor diffusion in air; and, j_m and j_T are densities of mass and heat flows from drop surface (for expression for j_T see Ref. 18). Using Eqs. (14) and (15) and following the procedure described in Ref. 17 for computation of j_m and j_T, the value of β_T can be found at given levels of incident radiation intensity I_*. For example, at initial temperature $T_0 = 273$ K and drop radius $r_{d0} = 5$ μm we obtain: $\beta_T = 0.47$, 0.62, 0.78, and 0.93 at intensity $I_* = 10^6$, $3\cdot10^6$, 10^7, and $3\cdot10^7$ W/m^2.

For field atmospheric conditions we consider a path $L = 100$ m in length with initial water content of mist $w_* = 2.91\cdot10^{-5}$ kg/m^3, wind velocity $V_\perp = 0.531$ m/sec, and initial beam radius $r_0 = 0.0283$. In so doing we obtain example I: $N_v = 1$, $N_b = 0.5$, $N = 0.915$, and $F = 4.74$. Evaporation time and aerodynamic time are equal to $t_v = t_a = 0.0532$ sec. Example I is indicated by a circle with point in Fig. 2. The intensity level I_{00} at the center of beam transmitted through aerosol medium amounts to a just less than 0.5.

In example II we take $L = 53.3$ m; $w_* = 5.57\cdot10^{-5}$ kg/m^3, $r_0 = 0.03$ m, and $V_\perp = 0.564$ m/sec. The other physical parameters are stated without changing. Computations of similarity factors yield: $F = 10$, $N_v = 1$, $N_b = 0.51$, and $N = 0.441$. Example II is marked by a circle with a point in Fig. 3. The intensity level I_{00} at the beam center at the end of path exceeds 0.6.

In the next example III we choose initial water content $w_* = 1.27\cdot10^{-4}$ kg/m^3, the other physical parameters are the same as in example II. We have $F = 10$, $N = 1$, $N_v = 1$, and $N_b = 1.16$. This example is marked by a circle in Fig. 4. Clearing up is provided at the level $I_{00} > 0.3$.

Let us consider several examples with laboratory paths. For laboratory conditions it is natural to take $L \sim 1$ m as a characteristic path length, beam radius $r_0 \sim 0.01$–0.001 m, blowing air velocity $V_\perp = 0.1$–1 m/sec. In example IV we choose the following physical parameters: $r_0 = 0.01$ m, $V_\perp = 0.187$ m/sec, $L = 4$ m, and $w_* = 7.25\cdot10^{-4}$ kg/m^3. Following values of similarity factors correspond to them: $F \gg 1$, $N_v = 1$, $N_b = 0.5$, and $N = 0.293$. This example is marked in Fig. 2 (by convention at $F = 10$) by square with a point. There is no influence of diffraction thermal, blooming is very small. We obtain the level of transmitted radiation I_{00} close to 0.7 as a result of aerosol medium clearing up at the central point.

Let us consider example V: $w_* = 0.00145$ kg/m^3; $\tau_0 \equiv N_b = 1.0$, i.e., the medium is optically dense. The rest physical parameters are the same as in the previous example. In this case, $N = 0.586$, $N_v = 1.0$, and $F \gg 1$. The considered version V is presented in Fig. 3. In comparison with the previous one IV more strong thermal blooming and aerosol extinction decrease the transmission level at the centre down to $I_{00} \cong 0.46$.

In example VI, presented in Fig. 4, we took $r_0 = 0.009$ m, $V_\perp = 0.262$ m/sec, $L = 4$ m, $I_* = 3\cdot10^6$ W/m^2, $\beta_T = 0.62$, and $w_* = 0.00145$ kg/m^3. Hence $F \gg 1$, $N = 1$, $N_b = 1$, and $N_v = 2.56$. We increase intensity of the beam incident on the aerosol medium a three times and velocity of air blowing the path almost one and a half times as compared with the previous example. In this case, the level of transmitted radiation at the central point amounts to $I_{00} \gg 0.65$.

Thermal blooming plays an essential part in all considered examples. The presented examples demonstrate that investigation of clearing up process of water aerosol carried out in general plan covers a wide range of variable concrete physical problems.

8

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