INTENSITY DISTRIBUTION OF LIGHT SCATTERED BY A TURBULENT JET FLOW

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Results are presented of a computation of the far-zone distribution of the intensity of radiation scattered by a turbulent nonisothermal air jet.

Investigation of the radiation intensity distribution in the far zone during the intersection of jet flow by a light beam is of practical interest of the development of optical diagnostic methods of light-dissipating media and the design of optical devices with large-diameter objectives in turbulent wind tunnels [1, 2].

The radiation scattering is due to gradients of the average values and the fluctuation characteristics of the dielectric permittivity that depend on the temperature, concentration, barometric, and other parameters affecting the refractive index of the medium.

We shall represent the instantaneous value of the dielectric permittivity in the form

$$\varepsilon = 1 + \langle \varepsilon \rangle + \tilde{\varepsilon}, \tag{1}$$

where $1 + \langle \varepsilon \rangle$ is the average value and $\tilde{\varepsilon}$ is the fluctuating component of the dielectric permittivity. Here $\langle \varepsilon \rangle$ and $\tilde{\varepsilon}$ are comparable in order of magnitude and $(\langle \varepsilon \rangle + \tilde{\varepsilon}) \ll 1$. Then by solving the Helmholtz equation by the perturbation method and limiting ourselves to the first term in the Born series for the mean scattered field intensity, we obtain the following expression:

$$\langle I_1 \rangle (\mathbf{r}) = \frac{\pi k_0^4}{2} \int_V \frac{I_0(\mathbf{R}) \left[E_{\langle\varepsilon\rangle}(\mathbf{R}, \mathbf{q}) + E_{\tilde{\varepsilon}}(\mathbf{R}, \mathbf{q}) \right] d^3\mathbf{R}}{(\mathbf{r} - \mathbf{R})^2}. \tag{2}$$

The Fourier-expansion function of the product of values of $\langle \varepsilon \rangle$ at two points $E_{\langle\varepsilon\rangle}(\mathbf{q}, \mathbf{R})$ can be computed from the results of an experimental investigation of the distribution of the average value of the temperature [4].

However, we shall concentrate here on a computation of the intensity of radiation scattered by random inhomogeneities of the dielectric permittivity, i.e., the function $E_{\langle\varepsilon\rangle}(\mathbf{q}, \mathbf{R})$ in (2) was not taken into account and the temperature fluctuation field was assumed to be quasihomogeneous. It was assumed that a plane incident wave is directed perpendicularly to the plane of jet symmetry. Under these conditions the expression (2) takes the following form in a cylindrical coordinate system

$$\frac{\langle I_1 \rangle (\mathbf{r})}{\langle I_0 \rangle} = \frac{\pi k_0^4}{2} \int_{z'}^{z''} \int_0^{\rho_0} \int_0^{2\pi} \frac{E_{\tilde{\varepsilon}}(|\mathbf{q}|, \mathbf{R})\, R dR d\Phi dZ}{R^2 + \rho^2 - 2R\rho(\cos\varphi\cos\Phi + \sin\varphi\sin\Phi) + (z - Z)^2}, \tag{3}$$

while the absolute value of the scattering vector is

$$|\mathbf{q}| = k_0\sqrt{2}(1 - \mathbf{n}_s\mathbf{n}_i)^{1/2} = k_0\sqrt{2}\left\{1 - \frac{z - Z}{[R^2 + \rho^2 - 2R\rho(\cos\varphi\cos\Phi + \sin\varphi\sin\Phi) + (z - Z)^2]^{1/2}}\right\}^{1/2}, \tag{4}$$

where $\mathbf{n}_s$ and $\mathbf{n}_i$ are unit vectors of the scattered and incident radiation.

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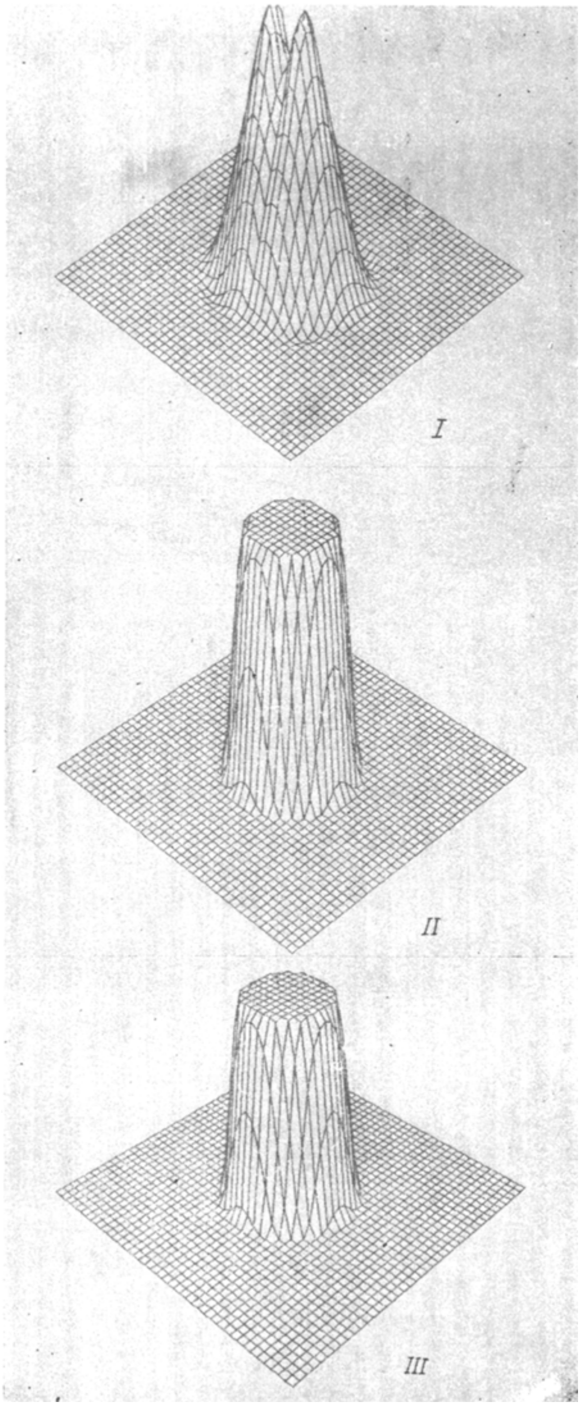

Fig. 1. Distribution of the relative mean intensity of scattered radiation $\langle I \rangle / I_0$ at distances of 100, 500, and 1000 m, respectively, from the scattering volume, from the top down.

The spectral density function of the dielectric permittivity fluctuations $E_\varepsilon(|\mathbf{q}|, \mathbf{R})$ is connected by a simple relationship [3] to the corresponding functions for the temperature fluctuation field whose one-dimensional value was approximated in the whole domain of wave numbers by a Karman spectrum model according to experimental data:

$$E_T(q,\ \mathbf{R}) = C_T^2 (q + q_0)^{-5/3} \exp[-\alpha (q/q_m)^{\beta}], \qquad (5)$$

where $q_0 = k/l_c$; $l_c = x - x_0$; $q_m = R_c^{3/4}/l_c$; $R_c = u_c l_c/\nu$; $u_c = u_0\sqrt{d}/\sqrt{l_c}$. A known equation connecting the three-dimensional $E_T(|\mathbf{q}|, \mathbf{R})$ to the one-dimensional $E_T(q, \mathbf{R})$ spectrum was used [5].

Experimental data from [4] are used for a two-dimensional nonisothermal air jet issuing from a slot nozzle with $d \times 40d$ transverse dimensions ($d = 3.175 \cdot 10^{-3}$ m) at the initial velocity and temperature drop at the nozzle exit of 15.24 m/sec and 60°, respectively.

Distributions of the mean scattered radiation intensity are given in Fig. 1 for the far zone at distances of 100, 500, and 1000 m from the scattering volume, respectively. For $z = 100$ m there are two characteristic peaks corresponding to the more intensive scattering process in the jet boundary layers. The magnitude of the relative intensity at the peaks here is $\langle I \rangle / I_0 = 0.5578 \cdot 10^{-2}$ while the size of the light spot is five apertures of the entrance beam. For $z = 500$ m no characteristic features are observed in the mean intensity distributions that are associated with the jet flow configuration, and the maximal value is $\langle I \rangle / I_0 = 0.1062 \cdot 10^{-5}$ and the light spot size is approximately ten apertures of the entrance light beam. For $z = 1000$ m the maximal value is $\langle I \rangle / I_0 = 0.1795 \cdot 10^{-7}$ and the size of the light spot is approximately 20 apertures of the entrance light beam. On the basis of the data obtained the angle of beam divergence can also be estimated for the scattered light, and is 3′. The computed data obtained agree in order of magnitude with the results of [6] for energy dissipated in the far zone.

It should be noted that the domain of application of the results obtained is limited by conditions for the applicability of the single-scattering approximation.

NOTATION

Here I_0 is the incident radiation intensity; k_0, wave number of the incident radiation; $\mathbf{R}$ and R, Φ, Z, respectively, scattering volume vector and coordinates; $\mathbf{r}$ and ρ, φ, z, respectively, vector and coordinates of the observation point in the scattered light beam; C_T^2, structural characteristic of the temperature fluctuation field; k, α, β, experimental constants.

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