LOCAL OPTICAL-PARAMETER DISTRIBUTIONS IN TUBULAR SHEAR FLOWS

O. G. Martynenko, I. A. Vatutin, N. I. Lemesh,
P. P. Khramtsov, and I. A. Shikh

UDC 532.517.4

Schlieren measurements have been made on the scattering-coefficient distributions in a two-dimensional nonisothermal turbulent air jet.

Interest attaches to the statistical characteristics of a beam propagating in a medium having random inhomogeneities in dielectric constant [1]. In turbulent liquid flows subject to shear, the scattering is due to random variations in density, which are dependent on the pulsations in the temperature, concentration, or other parameters.

The averaged-intensity distribution can be examined [2] from the radiation-transport equation, which is as follows if the absorption has negligible effect on the scattering:

$$\omega_k \frac{\partial}{\partial x_k} \langle I \rangle + \sigma \langle I \rangle = \frac{\sigma}{4\pi} \int_\Omega \gamma(\omega \cdot \omega') \langle I \rangle \, d\omega', \tag{1}$$

in which the scattering coefficient σ and scattering indicatrix $\gamma(\omega \cdot \omega')$ are parameters for an elementary volume and thus functions of the spatial coordinates. Successive approximation in the scattering order gives the following recurrence relations from (1):

$$\omega_k \frac{\partial}{\partial x_k} \langle I_n \rangle + \sigma \langle I_n \rangle = \frac{\sigma}{4\pi} \int_\Omega \gamma(\omega \cdot \omega') \langle I_{n-1} \rangle \, d\omega'. \tag{2}$$

The transmitted intensity in a two-dimensional turbulent shear flow (with characteristics only slightly dependent on the z coordinate) is found in the first approximation as follows for a homogeneous and collimated incident beam I_0 by solving (2):

$$\langle I_B \rangle = I_0 \exp(-\sigma(x, y) z). \tag{3}$$

The radiation conservation law is

$$I_0 - I_0 \exp(-\sigma(x, y) z) = \int_\Omega \langle I_s \rangle (\mathbf{r}, \omega) \, d\omega, \tag{4}$$

in which $\langle I_s \rangle (\mathbf{r}, \omega)$ is the scattered component. As $\langle I_s \rangle (\mathbf{r}) = \int_\Omega \langle I_s \rangle (\mathbf{r}, \omega) \, d\omega$, (4) implies

$$\sigma(x, y) = \frac{1}{z} \ln \left(\frac{I_0}{I_0 - \langle I_s \rangle (\mathbf{r})} \right). \tag{5}$$

Measured values for the radiation $\langle I_S \rangle(\mathbf{r})$ scattered in all directions and the incident flux I_0 give the scattering coefficient for unit volume as a function of the coordinates. In general, to determine the $\gamma(\omega \cdot \omega', \mathbf{r})$ distribution for a flow, one needs the scattered intensity as a function of angle $\langle I_S \rangle(\theta, \varphi, \mathbf{r})$, which involves an inverse treatment for the corresponding approximation $\langle I_n \rangle(\theta, \varphi, \mathbf{r})$ in (2), which can be implemented numerically.

Measurements on $\langle I_S \rangle(\theta, \varphi, \mathbf{r})$ can be made by the [1] method by means of an IAB-451 schlieren apparatus [3]. Circular stops are installed in the collimator and schlieren detector. The density in the schlieren picture is

$$D_{ij} = s \Delta t \langle I_s \rangle (\theta_i, \varphi_j, \mathbf{r}) \sin \theta_i \Delta \theta_i \Delta \varphi_j, \tag{6}$$

Lykov Institute for Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 5, pp. 715-718, May, 1989. Original article submitted February 9, 1988.

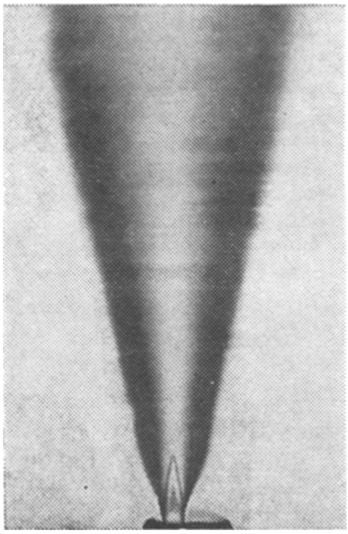

Fig. 1

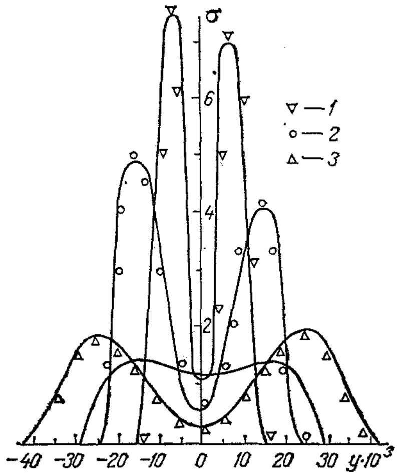

Fig. 2

Fig. 1. Schlieren picture of a turbulent nonisothermal gas jet with exposure time Δt = 2 sec.

Fig. 2. Distributions for the total scattering cross section in a nonisothermal jet for various distances from the nozzle: 1) x = 10h; 2) 20h; 3) 40h. σ, m^{-1}; y, m.

in which $\theta_i = y_i/F$, $\varphi_j = x_j/F$, F focal length, and y_i and x_j are the displacements of the stop center in the focal plane in the receiving instrument.

One can determine the intensity of the total scattered flux $\langle I_s\rangle(\mathbf{r})$ by the knife-edge and slot method [3]. The knifeedge should be at the focus perpendicular to the main flow. With the apparatus adjusted to maximal sensitivity, the blackening is

$$D = s\Delta t\left(\frac{1}{2}I_0 - \int_0^{\pi}\int_{-\pi/2}^{\pi/2}\langle I_s\rangle(\mathbf{r},\ \omega)\sin\theta d\theta d\varphi.\right. \tag{7}$$

The incident intensity is determined from a picture taken with the knife edge or displaying stop removed. The density then is

$$D_0 = s\Delta t I_0. \tag{8}$$

As $\int_0^{\pi}\int_{-\pi/2}^{\pi/2}\langle I_s\rangle(\mathbf{r},\ \omega)\sin\theta d\theta d\varphi = \frac{1}{2}\langle I_s\rangle(\mathbf{r})$, (6)-(8) give

$$\frac{\langle I_s\rangle(\theta_i,\ \varphi_j,\ \mathbf{r})}{I_0} = \frac{D_{ij}}{D_0\sin\theta_i\Delta\theta_i\Delta\varphi_j}, \tag{9}$$

$$\frac{\langle I_s\rangle(\mathbf{r})}{I_0} = \frac{D_0 - 2D}{D_0}. \tag{10}$$

The exposure should correspond to the averaging time required for a statistical study on the turbulent flow.

We have measured the scattering coefficient σ(x, y) in a turbulent nonisothermal air jet. The geometrical parameters in the nozzle and the geometrical and hydrodynamic ones in the jet were: nozzle end dimensions 3.175 × 127 mm, velocity at the end v = 15.24 m/sec, temperature difference between the end of the nozzle and the environment ΔT = 60 K, which corresponded approximately to what is described in [4]. The characteristics in this two-dimensional flow were only slightly dependent on the z coordinate, so the radiation from the collimator was directed along the z axis. The distributions for $\langle I_s\rangle(\mathbf{r})$ and σ(x, y) were derived from (5) and (10), while the optical density was measured with an IFO-451 microphotometer. Exposure time 2 sec. Figures 1 and 2 show the schlieren picture and σ(y) distributions at various distances from the nozzle, while Fig. 2 also shows $\sigma(y)$ calculated [5] for x = 40h. The discrepancies between theory and experiment are due to the calculations not incorporating the gradients in the averaged dielectric constant, inexact approximation for the kinetic-energy dissipation over the jet cross section, and the temperature-fluctuation dissipation, as well as the approximation involved in considering the jets similar.

The schlieren method can be applied to the scattered electromagnetic-radiation pattern and optical-parameter distributions in a shear-type turbulent flow. The known distribution for the scattering indicatrix enables one to recover the density-fluctuation spectrum [5]. Under certain conditions, the method can also be used to examine turbulence in temperature, concentration, and other patterns directly related to the density fluctuations.

NOTATION

$\langle I \rangle$, averaged radiation intensity; $\gamma(\omega \cdot \omega')$ scattering indicatrix as a function of the cosine of the scattering angle θ; $(\omega \cdot \omega') = \cos\theta$; Ω, surface of unit sphere; s, photographic sensitivity; Δt, exposure time; h, nozzle end thickness.

LITERATURE CITED

1. A. P. Ivanov, Scattering-Medium Optics [in Russian], Minsk (1969).
2. O. G. Martynenko and I. A. Vatutin, Izv. Akad. Nauk BSSR, Ser. Fiz.-Énerg. Nauk, No. 3, 41-45 (1987).
3. L. A. Vasil'ev, Schlieren Methods [in Russian], Moscow (1968).
4. Y. Bashir and M. S. Uberoi, Phys. Fluids, 18, No. 4, 405-410 (1975).
5. O. G. Martynenko, I. A. Vatutin, N. I. Lemesh, and P. P. Khramtsov, Inzh.-Fiz. Zh., 56, No. 1, 26-28 (1989).

LAWS GOVERNING THE INTERNAL REGION OF A TURBULENT BOUNDARY LAYER

V. V. Zyabrikov

UDC 532.526

A study was made of the effect of large positive pressure gradients on the distribution of friction and the velocity profile in the viscous sublayer, transitional section, and core of the internal region of a turbulent boundary layer.

The subdivision of an entire turbulent boundary layer into two regions — an internal region (the "wall" region) and an external region (the wake region) — is generally accepted in boundary layer theory [1-3] and reflects the fact, discovered by Clausius, that an external region where eddy viscosity can be assumed constant over the cross section exists a substantial distance from the wall. Eddy viscosity in this region decreases with approach toward the external boundary of the boundary layer due to alteration. In contrast to the external region, in the internal region the wall's effect on the size of the turbulent "eddies" causes eddy viscosity to decrease with decreasing distance to the wall. The flow characteristics in the internal region, with small-scale turbulence, depend only slightly on the history of the flow and are determined by the distance to the wall, the pressure gradient, and other local parameters [1, 2, 4]. It is known that pressure obeys the "wall law" in the internal region of turbulent boundary layers with small pressure gradients. This law, using dimensionless variables

$$\eta_* = \frac{yv_*}{\nu}, \quad u_* = \frac{u}{v_*} \quad \left(v_* = \sqrt{\frac{\tau_w}{\rho}}\right) \tag{1}$$

M. I. Kalinina Leningrad Polytechnic Institute.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 5, pp. 719-725, May, 1989. Original article submitted December 2, 1987.