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Abstract

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DETERMINATION OF THE CORRELATION BETWEEN VELOCITY AND TEMPERATURE PULSATIONS IN A TURBULENT FLOW OF AIR IN A PIPE

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The study of turbulent fluid flow in channels is usually limited to measuring velocity pulsations in isothermal flow or temperature pulsations under heat-exchange conditions. For investigating the mechanism of turbulent heat transfer, simultaneous measurement of velocity and temperature pulsations in a non-isothermal turbulent flow is of great interest. This makes it possible to find the correlation moments $\overline{ut}$, $\overline{vt}$ and, consequently, to calculate directly the turbulent heat transfer

$$q_i = -c_p \rho \overline{u_i t}. \tag{1}$$

Here c_p is the specific heat capacity; ρ is the density of the fluid; u, v, u_i are components of velocity pulsations in the axial, radial, and i directions, respectively; t is the turbulent temperature pulsation.

The experiments were carried out with stabilized air flow in a vertical smooth pipe with internal diameter $d = 113$ mm. The total relative length of the pipe reached 61 diameters. The Reynolds number was $\sim 32\,000$. Both an isothermal flow regime and flow with heat exchange during heating of the pipe wall by an electric heater were investigated. The specific heat flux at the wall was $q_w = 0.142$ kW/m^2, and the temperature head was $\theta_w - \theta = 7.5°$, where θ_w is the temperature of the pipe wall and θ is the bulk-mean temperature of the air.

Temperature pulsations of velocity and temperature were measured with a hot-wire anemometer. The sensor of the hot-wire anemometer was a single-wire element made of tungsten wire with a diameter of $5 \cdot 10^{-3}$ mm and a length of 1.05–1.1 mm. During measurements, the sensor wire was installed either perpendicular to the direction of the air flow or inclined at angles of 45 and 135°.

Fig. 1

Figure 1: Fig. 1

Measurements were performed at 6–7 levels of wire overheating relative to the local temperature of the medium. Determination of the velocity pulsations of the isothermal flow was carried out at overheating of 150–300°. During measurement of temperature pulsations, the overheating was no more than 0.5°, which ensured insignificant sensitivity of the sensor to velocity pulsations. The optimal overheatings of the sensor wire for measuring the correlation moments $\overline{ut}$ and $\overline{vt}$ proved to be overheatings that ensured a ratio of the sensor sensitivity coefficients to temperature pulsations (s_t) and to velocity pulsations (s_u) within the limits $s_t/s_u = 0.75 \div 2$.

The root-mean-square values of the sensor signals were recorded by a correlometer, which was an analog counting-and-solving device (^{2}).

The calculation of the intensities of turbulent pulsations and the correlation moments between them from sensor signals at different angles of wire installation and levels of its overheating was carried out analogously to the method described in (^{1}).

The mean flow velocity was measured with a total-pressure tube, and the mean temperature with a microthermocouple having a junction diameter of 0.2 mm.

Fig. 1. Distribution of the turbulent shear stress and the density of turbulent heat transport in a circular pipe.
1 $-q_r/q_w$; 2 $--\overline{uv}/u_\tau^2$; 3 $-q_x/q_w$ from measurements with a sensor installed perpendicular to the direction of velocity; 4 $-q_x/q_w$ from measurements with a sensor installed obliquely; 5 $-q_r/q_x$.

The obtained profiles of mean velocity and temperature coincide with one another over most of the flow ($2r/d = 0 \div 0.8$). The values of the intensities of the velocity and temperature pulsations are in good agreement with the data of (^{3},^{4}).

The experiment showed that, for the selected small value of the heat flux, the intensities of the velocity pulsations and the magnitude of the correlation moment $\overline{uv}$ are practically the same for both isothermal and nonisothermal air flows. In the region $2r/d = 0 \div 0.9$, the distribution of the turbulent shear stress, referred to the dynamic velocity $-\overline{uv}/u_\tau^2$, agrees well with a straight line (Fig. 1). The forces of molecular friction in this region are insignificant, and the turbulent shear stress is equal to the total stress in the flow.

The measured correlation moments $\overline{vt}$ and $\overline{ut}$ were used to calculate, by formula (1), the densities of the heat fluxes in the radial direction (q_r) and along the pipe axis (q_x). At all points of the flow, the values of q_x exceed the values of q_r (Fig. 1).

Fig. 2

Figure 2: Fig. 2

Simultaneous measurement of the correlation moments and of the intensities of the pulsations makes it possible to calculate single-point correlation coefficients both between the components of the pulsating velocity and between the pulsations of velocity and temperature. The axial symmetry of the mean fields of velocity and temperature leads to the fact that the correlation coefficients between the components of the pulsating velocity (R_{uv}) and between the pulsations of temperature and radial velocity (R_{vt}) on the flow axis are equal to zero. At the same time, the correlation of the pulsations of the longitudinal velocity component with the temperature pulsations is high; the coefficient R_{ut} has a value close to -1 (Fig. 2).

With increasing distance from the pipe axis, the correlation coefficients R_{uv} and R_{vt} increase, and at distances equal to the macroscale of turbulence they take on approximately constant values; moreover, the value of R_{vt} is close to -1 and almost twice as large as R_{uv}. This means that transverse velocity fluctuations in most cases cause temperature fluctuations.

Fig. 2. Distribution of the correlation coefficients between the fluctuating quantities u, v, t and the distribution of Pr_T in the cross section of a circular pipe.
1–R_{ut}; 2–R_{vt}; 3–R_{uv} (our data); 4–R_{uv} (according to data from (3)); 5–$\varepsilon_\nu/\varepsilon_a$.

At a distance $2r/d > 0.95$, the correlation of velocity and temperature fluctuations decreases. At the wall, the velocity fluctuations are equal to zero, whereas temperature fluctuations penetrate into the wall (5). Apparently, at the channel wall R_{ut} and R_{vt} take on a zero value. The channel wall restricts transverse turbulent disturbances to a greater extent than longitudinal ones; therefore, at distances close to the wall ($2r/d > 0.95$), the correlation of the longitudinal and transverse components of the turbulent velocity fluctuation begins to weaken. The obtained values of R_{uv} agree well with the measurements of (3).

The measurements performed make it possible to compare the characteristics of turbulent transport of momentum and heat. The ratio of the coefficients of turbulent viscosity ε_ν and thermal diffusivity ε_a, i.e., the turbulent Prandtl number, can be expressed through correlation moments

$$\underset{\mathrm{T}}{\mathrm{Pr}} = \frac{\varepsilon_\nu}{\varepsilon_a} = \frac{\overline{uv}}{\overline{vt}}\frac{d\theta}{dU}. \tag{2}$$

As noted, the dimensionless temperature and velocity fields in the air flow are practically similar; therefore

$$\underset{\mathrm{T}}{\mathrm{Pr}} = \frac{\overline{uv}}{\overline{vt}} \frac{\theta_0 - \theta_w}{U_0},$$

where θ_0 and U_0 are the temperature and velocity on the pipe axis.

A certain discrepancy of the fields at $2r/d > 0.8$ was taken into account in calculating Pr_{T}. However, the correction introduced proved to be insignificant and did not produce noticeable changes in the character of the dependence $\varepsilon_\nu/\varepsilon_a$ (Fig. 2).

Throughout the entire cross section of the flow, the turbulent Prandtl number is less than unity; moreover, in the core of the flow the values of Pr_t remain approximately constant, $\simeq 0.6$. This means that turbulent heat transfer exceeds momentum transfer. Apparently, this is associated with the large-scale motion of turbulent disturbances. Large eddies, having a small velocity and a small amount of motion, are capable of carrying a great deal of heat. Near the pipe wall the role of large-scale transfer decreases; therefore the values ε_v and ε_a approach one another, and the turbulent Prandtl number tends toward unity.

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Note: Figure translations are in progress. See original paper for figures.