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EFFECT OF THERMAL NONSTATIONARITY ON THE STRUCTURE OF A TURBULENT FLOW

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UDC 536.24

Results of an experimental study on the effect of thermal stationarity on the flow structure are given.

In experiments on the study of nonstationary heat exchange in the initial section of a cylindrical channel, temperature profiles along the cross section of the boundary layer were measured. Measurements were carried out by means of a rack of thermocouples placed at a distance of 6.5 bores from the entrance to the channel. The diameter of the cylindrical channel was 45 mm, the length 8 bores, and the thickness of the channel wall 0.1 mm. The last ensures a Biot number $Bi \ll 1$, which allows us to assume the same temperature along the thickness of the wall.

The apparatus consists of an aerodynamic tube of open type with plasma heating of the working substance, which is air. Use of a plasmatron allows us to change the air temperature from its initial value to its final value within a short period of time (~0.07 sec).

To measure the channel wall temperature, we used "nonregulus" thermocouples. The thermoelectrodes (Chromel and Copel) were first flattened to a thickness of 0.015 mm for a length of 0.8 mm; they were then welded to the outer surface of the channel at a distance of 0.5 mm from each other.

The thermocouples of the rack were made from wires of Chromel and Alumel of diameter 0.065 mm. To prepare the working junctions, the ends of the wires were first flattened to a thickness of 0.015 mm, and then welded by means of a capacitor machine. Selection of thermocouples using the apparatus described in [1] enabled us to use thermocouples with very similar characteristics according to the time constant of the latter.

The thermocouples were stretched over a frame of asbestos cement, which was placed on the divided section of the tube. The working junctions of the thermocouples were arranged strictly in diametral planes, and their distance from the wall was determined with an optical microscope.

The signal from the thermocouples is fed to a K-20-21 loop oscillograph; as a result, on an oscillogram (Fig. 1), information appears on the time variations of the gas temperature over the channel cross section and also the temperatures of the wall in sections where the thermocouple rack is positioned. Thus, thermal nonstationarity is created owing to time-varying temperatures of the gas and the streamlined surface. The error in determining the temperature of the gas and the streamlined surface under nonstationary conditions does not exceed ±7% [2].

For an analysis of the experimental data, in the first place we considered the region where the gas temperature is constant ($dT_0^*/dt = 0$), and only the wall temperature changes ($dT_w/dt > 0$). This enabled us to show the effect, on the thermal characteristics, of the nonstationarity due to the time variation of the temperature of the streamlined surface.

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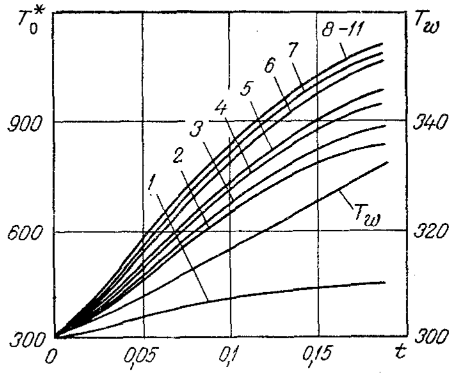

Fig. 1. Time variation of the temperature of the tube wall and of the gas over the cross section of the tube [1-11) T_0*]: 1) y = 0.1; 2) 0.15; 3) 0.5; 4) 1.0; 5) 1.5; 6) 2.5; 7) 4.5; 8) 6.0; 9) 9.0; 10) 15.0; 11) 22.5 mm.

A comparison of the results of the experimental data under the conditions being considered with the temperature profile corresponding to the 1/7 law, and also with the data of [3], enables us to ascertain that thermal nonstationarity of the form dT_w/dt = var within the limits of experimental accuracy does not distort the temperature field. The nonisothermicity, which has a considerable effect on the relative coefficient of heat transfer, practically does not deform the temperature field, and only leads to a redistribution of the density. By analogy with the effect of other forms of action on the deformation of the flow structure, the obtained results can be expected. Thus, a negative pressure gradient, which increases the coefficient of friction, at the same time weakly deforms the velocity profile.

The change in the thermal load ($dT_0^*/dt > 0$, $dT_w/dt > 0$) causes a deformation in the temperature field near the wall. The last point is explained by the fact that each thermal state of the system should correspond to its own temperature distribution. The time variation of the boundary or initial conditions leads to the formation of a new boundary layer in the interior region. The reaction from one of the boundary layers to the other also causes such effects as deformation of the temperature field and deviation of the heat-transfer coefficient from its value under steady-state conditions. The evolution of the temperature profile with respect to the steady state is determined to a great extent by the sign and magnitude of the parameter of thermal nonstationarity z_h [4]:

$$z_h = -\frac{\delta_h}{\mathrm{St}\, w_0 \psi_h (h_0^* - h_w)} \cdot \frac{d(h_0^* - h_w)}{dt}. \tag{1}$$

In the case being considered, when there is a simultaneous increase in the temperature of the gas and of the wall, the measurement results were treated in the form of the function

$$\vartheta = \frac{T - T_w}{T_0^* - T_w} = f(y/\delta_h^{**}). \tag{2}$$

The energy loss thickness here was calculated with account of the nonisothermicity, leading to a redistribution of the density.

Figure 2 shows experimental data of the temperature profiles for increasing times, which corresponds to various values of the parameter of thermal nonstationarity z_h. We see that the filling of the profiles corresponds to values of the parameter of thermal nonstationarity that are large in absolute value. In this figure the lines denote profiles calculated according to the equations of [5] for values of z_h corresponding to the experimental data. The factor of nonisothermicity in the given case was roughly the same ($T_w/T_0^* \sim 0.4$). In this case, the nature of the curves differs considerably from that which holds under conditions of action of isothermicity [3], where the lines are situated approximately parallel to each other, and their separation is small over a wide range of variation of the temperature factor ψ_h.

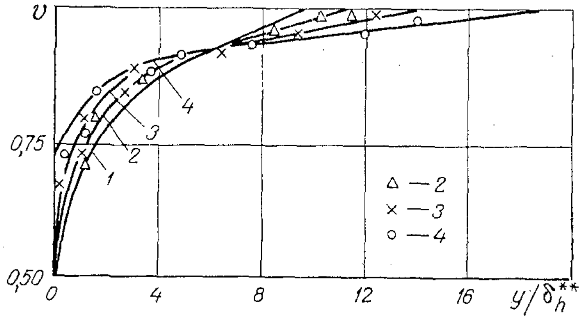

Fig. 2. The function $\vartheta = f(y/\delta_h^{**})$ (the curve represents the calculation): 1) according to the 1/7 law; 2) $z_h = -1.13$; 3) $z_h = -3.5$; 4) $z_h = -9.7$; (the points represent the experiment): 2) t = 0.035 sec, $z_h = -1.13$; 3) 0.075 sec and −3.5; 4) 0.125 sec and −9.7.

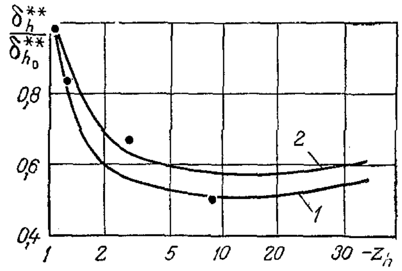

Fig. 3. Effect of thermal nonstationarity on the relative energy loss thickness (curves — calculation; points — experiment): 1) $R^{**} = 10^3$; 2) $2 \cdot 10^3$;

In Fig. 3, the relative energy loss thickness is represented as a function of the parameter of thermal nonstationarity. As is to be expected, the energy loss thickness decreases with increasing value of $|-z_h|$; this change, however, is small — of the order of 45% for $z_h = -10$ and $R_h^{**} = 10^3$.

The change in thickness of the displacement is mainly determined by the nature of the evolution of the profile of the tangential stresses, and is determined to a lesser degree by a temperature factor. Calculations carried out in [6] show that with change in the quantity ψ_h from 1 to 0.4 for $z_h = 1$ the relative energy loss thickness is increased by 14%; at the same time, the increase in the parameter of thermal nonstationarity up to $|-10|$ leads to a decrease in the energy loss thickness to almost one half of its value.

NOTATION

T_0^*, gas temperature; T_w, wall temperature; ϑ, dimensionless temperature; t, time; z_h, parameter of nonstationarity; y, distance from the wall; δ_h, thickness of the thermal boundary layer; δ_h^{**}, energy loss thickness; ψ_h, temperature factor; R_h^{**}, characteristic Reynolds number of the thermal boundary layer.

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CLOSURE OF EQUATIONS OF TURBULENT FLOWS WITH TRANSVERSE SHEAR

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Dependences are suggested for calculating rates of diffusion transport of kinetic turbulent energy and of scalar turbulence scale.

The description of turbulent effects by solving the exact Navier–Stokes equations encounters great difficulties at the present stage of development of fast computers. To solve practical engineering problems it is sufficient to calculate the average parameters of turbulent motion of a liquid and of heat and mass exchange. However, the equations of the averaged turbulent motion are not closed.

In calculating turbulent flows with account of its "prehistory," we use the system of equations:

$$\frac{\partial U_i}{\partial \tau} + U_j \frac{\partial U_i}{\partial x_j} = X_i - \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j} - \langle u_i u_j \rangle\right), \quad (1)$$

$$\frac{\partial U_i}{\partial x_i} = 0, \quad (2)$$

$$\frac{\partial E}{\partial \tau} + U_k \frac{\partial E}{\partial x_k} = -\frac{\partial}{\partial x_k}\left[\langle u_k E' \rangle + \left\langle \frac{p}{\rho} u_k \right\rangle\right] - \langle u_i u_k \rangle \frac{\partial U_i}{\partial x_k} - \nu \left\langle \left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right) \frac{\partial u_i}{\partial x_k} \right\rangle, \quad (3)$$

in which the unknowns are the normal and tangential Reynolds stresses $\langle u_i u_j \rangle$, the rate of diffusion transport of kinetic energy turbulence $D_E = \frac{\partial}{\partial x_k}\left[\langle u_k E' \rangle + \left\langle \frac{p}{\rho} u_k \right\rangle\right]$, and the rate of its dissipation $D_E = \nu \left\langle \left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right) \frac{\partial u_i}{\partial x_k} \right\rangle \simeq \left\langle \nu \left(\frac{\partial u_i}{\partial x_k}\right)^2 \right\rangle = \varepsilon.$

Analysis of the available closure models of Eq. (3) showed that approximating D_E by the form

$$D_E = \frac{\partial}{\partial x_k}\left(-\frac{\nu_\text{т}}{\sigma} \frac{\partial E}{\partial x_k}\right) \quad (4)$$

does not provide satisfactory agreement with experimental data [1, 2] (Fig. 1). This is explained by the fact that the available models do not take into account transport processes under the action of pressure pulsations [3]. Approximating the quantity ε by the Rotta equations [4] for $Re_E \gg 1$

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