10. B. V. Dzyubenko and L. A. Ashmantas, "Mutual effect of temperature and velocity fields in a bundle of spiral tubes," in: Interinstitute Collection of Scientific Transactions: Current Problems of Hydrodynamics and Heat Transfer in Elements of Power Plants and Cryogenic Equipment [in Russian], Vol. 13, Izd. VZMI, Moscow (1984), pp. 80-86.
11. B. V. Dzyubenko, M. D. Segal', L. A. Ashmantas, and P. A. Urbonas, "Nonsteady mixing of a heat carrier in a heat exchanger with spiral tubes," Izv. Akad. Nauk SSSR, Energ. Transp., No. 3, 125-133 (1983).

CONVECTIVE HEAT TRANSFER IN BOUNDED-VOLUME CHAMBERS OF VARIOUS CONFIGURATIONS

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The results are given from a comprehensive study of the heat transfer, aerodynamics, and combustion processes in regions of separation, reattachment, and subsequent evolution of flow in channels and chambers of various configurations.

The investigation of one of the most widespread techniques of combustion stabilization, namely by rational organization of the recirculation zones, presents a complex but timely theoretical and experimental problem. To determine the heat-transfer laws in bounded volumes we have carried out comprehensive studies of the aerodynamics (Fig. 1), heat transfer (Fig. 2), and combustion process (Fig. 3) in chambers of various configurations. The results can be analyzed to solve problems encountered in flow with recirculation zones and to show that the combustion and heat transfer in industrial plants of various configurations are intimately related to the aerodynamic and turbulent structure of the flow. We have investigated flows in cylindrical chambers in the form of sudden plane expansions (one-sided and two-sided steps with exit flow from one and three slots).

An important consequence of flow reattachment is a strong variation of the flow structure in the form of decay and scale reduction of the vortices. In the downstream zone from the reattachment point a sharply defined boundary is preserved as a result of the flow perturbation during separation and interaction with the separation zone. The combustion process is characterized by the correlation of the fluctuations $\overline{v't'}$.

It is important to note that the intensity of the velocity fluctuations varies insignificantly near the walls of chambers of different configurations in all operating regimes in comparison with its variation at the separation boundary; this fact further underscores the stability of wall flow against perturbations.

We have established the similarity of the turbulent transfer characteristics. The greatest structural changes and deviations from the uniform-flow heat-transfer laws for the investigated types of chambers take place immediately after the flow reattachment point in the zone for a symmetrical sudden plane expansion $\bar{x} = x/d_0{}^h = 18\text{-}20$, for flow from three slots $\bar{x} = x/d_0{}^h = 42\text{-}45$, and for cylindrical expansions $\bar{x} = x/d_0{}^h = 2.5\text{-}6$.

The equilibrium state of the flow sets in nonmonotonically, and the amplification of turbulent energy dissipation in the separation zone promotes an increase in heat transfer, as shown in Fig. 3. The maxima for $\overline{U'V'}$ (see [2]) and $\overline{v't'}$ practically coincide and are explained by the influence of the previous history of interaction of the flow with the separation zone. The following relations are recommended for engineering calculations (in the case of plane and axisymmetrical channels; Fig. 4, curves 1 and 2):

$$\log(\overline{v't'})\,m = x\log\alpha. \tag{1}$$

An analysis of the results has led to a number of conclusions characterizing the fundamental laws of flow in plane and cylindrical abrupt expansions prior to the onset of self-similarity for Re > 1000 for the axisymmetrical case and for Re $\le$ 1000 in the self-similar regime in the plane case.

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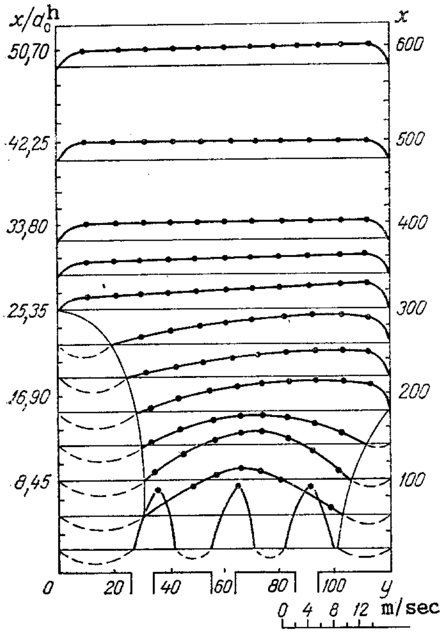

Fig. 1

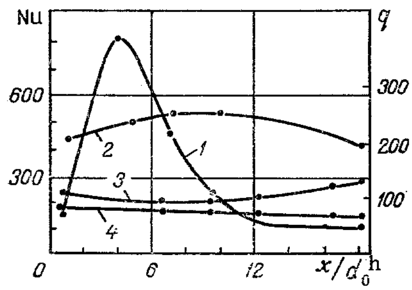

Fig. 2

Fig. 1. Velocity field in a plane channel, $H/h = 6$, $Re = 5 \cdot 10^3$ (flow from three slots). The dashed parts of the curves represent the velocities in the recirculation zone.

Fig. 2. Graphs of the functions: 1) $Nu = f(x/d_0^h)$; 2) $q = f(\bar{x})$; 3) $T_f = f(\bar{x})$; 4) $T_w = f(\bar{x})$ for $R_0^h = 76 \cdot 10^3$ (flow from three slots).

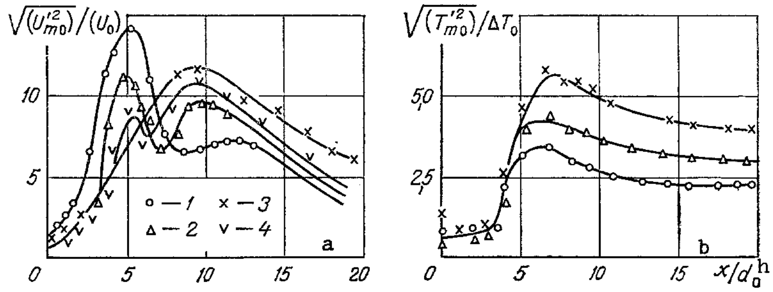

Fig. 3. Graphs of: a) $\sqrt{(U'^2_{m0})}/U_0$, %; b) $\sqrt{(T'^2_{m0})}/\Delta T_0$, %: 1) sudden cylindrical expansion; 2) plane discontinuity in the form of a step; 3) plane symmetrical flow from one slot; 4) the same, from three slots.

The length of the initial section is equal to five slot diameters for plane expansions ($\ell_e = 5d_0^h$), and $\ell_e = d_0^h$ in the case of cylindrical chambers.

In flow from three slots, the length of the initial section is preserved only over the first few diameters $\ell_e = 2d_0^h$ for a uniform entry velocity v_{iav} = const, and $\ell_e \simeq d_0^h$ for a variable entry velocity v_{iav} = var. Then a transition section is observed up to the cross section where the jet comes into contact with the channel walls. In this section, mainly heat and mass transfer takes place between the resulting common transition flow and the recirculation zones. It must be noted that, beginning with the third diameter ($x = 3d_0^h$), the emerging three jets for v_{iav} = const blend into a common transition flow, whereas for v_{iav} = var this happens at the fifth diameter $x = 5d_0^h$ (see Fig. 1). At a distance of roughly $L = 50d_0^h$ a steady-state velocity profile appears for various conditions of entry into channels of complex configuration.

The Coanda effect and the presence of recirculation zones are well observed according to the measured fields P_w. Flow reattachment occurs as a point where the tapering of the pressures terminates. The long and short separation zones are preserved in all regimes: $\ell_L = (24\text{-}45)d_0^h$, $\ell_S = (16\text{-}17)d_0^h$.

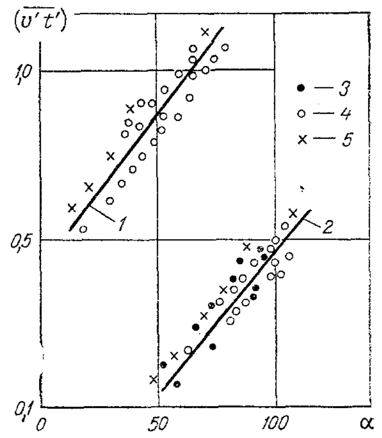

Fig. 4. Graph of $\overline{v't'}_m$ vs coefficient α. 1) $\bar{x} \leq 1.5$, before flow reattachment; 2) $\bar{x} \geq 1.5$, after reattachment; 3) two-sided step expansion; 4) single step; 5) axisymmetrical chamber.

A bounded jet differs substantially from a free jet from the energy point of view. The expansion of the jet in a bounded space is accompanied by large mechanical energy losses. With a sudden expansion of the flow, the bulk of the mechanical energy is converted as a result of the formation of vortex surfaces of demarcation between the transition jet and the reverse-flow zone. Energy dissipation in this case is associated with the decay of large vortices into small-scale vortices. A large turbulence scale from 0.68 to 1.0 mm prevails at a distance y/d_0^h = 0-0.4 from the jet axis. The Coanda effect is observed for Re $\geq$ 1000 in plane chambers and for Re $\leq$ 1000 in cylindrical chambers.

Recirculation zones begin immediately in the entrant cross section due to the presence of the end wall. The flow velocities in these zones are small and depend both on the degree of expansion and on the Reynolds number. The results of computer numerical calculations and experiments are compared in [1].

The velocity vectors are small near the jet axis and are a maximum on the vortex surfaces of demarcation between the jet and the recirculation zone. They attain 15-23% of the average flow velocity in this case.

After the cross section where the expanded jet touches the channel walls and where the recirculation terminates, the velocity profiles in the channel cross sections begin to equalize.

A definite degree of expansion exists such that the vortex zone becomes unstable. An analysis of visualized flow has shown that a plane jet acquires an extremely unstable behavior at degrees of expansion H/h $\geq$ 7, jumping spontaneously from one wall of the channel to the other.

In regard to temperature fluctuations, an increase in the parameter $\bar{x}$ causes $\overline{v't'}$ to decrease. The position of the maximum of the $\overline{v't'}$ curve is practically independent of $\omega = T_2/T_1$ here (see Figs. 3 and 4).

The heat transfer associated with the flow of a jet confined by channel walls has been investigated on the apparatus described in [2], and the results of our experimental study of the aerodynamics and heat transfer in the regions of separation, reattachment, and subsequent evolution of the flow in channels and combustion chambers of various configurations enable us to exhibit the flow laws. The Reynolds number was varied from 10^2 to $2 \cdot 10^5$ in the experiments, and the degree of expansion H/h was varied from 3 to 16. The heat-transfer rate was found to be intimately related to the aerodynamics and turbulent structure of the flow. With an increase in the distance from the end walls of the sudden expansion, the values of the heat-transfer coefficient and the number Nu increase, attaining a maximum in the cross section corresponding to the flow reattachment point, and then decrease like $\overline{U'V'}$. The heat-transfer rates at the two reattachment points of the long and short separation zones differ.

The Nusselt number in the separation region before the reattachment point for all types of chambers is well correlated by the empirical equation

$$\mathrm{Nu} = c\,(x/d_0^h)^k \mathrm{Re}^m, \qquad (2)$$

for the long separation zone m = 0.536, c = 0.037, k = 0.28; for the short zone c = 0.03 in the case of a plane jet, and for an axisymmetrical jet c = 0.4, m = 0.7.

For the region after the reattachment site

$$\mathrm{Nu} = c\,(x/d_0^{\mathrm{h}})^{-1}\,\mathrm{Re}. \tag{3}$$

The curves of the excess temperatures in dimensionless coördinates in different cross sections of the initial (entrant) length of the jet merge into a single universal curve. The isotherms of the dimensionless temperatures for all the investigated types of chambers are straight radial lines converging at the pole of the jet in the core and at the nozzle orifice in the boundary layer.

The assumption of additivity of the radiant and convective heat-transfer components can be used to determine the total heat transfer [2] to the walls of a combustion chamber in the first approximation.

LITERATURE CITED

1. V. I. Korobko, É. M. Malaya, and V. K. Shashmin, "Evolution of viscous incompressible fluid flow in a plane channel," Inzh.-Fiz. Zh., 35, No. 6, 1078-1083 (1978).
2. É. M. Malaya et al., "Heat transfer in the flow of a jet bounded by channel walls," in: Heat and Mass Transfer-VI [in Russian], Vol. 1, Part 1, ITMO AN Belorussian SSR, Minsk (1980), pp. 138-142.

SPECTRAL CHARACTERISTICS OF TURBULENCE IN ROTATING CHANNELS

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Spectral characteristics of turbulent flow in rotating channels are considered with allowance for the pulsating Coriolis forces and thermal heterogeneity of the flow.

As a fluid flows over a rotor of a turbomachine, the volume forces due to the rotation and curvature of the blade surfaces affect the character of the turbulent flow at the sides of condensation and rarefaction of the interblade channel.

Heterogeneity of the thermal and density fields leads to the appearance of Archimedian forces, which can intensify or reduce the turbulence. Similar flows in the atmosphere and ocean are often called flows with unstable and stable stratification. From now on, this terminology will also be used to characterize fluid flow in the rotating channel.

Let us consider the balance equation for the turbulent energy [1] of the flow of an incompressible fluid in a rotating radial channel. We direct the x axis along the channel surface, the y axis, in a perpendicular dirrection, into the flow, and we place the z axis on the axis of rotation:

$$\varepsilon = \langle u'_\alpha X'_\alpha \rangle - \langle u'_\alpha u'_\beta \rangle \frac{\partial u_\beta}{\partial x_\alpha} \mp \frac{2\omega u_\beta}{T} \alpha_T K \frac{\partial T}{\partial x_\alpha}, \tag{1}$$

where X'_α are the pulsations of the Coriolis forces, equal to $2\omega u'_\beta$. The upper sign designates the flow on the inlet side of the channel, while the lower sign designates the flow on the outlet side [2].

Writing the velocity correlation as

$$\langle u'v' \rangle = -K \frac{\partial u}{\partial y}, \tag{2}$$

we obtain

$$\varepsilon = K \left(\frac{\partial u}{\partial y} \right)^2 - 4\omega K \frac{\partial u}{\partial y} \mp \frac{2\omega u}{T} \alpha_T K \frac{\partial T}{\partial y}. \tag{3}$$

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