EFFECTIVENESS OF MIXING COAXIAL FLOWS SWIRLED IN OPPOSITE DIRECTIONS

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The mixing of coaxial turbulent flows swirled in opposite directions is experimentally studied. The effectiveness of this mixing is compared with mixing after an agitating grid.

The development of modern mixing apparatus requires a search for new ways of organizing the mixing of gases. Much attention is being given to methods based on the use of swirled flows, which can significantly intensify turbulent mixing. A considerable body of experimental data, along with several theoretical results [1], has now been accumulated concerning heat and mass transfer and fluid resistance in flows in pipes and other conduits. Most of these researches pertain to flows swirled in the same direction. The present work examines turbulent flow in an annular channel when the two flows entering the channel are swirled in opposite directions.

1. The flows were studied on a unit illustrated in Fig. 1. An air flow was created by a centrifugal fan 1 installed at the channel outlet. The flow was swirled by means of tangential swirl vanes 2. The air then traveled from the vanes into constant-height radial-axial channels 3 and thence into the working part 4, which was an annular channel with an inside diameter of 0.22 m, outside diameter of 0.34 m, and length of 0.5 m. The flows were separated at the working-channel inlet by an edge 5 1.2 mm thick. The ratio of the areas of the outer and inner annular channels was roughly equal to two.

The experiments involved measurement of the angle of the flow direction relative to the channel axis θ, the total and static pressure p_* and p, the axial v_z and tangential v_θ components of the mean velocity, and the turbulent pulsations of velocity v' in the direction of the mean-velocity vector **v**. It was assumed that the radial component of the mean velocity was small compared to its other components. The measurements were made with cylindrical three-point head meters and hot-wire anemometers. The site of installation of these instruments is indicated in Fig. 1 by dot—dash lines (in Fig. 1, $l \approx 100$ mm).

The experiments showed good reproducibility of the flow pattern. The peripheral nonuniformity did not exceed 5%. The accuracy of the measurements of the axial and tangential velocity components was also roughly 5%.

The measurements were made with the swirl vanes installed at angles of 30/—60° and 30/—30° in the inner and outer contours, respectively. For the sake of comparison, we also conducted experiments with unidirectional swirling of the flows: 0/—60° and 30/30°. The tests showed that turbulent exchange is more intensive in the flow with opposed swirling. This is expressed in the greater magnitude of the turbulent pulsations generated by the flow and the more rapid levelling out of the velocity profiles along the channel.

As an example, Fig. 2 shows the results of measurements of the mean axial and tangential components of velocity and the pulsative component v' with installation of the swirl vanes in the inner and outer contours at angles $\theta_1 = 30$ and $\theta_2 = -60°$, respectively. The mean angles of twist of the flows at the working-channel inlet were 10-15% greater in this case. All of the quantities represented in Fig. 2 pertain to the mean-flow-rate velocity of the flow, $v_0 = 26$ m/sec. This corresponds to a Reynolds number $\mathrm{Re} = v_0 H/\nu \approx 10^5$, where H is the width of the annular gap (points 1, 2, and 3 in Fig. 2 correspond to values of z/H = 0, 1.67, and 3.34; y is the distance from the inside wall of the channel in fractions of H).

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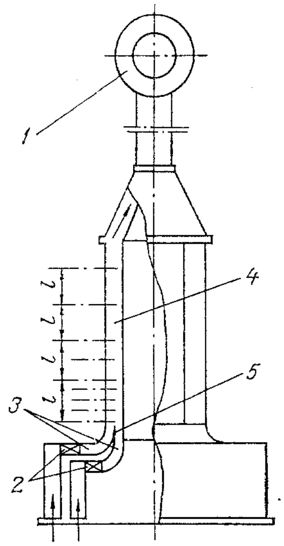

Fig. 1. Diagram of experimental unit.

It is apparent from Fig. 2 that the flows are nearly mixed at a distance of roughly 3.5H from the inlet. This near mixing is indicated by the smoothing out of the axial component profile and the appreciable decay of the tangential velocity component. Turbulent pulsations are generated close to the interface of the two incoming flows, which is explained by the presence of a radial gradient in the tangential component of the mean velocity. This generation is especially intense in the initial section ($z \leqslant 2H$). The turbulent pulsations in velocity reach a maximum at a distance $z_m \simeq 2.5H$ from the tip of the separating edge and account for about 20% of the maximum difference in the tangential velocity component. This percentage is somewhat higher than for unswirled streams [2].

In the case 30/—30°, $z_m \simeq 4H$ and the maximum value of the turbulent pulsations amounts to $v_m/v_0 \simeq 0.4$, which is evidence of a reduction in the rate of turbulent exchange compared to the previous case.

2. The rate of turbulent exchange will be judged from the rate of increase in the thickness of the mixing layer. As is known [2], in the companion movement of unswirled flows, the angle of thickening of the mixing layer

$$\frac{db}{dz} = c_1 \frac{|v_{z,1} - v_{z,2}|}{|v_{z,1}| + |v_{z,2}|} < c_1, \tag{1}$$

where b is the width of the mixing zone and $c_1 \simeq 0.22$ for the main section of the stream and 0.27 for the initial section.

In the case of oppositely swirled flows with the same assumptions as were made in [2] in deriving (1), i.e., assuming that the rate of thickening of the mixing layer is proportional to the pulsative component of the transverse velocity — which is in turn proportional to the velocity gradient — we obtain

$$\frac{db}{dz} = c \frac{|v_{\theta,2}| + |v_{\theta,1}|}{2 v_0}, \tag{2}$$

where $v_{\theta,1}$ and $v_{\theta,2}$ are the maximum values of the tangential components of the mean velocity in the inner and outer flows, respectively. Equation (2) corresponds to the assumption that, when the flows are swirled in opposite directions, the angle of expansion of the mixing layer is determined by the radial gradient of the tangential component of the mean velocity.

In analyzing the empirical data, for the width of the mixing layer we took the distance between the points at which the tangential component of velocity was 90% of its maximum value in each of the flows in the chosen section. Also, we assumed that

$$(|v_{\theta,2}| + |v_{\theta,1}|)/v_0 \simeq \operatorname{tg}\theta_2 + \operatorname{tg}\theta_1, \tag{3}$$

where θ_1 and θ_2 are the maximum angles of twist in the inner and outer flows.

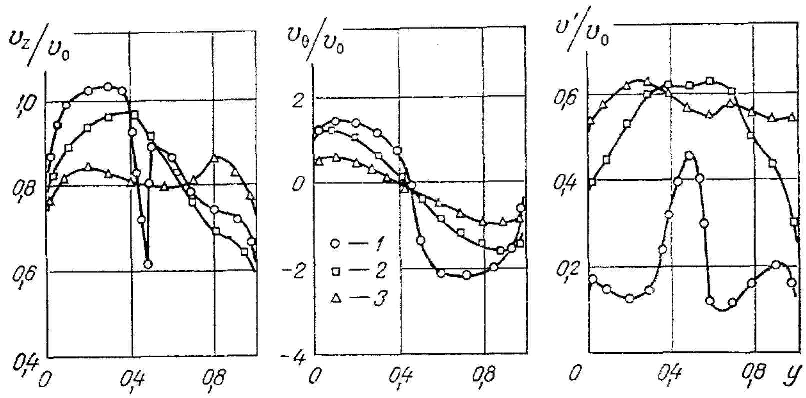

Fig. 2. Experimental profiles of axial v_z, tangential v_θ, and pulsative v' components of velocity in the sections z/H = 0, 1.67, and 3.34. v_0 = 26 m/sec, Re = 10^5.

Calculations of the coefficient c from the empirical data showed that, with allowance for the accuracy of the experiments, the value of c may be assumed to be the same as for companion unswirled flows, i.e., c ≈ 0.3.

Thus, an increase in the twist in opposite directions intensifies turbulent exchange in the flow.

3. We will use the following quantity to evaluate the loss in the channel:

$$\zeta = \frac{E(0) - E(z)}{E(0)}, \tag{4}$$

where

$$E(z) = \int_{r_1}^{r_2} v_z \left(p + \frac{\rho V^2}{2} + k\right) r dr,$$

which represents the relative change in the total energy of the flow on the channel portion from the inlet to the section with the coordinate z, i.e., the static pressure plus the kinetic energy associated with the averaged and pulsative motions. Here, k is the eddy kinetic energy of a unit mass of the gas.

Calculation with Eq. (4) for the case 30/–60° gives a value of the loss coefficient ζ equal to 0.55% at z = 3.4H. The losses along the channel are distributed approximately linearly in this case.

Let us examine the contribution of each of the terms in the integrand to the losses. For this, we will use the following equation of momenta in the direction of the z axis:

$$\int_{z_1}^{z_2} (r_2\tau_{rz,2} - r_1\tau_{rz,1})\, dz = \left[\int_{r_1}^{r_2} (p + \rho v_z^2 + \rho \langle v_z'^2 \rangle)\, r dr\right]_{z_1} - \left[\int_{r_1}^{r_2} (p + \rho v_z^2 + \rho \langle v_z'^2 \rangle)\, r dr\right]_{z_2}, \tag{5}$$

where $\tau_{rz,1}$ and $\tau_{rz,2}$ are the axial components of the friction stresses on the inner and outer walls, respectively; v_z' is the pulsative component of velocity in the direction of the longitudinal z axis.

The experimental data show that the changes in the quantities ρv_z^2 and $\rho\langle v_z'^2\rangle$ are usually small compared to the first terms. Thus, in accordance with (5), the change in static pressure in the given section is determined mainly by the work of frictional forces on the solid boundaries. If there is no substantial change in the profiles of the tangential velocity component v_θ in the flow – as is usually the case for unidirectionally swirled flows — then the losses in the channel will be determined by the changes in static pressure in the different sections. This case was investigated in [3], where it was shown that the loss coefficient can be calculated from a single relation for both swirled and unswirled flows.

As the experiments showed, in the case of oppositely swirled flows the change in static pressure along the channel is often negligible compared to the corresponding changes in v_θ^2. Thus, in such flows nearly all of the losses are connected with changes in the tangential component of velocity occurring as a result of turbulent exchange in the radial direction. It should be noted that the losses associated with changes in the other quantities did not exceed 10% of these losses in the experiments reported in this article.

Thus, when the flows are swirled in opposite directions, both the intensification of turbulent exchange and the increase in losses during mixing are associated with the same characteristic — the radial gradient of the tangential velocity component.

4. To determine the expediency of employing opposite swirling of flows, it is necessary to compare this method of mixing with other methods — such as mixing after an agitating grid.

Let there be two identical annular channels, one of which contains an agitating grid with a permeability equal to α. The other channel contains a device providing for swirling of the flow at angles of $+\theta_1/-\theta_2$ and having a permeability equal to α_s ($\alpha = F_1/F$, F_1 is the total area of the openings, while F is the area of the channel cross section). Both the grid and the swirler, shown schematically in Fig. 3, will be considered ideal, i.e., losses to friction in the grid and swirler will be ignored.

The mixing of the flows can be judged from the changes in the velocity profiles. Let there be a stepped profile for longitudinal velocity at the inlet, with the steps being small enough so that the agitation of the flows is determined by the design parameters of the corresponding devices (grid and swirler) rather than by the initial distributions of the characteristics of the flow. Also, let the mean-flow-rate velocities in each of the channels be identical. We will assume that the static pressure profile at the inlet is uniform and that the level of the turbulent pulsations is negligibly low compared to their level generated by each of the devices in question. All of these conditions are in keeping with the experiments in Part 1. We will also assume that turbulent exchange between the flows begins on the main section in the wake beyond the grid and immediately after the swirler (see Fig. 3). Allowing for the fact that the turbulence in the wake after the grid always degenerates and that the velocity of the fluid in the counterflow is always less than $\sim 0.5v_0$, we have the following estimate for the width of the mixing layer:

$$b_z = \frac{db}{dz} < c_1. \tag{6}$$

As shown earlier, for oppositely swirled flows:

$$b_{z,s} = \frac{db_s}{dz} \geqslant \frac{c_1}{2} (\mathrm{tg}\,\theta_1 + \mathrm{tg}\,\theta_2). \tag{7}$$

Despite the fact that Eq. (4) most fully characterizes the losses in a swirled flow, for the sake of comparison it is more convenient to use the customary expression for the loss coefficient. In accordance with [4], the losses in the grid on section 0—1 can be evaluated thus

$$\xi = \frac{\Delta p_*}{0.5\,\rho v_z^2} \simeq \left(\frac{1-\alpha}{\alpha}\right)^2. \tag{8}$$

The losses in the swirled flow are

$$\xi_s \simeq \left(\frac{1-\alpha_s}{\alpha_s}\right)^2 + \mathrm{tg}^2\,\theta, \tag{9}$$

where θ corresponds to $\min(M_1, M_2)$, with M_1 and M_2 being the moments of momenta of the inner and outer flows beyond the swirler.

Since the length of the section over which complete mixing of the flows occurs is inversely proportional to the angle of expansion of the mixing layer ($L \sim 1/b_z$; $L_s \sim 1/b_{z,s}$), then, with equality of the losses in both systems ($\xi = \xi_s$) and considering that the blockage for swirl vanes $1 - \alpha_s$ is usually considerably less than the corresponding value for agitating grids $1 - \alpha$, from (6) and (9) we obtain

$$\frac{L}{L_s} > 0{,}5\,(\mathrm{tg}\,\theta_1 + \mathrm{tg}\,\theta_2) > \frac{1-\alpha}{\alpha}.$$

Thus $L > L_s$ at $\alpha < 0.5$, i.e., swirling the flow in opposite directions is more efficient in the region of $\alpha < 0.5$.

5. Let us compare the efficiency of the above devices from the point of view of generation of the maximum eddy kinetic energy k_m.

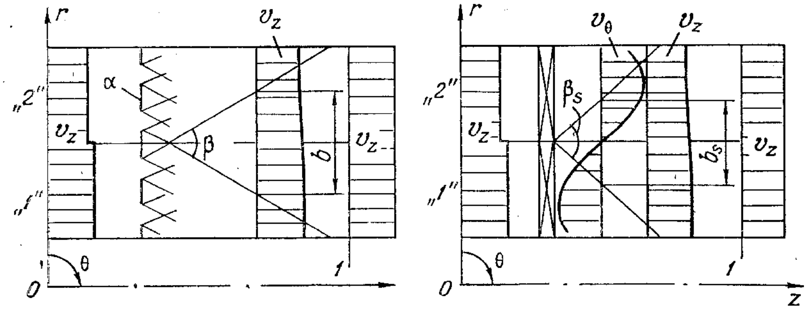

Fig. 3. Mixing schemes.

The following estimates are valid:

$$k_m \simeq c' \frac{v_z^2}{\alpha^2}, \tag{10}$$

$$k_{m,s} \simeq c_s (|v_{\theta,1}| + |v_{\theta,2}|)^2, \tag{11}$$

where c' and c_s are constant coefficients. It can be assumed that $c' \approx c_s \approx 0.04$. Then, with $\xi = \xi_s$, i.e., with $\tan\theta = (1 - \alpha)/\alpha$, from (8)-(11) we obtain

$$\frac{k_m}{k_{m,s}} < \frac{1}{4(1-\alpha)^2}.$$

Thus, with $\theta > 45°$ ($\alpha < 0.5$) and identical losses, the maximum eddy kinetic energy is higher in the swirled flow.

The above estimates testify to the expediency of using oppositely swirled flows to organize mixing processes.

NOTATION

z, r, θ, cylindrical coordinate system; r_1, r_2, inside and outside radius of annular channel; $H = r_2 - r_1$, radial gap in annular channel; $y_r = (r - r_1)/H$, dimensionless radial coordinate; $V(v_z, v_r, v_\theta)$, mean velocity vector; v', v_z, pulsative components of velocity in the direction of the mean velocity vector and in the axial direction; p_*, p, total and static pressure; ζ, ξ, loss coefficients.

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