SOME FEATURES OF THE HYDRODYNAMICS OF TURBULENT AIR STREAMS TWISTED BY A VANE SWIRLER

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The structure of an isothermal air stream twisted by a vane swirler with a central body mounted at the entrance to a tube is examined. The effect of the structural parameters of the swirler on the hydrodynamics of the stream is analyzed.

The twisting of a stream is one effective means of hydrodynamic action on the stream for the purpose of intensifying the processes of heat and mass exchange taking place in channels of different profiles. The variety of the procedures for twisting and their constructive design [1] require an individual approach and a detailed study of the structure of the twisted stream which completely determines the effects indicated above. Moreover, it is impossible to conduct a theoretical analysis without knowing the structure of such a stream.

We studied experimentally the features of the hydrodynamics of isothermal turbulent air streams, twisted by a vane swirler with a central body, in the initial section of a tube in the range of Re_d from $4.5 \cdot 10^4$ to $1.5 \cdot 10^5$. A diagram of the experimental apparatus, the structural parameters of the swirler, the method of conducting the experiments, and the initial data on the structure of a twisted stream are presented in [2].

The experiments were conducted on straight and profiled vanes; the profiling made it possible to obtain a power function for the variation in construction angle of the vane at the exit from the swirler [2]

$$\operatorname{tg}\varphi = \left(\frac{R}{r}\right)^n \operatorname{tg}\varphi_s.$$

It has been noted earlier [2] that a zone of potential flow exists outside the boundary layer in which the tangential velocity component varies according to the function $w_\varphi r = A(x)$, while below the potential zone the velocity profile w_φ is satisfactorily described by a function of the type

$$\frac{w_\varphi}{w_{\varphi_{max}}} = \left(2\frac{r r_{\varphi_{max}}}{r^2 + r^2_{\varphi_{max}}}\right)^k. \qquad (1)$$

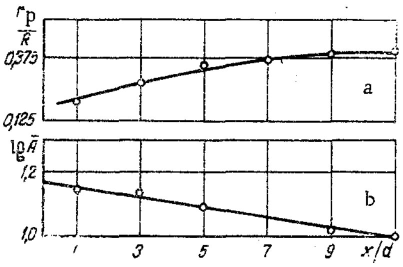

Fig. 1. Variation in width of potential zone (a) and function $\bar{A}$ (b) along length of tube: $\varphi_s = 60°$, $n = 3$; $Re_d = 1.07 \cdot 10^5$; $\bar{A} = 1.47 \exp(-0.0345\, x/d)$.

The experimental data presented in Fig. 1 for one of the swirlers show that with increasing distance from the swirler the width of the potential zone increases while A(x) decreases.

Let us examine in more detail some relationships of the variation in the tangential and axial velocity components in a twisted stream.

The tangential velocity varies in a curve with a maximum, and the radius of the surface of maximum velocity always lies in the zone

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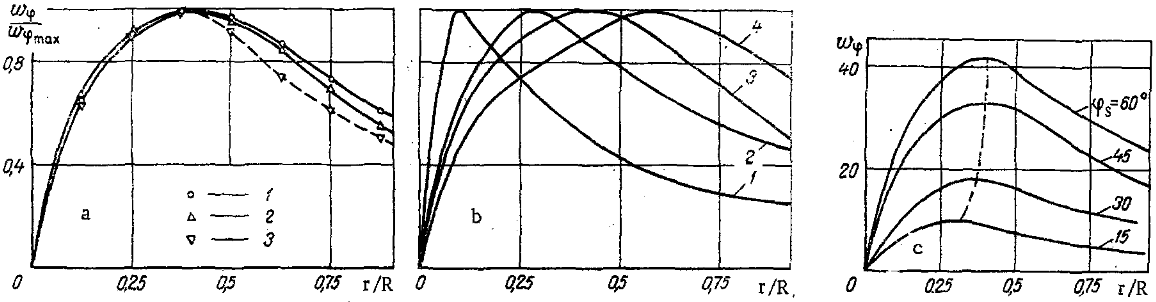

Fig. 2. Variation in tangential velocity component of motion over radius of channel as a function of Re_d (a), of n (b), and of φ_s(c). For a: 1) $Re_d = 1.6 \cdot 10^5$; 2) $1.07 \cdot 10^5$; 3) $4.51 \cdot 10^4$; $\varphi_s = 45°$; n = 3; x/d = 7; for b: 1) n = −1; 2) 1; 3) 3; 4) straight vanes; $\varphi_s = 45°$; x/d = 7; $Re_d = 1.07 \cdot 10^5$; for c) n = 3; $Re_d = 1.07 \cdot 10^5$; x/d = 7. w_φ, m/sec.

TABLE 1. Values of A and B

Coefficient	$\varphi_s = 45°$ $n = -1$	$\varphi_s = 45°$ $n = 0$	$\varphi_s = 45°$ $n = 3$	$\varphi_s = 15°$ $n = 3$	$\varphi_s = 60°$ $n = 3$	$\varphi_s = 45°$ straight vanes
A	0,155	0.36	0,52	0,52	0,51	0,64
B	0,005	−0,01	−0,023	−0,023	0,007	0

of rarefaction (Fig. 2). The value of $r_{\varphi_{max}}$ depends weakly on the twist angle φ_s and the number Re_d and very essentially on the exponent n in the twist function. With an increase in n at φ_s = idem the position of the maximum shifts closer to the wall of the tube. Consequently, n is one of the important factors affecting the position of the radius of maximum tangential velocity. At the same time we note that with an increase in φ_s (n = idem) the absolute value of $w_{\varphi_{max}}$ increases markedly whereas it is almost unchanged upon a change in n (φ_s = idem).

Since the self-similarity of the w_φ profile must be preserved for swirlers having the same values of $\bar{r}_{\varphi_{max}}$ one can conclude that the exponent k in Eq. (1) must depend on n and very weakly on Re_d and φ_s. Therefore the values of k given in [2] for swirlers with φ_s = 15, 30, and 45° (n = 3) differ little from one another. It can be concluded from this that the values of k obtained can be used for swirlers having any value of φ_s at a fixed value of n.

The equation of the surface $\bar{r}_{\varphi_{max}}$ is satisfactorily approximated by the linear equation

$$\bar{r}_{\varphi_{max}} = A + B(x/d), \tag{2}$$

in which the values of A and B for several swirlers are presented in Table 1.

Since $r_{\varphi_{max}} \neq f(Re_d, \varphi_s)$, the values of the coefficients A and B at a given n can be used for any Re_d and any angle φ_s in the range of 15-45°.

It must be noted that the radius of the surface at which $w_{\varphi_{max}}$ is reached is not equivalent to the radius of the surface of zero pressure in a given cross section. This must be taken into account in calculating the static pressure distribution over the radius of the channel.

Let us examine the relationships of the variation in the axial velocity component of the stream. At the exit from the swirler the stream is thrown out to the periphery of the channel by the centrifugal effect, pressing against the inner wall. Therefore the actual velocity w_x at the wall (in the potential zone) considerably exceeds the average flow rate velocity. For a swirler with $\varphi_s = 60°$ and n = 3 this excess is about 37% for $Re_d = 4.4 \cdot 10^4$ and 54% for $Re_d = 1.07 \cdot 10^5$. This must be taken into account in an analytical evaluation of the processes of heat and mass transfer in channels with twisted streams.

A characteristic property of twisted streams in short channels is the appearance of return air currents from the surrounding atmosphere at the end face. The presence of a zone of return flows leads to an additional increase in the axial velocity component in the potential zone because of the decrease in the straight-through cross section of the main stream and the inflow of outside air. These effects promote

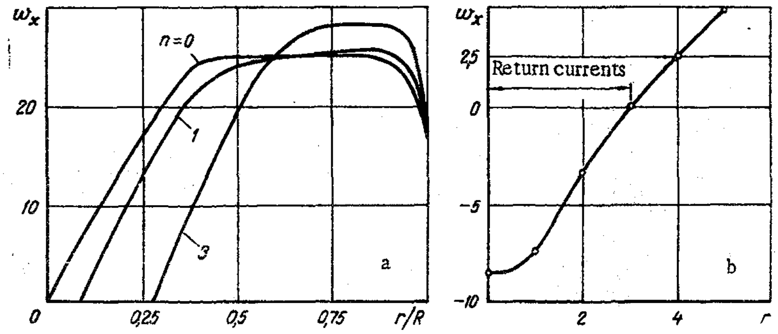

Fig. 3. Distribution over radius of channel of axial velocity component of motion as a function of n (a) and variation in axial velocity in axial zone (b). $\varphi_s = 45°$; $x/d = 7$; for a: $Re_d = 1.07 \cdot 10^5$; for b: $Re_d = 1.14 \cdot 10^5$; $n = 1$. w_x, m/sec; r, mm.

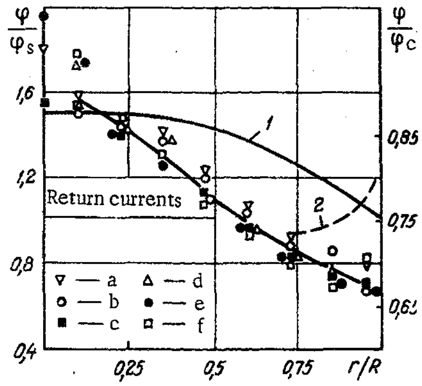

Fig. 4

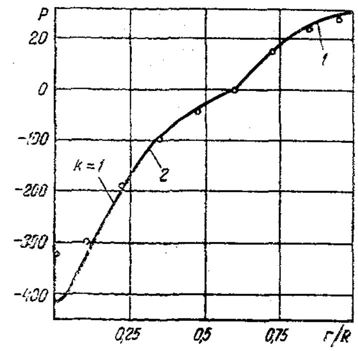

Fig. 5

Fig. 4. Dependence of angle of twist of stream along length and radius of tube: $\varphi_s = 60°$; $n = 3$; $Re_d = 1.07 \cdot 10^5$; 1) construction angle of twist at exit from vanes of swirler ($\varphi = \arctan (R/r)^3 \tan \varphi_s$); 2) actual angle of twist; points: experimental data (a) x/d = 1; b) 3; c) 5; d) 7; e) 9; f) 11).

Fig. 5. Distribution of excess static pressure over radius of tube: 1) from Eq. (5); 2) from Eq. (7); $\varphi_s = 45°$; $n = 0$; $x/d = 5$; $Re_d = 1.6 \cdot 10^5$.

turbulizing of the stream in the axial zone, the mixing zone, and the zone of potential flow. As thermo-anemometric studies show [3], the intensity of turbulent pulsations reaches 40% in the axial region of a cyclonic chamber into which return currents enter, and 10% in the region of potential flow.

The experimental study showed that the width of the zone of return currents in the range studied depends weakly on the number Re_d but depends significantly on the exponent n. The maximum width for this zone was observed for swirlers with $\varphi_s = 45°$, despite the fact that at $\varphi_s = 60°$ the rarefaction in the axial zone is greater than at $\varphi_s = 45°$. The results of the measurement of the velocity profile in the axial zone for one of the experiments are given in Fig. 3b. The maximum velocity of return flow is about 30% of the velocity of direct flow in the potential zone.

The solution obtained for cyclonic chambers [4] enables one to determine the coordinate of the surface of zero axial velocity from the equation

$$(1 + \eta^2)^2 - 6\eta^2 = 0.$$

Its solution gives two roots, $\eta = 0.52$ and $\eta = 1.93$, but the second solution does not have meaning. Consequently, for cyclones the return flow appears below the surface with radius $r = 0.52\, r_{\varphi_{max}}$. Since $r_{\varphi_{max}}$ essentially depends on the exponent n, with its increase the zone of return currents must expand, which is confirmed by direct measurements in streams twisted by vaned swirlers (Fig. 3a).

To clarify the role of the central body in the formation of a zone of return currents special experiments were conducted with a swirler in which the profiled vanes were replaced by four straight vanes mounted along the stream in order to eliminate twisting. Measurements of the static and total pressures with the subsequent calculation of the axial velocity showed that slight distortion of the velocity profile, resembling the flow behind a poorly streamlined body, occurs in the initial cross sections of the channel. Starting with x/d = 5 the velocity profile is analogous to the profile for turbulent flow in pipes.

Let us examine some relationships of the variation in the angle of twist of the stream along the length of the pipe. An analysis of numerous experimental data obtained for all the swirlers studied showed that a considerable deviation exists between the measured angles of twist of the stream over a cross section of the channel from the angles of the vanes of the swirler. These results are compared in Fig. 4. It is seen that satisfactory agreement is not observed in the entire region of variation of φ/φ_s. This can be explained, first, by the fact that the stream is not turned through the given angle φ but through a somewhat smaller angle because of the limited number of vanes in the swirler, and second, by an increase in the axial velocity compared with the velocity at the exit from the swirler owing to the centrifugal effect. An analysis of the experimental data shows that this increase is about 14% for a swirler with $\varphi_s = 60°$ and n = 3 ($Re_d = 1.07 \cdot 10^5$) in the cross section x/d = 1. Both these factors contribute to a decrease in the angle of twist compared with the construction angle at the exit from the swirler.

Since the return currents develop when $\varphi > 90°$, for the results of the experiment presented in Fig. 4 the radius of the boundary of the zone of return currents is about 0.16R ($\varphi/\varphi_s > 1.5$).

Let us examine the case of variation in the angle of twist of the stream in the potential zone for a swirler with $\varphi_s = 60°$ and n = 3 (see Fig. 1b).

The tangential velocity component varies according to the relation

$$w_\varphi = w_{x\,\mathrm{av}} \frac{\bar{A}}{\bar{r}},$$

where

$$\bar{A} = 1.47 \exp(-0.0345 x/d).$$

If it is assumed that this equality is satisfied when x/d = 0 then at the exit from the swirler we will have

$$w_\varphi = w_{x\mathrm{av}} \frac{1.47}{\bar{r}}; \quad \mathrm{tg}\,\varphi = \frac{w_{x\mathrm{av}}}{w_{x\mathrm{ex}}} \frac{1.47}{\bar{r}}.$$

The construction angle at the exit from the vanes of the swirler for this case has the form

$$\mathrm{tg}\,\varphi_c = \left(\frac{R}{r}\right)^3 \cdot 1.73.$$

Then the lag in the angle of twist behind the construction angle is determined by the equation

$$\frac{\varphi}{\varphi_c} = \frac{\mathrm{arctg}\, 1.47 \dfrac{w_{x\mathrm{av}}}{w_{x\mathrm{ex}}\bar{r}}}{\mathrm{arctg}\, 1.73 \left(\dfrac{R}{r}\right)^3}.$$

The results of a calculation from this equation are presented in Fig. 4 (curve 2), from which it is seen that the lag in the angle of twist behind the construction angle is more than 25%.

In [5] it is suggested that the attenuation of the twist is accounted for by the parameter

$$\Phi = \frac{M}{KR},$$

which takes the following form for the potential zone with the condition that w_{xp} = const:

$$\Phi = \frac{A(x)}{w_{xp}R} = \frac{r}{R}\,\mathrm{tg}\,\varphi.$$

For the conditions of the experiment presented in Fig. 1 the calculating equation is described by the equality

$$\Phi = 1.47\,\frac{w_{x\,av}}{w_{xp}}\exp(-0.0345x/d).$$

The calculations made from this equation showed that the relative decrease in Φ in the cross sections $x/d = 1$ and $x/d = 11$ is 29.1%.

In conclusion, let us consider the static pressure distribution across a twisted gas stream based on the equation

$$\frac{\partial P}{\partial r} = \rho\,\frac{w_\varphi^2}{r} \tag{3}$$

on the assumption that $w_r = 0$ and ignoring the variation in gas density over the radius of the channel.

Let us consider the potential zone. In this zone $w_\varphi = A(x)/r$; hence

$$P = -\frac{A^2\rho}{2r^2} + C_1, \tag{4}$$

with the constant C_1 being found to a first approximation from the zero static pressure at $r = r_z$. From this we have

$$P = \frac{A^2\rho}{2}\left[\frac{1}{r_z^2} - \frac{1}{r^2}\right]. \tag{5}$$

This equation can be applied right up to the outer edge of the boundary layer.

Below the surface $P_{st} = 0$ the tangential velocity profile is described by Eq. (1), so that after integration

$$\bar{P} = \frac{P}{\frac{1}{2}\rho w_{\varphi\,max}^2} = 2\int\left(2\,\frac{\eta}{1+\eta^2}\right)^{2k} d\eta + C_2. \tag{6}$$

This integral is divided into quadratures with values of 2k equal to 0, 1, 2, 3, etc.

If $k = 1$ Eq. (6) takes the following form (the constant C_2 is found from the condition $\bar{P} = 0$ at $\eta = \eta_z$):

$$\bar{P} = 4\left[\frac{1}{1+\eta_z^2} - \frac{1}{1+\eta^2}\right]. \tag{7}$$

If $k \neq 1$ then (6) is written in the form of an infinite series

$$\bar{P} = 2^{2k}\sum_{m=0}^{\infty}\left\{(-1)^m\,\frac{(k-m)!}{(k+m)\,m!}\left[\frac{1}{(1+\eta^2)^{k+m}} - \frac{1}{(1+\eta_z^2)^{k+m}}\right]\right\}. \tag{8}$$

The results of a calculation from Eqs. (5) and (7) are compared in Fig. 5 for a swirler with $\varphi_s = 45°$ and $n = 0$ and for which the exponent k is close to unity ($k = 0.975$). The agreement of the calculated and experimental results is rather good in a large part of the channel cross section. The divergence of the results in the axial zone is rather significant. Apparently the tangential velocity profile cannot be approximated by Eq. (1) in this zone.

NOTATION

$A(x)$	is the function $A = A(x)/w_{x\,av}R$;
d	is the diameter of tube;
k and n	are the exponents;
l	is the length of tube;
P	is the static pressure;
R	is the radius of tube;
$Re_d = w_{x\,av}d/\nu$;	
r, φ, x	are the cylindrical coordinates;

$r_{\varphi_{max}}$ is the radius of surface of maximum tangential velocity;

$\bar{r}_{\varphi_{max}} = r_{\varphi_{max}}/R$;

$\bar{r} = r/R$;

r_z is the radius of surface of zero static pressure;

r_p is the radius of potential zone;

$w_{x_{av}}$ is the average flow rate velocity;

$w_{x_{ex}}$ is the axial velocity at exit from swirler;

$w_{\varphi_{max}}$ is the maximum tangential velocity;

w_x, w_φ, w_r are the axial, tangential, and radial velocity components;

w_{xp} is the axial velocity component in potential zone;

$\eta = r/r_{\varphi_{max}}$;

$\eta_z = r_z/r_{\varphi_{max}}$;

ρ is the density;

ν is the kinematic viscosity;

φ is the angle of twist of stream;

φ_s is the angle of twist of stream at outer radius;

φ_c is the construction angle of twist;

M is the moment of momentum;

K is the momentum.

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