EXPERIMENTAL DETERMINATION OF THE STRUCTURE COEFFICIENT OF A TWISTED STREAM FLOWING IN THE INTERTUBE SPACE OF A HEAT EXCHANGER

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The dependence of the structure coefficient of a stream flowing in a bundle of helically curved tubes of oval profile on the determining parameters is established, along with the features of this system.

As is known, in calculating the interchannel mixing of a heat-transfer agent in bundles of cylindrical rods with spiral finning, in addition to the method of by-channel calculations, the method of homogenization of a real rod bundle can be used [1]. In using this method on the scale of a bundle diameter, we are examining the flow of a homogenized medium described by a system of differential equations of a continuum closed by means of an empirically determined effective diffusion coefficient D_t. In [1], a method was proposed for analyzing empirical data on D_t obtained by the method of heating the central rod, based on the use of the criterion Fr_M:

$$\mathrm{Fr}_M = S^2/dd_e \tag{1}$$

and the stream structure coefficient a, which determines the rate of damping of a stream flowing in such a bundle. This method can be used to study the transfer properties of a stream in the intertube space of a heat exchanger with a twisted flow [2], where helically curved tubes of oval profile form the structure of the flow. Such a flow is qualitatively similar to that which exists in a bundle of rods with spiral finning. In fact, the criterion Fr_M (1) is also the determining parameter in the case of twisted flow, and the entire region of flow of the heat carrier in the intertube space of the heat exchanger may be conditionally broken down into a thin boundary layer at the walls and a flow core with a roughly constant velocity through the bundle cross section [3]. In using this method to account for the effect of the length of the tube bundle on the coefficient D_t, a transformation of the longitudinal coordinate of the bundle $2ax/d$ is introduced [1]. Here, the structure coefficient of the stream a should be determined experimentally. In Tolmin's theory, this coefficient is a unique empirical constant and makes it possible to generalize empirical data on the decay of the maximum velocity along a free axisymmetric stream flowing from an opening with a variable degree of velocity profile irregularity, as well as in the case of the placement of agitating grids and swirlers at the mouth of the stream [4].

Strictly speaking, the basic assumptions and laws of the flow of free streams are not satisfied in a bundle of helically curved tubes, and the possibility of using these assumptions and laws approximately for the stream being examined here needs to be substantiated experimentally. A stream in a bundle of twisted tubes flows under conditions of its interaction with the walls of the tubes and the casing, and the equation of motion of such a stream, within the framework of the homogenized model [1], will have the following form at $Pr_f = 1.0$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} = -\frac{dp}{dx} + \frac{1}{r}\frac{\partial}{\partial r}\left(\rho r D_t \frac{\partial u}{\partial r}\right) - \xi \frac{\rho u^2}{2d_e}. \tag{2}$$

It is apparent from Eq. (2) that the equalizing effect on the stream in the bundle of spiral tubes is expressed by the diffusion term

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\rho r D_t \frac{\partial u}{\partial r}\right),$$

while $\xi\rho u^2/2d_e$ reflects the effect of friction against the wall.

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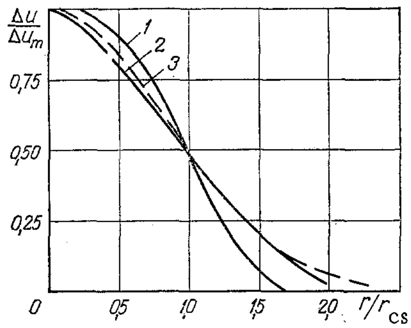

Fig. 1. Dimensionless profile of excess velocity in cross section of main part of stream flowing in a bundle of spiral tubes and its comparison with Schlichting's profile and the Gaussian curve: 1) empirical relation (4); 2) relation (5); 3) relation (6).

However, if it is shown experimentally that the effect of the term $\xi\rho u^2/2d_e$ on the process of stream flow is not decisive and that $dp/dx \approx 0$, then to a first approximation stream flow in a bundle of spiral tubes may be described by laws similar to the laws governing the flow of a free stream, and the dependence of the coefficient a on the number Fr_M can be determined.

The flow of a stream in a bundle of spiral tubes was studied experimentally on a unit described in [3, 5] by the method of the inverted motion of the stream source [5]. A jet of air was supplied by means of a movable circular tube 46 mm in diameter to the central spiral tube of the bundle. The spiral tubes, of oval profile and 1000 mm length with a maximum profile dimension d = 46 mm, were oriented in the bundle in such a way that in the outlet section of the bundle — where the velocity fields were measured — the axes of symmetry of the profiles of the tubes were parallel to one another. The stream in the tube bundle flowed in the intertube space of a heat exchanger bounded by the walls of a casing. The velocity fields were measured with pitot tubes 1.2 mm in diameter and 0.1 mm in wall thickness installed on a coordinate spacer [3].

The experimental unit, measurement system, and experimental method were checked by studying a circular stream on the unit. For this purpose, the spiral tubes were taken out of the casing and the circular stream flowed unobstructed inside the latter. The stream flowing out of the tube had the following parameters: velocity in cross section ~35 m/sec, $Re \approx 10^5$, nonuniformity of velocity at stream mouth ~1.22. As is known, within the range of numbers $Re = 0.2 \cdot 10^5$ to $40 \cdot 10^5$, changes in the maximum axial velocity along the stream are independent of Re [4], so that the study was conducted at fixed Re. Study of the flow of the circular stream showed that the empirical distributors of the dimensionless excess velocity in cross sections of the main part of the stream agree well with the Gaussian curve, while the change in the maximum velocity on the stream axis at $a = 0.0757$ is described by the hyperbolic relation of Tolmin's theory of flow from a turbulent source. This confirmed the possibility of using the above method of investigation with inverted motion of the stream source.

Our study of stream flow in bundles of spiral tubes of oval profile was conducted at numbers Fr_M = 80, 317, and 1560, bundle porosity with respect to the heat carrier $m \approx 0.4$–0.5, and numbers $Re \approx 10^5$–$1.5 \cdot 10^5$.

To confirm that the condition $P \approx \text{const}\ (x, r)$ was satisfied in the present case throughout the bundle volume and in the outlet section, where the static pressure was equal to the ambient pressure, we studied the static pressure distribution with a fixed position of the stream source. It turned out that the static pressure deviated from the ambient pressure by about ±3% only close to the stream mouth, due to deflection of the stream at this point, and that the condition $dp/dx \approx 0$, characteristic of free streams, was satisfied practically throughout the bundle volume in which the stream flowed.

Figures 1 and 2 show results of the study of stream flow in bundles of spiral tubes. The empirical distributions of velocity in successive cross sections of the main part of the stream are described well by the following interpolational relation (Fig. 1):

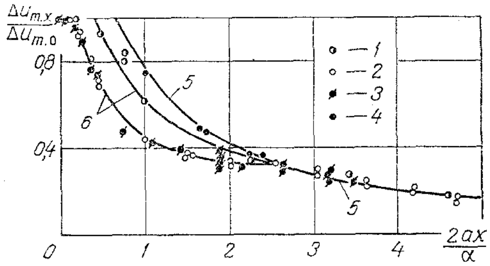

Fig. 2. Change in maximum excess velocity along a stream flowing in a bundle of spiral tubes: 1) test data, Fr_M = 80; 2) same, 317; 3) same, 1560; 4) test data for circular stream in a casing without spiral tubes; 5) relation (7); 6) relation (9).

$$\frac{\Delta u}{\Delta u_m} = \exp\left[-2.01\left(\frac{r}{r_{cs}}\right)^2\right] + 0.0288\exp\left[6.75\frac{r}{r_{cs}} - 4.21\left(\frac{r}{r_{cs}}\right)^2\right], \tag{3}$$

where $\Delta u_m = u_m - u_0$ is the maximum excess velocity in the stream cross section; $\Delta u = u - u_0$ is the excess velocity on a given radius r of the bundle.

Relation (3) for the bundle radius shows the similarity of the velocity profiles on the main part of the stream and the axisymmetrical nature of the problem. A comparison of the velocity profile (3) with the Schlichting profile

$$\frac{\Delta u}{\Delta u_m} = \left[1 - \left(0.44\frac{r}{r_{cs}}\right)^{1.5}\right]^2 \tag{4}$$

and the Gaussian curve

$$\frac{\Delta u}{\Delta u_m} = \exp\left[-2.79\frac{r^2}{4r_{cs}^2}\right] \tag{5}$$

shows (see Fig. 1) that relations (4) and (5) give understated values of dimensionless excess velocity close to the peak of the velocity distribution curve and overstated values of same in the boundary zone, i.e., velocity profile (3) is fuller with respect a free stream than profiles (4) and (5). However, since (3) is closer to the actual stream profile, it may be reasoned that the effect of friction on the stream in a bundle of spiral tubes is not decisive. This is indicated by the agreement of the test data on the change in the maximum excess velocity along a stream flowing in a spiral tube bundle on the main part of the stream (Fig. 2) with theoretical curve for an axisymmetric free stream [4]:

$$\frac{\Delta u_{m.x}}{\Delta u_{m.0}} = \frac{0.96}{(2ax/d) + 0.29}, \tag{6}$$

where $\Delta u_{m.0} = u_{m.0} - u_0$ is the maximum excess velocity at the stream mouth (x = 0).

As follows from Fig. 2, in a bundle of spiral tubes the maximum velocity decreases continuously along the stream, beginning with the coordinate $x/d \approx 1.0$, and the transition to the hyperbolic law of damping of maximum velocity along the stream (6) occurs at the value of longitudinal coordinate determined by the expression

$$(2ax/d)_l = 2.56. \tag{7}$$

In the range of values $x/d \approx (1.0\text{–}1.28)/a$, a transitional zone is seen in stream flow in the tube bundle which has no analogy with the flow of a free stream. The change in maximum velocity in the transitional zone is described by the exponential relation

$$\frac{\Delta u_{m.x}}{\Delta u_{m.0}} = k\frac{0.96}{b(2ax/d)^n + 0.29}. \tag{8}$$

At $2ax/d$ = 1-2.56, b = 1.87, n = 0.408, k = 1 for Fr_M = 317-1560; $k = 1.41(2ax/d)^{-0.365}$ for Fr_M = 80. At $2ax/d$ = 0.2-1.0, b = 1.9, n = 0.696, k = 1 for Fr_M = 317-1560; k = 1.41 for Fr_M = 80.

The transition to the main part of the stream corresponds to the moment of penetration of the stream beyond the second course of helical tubes, when more than 19 tubes are involved in its formation. It may be assumed that a dynamically similar stream flow structure has been formed by this point.

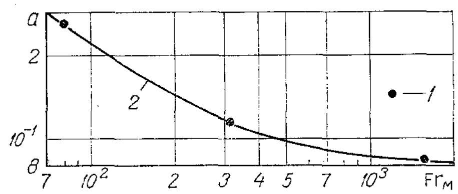

Fig. 3. Dependence of stream structure coefficient on the number Fr_M: 1) test data; 2) interpolation relation (10).

The stream structure coefficient a, characterizing the rate of stream damping, was determined experimentally from the measured maximum velocity $\Delta u_{m.x}$ on the main part of the stream using Eq. (6). The thus-determined coefficient a has the following values for the investigated bundles: $a = 0.256$ at $Fr_M = 80$, $a = 0.113$ at $Fr_M = 317$, and $a = 0.082$ at $Fr_M = 1560$. The value of a may be described by the rational fractional function (Fig. 3)

$$a = 0.0745 + 11.37\,Fr_M^{-1} + 246\,Fr_M^{-2}. \tag{9}$$

Using the coefficient a for a bundle of spiral tubes, test data are also generalized on the change in the velocity of the reverse currents u_0 in the zone of circulatory flow of the bundle and on the stream geometric characteristic r_{cs}. The change in velocity u_0, the presence of which is due to flow of the stream in a limited space, is described along the stream by the following relation for the range of numbers $Fr_M = 80$–1560:

$$u_0/u_m = -0.1165\,(2ax/d)^{0.775}. \tag{10}$$

The geometric characteristic of the stream in the spiral tube bundle r_{cs} changes linearly along the stream both in the main part of the stream

$$2r_{cs}/d = 1.75 + 0.568\,(2ax/d), \tag{11}$$

and in the transitional zone

$$2r_{cs}/d = 0.85 + 0.916\,(2ax/d). \tag{12}$$

The validity of using the above flow laws was also confirmed by estimates of the mean excess velocity in the stream, which proved equal to $(\Delta u_{av}/\Delta u_m)_x = 0.411$ ($u_{av}/u_m = 0.258$ for a full axisymmetric stream [4]), and by estimates of air flow rate and momenta, which turned out to be nearly constant along the stream.

Thus, study of the process of stream flow in a bundle of helical-curved tubes showed that such a flow for the most part obeys the laws governing free stream and that, using the stream structure coefficient — dependent on the number Fr_M — test data on the transfer properties of the flow can be generalized within the framework of a homogenized flow model.

NOTATION

Fr_M, criterion characterizing features of flow in a bundle of spiral tubes; S, tube fin spacing; d, maximum dimension of tube profile; d_e, equivalent diameter; ρ, density; u, v, velocity components; P, pressure; x, r, coordinates; D_t, effective diffusion coefficient; ξ, friction coefficient; r_{cs}, "half" radius of stream; a, stream structure coefficient; u_m, maximum velocity in stream cross section; u_0, velocity in zones of circulatory flow; Re, Reynolds number.

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FLOW OF TURBULENT GAS JETS IN A SUBMERGED SPACE

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The distribution of parameters in the cross section and along the axis of submerged jets of helium, air, and argon is shown. Theoretical formulas are proposed and compared with the results of other authors.

In the survey literature devoted to the study of the flow of turbulent gas jets of different densities [1-9], there are different points of view on the distribution of temperatures and concentrations in the mixing zone, the width of this zone, etc.

To refine representations of the turbulent mixing of gases with different physical properties, we conducted comparison tests involving the discharge from a nozzle of radius R = 4 mm of heated jets of helium, air, and argon into an immovable air space. In the tests, the light gas ($\rho_0 < \rho_n$) was fed vertically upward, while the heavy gas ($\rho_0 > \rho_n$) was fed vertically downward. The initial parameters of the gas jets were chosen from the conditions that: 1) a turbulent flow regime begin from the nozzle edge; 2) the dynamic heads and temperatures could be measured with sufficient accuracy; 3) in the measurement cross sections up to values $u/u_m \geqslant 0.2$, the additional velocity of the gas particles due to buoyancy Δu_* would be greater than $0.02u_m$. In the calculations, it was assumed that $\Delta u_* = g\tau(\rho_0 - \rho_n)/\rho_n$, where $\tau = x/u$ is the residence time of the gas particles in the jet.

Table 1 shows initial parameters of the gas jets.

In the tests, we used a combination packing with an inlet aperture diameter of 0.7 mm to determine the dynamic head, temperature, and composition of the gas mixture. The measurements were made in the cross section x = 102 mm = 25.5R along two mutually perpendicular directions. The sought values of the parameters were judged to have been correctly determined if the data for the two directions agreed. We also determine the parameters of the gas mixture on the stream axis $x \leqslant 50R$.

Figure 1a-b shows the relative velocities, dynamic heads, and mass concentration with the discharge of helium, air, and argon from the nozzle, respectively. The relative excess enthalpies and temperatures are also shown. The solid lines in Fig. 1 represent the relations in [1, 4, 10]

$$\frac{u}{u_m} = \left[1 - \left(\frac{y}{b_u}\right)^{3/2}\right]^2 \qquad (1)$$

and

$$\frac{\Delta i}{\Delta i_m} = \frac{i - i_n}{i_m - i_n} \equiv \frac{c}{c_m} = \left[1 - \left(\frac{y}{b_c}\right)^{3/2}\right]^2. \qquad (2)$$

The width of the dynamic ($2b_u$) and concentration ($2b_c$) mixing zones was determined from the relations

$$b_u = 2.27 b_{u=0.5u_m}, \; b_c = 2.27 b_{c=0.5c_m}. \qquad (3)$$

It is clear from the data shown that the fields of relative excess enthalpies and mass concentrations are identical. This result was noted earlier in a study of the characteristics of boundary layers on permeable walls [11]. The identity of the mass concentration and excess

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