INVESTIGATION OF THE TRANSFER PROPERTIES OF A STREAM IN A HEAT EXCHANGER WITH SPIRAL TUBES

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The article demonstrates the possibility of measuring the effective diffusion coefficients and intensities of turbulence in bundles of spiral tubes by the method of diffusion from a point source; relationships for calculating these magnitudes were obtained.

At present, spiral tubes with oval cross section are beginning to be used in heat exchangers and various types of devices [1-3]. Using bundles of such tubes with longitudinal flow around them makes it possible to intensify heat exchange, both with flow inside the tubes and in flow in the intertube space of the heat exchanger. To work out reliable methods of thermohydraulic calculation of heat exchangers with spiral tubes, it is necessary to investigate the structure of the flow and the characteristics of turbulent transfer in the intertube space of the heat exchanger where the flow is marked by being particularly complicated. The structure of the flow in longitudinal flow around a bundle of spiral tubes was investigated in [3]. Below we examine the results of the investigation of the transfer properties of flow in such bundles. The intensity of turbulence and the coefficient of turbulent diffusion can be measured on the axis of a circular tube by the method of heat or mass diffusion from a stationary point source [4] based on the static Lagrange description of a turbulent field in studying the history of motion of individual particles continuously emitted by the source. In this case, the mean static square of particle displacement can be determined by a Taylor equation for homogeneous and isotropic turbulence [4]:

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\overline{y^2}\right)=\int\limits_{t_0}^{t}\overline{u(t_0)u(t')}dt'. \tag{1}$$

The limit solutions of this equation for short and long diffusion times, respectively, have the form

$$\overline{y^2}=\frac{v_1^2}{u^2}x^2, \tag{2}$$

$$\overline{y^2}=2\frac{D_t}{u}(x-x_0). \tag{3}$$

The straight line (3) expresses the constancy of the diffusion coefficient and is the equation of the asymptote to the experimental curve $\overline{y^2} = f(x)$ [4]. Therefore the coefficient D_t/u determined by this method is the asymptotic diffusion coefficient.

The application of this method to a bundle of spiral tubes can be justified only by the coincidence of the experimental temperature distributions in the case of diffusion with normal distribution since the value $\overline{y^2}$ obtained from Taylor's theory is equal to $\overline{y^2}$ calculated from the experimental distribution if this is normal.

In a bundle of spiral tubes the basic assumptions of Taylor's theory are not strictly fulfilled. However, it was shown in [5] that in the calculation of the agitation of the heat carrier in channels of complex shape we need not take into account a real bundle but may go over to the model of flow of a homogenized medium with slip. In this case we examine the flow region outside the near-wall layer where, as the investigations by Dzyubenko [3] showed, the velocity field is close to homogeneous over the cross section of the bundle. In this region in particular the temperature fields were measured over the radius of the bundle of spiral tubes at different distances from the diffusion source. The investigations were carried out on models of a heat exchanger consisting of 37 spiral tubes with d = 46 mm, length

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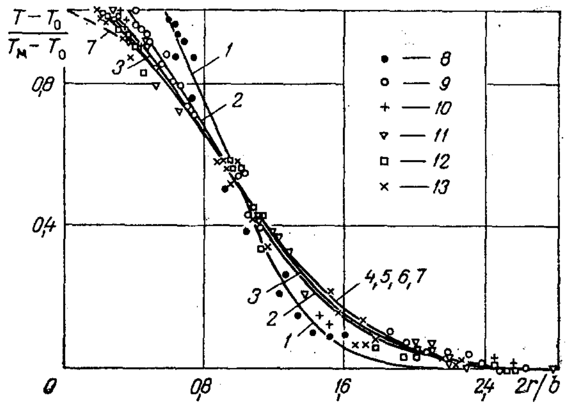

Fig. 1. Comparison of the experimentally measured and theoretical distributions of the dimensionless excess temperature for a bundle of spiral tubes with Fr_M = 314: 1-6) calculation by formula (9) for x = 150, 300, 450, 600, 750, 900 mm, respectively; 7) calculation by formula (10); 8-13) experimental data for x = 150, 300, 450, 600, 750, 900 mm, respectively.

1000 mm, and with d_e=24.6 and 11.5 mm, by the method of heat diffusion on an experimental installation described in [3]. The indicator gas, i.e., heated air, was continuously fed through a circular tube, wound around a central spiral tube of the bundle, into a concurrent flow of cold air flowing longitudinally around the bundle. The selected scale of the source of diffusion ensured the feeding of indicator gas amounting to 2% of the flow rate of air; this made it possible to neglect its influence on the turbulence. The flow rate of the indicator gas was selected such that it ensured that the flow rates of the indicator gas and of the principal gas were equal. A peculiarity of the experimental method was the mobility of the diffusion source relative to the outlet cross section of the bundle, where the temperature fields and flow rates were measured with the aid of a Chromel—Alumel thermocouple with a bead diameter of ∿0.5 mm and a full-head pipe, 1.2 mm in diameter and with a wall thickness of 0.1 mm mounted on a traversing gear. The possibility of using such a method was experimentally verified.

The experiments were carried out in the range of changes of Re numbers between Re = $4.3\cdot10^3$ and $8.2\cdot10^3$, with Fr_M = 314 and 1530, temperatures $T_M \leqslant 340°K$, temperature gradients $T_M - T_0$ = 10-45°K, and at a pressure close to atmospheric.

In determining the Reynolds numbers, the characteristic dimension was d_e, the characteristic temperature was the mean mass temperature of the heat carrier, and the characteristic flow rate was the mean mass flow rate in the tube bundle [3, 5].

The experimental investigations of the transfer properties of the flow were carried out both with ordered and with random disposition of the tubes in the bundle. It was found that the disposition of the tubes in the bundle has practically no influence on the radial temperature distribution in the bundle.

The tubes in the bundle were made of aluminum alloy D1-T. For evaluating the effect of the heat conductivity of the tubes on the measured temperature fields and the transfer characteristics to be determined, a series of methodological experiments with helium as indicator gas were carried out. The coincidence of the transfer characteristics measured by methods of heat and mass diffusion, and also theoretical evaluations showed that in the case under consideration, this influence is negligible.

Typical experimentally measured dimensionless excess temperature fields in successive cross sections of the bundle of spiral tubes away from the source of diffusion with the number Fr_M = 314 are presented in Fig. 1, where they are compared with the theoretical distributions for a point source and for a source of finite size.

To take the finiteness of the dimensions of the source into account, the following calculation scheme (Fig. 2) was adopted. We examined the diffusion from an annular source with radius r_0. In this case the local increase in temperature at the point N of the stream,

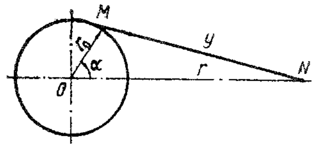

Fig. 2. Calculation scheme for an annular source.

situated at the distance y from the point M, is proportional to exp $(-y^2/2\overline{y^2})$. Then, the local increase of temperature at the point N, as a result of heat diffusion from all points of the annular source is proportional to

$$T-T_0 \sim 2\int_0^{\pi} \exp\left[-\frac{r_0^2\sin^2\alpha+(r-r_0\cos\alpha)^2}{2\overline{y^2}}\right]d\alpha. \qquad (4)$$

If we denote cos α = x and $rr_0/\overline{y^2} = a$, we obtain after some transformations

$$T-T_0 \sim 2\exp\left(-\frac{r_0^2+r^2}{2\overline{y^2}}\right)\int_{-1}^{+1}\frac{\exp(ax)\,dx}{\sqrt{1-x^2}}. \qquad (5)$$

The integral in expression (5) cannot be expressed in elementary functions. We therefore use the rule of integrating by expansion into a series of the integrand function exp (ax):

$$\exp(ax)=1+\frac{ax}{1!}+\frac{a^2x^2}{2!}+\frac{a^3x^3}{3!}+\ldots, \qquad (6)$$

which converges when $|x| < \infty$. We confine ourselves to six terms of series (6), and then we obtain from expression (5) approximately

$$T-T_0 \sim 2\pi\exp\left(-\frac{r_0^2+r^2}{2\overline{y^2}}\right)\left(1+\frac{r^2r_0^2}{4(\overline{y^2})^2}+\frac{r^4r_0^4}{64\,(\overline{y^2})^4}+\frac{r^6r_0^6}{2304\,(\overline{y^2})^6}\right). \qquad (7)$$

If we divide expression (7) by $T_M - T_0$:

$$T_M-T_0 \sim 2\pi\exp\left(-\frac{2r_0^2}{2\overline{y^2}}\right)\left(1+\frac{r_0^4}{4(\overline{y^2})^2}+\frac{r_0^8}{64\,(\overline{y^2})^4}+\frac{r_0^{12}}{2304\,(\overline{y^2})^6}\right) \qquad (8)$$

and introduce the dimensionless values $\bar{r}_0 = 2r_0/b$, $\bar{r} = 2r/b$ and $\overline{\overline{y^2}} = \overline{y^2}/b^2$, we have

$$\frac{T-T_0}{T_M-T_\theta}=\exp\left(\frac{\bar{r}_0^2-\bar{r}^2}{8\overline{\overline{y^2}}}\right)\frac{\bar{r}^6\bar{r}_0^6+576\,(\overline{\overline{y^2}})^2\bar{r}^4\bar{r}_0^4+147.5\cdot10^3(\overline{\overline{y^2}})^4\bar{r}^2\bar{r}_0^2+9.45\cdot10^6(\overline{\overline{y^2}})^6}{\bar{r}_0^{12}+576(\overline{\overline{y^2}})^2\bar{r}_0^8+147.5\cdot10^3(\overline{\overline{y^2}})^4\bar{r}_0^4+9.45\cdot10^6(\overline{\overline{y^2}})^6}. \qquad (9)$$

With $\bar{r}_0 = 0$, distribution (9) is identical with a normal distribution for a point source situated on the axis of the bundle:

$$\frac{T-T_\theta}{T_M-T_0}=\exp\left(-\frac{r^2}{2\overline{y^2}}\right), \qquad (10)$$

which is a partial solution of the energy equation

$$\rho u c_p\frac{\partial T}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left(\rho r c_p D_t\frac{\partial T}{\partial r}\right). \qquad (11)$$

Equation (11) describes heat diffusion from a point source in a homogeneous stream for a homogenized flow model [5]. In this case the problems of turbulent and molecular diffusion in isotropic bodies are identical [4].

The results of calculation by formula (9) for $x \geqslant 600$ mm agree well with the experimental data and with the calculation by formula (10) (Fig. 1). There is only a small difference near the peak of the distribution. On this basis we henceforth use for the determination of the effective diffusion coefficient by formula (3) the magnitude $\overline{y^2}$ for the distribution (10):

$$\overline{y^2}=0.179\ b^2. \qquad (12)$$

At short distances from the source of diffusion there is a considerable divergence of the results of calculation by formulas (10) and (9), which otherwise agree well with the experimental data for $x \leqslant 150$ mm. Therefore, when the method under examination is used for determining the effective intensity of turbulence, ε can be estimated only approximately.

In Fig. 3 the results of calculating $\overline{y^2}$ by formula (12) for experimentally measured temperature distributions at different distances from the source of diffusion are presented in

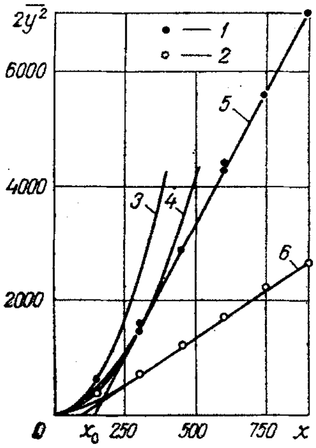

Fig. 3

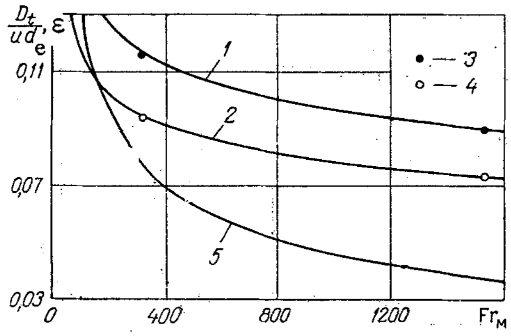

Fig. 4

Fig. 3. Experimental dependence of the double mean-static square of displacement $\overline{2y^2}$, mm², on the distance from the point source of diffusion x, mm: 1, 2) experimental data for Fr_M = 314 and 1530, respectively; 3, 4) relationship (2); 5, 6) relationship (3).

Fig. 4. Dependence of the dimensionless effective diffusion coefficient and of the effective intensity of turbulence on Fr_M: 1) relationship (13); 2) relationship (17); 3) experimental data on the effective intensity of turbulence; 4) experimental data on the effective diffusion coefficient; 5) relationship (18).

the form of the function $\overline{2y^2} = f(x)$. From this function, using the limit solutions of the Taylor equations (2) and (3), ε and D_t/ud_e were determined which, for the Reynolds number Re ≈ 8000 and Froude numbers Fr_M = 314 and 1530, are equal to 11.6 and 9%, and 0.094 and 0.073, respectively.

Using the measured values of ε and assuming that for $Fr_M \to \infty$, ε ≈ 4.4%, we obtain a formula for calculating the effective intensity of turbulence:

$$\varepsilon = 0.044\,(1 + 8.1\,Fr_M^{-0.278}). \tag{13}$$

The formula for calculating the effective diffusion coefficient with the turbulent Prandtl number Pr_T = 1.0 can be obtained from the correlation

$$D_t = \chi l_1 v_1, \tag{14}$$

where

$$v_1 = \sqrt{\overline{u'^2}} = \sqrt{\overline{v'^2}} = \sqrt{\overline{w'^2}}, \tag{15}$$

if it is accepted that in the core of the stream, pulsation rates along the axes of coordinates are equal. In dimensionless form, expression (14) has the form

$$\frac{D_t}{uR_0} = \chi \frac{l_1}{R_0}\,\varepsilon, \tag{16}$$

where R_0 is the radius of the tube bundle; R_0/d_e = 6.55.

The dimensionless mixing path for the examined flow region in the tube bundle was taken equal to $l_1/R_0 \approx 0.1$, which characterizes the outer part of the near-wall layer and jet flows [6]. The proportionality factor χ is determined from the condition of coincidence of calculated and experimental data in regard to the diffusion coefficient. For the examined case of flow, χ = 1.235. In determining the function (13) for the value of ε, which is contained in expression (16), it was assumed that with $Fr_M \to \infty$, the intensity of turbulence in a bundle of tubes with oval cross section is equal to the intensity of turbulence on the outer boundary of the near-wall layer for the case of flow in a straight tube ε ≈ 4.4% [4]. Then, if we substitute into expression (16), instead of ε, its value from (13), we obtain the function

$$k_{as}=\frac{D_t}{ud_e}=0.0356(1+8.1\mathrm{Fr}_M^{-0.278}), \tag{17}$$

which agrees well with the experimental data (Fig. 4). No effect of the Reynolds number on the coefficient k_{as} in bundles of spiral tubes was detected. For the purpose of comparison, Fig. 4 also contains the dependence

$$k_{as}=1.02\mathrm{Fr}_M^{-0.451}, \tag{18}$$

obtained in [5] for bundles of cylindrical rods with spiral fins. It can be seen from the comparison of relationships (17) and (18) that although the values of k_{as} for bundles of spiral tubes and finned rods are of the same order of magnitude in the investigated interval of Fr_M numbers, from the point of view of mixing of the heat carrier, bundles of spiral tubes are more efficient.

The investigation showed that the method of diffusion from a point source for measuring the effective diffusion coefficient and intensity of turbulence in bundles of spiral tubes makes it possible to obtain fairly reliable recommendations for calculating the mixing of the heat carrier in such bundles within the framework of a homogenized flow model.

NOTATION

$\overline{y^2}$, mean static square of particle displacement; t, time; x, longitudinal coordinate; r, radial coordinate; u, flow rate; d, maximum dimension of the tube profile; b, width of the temperature curve at the place where the excess temperature is half the excess temperature on the axis of the bundle; $Fr_M = S^2/d_e d$, criterion characterizing the flow features in a bundle of spiral tubes; d_e, equivalent diameter; S, pitch of the swirl of the tube blades; T, temperature; T_0, initial temperature of the flow whose turbulence is investigated; T_M, maximum temperature in the cross section of the bundle (near the axis of the bundle); ρ, density; c_p, specific heat; ε, intensity of turbulence; v_1, root mean square pulsation rate; l_1, mixing path; k_{as}, asymptotic value of the effective diffusion coefficient; Re, Reynolds number.

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