GENERALIZATION OF TEST DATA ON RESISTANCE IN TUBES WITH RIBBON SWIRLERS

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On the basis of identity of the mechanism of fluid motion in tubes with ribbon swirlers and in coils, criterial equations have been obtained for determining the resistance coefficient in a swirled flow in the laminar regime with macro-eddies and in the turbulent regime.

Because ribbon swirlers can be used to intensify heat transfer, numerous experiments have been conducted to determine the resistance coefficient and the heat transfer coefficient under these conditions.

The flow friction in a tube with a ribbon swirler depends not only on the upstream motion of the fluid, but also on the pitch of the swirler, which determines the degree of rotation of the fluid and the field of inertia body forces. When generalizing experimental data on flow friction in swirled streams, both these factors must be taken into consideration.

In the present paper the results of an experimental investigation of flow friction are generalized on the basis of a generalization of the fluid flow mechanism in tubes with ribbon swirlers and in coiled tubes. The channel formed by a ribbon swirler and the tube wall constitutes a coil with cross section in the shape of a semicircle. The pitch of the swirler defines the radius of curvature of this channel. There is therefore a vortex pair in the swirled stream, just as in a coil. The transverse circulation of fluid in the form of a vortex pair is an additional source of resistance and promotes intensification of heat transfer. Experimental study of the structure of a swirled stream confirms the existence of this vortex pair [1].

In tubes with ribbon swirlers, just as in coils, there may be laminar flow, laminar flow with macro-eddies, and turbulent flow.

The majority of experimental investigations of resistance in streams with ribbon swirlers has been made in turbulent flow, and only in Koch's work [2] do we find results obtained at low Reynolds number. The working section was preceded by a tube of length 50 diameters, the working section itself having an l/d ratio of 20. The tests were carried out in air, at three values of the relative pitch (s/d = 2.5, 4.25, 11).

White [3] found that in laminar flow with macro-eddies in coils the resistance coefficient is well generalized by the relation $\bar{\xi}_l = f(\mathrm{De})$. For flow in a tube with ribbon swirlers the following form of the Dean number was assumed:

$$\mathrm{De}^* = \frac{wd_e}{\nu}\sqrt{\frac{d}{D}} = \mathrm{Re}\sqrt{\frac{d}{D}}. \qquad (1)$$

The axis of the spiral channel is located on the surface of the cylinder with $d_m \cong d/2$ and has the half-turn pitch s. A geometrical analysis yields

$$\frac{D}{d} = 0.5 + \frac{8}{\pi^2}\left(\frac{s}{d}\right)^2. \qquad (2)$$

Figure 1 shows the relation $\bar{\xi}_l = f(\mathrm{De}^*)$ constructed on the basis of Koch's tests. The resistance coefficient for a stream in a straight tube was determined from the Poiseuille formula with A = 64.

In an investigation of the resistance of coils White formed the opinion that macro-eddies appear when the value of $\bar{\xi}_l$ becomes greater than unity, and that the onset of turbulence corresponds to conditions where the resistance of the specific coils becomes larger than the value indicated by the relation $\bar{\xi}_l = f(\mathrm{De})$ for laminar flow with macro-eddies. The latter hypothesis has been verified by visual observations [4]. This method of defining the flow regime boundaries has been used for streams in tubes with ribbon swirlers.

In laminar flow with macro-eddies the results of an experimental investigation of flow friction in swirled streams are generalized by the formula

$$\bar{\xi}_l = 0.099\,\mathrm{De}^{*0.526} + 0.4 \qquad (3)$$

or

$$\xi = \frac{6.34}{\mathrm{Re}^{0.474}}\left(\frac{d}{D}\right)^{0.263} + \frac{25.6}{\mathrm{Re}}. \qquad (4)$$

This formula was obtained with $\mathrm{De}^* = 50–8 \cdot 10^3$ and s/d = 2.5–11.0. The solid line in Fig. 1 corresponds to Eq. (3).

At s/d = 11 and low Re, the resistance proves to be less than in laminar flow with macro-eddies. This may be explained by the fact that for a weakly swirled stream the length of the test section proves to be insufficient to obtain developed macro-eddies. This region of conditions with underdeveloped secondary flows is bounded in Fig. 1 by the broken line, and has not been taken into account in generalizing the test data. The rest of the experimental points do not deviate from the straight line given by (3) by more than 9%.

For comparison, Fig. 1 shows the relation $\bar{\xi}_l = f(\mathrm{De})$ obtained by White [3] in studies of the resistance in coils. It may be seen that the resistance in tubes with ribbon swirlers is somewhat greater than that of the coils due to the less favorable shape of the cross section of the channel formed by the walls of the tube and the ribbon swirler.

The conditions for the onset of turbulence in a swirled stream are characterized by the quantity Re_{cr}. From Fig. 1 we obtain the following formula for Re_{cr}:

$$\mathrm{Re}_{cr} = 38900\,(d/s)^{1.16} + 2300. \qquad (5)$$

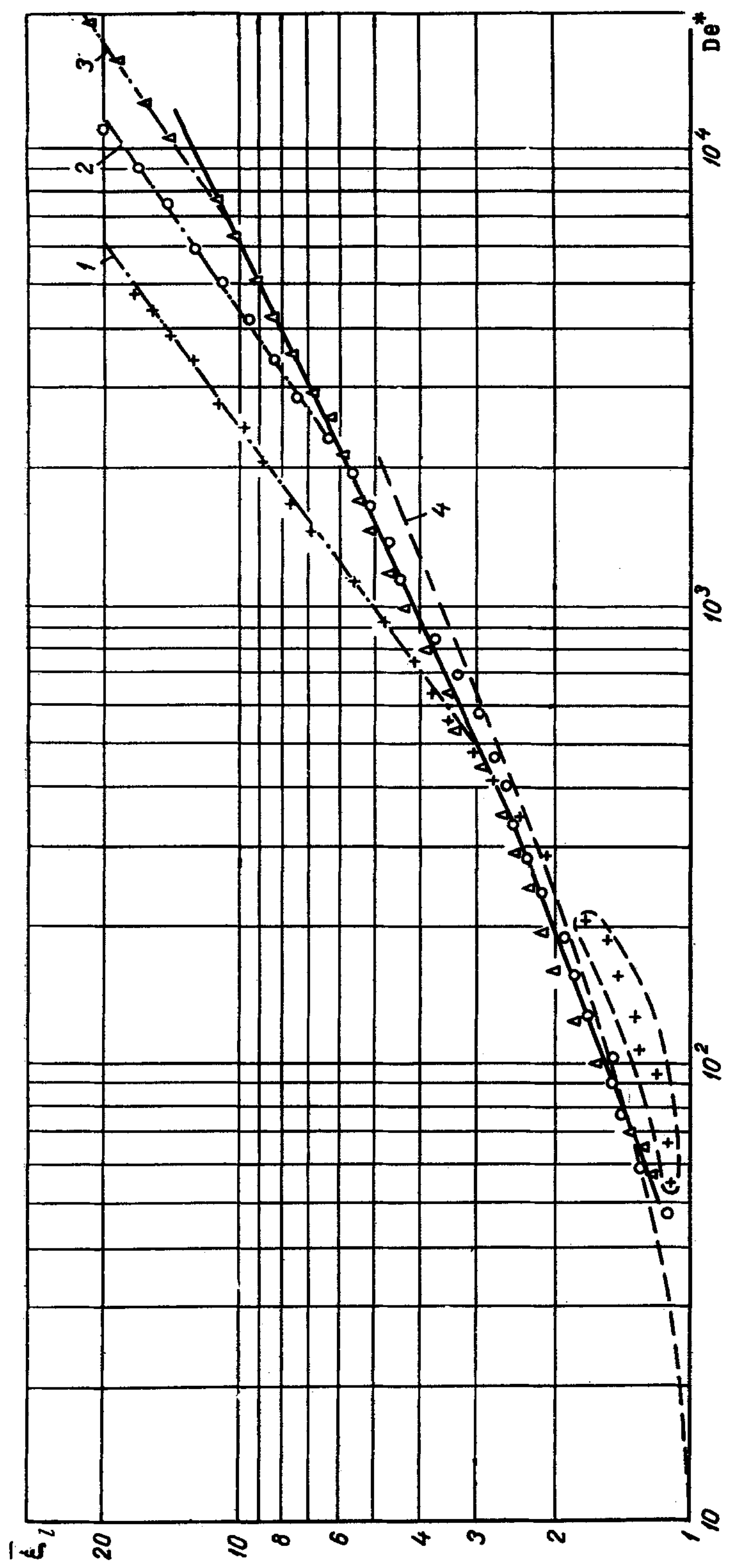

Fig. 1. Dependence of relative resistance coefficient $\bar{\xi}_l$ on the Dean number De* in tubes with ribbon swirlers at s/d = 11 (1), 4.25 (2), 2.5 (3) and in coils after [3] (4).

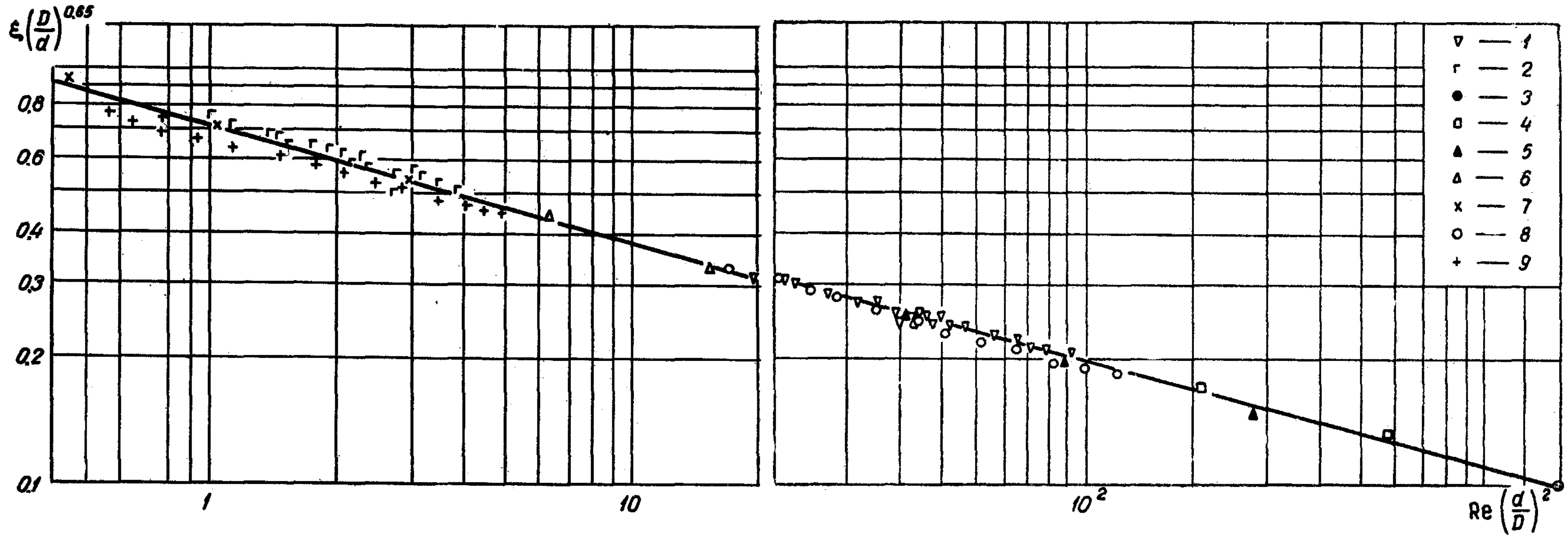

Fig. 2. Dependence of the resistance coefficient on $Re(d/D)^2$ at $s/d \geq 2.65$: 1) and 2) from [1] with $s/d = 5.15$ and 11; 3), 4), 5), 6), and 7) from [6] with $s/d = 2.65$, 3.42, 4.17, 6.75 and 13; 8) and 9) from [2] with $s/d = 4.25$ and 11.0.

A considerable number of papers has been devoted to investigation of the resistance of swirled streams in a turbulent flow, all the experiments being conducted in stabilized streams.

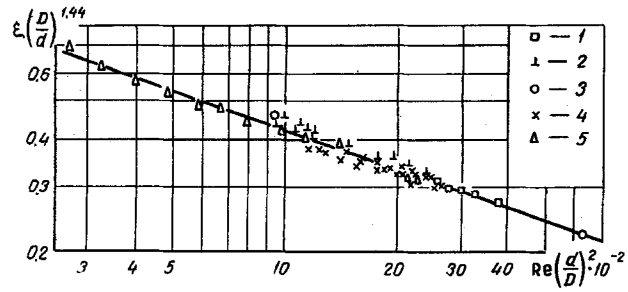

Fig. 3. Dependence of the resistance coefficient on $Re(d/D)^2$ for $s/d \le 2.5$: 1) and 2) according to [1] for s/d = 1.81 and 2.71; 3) according to [6], s/d = 1.79; 4) according to [5], s/d = 2.1; 5) according to [2], s/d = 2.5.

Ito [7] correlated data on the resistance coefficient in curved tubes in a turbulent flow by processing the experimental results in the form of the relation $\xi(D/d)^n = f[Re(d/D)^2]$. A satisfactory correlation was found with n = 0.5.

The same method was used to correlate the test data on resistance in tubes with ribbon swirlers. A satisfactory correlation of the test data for $s/d \ge 2.65$ was obtained with n = 0.65, and for $s/d \le 2.5$, with n = 1.44. Figures 2 and 3 show the results of the experiments described in [1, 2, 5, *6]. The tests were performed in air and water. Correlation of the experimental data in turbulent flow for s/d = 13.00–2.65 yields the formula

$$\xi\left(\frac{D}{d}\right)^{0.65} = 0.705\left[\mathrm{Re}\left(\frac{d}{D}\right)^2\right]^{-0.28} + 0.009 \qquad (6)$$

or

$$\xi = \frac{0.705}{\mathrm{Re}^{0.28}}\left(\frac{d}{D}\right)^{0.09} + 0.009\left(\frac{d}{D}\right)^{0.65}. \qquad (7)$$

This formula was obtained for $Re(d/D)^2 = 0.5\text{–}1.6 \cdot 10^3$ and Re from Re_{cr} (formula (5)) to $5.9 \cdot 10^4$.

*In [5] the experimental tube had a diameter of 12 mm, and the twisted ribbon a thickness of 1 mm. With these dimensions, d_e = 6.78 mm. This dimension was used in generalizing the corresponding test data, and not d_e = 6.35 mm, which was assumed by the authors.

Figure 2 shows the line corresponding to (6). In each range of variation of the pitch $s/d \le 6.75$, the experimental points did not deviate from the approximating line by more than 5%. For s/d = 11 the deviation reached 10%.

For s/d = 2.5–1.79 (Fig. 3) we obtained

$$\xi\left(\frac{D}{d}\right)^{1.44} = 4.72\left[\mathrm{Re}\left(\frac{d}{D}\right)^2\right]^{-0.35} \qquad (8)$$

or

$$\xi = \frac{4.72}{\mathrm{Re}^{0.35}}\left(\frac{d}{D}\right)^{0.74}. \qquad (9)$$

These formulas were obtained in the same range of variation of Re with $Re(d/D)^2 = 260\text{–}6 \cdot 10^3$. The largest deviation of the experimental points from the line given by (8) reached 8%.

NOTATION

D is the diameter of curvature of the channel axis; d is the tube diameter; d_e is the equivalent diameter of channel cross section formed by tube wall and ribbon swirler; De* is the Dean number for flow in a tube with ribbon swirler; l is the length of tube; Re = $= wd_e/\nu$; s is the half-turn pitch of ribbon swirler; w is the mean mass flow velocity; ν is the kinematic viscosity; ξ is the resistance coefficient of tube with ribbon swirler allowing for losses in friction and in the formation of secondary flows; $\overline{\xi_l} = \xi/\xi_{0l}$; $\overline{\xi} = \xi/\xi_0$; ξ_{0l} and ξ_0 are the resistance coefficients of a straight channel in the laminar and turbulent flow regimes.

REFERENCES

1. Smithberg and Landis, Heat Transfer, ASME, **86**, ser. C, no. 1, 1964.

2. R. Koch, VDI-Forschungsheft, **24**, Ausg. B, 469, 1958.

3. C. M. White, Proc. Roy. Soc., **123**, A. London, 1929.

4. G. J. Taylor, Proc. Roy. Soc., **124**, A. London, 1929.

5. M. Kh. Ibragimov, E. V. Nomofilov, and V. I. Subbotin, Teploenergetika, no. 7, 1961.

6. E. V. Seymour, Trans. Inst. Chem. Engrs., 41, 1963.

7. H. Ito, Trans. ASME, J. of Basic Engng., June 1959.

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