AN EXPERIMENTAL STUDY OF LOCAL SHEAR STRESS AT THE WALL OF A COILED TUBE

Yu. V. Vilemas, P. S. Poshkas, and V. A. Mikaila UDC 532.5:536.24

Experimental data are presented on the distribution of the shear stress about the perimeter of a tube, with various lines of curvature.

Curvilinear channels in the form of a coil are frequently employed in compact heat exchangers, chemical reactors, refrigerators, and steam generators; therefore, much work has been devoted to studying the average conduction of heat and the hydraulic resistance in such channels. A review of existing data can be found in [1-4].

When a liquid or a gas flows through a coil at a slow speed, the flow is laminar in nature. Increasing the velocity leads to the appearance of secondary flows whose existence in a laminar regime blocks the origination of turbulent pulsations. This causes an increase in the critical Reynolds number (Re_{cr}). To determine the boundaries of this transition, we can make use of the generalizing relationship derived in [2] from hydraulic-resistance measurements, as well as in accordance with [5-7]:

$$Re_{cr} = 2300\left\{1-\left[1-\left(\frac{2000d}{D}\right)^{-0,4}\right]^{2,2}\right\}^{-1}. \tag{1}$$

With an increase in D or with a reduction in d, Re_{cr} diminishes. When D/d > 860 the transition to the turbulent flow regime, because of the absence of secondary flows, occurs at Re ≈ 2300 [5], i.e., in straight tubes as well. For very large De the flow in a coil is self-similar, i.e., the hydraulic resistance is independent of Re. To determine the boundary of transition to the self-similar flow region we can use the generalizing relationship [8]

$$Re = 12.6\cdot 10^4 (d/D)^{0.2}. \tag{2}$$

To calculate the hydraulic resistance in various flow zones we can use the generalizing relationships given in [1, 2], as well as the recommendations of the authors of [9]. As was indicated in [4], the best agreement with experimental data achieved by various authors is offered by the relationships given in [9]. To determine the average heat conduction in a coil we can use the generalizing relationships from [1, 4].

In the case of forced heat loads, we have to know the local characteristics of friction and heat conduction both over the length and perimeter of the coiled tube; however, because of experimental complexities, systematic investigation of these characteristics was not carried out. Detailed data on the laminar flow regime with macrovortices were obtained by the authors of [10] who studied the distribution of local resistance over the perimeter of the tube coil with D/d ≈ 11.7 in the interval Re = 300-3500 (De = 100-1000). It turned out that with an increase in De the difference between the maximum and minimum values of τ_w increases, while the relationship between these varies from 1.7 (De = 100) to 4.6 (De = 918).

The authors of [11] undertook experimental studies of local heat conduction in a coil with D/d = 17 and 104 for water and oil with Re = $12\text{-}6.5\cdot 10^4$. It was demonstrated that in the laminar flow regime the ratio of the coefficients of heat conduction at the outer (maximum heat conduction) and inner (minimum heat conduction) generatrices of the inside coiled tube surface is equal to 4. In the turbulent regime the ratio of the maximum and minimum heat-conduction coefficients for D/d = 17 and 104 varies from 2 to 4.

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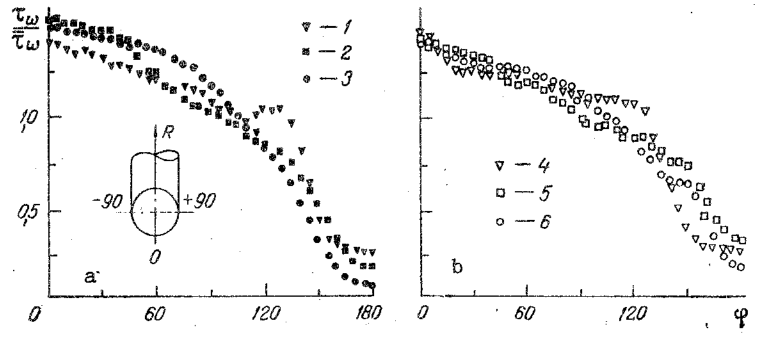

Fig. 1. Distribution of $\tau_w/\bar{\tau}_w$ about the perimeter of the tube coil for various Re: a) D/d = 6.67, Re = 6050 (1), 20,500 (2), 57,600 (3); b) D/d = 13.3, Re = 5760 (4), 17,170 (5), 94,600 (6). φ, deg.

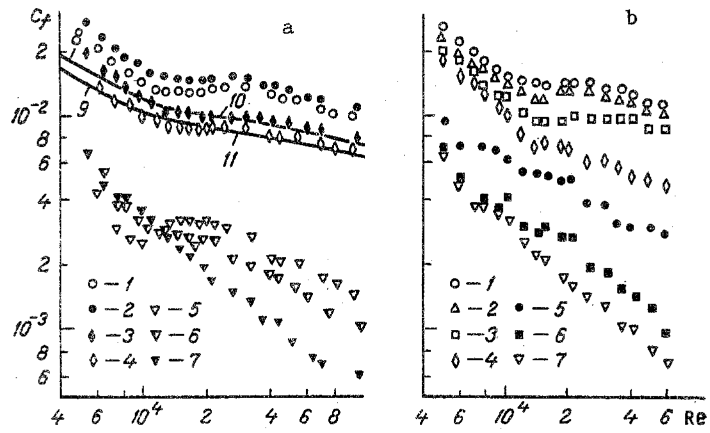

Fig. 2. Change in c_f as a function of Re: a) for various coils with different curvatures: 1, 2) at the outer generatrix with D/d = 13.3 and 6.67, respectively; 3, 4) averaged over the perimeter with D/d = 13.3 and 6.67, respectively; 5-7) at the inner generatrix with D/d = 13.3, 10.0, and 6.67, respectively; 8, 9) in accordance with the relationship from [2] when D/d = 6.67 and 13.3; 10, 11) in accordance with the relationship from [9] when D/d = 6.67 and 13.3; b) for a coil with D/d = 6.67 for various φ; 1) at the outer generatrix, φ = 0°; 2-6) for φ = 45, 90, 135, 150, and 165°, respectively; 7) at the inner generatrix, φ = 180°.

It is the purpose of this paper to obtain experimental data on the local shear stress for the transitional and turbulent stabilized flow of air through coils exhibiting various curvatures. The experiments were conducted on an open jet wind tunnel under isothermal conditions. The ratio of the coil diameter to the diameter of the tube amounted to 6.67, 10.0, and 13.3. The experimental segment was a coil fabricated of a reinforced rubber tube with an inside diameter of 0.075 m which was wound onto a steel cylinder at 450° [sic], forming a coil. Prior to the winding it was placed inside a specially fabricated steel spring to maintain its circular lateral cross section. The inlet portion of the tube with a length $\ell/d \approx 80$ was straight, which ensured stabilization of the flow at the inlet to the coil. For purposes of measuring the shearing stress about the perimeter of the tube we employed a film thermoanemometric sensor mounted in a special pivoting device flush with the inside surface. In order to calibrate the sensor, which was done on the inside of the straight tube, we used the relationship

$$E/E_0 = A + B\tau_w^{1/3}. \quad (3)$$

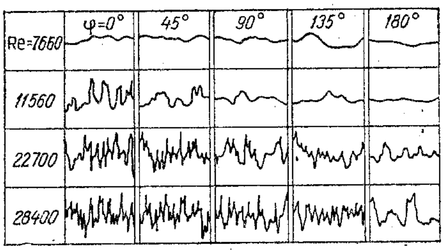

Fig. 3

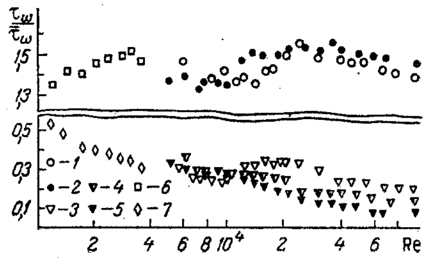

Fig. 4

Fig. 3. Change in the pulsations of friction about the perimeter of the coil tube with D/d = 6.67 for various Re.

Fig. 4. Change in $\tau_w/\bar{\tau}_w$ in coils of various curvatures as a function of Re: 1, 2) at the outer generatrix with D/d = 13.3 and 6.67; 3-5) at the inner generatrix with D/d = 13.3, 10.0, 6.67; 6, 7) at the outer and inner generatrices according to the data of [10] for D/d = 11.67.

The quantity $\bar{\tau}_w$ was determined from the Blasius relationship for a straight channel of circular lateral cross section:

$$\tau_w = 0.03955\rho\bar{u}^2\,\mathrm{Re}^{-0.25}. \tag{4}$$

The constants A and B were found from the calibration data by the method of least squares. All of the measurements and the calibration were performed with utilization of the thermoanemometric equipment of the "DISA" company (Denmark) with a standard 55M10 bridge. Measurements about the tube perimeter were taken every 5°, and in order to calculate τ_w we used the same relationship (3), but in this case τ_w was the unknown, whereas the constants A and B were known. The average value of τ_w was found by integration of the given distributions of τ_w over the perimeter of the tube coil.

The temperature of the air flow passing through the experimental segment was kept constant by means of a heater which was connected into a single-phase OSU40/0.5A transformer with a high-precision VRT-2 temperature control.

We employed a system of twin diaphragms to determine the flow rate of the air. The pressure in front of the diaphragms was measured by means of RZM sensors, while the pressure differences across the diaphragms were measured with PD1 sensors of the NVM company (FRG) or by means of a cup-type differential manometer filled with distilled water. The temperature of the air flow was measured with chromel-alumel thermocouples fashioned out of 0.5-mm diameter wire. The process of collecting and processing the experimental data was completely automated. All of the electrical signals were recorded on a perforated tape. The calculation was carried out on an IVK-2 measuring-computer unit. The random relative error in τ_w amounted to 3.0% with Re = 10^5 and 10% with Re = $5\cdot10^3$.

Prior to studying the local τ_w within the coil, in the region of transitional and turbulent flows we determined the critical Re for that same straight tube, and for this we used a straight single-filament thermoanemometer sensor. In this case, the turbulent pulsations in velocity appeared at Re ≈ 2000. However, the measurements of the local τ_w about the perimeter of the straight tube for Re = 4500 and 22,000 yielded a scattering of the experimental points within limits of 1-3%, which suggests the absence of irregularities on the surface of the rubber tube. The initial experiments showed a symmetrical distribution of τ_w at the wall of the coil tube; therefore, the measurements were subsequently carried out in the interval φ = 0-180°.

Our experimental research demonstrates that when D/d = 6.67 and 13.3 (Fig. 1) and for large Re (on the order of $5.76\cdot10^4$) the relative shear stress about the perimeter of the tube coil changes smoothly from the maximum value at the outer generatrix to a minimum value at the inner generatrix of the tube coil surface. In the case of a laminar flow regime with macrovortices (Re = $6.05\cdot10^3$ and $5.76\cdot10^3$) the distribution of the relative shear stress is more complex in nature than in the case of turbulent flow. The appearance of local extrema in the distribution of the shear stress about the perimeter of the coil tube can be explained by the formation of secondary flows in the form of a double vortex. With an increase in Re the local extrema diminish, while for R > 10^4 they are virtually absent, but the relative shear stresses no longer change as smoothly as in the case of developed turbulent flow. With a reduction in D/d of the coil the relative shearing stresses under the action of centrifugal forces increase slightly at the outer generatrix, while diminishing at the inner generatrix.

With an increase in Re (Fig. 2), the maximum coefficient of friction changes markedly, as does the minimum coefficient, and the coefficient averaged over the perimeter of the coil tube. In a laminar flow regime with macrovortices, as Re increases the difference between the maximum (at the outer generatrix) and the minimum (at the inner generatrix) values of the coefficient of friction increases to the point at which the laminar flow regime with macrovortices changes into a turbulent regime. The resulting data show that for all three investigated variants of D/d this transition at the outer generatrix occurs at $Re \approx 10^4$. [Calculation on the basis of relationship (1) for D/d = 6.67, 10.0, and 13.3 yields Re_{cr} = 10,900, 9370, and 8430, respectively.] The existence of this transition is clearly seen from the distribution of c_f at the inner generatrix when D/d = 13.3. On transition to the turbulent regime ($Re \simeq 10^4$) c_f increases noticeably, while with a further increase in Re ($2.2 \cdot 10^4$) it diminishes both at the outer and the inner generatrices. When D/d = 6.67 this transition is not observed at the inner generatrix over the entire investigated interval Re ($5 \cdot 10^3$-$6 \cdot 10^4$), whereas at the outer generatrix it takes place even in the region $Re = 10^4$. Comparison of the average values of the friction coefficients showed excellent agreement with the data of [2] for a laminar flow regime with macrovortices and with the data of [9] for a turbulent flow regime.

The distribution of c_f for various φ about the perimeter of the coil tube as a function of Re when D/d = 6.67 shows (Fig. 2b) that the transition of the laminar flow regime into a turbulent flow regime initially occurs at the outer generatrix ($Re \approx 10^4$). In the Re interval being studied here, no turbulent developed flow is found to occur at the inner generatrix. The existence of a transition from laminar flow with macrovortices into turbulent flow around the perimeter of the coil tube for various Re is confirmed also by the pulsation curves shown in Fig. 3. The friction pulsations τ_w were recorded by means of a universal S8-13 memory oscillograph and a "Zenith-E" camera. The pulsation curves show that when Re = 7660 and for all φ a laminar flow regime is observed. With an increase in Re, the turbulent pulsations initially appear at the outer generatrix ($\varphi = 0°$, Re = 11,560). When Re = 22,700 and 28,400 they appear at the points φ = 0, 45, 90, and 135°. However, at the inner generatrix the appearance of the first turbulent pulsations is observed only when Re = 22,700, while in the range studied here with maximum Re completely turbulent flow is not achieved. Consequently, in coils of greater curvature (D/d < 10) the transition of the laminar flow regime with macrovortices to a turbulent flow régime about the perimeter of the tube arises at various Re, and at the outer generatrix this transition occurs at smaller Re than at the inner generatrix.

As Re increases and with a reduction in D/d the difference between the maximum and minimum coefficients of friction increases. When $Re = 5 \cdot 10^3$ the maximum shearing stress is greater by a factor of 4-4.5 than the minimum, and with $Re = 9.5 \cdot 10^4$ it varies from a factor of 6.6 in the case of D/d = 13.3 to a factor of 17.2 when D/d = 6.67. The maximum and minimum relative values of τ_w at the wall of the coil tube also change significantly with an increase in Re (Fig. 4). A particularly clear stratification of the relative τ_w as a function of Re is observed at the inner generatrix when $Re > 2 \cdot 10^4$. At the outer generatrix the change in $\tau_w/\bar{\tau}_w$ as a function of the coil curvature is insignificant. Apparently, this is caused by the influence of the Taylor–Görtler vortices which arise at the outer generatrix of the coil. At this same generatrix, τ_w is greater than the average value by a factor of 1.4-1.6. At the inner generatrix, τ_w amounts to 20-35% of the average value for the case in which D/d = 13.3 and 8-30% when D/d = 6.67. The greatest degree of nonuniformity in the investigated Re interval is observed on transition to the turbulent flow regime and for the maximum value of Re. Figure 4 also shows the results from [10] in which an experimental investigation was conducted into the friction which occurs in a laminar regime of flow with macrovortices in a coil with D/d = 11.67. We see that with a reduction in Re the difference between the relative τ_w at the outer and inner generatrices diminishes, i.e., the flow changes to the laminar regime.

NOTATION

d, inside diameter of the coil tube; D, coil diameter; E, voltage at the bridge output; E_0, voltage at the bridge output in the case of zero flow velocity; $\bar{u}$, mean mass velocity;

c_f, coefficient of friction; τ_w, shearing stress at the wall; ρ, density; ν, coefficient of kinematic viscosity; De, Dean number $(Re\sqrt{d/D})$; Re, Reynolds number (ud/ν); φ, angle.

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FLOW IN THE INITIAL SEGMENT OF A TUBE WITH A SHARP LEADING EDGE. 1. PHYSICAL MODEL OF THE FLOW

V. M. Legkii and V. A. Rogachev

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Visualization is used to study the three-dimensional structure of detached flow in the initial segment of a circular straight tube with a sharp 90°-angle leading edge. It is demonstrated that at $Re > 75\cdot10^3$ there is no attachment of the separated shear layer, while a secondary flow develops at the wall.

The difficulties which arise in attempts at physical interpretation of experimental material on local characteristics of heat exchange and friction in channels of small reduced length with sharp leading edges causing flow separation provide an adequate basis for a critical approach to the opinions being formed with respect to the structure of a flow such as arises within the detachment zone itself, as well as in the region in direct contact farther downstream with that zone. It is commonly assumed that the phenomenon of separation behind a sharp leading edge is the source of the perturbation which results in rapid agitation of the boundary layer and, consequently, in a sharp rise in the intensity of local heat exchange in the segment of assumed flow reattachment. This point of view with respect to the flow behind a sharp leading edge is essentially supported by intuitive concepts which, although seemingly incontrovertible at first glance, have not been confirmed by convincing direct observations.

In this study a soot-kerosene mixture similar to that used in [1, 2] was employed to conduct a visual examination of flow detachment behind a sharp edge in the initial segment of a circular tube. For these experiments we chose the technically popular sharp 90°-angle edge configuration which simulates the entry of a flow into a tube of unlimited extent, through an opening in the wall which extends in the radial direction.

The aerodynamic installation with a 36-mm diameter flowthrough section on which the experiments were carried out is described in [3]. The rapidly demountable initial segment

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