PROPERTIES OF TRANSVERSE DISTRIBUTIONS OF LOCAL HEAT EXCHANGE COEFFICIENTS IN THE INITIAL SECTION OF RECTANGULAR CHANNELS WITH MIXED FLOW IN THE BOUNDARY LAYER

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It is shown that with mixed flow in the boundary layer at the dynamic initial section of a rectangular channel the local heat exchange coefficients are considerably lower at the middle part of the wall than near the corners.

The process of transition from laminar to turbulent flow in the boundary layer at the dynamic initial section of a rectangular channel develops differently from that in a round tube or at a plate in a longitudinal flow [1]. The laminar boundary layer initially loses stability in the corner zones (points A in Fig. 1). Below the points of loss of stability in the corners the boundaries of the transition region are inclined to the longitudinal axes of the channel walls in the same way as is observed at an unbounded plane beyond a point source of disturbance [2]. At low and moderate values of Re_d the front of loss of

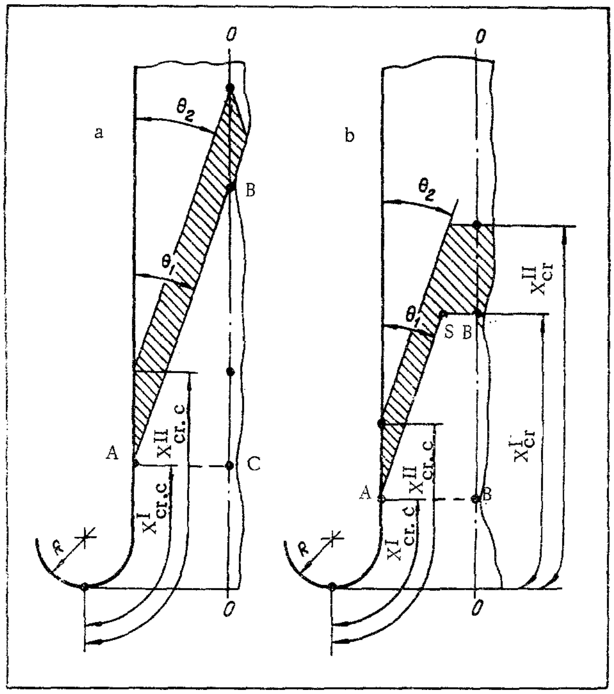

Fig. 1. Diagram of the development of the transitional process at the wall in the initial section of a rectangular channel. The transition region is shaded: a) small Reynolds numbers; b) large Reynolds numbers.

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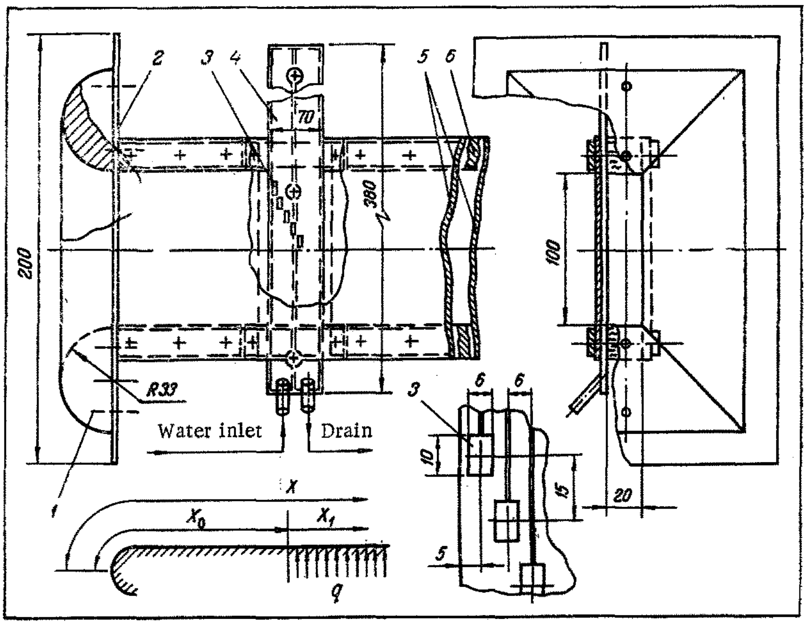

Fig. 2. Diagram of working section of experimental apparatus: 1) entrance attachment; 2) mounting flange; 3) heat flux pickups; 4) measuring strip; 5) covers of rectangular channel; 6) side racks.

stability forms a narrow wedge at each wall with the vertex lying at the point B (Fig. 1a). At high Reynolds numbers the laminar boundary layer also loses stability in the middle part of the wall because of the development of the transitional process at the corners. Here the transition front is parallel to the entrance rim of the channel (line BS in Fig. 1b). The configuration of the boundaries of the transition region as a whole becomes similar to a trapezoid. According to the data of [1], where the critical parameters are determined in the dynamic initial sections of five rectangular channels having ratios of sides of 1:1, 1:5, 1:13.5, and 1:25 with the entrance rim rounded on the radius of a circle, a temperature factor approaching unity $(T_{str}/T_{str} \rightarrow 1.0)^*$, and the intake of air from the atmosphere, the angles of inclination of the transition boundaries at the corners θ_1 and θ_2 are equal to each other, $\theta_1 = \theta_2 = 5°40'$, and the coordinates of the transition points at the corners are

$$\frac{X^{\mathrm{I}}_{\mathrm{cr.\,c}}}{d} = \frac{75000}{\mathrm{Re}_d}, \tag{1}$$

$$\frac{X^{\mathrm{II}}_{\mathrm{cr.\,c}}}{d} = \frac{110000}{\mathrm{Re}_d}. \tag{2}$$

With the same boundary conditions and relative radius of rounding of the entrance rim $R/d \geq 1.0$ to the critical coordinates of the natural transition are determined by the equations

$$\frac{X^{\mathrm{I}}_{\mathrm{cr}}}{d} = \frac{800000}{\mathrm{Re}_d}, \tag{3}$$

$$\frac{X^{\mathrm{II}}_{\mathrm{cr}}}{d} = \frac{1300000}{\mathrm{Re}_d}. \tag{4}$$

The concurrent existence on the segment BC of the dynamic initial section of a rectangular channel of surfaces with laminar, transitional, and turbulent flow in the boundary layer predetermines the irregular distribution of local heat exchange coefficients in the cross sections, with the fact that here the heat exchange intensity must be lower in the middle part of the wall than near the corners being especially noteworthy.

We attempted to confirm experimentally the properties of the flow in the corners of rectangular channels by measuring the local heat exchange coefficients developed in [1]. A diagram of the working section of the stand is shown in Fig. 2. The isothermal rectangular channel, made of wooden side racks 6 and textolite covers 5 with a length of 1050 mm and a cross section of 100 × 20 mm^2 (d = 33.3 mm) and

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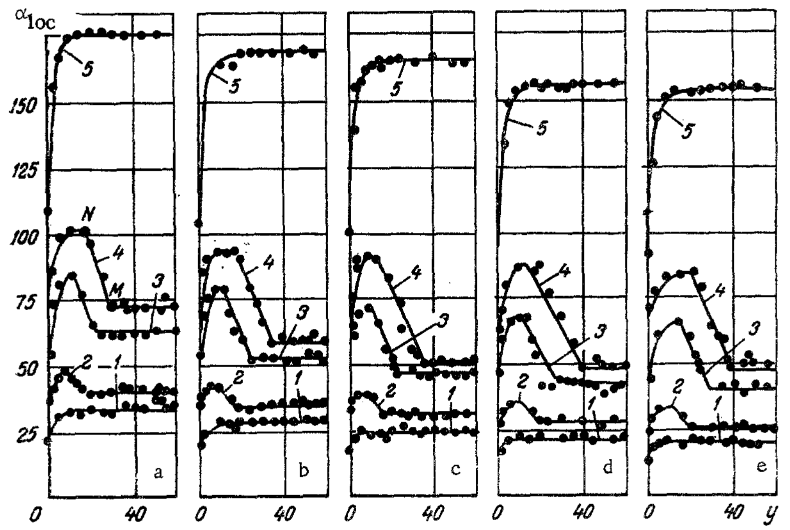

Fig. 3. Distribution of local heat exchange coefficients in cross sections of dynamic initial section of rectangular channel at $X_0 = 0.242$ m: 1) $Re_d = 8250$; 2) $Re_d = 12,800$; 3) $Re_d = 31,400$; 4) $Re_d = 45,000$; 5) $Re_d = 89,500$; a) pickup No. 1, $X_1/d = 7.48$; b) No. 2, $X_1/d = 7.64$; c) No. 3, $X_1/d = 7.82$; d) No. 4, $X_1/d = 8.0$; e) No. 5 $X_1/d = 8.18$. y, mm; α_{loc}, $W/m^2 \cdot {}^\circ C$.

an entrance attachment 1 shaped with an arc of a circle of $R/d = 1.0$, is attached to the intake of a ventilator. The ventilator provides air speeds of 1.0-55.0 m/sec.* A heated steel measuring strip 4 extending 70 mm along the flow is set flush with the lower wider wall of the channel. Five "isolated" heat flux pickups 3 with active faces 10×6 mm^2 in size [5] are built into the surface of the measuring strip. The first of them is located at a distance of 5 mm from the edge of the measuring strip ($X_1 = 5$ mm). The others are arranged at 6 mm intervals along the coordinate X_1. Two thermocouples are caulked with the pickups to measure the temperature of the heat-emitting surface.

The measuring strip is kept in a fixed position by a fast-acting clamping device thanks to which it can be shifted in a direction transverse to the channel axis. The joints with textolite covers are hermetically sealed with felt packings. The construction of the measuring strip is described in more detail in [4]. The strip is heated with water supplied through flexible hoses. The water flow rate was regulated so that its temperature drop within the heat-exchange surface did not exceed 1°C. A mode with $t_{wa} = \text{const}$ was thereby maintained with sufficient accuracy. The absolute temperatures of the heat-emitting surface were $t_{wa} = 60\text{-}80^\circ C$ and the temperatures of the air supplied to the channel from the atmosphere were $t_{in} = 18\text{-}20^\circ C$.

The heat-exchange measurements were conducted at different distances from the entrance to the channel, varying the length of the unheated section included ahead of the measuring strip, at four to five values of the air speed. The initial unheated length of the channel was successively $X_0 = 0.129$ m, $X_0 = 0.242$ m, $X_0 = 0.342$ m, $X_0 = 0.442$ m, and $X_0 = 0.542$ m. The measuring strip was shifted with a step of 5-10 mm in the transverse direction and with a step of 2.5 mm when each of the pickups passed the corner zone. The local convective heat exchange coefficients were determined in the stationary modes from the equation

$$\alpha_{loc} = \frac{EK}{t_{wa} - t_{in}} - \alpha_l. \qquad (5)$$

As the estimating calculations show, because of the small relative length of the heat-emitting surface of the measuring strip and, consequently, the small thickness of the thermal boundary layer in the zone where the heat flux pickups are located, the temperature differences $t_{wa} - t_{in}$ coincide almost exactly with the temperature drop between the wall and the core of the flow. The radiant heat exchange coefficients, found according to the recommendations of [6], where $\alpha_l = 2.5\text{-}3.5$ $W/m^2 \cdot deg$, while the calibration constants of the pickups were $K_1 = 560$ $W/m^2 \cdot \mu V$, $K_2 = 490$ $W/m^2 \cdot \mu V$, $K_3 = 580$ $W/m^2 \cdot \mu V$, $K_4 = 565$ $W/m^2 \cdot \mu V$, and $K_5 = 505$ $W/m^2 \cdot \mu V$.

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*The construction of the stand is described in [3].

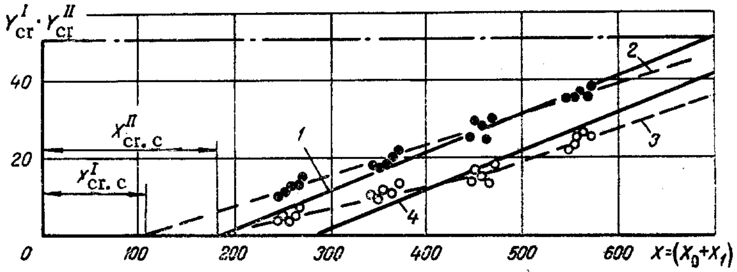

Fig. 4. Configuration of boundaries of transitional zone for $Re_d = 12{,}800$: 1) according to Eq. (1); 2) $Y^{I}_{cr} = f(X)$ according to the experimental data; 3) $Y^{II}_{cr} = f(X)$ according to experimental data; 4) according to Eq. (2). X and Y, mm.

A series of transverse distributions of local heat exchange coefficients obtained at $X_0 = 0.242$ m is presented in Fig. 3. The distance Y, measured from the edge of the wide wall of the channel where the measurements were conducted to the center of each pickup, are plotted along the abscissa. The experimental data are shown only for the interval Y = 0-60 mm since the graphs of $\alpha_{loc} = f(Y)$ are practically symmetrical relative to the longitudinal axis 0-0 of the wall.

The lowest curves 1 for $Re_d = 8520$ indicate laminar flow in the boundary layer over the entire width of the wall. Curves 5 for $Re_d = 89{,}500$, conversely, pertain to conditions where turbulent flow in the boundary layer existed over the entire width of the wall. In both cases the middle part of the graph of $\alpha_{loc} = f(Y)$ represents an extended region with uniform heat emission. The heat emission coefficients decrease smoothly near the corner.

The transverse distributions of local heat exchange coefficients for the intermediate Reynolds numbers ($Re_d = 12{,}800$, 31,400, and 45,000) look different. If one turns to curve 4 in Fig. 3a, for example, then here, as usual with mixed flow in the boundary layer, one observes three characteristic regions with sharply differing laws of heat exchange. In the middle part of the wall to the right of point M, where flow in the boundary layer is laminar, the values of α_{loc} are practically constant and markedly reduced. The section M-N corresponds to the transitional zone. To the left of point N is located a section with a turbulent mode of flow in the boundary layer and high local heat exchange coefficients. It is important that the differential in the absolute values of α_{loc} in the segments of the cross section containing laminar and turbulent modes of flow reaches 40-70%. This differential rapidly increases along with the Reynolds number.

The transverse coordinates of the critical points established from the graphs of $\alpha_{loc} = f(Y)$ for different distances from the channel entrance and a constant Reynolds number $Re_d = 12{,}800$ are compared in Fig. 4. In the determination of Y^{I}_{cr} and Y^{II}_{cr} a correction was introduced taking into account the finite dimensions of the sensitive zone of the heat flux pickup. The "isolated" pickup with central mounting of the potential leads and a constantan layer about 1 mm thick reacts to a disturbance in the local heat flux if it occurs at a distance on the order of 5-6 mm from the center [5]. In this case the recorded heat flux comprises less than 1% of the level of the disturbance. Such a deviation in the instrument readings will obviously remain unnoticed under ordinary experimental conditions. However, if the disturbance is applied at a distance of 3 mm from the center of the pickup the signal will correspond to 5-6% of the true value of the heat flux and will be detected. When the pickup is shifted along the wall from the middle of the channel toward the corner the heat fluxes do not change for some time and then starting from the point M they increase. Consequently, $Y_{cr} = Y_M + \Delta Y$, where ΔY is the radius of a field centered at the point M within which the pickup is not yet sensitive to changes in the local heat flux. The size of the correction ΔY is taken as equal to 3 mm. The sign of the correction is determined by the direction of movement of the pickup relative to the Y axis.

The solid lines in Fig. 4 are plotted in accordance with Eqs. (1) and (2) with $\theta_1 = \theta_2 = 5°40'$. On the whole the experimental and calculated data are in satisfactory agreement, although as $Y \to 0$ the disagreement of the longitudinal critical coordinates at the corner reaches 40%. The latter circumstance allows one to assume that the functions $Y^{I}_{cr} = f(X)$ and $Y^{II}_{cr} = f(X)$ are slightly nonlinear in the immediate vicinity of the corner zone. The experimental values of the angles of inclination θ_1 and θ_2 are somewhat smaller than 5°40', with $\theta_1 > \theta_2$. Using Eqs. (1) and (2) it is appropriate to adopt $\theta_1 = 5°10'$ and $\theta_2 = 4°50'$.

We note in conclusion that the irregular distribution of the local heat exchange coefficients, and consequently of the local coefficients of friction in cross sections of the dynamic initial section of rectangular channels, makes understandable the nature of the secondary flows discovered relatively long ago in their corner zones [7, 8].

NOTATION

d, m: equivalent diameter of rectangular channel; $X^{I}_{cr.c}$ and $X^{II}_{cr.c}$, m: longitudinal coordinates of transition points at corner; X^{I}_{cr} and X^{II}_{cr}, m: longitudinal coordinates of boundaries of region of natural transition in middle part of wall; X: longitudinal coordinate measured from entrance rim; X_1: longitudinal coordinate measured from start of heating; X_0: length of initial unheated section; Y_{cr}, m: transverse coordinate of boundaries of transition region; α_{loc}, W/m$^2\cdot$°C: local coefficient of convective heat exchange; α_l, W/m$^2\cdot$°C: local coefficient of radiant heat exchange; Re_d: Reynolds number referred to equivalent diameter of channel; E: emf developed by heat flux pickup, μV.

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