EXPERIMENTAL INVESTIGATION OF TURBULENT HEAT TRANSFER AT THE BOUNDARY OF A SEPARATION ZONE

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An account is given of a steady thermal method for direct determination of the intensity of turbulent transfer at the boundary of a separation zone behind bluff bodies. A substantial advantage in the use of this method, in comparison with other known methods, is the fact that the temperature is constant in the whole of the separation zone, which allows us to avoid large errors in determining the mean-integral temperature of the zone. Using this method, data have been obtained on the distribution of local turbulent heat transfer coefficients along the zone interface in separated flow of a two-dimensional stream over steps and a flat plate. It is shown that the turbulent transfer coefficient in the zone is proportional to the velocity of the oncoming stream, and depends on the shape and dimensions of the bluff body. By replacing the velocity of the oncoming stream by the velocity in the constrained section over the body, a generalized relation has been obtained for bodies of different dimensions and shape.

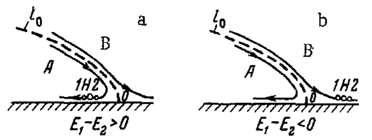

Fig. 1. Variation in the sign of the thermal emf of a differential thermocouple in passing through the junction point. A is the separation zone, B is the main stream, l_0 is the interface line, O is the junction point, H is the heater, 1 and 2 are thermocouples.

An experimental confirmation was performed in [1] of Lavrent'ev's hypothesis that the vorticity of the fluid is constant in the separation zone. This hypothesis is basic to the "mixed" motion scheme, according to which a stream of ideal fluid flowing over a body and undergoing separation may be divided into two regions: a region of eddying motion (ω = const), and a potential region, the requirement being that the velocity field remain continuous at transition through the interface. The scheme is purely kinematic and assumes that the flow in the separation zone does not damp the eddying motion of the ideal fluid. In a real fluid the eddying motion in the separation zone is maintained due to the energy of the external stream, via turbulent mass and momentum transfer through the interface between the regions.

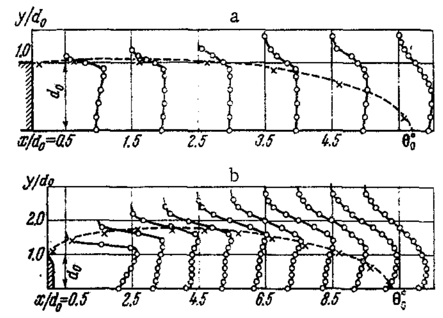

Fig. 2. Temperature in the separation zone behind a step with d_0 = 100 mm (a), and behind a plate with d_0 = 50 mm (b). The scale is 1 mm corresponds to 0.4° K.

The task of the present paper is an experimental investigation of the laws of turbulent transfer at the interface between the vortex and potential flow regions.

The literature has only a few papers devoted to this question [2–6]. In the majority of these, the turbulent transfer intensity is determined indirectly through the value of the mean residence time for outside gas mixed into the separation zone:

$$D^\circ = V^\circ r^\circ / S^\circ \tau^\circ. \qquad (1)$$

Here V°, S°, r° are the volume, surface area, and mean radius of the zone, respectively, $\tau°$ is the mean residence time of impurity in the zone, and D° is the turbulent transfer coefficient.

Only [1] gives results of direct measurement of mass transfer intensity in the circulation zone behind a cylinder with respect to the main stream. Hydrogen was fed steadily into the circulation zone through a narrow slit near the rear of the cylinder, and its concentration field was determined after steady conditions were established. The mass transfer intensity was determined to be

$$m = g / C. \qquad (2)$$

Here g is the mixture source strength, and C is the mean integral concentration of impurity in the separation zone.

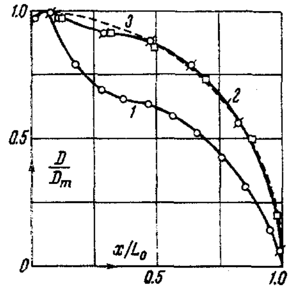

Fig. 3. Distribution of local turbulent transfer coefficients along the separation and main stream zone interface line for the plate 1 and the step 2, and a calculated curve for the step 3.

Neither of the above methods allows the possibility in principle of determining local values of turbulent transfer coefficient at the zone interface.

The present paper makes use of a thermal stationarity method which yields a picture of the distribution of local values of the turbulent transfer coefficient, in addition to the mean values. In this method a heat source of total strength Q is distributed continuously over the zone interface. As is shown below, the method of distributing the power of the individual heaters q_i along the zone interface line has an appreciable effect on the temperature field in the separation zone, but has no effect on the mean turbulent transfer coefficient. Let m be the mass of gas carried away from the separation zone through the interface in unit time. Under steady conditions the amount of heat emitted by the sources must equal that removed from the separation zone by turbulent transfer, i.e.,

$$Q = mc_p (T_0 - T_\infty) = mc_p\theta_0. \qquad (3)$$

Here T_0 is the mean gas temperature in the separation zone; T_∞ is the temperature of the gas in the external stream; c_p is the specific heat of the gas.

Therefore the turbulent transfer intensity is determined to be

$$m = Q / c_p\theta_0. \qquad (4)$$

Using Eq. (4) we may determine the turbulent transfer coefficient of the zone D°, and the mean dwell time, τ_0, of the heated gas in the separation zone:

$$D^\circ = Q / c_p\theta_0\rho l_0,$$
$$\tau_0 = V^\circ\rho / m = M / m. \qquad (5)$$

Here ρ is the gas density, l_0 is the length of the zone interface line, $M = V^\circ\rho$ is the mass of gas accumulated in the separation zone, and V° is the volume of the separation zone.

The experiments were conducted in a rectangular wind tunnel with channel dimensions 150 × 260 mm. Measurements were taken on two types of bluff bodies producing widely different flows: a body with steps of height d_0 = 25, 50 and 100 mm, and a flat plate of thickness d_0 = 50 mm. The channel blockage for the steps was 0.096, 0.192 and 0.385. The oncoming stream velocity was varied from 3 to 21 m/sec,

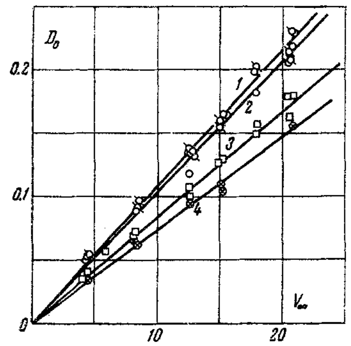

Fig. 4. Dependence of the mean turbulent transfer coefficient, D_0 m^2/sec on the oncoming stream velocity, V_∞ m/sec for the plate 1 and the step of height d_0 = 100 mm (2), 50 mm (3), and 25 mm (4).

corresponding to variation of Reynolds number $R = V_\infty d_0/\nu$ from $1\cdot10^4$ to $14\cdot10^4$. The zone interface line was calculated from the straight through stream velocity field behind the cut-off edge of the bodies as being the total mass flow line. The point of reattachment of the separated stream to the floor of the channel was determined by means of a specially developed differential thermal method. The method was based on the well-known fact that the direction of the stream velocity vector changes to the opposite sign in going through the reattachment point.

A wire heater mounted near the supposed reattachment point and having thermocouples equally spaced from it and joined in a differential circuit may be used to determine the direction and magnitude of the stream velocity vector in the form of a thermal emf imbalance of definite sign (Fig. 1). The stream reattachment point is determined as the coordinate where the thermal emf changes sign. The lengths L_0 of the separation zones found in this way turned out to be 5.75, 5.3, and 5.7 for steps of height d_0 of 25, 50, and 100 mm, respectively.

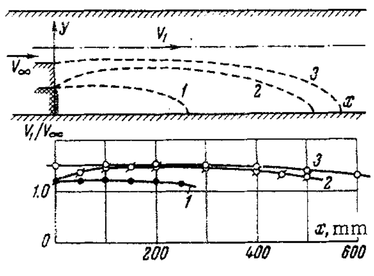

Fig. 5. Distribution of main stream velocity along the separation zone on the line y = = 130 mm for a step with d_0 = 50 mm (1), a plate with d_0 = 50 mm (2), and a step with d_0 = 100 mm (3).

Heat sources of different strengths were set up along the entire zone interface line (somewhat below it).

In the first experiments the power of all the heaters was the same, which led to considerable non-uniformity in temperature distribution along and over the zone interface. This temperature non-uniformity indicated a variation in local turbulent transfer coefficient along the zone interface line. From our first tests, and also from the results of other work, it was known that the mean turbulent transfer coefficient for the whole zone was directly proportional to the velocity

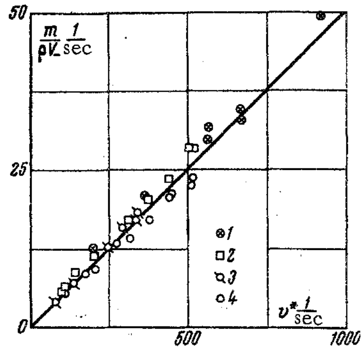

Fig. 6. Generalized dependence of the turbulent transfer at the boundary of the separation zone on the parameter $V^* = V_1/d_0$ for the steps of different dimensions and for the plate; for the steps 1) d_0 = = 25 mm, 2) d_0 = 50 mm, 3) d_0 = 100 mm; for the plate 4) d_0 = 50 mm.

of the stream washing the body. From this, the assumption was made that the local turbulent transfer coefficient is directly proportional to the stream velocity at any point of the zone interface line. From this assumption, if the distribution of heater power along the interface line is proportional to the stream velocities, we should expect that the temperature proves to be the same over the entire zone.

An experimental verification of this assumption was done. The temperature in the separation zone was measured with a differential nichrome-constantan thermocouple formed from wire of diameter 0.2 mm. The thermocouple cold junction was located in the external stream, while the hot junction could be positioned at any point in the separation zone by means of a traverse mechanism. The temperature at each point was measured twice—at the start and at the end of the regime, and the arithmetic mean value was taken. Recording of the temperatures was done with a P2/1 multipoint automatic potentiometer.

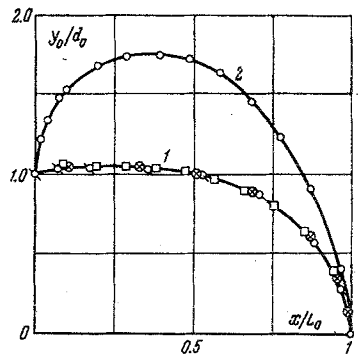

Fig. 7. The line dividing the zones for steps of height d_0 = 25, 50 and 100 mm (1), and for the plate with d_0 = = 50 mm (2).

Figure 2 shows the temperature field in the separation zone behind a flat plate (b) and behind a step (a) of height 100 mm, corresponding to a total heater power Q = 500 W and oncoming stream velocity v_∞ = = 8.3 m/sec. The dashed lines indicate the position of the zone interface line, and the crosses indicate the position of the heat sources. The temperature distribution in the separation zone is similar in nature for all the other values of oncoming stream velocity and total heater power. It is seen in Fig. 2 that the temperature in the separation zone is constant along the length. Calculation shows that the deviation $\theta_i(x)$ of mean integral temperature at the different sections of the zone from the mean integral temperature of the zone θ_0 did not exceed 5%. The deviation of the local temperature values $\theta(x, y)$ in various sections from the mean integral value $\theta_i(x)$ also did not exceed 5%. Only in the region adjacent to the rear of the bluff body did the latter error reach 13%.

Thus, it may be considered, with sufficient accuracy, that the temperature in the separation zone is indeed constant under the above distribution of heat source power along the interface line. It may therefore be considered valid to assume that the local turbulent transfer coefficient is proportional to the stream velocity at any point along the zone interface line. Figure 3 shows distribution curves for relative values of local turbulent transfer coefficient along the interface line for the plate 1 and the steps 2. The local coefficient values for all the steps lie on one curve which is well approximated by the equation for a circle (the dotted line in Fig. 3):

$$(D/D_m)^2 = 1 - (x/L_0)^2. \qquad (6)$$

The curve for the plate has a more complex form and does not lend itself to simple analytic description. To calculate the mean value of the turbulent transfer coefficient the mean integral zone temperature was determined:

$$\theta_0 = \sum_{i=1}^{n} F_i \theta_i(x) \Big(\sum_{i=1}^{n} F_i \Big)^{-1} = \frac{1}{F_0} \sum_{i=1}^{n} \theta_i(x) F_i,$$

$$\theta_i(x) = \frac{1}{y_0(x)} \int_0^{y_0(x)} \theta(x, y)\, dy. \qquad (7)$$

Here $\theta_i(x)$ is the mean integral temperature at the section $x = x_i$ of the separation zone, $\theta(x,y)$ is the local temperature, $y_0(x)$ is the ordinate of the zone interface line at the section $x = x_i$, F_i is the area of the separation zone between sections i and i + 1, and F_0 is the area of the whole zone.

From the mean integral zone temperature thus found, the turbulent transfer coefficient* is determined according to Eq. (4). The results obtained are shown in Fig. 4 in the form of the dependence of the turbulent transfer coefficient of the zone on the oncoming stream velocity. There 1 corresponds to the plate, and 4, 3, and 2 to steps of height d_0 = 25, 50, and 100 mm, respectively. It may be seen from Fig. 4 that the turbulent transfer coefficient is directly proportional to the oncoming stream velocity and depends on the shape and dimensions of the bluff body. The effect of the bluff body shape may be seen, other conditions being equal, by comparing Lines 1 and 3. The turbulent transfer coefficient for the plate is 25% higher than for the step of the same height. This may be explained by the fact that the stream velocity along the separation zone is higher in flow over the plate than in flow over the step, as is seen in Fig. 5. The upper part of Fig. 5 shows contours of the separation zone in flow over steps of height d_0 = 50 (1) and 100 mm (3), and over a plate of height d_0 = = 50 mm (2), while the lower part shows the stream velocity distribution, with the same notation, along the separation zone, on the line y = 130 mm. This velocity increase is connected with the large compression of the main stream behind the plate, in comparison with the step of the same size.

Comparison of relations 2, 3, and 4 in Fig. 4 enables us to estimate the effect of bluff body dimensions. However, since the height of the channel, H, remained constant in all the tests, the effect of body dimensions may be investigated only in combination with change in the section blockage $\varphi = d_0/H$. It may be seen from Fig. 4 that an increase of body size and of the blockage associated with it leads to an increase in turbulent transfer. This may also be explained by an increase in velocity of the main stream along the separation zone with increase of section blockage (Curves 1 and 3 on Fig. 5).

Following on from what has been said, we may attempt to combine results obtained for the bluff bodies of different sizes and shape by bringing in the velocity in the constrained section above the body in lieu of the velocity V_∞ of the oncoming stream

$$V_1 = V_\infty \frac{H}{H - d_0} = V_\infty \frac{1}{1 - \varphi}.$$

The results of the generalization are given in Fig. 6 in the form of the dependence of the quantity $m/\rho V^\circ$ on the hydrodynamic parameter V_1/d_0; they are described by the straight line

$$m / \rho V^\circ = K V_1 / d_0 \qquad (K = 0.05). \qquad (8)$$

The scatter of the points around the above relation does not exceed 8%. In order to calculate the values of the separation zone volumes appearing in Eq. (8) we need to know the position of the division line. Figure 7 shows the generalized experimental curve 1 for the steps of three sizes in the form of the relation $y_0(x)/d_0 = f(x/L_0)$, and a similar curve 2 for the plate. The piecewise approximation of curves 1 and 2 allows us to obtain an expression, with an error not exceeding 3%, for the area of the separation zone in terms of the height of a bluff body and the length of the separation zone. The area of the separation zone behind the step is

$$F_0 = {}^1\!/_2\, d_0 L_0 \,[1 + {}^1\!/_4\, \pi], \qquad F_0 = {}^7\!/_{16}\, \pi\, d_0 L_0. \qquad (9)$$

Hence we determine the volume of the separation zone $V^\circ = F_0 B$, where B is the width of the channel.

From the fact that the left side of Eq. (8) is a quantity which is the reciprocal of the mean residence time of the heated gas in the separation zone, we may obtain

$$\tau_0 = 20\, d_0 / V_1. \qquad (10)$$

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*The error in determining D_0 by this method is 4–5%

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