TRANSFER COEFFICIENTS BEHIND A SYSTEM OF PARALLEL CHANNELS AND IN AN ANNULAR CHANNEL OF COMPLEX FORM

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As a result of measuring the temperature (concentration) field behind the source, the transfer coefficients are determined for flow in a tube behind a system of parallel channels ($l/d = 50$) and in an annual channel of complex cross section.

I. With a view to predicting the development of nonuniformities of various types in the flow behind a system of parallel channels in a tube and in an annular channel of complex form, the corresponding transfer coefficients in turbulent flow are determined experimentally. Their magnitudes and the particularities of their variation are established as a result of analyzing measurements of the temperature and concentration fields behind a source placed in the flow.

Under the assumption that the transfer coefficient D_m remains constant over the cross section and varies weakly with increasing distance from the source, the energy equation for the flow symmetric with respect to the axis is obtained

$$V\frac{\partial T}{\partial x} = D_m\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right). \tag{1}$$

It is assumed that viscous forces, molecular diffusion, the variation in static pressure, and the turbulent transfer in the longitudinal direction may be neglected.

A particular solution of Eq. (1) is the solution for a point source. As a result of analyzing this solution, it is simple to show that for any cross section a relation of the following form may be written

$$T(x,\ y)/T(x,\ 0) = \exp(-y^2/2\overline{y^2}), \tag{2}$$

where $\overline{y^2}$ is the square of the mean square displacement of the elements in the direction y.

If b denotes the "width" of the Gaussian curve at $T = 0.5T(x,\ 0)$, Eq. (2) may be rewritten in the following form, after taking logarithms

$$\overline{y^2} = 0{,}179b^2. \tag{3}$$

The relation between $\overline{y^2}$ and D_m may be obtained by integrating the solution for a point source over the cross section and differentiating the result with respect to x.

Without reproducing the analysis of the relation of $\overline{y^2}$ with ε and D_m, in particular, outlined in detail in [1], its results are used for the case of homogeneous isotropic turbulence:

1) for small diffusion times (small distances from the point source)

$$\overline{y^2} = \varepsilon^2 x^2,$$
$$x = Vt,\quad \varepsilon = \sqrt{\overline{v'^2}}/V; \tag{4}$$

2) for large diffusion times (large distances from the source)

$$\overline{y^2} = 2D_m(x - x_0). \tag{5}$$

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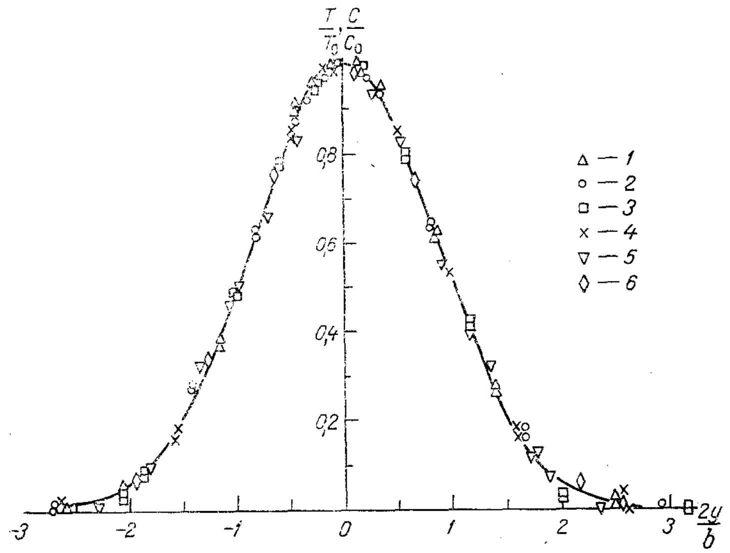

Fig. 1. Distribution of T/T_0 (C/C_0) in the direction transverse to the flow: a) beyond the system of channels with x/M = 3.05 (1), 6.1 (2), 9.14 (3), and 12.2 (4); b) in an annular channel in the rod zone (5) and in the smooth zone (6).

II. The flow characteristics behind grids in aerodynamic tubes have been investigated in sufficient detail in [2, 3] and elsewhere. There are also data on the flow behind grids and perforated barriers in engineering tubes; see [4, 5], etc.

Experimental results for the turbulent diffusion coefficient with flow in a tube behind a system of parallel, sufficiently long, circular channels (l/d = 50) are considered below. The working section of the apparatus includes a block (porosity 0.35) of 31 tubes arranged in a grid with a triangular aperture distribution (the internal diameter of a single tube d = 8 mm; the distance between the tube axes M = 12.8 mm; the distance between the ends of the grid is 400 mm). The tube length corresponds to l/d = 50; therefore, it may be reliably supposed that the characteristics of turbulence in the channels correspond to developed turbulent flow in the tube.

In the central channel of the block, heated air is supplied (indicator flow rate); in the other 30, air at normal temperature is supplied (basic flow rate). The temperature distribution in the tube cross section at different distances from the channel inlet is studied. The air flow rate is determined using critical nozzles, which are preliminarily calibrated to an accuracy of ∿2%. The air temperature over the cross section behind the end of the block is measured using a thermocouple fixed in a tracking unit. The accuracy with which the thermocouple coordinate is established is 0.2 mm.

For diffusion behind a point source, Eq. (2) is strictly true. Estimates show that, in the present experiments, with a tube radius R = 4 mm and $\overline{y}^2 \simeq 50$ mm² (at a distance from the end corresponding to x/M ≃ 5), the error in determining $\overline{y}^2$ from the point-source formula is ∿7.5% and decreases considerably with increasing distance from the source.

For engineering applications, the characteristics of the flow at moderate distances from the ends of the blocks with a system of parallel channels (up to x/M ∿ 10-20) are of most interest. This is the region investigated in the present experiments.

The temperature distribution of air in the cross section at various distances from the end of the block for one set of experimental conditions (air velocity in basic-flow-rate channels V_{ba} = 63 m/sec; air-velocity ratio in indicator- and basic-flow-rate channels V_{in}/V_{ba} = 0.75) is shown in Fig. 1. For other experimental conditions, the experimental points are also sufficiently well described by a Gaussian distribution; the continuous line in Fig. 1 corresponds to Eq. (2). Usually, this indicates that the diffusion process occurs in an isotropic-turbulence field.

In most experiments, equal air velocities are maintained in the outlet cross sections of the channels of basic and indicator gas flow rates. The equal velocity values vary in the experiments from 16 to 63 m/sec — Re = $(0.9\text{-}3.6)\cdot 10^4$, respectively. To estimate the

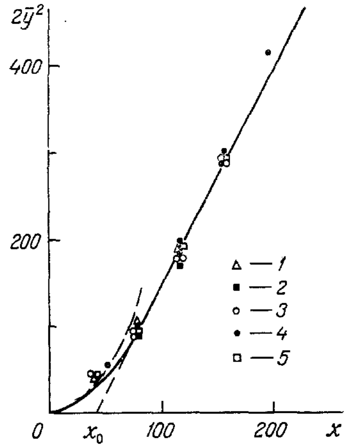

Fig. 2

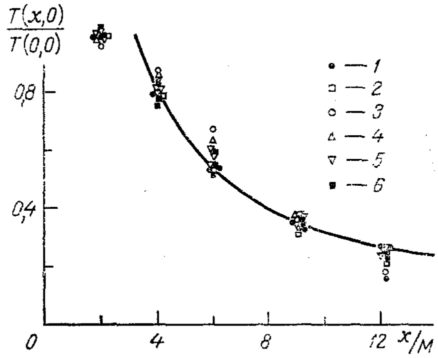

Fig. 3

Fig. 2. Dependence of $2\overline{y}^2$ on x: 1) V_{ba} = 16 m/sec; V_{in}/V_{ba} = 1.3; 2) 31; 1.27; 3) 47; 1.0; 4) 61; 0.08; 5) 63; 0.75. $2\overline{y}^2$, mm²; x, mm.

Fig. 3. Distribution of T downstream from the source: 1) V_{ba} = 16 m/sec; V_{in}/V_{ba} = 1.2; 2) 24; 0.6; 3) 31; 1.2; 4) 48; 0.8; 5) 62; 0.65; 6) 62; 0.8.

influence of the error in specifying equal velocities at the channel outlet, experiments are performed with variation in the ratio of mean air velocities in the central and other channels in the range 0.75-1.3.

As a result of analyzing the experimental data it is found that the absolute value of $\overline{y}^2$ is practically (within the limits of experimental accuracy) independent of the ratio of the air flow rates and the absolute air velocity in the given ranges of variation.

Values of $\overline{y}^2$ are shown in Fig. 2 for different distances from the channel outlet; they fit satisfactorily on a straight line passing through the coordinate origin

$$2\overline{y}^2 = 4(x - x_0)\,D_m/V\ (\overline{y}^2 = 0 \text{ when } x = x_0 = 41\,\text{mm}).$$

The data in Fig. 2 show that, at the given distances from the end of the block, beginning at x = 70 mm (x/M ∿ 5.5), the turbulent diffusion coefficient remains constant with respect to x, within the limits of experimental accuracy (D_m/V = 0.625 mm; D_m/VM = 0.0488), and does not depend on the ratio of the basic and indicator air flow rates and the absolute air velocity in the experimental range. Close to the end of the block, the curve of $2\overline{y}^2 = f(x)$ touches the parabola $2\overline{y}^2 = 2\varepsilon^2 x^2$ when $\varepsilon = 0.1$.

Experimental results for the excess temperature at the axis of the central jet beyond the end of the channel block are shown in Fig. 3. The curve in Fig. 3 is plotted for y = 0 using the solution of Eq. (1) for a point source. At the point $x = x_0$ (x_0 from the data of Fig. 2), $T(x_0, 0)/T(0, 0) = 1$; when $x \geq x_0$, $T(x, 0)/T(x_0, 0) = x_0/x$. It is evident from Fig. 3 that, for all experimental conditions, the core of the heated jet disappears at a distance from the end of the block corresponding to x/M ∿ 2, and the amplitude of the temperature nonuniformity with respect to x is considerably reduced; at x/M = 12, it is ∿25% of the initial value.

III. Using the above procedure, in a somewhat simplified version for a two-zone thin annular channel (the zones differ in the form of the cross section), the effective mean (over the channel thickness) transfer coefficient is determined, under the assumption that it does not vary over the length and angle in each zone. The channel considered is formed by two coaxial cylindrical surfaces; the inner surface has a smaller radius in the sector ∿100° than elsewhere in the channel. In this depression, along the cylinder generatrix, small-diameter rods are fitted flush with the remainder of the internal cylindrical surface along the cylinder generatrix. Separators to reinforce the rods are fitted periodically over the length of the channel in the depression. The effective transfer coefficient at the section of steady flow in the smooth part of the annular channel and in the rod-distribution sector is determined.

In determining the effective transfer coefficient in narrow channels with walls that are good heat conductors, the indicator gas is expediently chosen as a gas which is different in chemical composition from the basic-flow-rate gas but is at the same temperature so as to eliminate the heat transfer over the wall possible in the thermal measurement method; such heat transfer may significantly distort the temperature field in the gas due to turbulent transfer. In the present work, helium is used as the indicator gas and air as the basic gas. The helium flow rate is chosen so that its velocity at the outlet from a tube source aligned along the flow is equal to the local air velocity. Downstream in the channel cross sections, a mixture of the basic and indicator gases is sampled by a device which is free to move over the periphery of the annular gap and sent to a gas analyzer. In each zone (smooth and with rods), the indicator-gas source is positioned on the median line at equal distances from the lateral geometric boundaries of the zone. The indicator-gas concentration is measured at a distance from the source such that there is no penetration of the indicator gas into the adjacent zone. The transfer characteristics are not investigated immediately in the vicinity of the geometric boundaries of the zones. The experimental data are used to plot a graph of $C_{He} = f(y)$ for the channel cross section with the sampling device. For pressure flow in a plane channel, turbulence is statistically homogeneous in the direction for which the boundary conditions are unchanged (parallel to the walls and perpendicular to the direction of motion). It is assumed that, in these conditions, for a thin annular channel ($\delta/R = 0.035$), the distribution of the mean (over the channel thickness) indicator-gas concentration downstream from a linear source extended from wall to wall is described by the solution of an equation of the type in Eq. (1) for plane flow (a particular solution of the equation is the Gaussian distribution for each x).

Experimental data for $C/C_0 = f(2y/b)$ obtained in a channel with $d_{ex} = 90$ mm (in the smooth zone, $R_{int} = 38.2$ mm; the rod diameter is 4 mm; the distance between the separators is 75 mm) are shown in Fig. 1. The source of indicator gas (helium) is placed at a distance of $l/\delta > 200$ from the channel inlet. The concentration profile is measured at a distance $l/\delta \simeq 245$ from the source.

The experimental profile of the mean (over the channel thickness) indicator-gas concentration downstream from the source in the smooth-wall zone of the channel confirms the assumption that the concentration distribution of indicator gas in the azimuthal direction is Gaussian. At a distance $l/\delta = 245$ from the source, there is practically no penetration of the indicator gas from the smooth zone to the adjacent zone over the circumference of the zone with significantly different flow conditions. At the same distance from the source, an absolute-concentration profile of the indicator gas that is analogous in form but broader in profile is obtained in the zone with rods. The experimental concentration profiles in both zones of the channels (Fig. 2) are described sufficiently well by Eq. (2), which is the solution of Eq. (1) for a point source in plane geometry. This means that an equation of the form in Eq. (1) with a transfer coefficient determined experimentally for each zone may be used in calculating the impurity-component or heat transfer in channels of similar type.

Analysis of experimental data on indicator-gas concentrations in a cross section of the annular channel (under the simplifying assumption that $x_0 = 0$) yields the following values of $D_m/V\delta$ for $R_e = (2.8\text{-}5)\cdot 10^4$: in the smooth zone of the channel 0.015; in the zone with rods 0.114.

NOTATION

V, mean velocity; v', pulsational component of velocity; T, temperature; x, coordinate along the flow; y, r, coordinate transverse to the flow from the source axis for plane and cylindrical geometry, respectively; l, length in the direction x; d, diameter; ε, intensity of turbulence; $\bar{y}$, mean square displacement of the elements of the substance being transferred along the y axis; D_m, turbulent diffusion coefficient (effective transfer coefficient for annular channel); δ, thickness of annular channel in its smooth part; R, radius; M, distance between centers of apertures in spacing grid of tube assembly; Re, Reynolds number; t, time; C, percentage concentration of indicator gas in basic-flow-rate gas. Indices: 0, parameters at the source axis (for T and C) and at $\bar{y}^2 = 0$ (for x); ex, external; int, internal; in, indicator; ba, basic.

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