IMPURITY DIFFUSION IN A FLOW DOWNSTREAM OF TURBULENCE-GENERATING GRIDS

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UDC 533.73

The velocity fields and intensity of flow turbulence after grids in ordinary pipes have been measured. The diffusion of an impurity (helium) injected into the flow immediately after the the grid is investigated.

The flow downstream of grids placed in ordinary pipes has a structure that is very similar to flow in furnaces and combustion chambers for certain chemical industrial equipment.

Very few measurements have been conducted immediately after the turbulence-generating grid, and there is almost no information on the flow structure there. At large distances from the grid, for $X/M > 10$ to 20, the turbulence problem has been studied in several papers ([1-3] and others). In those papers the basic laws governing the variation of the turbulence scale and intensity with distance from the grid have been found, the fluctuation energy distribution with respect to the frequency spectrum determined, etc. The turbulent diffusion process behind the grid has received less attention [4, 5].

The transport of mass across the flow is characterized by the variance σ^2 of the concentration distribution C(r) or standard deviation σ. In a homogeneous isotropic turbulence field, σ^2 is related to the turbulence parameters by the fundamental turbulent diffusion equation

$$\sigma^2 = 2v^2 \int_0^t d\tau_1 \int_0^{\tau_1} R d\tau. \tag{1}$$

This equation has two limiting solutions, which, expressing the diffusion time t in terms of the distance x from the impurity source to the plane of measurement and the average flow velocity U over the length x, may be represented in the form

$$\sigma = \varepsilon x \tag{2}$$

for small x, and

$$\sigma^2 = 2 \frac{D}{U} x + \text{const} = 2\varepsilon l x + \text{const} \tag{3}$$

for large x. Relations (2) and (3) enable us to relate the quantity σ to the turbulence intensity $\varepsilon = v/U$, the turbulent diffusivity $D = vl$, and the turbulence scale l.

In practice the values of σ are determined from the spreading of an impurity jet introduced into the flow through a small-dimension source. Inasmuch as the impurity concentration profiles C(r) in turbulent flow are well described by a Gaussian curve in the majority of cases, the value of σ can be defined as the half-width of C(r) for $C \approx 0.607\,C(0)$, where C(0) is the impurity concentration on the injected jet axis in the measurement plane.

Immediately behind the grid the flow represents a set of individual streams issuing from the grid openings and gas eddy zones after the grid connecting strips. In the jet flow region the flow turbulence is anisotropic, and in the radial direction r it is inhomogeneous. According to the data of [2], however, for $X = 4M$ the turbulence can already be regarded as practically isotropic. An analogous conclusion is inferred from a comparison of the results of measurements of the longitudinal [6] and transverse [7] components of the fluctuation velocity after grids in ordinary pipes.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 19, No. 5, pp. 818-825, November, 1970. Original article submitted October 17, 1969.

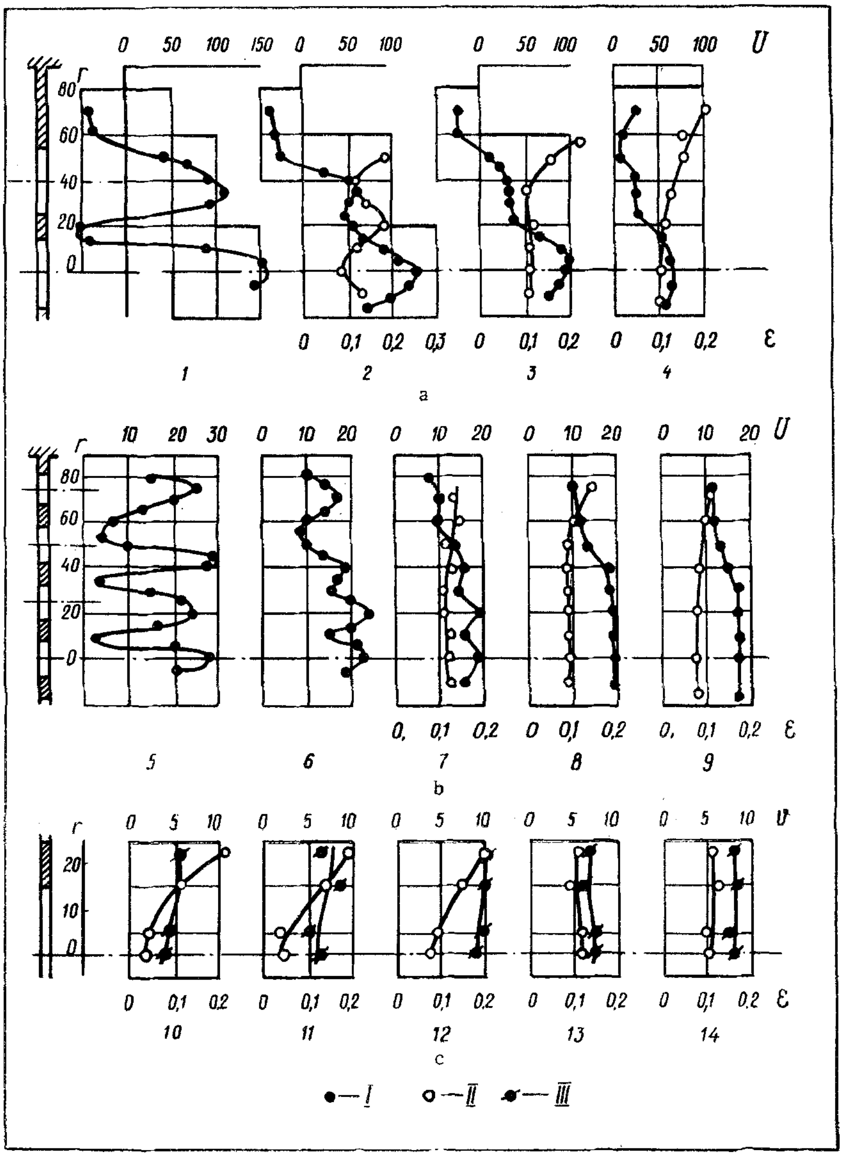

Fig. 1. Average velocity fields and turbulence intensities after grids No. 1 (a) and No. 2 (b) and turbulence intensity and turbulent fluctuation velocity v after the center opening of grid No. 1 (c). I) U; II) ε; III) v; values of X/M: 1) 0.75; 2) 1.5; 3) 2.5; 4) 4.5; 5) 0.4; 6) 1.2; 7) 2.4; 8) 4.8; 9) 8.0; 10) 0.5; 11) 1.0; 12) 1.5; 13) 2.2; 14) 3.5. Grid No. 1: M = 40 mm, d = 30 mm, S = 0.67; grid No. 2: M = 25 mm; d = 16 mm, S = 0.71.

Below we give data from measurements of the velocity profiles and intensity of turbulence downstream of grids and the results of a determination of the standard deviation σ for helium injected into a flow directly after a grid.

The standard deviation σ was determined from the results of measurements of the helium concentration profile C(r) for injection of the gas through a tube having an inside diameter of 1 mm. The helium concentration was determined by the tapping of gas samples and their analysis in an instrument analyzer.

The turbulence intensity ε was determined according to Eq. (2). For the measurements of ε the distance between the helium source and the sampling tube was x = 15 to 25 mm, and the helium was injected along the main flow through a tube 1 mm in diameter. The helium source could be moved along the main flow and in the radial direction, its position being fixed with ± 0.5 mm error. The gas sampling tube, also

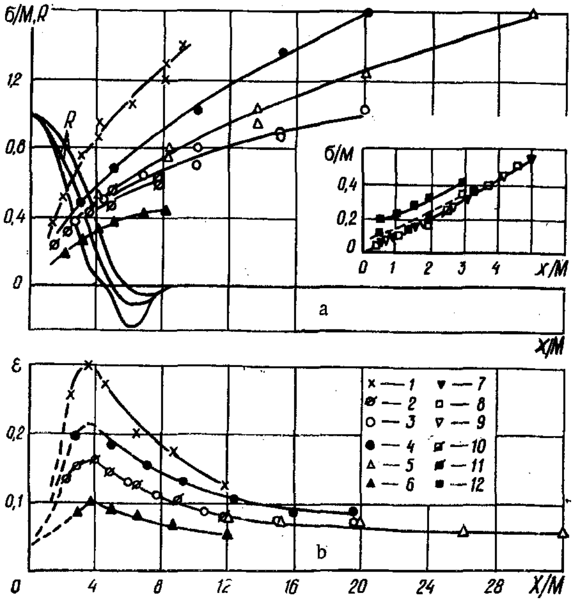

Fig. 2. Standard deviation σ, correlation coefficient R (a), and turbulence intensity ε (b) versus X/M:

Nomenclature	Grid No.	M, mm	d, mm	n	S
	3	34	20	7	0,78
1	4	24	8	13	0,92
2	5	24	16	13	0,67
3	6	12	8	55	0,65
4	7	8	4	127	0,80
5	8	6	4	217	0,65
6	9	24	20	13	0,48

Grid No. 3		
Nomenclature	r_1/M	X_1/M
7	0	0
8	0	0,5
9	0	0,88
10	0,37	0,88
11	0,5	0,88
12	0,5	0,45

1 mm in diameter, was moved simultaneously with the source or independently of it. The displacement and positioning error was ± 0.05 mm in the radial direction and ± 0.5 mm in the longitudinal direction. The value thus determined for ε is the average for the segment x, so that in our presentation of the experimental data we have conditionally referred ε to the midpoint of the segment x.

We investigated the influence of various factors on the measurements of σ and ε and estimated the error of the method. On the basis of the results, we chose helium injection and sampling regimes in which the velocity differences between the main flow, helium injection, and gas sampling did not influence the measurement of σ, determined the distance x required for the measurements of ε, and so on. The influence of the dimensions of the accessory attachments on σ was accounted for by the relation

$$\sigma^2 = \sigma_0^2 - 0.7R_1^2, \tag{4}$$

in which R_1 is the radius of the source and of the sampling tube, and σ_0^2 is the measured value of the variance. In most cases the possible relative error in the determination of σ and ε did not exceed 5%.

The total and static pressures were measured with a standard T-fitting. The values of v were determined from the data of measurements of the turbulence intensity and flow velocity.

We investigated the flow after grids comprising perforated disks 8 mm thick, which were set up in pipes 105 and 180 mm in diameter. The grid openings were spaced at the vertices of equilateral triangles having a side M (equal to the spacing of the grid openings). The opening diameter d was varied from 4 to 20 mm, and M from 6 to 35 mm. The blockage S of the pipe cross section by the grid, i.e., the ratio of the area occupied by the grid metal to the pipe cross section, ranged from 0.48 to 0.92 for different grids.

The experiments were conducted at an average volumetric flow rate across the grid of 10 to 20 m/sec, and the pressure and temperature were close to the atmospheric values.

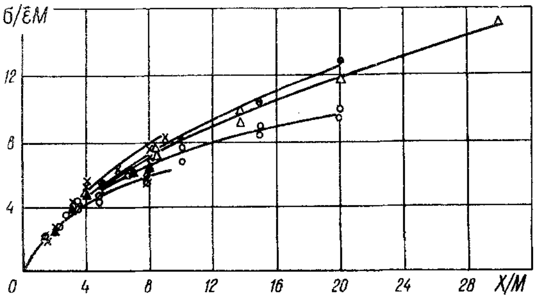

Fig. 3. Generalization of the measurement data for the variance σ in the form $\sigma/\bar{\varepsilon}M = f(X/M)$. See Fig. 2 for the nomenclature.

The flow velocity fields were measured after grids set up in the 180-mm-diameter pipe. The velocity fields U(r) at various distances from grids No. 1 and No. 2 are shown in Fig. 1. Comparing the flow velocity fields after the different grids and, in particular, those represented in Fig. 1, we note that the nonuniformity of the velocity profiles at a large distance from the grid is more pronounced, the greater the "shadowing" of the peripheral part of the flow by the grid and the larger the spacing M between grid openings. The experimentally determined length of the reverse-flow zones after the grid strips does not exceed two or three strip widths, but it is considerably greater at the pipe walls (Fig. 1a).

The turbulence intensity field ε and rms fluctuation velocity field v equalize rapidly with distance from the grid, becoming practically level by the time $X/M > 2$ or 3. This result is illustrated, in particular, by the measurement results for $\varepsilon(r)$ and v(r) at various distances from the center element (opening plus adjacent strips) of grid No. 1; see Fig. 1c. The fields $\varepsilon(r)$ after the grids are also given in Figs. 1a and 1b. In the central part of the flow at $X/M > 4$ they are fairly level, but at the pipe walls the level of ε increases. It is noticeable that for small dimensions of the reverse-flow zones the increase in the turbulence intensity as the pipe wall is approached is small (as in the case of grid No. 2). On the other hand, if the dimensions of the region "shadowed" by the grid at the wall are large, the increase in ε is more appreciable, but even in this case the turbulence in the central part of the flow may be regarded as nearly uniform in the radial direction.

Consequently, the inhomogeneities of the scale M of the velocity field U(r), fluctuation velocity field v(r), and turbulence intensity field $\varepsilon(r)$ of the flow after the grids practically equalize at a distance X = (3-4)M.

Since the field $\varepsilon(r)$ near the grid is nonuniform, the results of measurements of the variance σ^2 can depend on the position of the impurity source relative to the grid elements. Of course, the more nearly uniform the flow turbulence, the weaker will be this dependence and the "more representative" will be the value of σ^2 obtained in the experiment.

We measured the values of σ after a source set up at distances X_1 = (0-0.88)M from grid No. 3 in various positions: on the axis of the center opening ($r_1/M = 0$), after the edge of the opening ($r_1M \approx 0.37$), and after the grid strip ($r_1/M = 0.5$). The results of these experiments are given in Fig. 2a.

It is seen that the experimental points obtained for different positions of the helium source on the axis of the opening ($r_1 = 0$) provide a good fit to a single curve in the coordinates (σ/M, x/M). The displacement of the helium source from the opening axis at X_1 = 30 mm ($X_1/M \approx 0.9$) also does not alter the value of $\sigma(x)$. The dependence $\sigma(x)$ determined at $r_1 = 0.5M$ and $X_1 = 0.45M$, i.e., with the source placed after the grid strip (center), differs appreciably from the other values of $\sigma(x)$. As the distance X_1 is decreased to 0 the value of $\sigma(x)$ does not decrease to the size of the helium source, but remains larger, $\approx$ 6.5 mm at $X_1 = 0.45M$. In this case the source was situated in the reverse-flow zone after the center grid strip. The helium is entrained by the gas flows, filling up the eddy zone; the dimensions of the latter were thus responsible for the large values of $\sigma(x)$. The influence of the size of the eddy zone on σ was taken into account according to Eq. (4), in which the source radius R_1 was replaced by the equivalent zone half-width, which in the given case was $\approx$ 6.5 mm. The dependence $\sigma/M(x/M)$ at $r_1/M = 0.5$ and $X_1/M = 0.45$, corrected according to (4), is represented by the dashed curve in Fig. 2a.

These results suggest that within the limits of experimental error the value of $\sigma(x)$ at distances from the source $x > (1$ to $2)M$ is independent of the position of the source relative to the grid elements and is equal to the standard deviation $\sigma(X)$ measured after the impurity source placed immediately in the grid opening. The dependences $\sigma(X)$ were subsequently determined after the helium source placed on the axis of the center grid opening at $X_1/M = 0$ to 0.5.

The results of our measurements of the standard deviation after grids set up in the 105-mm pipe are shown in Fig. 2a. With increasing distance from the grid the value of σ increases monotonically, but its most rapid growth is observed for $X \leq (3$ to $4)M$. The σ/M level is higher, the greater the blockage of the pipe by the grid. For grids such that the ratio d/M and blockage factor S were equal (grids Nos. 4, 6, and 7) the experimental points for $X/M < 4$ provide a satisfactory fit to a single curve; for large values of X/M the dependence $\sigma/M = f(X/M)$ becomes segregated.

The variation of the turbulence intensity with the relative distance X/M from the grid is given in Fig. 2b. The maximum intensity ε_m is greater, the greater the blockage S of the pipe by the grid, and is identical for geometrically similar grids. The relationship of the $\varepsilon(x)$ level to the blockage parameter S has been noted [8]. The distance X_m from the grid where the turbulence intensity attains the maximum ε_m is equal to (3-4)M for the investigated grids. An analysis of the results and data from other papers (e.g., [2]) shows that the distance X_m is determined not only by the quantity M, but also depends on the relative position and shape of the openings. Thus, for flat square-mesh grids $X_m = (2\text{-}3)M$. Clearly, the value of X_m can also depend on the flow parameters (Reynolds number).

In order to exhibit the influence of the turbulence parameters on $\sigma(X)$ assuming flow isotropicity and homogeneity, we used the experimental curves for $\sigma(X)$ to calculate the Lagrangian correlations R(X). The calculations were carried out according to the equation

$$R(X) = \frac{d^2\sigma^2(X)}{dX^2} \bigg/ \frac{d^2\sigma^2(0)}{dX^2}. \tag{5}$$

The results of the calculations are presented in Fig. 2a. It is important to note that the determination of R(X) according to Eq. (5) incurs sizable errors (by our estimates, as much as 20 to 30% in certain cases), so that the dependences R(X) are given here merely as an example. It is possible on the basis of these data, however, to verify that the correlation coefficient is greater than zero after all the investigated grids for $X/M < 4$ and is equal to zero for $X/M > (7\text{-}10)M$. Consequently, the variance σ^2 for $X/M < 4$ is determined mainly by the turbulence intensity level, and for $X/M > (7\text{-}10)M$ it is determined mainly by the turbulent diffusivity, i.e., by the turbulence intensity and scale.

Knowing the quantity ε_m (Fig. 2b) and the flow turbulence intensity ε_0 in the grid openings (in our case $\varepsilon_0 \approx 0.04$), we can generalize the resulting dependences $\sigma(X)$ at large distances from the grid with acceptable accuracy for practical applications. The experimental data are presented in Fig. 3 in the form $\sigma/\bar{\varepsilon}M = f(X/M)$, where $\bar{\varepsilon} = 1/2(\varepsilon_m + \varepsilon_0)$ is the average value of the turbulence intensity over the segment $X = (0\text{-}4)M$. Despite the approximation used in determining $\bar{\varepsilon}$ the given generalization of the experimental data may be regarded as satisfactory. The discrepancy of the experimental dependences in the interval $R(X) = 0$ for $X > 4M$ is attributable to the differences in the turbulence scales for the investigated grids. Inasmuch as the turbulence scale can be determined by the diffusion method only for $R(X) = 0$, the scale l after the grids can only be determined for $X \geq (7\text{-}10)M$.

Therefore, the diffusion rate of an impurity injected into the flow immediately after the grid is determined for $X \leq (3\text{-}4)M$ only by the turbulence intensity level of the flow after the grid. For $X > (7\text{-}10)M$, i.e., for $R(X) = 0$, the impurity diffusion rate is determined by the turbulent diffusivity.

NOTATION

C	is the helium concentration;
D	is the turbulent diffusivity, mm^2/sec;
d	is the diameter of grid opening, mm;
l	is the turbulence scale, mm;
M	is the grid mesh size, or "spacing" between openings, mm;
n	is the number of grid openings;
R	is the Lagrangian correlation coefficient;
r	is the coordinate of the point in the radial direction, mm;
R_1	is the radius of the injected helium stream, mm;
$S = 1 - F/F_p$	is the blockage of pipe by grid;
F	is the total opening area of grid;
F_p	is the pipe cross section;
t	is the diffusion time, sec;
U	is the average flow velocity, m/sec;
v	is the rms fluctuation velocity, transverse component, m/sec;

X	is the distance from the grid to the plane of measurement, mm;
X_1	is the distance from the grid to the helium source, mm;
X_m	is the distance from the grid at which $\varepsilon = \varepsilon_m$, mm;
x	is the distance from the helium source to the sampling tube, mm;
$\varepsilon = v/U$	is the flow turbulence intensity;
ε	is the flow turbulence intensity in the grid openings;
ε_m	is the maximum value of ε after the grid opening;
σ	is the standard deviation of the helium concentration distribution $C(r)$, mm.

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