SPREADING OF A PASSIVE IMPURITY FROM A POINT SOURCE IN FLOWS WITH DIFFERENT INTENSITY OF TURBULENCE

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The quantitative characteristics of the spreading of a passive impurity from a point source in drift flows with the intensity of turbulence ranging from 0.05 to 0.17 are presented.

In many engineering physics problems it is necessary to know the spreading of passive impurities in flows with a different intensity of turbulence. This work was undertaken in this connection. The experiments were performed in a wind tunnel of the closed type with a cross section of 650 × 650 mm (d_e = 732) and 2000 mm long [1]. In addition, the coefficient of turbulent diffusion along the axis of the air flow in the working serction with $d_e/2\sigma \geq 10$ and Reynolds numbers $Re_M = 2 \cdot 10^3 - 6.35 \cdot 10^3$ were maintained constant, the diameter of a cell in the perforated grid was used as the linear scale. Different intensities of the turbulence of the air flow in the wind tunnel were created by turbulizing grids with different geometric characteristics (Table 1). Depending on the form of the cells and the type of turbulizing grids the intensity of the turbulence of the drift flow in the working part of the wind tunnel varied from 0.05 to 0.17. The measurements performed showed that it is possible to form in the working section of the wind tunnel turbulent flows with different levels of intensity of turbulence in the low-velocity range 0.6-6 m/sec. The formation of turbulent flows for the working section of the wind tunnel ceases at a distance $x/M \geq 15$ from the turbulizing grids.

Separate measurements of the turbulence intensity were compared with the results of other studies [2, 3], and they were practically the same. A 55M10 thermoanemometer combined with a 55D31 integrating digital voltmeter and a 55D35 rms voltmeter were used to perform control measurements of the flow characteristics. These blocks are part of the 55M system of thermoanemometric apparatus manufactured by DISA ELEKTRONIK. The measurements were performed with the help of a 55R01 probe. According to the data provided by the DISA ELEKTRONIK company, the transmission band of the thermoanemometer whose sensitive element consisted of a five micron tungsten filament ranged from 0 to 200 kHz [4]. The calibration voltage dependence at the output of the bridge E versus the velocity u was determined on a special calibrating stand, which is described in detail in [5]. The data obtained were analyzed using a dependence of the form $E = E_0 + Au^n$, it corresponds to the well-known King law [6], describing the heat transfer of a cylinder in a transverse flow. The constants E_0, A, and n were determined by the method of least squares based on minimum variance of the approximation.

The intensity of the velocity pulsations was calculated from the relation $\varepsilon = \varepsilon_e \, \partial u/\partial z$, where ε_e is the rms value of the pulsations of the velocity signal measured with the 55D35 voltmeter.

The accuracy of the measurements was estimated based on the recommendations of [7] taking into account the instrumental errors, calibration errors, errors in the approximating dependences, and errors associated with the method used for the statistical analysis of the random signal [8]. The calculations showed that the error in the measurements did not exceed 5% for the velocity and 12% for the intensity of the velocity pulsations.

In addition to the intensity of the turbulence of the drift flow, determining the structure of the flows and correspondingly the spreading of passive impurities in them, the frequency distribution of the energy of turbulence (energy spectra) was also evaluated. To determine the spectral characteristics of the flows created with the help of turbulizing grids in the wind tunnel, special measurements of their characteristics were performed with the

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TABLE 1. Dependence of the Intensity of Turbulence (ε) of Air Flows on the Geometric Characteristics of Turbulizing Grids

Intensity of turbulence ε	Geometric characteristics
0,05	Grid with square cells, d = 1.6 mm, M = 8 mm
0,07	Perforated sheet with checkerboard arrangement of openings, δ = 3 mm, d=10 mm, t_M=13 mm
0,10	Grid with square cells. d = 7 mm, M = 123.5 mm
0,14	δ = 3 mm, b = 12 mm, M = 24 mm
0.17	d = 25 mm, M = 40 mm

TABLE 2

Dynamic range, dB	Frequency range, Hz	Error, %
0—40	$2\cdot10$—$2\cdot10^4$	±6
0—40	$2\cdot10^4$—$2\cdot10^5$	±10
Above 40 and up to 50	2—$2\cdot10^4$	±10
Above 50 and up to 60	2—$2\cdot10^4$	±25

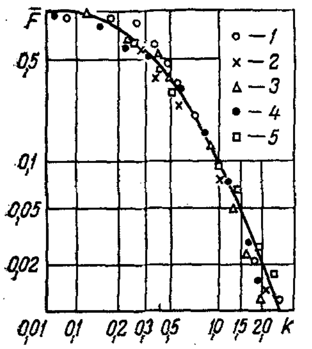


Fig. 1

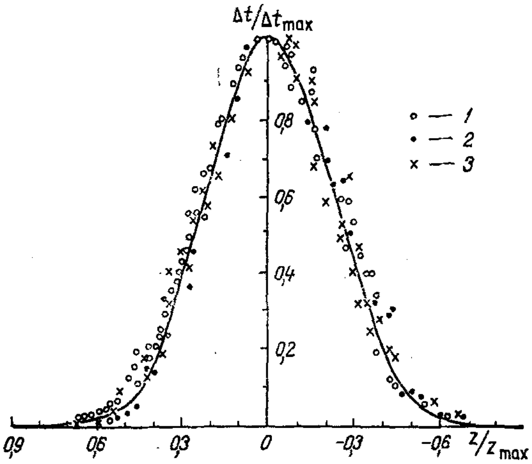


Fig. 2

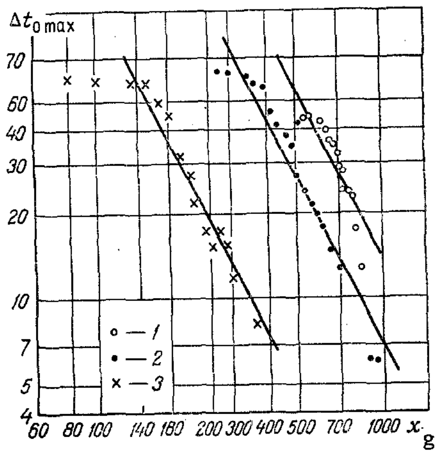
Fig. 1. Generalized energy spectra of turbulent flows with different intensities of turbulence in the drift flow ε: 1) 0.17; 2) 0.14; 3) 0.1; 4) 0.07; 5) 0.05.

Fig. 2. Generalized dependence of the change in the temperature field (concentration of passive impurity) at different distances along the x axis in a direction perpendicular to the drift flow: 1) ε = 0.05; 2) 0.07; 3) 0.17.

help of an S4-34 spectrum analyzer in the frequency band 20 Hz-200 kHz and of the turbulence intensity of the flow 0.05-0.17. The error in the frequency did not exceed $\pm(0.1f + 10)$ Hz, where f is the frequency measured on the analyzer scale.

The errors in the measurements of the absolute levels of the components of the spectra as a function of the frequency and dynamic ranges are presented in Table 2. The frequency characteristics of turbulent flows, formed in a wind tunnel with different turbulizing grids, were determined. With their help the energy spectra shown in Fig. 1 were constructed in a dimensionless form. As can be seen from the figure, the expreimental spectral characteristics of the flows behind different turbulizing grids, forming different levels of turbulence intensity, are practically identical.

The quantitative relation describing the spreading of a passive impurity was determined by the method used to investigate experimentally the temperature distribution in different



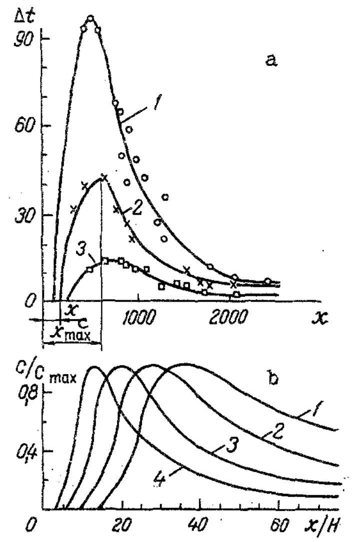


Fig. 3 Fig. 4

Fig. 3. Change in the maximum temperature from a point source along the x axis: 1) $\varepsilon = 0.05$; 2) 0.07; 3) 0.17. Δt_{0max}, °C: x_g, mm.

Fig. 4. Temperature distribution (concentration of passive impurities) along the x axis on the standard surface of the channel: a) with constant intensity of turbulence $\varepsilon = 0.07$ and different source heights H: 10 mm; 2) 15; 3) 20; b) with a constant source height and different levels of turbulence in the drift flow ε: 1) 0.07; 2) 0.12; 3) 0.17; 4) 0.27. Δt, °C; x, mm.

sections of the flow behind a point source [9]. The temperature fields were created by injecting hot air through a tube 30-60 mm in diameter positioned coaxially relative to the main flow. During the experiments the following basic characteristics were measured: the average velocity and temperature of air flows in the working section in the wind tunnel and in the tube used to inject the impurity, the temperature fields in different sections along the flow, the turbulent pulsations of the velocity of the drift and injected flows, and their frequency characteristics. The necessary condition for carrying out experiments is that the velocities at the outlet from the continuous point source and of the main flow must be equal and the flow structure must be the same. For this condition to be satisfied, a turbulizer, forming an impurity flow structure which was approximately the same as that of the drift flow, was placed into the tube used to inject the impurity. During the experiments the temperature fields were recorded automatically and then analyzed.

As follows from an analysis of the experimental data, the spreading of the temperature field (flare angle of the impurity plume) in the working section of the wind tunnel remains constant for the fixed perforated grid responsible for the peaking. The temperature fields for different sections along the x axis are presented in the general form $\Delta t/\Delta t_{max} = f(z/z_{max})$ in Fig. 2. It should be specially noted that the conditions under which hot air was injected into the drift flow were chosen so as to practically exclude flotation of the plume in the working section of the wind tunnel. The temperature fields in the velocity range under study at different distances along the flow, formed by the turbulizing grids, turned out to be similar to one another and are described quite well by the equation

$$\frac{\Delta t}{\Delta t_{max}} = \cos^8\left(\frac{z}{z_{max}}\right),$$

where z/z_{max} varies over the interval $(-\pi/2, \pi/2)$.

The nature of the spreading of the maximum temperature (or maximum concentration of the passive impurity) from the point source along the x axis is important. It is evident from the experimental curve shown in Fig. 3 that the jet effect appears next to the source, and the temperature of the jet simulating the passive impurity is practically constant. But already at distances of $(3\text{-}10)d_0$ (depending on the intensity of the turbulence in the drift flow) the change in the maximum impurity concentration is inversely proportional to the square of the distance from the source of emission.

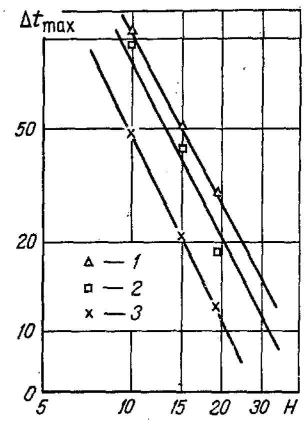


Fig. 5. Maximum temperature on the surface of the channel versus the height at which the point source is located 1) $\varepsilon = 0.05$; 2) 0.07; 3) 0.17. H, mm.

Because of the finite rate of spreading of the impurities in the turbulent flow, their motion occurs in a statistically definite conical space. When impurities flow out of a source raised above a surface, there exists a zone in which there are virtually no passive impurities, i.e., the so-called "transition zone" of the plume. It is of practical importance to know the length of this zone as a function of the characteristics of the drift flow, since this would make it possible to solve in a better-founded manner the problem of the spreading of impurities both in the drift flow itself and at the wall of the channel.

To find the transition zone of the plume and the concentration distribution at the surface of the channel we shall use Seaton's hypothesis about two sources of identical intensity, with the coordinates $z_1 = H$ and $z_2 = -H$, respectively. Here H is the distance between the impurity and the boundary surface of the channel. We obtain the concentration distribution on an "arbitrary surface" by summing the concentration from both sources (in this case the boundary condition $\partial c/\partial z = 0$ holds at $z = 0$, i.e., it is assumed that the surface of the channel is an impenetrable surface in the absence of impurity absorption). It is undoubtedly more accurate to take into account impurity absorption by the surface, but this substantially complicates the experiment without significantly increasing the accuracy of the solution of the problem, especially in practical applications of the computational results. The study of impurity absorption by different surfaces is an independent problem.

To construct a graph of the impurity concentration distribution on the surface, we shall use the standard arrangement of surfaces at three levels from the axis of the source of passive impurity, and we shall thereby determine the effect of the height at which the source is located on the maximum concentration of the passive impurities. It should be noted that because of the comparatively small dimensions of the experimental setup and the relatively low intensity of the source, under these conditions, the experimental possibilities were substantialy restricted, so that in order to determine the transition zone of the plume and to study the effect of the source height on the maximum concentrations at the surface, standard planes placed at three levels were used: 10, 15, and 20 mm from the location of the concentration maximum. The point source was placed on an axis parallel to the x axis, passing through the axis of the tube used to inject the impurities.

The experimental dependence of the temperature distribution (impurity concentration) at different distances from the source on the axis passing at the level of the "standard surface" with a turbulence intensity of 0.07 is shown in Fig. 4a. Analysis of the dependence presented shows the relationship between the maxima of the concentrations, the position of the maximum points, and the transition zone of the plume. The size of the latter is determined with a definite accuracy, so that the distance up to the point of contact of the plume and the surface of the channel is established with an error. However, from the nature of the spreading of a passive impurity in turbulent flows, automatically recorded in experiments with different intensities of turbulence in the drift flows, it follows that the plume, as it spreads has a distinct conical form and the average concentrations permit establishing the transition with quite high accuracy. In experiments employing a microthermocouple, which makes it possible to measure the temperature difference between the heated impurity and the drift flow to within 0.1°C, the boundary of spreading of the plume in the drift flow was determined with an error of 0.1% at the beginning of spreading of the impurity and with an error of 1% at the end. In determining the boundary of the plume, however, in the case of different source heights this quantity varies from 0.3% for $\varepsilon = 0.05$ to 0.5% for $H = 15$ mm and $\varepsilon = 0.17$. If the temperature pulsations and the error in averaging the temperature fields are taken into account, the error in the determination of the point of contact of the plume and the surface of the channel increases, and in the case when the temperature fields are recorded with the help of the automatic probe of the thermocouple (an error of 0.3°C) and taking into account the error in the recording devices the minimum error in the determination of the jet boundary increases to $\delta_{min} = 0.64\%$, while the maximum error equals $\delta_{max} = 8.6\%$ in the case H = 15 mm and $\delta = 0.17$. Figure 4b shows in relative coordinates the average curves of the spreading of a passive impurity for different intensities of turbulence in the drift flow along the x axis from a source at constant height. From an analysis of these curves, constructed based on a large number of experiments in a wind tunnel (including repeated experiments), it may be concluded that the point of contact of the plume with the surface of the channel depends on the intensity of the turbulence in the drift flow and on the distance between the source and the surface of the channel. The ratio of the distance along the x axis between the source and the point of maximum concentration x_{max} to the distance between the source and the point of contact of the plume at the surface x_c is a constant, irrespective of the turbulence intensity in the drift flow and the height of the source: $x_{max}/x_c \cong 3.24$.

The experimental dependence of the maximum temperature at the standard surface on the distance between the source of passive impurity and the surface with different levels of turbulence in the drift flow is shown in Fig. 5. It is evident from the graph that the maximum concentration varies as the inverse square of the height of the source.

Thus, the experiments performed yield the quantitative characteristics of the spreading of passive impurities in turbulent flows with different levels of turbulence and the general relation describing the variation of the concentration of passive impurities along the flow, including the transition zone of the plume.

NOTATION

$\bar{d}_e$, equivalent diameter of the working part of the wind tunnel, mm, σ, variance of the spreading of the impurity, m; Re, Reynolds number; x, distance downstream from the turbulizing grid, mm; z, ordinate, mm; ε, intensity of turbulence; $\bar{F}$, dimensionless energy spectrum; f, frequency of variation of pulsations of the velocity, Hz; T, time, sec; E, voltage, mV; u, flow velocity, m/sec; t, temperature, °C; Δt, instantaneous excess of the temperature in the transverse section of the impurity plume above the temperature of the drift flow; E_0, A, and n, constants; k, wave number. Indices: M, a step in the turbulizing grid, mm; g, turbulizing grid, and 0, tube for injecting the impurity.

LITERATURE CITED

1. L. A. Rikhter, É. P. Volkov, and V. I. Kormilitsyn, Teploénergetika, No. 2, 52-57 (1973).
2. N. V. Zozulya, Yu. P. Vorob'ev, and A. A. Khavin, Thermophysics and Heat Engineering [in Russian], No. 19, Kiev (1971), pp. 116-118.
3. I. Ya. Bitsyutko and V. K. Shchitnikov, Turbulent Flows [in Russian], Moscow (1970), pp. 107-110.
4. Instruction Manual DISA 55 System with 55M10 Standarte Bringe, DISA Elektronik, Denmark (1971).
5. B. S. Petukhov, A. F. Polyakov, V. V. Troitskii, and Yu. L. Shekhter, "Method for performing thermoanemometric measurements in three-dimensional nonisothermal flows," Preprint No. 2-008, Moscow (1977).
6. J. O. Hinze, Turbulence, McGraw-Hill (1960).
7. A. I. Zaidel', Errors in Measurements of Physical Quantities [in Russian], Leningrad (1974).
8. J. S. Bendat and A. G. Piersol, Random Data: Analysis and Measurement Procedures, Wiley (1971).
9. A. S. Monin and A. M. Yaglom, Statistical Fluid Mechanics, Vol. 1, MIT Press (1971).