EXPERIMENTAL STUDY OF THE STRUCTURE AND MASS TRANSFER OF A TURBULENT VORTEX RING

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1. Introduction. Turbulent vortex rings are formed at Reynolds numbers greater than 10^3 after relatively short stages of laminar flow and instability [1]. Results of study of the structure of the flow in laminar rings were reported in [2]. Turbulent vortex rings have been studied mostly qualitatively [5], despite the fact that they are of interest in the solution of certain practical problems [3, 4].

In the present investigation, we report the results of several experimental studies of the structure of a turbulent vortex ring and its mass transfer with the environment. We determine and analyze spectra of the pulsations of the longitudinal component of flow velocity and turbulence intensity in several regions of an atmospheric vortex. A study is made of the formation and evolution of profiles of the concentration of a conservative passive impurity under the influence of eddy diffusion in a vortex ring. The rate of mass transfer between the ring and the environment is also examined. Direct practical applications of the studies include making it possible to predict the scattering of radio and sound waves by refractive index irregularities in a vortex ring. This has particular value for atmospheric probes [3].

2. Description of the Experiment. The vortex ring was formed by the classical method – by the impulsive discharge of a certain amount of air from a cylindrical nozzle mounted on one end of a hermetic container. The length and inside diameter of the nozzle were 0.14 and 0.075 m, respectively. The air was ejected from the nozzle with the aid of an air valve secured to the opposite end of the container and opened at the required moment of time. The initial velocity of the resulting vortex rings was 8 m/sec, and a diameter of 0.1 m was maintained in the tests to within ±5 and ±3%, respectively (the confidence intervals indicated in this study are for a 90% confidence level). The average air velocity in the surrounding medium was no greater than 0.03 m/sec. This ensured that the path of the ring would be straight and that it would encounter the unifilar temperature and velocity gauges positioned 2 m from the ring generator. Located immediately behind the gauges was a target consisting of a field of flag indicators secured in an unstable position to a wire frame. Use of the field of indicators allowed us to check the coordinates of the ring to within ±0.003 m at the moment it passed the gauges. After being converted in a Disa unit, the signal from the gauges was recorded on a sound track. An oscillograph and video camera were used to record the signal on a video recorder. The first recording was used together with a tunable band-pass filter to determine the spectrum of the turbulent pulsations, while the second recording was used to visually analyze the profiles of velocity and temperature in the vortex ring.

3. Results of Anemometric Measurements. The transition from the stage of laminar motion of the ring to turbulent motion occurred at a distance from the generator corresponding to 6-8 nozzle diameters and was manifest in the appearance of high-frequency pulsations on the initially smooth velocity profile within the vortex ring. Figure 1 shows typical (with respect to the form of the curve and the character and intensity of the pulsations) oscillograms of the square of the difference between the output and reference voltages from the anemometer. After multiplication by the calibration coefficient, these oscillograms are equivalent to the profile of flow velocity u along the axis of the vortex ring for its laminar and turbulent (lines 1 and 2) stages of motion. Here, the anemometer is positioned so that it can react simultaneously to the axial and transverse components of flow velocity. It should be noted that there were only small changes in the regular profiles of velocity in identical sections on the vortex for the laminar and turbulent stages. One illustration of the latter is Fig. 2, where a coordinate system that moves with the velocity of the vor-

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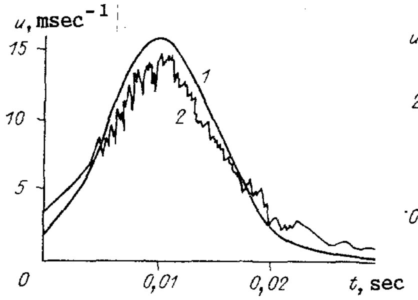

Fig. 1

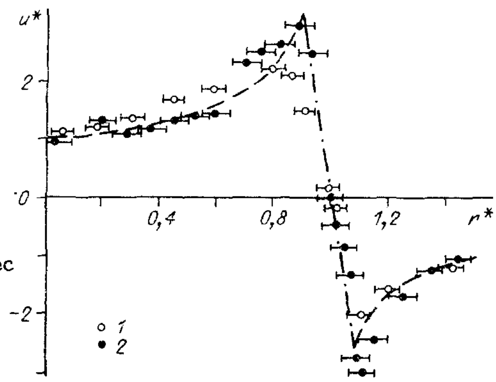

Fig. 2

tex ring is used to show individual measurements of the velocity of the flow in its equatorial plane for the laminar and turbulent stages (points 1 and 2). This data is for distances of 0.3 and 1.0 m from the generator, respectively. Plotted off the x axis are the distances from the axis of the ring r* referred to the radius of the ring. The values plotted off the y axis represent values of flow velocity u* referred to the translational velocity of the ring (we assumed that there were no transverse flows in the equatorial plane of the ring). For the laminar stage, flow velocity u_0 and the radius of the ring R were equal to 8.0 m/sec and $5 \cdot 10^{-2}$ m. The corresponding figures for the turbulent stage were 7.5 m/sec and $5.2 \cdot 10^{-2}$ m. The test results in Fig. 2 not only allow us to evaluate flow velocity in a turbulent vortex ring as a function of r*, but also confirm that the character of profiles 1 and 2 is roughly the same. The similarity of the profiles obtained with the unifilar velocity gauge is significant for two reasons: It allows us to make difficult measurements of the three-dimensional velocity field in a turbulent vortex ring; it makes it possible to use published experimental data on the velocity field in a laminar vortex [2] for engineering purposes.

Most of the attention in anemometric studies being conducted at present is focused on determining the turbulence structure of vortex rings. Visual inspection of dozens of oscillograms obtained for identical sections of turbulent vortices but different realizations and different distances from the generator have shown a great similarity with regard to turbulence structure as well as the regularity of the profiles. Analysis of oscillograms similar to those shown in Fig. 1 suggests that there is a fairly abrupt transition from laminar flow ahead of the ring to intensive turbulence within the ring. This transition takes place over distances less than 0.1 of the radius of the vortex. At the same time, turbulence intensity behind the ring decreases fairly slowly. This is evidence of the presence of a turbulent wake behind the vortex. It is very surprising that the pulsations of the longitudinal (coincident with the direction of the vector of mean velocity) component of velocity in the vortex are roughly of the same monoharmonic nature and that large-scale (commensurate with the diameter of the vortex) pulsations are absent. Such a "natural" scale of subdivision of the vortical (regular) and turbulent components of flow velocity in the ring makes it possible to use spectral analysis to study turbulent pulsations.

Figure 3 uses logarithmic coordinates to show the wave spectra of pulsations of the longitudinal component of flow velocity E(Ω) in several regions of a vortex ring with approximately uniform turbulence. The pulsations immediately behind the vortex are also shown. Here, the vortex has traveled ~1 m from the generator. Numbers 1-3 in the spectrum pertain to spectra corresponding to the axial regions of the ring (r* ≈ 0) for the front and rear halves and the wake, respectively. The numbers 4 and 5 pertain to regions of the ring with r* ≈ 0.5 and 1.2. In determining the spectra, we used the usual assumption that the turbulence was "frozen." With allowance for mean flow velocity and the time the gauge was within the investigated regions, the amount of space covered by the different realizations was approximately equal to the diameter of the vortex ring for spectra 1, 2, and 4 and 1/3 the diameter of the ring for spectra 3 and 5. The finiteness of the realizations resulted in certain relative errors in the spectrum determinations [6], these errors reaching 100% for the lowest wave numbers that were studied. The reproducibility of the spectra for different vortex rings was satisfactorily high. The rms error of the test data for the corresponding regions of the ring was 20-40% over 3-4 realizations.

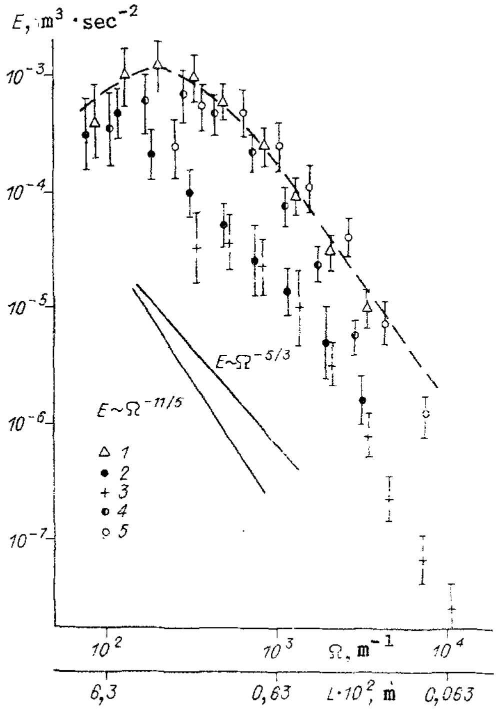

Fig. 3

Let us discuss the conclusions that were reached from an analysis of the spectra — spectra whose characteristics were for the most part similar to the characteristics of turbulent vortex rings. First of all, the spectra were all similar. Within the investigated range of wave numbers Ω, they can be approximated by the simple expression

$$E(\Omega) = E_m\left(\frac{\Omega}{\Omega_m}\right)^2 \frac{4}{[1+(\Omega/\Omega_m)^2]^2}, \tag{3.1}$$

where E_m and Ω_m are the maximum values of the spectral density of turbulence energy and the corresponding wave numbers for spectra 1-5.

As an illustration, the dashed line in Fig. 3 shows results calculated from (3.1) for spectrum 1. One advantage of the given approximation is the possibility of obtaining analytical estimates of turbulence characteristics in a vortex ring. In particular, we obtain the following for the longitudinal correlation function H(L)

$$H(L) \equiv 2\int_0^\infty E\cos\Omega L dL = 2\pi E_m\Omega_m(1-\Omega_m L)\exp(-\Omega_m L),$$

which we then use to find the integral turbulence scale L_0. The latter quantity characterizes the linear dimensions of the region with a high degree of correlation with flow-velocity pulsations:

$$L_0 \equiv \int_0^\infty |H(L)|dL/H(0) = \frac{2}{\Omega_m}.$$

It follows from an analysis of Fig. 3 that the quantity L_0 is close to (1/5)R for most of the vortex ring. This finding is consistent with the qualitative estimate $L_0 \simeq (1/4)R$ [5] obtained on the basis of flow visualization in a vortex ring. At the periphery of the vortex, $L_0 \simeq (1/10)R$. We have $L_0 \simeq (1/3)R$ in the rear half of the ring near its axis, while $L_0 \simeq (1/8)R$ in the wake behind the ring. The fact that L_0 is limited to small (compared to the size of the vortex ring) scales is indicative of the stability of the average flow. This stability is probably connected with the suppression of turbulence due to rotation — a phenomenon which has been noted by several authors who have studied vortices [7, 8].

Secondly, the generation of turbulence energy predominates over its loss up to the scale $L \simeq (1/8)R$. The rate of generation of energy ε in a vortex ring averages 180 $m^2 \cdot sec^{-3}$, reaching 400 $m^2 \cdot sec^3$ at its periphery. These values are consistent with the rate of energy loss due to regular flow in the vortex ring. The latter is equal to ~800 $m^2 \cdot sec^{-3}$ for the chosen conditions. Assuming that the rate of generation of turbulence energy in the vortex ring is proportional to the rate of energy loss to the average flow and using the known dependences of U_0 and R on the distance traveled by the ring z [1], we obtain $\varepsilon \simeq 6(U_0{}^3/R)(dR/dz)$ to estimate ε in the atmosphere of the ring.

Thirdly, at scales smaller than 0.1 R, a more rapid decay of the spectra occurs than would take place in the presence of an "inertial" interval. At the same time, the effect of viscosity on the turbulence energy spectrum is still negligible. Evidence of this comes from the fact that the internal turbulence scale in the atmosphere of the vortex – estimated to be $\ell \sim (\nu^3/\varepsilon)^{1/4} \simeq 10^{-3}R$ (where ν is kinematic viscosity) – is considerably smaller than 0.1 R. The reason for the suppression of turbulence in the region of wave numbers might be rotation of the flow in the vortex ring. Some authors have suggested that an analogy can be made between rotating and stably stratified flows in relation to their turbulence characteristics [8, 9]. This analogy is found to hold in the present study, since we see that the slope of the empirical spectra in the right side of Fig. 3 is close to the relation $\Omega^{-11/5}$ corresponding to the turbulence spectrum in a stratified medium [10].

Fourthly, the rms amplitude of the longitudinal pulsations of the flow is roughly the same throughout the vortex except for the rear part near the axis. There, it decreases rapidly from $\pm 0.15\ U_0$ to $\pm 0.05\ U_0$. Significant changes in turbulence energy and scale indicate that different mechanisms are responsible for its generation in this and other regions of the ring. One probable source of turbulence energy in the rear part of the ring near its axis is the suction of quantities of air from the surrounding medium into this part and their breakup. At the same time, most of the turbulence energy enters the ring at its periphery from the mixing region. In the front half of the ring, there is sufficient time for the displacement of quantities of air that are drawn in by eddy diffusion and suction. Thus, the velocity pulsation spectrum for this part takes a form intermediate between spectra 2 and 5.

4. Results of Experimental Study of Diffusion in a Turbulent Vortex Ring and Its Mass Exchange with the Environment. From a methodological viewpoint, the diffusion of a conservative passive impurity in a vortex ring is most easily studied by forming such an impurity from slightly heated (or cooled) air and then performing thermometric measurements in several sections of the resulting vortex ring at different distances from the generator. To "connect" the temperature profiles that are obtained with specific regions of the vortex ring that can be identified from profiles of the longitudinal component of flow velocity, we placed a hot-wire anemometer in the immediate vicinity of the temperature-sensitive element. The resulting profiles of excess temperature ΔT in the turbulent vortex ring are shown in Figs. 4 and 5. These results represent the averages of 3-4 realizations. The interval between the isotherms in Fig. 4 for the initially uniform vortex ring is 0.4 K. The distance from the generator was 0.8 m in this case. Due to the axial symmetry of the ring, the isotherms are shown only for part of it. The dashed line shows a roughly elliptical region moving at the velocity of the vortex ring. The forward part of this region delineates the turbulent and nonturbulent media (see Part 3). The dot–dash line represents the core of the vortex ring. Figure 5 shows profiles of excess temperature in the equatorial plane of the ring at distances 0.3, 0.8, and 1.4 m (points 1-3) from the generator. At the initial moment, the vortex ring was overheated relative to the surrounding medium in all the tests ($\overline{\Delta T_0} = 2.4 \pm 0.2$ K).

An analysis of the results in Figs. 4 and 5 permits the following conclusions. First, the curvature of the temperature front, moving at the velocity of the ring, is indicative of the weakness of mass transfer across the leading surface of the ring. Second, the distribution of temperature in the central part of the ring is very uniform, which indicates that relatively intensive mixing takes place. Third, the severe turbulence, the weak temperature gradients, and the character of the isotherms in the lower part of the vortex ring are evidence that air is rapidly being moved from the surrounding medium into this part of the ring by diffusional and dynamic processes. Fourth, as the ring moves, the profile of the conservative passive impurity (excess temperature, in the present case) become increasingly toroidal in form. This can be seen visually for smoke rings. It is also evident that eddy diffusion coefficient and diffusivity decrease rapidly as the ring is approached, reaching a minimum at the boundary of the ring.

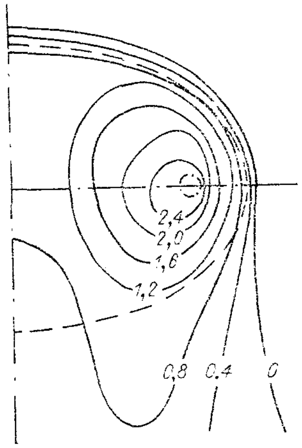

Fig. 4

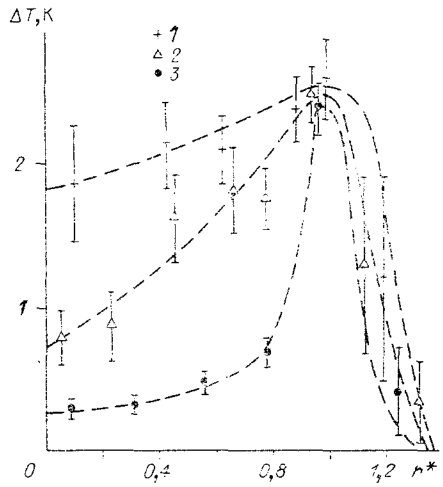

Fig. 5

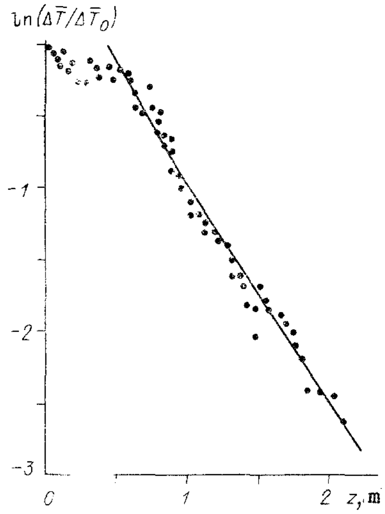

Fig. 6

In contrast to its laminar analog, the turbulent vortex ring intensively exchanges mass with its environment [5, 11]. Evidence that this occurs is provided in particular by the presence of the aerosol "tail" behind the ring and the relatively rapid decrease in the content of aerosol in the atmosphere of the vortex. To analyze the rate of this process quantitatively, we determined the rate of decrease in excess temperature $\overline{\Delta T}$ with increasing distance from the generator; $\overline{\Delta T}$ was calculated approximately by multiplying values of overheating measured at the center of the ring by a coefficient which is a function of distance and changes from 1 to 1.4, in accordance with the approximation of the profiles shown in Fig. 5. By virtue of the large range of variation of $\overline{\Delta T}$ in the experiments, such an approximation could not have led to significant errors in the evaluation of the rate of mass transfer between the ring and the surrounding medium. Figure 6 shows the experimentally obtained dependence of $\ln(\overline{\Delta T}/\overline{\Delta T_0})$ on the distance to the generator z. It follows from analysis of Fig. 6 that beginning with the distance z_0 at which the turbulent vortex ring is formed, the experimental data (points) are approximated well by the expression

$$\overline{\Delta T} = \overline{\Delta T}_0 \exp\left[-\beta(z - z_0)/R\right], \tag{4.1}$$

which agrees with the empirical formula obtained in [11] for the ring transport of a passive impurity in water. The experimental value of the coefficient $\beta = 0.09$ is close to 0.1 [11]. The results of calculations performed with (4.1) when $\beta = 0.09$ are shown by the line in Fig. 6.

In contrast to the velocity pulsations, the temperature pulsations in the ring were undeveloped and indistinct. Qualitatively, it can be noted that the mean amplitude of the small-scale pulsations (≤0.2) was at a level not exceeding 0.05 $\overline{\Delta T}$. At the same time (particularly when a layer of heated air was created in the path of the ring), discrete intensive irregularities with a scale on the order of (1/2)R developed on the temperature profile in the ring. As the ring moved into the medium having a uniform temperature, these irregularities were smoothed out and did not exceed 0.2 $\overline{\Delta T}$ at distance equal to (5-10)R.

On the whole, the experimental results obtained here make it possible to represent a turbulent vortex ring in the form of a translating spheroidal body with an impermeable leading surface, circulation, and severe internal turbulence. The difference in the diffusion coefficient inside and outside the ring cause concentrative and dynamic boundary layers to be formed on the leading surface of the ring. The boundary layer on the trailing surface is evidently destroyed under the influence of an opposing pressure gradient. A mixing zone is formed, with turbulent mass exchange between the ring and the surrounding medium taking place through this zone. This representation can be used in mathematically modeling the diffusion of an impurity in the atmosphere of a vortex ring (which we did not do in the present study).

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