Experimental observation of turbulent exchange between heterogeneous vortex ring and surrounding medium by the shadowgraph method

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Abstract. A shadow visualization of turbulent exchange between vortex ring containing fluid less dense than that out of it and surrounding medium is performed. A characteristic distance and time of this process are determined and the dependence of time on both vortex velocity and the related Reynolds number is obtained. Using characteristic time, the turbulent diffusion coefficient in the vortex atmosphere is estimated.

1. Introduction
The study of turbulent exchange between a vortex ring and surrounding medium is of fundamental and practical interest. A fundamental importance is that the vortex ring is the example of isolated concentrated vortex. Therefore, the regularities obtained in the study of it are related to a vortex flow pattern and may refer to other concentrated vortices, in particular, to linear ones. A practical importance is due to the fact that vortex rings often appear in different artificial and natural processes taking place, for instance, during explosions, volcanic eruptions, etc. Hence, it is necessary to be able to estimate the characteristics of turbulent exchange as it causes the removal of impurities and heat from the vortex. Moreover, the dynamics of vortex rings, particularly, their expansion coefficient is intimately related to rotation decay owing to dissipation processes caused by turbulence [1].

It is known that a vortex ring is a torus-shaped volume of vortex-type fluid or gas (vortex core) that moves with some surrounding volume of medium called a vortex atmosphere. The study of turbulence in such volumes is essentially complicated due to the presence of non-stationary and vortex pattern of the flow, therefore, the obtaining of turbulent characteristics is an important achievement. By now it has been established experimentally that the exchange takes place mainly between the vortex atmosphere and surrounding medium while the turbulence is suppressed in the core [2]. In [3, 4] a new method of observation of turbulent exchange between vortex ring atmosphere and surrounding medium has been proposed. To this end, vortex rings whose interior fluid density is more than exterior one in the beginning of motion are produced. It is possible to visualize the vortex due to optical inhomogeneities arising during a turbulent exchange of fluids with different optical density inside and outside of it. In [3] the case when the difference of densities has one value has been considered. In [4] the experiments have been performed for three differences of density values. It has turned out that the result was almost independent of the value of this difference at sufficiently large values of velocities of vortex motion.
This work deals with the case when the fluid density in vortex interior is less than that in its exterior in the beginning of motion. A characteristic distance and time of turbulent exchange have been established. Basing on characteristic time, the coefficient of turbulent diffusion in vortex ring atmosphere has been estimated.

2. Experimental results
The experimental setup is shown in figure 1. It consists of uniformly illuminated matte screen (1), vertical chamber with cross-section of 150×150 mm and height 300 mm (2). The chamber is filled with two-layer fluid. The upper layer is water of density $\rho_1 = 1\,\text{g/cm}^3$ and depth 100 mm. The lower layer is a sugar solution of density $\rho_2 = 1.08\,\text{g/cm}^3$ and depth 150 mm. A vortex ring is formed by forcing out a pulse jet with the help of a piston from cylindrical tube (3) 21 mm in diameter through a nozzle 12.5 mm in diameter. The piston stroke is 10 mm, so the jet length is 28 mm. The distance from the nozzle to the interface between the layers (4) equals 50 mm. Vortex (5) is formed in the upper layer, moves vertically downward and enters the lower layer containing fluid less dense than the surrounding medium. Vortex ring motion is recorded by the high-speed video camera (6) in the lower layer. The distance between camera and vortex ring is 2.3 m, the pathway passed by the vortex is within the camera view. The record of vortex shadow image is performed perpendicular to vortex motion direction with frequency from 125 to 1000 frames per second. The velocity $u$ and radius of the vortex core $R$ are defined in the lower layer at the distance 20-25 mm from the interface. Kinematic viscosity taken to be equal to $10^{-2}\,\text{cm}^2/\text{s}$, experimentally measured velocity and radius are used for calculation of the Reynolds number. The temperature of fluids is within the range 20–22 °C. Consequently, the variation of fluid kinematic viscosity is less than 5%. The initial vortex velocity is varied in the experiments. The vortex core of diameter $2R$ is approximately constant and equals $(14.3 \pm 0.3)$ mm. The diffusion coefficient of sugar solution in water is $3\cdot10^{-6}\,\text{cm}^2/\text{s}$. The time duration of the process is less than 0.5 s. Then a characteristic length of molecular diffusion is less than $1.2\cdot10^{-3}\,\text{cm}$ and consequently much less than the vortex dimensions. Therefore, molecular diffusion can be neglected.

![Figure 1. Experimental setup.](image_url)
observable during the whole transition time. In the process no virtual images exist. During the transition from less dense medium to a denser one before the vortex moves from the interface to a sufficient distance, apart from a real shadow image of atmosphere having passed through the interface, firstly, two virtual images are observed: one of them is reflected from the interface, another one appears due to bended light rays passing through diffusion zone of the interface.

Figure 2 demonstrates shadow images of vortex ring passing through the interface.

![Figure 2](image.png)

**Figure 2.** Shadow record of vortex ring transition from upper to lower layer. A real image of front part of the vortex atmosphere and its two virtual images (a), virtual images are partially merged (b), vortex atmosphere and one virtual image (c).

The virtual image disappears when the vortex ring moves from the interface to a distance approximately equal to 20 mm. The further behavior of image is qualitatively identical to that for the motion of vortex ring having a denser fluid than a surrounding one [3, 4]. Figure 3 shows shadow images of vortex ring in the lower layer at various distances from the interface.

![Figure 3](image.png)

**Figure 3.** Shadow records of vortex ring at various distances from the interface: 18 (a), 40 (b) and 120 mm (c). Vortex velocity \( u = 2.7 \text{ m/s} \), \( \text{Re} = 19300 \).

At the distance about 20 mm from the interface, the boundary of the vortex atmosphere is visible, since at such distance turbulent exchange is insignificant; therefore, the fluids inside and outside the vortex are almost uniform, figure 3 (a). As it moves, the uniformity of the media is disturbed and turbulent volumes of one fluid penetrate into another causing the appearance of density gradients and shadow visualization becomes possible. For a vortex ring it looks like an abrupt darkening of the atmosphere. At first, the darkening grows, figure 3 (b), then it starts decreasing at some distance, figure 3 (c). This means that the amount of less dense fluid in the vortex decreases being replaced by the surrounding medium. In the shadow images, the vortex core can be seen, which is brighter than its surroundings due to the effect of turbulence suppression. The centerline diameter of the core torus is determined from the images. The distance from the interface to the centerline was taken as distance \( z \) from the interface to the vortex ring, since the core is parallel to the boundary. The average velocity when the vortex passes the distance of 10-20 mm is taken as velocity.

To obtain quantitative characteristic for darkness, the following method is used. According to figure 3 (a), the vortex with its atmosphere is well visible at the distance about 20 mm from the interface. Using such records, the pattern of its atmosphere is constructed. The atmosphere is assumed
to be unchangeable during the observation although the outer part of atmosphere may be invisible, figure 3 (c). This assumption is justified by the fact that distance of observation is not more than six vortex diameters. It is known that along such a distance the vortex parameters do not practically vary. The pattern of atmosphere is superposed on the shadow records positioning the pattern to vortex core in the same way. Records are taken at various distances from the interface. Then, average darkness \( J \) of the region corresponding to shadow image of vortex ring atmosphere is established.

The typical dependence of average darkness \( J \) on distance from interface \( z \) is shown in figure 4. Figure 4 illustrates a clearly defined maximum of darkness. The experimental results are shown by the points; solid line is b-spline interpolation of the points. Similar dependence is typical, darkness maximum is observed at all vortex velocities. The value of darkness maximum changes with variation of vortex velocity: the higher velocity the higher darkness maximum.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4}
\caption{Average darkness of vortex shadow image \( J \) versus distance from interface \( z \), \( u = 130 \text{ cm/s}, \text{Re} = 9300 \).}
\end{figure}

As in [3, 4], the distance from the interface to vortex position where darkness has a maximum is characteristic distance of the turbulent exchange process because darkness is related to turbulent exchange. This distance is well defined in every experiment and it is denoted as \( z^* \). So \( z^* \) is characteristic distance of the turbulent exchange process between vortex ring and surrounding medium. Using \( z^* \) and vortex velocity \( u \), we introduce characteristic time of turbulent exchange as follows: \( t^* = z^*/u \). As dimensionless characteristic time we take \( \tau = t^* \cdot u/R \), where \( R \) is a vortex ring radius. Using expression for \( t^* \), we obtain: \( \tau = z^*/R \). In figure 5, the dependence of \( z^* \) on Re number is shown.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5}
\caption{Dimensionless characteristic time of the turbulent exchange process between vortex ring and surrounding medium versus Re number.}
\end{figure}
According to figure 5, the dimensionless characteristic time initially decreases with an increase in Re number. Then for Re approximately greater than 5000, it is practically independent of Re and equal to $5.5 \pm 0.34$.

3. Analysis of the results and conclusions
According to [4], vortex radius is 7.5 mm, the average value of $z_*$ and its variance are $32.7 \pm 3.8$ mm. Then dimensionless characteristic time for data [4] is $4.4 \pm 0.5$. So turbulent exchange between vortex atmosphere and surrounding medium depends slightly on density differences but the exchange occurs more rapidly when the fluid in the vortex is denser then that out of it.

To estimate the coefficient of turbulent diffusion in vortex atmosphere, we consider diffusion from the volume of spherical form. It has been known that characteristic diffusion time $t_d$ from the sphere of radius $R$ is: $t_d = (R/\pi)^2(1/D)$, where $D$ is a diffusion coefficient. In the experiments presented here, characteristic time $t_* = \tau R/u$. We found diffusion coefficient $D$ such that characteristic diffusion time from the spherical volume will be the same as that from the vortex. Then from equation $t_d = t_*$, we obtain expression for $D$: $D = (R\tau u)/(\pi^2\tau)$. Since for $Re > 5000$ $\tau$ is approximately constant, then $D$ in this area of Re numbers is proportional to vortex velocity $u$. The substitution of $\tau = 5.5$, $R = 0.72$ cm, $u = 100$ cm/s into the expression for $D$ yields $D \approx 1.3$ cm$^2$/s. Thus, the turbulent diffusion coefficient in the atmosphere of experimental vortex is larger than the molecular one by many times.

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