Experimental observation of turbulent exchange between vortex ring and surrounding medium of different density

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Abstract. A method for experimental observation of turbulent exchange between vortex ring and surrounding medium is proposed. The method is based on a shadow visualization of the process. For this purpose a vortex ring containing liquid more dense than outside is created. It is established that there is a characteristic distance for turbulent exchange and this distance depends on vortex velocity. The dependence of characteristic distance on Reynolds number of vortex is obtained.

1. Introduction
Turbulent exchange between vortex ring and surrounding medium plays an important role in dynamics of vortices [1] and transfer processes associated with them [2]. The investigation of turbulent exchange between vortex ring and surrounding medium is of fundamental and practical interest. Fundamental interest is that laws established in investigations of vortex rings can be extended to other concentrated vortices, in particular to linear vortices. A practical importance is that the vortex rings are often formed in various natural and technogeneous processes. Up to now the investigations of turbulent exchange have been restricted by studying passive impurity transport by vortex rings in homogeneous liquid [2]. In heterogeneous liquids the investigations of turbulent exchange were not performed.

It is known that vortex ring is a toroidal volume of vortex-type liquid or gas (vortex core) entraining some volume of surrounding medium (vortex atmosphere). The investigation of turbulence in such objects is significantly complicated by non-stationary and vortex character of the flow, therefore the determination of any turbulent characteristics of such flows is an essential achievement. It is known that the exchange between vortex and surrounding medium occurs mainly from vortex atmosphere, as turbulence in a core is suppressed [3] but quantitative characteristics of turbulent suppression are not obtained. The theoretical explanation of turbulent suppression in liquid rotating as a rigid body is given in [4].

In the present work a new method for experimental observation of turbulent exchange between vortex ring and surrounding medium is proposed. For this purpose a vortex ring containing liquid more dense than outside is created. A high-speed photography of vortex shadow image is performed perpendicular to the vortex motion direction.

2. Experimental results
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 of 300 mm (2). The chamber is filled with
two-layer liquid. The upper layer is water of density $\rho_1 = 1\, \text{g/cm}^3$ and depth of 180 mm. The bottom layer is a sugar solution of density $\rho_2 = 1.08\, \text{g/cm}^3$ and depth of 70 mm. A vortex ring is formed in the bottom layer by forcing out a pulse jet with the length of 34 mm from cylindrical tube (3) of 21-mm diameter through a nozzle of 12.5-mm diameter. The distance from the nozzle to the interface between the layers (4) equals 40 mm. Vortex (5) is formed in the bottom layer, moves vertically upward and enters the upper layer containing liquid more dense than the surrounding medium. Vortex ring motion is recorded by the high-speed video camera (6) in the upper layer. The distance between camera and vortex ring is 1 m, the pathway taken by the vortex falls within the camera view. The photography of vortex shadow image is performed perpendicular to vortex motion direction with the frequency from 125 to 1000 frames per second. The velocity $u$ and radius of the vortex core $R$ are defined in the upper layer at the distance of 15-20 mm from the interface. Kinematic viscosity is taken equal to $10^{-2}\, \text{cm}^2/\text{s}$, experimentally measured velocity and radius are used for calculation of Reynolds number. Temperature of the liquids lies in the range of 20 – 22°C. Consequently variation of water kinematic viscosity is less than 5%. The initial vortex velocity is varied in the experiments. The vortex core diameter $2R$ is approximately constant and equals $(15 \pm 0.5)\, \text{mm}$. Diffusion coefficient of sugar solution in water is $3 \cdot 10^{-6}\, \text{cm}^2/\text{s}$. Time of the process is less than 0.5s. Then characteristic length of molecular diffusion is less than $1.2 \cdot 10^{-3}\, \text{cm}$ and consequently much less of vortex dimensions. Therefore molecular diffusion can be neglected.

![Figure 1. Experimental setup.](image)

Shadow records of laminar vortex ring are shown in figure 2. Laminar vortex remains transparent during the motion and only its boundary is visualized because liquids are homogeneous inside and outside, figure 2 (a). Transparency is disrupted when vortex becomes disintegrating, figure 2 (b).

![Figure 2. Shadow records of laminar vortex ring: before disintegration (a), during disintegration (b). Vortex velocity $u = 0.28\, \text{m/s}$, $Re = 2100$](image)
Shadow records of turbulent vortex ring are shown in figure 3.

![Figure 3](image)

**Figure 3.** Shadow records of turbulent vortex ring at various distances from the interface: 5 (a), 30 (b) and 83 mm (c). Vortex velocity \( u = 2.9 \) m/s, \( \text{Re} = 21750 \).

If the vortex is turbulent, it is transparent only immediately after it leaves the bottom layer, figure 3 (a). During the vortex motion the homogeneity of media breaks down because turbulent volumes of one liquid penetrate into another. As a result the shadow visualization of vortex takes place. At first, vortex image grows darker, figure 3 (b), then after it reaches maximum darkness, it begins decreasing, figure 3 (c), up to full vortex transparency. This means that the amount of heavy liquid in the vortex decreases up to its full replacement by the surrounding liquid. In figures 3 (b) and 3 (c), the vortex core, which is less dark than the surrounding liquid due to turbulent suppression, is seen. By using such records, the diameter of core is obtained.

To obtain quantitative characteristic for darkness, the following method is used. According to figure 3 (a), the vortex with its atmosphere is well visible immediately after leaving the bottom layer. 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 in percentage of maximum allowable darkness.

Figure 4 illustrates typical dependence of average darkness \( J \) on distance from interface \( z \). The experimental results are shown by the points; solid line is b-spline interpolation of the points.

![Figure 4](image)

**Figure 4.** Average darkness of vortex shadow image in percentage of value of maximum allowable darkness \( J \) versus distance from interface \( z \), \( u = 225 \text{cm/s}, \text{Re} = 16900 \).
Figure 4 illustrates a clearly defined maximum of darkness. 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.

Since darkness is related to turbulent exchange evidently, the distance from interface to vortex position where darkness has a maximum is characteristic of the turbulent exchange process. It can be proposed that maximum stirring is reached at this position, i.e., approximately half of primary liquid contained in vortex is replaced by the surrounding liquid. In this connection, the distance from interface to the position where darkness has a maximum is taken as characteristic of the turbulent exchange process between vortex ring and surrounding medium. This distance is well defined in every experiment and it is denoted as $z_*$. In figure 5, the dependence of $z_*$ on Re number is shown.

![Figure 5](image.png)

**Figure 5.** Distance from interface to position where vortex has maximum darkness versus Re number.

The dispersion values of $z_*$ is due to turbulent character of the flow and error connected with discreteness of registration. Due to discreteness of registration $z_*$ is measured accurate to one frame. This causes the error not more than 2mm for $Re < 2 \cdot 10^4$, 3mm for $2 \cdot 10^4 < Re < 3 \cdot 10^4$ and 4mm for $Re > 3 \cdot 10^4$. According to figure 5, the characteristic distance initially decreases with an increase in Re number, then, for $Re > 10^4$ it is practically independent on it.

### 3. Conclusions

Thus, the experimental observation of turbulent exchange between vortex ring and surrounding medium is performed by using shadow visualization of the process. For this purpose vortex containing liquid more dense than outside is created. It is established that there is a characteristic distance for turbulent exchange. The dependence of this distance on vortex velocity and Reynolds number is obtained. It is established that characteristic distance is practically independent on vortex velocity for $Re > 10^4$.

### Acknowledgments

The work was supported by the RFBR grant No. 18-08-00824.

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