Regularities of vortex motion in gas-vortex bioreactor

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Abstract. Regularities of the vortex motion in an industrial glass bioreactor with a volume of 12 liters with a reactor vessel diameter D = 190 mm and with a filling of 50% was studied. A 65% water solution of glycerin was used as a model culture medium (density $\rho = 1150$ kg/m$^3$ and kinematic viscosity $\nu = 15$ mm$^2$/s). Methods of particle image velocimetry and adaptive track visualization were used to observe the vortex pattern. The regularities of the vortex motion of the cultural medium were determined. It was found that, similar to the case of two rotating immiscible liquids, a strongly swirling jet was formed near the axis, and the entire flow took on the structure of a miniature gas-liquid tornado. The aerating gas interacted with the liquid only through the free surface, without mixing with it. As a result, the intensification of interphase mass transfer was provided due to the high speed of motion of the aerating gas.

1. Introduction

Today, the versatile application of swirling centrifugal flows and vortex technologies is ahead of the process of their detailed study. The importance of methods development for heat and mass transfer study in strongly swirled vortex flows is dictated by the complexity of the object, in most cases characterized by expressed unsteady technological regimes. An increased accuracy in the diagnosis of unsteady vortex flows is necessary both for the operating regimes determination and optimization, and for research and development of modern computational methods. Since the structure of vortex flows is very sensitive to external disturbances, contactless research methods are used for their study. The main optical methods of flow diagnostics are visualization [1, 2], Laser Doppler Anemometry (LDA) [3, 4] and Particle Image Velocimetry (PIV) [5]. For example, in [6], using a high-speed camera, for the first time, it became possible to experimentally visualize the process of vortex reconnection on a helical vortex, which is formed in a swirling flow in a conical diffuser. In [7, 8], using the visualization and PIV, the development of a cellular structure of a closed vortex flow of two immiscible liquids in a vortex bioreactor model was illustrated and it was shown that a jump in the radial and azimuthal velocities occurred at the interface. In [9], the instabilities of a confined vortex flow in polygonal containers were experimentally investigated by combining a high spatial resolution of PIV and temporal accuracy of LDA.

The aim of the work is to study the regularities of vortex motion in a gas-vortex bioreactor using the developed hardware and software complex for track visualization of swirling flows.

The work uses the adaptive track visualization method developed by the authors of the article using a moving average and automatic background illumination subtraction. This visualization method was successfully used in works [10, 11]. To measure the kinematic characteristics of the flow, the PIV method was used.
2. Experimental setup

To study swirling flows in vortex devices, a software and hardware complex has been created for carrying out adaptive track visualization, which includes a system for controlling the Reynolds number of a swirling flow and a track visualization system. The hardware part includes: power supply, stepper motor driver, low frequency amplifier, CMOS camera, Arduino board and temperature sensor, laser sheet source.

In confined flows, due to viscous friction, the liquid is heated, which is coupled with a change of viscosity. The Reynolds number control system, which controls the rotational speed of the swirling device, has a negative temperature feedback. A temperature sensor TSic 716 (Innovative Sensor Technology IST AG, Switzerland) is used to measure the temperature of the working fluid. The measuring range is $-10^\circ C$ to $+60^\circ C$. The measurement error of this sensor is $\pm 0.07^\circ C$ in the range from $+25^\circ C$ to $+45^\circ C$, and $\pm 0.2^\circ C$ in the range from $-10^\circ C$ to $+60^\circ C$. This sensor is equipped with a 14-bit ADC, with a resolution of 0.004$^\circ C$. The measured temperature value is transmitted using the ZACWire digital protocol. The Arduino Due microcontroller board based on the Atmel SAM3X8E ARM microcontroller is used as an ADC for reading the information transmitted by the sensor. Using the readings of the temperature sensor and the coefficients of the viscosity polynomial, the value of the kinematic viscosity of the working fluid is calculated. The required rotational speed of the disk is calculated using the required value of the Reynolds number. Rotational frequency after multiplying by the gear ratio of the stepper motor is transmitted by frequency modulation to the stepper motor driver SMD-4.2PL (Electroprivod, Russia), which controls the stepper motor rotation. The control harmonic signal, generated using a PC sound card and passing through the low frequency amplifier to match the level, is fed to the input of the stepper motor driver.

The track visualization system implements the adaptive real-time track visualization technique developed and tested by the authors. The investigated optically transparent liquid should contain tracer particles, which are illuminated by a constant light sheet. To increase the signal-to-noise ratio, digital filtering, based on averaging with a sliding window, and subtraction of the static background are used, which allows observing low-contrast movements of light-scattering particles in a wide dynamic range even in the presence of a significant background illumination. CMOS camera MC023MG-SY Ximea (resolution - 2.3 MP 1936 x 1216, framerate - 165 fps, sensor - Sony IMX174 LLJ-C) is used.

Visualization processing algorithm:

1. Extraction of the background - the average image $A_m$, averaging $N_m$ images.
2. In real time, the last $N_b$ images from the camera are stored in a buffer.
3. The images in the buffer are summed and the average image is subtracted.
   \[
   A_v = \frac{\sum_{i=1}^{N_b} (A_i - A_m)}{N_b}
   \]
4. When a new image is transmitted from the camera, steps 2 to 3 are repeated.

The length of the tracks in the resulting visualization is influenced by the frame exposure time and the size of the buffer $N_b$.

Based on this technique, a program has been created to adjust the parameters of image registration with a digital camera and subsequent filtering for application to various flows. The program allows saving the resulting visualization in image or video format.

The program interface allows setting the following parameters of the experiment: coefficients of the polynomial approximating the viscosity-temperature dependence of working fluid, swirling disc diameter, required Reynolds number.

The hardware and software complex serves to control motorized linear guide rails for precise movement of the optical system elements: camera, laser or mirrors. The choice of direction and amount of movement is made in the program interface.

To carry out the experiment, it is necessary to form a laser sheet in the diagnosed region of the flow, which forms the investigated cross section. The optical axis of the camera is directed perpendicular to the laser sheet. The liquid should be seeded with light-scattering particles - tracers. To perform visualization, it is necessary to select the opening of the lens aperture, the exposure time of
the frame and the power of the laser illumination, while balancing the noise level in the resulting image and framerate of frames received.

![Figure 1](a), photo of impeller (b).

**Figure 1.** Experimental setup (a), photo of impeller (b).

Figure 1(a) shows application of a hardware-software complex to study a swirled flow in a gas-vortex bioreactor. A laser source with a laser sheet shaper is mounted on a motorized guide rail. The laser sheet shaper allows setting different angles of inclination of the laser sheet plane relative to the horizon to conduct research both in the horizontal and in the vertical plane. The CMOS camera is mounted on a tripod perpendicular to the plane of the laser sheet.

The study of the laws of vortex motion was carried out in an industrial glass bioreactor with a volume of 12 liters with a reactor vessel radius $R = 95$ mm (figure 1(a)). The vortex air movement was generated by an impeller (figure 1(b)) with a rotation frequency $\Omega$ of up to 2700 rpm at a filling of 50%. The rotation strength is characterized by the Reynolds number $Re = \omega R^2/\nu_{air}$, where $\nu_{air}$ is kinematic viscosity of air ($\nu_{air} = 15.06 \text{ mm}^2/\text{s}$ at a temperature of 20°C), $\omega$ is angular velocity of impeller. The experimental study was carried out at a constant temperature, so the rotational frequency of the impeller was constant. During the experiment, the Reynolds number varied from 10,000 to 80,000, so $\Omega$ is used instead of Re for convenient notation. A 65% water solution of glycerin was used as a model fluid (density $\rho_g = 1150 \text{ kg/m}^3$ and kinematic viscosity $\nu_g = 15 \text{ mm}^2/\text{s}$ at a temperature of 20°C).

To measure the kinematic characteristics of the flow, the PIV method was used. PIV served to obtain an instantaneous velocity distribution in the investigated cross section and to observe an instantaneous flow pattern within the two-dimensional plane of a light sheet. The pulsed laser created the thin light sheet and illuminated small particles suspended in the investigated stream. The particle positions at the time of two consecutive laser flashes were recorded on two frames of a digital camera. The flow velocity was determined by the calculation of the motion that the particles make during the time between laser flashes. Polyamide beads with the density of 1030 kg/m$^3$ and diameter around 20 $\mu$m were employed as seeding light-scattering particles for both the flow visualization and PIV measurements. The air flow was seeded with fog generator.

3. Results
Using the developed hardware and software complex, an experimental study was carried out in a horizontal section in the area of the interface and at the bottom by the method of contactless track
diagnostics of a vortex flow. The use of a 2.3 MP Sony IMX174 sensor with 10 Hz framerate and an exposure time of up to 100 ms significantly improved the quality of recorded images, and the preliminary subtraction of the background image reduced the level of noise. The study was carried out in a horizontal section near the interface and the bottom in the liquid. Using the adaptive visualization method, it was possible to qualitatively examine the flow structure; in figures 2 converging and diverging helical structures are shown. A swirling gas flow of the "tornado" type was generated by the impeller above the flow surface. The swirling gas flow sets the liquid in motion due to friction at the interface and the pressure difference between the periphery and the center of the gas vortex and centrifugal circulation occurs in the liquid. As in the case of a system of two liquids [10], the lower heavier fraction has a diverging flow under the interface (figure 2(a)) and a converging flow near the bottom (figure 2(b)).

![Figure 2](image1.jpg)

**Figure 2.** Visualization of the diverging flow under the interface (a) and the converging flow near the bottom (b) at $\Omega = 1440$ rpm.

![Figure 3](image2.jpg)

**Figure 3.** Structure of the air flow in a horizontal section near the interface at $\Omega = 180$ rpm (a) and 360 rpm (b).
Figure 3 shows streamlines reconstructed from vector fields obtained using the PIV method in a horizontal section near the interface in the air flow at $\Omega = 180$ rpm and 360 rpm. At $\Omega = 180$ rpm, a strongly converging flow is observed (figure 3(a)). But at $\Omega = 360$ rpm, the flow becomes moderately convergent, since the tangential component of the velocity becomes much larger than the radial one (figure 3(b)). As in the case of a system of two liquids [10], the light fraction has a converging flow near the interface.

Figure 4 shows a comparison of the velocities near the interface in liquid and in air at $\Omega = 360$ rpm. The velocity during the experiment was measured in mm/s, but since the velocity in air is many times higher, figure 4 shows r-profiles of the cube root from the radial (figure 4 (a)) and tangential (figure 4 (b)) components of velocity. The r-coordinate was normalized to the bioreactor radius. On the r-profiles of the radial velocity component, there is a converging flow above the interface and a diverging flow below the interface.

Conclusions
An experimental study of the vortex flow in a gas-vortex bioreactor has been carried out. Functional dependences of the formation of vortex structures of a two-phase flow in a gas vortex bioreactor have been established. As in the case of the system of two liquids [10], the lower heavier fraction has a diverging flow under the interface and a converging flow near the bottom. Regardless of the type of the upper fraction (gas or liquid), centrifugal circulation is found to prevail in the lower one. At a low rotational speed of the impeller, centrifugal circulation is found to occur in the air flow.

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References
[1] Boiko V M, Orishich A M, Pavlov A A and Pikalov V V 2009 Optical Diagnostics Methods in Aerophysical Experiment (Novosibirsk: NSU) 450
[2] Dubnischev Yu N, Arbuzov V A, Belousov P P and Belousov P Yu 2003 Optical Methods for Flow Study (Novosibirsk: Siberian University Publ.)
[3] Albrecht H-E, Borys M, Damasche N and Tropea C 2009 Laser Doppler and Phase Doppler Measurement Techniques (Berlin: Springer) 738
[4] Durst F, Melling A and Whitelaw J H 1976 Principles and practice of laser-doppler
anemometry (Academic Press) 410

[5] Raffel M, Willert C E and Kompenhans J 2001 Particle Imaging Velocimetry (Berlin: Springer-Verlag) 269

[6] Alekseenko S V, Kuibin P A, Shtork S I, Skripkin S G and Tsoy M A 2016 JETP letters 103 455–9

[7] Naumov I V, Herrada M A, Sharifullin B R and Shtern V N 2018 Phys. Fluids 30 074101

[8] Naumov I V, Sharifullin B R, Kravtsova A Yu and Shtern V N 2020 Exp. Therm. Fluid. Sci. 116 110116

[9] Naumov I V, Tsoy M A and Sharifullin B R 2019 Exp. Fluids 60 178

[10] Naumov I V, Sharifullin B R, Tsoy M A and Shtern V N 2020 Phys. Fluids 32 061706

[11] Skripkin S G, Tsoy M A and Naumov I V 2020 J. Phys. Conf. Ser. 1675 012019