5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

Experimental investigation of the vortex flow instability in closed polygonal containers

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Abstract

Unsteady flow control, including by vortex breakdown, is necessary to improve heat and mass transfer processes in power technologies. Unique vortex breakdown phenomenon in the confined flow for uncompressible fluids such as water, oil, glycerin-water mixture has been investigated experimentally. The new insight into some practical aspects of confined flows enables a more detailed investigation of the flow structure for non-axisymmetric geometry of closed container. Regularities of counter flow formation and conditions of conversion to unsteady flow regime were determine in various configurations of closed polygonal container. The results show that at steady conditions there are no asymmetric distortions of the flow topology due to the non-axisymmetric effect of the polygonal geometry of the used containers. It has been found that reducing the number of cross-section angles from eight to four shifts the instability onset to lower Reynolds numbers and smaller aspect ratios. The vortex flow structure in the near-axis area remains similar to that in the cylinder. We can assume that the onset of the three-dimensional instability based on appearance of vortex multiplets in polygonal configurations is similar to that in the cylinder at increasing Reynolds number.

1 Introduction

Development of the vortex devices in chemical, biological and power technologies requires investigation of the characteristics of confined vortex flows defining the regimes of emergence and destruction of self-organized vortex structures and the steady/unsteady regimes of the vortex flow to improve control of heat and mass transfer. Vortex breakdown phenomenon is one of the key parameters that influence transfer processes appearing in many engineering applications. It is well known (Escudier (1984), Lopez (1990) and Naumov *et al*. (2014)) that the onset of vortex breakdown (VB) in a sealed cylinder depends on aspect ratio h (ratio of cylinder high H to radius R) and Reynolds number $Re = \Omega R^2/\nu$ (where Ω is the angular velocity of lid rotation, and ν is the kinematic viscosity of liquid) when the rotating lid drives the fluid around the container axis. It should be added that even in the axisymmetric cylindrical configuration, multiplex structures of helical vortices (doublets, triplets and even quadruplets Sørensen *et al*. (20011)) are formed with increasing aspect ratio, which causes the transition to the unsteady flow regime. The new insight into some practical aspects of container flows enables to investigate the flow structure for non-axisymmetric geometry of closed container in details. However, the majority of previous studies focused on the case of a closed cylindrical container. Other geometries have not been well explored experimentally, and only a few numerical studies have considered the problem in asymmetrical geometry where the container consists of an inclined sidewall by Yu *et al*. (2008) or wave sidewall by Yu and Meguid (2009). In the meantime, these studies show that the inclined or wave sidewalls do play an important role in precipitating/suppressing the occurrence of the vortex breakdown.

The main purpose of this experimental work is to expand the investigation of influence polygonal geometry with rotating lid (Naumov *et al*. (2015), Naumov and Podolskaya (2017) and Podolskaya *et al.* (2018)) on the appearance of non-axisymmetric instabilities especially on the unsteadiness boundary where the vortex multiplets were formed. The structure of confined vortex flow generated by a rotating lid in a closed container with polygonal cross-section geometry has been investigated experimentally for different h ranging from 0.5 to 5.0 and for Reynold numbers ranging from 1500 to 3000.

2 Experimental Set-up and Data Processing

The topology of VB and instability of the confined flow generated by a rotating disk in closed containers with polygonal cross-sections (square, pentagonal and hexagonal) was analyzed experimentally. The problem formulation and experimental technique are described in detail in Naumov *et al.* (2015) and Naumov and Podolskaya (2017). The schematic of the problem geometry is presented on figure 1.

Aspect ratio h was changed in the range from 0.5 to 3.0. The rotating disk radius is $R_D = 49.6$ mm. The gap between the rotating disk and the hole in the upper end wall is 0.4 mm. This hole with radius $R = 50$ mm represents an incircle in the upper lid of polygonal containers. The minimal width of the lid near the flat vertical edge of the polygon is 0.5 mm (fig. 1c). Thus, the side length of a regular polygon with a number of angles N, is determined on the incircle with radius $r = 50.5$ mm. The gap between the rotating disk and the container sidewall is negligibly small, not more than 2% of the disk size, and has no noticeable effect on the vortex breakdown phenomena.

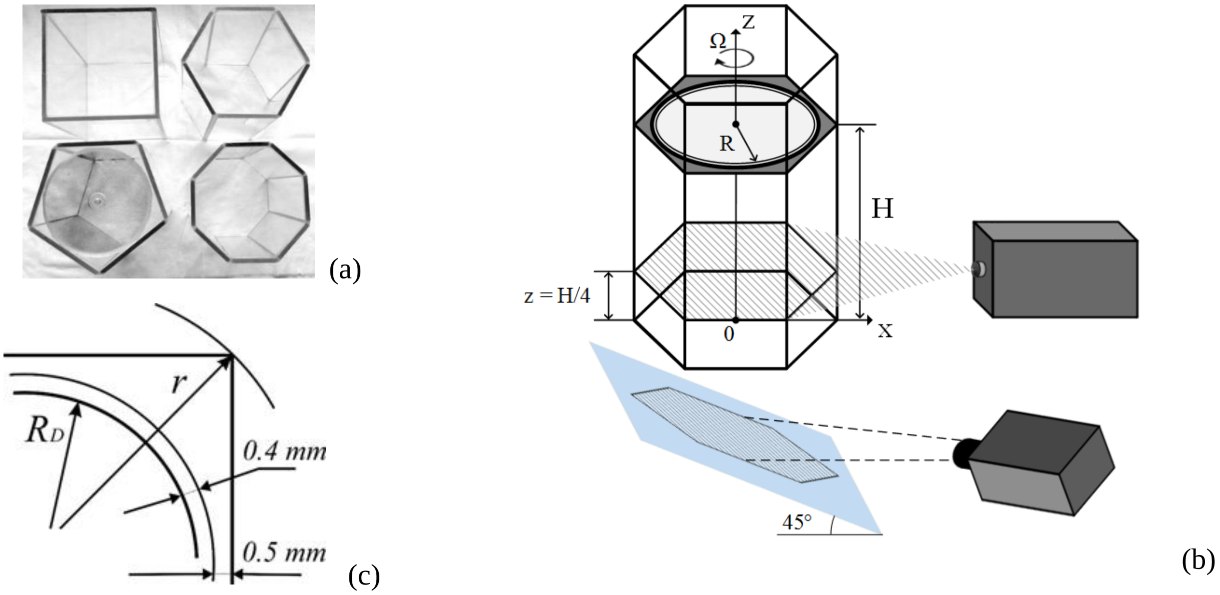

Figure 1: Photo of glass containers with polygonal cross-sections (a), schematic of the problem in polygonal geometry (b) and schematic of the rotated disk and upper stationary end wall (c).

During the experiments, each container was placed inside a rectangular box with dimensions of 200x200x200 mm that was made of glass and filled with tap water, in order to minimize optical aberrations and temperature fluctuations. A 70% glycerin-water mixture was used as a working fluid. The temperature dependence of viscosity was approximated by the second order polynomial, with reference points equal to 26.82 cSt at 20 °C and 19.95 cSt at 26 °C. As the viscosity of the working fluid was very sensitive to temperature changes, the temperature dependence of liquid viscosity was carefully controlled during the experiments. The fluid temperature was measured with an accuracy of 0.1 ^{o} C, thus reducing the uncertainty of viscosity determination to 0.2%. The total error of Re did not exceed ± 10 in the range of Reynolds numbers from 500 to 3000.

The flow pattern and velocity distribution were observed and measured combining the seeding particle visualization and Laser Doppler Anemometry (LDA). Flow visualization was performed using laser (laser power of 250 mW and wavelength of 684 nm) and digital camera. The flow patterns were observed by seeding particle visualization (polyamide beads with mean size of 10 microns). The obtained results were adjusted by more accurate LDA measurements of the axial velocity along the container *z*-axis. The critical Reynolds numbers at which the flow becomes unsteady were determined by LDA measurement and velocity field was determined by PIV (Particle Image Velocimetry) with phase averaging technique described in Sørensen *et al.* (2006). The image of the azimuthal projection of the rotating flow, generated by the rotating lid, is reflected on a mirror placed at an angle of 45° below of the polygonal containers (Fig. 1b).

For instantaneous flow field diagnostics, the 2D PIV was used. The PIV system was designed and manufactured at the Kutateladze Institute of Thermophysics SB RAS. As an optical source for forming the light sheet was used Nd: YAG pulsed laser POLIS v3.2 with the following characteristics: wavelength of 532 nm, light sheet thickness of 2 mm, the energy pulse power of 120 mJ, and the operation frequency of 2 Hz. Images were registered by POLIS camera v1.0 with lenses Nikon AF 28 mm f/2.8D Nikkor at a resolution of 1352x1016. To calculate the two-dimensional velocity field the Actual flow software Version 1.16.7.0 was used.

Time histories of axial velocity were recorded at various points in the flow field using the LDA and then were analyzed for their frequency content using spectral analysis. The signals recorded at $z = H/4$ were further employed to detect the characteristic frequencies of the azimuthal modes. These were subsequently extracted from the processed PIV images. Each time history was recorded in a period of 60 sec, which was sufficient for determining the frequencies of the modes. The analysis of the PIV images proceeds as follows. First, for each combination of aspect ratio and Reynolds number, (*h, Re*), the mean flow field is determined by averaging 200 recorded PIV images. Next, based on the characteristic frequencies appearing in the LDA samples, time intervals proportional to the instability frequencies are defined. In the next step, velocity fields are measured in a time interval consisting of oscillation periods. By selecting samples at equidistant time instants, phase averaged velocity fields were obtained by averaging 20-40 PIV samples during a full-time interval. In the final step, the mean field is subtracted from the phase-averaged PIV samples and, as a result, the modes become visible. Thus, combining LDA and PIV like Sørensen *et al.* (2006) allows detecting frequencies and associated modes of the underlying flow structures.

3 Results and Discussion

There are complicated spatio-temporal flow structure modifications in polygonal containers with increasing Reynolds number. In contradistinction to flow in cylindrical container that remains axisymmetric up to Re ~ 2000 in the entire range of aspect ratio flow in polygonal container is a priori asymmetric even at Re ~ 1000 that presumably induces shift of unsteadiness onset boundary. Nevertheless, the flow structure and VB remain axisymmetric near the container axis and remains similar to the flow structure and VB in the cylinder; therefore, the shape of the container does not influence the near-axis region (neither in horizontal nor in vertical cross-section).

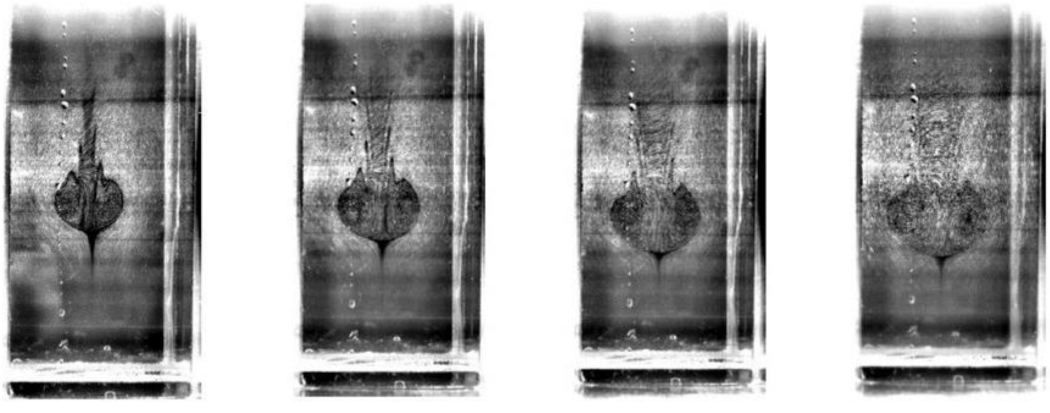
Re = 1600 *Re* = 1800 *Re* = 2000 *Re* = 2200

Figure 2: The flow with VB regime at *h* = 2.25 and different Re for hexagonal configuration.

The example of the flow comparison for $h = 2.25$ and different *Re* for hexagonal configuration is presented on figure 2 and corresponds to the behavior of breakdown bubble for $h = 2.0$ in cylinder (Fig. 6 from Naumov *et al*. 2015).

The LDA measurements were systematically carried out in the range $h \in [1.0, 5.0]$, starting at $h = 1.0$ with an increasing step size $\Delta h = 0.2$, and in the range $Re \in [1800, 2800]$, with a step size $\Delta Re = 100$. The obtained results were compared with the flow structure in the closed cylindrical container (fig. 3). It has been found that reducing the number of cross-section angles from eight to four shifts the instability onset to lower Reynolds numbers and smaller aspect ratios. It can be seen from the figure 3 that VB area stabilizes the flow by shifting unsteadiness onset boundary to higher *Re* both in the cylinder and in the polygonal containers. We can assume that the onset of the three-dimensional instability based on appearance of vortex multiplets in polygonal configurations is similar to that in the cylinder at increasing Reynolds number. Analysis of figure 3 allows us to assume that the VB onset in a triangular configuration may appear only at an extremely high Reynolds number. Numerical simulation has shown that VB onset becomes possible at *Re* over 3000 for an aspect ratio $h < 1.0$ (Naumov and Podolskaya, 2017).

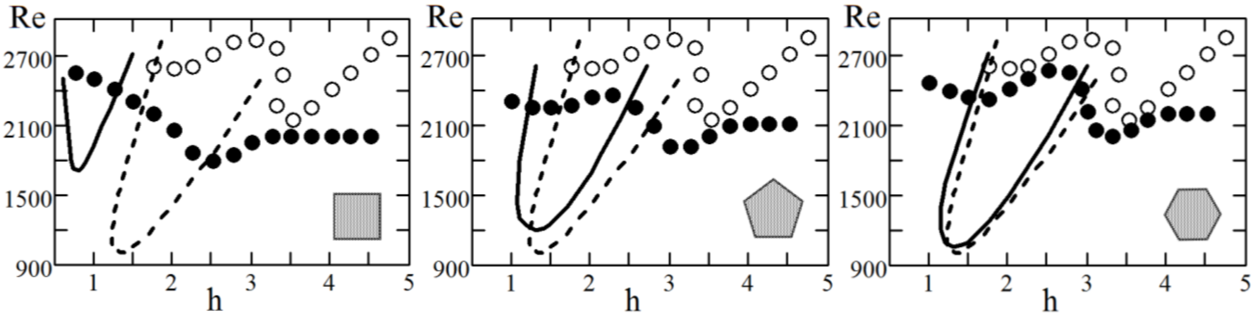

Figure 3: VB location in the cylinder (dashed line) and in the polygonal geometry containers (solid line), the onset boundary of the instability: open circles correspond to the critical Reynolds numbers in the cylinder and solid circles in polygonal geometry containers.

Using LDA measurements the characteristic frequencies of the velocity were extracted and compared to the cylindrical configuration. For aspect ratio 2.5 and 3.0 the non-dimensional frequencies for square, pentagonal and hexagonal configurations correspond to $f_4 = 0.35$, $f_5 = 0.36$ and $f_6 = 0.34$ respectively. For cylindrical configuration this non-dimensional frequency was equal $f = 0.34$ and corresponded to the rotating triplet (Sørensen *et al.,* 2011). From the experimental observations it is found that the azimuthal mode $k = 3$ (triplet) is dominant in the range $2.5 < h < 3.5$. In the range $3.5 < h < 4.0$ the measurements show that the duplet is formed, which also causes the transition to the unsteady flow regime. The non-dimensional frequencies in this case was equal $f = 0.15 - 0.16$ and corresponded to the rotating duplet like in the cylindrical configuration. At $h > 4.0$ the measurements showed that $k = 4$ is the most unstable mode with the non-dimensional frequency $f = 0.31 - 0.32$. This research has revealed that the increase in Reynolds number creates same development of the instability onset scenarios in the closed polygonal containers and in the closed cylindrical container (Sørensen *et al.,* 2011). It has been found that reducing the number of cross-section angles shifts the instability onset at low Re to the smaller aspect ratios.

Based on the information gained from the time histories of the LDA measurements, the time ranges for averaging instantaneous velocity fields are determined for the PIV method. The resulting perturbed velocity fields were derived by averaging over a series of realizations at divisible time-periods. To illustrate the details of the multiplet which causes the transition to the unsteady flow regime the perturbed velocity fields in a horizontal cross-section $z = H/4$, measured from the bottom of the cylinder was extracted from mean velocity field. Figure 4 illustrates examples of the instantaneous velocity field of the azimuthal wave (corresponding to triplet) with wave number $k = 3$ at phase averaging for $h = 3.0$ and different Reynolds number corresponding of the instability onset.

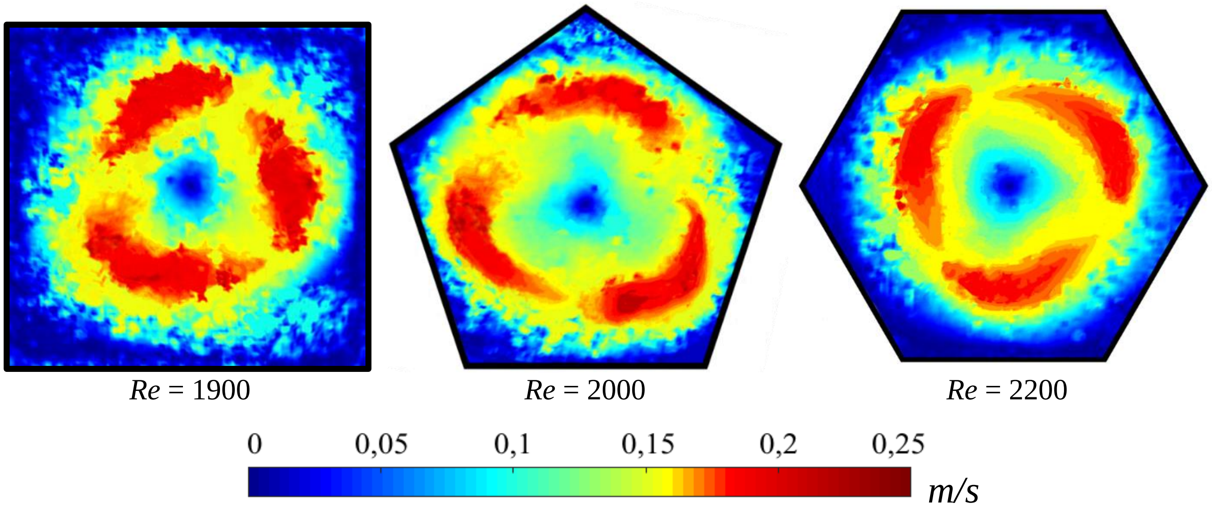

Figure 4: Instantaneous phase-averaging PIV velocity fields at h = 3.0 and z=H/4.

Both the experimental and previous numerical study showed that polygonal geometry of container does not affect the vortex structure near the container axis when rotating triplets arise (fig. 5) and triplets are formed according to the same scenario as in the axisymmetric cylindrical configuration. Figure 5 illustrates the distribution of the axial vorticity for same intensity in different polygonal container configurations with aspect ratio *h* equal to 3.0 and Reynolds number equal to 2100, 1900 and 1900, respectively, being the critical Re for those configurations. As a result, these plots show the appearance of a ‘triplet symmetry’ and demonstrate that the flow instability is associated with a uniform rotation of a vortex triplet embedded in strong assigned axisymmetric flow like in cylinder.

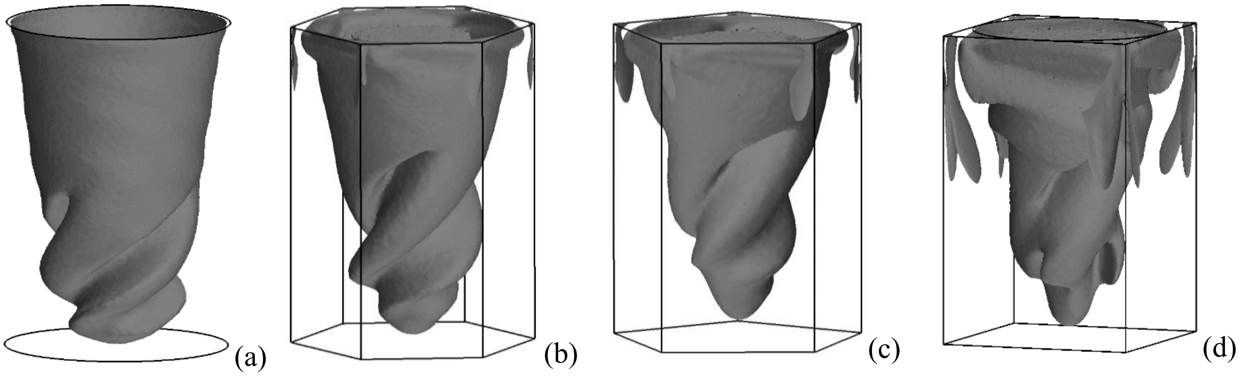

Figure 5: Isosurface of axial vorticity equals 3.0 in: cylindrical container at *Re* = 2300 and *h* = 3.5 (a), hexagonal container at *Re* = 2100 (b), pentagonal (c) at *Re* = 2000 and tetragonal (d) at *Re* = 1900 for *h* = 3.0 from Podolskaya *et al*. (2018).

It is seen that the structure of multiplets is of the same type. In addition, despite the smaller rotating energy (smaller Reynolds number) the multiplet is formed downstream along the container axis in polygonal configuration (closer to the rotating lid) compared to the cylinder. Thus, more intensive mixing occurs in the middle of the container rather than near the bottom. The same tendency was observed for the recirculation zone of VB in the polygonal container geometry. In this case, the effect of the number of angles in the cross-section of polygonal container on the flow pattern in the axial region of the container is not observed. We can assume that the behavior of three-dimensional instability in pentagonal, hexagonal and tetragonal configurations is similar to that in the cylinder at larger Reynolds numbers.

4 Conclusion

The influence of container configuration at confined vortex flow structure was investigated. The critical Reynolds numbers, and associated frequencies of the perturbed velocity field, were determined and azimuthal periodicities, patterns and characteristic frequencies of the velocity were extracted and compared to the cylindrical configuration of Sørensen *et al.* (2006, 2009). This research has revealed that the increase in Reynolds number creates same swirling flow development scenarios in the closed containers with polygonal cross-sections and in the closed cylindrical container. From the experiments it is found that triplet is dominant in the range $2.5 < h < 3.5$. In the range $3.5 < h < 4.0$ the measurements show that duplet is formed that causes the transition to the unsteady flow regime. It has been found that reducing the number of cross-section angles shifts the instability onset to the smaller aspect ratios and the VB stabilizes the flow shifts the instability onset to lower Reynolds numbers.

It is showed that the flow structure in the polygonal container has common regularities with the flow structure in the axisymmetric container. It is necessary to consider these scenarios at the design of industrial vortex combustion chambers, which often have the shape of polygonal container. The obtained results also have relevance for development of vortex technology in biochemical reactors, etc., where heat and mass transfer depend significantly on the flow instability and vortex breakdown phenomena.

Acknowledgements

This work was supported by the Russian Foundation for Basic Research No.18-08-00508.

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