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Investigating the structure of a vortex flow in the closed polygonal containers

I Yu Podolskaya[1,2], G V Bakakin[1], I V Naumov[1]

[1]Kutateladze Institute of Thermophysics SB RAS, Novosibirsk 630090, 1 Lavrentyev Ave., Russia
[2]Novosibirsk State University, Novosibirsk 630090, 1 Pirogova Str., Russia

Email: naumov@itp.nsc.ru

Abstract. The structure of confined vortex flow generated by a rotating lid in a closed container with polygonal cross-section geometry (eight, six and five angles) has been investigated numerically for different height/radius aspect ratios *h* from 3.0 to 4.5 and for Reynold numbers ranging from 1500 to 3000. The critical Reynolds numbers at which the flow becomes unsteady were determined numerically by STAR-CCM+ computational fluid dynamics software for pentagonal and hexagonal cross-section configurations. The obtained results were compared with the flow structure in the closed cylindrical container. The boundary of a nonstationarity in polygonal containers is found to shift to the region of smaller aspect ratio and smaller Reynolds numbers with a decrease in the number of angles in the cross-section of the container relative to the boundary in a cylindrical container. It is additionally established that the structure of the flow in the near-axis region remains similar to the vortex structure in the cylinder, therefore the shape of the container does not influence the near-axis region.

1. Introduction

Development of the vortex devices in chemical, biological and power technologies requires investigating 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 heat and mass transfer control. One of the key parameters influencing transfer processes is vortex breakdown phenomenon that appears in many engineering applications.

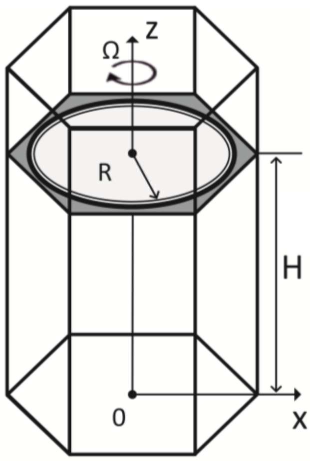
It is well known [1, 2] that the onset of vortex breakdown (VB) in a classical closed cylinder depends on aspect ratio *h* (ratio of cylinder high *H* to its radius R), Reynolds number $Re = \Omega R^2/\nu$ (where Ω is the angular velocity of lid rotation, and ν is the liquid kinematic viscosity) and boundary conditions, when the rotating lid drives the fluid around the container axis.

It is necessary not only to determine the regime parameters at which vortex breakdown occurs but also to control vortex breakdown formation. In work [3] it was experimentally found that the scenario of VB development is the same for cylinders with both low and high aspect ratio, and it remains independent of stationary-nonstationary transition boundary for the main vortex flow at *h*, ranging from 1 to 6. VB control without an input of significant additional energy but with a change in container geometry is a very attractive way of manipulating the flow environment. A non-intrusive control method of VB, based on co-rotation and counter-rotation of a small disk embedded in the non-rotating end wall was successfully applied [4, 5]. They showed that the aspect ratio has a dominant effect on the VB appearance, and that varying the size of the rotating disk one can control the VB behavior. They found that the co-rotating disk increases the swirl decay downstream. As a result, the VB onset occurs at a smaller Re than that with no control. By contrast, for the counter-rotating disc the bubble appears at larger Re. The chamber geometry may also have its influence. 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 considered the problem where the container consists of an inclined or wave sidewall [6].

In various technical applications the configuration of the container may also differ from the axisymmetric cylindrical one, for example, a polygonal cross-section geometry. Recent papers [7, 8] have shown that in the near-axis region of VB location the flow structure remains axisymmetric (Fig.1) in polygonal containers. The VB region for the octagonal cross-section was detected to almost correspond to the one for cylindrical container but these areas for square and cylindrical containers do not overlap in entire range of aspect ratios [8].

It should be added that even in the axisymmetric cylindrical configuration, multiplex structures of helical vortices: doublets, triplets and even quadruplets [9, 10], are formed with increasing aspect ratio, which causes the transition to the unsteady flow regime. Recent numerical [11] and experimental [12] investigations of the boundary of the unsteady flow regime formation have shown that the critical Reynolds number (Re ~ 3000) is independent from the aspect ratio, exceeding 5.

The purpose of this work is to expand the investigation of influence of polygonal geometry on the vortex flow especially on the unsteadiness boundary at regime parameters (h, Re) where the vortex multiplets was formed. The pentagonal and octagonal cross-section configurations have been chosen in this study (Fig.1) since the vortex breakdown region for the octagonal cross-section almost corresponds to the one for cylindrical container and these areas for square and cylindrical containers do not overlap in the entire range of aspect ratios [7, 8].



(a)

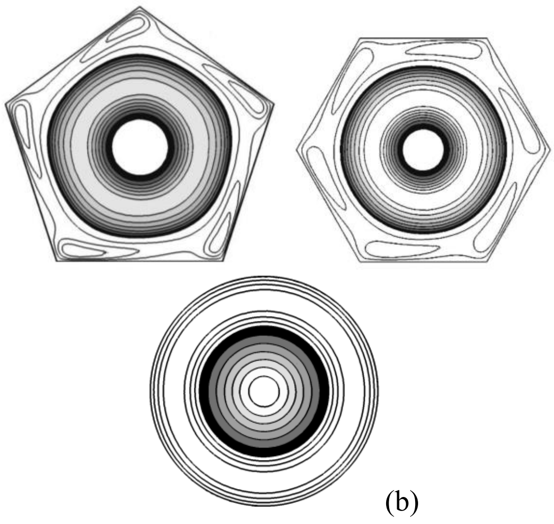

(b)

Figure 1. Schematic of the problem (a). Distribution of axial velocity in (x, y) plane, z = 0.3H, 0.5H and 0.25H for pentagonal, hexagonal and cylindrical configuration, respectively (b).

2. Problem formulation and technique of numerical simulations

The topology of confined vortex flow generated by a rotating disk in closed containers with polygonal cross-sections (pentagonal and hexagonal) was analyzed numerically by STAR CCM+ computational fluid dynamics software at h ranging from 3.0 to 4.5. The schematic of the problem geometry is

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presented in figure 1. The reference point of the coordinate system is set in the center of each polygon bottom. The *x*-axis passes through the non-rotating bottom plane. The *z*-axis coincides with the vertical container axis. Contrary to the cylindrical geometry, where the rotating lid is also an upper end wall of the container, in the polygonal geometry, the rotating disk is embedded in the upper end wall since its rotation is impossible due to the non-circular geometry.

The critical Reynolds numbers at which the flow becomes unsteady were determined experimentally and numerically by STARCCM+ computational fluid dynamics software. The assumption that the flow was incompressible and steady was made to compute the three-dimensional flow field in the containers with rotating end walls. The well-established STAR CCM+ commercial package is based on the finite volume method. In numerical calculation, the rotating disk radius was 50 mm. The pressure-based segregated flow model was employed to solve the governing equations. The standard no-slip boundary condition was imposed on all surfaces.

The linkage between the momentum and continuity equations was achieved using a predictor–corrector approach. The second-order upwind scheme was applied to the convective term. The SIMPLE solver algorithm was used to couple the continuity and momentum equations. To neglect total diffusion at flow boundaries near the container walls, the flow boundary diffusion property of segregated flows was used. Double precision (15 d.p.) was used for all the calculations to neglect round-off errors. Detailed description of numerical simulation and its verification is presented in papers [7, 8]. These parameters of numerical simulation allowed determining both the Reynolds numbers at which vortex breakdown bubble occurs, the position of this vortex breakdown bubble on the axis and the size of the recirculation zone, which were confirmed experimentally [8]. Therefore, it is possible to use these numerical parameters to determine the critical Reynolds numbers of the unsteadiness boundary and regimes of multiplets flow in polygonal cross-section configuration of containers.

3. Results and discussion

The structure of confined vortex flow generated by a rotating lid in a closed container with polygonal cross-section geometry has been investigated numerically for different height/radius aspect ratios *h* from 3.0 to 4.5 and for Reynolds numbers ranging from 1500 to 3000 to determine boundaries of multiplets formation and the onset of unsteady flow regime. In contrast to cylindrical configuration, the polygonal container geometry a priori assumes the dependence on the azimuthal coordinate.

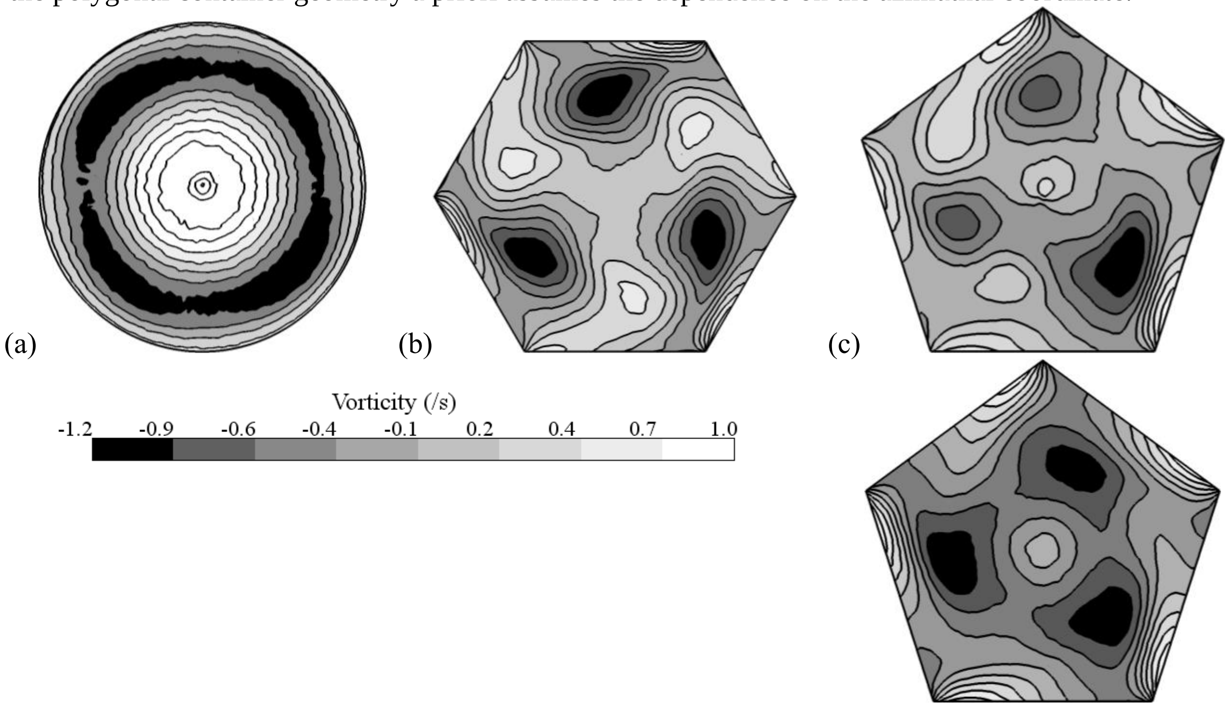

Figure 2. Numerical calculation of radial vorticity at horizontal cross-section at $z = H/4$ in cylindrical (a), hexagonal (b) and pentagonal (c, d) container configurations with aspect ratio h equal to 3.5 at Reynolds number Re equal to 2100 (a, b, c) and 1900 (d).

Figure 2 shows the distribution of radial vorticity at horizontal plane at $z = H/4$ (the area where vortex multiplets have maximal amplitude of oscillations [9, 11]) with aspect ratio $h = 3.5$. Figure 3 shows the distribution of the axial vorticity in cylindrical (a), hexagonal (b) and pentagonal (c) container configurations with aspect ratio h equal to 3.5 at Reynolds number equal to 2100.

At $Re = 2100$ the flow remains steady in the cylinder and there are no multiplets (a); in the hexagonal container it is clearly seen that the triplet occurs (b); in the pentagonal container there are several wave modes (c) that become obvious at larger Re in the cylinder [2, 12]. With a decrease of Re to 1900 (d) only one mode contributes to the distribution of radial vorticity, and the flow pattern looks like the one in the cylindrical configuration [10]. It is seen that for a fixed Re in the cylinder there are no multiplets and in hexagonal and pentagonal configurations triplets occur that is also evident from the diagram on figure 4. The triplet in the pentagonal configuration has a lower intensity compared to the one in the hexagonal configuration due to the appearance of additional oscillation modes. As for the cylinder, the triplet vortex structure is primarily formed in the hexagonal and pentagonal configurations.

(a) (b) (c)

Figure 3. Isosurface of axial vorticity equals 3.0 in cylindrical (a), hexagonal (b) and pentagonal (c) container configurations with aspect ratio $h = 3.5$ at Reynolds number $Re = 2100$.

The obtained results are compared with the flow structure in the closed cylindrical container. Figure 4 illustrates VB boundaries in the cylinder (dashed line) and the pentagonal cross-section (solid line) in the (h, Re) plane. Open circles correspond to critical Reynolds numbers where unsteadiness appears in the cylinder; triangles are used in hexagonal and solid circles are used in pentagonal cross-section of containers. Figure 4 shows the trend of unsteadiness boundary shifting to the area of smaller aspect ratio and lower Reynolds numbers with decreasing angle numbers in the container cross-section. The same tendency is observed for the recirculation zone of vortex breakdown [7, 8], where VB onset shifts to smaller aspect ratio but to higher Reynolds numbers. The critical Reynolds number is seen to rapidly decrease (especially in the cylinder [2, 9-10] when the boundary of unsteadiness overlaps the VB onset boundary. It probably means that the vortex breakdown can make the flow stable that may be used in technical applications. In addition, figure 4 illustrates that the unsteadiness boundary starts tending to the horizontal line at aspect ratio over 4.0 and is independent from Reynolds number, that was observed in the cylindrical container [11, 12], where the critical Reynolds number was found to be nearly h-independent for $h > 5.0$.

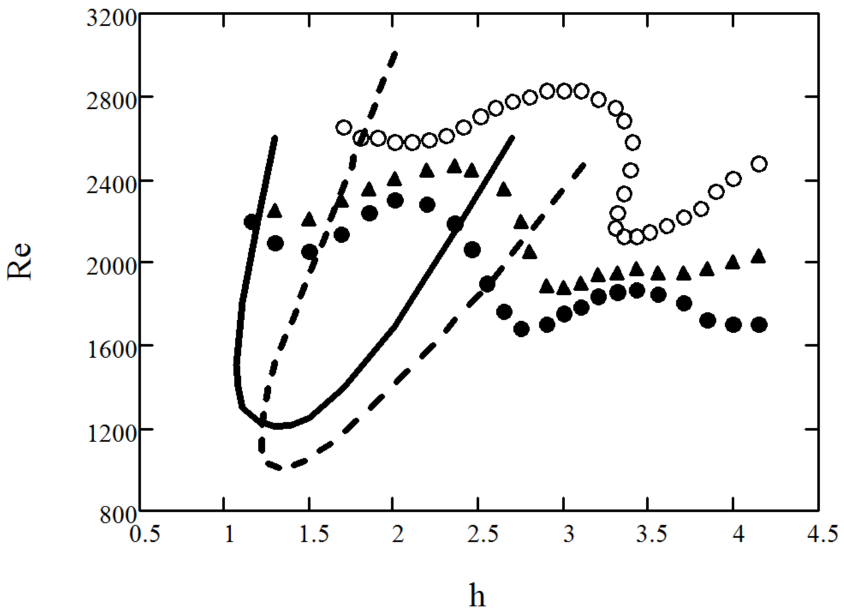

Figure 4. VB boundaries in the cylinder (dashed line) and pentagonal cross-section (solid line). Open circles correspond to critical Reynolds numbers in the cylinder, triangles – in hexagonal, and solid circles – in pentagonal cross-section configuration of containers.

Figure 5 illustrates the distribution of the axial vorticity for same intensity in cylindrical (a), hexagonal (b) and pentagonal (c) container configurations with aspect ratio h equal to 3.5 and Reynolds number equal to 2300, 2100, and 1900, respectively, being the critical Re for those configurations.

(a) (b) (c)

Figure 5. Isosurface of axial vorticity equals 3.0 in cylindrical container at Re = 2300 (a), in

hexagonal container at *Re* = 2100 (b) and in pentagonal one at *Re* = 1900 (c) for aspect ratio *h* = 3.5.

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 much lower 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 vortex breakdown in the polygonal container geometry [7, 8]. 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 and hexagonal configurations is similar to that in the cylinder at larger Reynolds numbers.

4. Conclusions

The initial axisymmetry-breaking instability of the flow in closed containers with polygonal geometry for different aspect ratios was investigated for steady flow conditions. The influence of the container configuration on the closed vortex flow structure was studied, and the unsteadiness boundary was determined for aspect ratios ranging from 3.0 to 4.5. The flow structure in containers with polygonal cross-section and without axial symmetry was compared with a vortex flow in axisymmetric configurations. The results allow revealing regularities of formation both VB and vortex multiplets depending on Re, *h* and cross-section geometry of the closed container.

The new insight into some practical aspects of container flows enables a more detailed investigation of the flow structure for non-axisymmetric geometry of closed container. It has been found that reducing the number of cross-section angles from eight to five shifts the instability onset to lower Reynolds numbers and smaller aspect ratios. 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 (neither in horizontal nor in vertical cross-section).

The self-organizing coherent vortex structures have been found and analysed. The vortex flow structure in the near-axis area remains similar to that in the cylinder; therefore, the polygon form of the container does not exert considerable impact on the multiplet structure. We can assume that the onset of the three-dimensional instability based on appearance of vortex multiplets in pentagonal, hexagonal and octagonal configurations is similar to that in the cylinder at increasing Reynolds number.

5. Acknowledgments

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