Simulation of vortex breakdown in an enclosed cylinder as a preliminary study of the draft tube vortex rope creation

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Abstract: Vortex breakdown occurs as instability of the steady flow in many engineering applications (turbine diffusers, swirl chambers, etc.). Paper presents investigation of this phenomena in an enclosed cylinder. This original problem is further extended to study the influence of the cone inserted inside the cylinder. The cone shape (sharp or blunted) and the cone rotation are examined. It is concluded that especially cone rotation significantly influences the initiation of vortex breakdown and the overall flow pattern.

Key-Words: vortex breakdown, enclosed cylinder, cone, vortex rope, stability, laminar flow

1 Introduction
Flow in the draft tubes (i.e. diffuser shaped section at the turbine exit) of hydraulic turbines exhibits very peculiar phenomenon called vortex rope for off-design point turbine operation. Vortex rope is periodic concentrated swirl resulting from instability of the flow, which is leaving turbine runner with non-zero circumferential velocity component. It can be stated that it is a form of helical vortex breakdown. Helical, or spiral, form of vortex breakdown is cause of severe pressure pulsations and performance deterioration.

Photo from present experimental investigation shows the runner cone and the cavitating spiral vortex breakdown in a diffuser with axial and circumferential velocity component at the inlet, see Fig.1.

Fig.1 Cavitating spiral vortex in a diffuser

Numerical simulations of the vortex rope are possible (e.g. [1], [2]), but understanding of the physical mechanism itself is still incomplete. A lot of work in experimental and theoretical field has been devoted to this problem [3-6], over last decades, but new insights are still necessary [7], [8].

Presented paper is focused on simulation of the vortex breakdown in very simple geometry - enclosed cylinder. Cone is inserted at the bottom wall and co- and counter-rotation is prescribed to mimic real turbine topology. This geometry was for very accurate boundary conditions, because walls are surrounding whole computational domain. Therefore it is an excellent case to study the isolated influence of the different geometry modifications (e.g. cone shape) on the vortex breakdown behavior.

2 Vortex breakdown in an enclosed cylinder
Confined flow in an enclosed cylinder has been a subject of many studies, see [9-13]. The flow is driven by rotation of the top wall ($\omega_t \neq 0$), the bottom and side walls do not rotate ($\omega_b = 0$), see Fig.2. Eckman boundary layer develops on the spinning top disc and Stewartson boundary layer on the side walls. Stewartson boundary layer growth forms diffuser like flow within the cylinder. For low Reynolds numbers ($\text{Re} = \omega_t R^2 / \nu$) a laminar flow characterized by a columnar vortex appears. A zone of decelerated flow is establishing along the axis for increasing top wall rotation. Finally a backflow near the axis is reached for certain value of Reynolds number and bubble visualized by a closed streamline emerges. This phenomenon is called vortex breakdown. Further increase of Reynolds number can eventually lead to double or triple bubble formation. The different flow patterns for different values of Reynolds number and aspect ratio (H/R) can be summarized into a map, see Fig.3.
It is advantageous to exploit the axisymmetry of the flow and simplify the computational model to two dimensions. The laminar flow is governed by Navier-Stokes equations with no-slip boundary conditions on the walls. Rotation is prescribed for the top wall.

Commercial CFD code Fluent, which is based on the finite volume method was used for the numerical simulation.

Comparison of the computed results and experimental data is presented in the flow pattern diagram, Fig.3. Very good agreement is obtained for all Reynolds numbers and aspect ratios, simulations are capable to catch even the multiple vortex breakdowns. Vortex breakdown was located by sudden appearance of a closed streamline, which is a methodology adopted from [14].

Visualization of vortex breakdown bubbles and axial velocity profiles is in Fig.4.

Further confrontation with the experiment is in Fig.5, where experimentally visualized flow pattern is matched to computed streamlines for one particular combination of Reynolds number and aspect ratio. Only the streamlines with very low streamfunction value are drawn.
bubble formation. However the second bubble appearance is not touched by this modification and is formed exactly for the same value of Reynolds number as for the cone with spike. Difference in flow patterns between sharp and blunted cones can be explained by sudden change in pressure gradient and axial velocity, which is induced by spike removal. The axial velocity drop just behind the cone initiates the vortex breakdown. The second bubble is only influenced by the first one, therefore no difference is observed between the two modifications in this point.

4 Cone rotation

Cases of the top and bottom wall rotation in an enclosed cylinder were studied by [16] and for rotating cone by [17]. However the cone in paper [17] was of the same radius as the cylinder and the top wall was not spinning. It was found that bubbles of recirculation zones along axis appear in case of co-rotating top and bottom walls, contrary to counter-rotating walls, where purely circulating motions occur. Sharp cone is set to constant rotation with 
\[ \text{Re} = \omega_c R_c^2 / v = 62 \] in the present study and top wall is increasing its spinning to observe emerging of the vortex breakdown bubbles. Both co- and counter-rotation were tested.

The dramatic difference between co- and counter-rotation is obvious from Fig.7, where axial velocities along cylinder axis are plotted. Recirculation region extending to 80% of the cylinder height develops for the co-rotation of the cone and top wall, whereas no backflow occurs for counter-rotation. Cone without rotation with one vortex breakdown bubble, which is also plotted in the figure, is added to illustrate the contrast between those two diverse cases.

Fig.7 axial velocity along axis, Re = 1810, H/R = 2

The best tool for detecting the differences is again streamline visualization. Figs.8-11 show the evolution of the flow patterns for original cylinder, cone without rotation and cone with co- and counter-rotation. Only the
streamlines with very low streamfunction value are plotted.
In the case of co-rotation, bubble first appears at the cone and slowly contracts with increasing top wall rotation, the first bubble on the cylinder axis appears about 15% (measured using Reynolds number) earlier than in the case with no cone rotation. The second bubble is accelerated by the same percentage. Fig.10 shows the two bubbles which are merging together. On the other hand counter-rotation retards the vortex breakdown by about 23% and by the same value also the second bubble. Figs. 8-11 also illustrate influence of the cone and its rotation on the bubble extent in the radial direction.
5 Conclusion

Vortex breakdown in enclosed cylinder with geometrical modifications was studied. It was found that the computational model is in very good agreement with experimental data for the original problem of the enclosed cylinder. The geometrical modifications were introduced to simulate the real turbine runner cone in a diffuser. The sharp cone delayed appearance of both vortex breakdown bubbles, whereas blunted cone initiated this phenomenon, but still at higher Reynolds number than cylinder without cone.

It was found that the cone rotation has dominant influence on vortex breakdown formation. Co-rotation intensifies the vortex and accelerates the bubble creation. On the other hand, counter-rotation works in opposite fashion, formation of the bubbles is retarded. These results might shed light on the creation of the vortex rope in a draft tube of hydraulic turbine. It is assumed that the real runner cone will exhibit similar influence on the spiral vortex breakdown, but might be less pronounced, because of strong axial flow.

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