Parametric study of cone angle influence on bubble vortex breakdown onset in laminar conical flow at various swirl numbers

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Abstract. The current work studies a swirling laminar viscous pipe flow with a controllable swirl number and varying pipe divergence cone angle. Such flows are widely used in various engineering applications. When a certain level of flow swirl is reached, a phenomenon called vortex breakdown occurs, the characteristics of which depend on the intensity of swirling of the flow and the Reynolds number. However, in addition to these two parameters, an important influence is exerted by the pipe opening angle, which often does not allow generalizing the results obtained in the pipe flow with even slightly different angles. Since experimentally it is quite difficult and expensive to change the pipe angle, especially considering the water as working fluid, this issue could be solved using CFD techniques. Using the design study, 63 different combinations of $S$ and $\alpha$ are considered. The effect of the pipe divergence angle on the position of the bubble vortex breakdown and its properties is demonstrated. It is shown that there is a nonlinear relationship between the position of the bubble breakdown onset and the minimum value of the axial velocity at the axis depending on the opening angle of the cone.

1. Introduction
The current interest in swirling flows is directly related to the significant number of technical applications in which they are used. Swirling flows are often accompanied by various vortex phenomena, so the formation of a bubble-like or spiral vortex breakdown is observed when a certain level of flow swirl is reached. Generally, this phenomenon is described as a structural change in the vortex core associated with deceleration of the velocity on the axis of the vortex up to the onset of the recirculation zone.

There are three main forms of vortex breakdown: bubble vortex breakdown, generally observed in axisymmetric swirling flow, spiral and multispiral breakdowns; and the latter may lack a stagnation point, which is not always considered as vortex breakdown in its classical sense. The bubble vortex breakdown can be described as a velocity stagnation point on the flow axis, followed by a substantially axisymmetric region of recirculation. In the spiral type of breakdown, the axial filament is deformed into a spiral configuration following an abrupt kink close to the stagnation point. More detailed information on the causes of vortex breakdown and its various patterns can be found in the review paper of Lucca-Negro and O'Doherty [1]. The flows in which bubble vortex breakdown is observed can be divided into two large classes, these are confined flows, which are mainly found in various kinds of mixers, bioreactors, rotating lid-driven cavity [2–4] and pipe flows [5–8].
It is generally accepted that the main parameters that determine the characteristics of the swirling flow are the integral swirl parameter \( S \) \([9]\) and the Reynolds number \( (Re) \). However, it should be noted that despite the prevalence of the parameter \( S \) as a criterion characterizing a swirling flow, the flow structure, even within the framework of similar geometric conditions at the same \( S \), can differ significantly \([10]\). The swirling flow developed in such a way in a conical diffuser is highly dependent on the cone angle of the pipe geometry. Thus, it becomes an important issue to study the divergence angle of the pipe geometry influence on the flow structure at a fixed integral parameter \( S \) and \( Re \) and vice versa.

A conical pipe with a small angle of divergence of the tube, well-studied experimentally \([11,12]\), was chosen as the initial geometry. The main feature of the installation was the ability to change smoothly the angle of the swirling device blades, thereby varying the swirl of the flow. However, the integral parameter of the flow swirl was not directly introduced in these studies; to estimate the intensity of the swirling flow, the circulation number \( \Omega = \Gamma/W \), \( \Gamma = 2\pi R/V \) (where \( R \) is the radial distance from the tube center to the trailing edge of vanes, \( V \) is the azimuthal velocity) was used. At one time, the main purpose of the experimental setup was to perform critical experiments to study the merits of the theory of finite transitions and the dependence of the vortex jump on various flow parameters. The limitations of the work include the fact that all the conclusions were drawn from the results of experiments carried out at a fixed divergence angle of the working area pipe. This question arises not only at low \( Re \) numbers, so the formation of a spiral decay of a vortex in the form of a powerful precessing vortex bundle behind the impeller of a hydraulic turbine is closely related not only to the operating mode of the turbine, meaning that the flow rate is relatively optimal, but also to the geometrical features, namely the opening angle of the draft tube cone. On the one hand, the conical shape is necessary, since it allows the use of a significant part of the kinetic energy of the flow leaving the impeller due to the restoration of part of the kinetic energy losses, slowing down the flow due to the increase in the channel cross-section; on the other hand, a significant expansion can lead to an earlier occurrence of the reverse flow and formation of the precessing vortex.

Since the turbulent swirling flow is a rather complex object of research and the accuracy of the numerical simulation depends significantly on the choice of the turbulence model, the study is, first of all, focused on the laminar regime, in which it is easier to study the dynamics of the formation of bubble vortex breakdown than in the turbulent flow.

2. Numerical simulations

The numerical simulation was carried out using the Star-CCM + software package. For numerical simulation, a CAD model that reflects the geometry of the flow path of the experimental setup was designed \([11]\). The computational mesh (showed in figure 1) of the unstructured type contained a total of 0.95 million cells with a mesh refinement in the assumed region of vortex breakdown onset and boundary layer refinement near the walls. The inlet velocity profiles, the swirl parameter, and the Reynolds number were set as the boundary conditions that determine the flow, and the pressure was set as the outlet condition. It uses a laminar non-stationary simulation with an adaptive time step based on the average Courant number <1.2. The physical time equal to 1000 seconds was chosen as the stopping criterion; during this time, the flow had time to fully develop, and several of used monitors showed good convergence.
Figure 1. Example of unstructured mesh of the axial plane section of the conical pipe and convective Courant number distribution, $\alpha = 0^\circ$.

As the boundary conditions, the tangential and axial velocity profile taken from experiments [11] and according to [13] was parameterized as follows:

$$V_{ax} = V_{corr} \left( \frac{1 + C_1 e^{-C_2 r^2}}{1 + C_1} \right)$$
$$V_{tg} = S_{corr} \frac{C_3}{r} (1 - e^{-C_2 r^2})$$

Here, $C_1 = 1.43$, $C_2 = 11.84$, $C_3 = 0.304$, $V_{corr}$ is the varied free parameter providing required $Re$ number, $S_{corr}$ is the varied free parameter providing required swirl number. Moreover, the swirl parameter was also fully parameterized, the desired velocity distribution was supplied to the input, after which the swirl of the flow was calculated by the integral parameter $S$:

$$S = \frac{\int_0^\infty \rho V_{ax} V_{tg} r^2 \, dr}{R \int_0^R \rho V_{ax}^2 r \, dr}$$

where $V_{ax}$ is the axial velocity component, $V_{tg}$ is the tangential velocity component, and for each given swirl parameter $S_{corr}$ was recalculated. Numerical simulations were carried out for $Re = 300$ in the $S$ range from 0.2 to 1.4 with a step of 0.2 and in the range of cone divergence angles $\alpha$ from $0^\circ$ to $4.5^\circ$ with a step of $0.5^\circ$; in total, flow patterns were obtained for 63 different combinations of $S$ and $\alpha$. The main results in current work are presented for the swirl parameter $S = 0.6$, which is chosen as the main one, since in a number of literary sources [9,14,15] it is considered critical at which unsteady phenomena appear and various forms of vortex breakdown are observed.

3. Results
The figures 2-4 below show the results of numerical simulation. The results of numerical simulation of the axial velocity component distribution along the axis of the working section are given in Figure 2 as an example.
Figure 2. Axial velocity distribution along cone axis at different cone angles and $S = 0.6$.

One can see that at a given swirl parameter of the flow, even in a straight-through pipe, velocity deceleration arises on the axis, associated with the appearance of an adverse pressure gradient on the axis. In turn, the adverse pressure gradient is caused by a decrease in the tangential velocity component due to friction on the walls and expansion of the diffuser [16].

Figure 3. Minimum value of axial velocity and its position along axis at different cone angles and $S = 0.6$.

It can be concluded that the appearance of bubble vortex breakdown is very sensitive in the region of small aperture angles in a conical swirling flow. Beginning with a cone opening angle of $4^\circ$, an unsteady spiral trail begins to form behind the symmetric shape of the bubble vortex breakdown. An increase in cone angle moves breakdown position upstream and the bubble shrank in size both in length and in diameter.

Figure 4 shows the upper part of the conical tube in the region of interest; the flow field is colored by the magnitude of the absolute velocity and visualized using the line integral convolution method. These numerical data are in good agreement with experiments conducted by Faller and Leibovich [11] and at the same time they expand the results obtained for other pipe divergent angles.
4. Conclusion

An extensive numerical parametric study was carried out, including 63 different cases. Vortex-breakdown position and properties as a function of Reynolds and Swirl numbers should be considered taking into account the angle of pipe divergence. It is logical to assume that in the transition to large Reynolds numbers and turbulent swirling flow, the pipe angle will also affect the vortex breakdown onset. The value of its influence for different Reynolds numbers at a fixed swirl number of the flow could also be established for accurate analytical analysis like linear or global stability analysis or others. Expansion of the regime map for other Reynolds numbers will be a continuation of this work.

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