Pressure measurements in a conical diffuser with swirling flow and axial jet control

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Abstract

Operating Francis turbines at partial discharge is often hindered by the development of the helical vortex (so-called vortex rope) downstream the runner, in the draft tube cone. The unsteady pressure field induced by the precessing vortex rope may also lead to hydro-acoustic resonance. In this paper a simple and robust, method to mitigate the vortex rope by using an axial water jet issued from the crown tip is evaluated. The vortex rope jet control method is investigated experimental on the test rig developed at the Politehnica University of Timisoara (UPT) – National Center for Engineering Systems with Complex Fluids (NCESCF).

Introduction

The present paper presents our ongoing developments of the jet control technique for swirling flows in a conical diffuser in order to mitigate the precessing vortex rope. The helical vortex breakdown, also known as precessing vortex rope in the engineering literature, benefits from a large body of literature aimed either at elucidating the physics of the phenomenon, and building mathematical models or at developing and testing practical solutions to control the causes and/or the effects. Since in this paper we investigate a new technique introduced by Susan-Resiga et al. [13] to control the draft tube flow instability, we will briefly review some relevant studies on both swirling flow hydrodynamics and precessing vortex rope.

The obvious practical importance of predicting the complex flow downstream the turbine runner, in the draft tube, led to the FLINDT research project of Flow Investigation in Draft Tubes [2]. The main objective of this project was to investigate the flow in hydraulic turbine draft tubes for a better understanding of the complex 3D swirling flow physics and to build up an extensive experimental database describing a wide range of operating points. Ruprecht et al. [8] have proved that present hight performance computing capabilities with carefully chosen turbulence models and suitable boundary conditions are able to capture the complex features of 3D precessing vortex rope. Full 3D unsteady flow simulations performed by Stein [10] was carefully validated with FLINDT experimental data measured by Ciocan et al. [4]. A comparison of experimental data with computational results for the FLINDT draft tube at 70% Q_{BEP}, where a single vortex rope is fully developed, is presented by [10] and [14]. Stein et al. [11] reported a first successful two-phase flow numerical simulation of cavitating vortex rope, while Iliescu et al. [6] have shown that two-phase PIV measurements can provide the full 3D unsteady velocity field and allow the accurate reconstruction of the instantaneous cavitating vortex rope geometry together with the determination of the precession frequency. Detailed PIV investigations have revealed the structure of the unsteady 3D hydrodynamic field for helical vortex breakdown in conical diffusers [7]. Additionally, the vortex rope precession frequency as well as local wall pressure fluctuation amplitudes were measured by Doerfler et al. [5], Rus et al. [9] and Arpe [1].

Test rig and swirling flow apparatus

In Figure 1 the test rig developed at the UPT – NCESCF is presented. The test rig is a closed loop hydrodynamic circuit with the possibility to modify the pressure level to investigate both non-cavitating and cavitating flows. In our experimental investigations of the swirling flows into the conical diffuser, the vortex breakdown evolves into the precessing spiral vortex (vortex rope). In order to investigate the axial jet control technique for mitigating the precessing spiral vortex we have developed a special apparatus able to generate swirling flows similar to the ones downstream Francis turbine runner operated at partial discharge, Susan-Resiga et al. [12]. The whole swirl apparatus ensemble is presented in Figure 2(left). Our swirling flow apparatus include a swirl generator and a convergent-divergent test section.

The central body ensemble called swirl generator is marked with yellow color in the Figure 2(left). The swirl generator is supported by a piece called ogive with four struts, provided with holes for control jet water supply. One can observe the jet supplying ring and pipes, which communicates with the holes in the struts and provide the jet discharge at the nozzle. The struts sections have a NACA profile cross-section, and are leaned forward in order to insure a monotone average velocity increase. The axial blades of the swirl generator are located in the ø150/ø90 mm annular section, and are 80 mm in length.

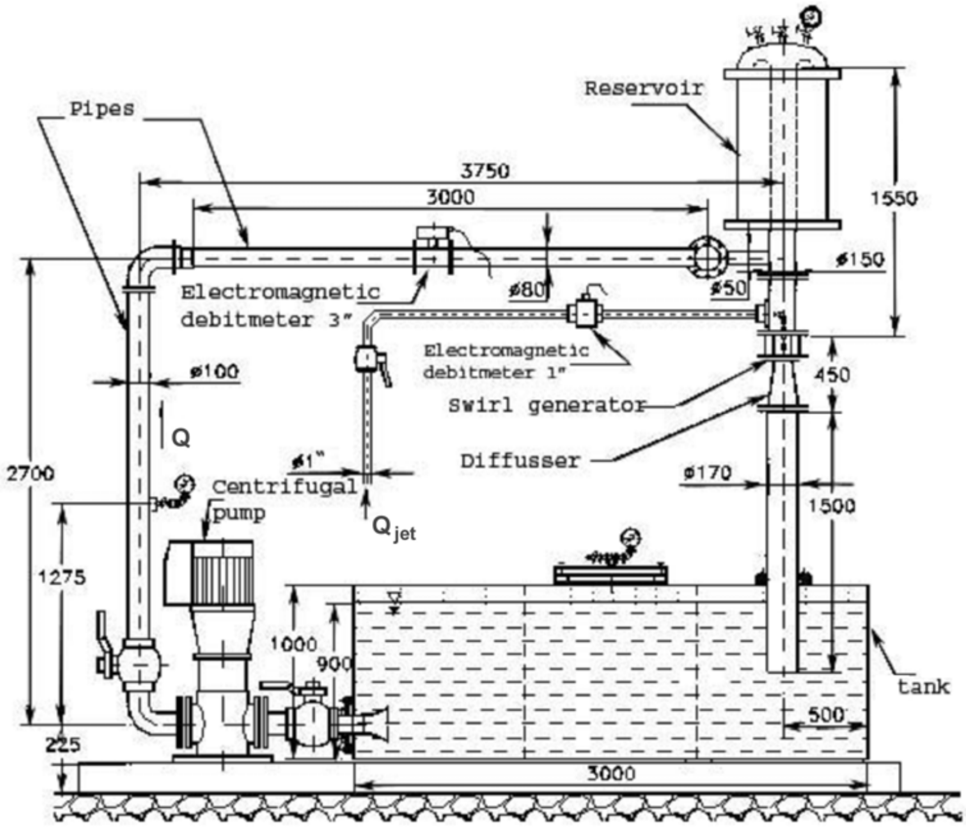

Fig. 1: Closed loop test rig for experimental investigations of swirling flows, at the UPT-NCESCF

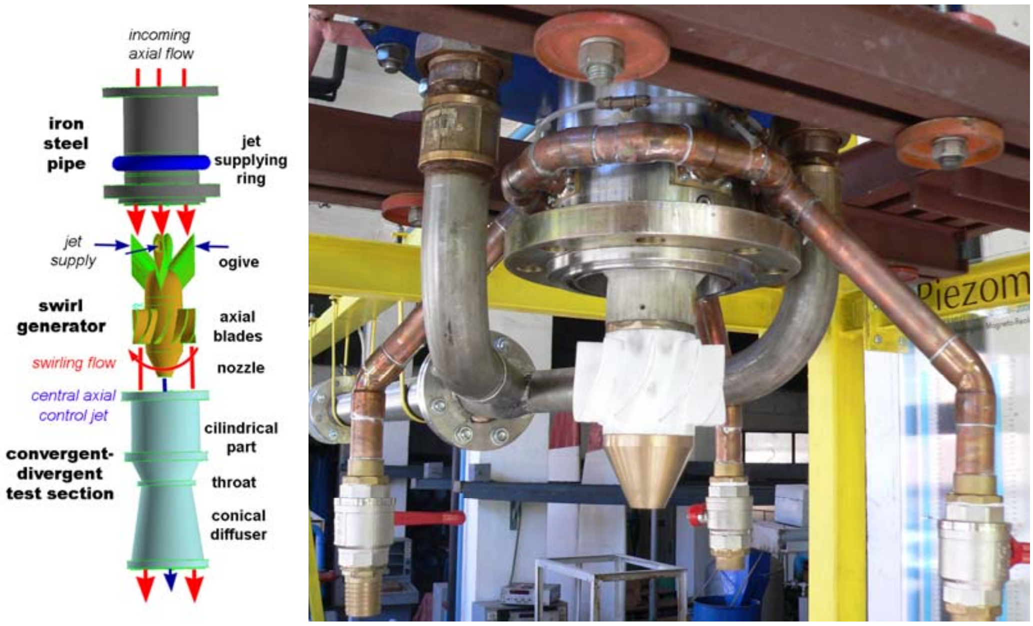

Fig. 2: The swirling flow apparatus designed (left) and installed (right) on the test rig

Axial blades in the upstream annular section provide a controllable swirling flow profile. A tandem of guide vanes and free-wheel runner will be considered in a future design. The hub of swirl generator ends with a cone shape, and has the jet nozzle located at the diffuser cone inlet that allows the injection of a control jet along the axis, downstream in the cone. The convergent-divergent test section has ø100 mm throat diameter and a conical diffuser 8.5° half angle. The conical diffuser, upstream convergent and cylindrical parts are made of transparent plastic glass.

The photo presents in Figure 2(right) the swirl generator with axial blades and jet nozzle with supplying ring and pipes for axial injection while the convergent-divergent section is removed. The first version of the swirl apparatus with axial blades installed on the test rig is shown in Figure 3.

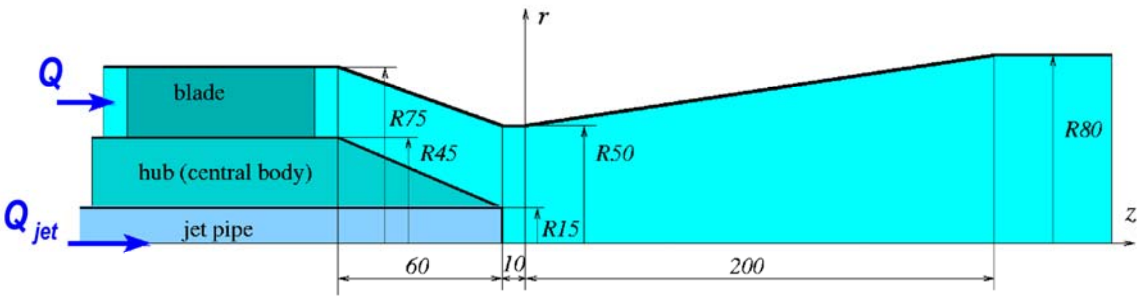

Fig. 3: Meridian cross section of the apparatus for swirling flow generation and analysis in a conical diffuser. Actual dimensions in mm.

Visualization of the precessing vortex rope

First, the precessing vortex rope in our test rig section is visualized. Figure 4a presents the precessing vortex rope developed in the test rig section.

a) no jet control b) with axial control jet discharge at two different values

Fig. 4: Visualization of the precessing vortex rope without jet control (a) and quasi-stagnant central region for two discharge values of the axial control jet (b)

When the control jet is switched-off, the main flow occupies an annular region near the wall, leaving a large stagnant region in the center. When water is injected along the axis, the central stagnant region is pushed downstream in the cone (see Figures 4b), and it is no-longer connected to the nozzle cone. By further increasing the jet discharge, the central stagnation region leaves the cone and eventually develops in the cylindrical part of the diffuser. For large enough jet discharge, the vortex breakdown is eliminated completely.

Unsteady pressure measurements on conical wall of the test section with axial jet flow control

The unsteady pressure measurements on the cone wall are performed in order to evaluate axial jet control technique. Consequently, two unsteady pressure transducers are flush mounted on the element of cone wall, see Figure 5. The section S1 is located at 25 mm relative to the cone inlet section while 150 mm is considered between section S1 and section S2.

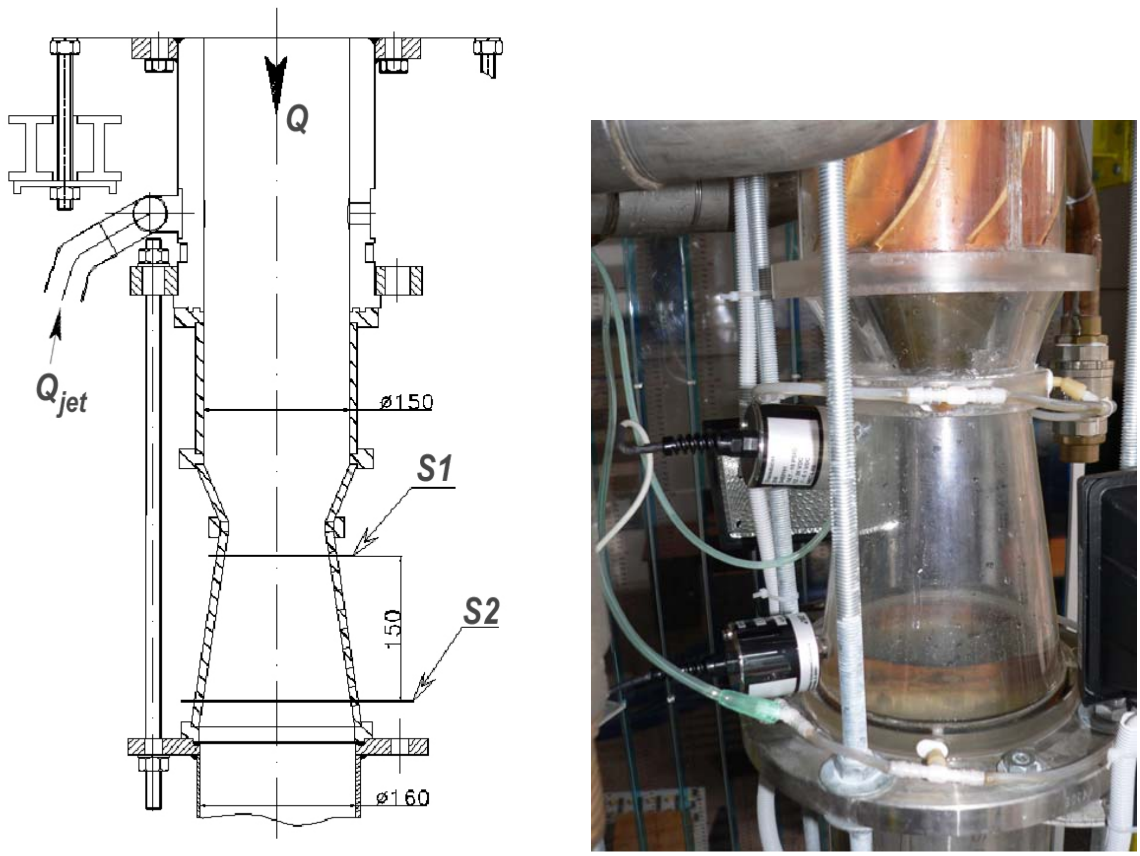

Fig. 5: Pressure transducers mounted on the cone wall

In Figure 6 the unsteady pressure measurements in sections S1 and S2 are presented. The unsteady pressure measured without axial jet is marked with black color while the data recorded with axial jet control (Q_{jet}=0.1*Q) are presented with green color. Moreover, the unsteady pressure measured in section S1 is marked with light green color while the unsteady pressure from section S2 is presented with dark green color.

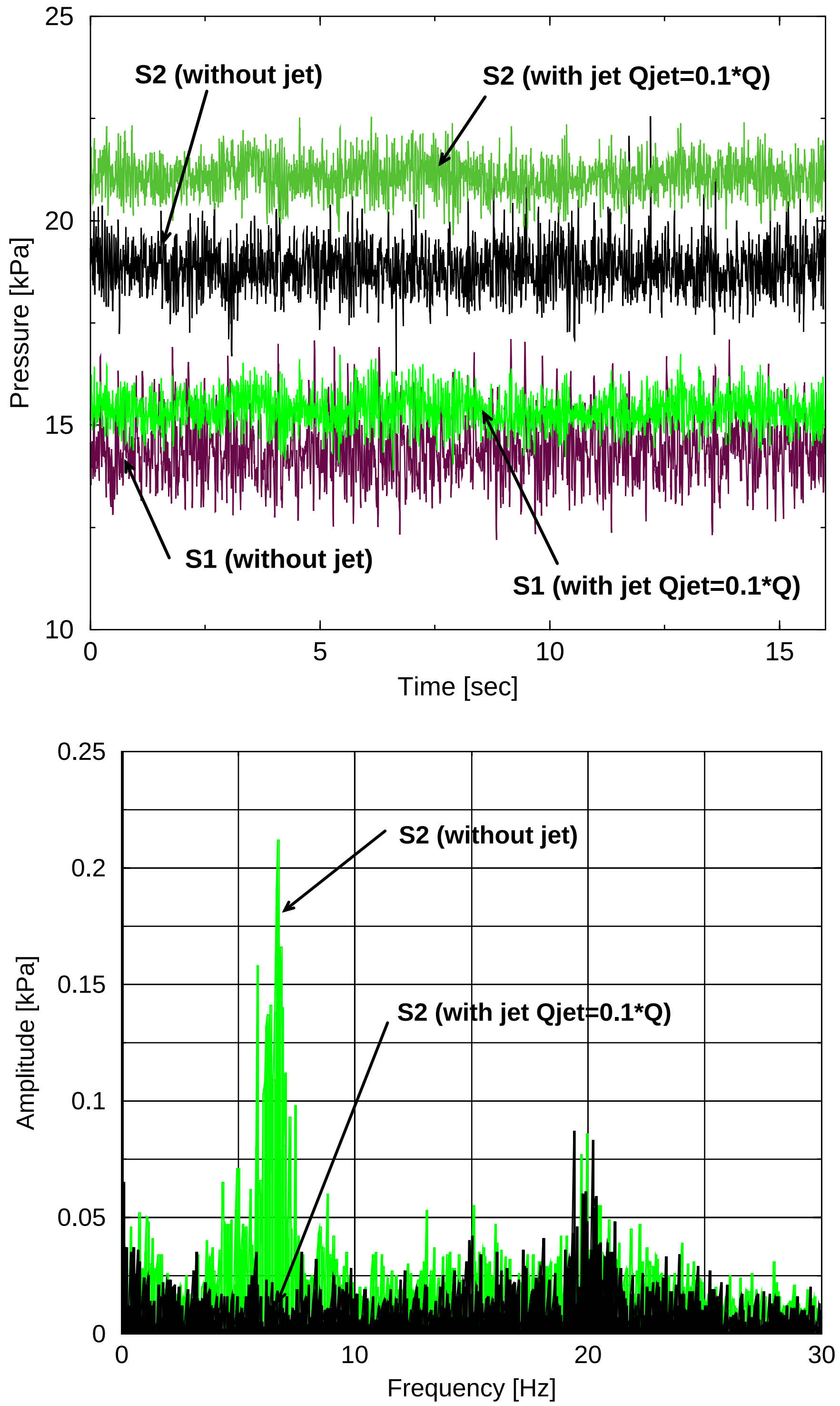

Fig. 6: Unsteady pressure measured on the cone wall in sections S1 and S2 without and with axial jet control (above). Fourier spectrum of the experimental data recorded in section S2 without and with axial jet control (below).

Applying the Fourier transform to the unsteady pressure signals in section S2 the Fourier spectrum is obtained. Large pressure amplitude corresponding to the frequency around 7 Hz associated to the vortex rope is identified if the jet is switched-off. The vortex rope is mitigated when the water jet is switched on. Consequently, the pressure amplitude associated to the vortex rope is removed.

Pressure recovery coefficient on conical section with axial jet flow control

The pressure recovery coefficient on the conical section is computed based on experimental data using the equation (1):

$$c_p = \frac{(p_2 - p_1) - (p_2^0 - p_1^0)}{\frac{\rho v_0^2}{2}} \tag{1}$$

where p is the static pressure, p^0 the hydrostatic pressure, ρ the density ($\rho = 1000\, kg/m^3$ for water) and v^0 the average axial velocity computed at the throat test section taking into account the overall discharge that means the sum of the main flow discharge (Q) and jet discharge (Q_{jet}). Additionally, the subscripts 1 and 2 correspond to the section S1 and section S2, respectively. Pressure recovery coefficient versus ratio between jet discharge (Q_{jet}) and main flow discharge (Q) is presented in Figure 7. Four sets of experimental data are presented in order to check the repeatability. Moreover, each set of experimental data refined the investigations at different regimes. The set number 3 refined the experimental investigations for $Q_{jet} \in (0.04...0.09)Q$ while the set number 4 is focused on $Q_{jet} < 0.04Q$.

The pressure recovery coefficient without jet is 0.4 and the vortex rope is developed. Moreover, for weak axial jet $Q_{jet} < 0.04Q$ the pressure recovery coefficient remains practically unchanged. After that, the pressure recovery coefficient decreases up to 0.14 at $Q_{jet} = 0.075Q$. Increasing water injection through the central body from $Q_{jet} = 0.04Q$ to $Q_{jet} = 0.075Q$, a quasi-axisymmetrical stagnation central region is developed instead of the vortex rope. Consequently, the pressure fluctuations on the diffuser wall are easy mittigated. When the axial jet discharge increases over $Q_{jet} = 0.075Q$ then the quasi-axisymmetrical stagnation central region move away downstream in cone. As a result, the pressure recovery coefficient increases from

0.14 to 0.48. When the jet discharge is larger than 10% from main flow discharge ($Q_{jet} > 0.1Q$) the quasi-axisymmetrical stagnation central region is moved out from the cone, see Figure 4 right. Consequently, the pressure pulsations associated to the vortex rope are removed (see Figure 6 below) and the pressure recovery coefficient 0.48 remain practically unchanged, see Figure 7.

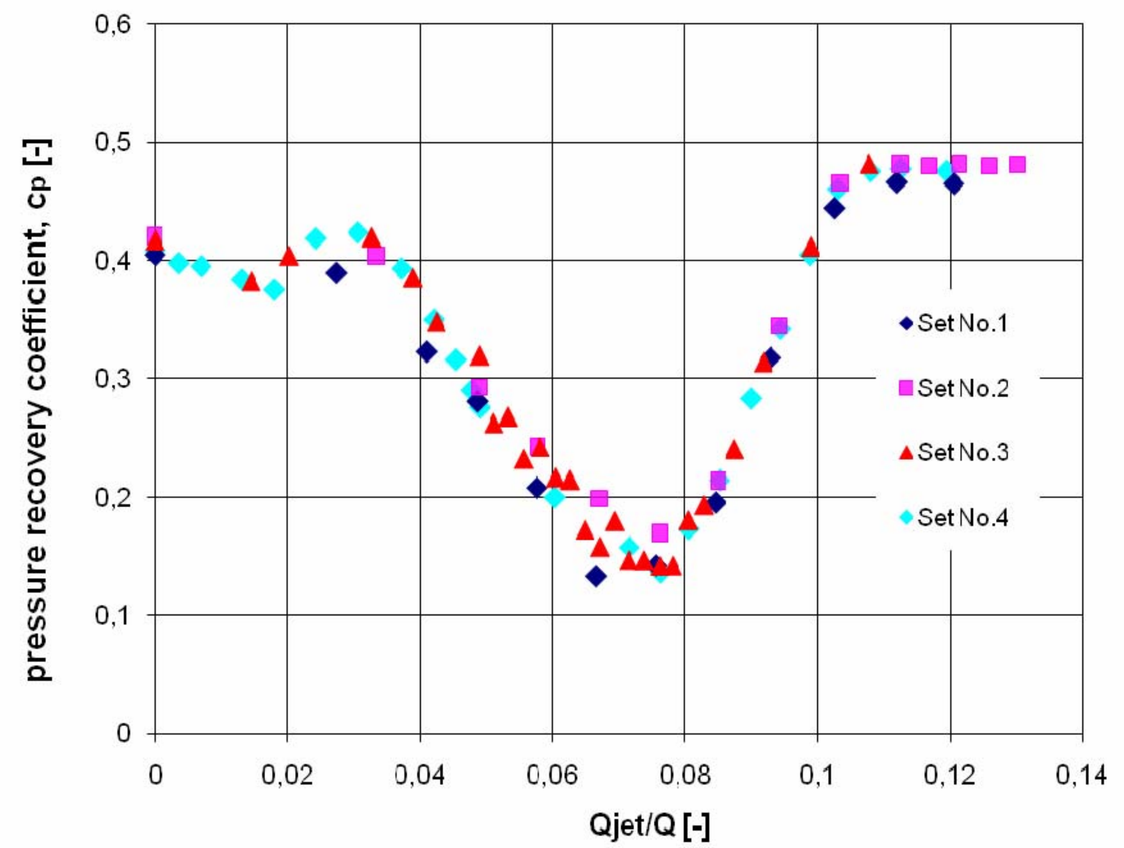

Fig. 7: Pressure recovery coefficient against ratio between axial jet control discharge (Q_{jet}) and main flow discharge (Q).

The main conclusion reveals from our experimental investigation point out an axial jet discharge larger than 10% from main flow discharge in order to operate with maximum pressure recovery and without pressure pulsations generated by vortex rope. This conclusion agrees very well with numerical investigations performed by our group, Susan-Resiga el al. [12]. However, a practical solution with 10% discharge into the axial jet control can be valid only if a hydrodynamic flow feedback method introduced by Susan-Resiga el al. [12] is considered.

Conclusion

A flow control technique for decelerated swirling flows is investigated experimentally. It is found that a jet injected axially at the conical diffuser inlet effectively suppress the vortex breakdown. Consequently, the pressure pulsations on cone wall associated to the precessing vortex rope are mittigated or completely eliminated. It is found that the required control jet discharge reaches 10% of the incoming discharge in order to operate with maximum pressure recovery and without pressure pulsations generated by vortex rope. As a result, in order to efficiently apply the jet control technique to hydraulic turbines a flow-feedback approach must be taking into account.

Acknowledgements

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