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LDV Experimental Measurements of Swirling Flow using Flow-Feedback Jet Injection Method

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Abstract

The water jet injection developed by Resiga et al. has been proved to be successful in mitigating the vortex rope and the corresponding pressure fluctuation. This method uses for supply of the jet, 10% from the flow discharge to eliminate the stagnant region, and this water is taken from upstream. Is not acceptable to bypass the runner with such a large fraction of the turbine discharge because of volumetric losses which appear into the system. The new flow-feedback control technique which has been implemented on the test rig of "Politehnica" University of Timisoara, take a fraction of the discharge from the draft tube cone wall, and redirects upstream to form an axial jet to mitigate the pressure fluctuations associated to the vortex rope. But from experimentally point of view the flow-feedback jet control discharge cannot be evaluated. This paper presents a method of determination of the discharge value based on velocity profiles match. Flow-feedback velocity profiles measured with Laser Doppler Velocimetry are going to be compared against profiles obtained using upstream, pump-generated-jet. A match of two velocity profiles will result in the same value of flow injected in case of flow-feedback and pump-generated-jet, respectively. In that way we can find the flow-feedback discharge.

Keywords: Laser Doppler Velocimetry, draft tube cone, vortex rope, flow-feedback.

1. Introduction

The conical diffuser (discharge cone), is an essential component of the hydraulic turbines, which converts the excess of kinetic head at runner outlet into static head, thus reducing the hydraulic losses in the draft tube. When the turbine operating far from the best efficiency point, the swirling flow in the discharge cone becomes unstable, with large pressure fluctuations and with increased of hydraulic losses. The researches of the swirling flow in the draft tube cone, today is necessary, because the hydraulic turbines with fixed blades (like Francis turbines), are imposed to work in a large scale of regimes. At partial discharge the flow downstream the runner of a Francis turbine evolves in a precessing helical vortex (or vortex rope), with high amplitude pressure pulsation. The vortex rope has badly effects on the energy performance of the turbine, also has bad effect leading in time to cracking or breaks the blades, and damage of the machine bearings, respectively.

The appearance of the vortex rope has a strong connection with the operation mode of the turbine at different flow rates. Jacob, in his PhD. thesis [6], show, as vortex rope appears at various flow rates regimes, but the consequences of vortex appear just at part load. Current research allowed accomplishment of test rigs and development of methodology that will lead to reducing or even eliminating the vortex rope. Thike et al. [16] present some practical solutions for the draft tube instability, which requires the introduction of air or water vapors in the vortex, leading to a decrease of pressure pulsations, but the disadvantage is the high cost of energy to compress the air, and the sealing to be done. In order to control and suppress a draft tube surge in a Francis turbine, Kurokawa et al. [8] proposed a new passive device using shallow grooves machined on a casing wall. To reveal the possibility and the effect of the present device on controlling and reducing the swirl strength of a runner outlet flow, a steady rotational flow in a conical diffuser of divergent angle of 30° is studied experimentally. The results show that the shallow grooves with adequate dimensions can reduce the swirl rate of the main flow by about 85% of the inlet swirl rate.

Nishi et al. [9] examined the applicability of Vortex Generator Jets to suppress the separation in a conical diffuser with a 14° divergence angle, an inlet diameter of 125 mm, and area-ratio of 2.56 from inlet to exit plane. In their investigation, they mainly studied the effect of velocity ratio.

Kirschner et al. [7] developed a test rig for swirling flows investigations in the conical diffuser, with a swirl generator, which presents adjustable blades, and with air introduction to emphasize the cavitating vortex rope, respectively. They do measurements of pressure and velocity field, and numerical simulation, respectively. From comparisons between experimental and numerical, result a good agreement between them. Ciocan et al. [5], investigate the swirling flow on a real turbine model in the FLINDT project. On that model they did measurements of velocity profiles with LDV, measurements of velocity field with PIV, and measurements of pressure pulsation on the draft tube cone wall, respectively. In parallel with experimental investigations they did numerical 3D simulation, and the comparison of results led to a good validation between them.

By examining the swirling flow which appears in the draft tube cone of Francis turbine, Susan-Resiga et al. [10], introduce a novel, robust and simple method to mitigate the vortex rope using a water jet issued from the crown tip (Fig.1). The advantages of this solution compared with others that relate to the same problem, are: it successfully addresses directly the main causes of the flow instability, rather than the effects; it does not require geometrical modifications of the runner, and no other devices need to be installed in the draft tube; it is continuously adjustable according to the operating point, and it can be switched-off when it is not needed; the practical implementation is simple and robust.

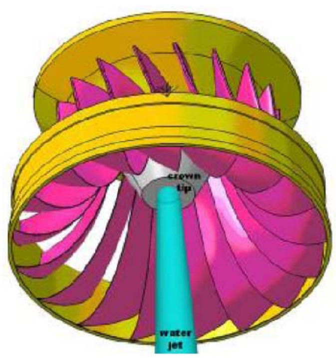

Fig.1 Water jet injection along the runner crown.

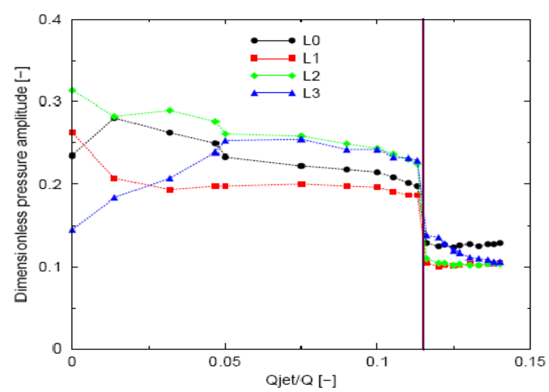

Fig.2 The sudden drop of pressure amplitude starting with 11.5% from the main discharge, jet injection [3].

The method of swirling flow jet control has been implemented on a test rig developed at the "Politehnica" University of Timisoara. Bosioc in his PhD. thesis [1] has presented the design, implementing and experimental measurements of this method. The flow control technique requires 10% or more from the main discharge to supply the jet. The water which supplies the jet is taken from upstream with an auxiliary energy source (pump).

The results presented by Bosioc et al. in [2] [3], show that the pressure fluctuations associated to the vortex rope, has an sudden drop when the jet is supply with approximately 11-12% from de main discharge (Fig.2). Obviously it is not acceptable to by-pass the runner with such a large fraction of turbine discharge, because of volumetric losses which appear into the system, and that leads to a decrease of the turbine efficiency.

By examining the flow on the discharge cone, when the turbine operates at part load, Resiga et al. [12], [13] observe that it is an excess of static and total pressure on the cone wall. This conclusion led him to introduce a new flow-feedback control technique, by taking a fraction of the flow from downstream of the cone wall, which is redirected to upstream, for eliminating the vortex rope, by injecting it through the runner crown (Fig.3 and Fig.4). This technique does not require any additional energy input and the turbine efficiency is not affected.

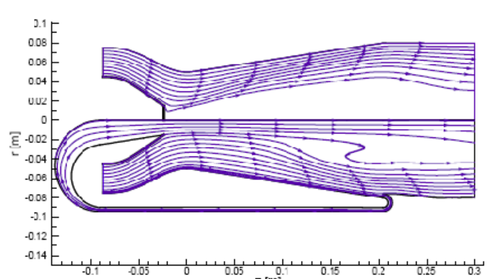

Fig.3 Streamlines for the axisymmetric swirling flow without flow control (upper half-plane) and with flow-feedback control (lower half-plane) [12].

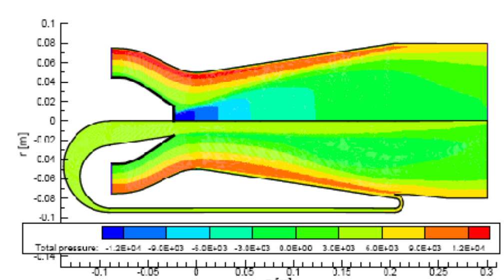

Fig.4 Total pressure for the axisymmetric swirling flow without flow control (upper half-plane) and with flow-feedback control (lower half-plane) [12].

The flow-feedback technique was implemented on the same test rig, from “Politehnica” University of Timisoara (Fig.6), and presented by Tanasa et al. in [14]. The implementation of the flow-feedback technique is supposed to introduce a spiral case with double exit (Fig.5), at downstream of discharge cone. The spiral case takes the water from the outlet of the cone and redirected through a pipes system to the nozzle to form an axial jet.

The test rig has some main parts like: swirl generator, test section for measuring pressure filed, another one for measuring velocity profiles with Laser Doppler Velocimetry (LDV), and the spiral case with double exit. The swirl generator presented by Resiga et al. in [11], [12] has an upstream ogive with four leaned struts, followed by a set of guide vanes and a free runner, and ending with a nozzle. The test sections presented by Bosioc et al. [4] have a convergent-divergent shape, and one of the test section has 8 pressure transducers installed two by two at four levels (L0…L3), which allow the pressure to be measured, and the second one has three optical windows for measuring the velocity profiles. The first window is positioned in the convergent part of the test section, the second, on the convergent-divergent part and the third at the exit from the divergent part (Fig.8).

The results of pressure measurements with flow-feedback technique shows that the amplitude has a decrease with approximately 28% than the case without flow-feedback jet control, and the frequency decreases with 32%. That results of flow-feedback technique, was compared with the results of the method with 10% from the main discharge jet supply, from upstream. In that way we can approximate the flow-feedback discharge (Fig.7) [14].

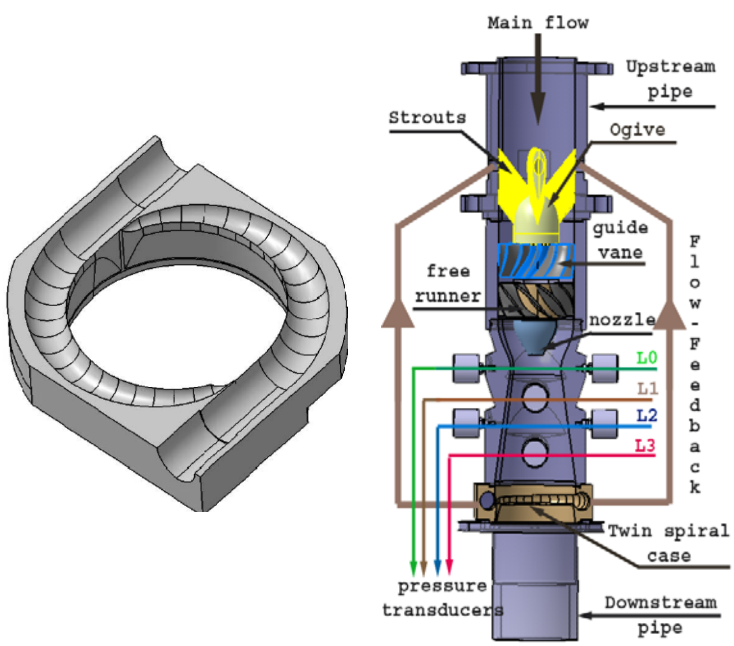

Fig.5 Spiral case with double exit (left), and cross-section of the assembled test section with twin spiral case (right).

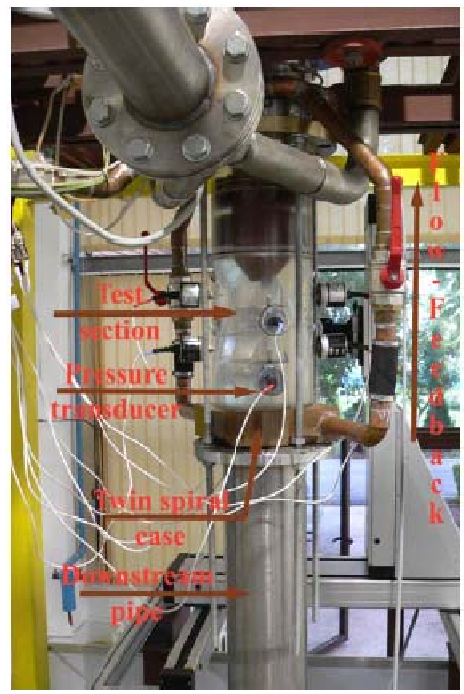

Fig.6 Implementing of flow-feedback technique on the test rig.

The main problems are that, on one hand we cannot determine the flow-feedback discharge, from experimentally point of view (because it is not possible to install a flowmeter on the flow-feedback system pipes), and the second problem is how we can catch the same sudden drop of the pressure amplitude like in the case of 12% from the main discharge jet control, with water from upstream.

The goal of this paper is to find answers at the questions presents above. The flow-feedback discharge can be found based on velocity profiles match. Flow-feedback velocity profiles measured with LDV are going to be compared against profiles obtained using upstream, pump-generated-jet. A match of velocity profiles with the two jet injection methods will result in the same value. In that way we can find the flow-feedback discharge. The sudden drop of the pressure amplitude can be catch by introduction of an ejector pump along the flow-feedback system. Section 2 of this paper presents experimental measurements of velocity profiles with LDV. Section 3 is dedicated to the results, and section 4 summarized the conclusions.

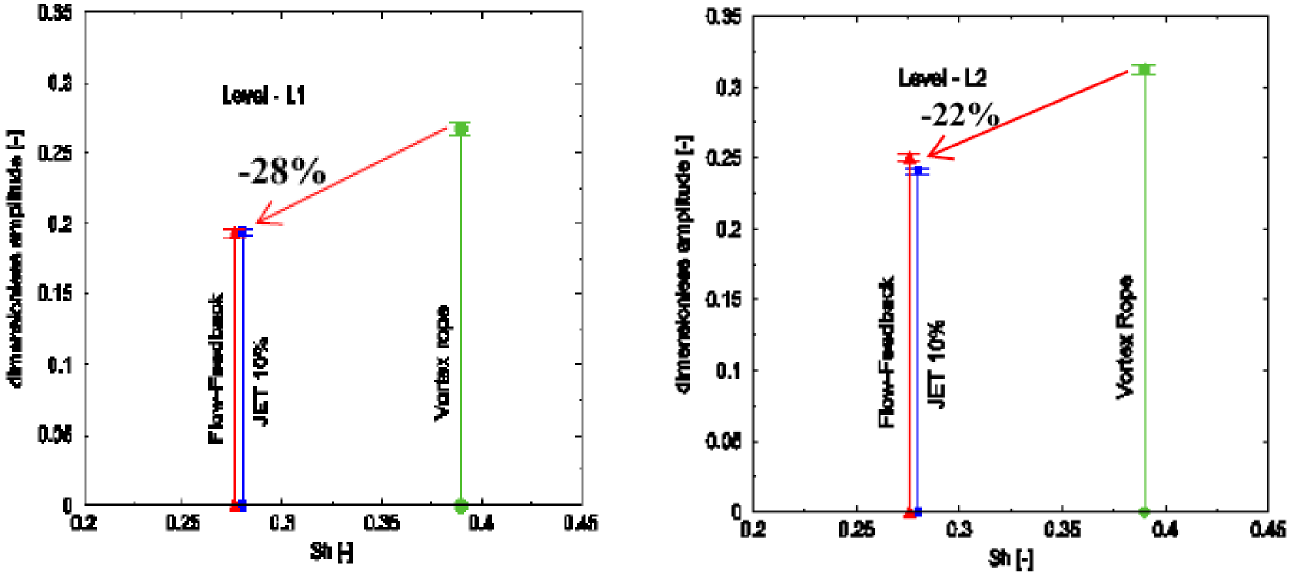

Fig.7 Comparison of the two jet injection methods and the case without jet injection method respectively, in terms of dimensionless amplitude vs. Strouhal number.

2. Laser Doppler Velocimetry investigation

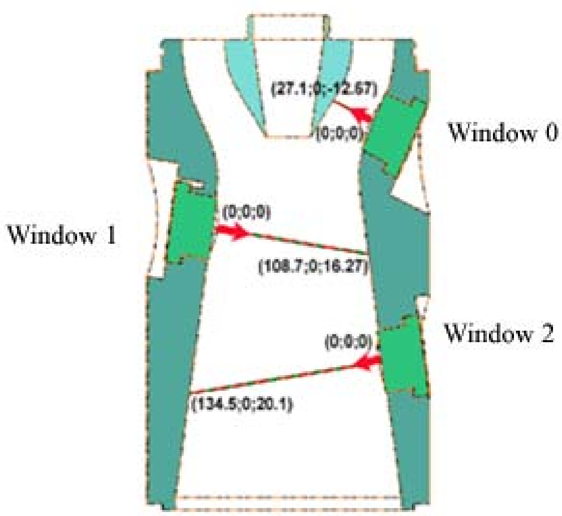

Fig.8 Test section with the three optical windows and the corresponding survey axis for measuring the velocity profiles.

Fig.9 LDV system during the velocity profiles measurements.

The experimental data were measured with Dantec Dynamics 2D LDV system with two components (meridian and circumferential velocity). The main characteristics of the optical system are: focal length of the probe 159.6 mm, beam diameter 2.2 mm and the beam spacing 39.2 mm. Two pairs of beams with wavelength of 488 nm and 514.5 nm are generated, and the probe includes a photo multiplier with incorporated amplified. A 3D traversing system is installed for probe positioning within 0.01 mm accuracy on each axis. Measurements were made with a step of 1 mm, and with 15000 samples or 20 seconds acquisition time, which was set before. In order to reflect the light which is produced by the laser, in the test rig were introduced silver particles with 10 µm mean diameter. The measurements were performed along the survey axis corresponding to window 1 of the test section (Fig.8 and Fig.9).

3. Results

It was shown that, from the pressure measurements and comparison between the two jet injection methods (flow-feedback, and jet supply with water from upstream), that the flow-feedback discharge can be approximately 10% from the nominal flow [14]. But this is just an approximation, and from the results of Bosioc et al. [3] it is observed, that until the sudden drop of the pressure pulsation associated to the vortex rope, the jet discharge can be around 5-10% from the nominal flow (Fig.2).

That means, the flow-feedback discharge can be between this values. To find the flow-feedback discharge, it was used a more precisely method which supposed to measure the meridian and circumferential velocity profile with LDV, for the cases with flow-feedback jet injection technique, jet injection method supplied with water from upstream at different values of the jet discharge, and the case without jet injection method. From the match of the velocity profiles of each case it is shown that the flow-feedback discharge is the same like in the case of the jet supplied with water from upstream with 10% from the nominal flow. The measurements were performed at the nominal flow Q = 30 l/s, in order to find the flow-feedback discharge.

Figures 10 and 11, shows the meridian and circumferential velocity profiles measured along the survey axis corresponding to window W1, for the cases without jet injection (red solid line), with flow-feedback jet injection (blue solid line), and jet injection method with water from upstream at different values of jet discharge (10% from the nominal flow – brown solid line, 12% from the nominal flow – violet solid line, and 14% from the nominal flow – green solid line).

It can be observed that the match between the velocity profile for both meridian and circumferential, are in a good agreement for the case with flow-feedback jet injection method and the case of jet supplied with water from upstream at 10% from the nominal flow. That means the flow-feedback discharge is 10% from the nominal flow.

Next step was to represent the velocity profiles (meridian and circumferential), for the case without flow-feedback, and with flow-feedback jet injection method. In that way the measurements are done at two different nominal discharge values, of 25.5 and 30 l/s. Figures 12 and 13 represent the dimensionless meridian (with black filled circle), and circumferential (with red filed circle) velocity profiles.

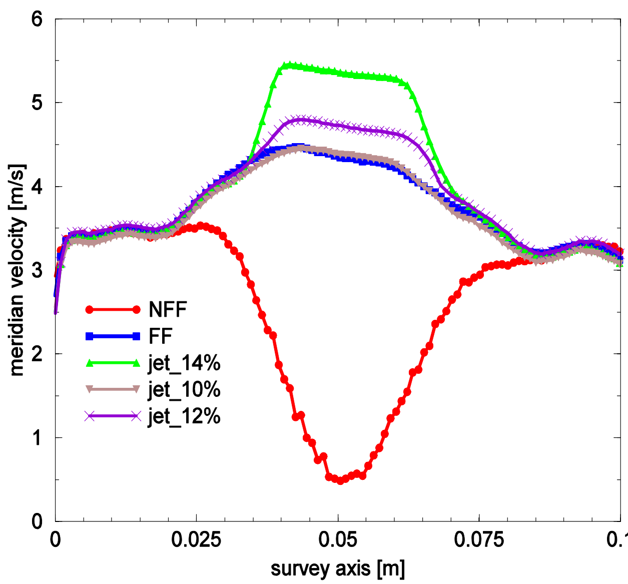

Fig.10 Meridian velocity profiles.

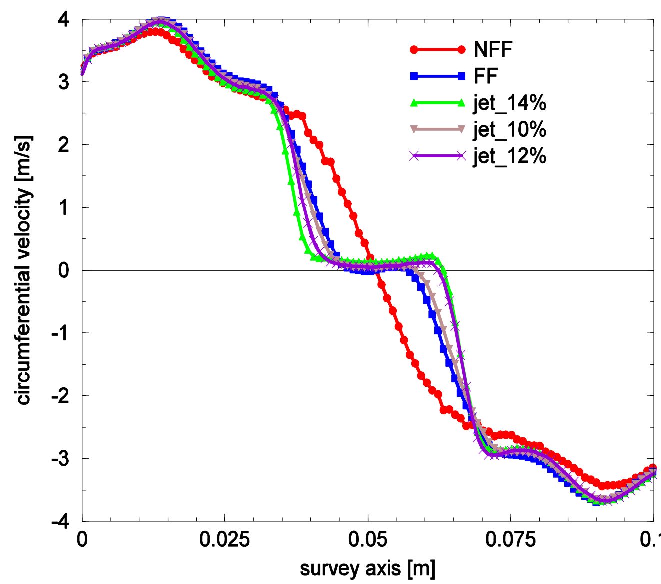

Fig.11 Circumferential velocity profiles.

The survey axis was dimensionless with respect the minimum radius of the test section (the radius from the throat test section): $R_{throat} = 0.05$ m. The velocity is dimensionless wit respect the throat velocity:

$$v_{throat} = \frac{Q_{nominal}}{\pi \cdot \frac{D^2}{4}} \tag{1}$$

where $Q_{nominal}$ is the main flow discharge, and D is the throat diameter.

All graphics of velocity profiles have the variation of the Random Mean Square (v_{RMS}) for each measured point, also in dimensionless form, with respect the throat velocity; v_{RMS} was calculated as:

$$v_{RMS} = \sqrt{\sum_{i=0}^{N-1} \frac{1}{N} \cdot \left(v_i - \bar{v}\right)^2} \tag{2}$$

Where N is number of samples, v_i the velocity for each sample, and $\bar{v}$ is the time averaged velocity which is calculated with the next equation: $\bar{v} = \sum_{i=0}^{N-1} \frac{1}{N} \cdot v_i$

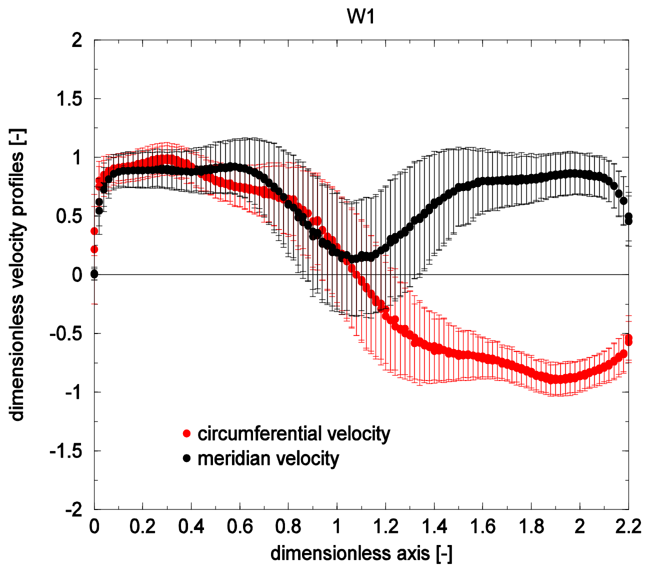

Fig.12 The velocity profiles for the case without flow-feedback jet injection method, with nominal flow at 25.5 and 30 l/s.

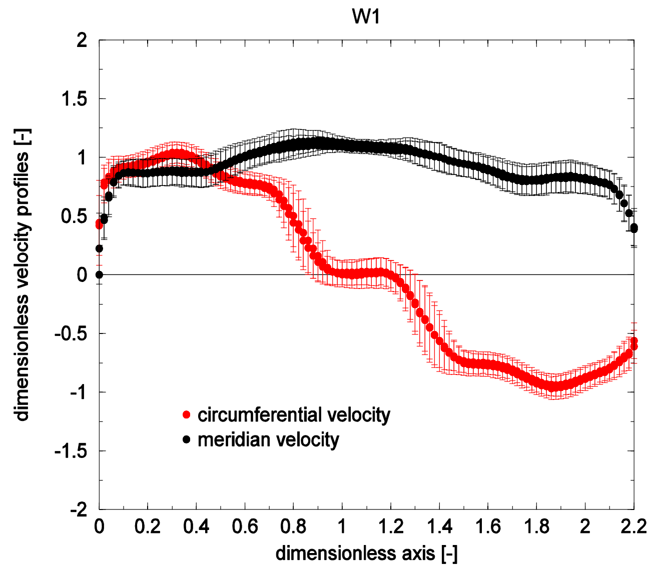

Fig.13 The velocity profiles for the case with flow-feedback jet injection method, with nominal flow at 25.5 and 30 l/s.

From the case of velocity profiles without flow-feedback jet injection method (Fig.12), it can be observed that the meridian velocity profile has a value which is decrease until 0 in the middle of test section. That means it that region it exist a quasi-stagnant region. The tangential component of the flow is pushed towards the wall. Consequently, the main stream is near to the cone wall. Moreover, one can observe the central region has a solid body rotation. For both meridian and circumferential velocity profiles the errors (RMS), are bigger especially in the middle part of the test section which is means bigger velocity fluctuations, in that area. When it is injected jet with flow-feedback (Fig.13), the meridian velocity profile is at a double value than the case without flow-feedback that leads to vanishing of the quasi-stagnant region. Once with increasing the velocity in the middle, the errors are decreasing, and the circumferential profile is placed around 0 with smaller velocity fluctuations. In that way the tangential component from the middle part of the test section is disappearing and place of this is taken by the axial component that means the quasi-stagnant region is eliminated.

4. Conclusion and perspective

This paper was presented experimental measurements of the velocity field, using 2D Laser Doppler Velocimetry (LDV). By matching the velocity profiles, in two different cases of water jet injection method, it was found that the flow-feedback discharge is the same like in the case of the jet method supplied with water from upstream at 10% from the nominal flow.

From the measurements of meridian and circumferential velocity profiles, at two nominal discharges, for the cases with and without flow-feedback jet injection method, it was found that the flow-feedback method eliminates the quasi-stagnant region.

For the future work it will be presented a method of flow-feedback and energy supplies, which can catch the same sudden drop of the pressure fluctuations like in the case of jet injection method with water from upstream when is used 12% from the nominal flow. It was proved that the flow-feedback generate a discharge of 10% from the nominal flow, without energy supply and without decreasing the turbine efficiency. To catch the same value of the discharge of 12% like in the case with water supply from upstream, and to have a sudden drop of the pressure fluctuation associated to the vortex rope, it will be necessary 2% more. That 2% are supplied using a pump ejector which is mounted on the flow-feedback system pipes.

Acknowledgments

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