Experimental investigation of flows in a high-head pump-turbine draft tube at turbine mode

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Abstract. The accurate prediction of flow patterns is essential during the optimization design of a pump-turbine. To determine the flow patterns and validate the flow simulation inside a pump-turbine, Laser Doppler Velocimetry (LDV) measurements and 3D flow simulation in the draft tube cone of a high-head pump-turbine model have been performed at normal operating conditions in turbine and pump modes. Velocity distributions were measured for operating conditions covering the speed factor $n_{ED}=0.21$ and $0.19$ at turbine mode for loads ranging from 40% to 100% of the rated power as well as best efficiency point. Measurements of unsteady flows inside the draft tube cone were conducted at a high precision hydraulic model test rig with LDV system from TSI Co. The 3D flows through the pump-turbine model were numerically simulated with ANSYS/CFX® software at all the measured operating points. Both measured and simulated velocity profiles are presented and analyzed to show the influence of operating parameters on the velocity and swirl characteristics in draft tube inlet. Comparison of the measurement and simulation shows rather good agreement at the best efficiency point and full load but clear discrepancies at part load. The experiment data such as the velocity profiles, pressure signals, and amplitude and frequency characteristics of the instantaneous tangential velocity at various loads offers the possibility to assess the precision in performance prediction in the pump-turbine using the numerical simulation methods. The measured instantaneous tangential velocity at part loads reveals a periodic peak, which is asynchronous to that of runner’s rotating speed and can be used to determine the characteristic frequency of rotating vortex rope at part loads. Axial and tangential velocity fields obtained from LDV measurements at normal operating points can be used to validate the numerical simulation in optimization design.

1. Introduction
Flexibility and energy storage is one of the main challenges in the energy industry at the present time. Pumped storage Power plants (PSP) equipped with the reversible pump-turbine are among most
cost-efficient solutions to answer these needs. To provide a rapid adjustment to the electricity grid, pump-turbines are subject of quick switching between pumping and generating modes and to extend operation at off-design conditions \cite{1}. Due to the continuously increasing requirements of wide operating capability, to accurately analyze the unsteady flows in draft tube has become more and more important in the process of design as well as in the operation of existing plants for a reversible pump-turbine. Numerical flow simulations are widely applied to investigate flow structures inside hydraulic machines \cite{1-6}. The possibilities of computational fluid dynamics (CFD) simulations to accurately predict the flow in part load operation of a Francis turbine were examined by using commercial code \cite{2}. As the flow has a strong swirling component in part load operation, it is very difficult to accurately predict the flow and in particular the flows inside draft tube \cite{2}. To better understand the differences in the results by details of the flow prediction and classify the results which still might depend on the mesh size, a comparison with measurements are required in the draft tube cone. There are great differences in the design as well as operation between a high-head pump-turbine and a Francis turbine. The purpose of this experimental investigation was to reliably determine the structure of the flow in the draft tube of a Francis pump-turbine model, as well as to obtain experimental data to verify the method for numerical simulation. To achieve this goal, velocity measurements with Laser Doppler Velocimetry (LDV) are carried out on a high precision commercial hydraulic machinery test stand at typical operating points under operating modes of turbine. As the radial velocity component in draft tube cone of a high head Francis pump-turbine is small \cite{7}, the measurements comported the axial and the tangential velocities. LDV is an optical and laser based technique used to measure velocity at single point with very high spatial resolution and high sampling rate. LRJ Sundstrom et al.\cite{8} used LDA (Laser Doppler Anemometry) to investigate the velocity distribution in Francis turbine draft cone with two sections, and presented the tangential and axial velocity and the Reynolds stresses on two sections below the runner at part load (PL), best efficiency point (BEP), and high load (HL) operating conditions. The agreement between experimental and numerical results were fair at BEP and HL, and with largest discrepancies at part load. Although some recent investigations with LDV have been carried out in the turbine \cite{8-10}, which show significant work on this issue, it is still a great challenge of measuring the flow field in the draft tube of a Francis pump-turbine model at different operating points under turbine and pump modes. This paper shows the results of LDV velocity measurement in the draft cone of a high head Francis pump turbine. Measurements were taken for typical operating points covering the unit speed \(n_{ED}=0.21\) corresponding the rated head \(H=600m\) and the unit speed \(n_{ED}=0.19\) corresponding the optimum head \(H=750m\) at turbine mode, at loads ranging from partial to maximum value including the best efficiency point. Meanwhile, the 3D flows through the completed pump-turbine model were numerically simulated with ANSYS/CFX® software at all the measured operating points. The dimensionless velocity profiles both the measured and simulated time-averaged axial and tangential velocity are presented and compared to show the velocity profiles at different loads, which are used to analyze that how the operating parameters of flowrates and heads effects on velocity profiles and swirl flow inside draft tube. The measured instantaneous tangential velocity is used to determine the dominating frequency of rotating vortex rope and verify the 3D unsteady flows simulations at part loads. The results of LDV velocity measurement will further be used as validation data for numerical simulation in optimization design.

2. Experimental Set Up and LDV Measurement

2.1. Test Rig
The experimental study was undertaken on a scaled Francis pump-turbine model with runner outlet
diameter of 260mm. The distributor of the model is equipped with 16 guide vanes and a runner with 5 splitters and 5 full length blades. The model was mounted in a high precision commercial hydraulic machinery test rig with a closed-loop system at Hydraulic Laboratory of DFEM Co. Ltd. in China, in which the head was controlled by the main pump. The flow rate, controlled by the head and the guide vanes position, was monitored by an electromagnetic flow-meter installed between the upstream pressure tank and the spiral casing inlet. The systematic errors of the test stand is within \( \pm 0.25\% \) according to IEC60193 standard [11]. The draft tube cone had been manufactured in Plexiglas to visualize the flow downstream of the runner. Due to its high demand for optical access of LDV measurement, an optical interface for measurements were carefully designed in the draft tube by taking into account the internal geometry of the model, local optical distortions and perspective effects from the curved surface. For the velocity measurements, a LDV system from TSI Co. Ltd. was used with a NC controlled traverse system which servomotor is placed to accurately move and position the probe. The model turbine setup and the LDV probe mounted on the traverse system are shown in figure 1.

![Figure 1. The model turbine setup and the LDV probe](image)

2.2. LDV setup and in-situ calibrations
The TSI LDV system with 5W Diode Pumped Solid State lasers to generate high quality Doppler signals, which consisted of laser unit (type LA70-5), multicolor beam separator(type FBL-3 Fiberlight™), signal processor(type FSA4000-3P), photoelectric detector module(type PDM1000-3P), transmitting laser probe(type TM250) and FlowSizer® software, was used to measure the axial and tangential velocity components of flows inside draft tube. In order to accurately locate the measurement position, the radial movement of the laser probe was controlled by a NC controlled traverse with minimum step length of 0.01mm. Signals were captured by the transceiver probes and sent to a PDM100 detector module, and FSA 4000-3P signal processor and FLOWSIZER™ software were used to process and analyze the data. The measurement system consisted of a 70mm in diameter of fiber probe operating in backscattering mode, the probe front lens had a focal length of 363mm with standard laser beam diameter of 2.1mm, when a multicolor argon-ion laser beam is directed through the Fiberlight separator, the system output contains three pairs of beams: green (514.5nm), blue (488nm) and violet (476nm), the two dimensional measurements are performed with the wavelengths 488nm and 514.5nm. The range of velocity measurements is within-150m/s to +1000m/s, velocity accuracy< 0.2%, and the repeatability of individual velocity measurements has been shown to be better than 0.05% for this LDV system. To evaluate the accuracy of the measured velocity components
with this experimental setup, the flowrates measured with LDV are calculated by integrated the axial velocity components with the measurement plane, the flowrates deviations between the integral of LDV measured axial velocity profiles and measured by high precision electromagnetic flowmeter mounted on test rig are within ±1.85% for all measuring points. The larger deviations at part load compared to BEP and full load is attributed to presence of the rotating vortex rope. An encoder installed on the main shaft allowed the measured velocity components to be phase-resolved with respect to the runner frequency.

Flow velocity is measured from the point where laser beams were crossing, and the position was directed with respect to cone diameter and the horizon in LDV measuring. As there has great difference of the laser speed in water, air and Plexiglas, the actual position of the optical axis of LDV is required to be calibrated in-situ. After many times measurement for the draft tube cone, the transform ratio of this optical access is 1.33, which means it is necessary to increase coordinate in the water 1.33 times than actual measured coordinate in the air while LDV measuring.

2.3. Data acquisition and processing
As Doppler velocity measurement method is based on measuring the frequency of the laser radiation scattered of moving subject, spherical particles in hollow glass spheres, are added to the water as flow tracers. Its relative density is about 1.008 against the water and the average size of 10μm glass spheres allow these particles to accurately follow the flow inside the draft tube. The measurement time per point is not less than 300 seconds, assuring a sufficiently high number of vortex rope revolutions. The count number of all points is at least 30000, up to 50000 counts, which makes the total averaged value highly accurate.

The control and synchronization of the LDV and external trigger input, as well as the data acquisition and processing, are realized with a specific TSI FlowSizer™ software. All settings for the FSA processor, the PDM receiver unit, PowerSight laser module, EB external input module, and NC-controlled traverse can be set in the software, and control is provided through an advanced FireWire® (IEEE 1394) interface. A utility is integrated into FlowSizer™ software to provide user defined graphs for displaying the signal frequency and the data of the axial and the tangential velocities. To determine the periodic influence of the rotating vortex on the flow, the information about the position of the vortex has to be linked to the velocity measurements. This is done by a trigger signal which is forwarded to the LDV system. A pressure sensor, was installed in the cone wall at location of 260 mm in axially below the centerline of distributor, records the pressure fluctuations caused by the precession of the vortex rope.

Due to the periodicity of the flow leaving the runner, a Reynolds triple decomposition as proposed by Telionis[9] was utilized to analyze the flow inside draft tube. The instantaneous velocity at radius \( r \) phase \( \theta \) and time \( t \) as decomposed into its mean value, periodic component and random fluctuation as bellows

\[
\begin{align*}
    u(r, \theta, t) &= C(r) + u_p(r, \theta) + u_s(r, \theta, t) = \langle u(r, \theta) \rangle + u_s(r, \theta, t)
\end{align*}
\]

Where: \( C(r) \), \( u_p(r, \theta) \), \( u_s(r, \theta, t) \) and \( \langle u_p(r, \theta) \rangle \) are the time-average, periodic component, random fluctuation and phase-average respectively.

3. LDV measurement of velocity profile

3.1. Measurement positions
The measurements were performed on the section located $D_2=260\text{mm}$ in axially below the centerline of distributor, and the measurement window and tangential locations are shown in figure 2. The velocity components were measured at 29 radial points which at step-length of $0.05R$ (the radius of internal circle on the measurement plane) from $r_a=0$(the center of measurement section) to $r_a=0.9R$ and at step-length of $0.01R$ from $r_a=0.9R$ to $r_a=1.0R$ ($R=138.6\text{mm}$). The higher number of measuring points at PL is required in order to better resolve the larger gradients as expected the rotating vortex rope at these operating points. To position the laser probe along radial position of the measurement path, a NC controlled traverse system is constructed and the radial coordinate of laser probe is positioned automatically by the linear traverse according to the setup in FLOWSIZER™.

![Figure 2. Axial and tangential location during measuring](image)

### 3.2. Operating conditions for investigation

Model operating conditions comply with the IEC60193 Standard. LDV measurements were carried out at steady-state and non-cavitation (at higher Thoma number) operating conditions. Dimensionless parameters $n_{ED}$ and $Q_{ED}$, which are defined by equation (2), are used to characterize the turbine operations. 10 measured operating conditions were taken at the speed factor $n_{ED}=0.21$ corresponding to the rated head $H=600\text{m}$ and the speed factor $n_{ED}=0.19$ corresponding to the optimum head $H=750\text{m}$ at turbine mode for a wide range of loads ranging from partial to maximum value at two constant unit speeds, corresponding to these operating points are presented in table1 and 2. The absolute values of test head, flow rate and runner’s rotating speed were therefore adjusted according to table1 and 2 while the non-dimensional quantities $n_{ED}$ were kept constant approximately.

$$n_{ED} = n.D / \sqrt{gH}, \quad Q_{ED} = Q / D^2 \sqrt{gH}$$

(2)

Where: $n$ is the rotating speed; $D$ is the diameter of the runner; $g$ is the local gravitational acceleration; $H$ is the measured head; $Q$ is the measured discharge.

| Relative Power $P/P_r(\%)$ | $Q_{ED} \times 10^{-3}$ | Runner speed $n$ rpm | Test head $H_{test}$ m | OP No.       |
|-----------------------------|------------------------|----------------------|------------------------|-------------|
| 40                          | 85.42                  | 939.87               | 36.94                  | $H_{rat-40\%P_r}$ |
| 60                          | 118.94                 | 925.87               | 35.52                  | $H_{rat-60\%P_r}$ |
| 80                          | 153.22                 | 919.86               | 35.04                  | $H_{rat-80\%P_r}$ |
| 100                         | 192.43                 | 919.85               | 35.21                  | $H_{rat-100\%P_r}$ |
| Opt (closer to BEP)         | 141.92                 | 919.86               | 35.60                  | $H_{rat-opt}$  |
Table 2. Operating conditions were measured under $n_{ED} = 0.19$ at turbine mode

| Relative Power $P/P_r(\%)$ | $Q_{ED}(x10^{-3})$ | Runner speed $n$ rpm | Test head $H_{test}$ m | OP No.               |
|---------------------------|--------------------|----------------------|------------------------|----------------------|
| 40                        | 52.13              | 839.90               | 38.15                  | $H_{opt}-40\% P_r$  |
| 60                        | 83.23              | 825.01               | 36.93                  | $H_{opt}-60\% P_r$  |
| 80                        | 103.68             | 821.94               | 35.81                  | $H_{opt}-80\% P_r$  |
| 100                       | 127.41             | 809.93               | 35.02                  | $H_{opt}-100\% P_r$ |
| Opt (closer to BEP)       | 155.71             | 809.78               | 34.98                  | $H_{opt}$            |

4. Numerical Simulation Setup

The numerical simulations were carried out by using the commercial flow solver ANSYS CFX applied to the complete pump turbine with all its hydraulic components: spiral case, stay vanes, guide vanes, runner and draft tube. The calculations were conducted in a coupled manner, i.e. considering all the turbine components and interfaces between them, as long as the dynamic effects in the fluid flow through the turbine arise from the interaction between its components, caused by the rotating runner and the stationary parts.

Different computational mesh densities were tested and optimized to deliver accurate results with acceptable computation times. The final computational mesh counted with around 18 million cells and part of it can be seen in figure 3. The computational domain was artificially extended at the spiral case inlet and draft tube outlet with the objective to eliminate any boundary effects on the turbine inlet and outlet sections. As inflow boundary condition the volume flow was prescribed together with 5% turbulence intensity. At outlet a reference integral pressure level was prescribed and allowed any eventual backflow.

Figure 3. Mesh of the complete pump turbine model

Considering the turbulence modelling, the unsteady RANS (averaged Navier-Stokes equations) model introduced, as expected, excessive artificial dissipation in the flow simulation and turned out to be unable to reproduce the highly transient effects in the turbine draft tube. Therefore, adequate and more sophisticated turbulence models had to be employed. The scale adaptive simulation (SAS)\(^{14}\) was chosen to simulate the flows through turbine as it was already repeatedly and successfully employed in the past for the numerical simulation of the transient fluid flow with accurate results.

5. Results and analysis of LDV measurements

To describe the velocity in draft tube, the positive axial velocity is defined in the stream-wise direction and the tangential velocity is positive in the runner rotational direction for turbine mode, and the
velocity is negative in the runner rotational direction for pump mode. All the spatial coordinates of measured position are normalized with the draft tube radius R from the center to cone wall on the measured section. The velocity components are made dimensionless using the following equations for turbine mode:

\[
K_{cu} = C_u / \sqrt{2gH}, \quad K_{cm} = C_m / \sqrt{2gH}
\]

Where: \(K_{cu}, K_{cm}\) are the tangential and axial velocity coefficient respectively; \(C_u, C_m\) are the measured tangential and axial velocity; \(H\) is the measured head in testing.

5.1. Time-averaged velocity

To analyze the measured velocity components on the measurement plane, the tangential and axial velocity coefficients are calculated based on equation (3). To present the total time-averaged velocity data, the measured tangential and axial velocity coefficients are plotted along the radial measurement line. On the relative abscissa, the radial measurement point position referred to the cone radius R is plotted. The centerline of the cone is defined as \(r/R=0\), accordingly, at the center of the measuring volume meets the inner cone wall is \(r/R=1\).

5.1.1. Under the unit speed \(n_{ED}=0.21\). Figure 4 shows the measured tangential and axial velocity coefficients at 5 operating conditions under the speed factor \(n_{ED}=0.21\) corresponding to the rated head \(H=600\text{m}\) of prototype at turbine mode. At \(H_{\text{rat-opt}}\) and \(H_{\text{rat-80\%Pr}}\), operating points, the axial velocity are almost uniformly distributed within \(r/R=0.2\sim0.95\) along the radius on the measurement plane except the axial velocity decreases close to cone wall due to the boundary layer, and the tangential velocity slightly and linearly increase within \(r/R=0.2\sim0.95\) but there exist negative tangential velocity for \(H_{\text{rat-80\%Pr}}\), within \(r/R=0.0\sim0.3\) and \(H_{\text{rat-opt}}\) within \(r/R=0.0\sim0.15\) due to the runner hub wake, it shows that exist very small swirl flow in the operating zone. An integration of the velocity profiles results in comparable flowrate for these two operating points agree well with flowrate measured by electromagnetic flowmeter. At \(H_{\text{rat-40\%Pr}}, H_{\text{rat-60\%Pr}}, \) and \(H_{\text{rat-100\%Pr}}\), operating conditions, the tangential and axial velocity are not uniformly distributed and varied greatly along the radius on the measurement plane. There exists strong recirculation flows in the axial velocity components within
r'/R=0~0.5 at H/r=40%Pr and small backwards flows within r/R=0~0.15 at H/r=100%Pr, and the axial velocity sharply increase ranging from r/R =0.5 to -0.95 at H/r=40%Pr, and r/R =0.15 to -0.48 at H/r=100%Pr. The tangential velocity components are very small ranging from r/R =0~0.6 and sharply increase in ranging from r/R =0.6 to 0.99 at H/r=40%Pr, it shows that exists the column vortex rope with the same direction of runner’s rotation. At H/r=100%Pr operating point, the direction of the tangential velocity component is reversed with rotating of the runner and minimum tangential velocity value appears at the position near r/R =0.5, the tangential velocity sharply decrease from r/R =0.0 to 0.5 then linearly increase from r/R =0.5 to 0.95. At H/r=60%Pr operating point, the tangential velocity linearly decrease from r/R =0.0 to 0.4 and almost equally distributed from r/R =0.4 to 0.8, then linearly increase from r/R =0.8 to 0.95, it shows that exists the vortex rope with the reversed direction of runner’s rotation.

5.1.2. Under the unit speed nED=0.19. The figure 5 shows the measured tangential and axial velocity coefficients at 5 operating conditions under the unit speed nED=0.19 corresponding to the head H=750m of prototype at turbine mode. At Hopt,100%Pr and Hopt,80%Pr operating points, the axial velocity are almost uniformly distributed within r/R =0.3~0.95 along the radius on the measurement plane except the axial velocity decreases close to cone wall due to the boundary layer, and there exist smaller backwards flows within r/R =0~0.15 at Hopt,100%Pr. The tangential velocity slightly and linearly increase within r/R =0.4~0.95 but there exist smaller negative tangential velocity for Hopt,100%Pr within r/R =0~0.4 due to the runner hub wake, and the tangential velocity linearly decrease from r/R =0.0 to 0.2 and almost equally distributed from r/R =0.2 to 0.8, then linearly increase from r/R =0.8 to 0.95 at Hopt,80%Pr. At Hopt,40%Pr, Hopt,60%Pr and Hopt,opt operating points, the tangential and axial velocity are not uniformly distributed and varied greatly along the radius on the measurement plane. There exists strong backwards flows in the axial velocity components ranging from r/R =0~0.63 at Hopt,40%Pr and ranging from r/R =0~0.5 at Hopt,60%Pr. The tangential velocity components are very small ranging from r/R =0~0.6 and sharply increase in ranging from r/R =0.6~0.99 at Hopt,40%Pr and Hopt,60%Pr, it shows that exists the vortex rope with the same direction of runner’s rotation. At Hopt,opt operating point, the direction of the tangential velocity component is reversed with rotating of the runner and minimum tangential velocity appears at the position near r/R =0.28, it shows that exists the swirl flow with the reversed direction of runner’s rotation.

(a) axial velocity coefficients
(b) tangential velocity coefficients

**Figure 5.** Velocity coefficients at 5 operating conditions under nED=0.19
5.2. *Instantaneous tangential velocity and fluctuation characteristics at part load*

When turbine is operating in part load, a rotating vortex rope occurs inside draft tube cone. The measured velocity fluctuations can be further used to validate the characteristics of vortex rope. Taking operating point at part load of 60% $P_r$ ($H_r-60\%P_r$) for example, the measured tangential velocity fluctuations of 12 measuring positions from $r/R = 0$ to 0.55 within 2 seconds were recorded and fitted to obtain the time domain of the measured tangential velocity, and figure 6 shows the time domain for measuring positions at $r/R = 0.3$ and 0.5. In order to determine the frequencies of the measured velocity fluctuations, FFT was carried out to analyze the frequency domain, and figure 7 shows the frequency domain for measuring positions at $r/R = 0.3$ and 0.5.

![Figure 6](image)

**Figure 6.** Tangential velocity time domain within 2s at measuring positions $r/R=0.3$ and $r/R=0.5$

![Figure 7](image)

**Figure 7.** Tangential velocity frequency domain within 2s at $H_r=60\%P_r$

The main frequency of the measured tangential velocity fluctuations of 12 measuring positions from $r/R = 0$ to 0.55 are listed in Table 3, the arithmetic mean of the main frequency for 12 measuring positions is 4.65Hz, which is 0.28 times of rotating frequency of turbine runner at this operating point.
Table 3. Main frequency of instantaneous tangential velocity fluctuations for measuring positions

| position | 0      | 0.05R  | 0.10 R | 0.15 R | 0.20 R | 0.25 R |
|----------|--------|--------|--------|--------|--------|--------|
| freq/Hz  | 4.49   | 4.72   | 4.73   | 4.78   | 4.61   | 4.57   |
| position | 0.30 R | 0.35 R | 0.40 R | 0.45 R | 0.50 R | 0.55 R |
| freq/Hz  | 4.71   | 4.53   | 4.80   | 4.72   | 4.61   | 4.57   |

6. Numerical simulated results in comparison with experimental data

To evaluate the method for simulation of flows, the flow through the pump-turbine was numerically simulated with computational fluid dynamics (CFD) for all the measured operating points using the numerical simulation setup described in the above. To validate the simulated results, 4 operating points including the best efficiency at optimum head ($H_{opt}$), full load ($H_{opt} - 100\%Pr$), part load ($H_{opt} - 60\%Pr$) and deep part load ($H_{opt} - 40\%Pr$) are selected to compare with experimental data. These different operating conditions constituted an interesting benchmark for the prediction capability of the numerical simulation model. They counted with different flow effects taking place in the hydraulic turbine, rotor-stator interaction, rotating draft tube vortex rope and runner channel vortex.

![Graphs showing simulated vs measured velocity coefficients](image)

Figure 8. The comparison of the simulated with the measured tangential and axial velocity coefficients

The measured time-averaged velocity data of the 4 selected operating points had been presented in figure 5. The comparison of the simulated tangential and axial velocity coefficients with the measured
at 4 selected operating conditions is shown in figure 8. At deep part load (Hopt-40%Pr), there are larger discrepancies between the measured and CFD computed in the axial velocity components ranging from $r/R=0$ to 0.45 as strong backwards flows observed and the largest discrepancies is close to the draft tube axis, but their profiles agree well in trends ranging from $r/R=0.45$ to 0.9. The measured and CFD computed tangential velocity agree well in ranging from $r/R=0$ to 0.3 and their profiles agree well in trends ranging from $r/R=0.3$ to 0.9. The measured and CFD computed tangential velocity along the radius agree well but magnitude is over-estimated, there are larger deviations in magnitude and the largest deviation is at $r/R=0.5$ as shown in figure 8(a). At part load (Hopt-60%Pr), their profiles are similar to the Hopt-40%Pr, the larger discrepancies existed in the axial velocity components ranging from $r/R=0$ to 0.3 and their profiles agree well in trends ranging from $r/R=0.3$ to 0.9. The measured and CFD computed tangential velocity along the radius agree well but magnitude is over-estimated, there are larger deviations in magnitude and the largest deviation is at $r/R=0.5$ as shown in figure 8(b). At full load (Hopt-100%Pr), as shown in figure 8(c), it shows very good agreement for axial velocity apart the ranging from $r/R=0$ to 0.2. The measured and CFD computed tangential velocity agree well in ranging from $r/R=0.5$ to 0.8 and the larger discrepancies in ranging from $r/R=0$. to 0.45, and profiles agree well in trends ranging from $r/R=0.8$ to 0.95 but magnitude is over-estimated.

Analysis shows that axial velocity profiles are much better predicted than the tangential ones at full load (Hopt-100%Pr) and Hopt-opt, while in the wall region the inaccuracy between measurements and computations is probably caused by the near wall modelling, the significant variation in the central region is attributed to both inaccuracy of LDV measurements and inaccuracy in turbulence models.

7. Conclusions

Velocity fields in the draft tube cone of a high-head Francis pump-turbine model at cavitation-free operating conditions were preliminarily investigated with LDV measurements and CFD simulations for operating conditions covering at the speed factor $n_{ED}=0.21$ and 0.19 at turbine mode for loads ranging from 40-100% rated power including the best efficiency. It has shown that:

- It was possible to investigate unsteady flow in the draft tube of a pump-turbine model and to get reliable measuring results at different operating conditions with LDV measurements. The measured velocity profiles are well-distribute and the measured results indicate a well-functioning turbine when operating at best efficiency point, and 80%-100% rated power. However, at part load (40%, 60% rate power) operating points, the velocity profiles are distorted and vortex breakdown occurs which creates a recirculation region covering more than half of the cone radius, and it will significantly affects the measuring accuracy of velocity.

- Comparison of the measurement and simulation shows rather good agreement at the best efficiency point and full load but clear discrepancies at part load. The velocity components prediction accuracy of the numerical simulations depends on the operating zones. For this pump-turbine, the measured velocity profiles agree well with the simulated at best efficiency, and 80%-100% rated power operating point. The measured low frequency pressure pulsations are quite similar to the predicted by the simulations.

- The LDV measured results show the periodic behavior of the velocity components in tangential direction. The main frequency of the measured instantaneous tangential velocity fluctuations can be used to determine the characteristic frequency of rotating vortex rope when turbine operating at part load.

- Although 2D LDV measured velocity data can be provided as a reference for validation data for numerical simulation in optimization design, flow visualization or joint LDV and PIV measurements should be used for further investigations of 3D complex structures inside draft tube at unsteady and cavitation operating conditions.
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