

Modern challenges for flow investigations in model hydraulic turbines on classical test rig

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Abstract. The BulbT project involved several investigations of flow phenomena in different parts of a model bulb turbine installed on the test rig of Laval University Laboratory. The aim is to create a comprehensive data base in order to increase the knowledge of the flow phenomena in this type of turbines and to validate or improve numerical flow simulation strategies. This validation being based on a kinematic comparison between experimental and numerical data, the project had to overcome challenges to facilitate the use of the experimental data for that purpose. Many parameters were checked, such as the test bench repeatability, the intrusiveness of a priori non-intrusive methods, the geometry of the runner and draft tube. This paper illustrates how some of those problematic were solved.

1. Introduction

Traditionally, experimental measurements on model turbines are used to design and validate turbine conception for scaled on-site conditions (head, flow rate, size and rotational speed). As such, the standards used to define those performance measurements were elaborated with those concerns in mind. Within the last 20 years or so, there is a trend to use model testing to validate numerical simulations: Turbine99 [1], Flindt [2], AxialT [3]). Mainstream numerical simulations offer benefits over model testing. First of all they give the user a precise control over flow quantities (the boundary conditions) and turbine geometry. They enable a detailed analysis of the flow field impossible to achieve with current flow measurements technologies. Most importantly, they can be used to cheaply compare the performance of many different variations of a turbine design, thus optimizing turbine performances and decreasing costs [4]. On the other hand, numerical simulations suffer from lack of reliability to predict performance in off-design operating conditions and even in some cases at their best operating conditions.

The BulbT project, underway at Laval University Hydraulic Machine Laboratory (LAMH) is aimed at intimately coupling both numerical simulations and experimental measurements to study the idiosyncrasies of bulb turbine flow dynamics. The project was initiated within the framework of the Consortium on Hydraulic Machines involving hydraulic turbine manufacturers, electric utilities and Canadian government agencies. It is centered on a vast experimental measurements database tailored specifically as a test case to validate different numerical simulations technologies.

The database was planned through many inquiries made with the Consortium partners to clearly identify the needs both in terms of problematic to be studied and of measurements required to study those problematic by coupling numerical and experimental data. The main topics of BulbT are:



- 1- The dynamics of draft tube and runner flows associated with performance break-off at best efficiency.
- 2- The use of hybrid turbulence treatments applied to draft tube numerical simulations.
- 3- The effects of inflow conditions on turbine performance.
- 4- The transient flow dynamics during start-up.

Bulb turbines present interesting opportunities to study hydraulic turbine flow dynamics. Being low-head units, the draft tube flow has a significant impact on their overall performance. Interestingly, even without a bend, their straight draft tube can exhibit the same topological behavior as medium head Francis turbine, such as vortex breakdown in the core flow and near wall separation leading to sharp drop in efficiency close to their optimal performance peak.

For steady-state operating conditions, detailed flow measurements were carried out in critical locations of the turbines (intake, runner, draft tube). Those measurements, based on Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV) and unsteady pressure sensors, were performed on predefined operating conditions over several months. In order both to reduce the number of flow simulations required to match the kinematics of each measurement and to perform cross-correlation analysis of the measurements in between themselves, the requirements on the definition of the operating conditions became more stringent. Stemming from the experience gained in AxialT, the 5 selected combinations of flow rate, runner speed and guide vanes angles were judged based on dimensional quantities instead of non-dimensional ones.

This paper presents the different strategies put in place during the project to address the challenges associated with providing kinematically comparable experimental measurements within a steep performance drop. Furthermore, it also presents how the model was adapted for numerical simulations, how the impact on the performance of local geometrical features was controlled and how measurements intrusiveness was estimated and circumvented. The first part is a summary of the BulbT test case, the second part illustrates the challenges associated with a complex performance hill chart, and the third part presents the geometrical considerations and the CMM (Coordinate Measuring Machine) measurements of the runner and draft tube. The last section deals with the measurements intrusiveness.

2. Experimental set-up and measurement campaigns

2.1. Test bench and bulb turbine model

LAMH's test rig consists of a classical hydraulic closed-loop that can accommodate axial and radial turbo machinery models. The test rig is powered by a pump with a maximal flow rate of $1 \text{ m}^3/\text{s}$ and a maximal head of 50 m. The turbine operates with rotational speed up to 2000 rpm and a maximal net power output of 170 kW. A vacuum pump is installed on the downstream tank to control the relative pressure in the test loop to perform cavitation studies. The test rig is set up to perform measurements according to the IEC 60193 standard. The water temperature is regulated with a 100 kW heat exchanger.

The turbine model which is currently under investigation at the LAMH is a four blade bulb turbine with a spherical hub and semi spherical shroud. A section view of the model is shown in figure 1. The inlet is composed of a bulb held with piers and of a distributor with 16 guide vanes. The first portion of the draft tube is conical with an opening half angle of 10.25° and made of transparent PMMA to allow optical access to the runner and diffuser flow. The second portion is a transition from a circular to a rectangular section.

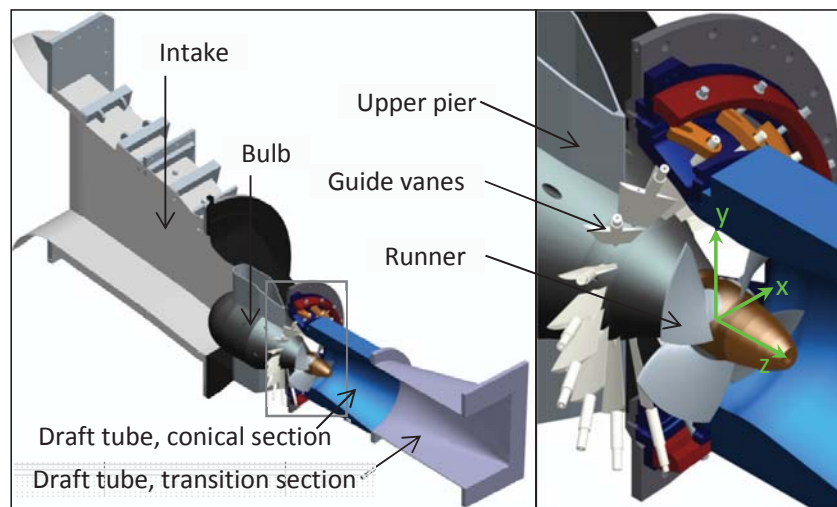


Figure 1. Left: View of the model bulb turbine. Right: Zoom on the runner.

2.2. Flow measurements

The experimental flow measurements on the BulbT model uses mainly 3 types of instrumentation: Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV) and unsteady wall pressure measurements. For the steady states regimes, 9 measurement campaigns were performed at 5 different locations illustrated in Figure 2.

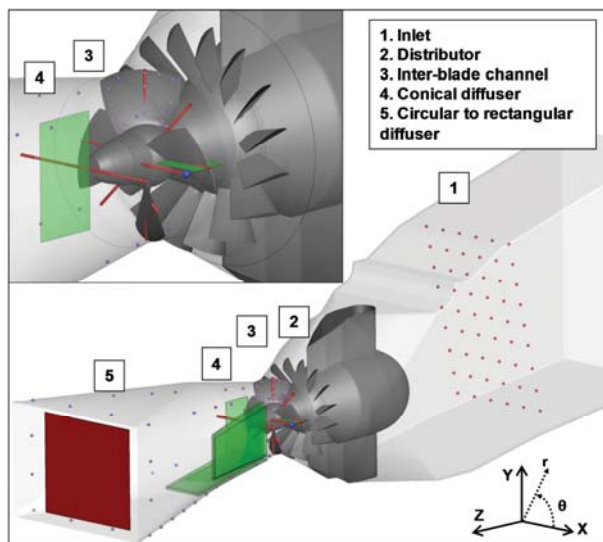


Figure 2. BulbT model and measurement locations. Colors represent measurement techniques. Green: PIV; red: LDV; purple: unsteady wall pressure sensors; blue: near wall LDV.

The main advantage of PIV and LDV is their limited intrusiveness when compared with traditional Pitot probing, but they require optical accesses with the minimum distortion. One PIV measurement campaign [5] was performed with endoscopes to gain better access to the inter blade channel flow within the runner. As will be shown in section 5, the effect of the optical accesses and the endoscopes were controlled thoroughly in order to estimate their impact on the measurements and to circumvent their effect when possible. The steady-state measurements campaigns performed so far are presented and analysed in Duquesne *et al.* [6][7][8] (hill chart measurements, wall pressure, draft tube PIV),

Lemay *et al.* [5] (runner PIV and LDV), Julien *et al.* [9] (draft tube inlet LDV) and Longchamp [10] (intake channel LDV).

3. Definition of the common operating conditions and repeatability

3.1. Hill chart

To characterize the hill chart of the turbine, 4 runner blade angles were tested ($\beta = 15^\circ, 22.5^\circ, 30^\circ$ and 37.5°) along with several guide vanes opening. The best efficiency point (BEP) was found at $\beta = 22.5^\circ$ and $N_{11} = 150$. Abrupt efficiency and power drops were associated with the development of a draft tube flow separation just after the BEP, especially in the low head part of the hill chart [6]. Five operating conditions, OP1 to OP5, were selected with $\beta = 30^\circ$ and $N_{11} = 170$ (figure 8) to perform detailed flow field and pressure measurements. The choice of these operating conditions was based on a thorough study of the required flow dynamics to address the desired problematic to be studied.

The final performance curves (Figure 9a-b) have a narrow range of investigated flow rate Q ($Q_{OP5} - Q_{OP1} = 0.027 \text{ m}^3/\text{s}$) in order to catch the sharp performance drop. Such narrow variations along with the large gradients on the model's η hill chart (figure 8) imply that careful setting of the test bench is required to avoid dispersion between the successive experimental campaigns. Extensive performance measurements were performed to define operating procedures that would give the best repeatability for the different measurement campaigns to be performed over several months.

During the repeatability study, it was found that the flow separation and the model global performances presented a hysteresis within the efficiency drop. The flow separation development depends on the operating sequence, mainly triggered by the guide vane opening or closing [6] [11]. Furthermore, the flow conditions in the operating range of OP3 to OP5 present low frequency, large scale fluctuations. These fluctuations imply longer observation time to reach a sufficient statistical convergence level.

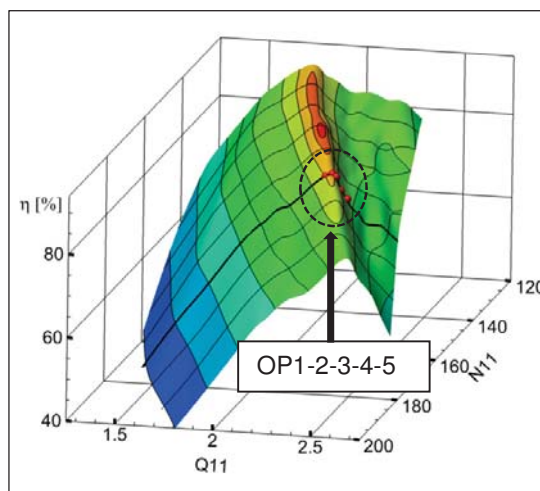


Figure 8. Efficiency hill chart ($\beta = 30^\circ$) (colour levels are efficiencies and contours are iso-efficiency and iso- N_{11} , thick black line is $N_{11} = 170$, OP1 to OP5 are represented with red dots).

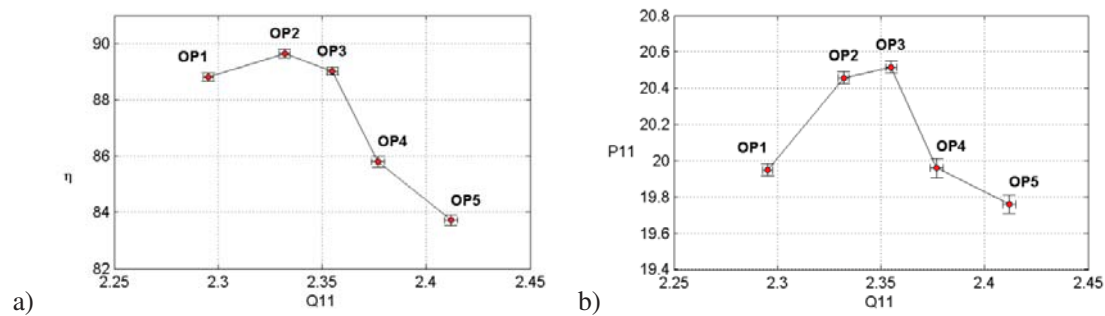


Figure 9. Localisation of the operating points at $N_{11} = 170$; a) Efficiency break-off; b) Power break-off. Error bars represent the measurement accuracy.

3.2. Performance measurement accuracy

Accuracy of model performance measurements is estimated from the apparatus calibration and the statistical convergence of the data sample. A systematic error f_S comes from the apparatus calibration and the random error f_R is estimated from the sample size and its standard deviation. In the operating range of the five selected OP, the flow meter had an accuracy of $f_{SQ} = 0.1\%$, the differential pressure sensor for the net head estimation $f_{SAP} = 0.05\%$, the torque meter $f_{ST} = 0.05\%$ and the runner speed $f_{SN} = 0.001\%$. The water temperature was regulated to $22 \pm 0.05^\circ\text{C}$.

In this operating range, fluctuation levels vary significantly, they increase from OP1 to OP5. Thus, the random error also increases and is estimated for each OP. The sample sizes are $nb = 600$ acquired at 1 Hz giving a 10 minute observation time. The statistical convergence is estimated using a Student law with confidence level of 95% ($t = 1.96$):

$$f_{Ri} = \frac{t}{\bar{X}_i} \sqrt{\frac{\sum (X_i - \bar{X}_i)^2}{nb}}$$

For example, the net head random error is $f_{RH} = 0.07\%$ at OP1 and reaches 0.14% at OP5. The total measurement accuracy f_M is estimated from the quadratic sum of the systematic and the random errors:

$$f_{Mi} = \sqrt{f_{Si}^2 + f_{Ri}^2}$$

Table 1 summarises the estimated measurement accuracies for each OP and main model performances. Measurement accuracy is represented with error bars in figure 9.

Table 1. Measurement accuracy f_M (%) estimated at OP1 to OP5.

	Net head	Torque	Runner speed	Flow rate	N_{11}	P_{11}	η	Q_{11}
OP1	0.09	0.11	0.01	0.1	0.05	0.17	0.17	0.11
OP2	0.09	0.11	0.01	0.1	0.04	0.17	0.17	0.11
OP3	0.09	0.10	0.01	0.1	0.05	0.16	0.17	0.11
OP4	0.16	0.12	0.02	0.1	0.08	0.27	0.23	0.13
OP5	0.15	0.12	0.02	0.1	0.08	0.26	0.22	0.13

3.3. Operating condition repetition

The test bench allows regulation of four parameters: water temperature ($\pm 0.05^\circ\text{C}$), guide vane angle ($\pm 0.1^\circ$), runner speed ($\pm 1\text{ rpm}$), and test bench pump speed ($\pm 1\text{ rpm}$). The water temperature is set at 22°C for all studied cases. For all OP, with predefined guide vanes angles, the target runner speed and head are respectively 1000 rpm and 4 m . The pump speed provides the adjustment in flow rate that will yield the target values.

Slight variations in the target values brought about by the different factors such as “user” input or the pumps speed control increments bring dispersion of the measured performances. It is possible to estimate approximately the minimum dispersion that could be expected when repeating operating conditions one campaign after the other based on observed range variation of H , Q , N . For example, it was estimated that the repetition range for Q_{11} was $f_{KQ11} = 0.28\%$ and for N_{11} , $f_{KN11} = 0.24\%$.

For comparison sake, performances are presented as constant N_{11} curves for the five selected OPs. The N_{11} dispersion associated with the head and runner speed has an impact since the performance gradients in the vicinity of the five OPs are large and the selected operating conditions are focused on a limited zone. The effect of the N_{11} dispersion can be estimated using the local gradients from the complete hill chart data (figure 8):

$$\left| \frac{\partial \eta}{\partial N_{11}} \right|_{Q_{11}=\text{cst.}} \quad \text{and} \quad \left| \frac{\partial P_{11}}{\partial N_{11}} \right|_{Q_{11}=\text{cst.}}$$

Figure 10 presents the efficiency and power with the repetition ranges estimated for the five operating conditions compared against the results from 3 measurement campaigns. The results indicate clearly that the performance gradients for OP3-5 and the small uncertainties over N_{11} do have detrimental effect on the repeatability for such a narrow range of Q_{11} .

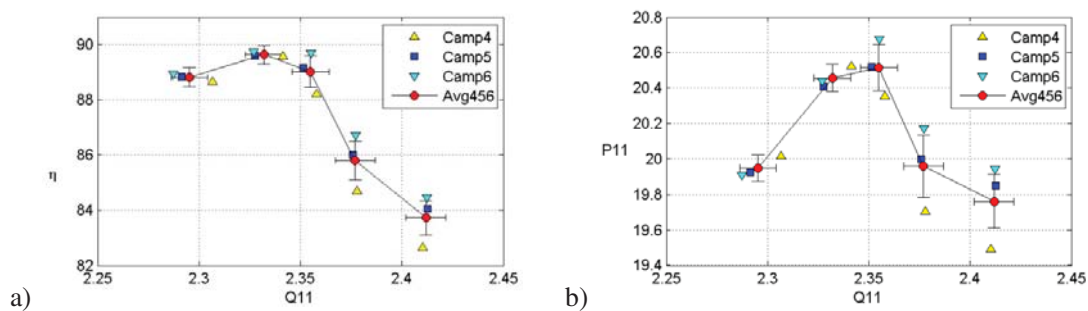


Figure 10. Localisation of the operating points at $N_{11} = 170$; a) Efficiency break-off; b) Power break-off. Error bars include the measurement accuracy and repetition dispersion.

4. Geometrical consideration

Given the nature of the BulbT project where numerical simulations are to be compared with detailed and precise flow measurements, a great deal of resources were devoted to tailor the geometry to yield the sought flow behaviour (efficiency drop) with minimum impact from local geometrical features. This was accomplished by performing numerical simulations prior to the model final installation and by the creation of accurate CAD models of the turbine. This section presents modifications made to the turbine to facilitate numerical simulations; the procedure used to recover the runner and draft tube geometries and the effect of the optical accesses.

4.1. Geometry modification for numerical simulations

Prior to the installation of the BulbT model on the bench, Reynolds Averaged Navier-Stokes (RANS) simulations based on were performed to study the main flow characteristics [12]. From those results two important issues arose:

- 1- The bulb casing pier configuration introduced large scale fluctuations that were affecting simulations convergence.
- 2- The shallow divergence of the draft tube (6°), coupled with a well-designed runner, did not yield any flow separation in the draft tube across most of the efficiency hill chart.

For the first problem, the original BulbT project aimed at providing a model in full homology with a prototype bulb unit. Hence an eddy current brake was designed to fit into the bulb casing along with a telemetry system required to perform unsteady pressure measurements on the runner blades [13].

This configuration had the bulb supported by two upper piers and one lower pier. Unfortunately, the two upper piers exhibited a complex dynamic interaction where the wake of the upstream pier was destabilized in such a way by the pressure field of the downstream pier that RANS simulations, based on a very diffusive time stepping scheme to solve the “time averaged” matrix, was able to capture part of this unsteadiness (figure 11). This translated into difficulty in obtaining converged solution for what should have been an otherwise well behaved intake channel flow. Since no measurements were planned in that area, a new pier configuration was designed to alleviate intake channel numerical simulations complexity, with only a single upper pier symmetrical with the lower pier.

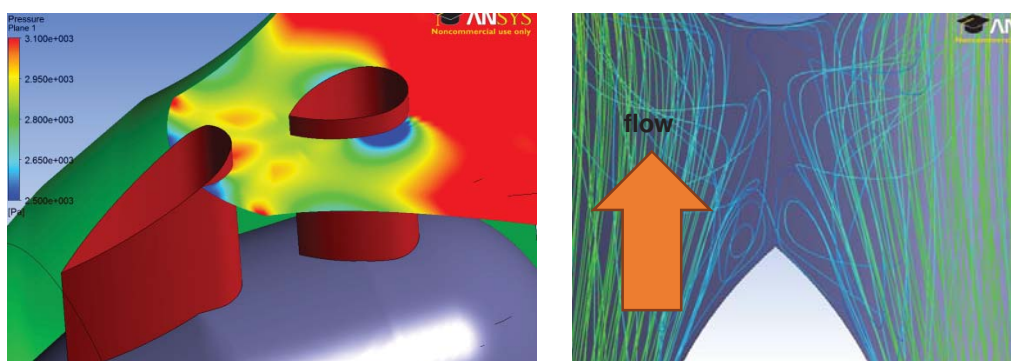


Figure 11. RANS flow simulations of the original two piers configuration illustrating the interaction between the upstream pier wake and the downstream pier leading to poor convergence.

The second problem was solved by designing a new shorter draft tube that presented a larger average divergence angle (10.25°) and that could be fitted on the LAMH test stand. RANS simulations were used to study different draft tube configurations with area law that would be representative of actual bulb turbine draft tube and yielded separated flow after the best efficiency conditions. The final design was based on a conical diffuser representing 38% of the draft tube length and a trumpet providing a transition from a circular to a rectangular cross section for the remaining length. This trumpet has a horizontal upper wall, a slightly diverging lower wall with most of the divergence coming from the side walls.

4.2. Runner and draft tube geometry recovery

Given the nature of the BulbT project, where experimental flow measurements are to be compared with numerical simulations results, the representativeness of the CAD models relative to the actual geometry must be strictly controlled. On the AxialT project, the six blades of the propeller runner presented geometrical differences above the IEC standard [14]. It was demonstrated by Nicolle et al. [15] that the standard numerical procedure of neglecting geometrical differences between the blades could lead to discrepancies between measurements and simulations. Their numerical work compared simulations done with the 6 individual blades to one done with all 6 blades simultaneously. The results outlined that the differences between the blades yielded different efficiency curves. Hence, for BulbT, significant resources were devoted to provide a representative CAD geometry to be used by all partners.

First, the runner geometry was recovered with a laser based CMM technology (FaroArm Quantum) providing a high density cloud of coordinates (14 million raw data for the entire runner), with high precision ($\pm 90 \mu\text{m}$) [16]. The 4 blades and the hub surfaces were reconstructed individually from those measurements. Since the flow measurements in the BulbT project involved only one runner blade angle, after the initial investigation into the turbine hill chart, new CMM measurements were performed to precisely define the angle of the four blades in their final configuration. This was deemed necessary in order to limit to number of unknown discrepancies between the numerical and the physical models. Geometrical data analysis indicated that the runner model was manufactured

within the IEC 60193 standard, with a maximum deviation of the blade hydraulic surfaces of 0,15% of R_{ref} , each blade angle being positioned within $\pm 0.015^\circ$.

The second component to be controlled was the draft tube trumpet. This geometry was recovered using the techniques developed to recover the runner (10 million coordinates). Interestingly, it was shown that the final model geometry differed from the theoretical drawings. Firstly, the folded sheet steel manufacturing process brought unexpected deviations in the curved corners (figure 4). Secondly, the PIV optical accesses led to the introduction of surface distortions and discontinuities. The reconstructed models provided to all partners offer the possibility to compare the effect of geometrical uncertainty on draft tube flow dynamics while ensuring that they have access to a CAD model as close as possible to the measured geometry, thus improving the kinematic similitude between the simulations and measurements.

4.3. Conical diffuser to trumpet bridge

One concern on the draft tube geometry was the influence of the connection between the conical part and the trumpet section. The model design presents a small cavity between these two parts (figure 4). A pressurized seal is used on the inner surface leaving a 1.5 mm wide gap (Δz). This gap could not be permanently filled since the draft tube has to be disassembled frequently for PIV and LDV calibration. Since such a geometrical feature only add complexity to numerical simulations, for the sake of rigour and accuracy, one comparison test was performed with the cavity filled with a temporary solution. This test confirmed that no differences could be measured on the global performance of the model. This is a good indication that numerical simulation can consider the draft tube as a continuous hydraulic profile without gap.

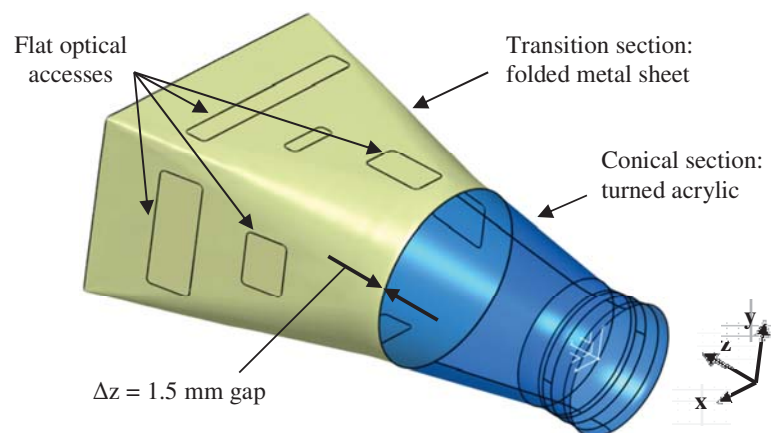


Figure 4. Hydraulic profiles of the draft tube.

5. Measurements intrusiveness

The flow measurement methods used for the BulbT projects are mainly optical methods (PIV, LDV) based on measuring the displacement of a passive marker, in the present case silver coated hollow glass spheres of $10\ \mu m$ diameter. Both of these methods have the main advantage that, in themselves, they are non-intrusive as far as the particles size and density do not affect the flow dynamics. But both methods require optical accesses with specific constraint. This section presents examples of how the endoscopic PIV method was applied to measure the inter-blade channel flow in the runner while controlling its intrusiveness and how the effect of the optical accesses was circumvented to perform near wall LDV measurements in the conical diffuser.

5.1. Inter-blade channel

Endoscopic PIV measurements were developed at the LAMH to study the flow in the inter-blades channels of the BulbT turbine [5]. The basic idea was to get rid of the complex optical interfaces introducing significant distortion and limiting the measurements area that were used in the previous AxialT project. In the present study, the PIV cameras were coupled with endoscopes to deport their point of view inside the turbine and thus to avoid any optical distortion caused by the discontinuous water/acrylic interface (figure 5). The model performances were affected according to IEC 60193 standards because of the intrusiveness of the endoscopes. Nevertheless, the runner rotation speed was preserved and only a minor mass flow rate reduction occurred (0.7%).

Furthermore, the endoscopes were positioned to ensure that the measurement zone was not in their wakes and one operating condition was measured while maintaining the flow rate and the runner rotation speed, thus enabling a control of the effect of the flow rate losses on the velocity field. Therefore, in the investigated inter-blade channel, the measured data were considered representative of the velocity field at the common operating conditions. For the first time in hydraulic turbine domain, the three component of the velocity were measured over 62% of the inter-blade channel.

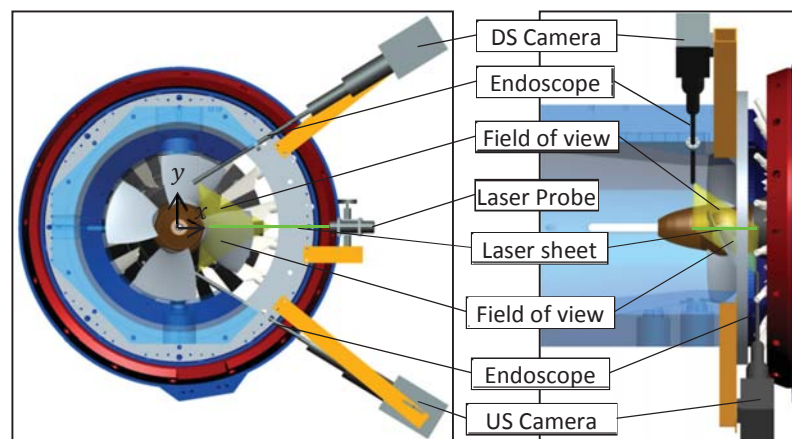


Figure 5. Endoscopic S-PIV measurement setup. Left: view from downstream. Right: side view (DS: downstream, US: upstream).

5.2. Near wall velocity measurements

The draft tube inlet velocity field is key information both for validation of runner simulations and as inlet boundary conditions for draft tube simulations. The LDV measurement technique was selected for its accuracy and its small measurement volume size. Nevertheless, to perform LDV measurements in this area, it was necessary to modify locally the conical hydraulic profile with flat windows with parallel wall and normal to the measurement axis [9]. Those flat windows introduced discontinuities (figure 6a) that appeared like backward steps for the near wall flow field. The velocity field downstream of the step is affected at some distance from the wall by the step wake. Given the flow condition and the 40 mm diameter windows (figure 6b), it was estimated from measurements that an axial velocity deviation of 1% was present at a distance of 25 mm normal to the real wall position, with a maximum deviation of 8% at 5 mm. A second set-up was used to measure the axial velocity near the wall without the effect of the optical accesses (figure 6c). Using this transversal set-up, axial velocity measurements could be performed close to 400 μm from the wall.

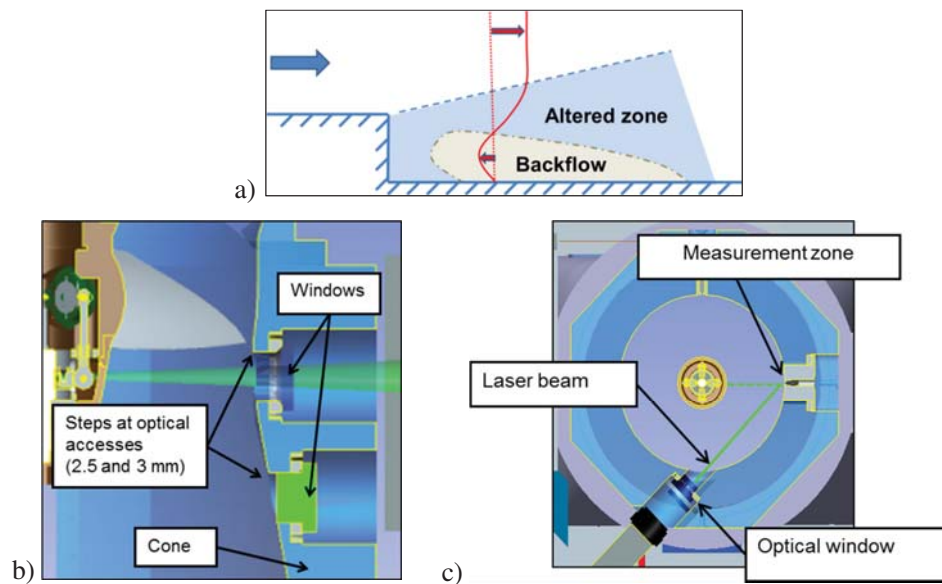


Figure 6. a) Schematic of the optical accesses discontinuity effect on the near wall flow; b) Hydraulic profile modification due to flat LDV optical accesses (top view); c) Near wall LDV set-up (downstream view).

6. Conclusion

The BulbT objectives of studying the flow dynamic inside a bulb turbine are being met through minutiae and care in the application of experimental methods and the tailoring of the project to facilitate the relationship between measurements and numerical simulations. The sharp drop in efficiency at the best operating condition being the main focus of the project, specific challenges were encountered for the application of different experimental methodologies to be cross-correlated and used for kinematic comparison with flow simulations.

Specifically, the test bench control parameters were extensively studied to yield repeatable operating conditions that would be used over many months for different measurements campaigns. Given the limited range of flow rate to be studied and the presence of a hysteresis on the efficiency curve, the observed repeatability felled within the estimated boundaries based on the measured efficiency hill chart.

The geometry of the runner and draft tube were precisely measured at different interval in the project to reflect minute changes that could affect CFD predictions. Furthermore, CFD simulations were used to adapt the geometry in order to limit unknowns and to induce flow separation in the draft tube.

Finally, the intrusiveness of the different measurements technology was evaluated and documented. For the runner blade channel endoscopic PIV measurements, measurements were performed both with a flow rate and head reflecting the additional endoscope losses and by correcting the head to obtain the flow rate of the predefined operating conditions. For the draft tube inlet LDV measurements, it was shown that the discontinuities introduced by the flat optical accesses on the conical diffuser wall were affecting the near wall measurements up to a certain distance. Measurements of the axial velocity were thus made through a transversal access to circumvent the problem and yield precious data on the near wall velocity.

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