Investigation of the BulbT conical diffuser flow dynamics with TR-PIV and pressure measurements

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Abstract. The three dimensional unsteady swirling flow inside the draft tube of a bulb turbine is investigated using time-resolved stereoscopic particle image velocimetry. The measurement plane located inside the conical diffuser, together with synchronous pressure measurements from thirteen sensors distributed across the draft tube, allow to link the draft tube flow dynamics to a known efficiency drop of the turbine. This paper presents the experimental setup and the first observations based on statistical analyses and instantaneous snapshots of the velocity field. After the efficiency drop, the intermittency and skewness of the draft tube pressure recovery are found to be reflected onto the velocity fields. Spectral analysis reveals the presence of a coherent and non-axisymmetric structure that rotates at the same frequency as the runner, but in the opposite direction.

1. Introduction
With the growing inclusion of alternative sources of energy, the role of hydroelectricity is changing. In addition to their usual production, there is now a need for hydraulic turbines to regulate the production on electrical networks. Therefore, the turbines must have a high energetic efficiency on a large range of operating conditions. However, modern low head reaction turbines sometimes display an abrupt performance drop when the discharge is raised above its optimal value. The BulbT model studied at the Hydraulic Machine Laboratory (LAMH) of Laval University exhibits such a behavior and is the subject of this paper.

The efficiency drop has been the focus of many research groups in recent years. Pressure measurements were made by Arpe and Avellan [1] inside the elbowed draft tube of a low head Francis turbine, showing that the performance drop corresponds to a restructuration of the average flow. With $k$-$\epsilon$ RANS simulations, Mauri et al [2] associated this behavior to an instability resulting in a flow separation that propagates in one of the draft tube outlet channels. Similar conclusions were drawn experimentally by Tridon et al [3]. More recently, the flow in the straight draft tube of the BulbT model was extensively investigated. Duquesne et al [4] demonstrated the correlation between a large separation coming from the trumpet wall and the efficiency break-off. They also highlighted the importance of a well behaved flow in the upstream part of the draft tube, where more than 85% of the pressure recovery occurs [5].

Turbulent swirling flows in many practical applications are known to be propitious to instabilities and vortex breakdowns [6]. From this point of view, Susan-Resiga et al [7] conducted linear stability analyses based on the diffuser inlet velocity distributions and found that a transition in the flow state occurs near the best efficency point. The impact of slight modifications...
in the BulbT draft tube inlet flow was also shown by Houde et al [8], who obtained two distinct flow topologies for a discharge located inside the performance break-off.

Despite all these efforts, the physical explanation behind the efficiency drop is a question that remains open. Whether its primary cause is the wall separation or an instability of the vorticity field exiting the runner is still unknown. In the context of confined flows, a dynamical interaction between the two phenomena is a plausible hypothesis. The measurements presented in this paper come from these considerations and are meant to be a new step in a better understanding of the physical processes involved.

2. Experimental campaign

2.1. The BulbT model

The BulbT model is a four blade bulb turbine whose components are illustrated in the cross-section view of figure 1. The bulb unit is located inside the intake channel where it is supported by two symmetric vertical piers. An eddy current brake is located inside the bulb to control the runner rotation speed and measure the runner torque. The intake is followed by sixteen guide vanes in the distributor. The model is operated similarly to an axial turbine by keeping the runner blades at a constant angle. Downstream the runner is a horizontal draft tube which is composed of a $10.25^\circ$ conical diffuser made of transparent acrylic and a non-symmetric trumpet whose cross-section transitions from a circular to a rectangular shape.

![Figure 1. BulbT turbine model front view (left) and cross-section view (right).](image)

2.2. TR-PIV measurements

A Dantec Dynamics time-resolved stereoscopic particle image velocimetry system (sTR-PIV) was used to measure the three velocity components on a plane located inside the conical diffuser with a high temporal resolution. The images were acquired with two Phantom v641 CMOS cameras with a resolution of $2560 \times 1600$ pixels equipped with Nikkor 28mm f2.8 AF lenses. The light sheet was generated with a Litron LDY304 $2 \times 30$ mJ Nd:YLF pulsed laser with a wavelength of $527$ nm. To reflect light towards the cameras, the flow was seeded with $10 \mu m$ silver-coated hollow glass spheres.

The measurement section and instruments positionning were selected using ray tracing to maximize the cameras field of view, to allow a direct measurement of the $v_z$, $v_r$, and $v_\theta$ velocity components, as well as to keep the relative angle between both cameras at ninety degrees. These criteria resulted in a plane inclined at $45^\circ$ passing through the runner rotation axis and covering $76\%$ of the cone cross-section area. This setup, illustrated in figure 3, was also chosen with the hope to detect direct traces of the flow separation measured by Duquesne et al. [9].

Prior to the measurements, both cameras were calibrated using a dual-sided target with checkerboard patterns (see figure 2). The target was positionned relative to the runner hub
using two precision micrometers. It was translated in the direction normal to its plane over 8 mm (plus the target thickness) and seventeen calibration images per camera were taken. The important optical deformations resulting from the diffuser hydraulic surface required the use of a custom calibration procedure based on a fourth order polynomial model in order to maintain a good precision at the extremities of the measurement plane.

All acquired PIV images were treated with DynamicStudio 2015a using an iterative multigrid interrogation scheme. The FFT-based cross-correlation was applied iteratively to three successive interrogation window sizes using window offsets, subpixel interpolation, and 50% overlap in both directions. The final interrogation area was $32 \times 32$ pixels. Aberrant vectors were identified with a range validation and three successive universal outlier detections after which they were substituted by the $5 \times 5$ local median vector. Because of the large field of view of the cameras and shape of the acrylic cone, optical reflections were unavoidable; the analyses were thus repeated after the removal of the background image. Since this operation results in an increased number of aberrant vectors, the original ones were substituted locally only. This allowed to recover most of the bad vectors in the zones with high background intensity while preserving the quality of the acquisitions everywhere else. The custom calibrations were then used to reconstruct the three components vector fields on a mesh of $151 \times 97$ points. This mesh is illustrated in figure 3.

Despite all the validation steps, small groups of aberrant vectors remained in most instantaneous fields. These vectors were identified and replaced using local thin plate spline interpolations.

![Figure 2. TR-PIV experimental setup.](image1)

![Figure 3. Locations of the thirteen pressure sensors across the draft tube (left) and position of the TR-PIV mesh (right).](image2)
2.3. Other measurements

One of the objectives of the experimental campaign being to investigate the link between the core flow phenomena and wall separation, thirteen Unisensor IS 3085 pressure sensors were also installed around the turbine draft tube to gather time-resolved signals and pressure recovery coefficient. The locations of these sensors is showed in figure 3. The runner position, given by a 2048 ppr EL120 encoder, was acquired by both the TR-PIV system and the computer to which the various sensors were connected. These signals were cross-correlated in order to synchronise the velocity and pressure data.

2.4. Acquisition parameters and operating conditions

The five main operating points (OP) of the BulbT project, denoted OP1 to OP5, were investigated. These points, parametrized by the following unit coefficients:

\[ N_{11} = \frac{ND_{ref}}{\sqrt{H}} = 170, \quad Q_{11} = \frac{Q}{D_{ref}^2\sqrt{H}}, \quad P_{11} = \frac{P}{D_{ref}^2 H^{3/2}}, \]

are located around the efficiency drop and have been extensively discussed in previous works [9, 10, 11]. Furthermore, a sixth point denoted OP3.5 was added between OP3 and OP4, inside the drop. For the first four operating points, eight acquisition runs were made while twelve runs were required at OP4 and OP5 where the flow separation is the most frequent and intense. Each run consists of 2711 double-framed, single-exposed images per camera taken at six times the frequency of the runner rotation. This frequency was chosen as a compromise between the required storage space, a good temporal resolution, and the relatively large time scale of the flow separation sporadic events. As for the pressure signals, they were measured at a frequency of sixty times the runner rotation speed. More acquisitions of the performance and pressure values were made between each TR-PIV run to ensure a good statistical convergence.

The measured operating conditions are shown in figure 4, where the efficiency and pressure recovery coefficient estimate are respectively given by:

\[ \eta = P \frac{\rho g H}{Q}, \quad \chi = \frac{\sum_{i=10}^{13} P_i - \sum_{i=1}^{4} P_i}{\frac{1}{2} \rho \left( Q/A_{in} \right)^2}. \]

Each circle mark corresponds to the average value over the time span of a single run (≈ 450 runner rotations) while the black lines correspond to the global averages for the whole measurement campaign. Note that \( \eta \) and \( P_{11} \) are not available for OP3.5 because of a failure of the torque meter. For the first points, each run yielded values near the global averages. As expected, from OP3.5 towards OP5, the performance indicators get increasingly spread out.

**Figure 4.** Operating conditions of the BulbT model around the efficiency drop at \( N_{11} = 170 \).
To make sure the limited number of TR-PIV measurements are representative of the phenomenon under investigation, the probability density functions (PDF) of $\chi$ calculated only from the acquisition runs are compared to those obtained from the whole operating point measurements in figure 5. The number of runner rotations corresponding to each curve as well as the distributions skewness and kurtosis are given in table 1.

![Figure 5](image)

**Figure 5.** Probability density functions of the pressure recovery coefficient computed from the TR-PIV runs (blue lines) and from the whole performance measurements (black lines). The normal distribution is illustrated in gray.

**Table 1.** Statistical parameters corresponding to the PDFs of figure 5.

|                  | OP1 | OP2 | OP3 | OP3.5 | OP4 | OP5 |
|------------------|-----|-----|-----|-------|-----|-----|
| Nb. of runner rotations | Total | 22000 | 44000 | 44000 | 44000 | 92000 | 64000 |
|                   | TR-PIV runs | 3613 | 3613 | 3613 | 3613 | 5420 | 5420 |
| Skewness          | Total | −0.089 | 0.014 | −0.116 | −1.182 | −1.518 | −0.968 |
|                   | TR-PIV runs | −0.135 | 0.059 | −0.037 | −0.533 | −1.427 | −0.984 |
| Kurtosis          | Total | 3.048 | 2.999 | 3.235 | 5.572 | 6.143 | 4.151 |
|                   | TR-PIV runs | 3.169 | 2.956 | 3.052 | 3.172 | 6.417 | 4.047 |

These data reveal that the pressure recovery coefficient follows a normal distribution before the efficiency drop and that the eight runs of approximately 450 runner rotations are adequate to represent the flow behavior. For the three operating points where flow separation is present, a relatively large negative skewness is observed, particularly at OP4. The average draft tube recovery is dragged down by irregular events that are characteristic of the known intermittency of the separation. At OP5, these events occur more frequently and thus have more weight on the average of $\chi$, resulting in a lower skewness for similar fluctuation levels. To support these observations, two typical time series of $\chi$ at OP4 and OP5 are illustrated in figure 6. Over the 450 runner rotations at OP4, the draft tube exhibits the same recovery coefficient as OP2 for almost fifty percent of the run duration. At OP5, flow separation occurs for approximately 200 runner rotations after which the draft tube performance remains stable. Another run where the performance shows more fluctuations is plotted later, in figure 9.

For both OP4 and OP5, the PDFs and coefficients computed from twelve runs each give a reasonable approximation of the expected values obtained with longer acquisitions. These runs can thus be considered statistically meaningful to describe the flow dynamics. At OP3.5, the coefficients differ more and further analyses will need to be conducted.

In the remaining sections of this paper, we concentrate on the analysis of the best efficiency point, OP2, as well as OP4 and OP5 in order to emphasize the different flow behaviors observed before and after the efficiency drop.
Figure 6. Pressure recovery coefficient for one run at OP4 (top) and one run at OP5 (bottom). These runs are identified with filled circles in figure 4. The global OP averages and standard deviations are illustrated by blue and grey lines, respectively.

3. Results and discussion

3.1. Validation with LDV data

Laser Doppler velocimetry (LDV) measurements of the velocity profiles at the conical diffuser entrance were made by Vuillemard et al. [11] and are used here to validate the TR-PIV analysis sequence. The profiles were obtained at $z = 0.47D_{\text{ref}}$, which coincides with the plane where the pressure sensors P1 to P4 are located. The overlap between the TR-PIV mesh and the LDV axis, whose actual azimuthal positions differ by $45^\circ$, is highlighted in figure 3.

The velocity profiles of the two methods are compared in figure 7 for OP2 and OP5. The main features of the profiles are replicated, notably the slight increase in the mean axial velocity attributed to the higher flow rate at OP5. The positive shift of the circumferential velocity as well as the widening of the counter-rotating zone with respect to the runner rotation direction are also correctly captured. The main difference lies in the circumferential profiles where the TR-PIV underestimates the highest gradients, a difficulty that is inherent to this measurement method. Operating conditions repeatability, asymmetries of the flow entering the draft tube, and measurements uncertainties are factors that could explain the small discrepancies that remain.

Figure 7. Comparison of TR-PIV $v_z$ and $v_\theta$ profiles with LDV data at $z/D_{\text{ref}} = 0.47$ [11]. The right figure shows the projected LDV survey location in blue. The three numbered vertical solid lines correspond to the slices of section 3.2.

3.2. Average velocity profiles

In order to analyse the spatial evolution of the flow inside the conical diffuser, average velocity profiles are extracted on three $z$-slices. They are located at $z = 0.59D_{\text{ref}}$, $z = 0.91D_{\text{ref}}$, and
z = 1.24D_{ref}, as illustrated in figure 7. The corresponding profiles are plotted from right to left in figure 8 for three operating points together with their respective \( r m s \) fluctuations.

On the first slice, a velocity deficit associated with the runner hub wake is present. The relative prominence of this low velocity zone decreases with an increase in flow rate and the rotating component surrounding it gets stronger. From section 1 to section 3, the increase in cross-sectional area results in lower velocities. The radial extent of the velocity deficit increases axially, although this effect is less important at higher discharges.

At OP2, the fluctuations levels remain similar from one section to the other and tend to become more uniform as they are convected downstream. However, at higher discharges, the axially, although this effect is less important at higher discharges.

The extent of the measurement plane made possible the observation of many large scale flow decelerations that sometimes reach the rotation axis of the turbine on the downstream part of the field of view. Furthermore, the occurrence of such events follows the evolution of the pressure recovery. Figure 9 illustrates this with three snapshots of axial velocity taken from a measurement run at OP5. The pressure recovery is plotted on the top axis with three vertical red lines identifying the times that correspond to the snapshots.

3.3. Description of the flow topology

The extent of the measurement plane made possible the observation of many large scale flow fluctuations that sometimes reach the rotation axis of the turbine on the downstream part of the field of view. Furthermore, the occurrence of such events follows the evolution of the pressure recovery. Figure 9 illustrates this with three snapshots of axial velocity taken from a measurement run at OP5. The pressure recovery is plotted on the top axis with three vertical red lines identifying the times that correspond to the snapshots.
The first contour corresponds to a high pressure recovery and the velocity profiles are similar to the averages shown in figure 8. This flow topology is akin to what is observed at the lower discharges with a well defined velocity deficit zone below the hub. When the pressure recovery starts to drop, $v_z$ becomes more uniform and the flow accelerates both on the upper and lower parts of the measurement plane. At this point, the low velocity zone in the center tends to vanish, as illustrated on the second contour. On some occasions, the draft tube performance drops to as low as forty percents of $\chi$ at the best efficiency point. When this happens, large zones of low-velocity flow are ejected towards the center of the cone and negative axial velocity is observed, as shown on the third contour.

The more general behavior of the flow in the diffuser can be analyzed statistically through the skewness coefficients of the velocity components. The values corresponding to the twelve runs at OP5 are shown in figure 10 for $v_z$, $v_r$ and $v_\theta$ from left to right, respectively.

The axial component is characterized by an important negative skewness for $r/D_{ref} > 0.4$. The flow is intermittently decelerated in a region concentrated near the wall that extends to the upstream part of the cone. This could indicate that the onset of the flow separation observed by Duquesne et al [9] comes from a weakening of the boundary flow relatively close to draft tube inlet. Although not illustrated here, this region of negative $v_z$ skewness is also observed at OP4.
starting at around \( z/D_{\text{ref}} = 1 \), but it is not visible in the measurement plane for OP1 to OP3.5. Finally, the part of the measurement plane that is more directly affected by the back flow events appears to be better represented by the skewness coefficients of the radial and circumferential components.

3.4. Spectral analysis
As introduced in the first part of this paper, a better understanding of the core diffuser flow dynamics is required to identify the physical process behind the efficiency drop. So far, most of the discussions concerning the BulbT draft tube have focused on the non-periodic character of the flow. In this section we thus turn our attention to the time-resolved dynamics.

Inspection of the instantaneous flow fields revealed that within the low-velocity zone, in the diffuser axis region, fluctuations appear to be associated with a dominant periodic phenomenon. Spectral analysis of a selection of sample points in the measurement plane revealed a coherent behavior occurring at the same frequency as the runner rotation for the six measured operating conditions. Fourier transforms of the velocity magnitude at points located on the first and third slices of section 3.2 are displayed in figure 11.

![Figure 11](image)

Figure 11. Power spectral densities of the velocity magnitude for eight sample points at OP2 (blue curves) and OP5 (orange curves).

At \( f/f_R = 1 \), the runner rotation frequency stands out for all operating points. The energy associated to this frequency is higher near the rotation axis and is attenuated in the radial direction. At OP5, the peak values remain relatively constant axially. However, at OP2, they decrease for the nearest points from the axis and increase for the points further away.

From these observations, periodic fluctuations at the runner frequency appear to dominate the low frequency range of the spectrum in the velocity deficit zone after the runner hub. To identify the source of these oscillations, the coherence function and phase shift between sample points located on both sides of the rotation axis were computed and are plotted in figure 12 for the best efficiency point. The coherences between pairs of points \( \{1b, 1c\} \) and \( \{3a, 3d\} \) are close to one for \( f/f_R = 1 \) and the corresponding phase shifts are near \( \pm 180^\circ \). The sample points being located at opposite azimuthal positions, this shift would indicate that a coherent structure is rotating around the central axis and passing through these points.

To validate these findings, the coherence functions and phase shifts were also calculated between pairs of pressure sensors at the diffuser inlet. The values obtained for sensors P1 and P2, located at 90° from each other, are shown on the right of figure 12. Clearly, fluctuations at \( f/f_R = 1 \) are also felt by these sensors, and the phase shift of \(-90^\circ\) is in agreement with a rotating pressure pulsation. Furthermore, the negative sign of this shift implies that the pulsations are first felt by sensor P2 and then by sensor P1, indicating that the rotation occurs in the positive \( \theta \) direction, opposite to the runner rotation.
Putting these results together, it would seem that a periodic, non-axisymmetric structure related to the velocity deficit zone rotates in the conical diffuser for operating conditions around the best efficiency point. Considering that this zone is concentrated near the axis, it also suggests that it rotates in the same direction as the mean flow, whose circumferential component is also positive in the central part of the diffuser, as shown in figure 8.

4. Conclusion
This paper presented the first analyses from the TR-PIV measurement campaign in the draft tube of the BulbT turbine. The experimental setup was described and the methodology was validated through statistical analysis of the pressure recovery coefficient and comparisons of velocity profiles with available LDV data.

The measurements highlighted the known intermittency of the flow separation and its correlation with the pressure recovery temporal evolution. The resulting fluctuations were also linked to the occurrence of large zones of low-velocity flow in the upper part of the measurement plane. Skewness of the velocity components showed that the extent of the flow separation events is higher than previously thought. Furthermore, spectral analyses revealed the presence of periodic and non-axisymmetric fluctuations in the wake of the hub at the same frequency as the runner rotation. The phenomenon is present for the six measured operating points and appears to be rotating in the opposite direction than the runner. Further investigations are required to clearly identify the nature of this phenomenon, the way it evolves with increases in discharge, and its role in the sudden decrease of performance.

Finally, although a better understanding of the flow evolution across the efficiency drop is achieved, its actual causes remain unknown. Further analyses of the extensive TR-PIV database are underway, and analysis methods exploiting the temporal resolution of the measurements such as dynamic mode decomposition (DMD) and wavelets are expected to provide more information in this regard. Numerical simulations are also planned and offer a promising avenue to answer the questions raised in this paper.

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Nomenclature

\[ A_{in} \] Draft tube entrance area \[ [m^2] \]
\[ D_{th} \] Throat diameter of the runner \[ [m] \]
\[ f \] Frequency \[ [Hz] \]
\[ f_R \] Runner rotation frequency \[ [Hz] \]
\[ H \] Net head \[ [m] \]
\[ N \] Runner rotation speed \[ [rad/s] \]
\[ N_{11} \] Unit runner rotation speed \[ [RPM] \]
\[ p_i \] Static pressure from \( i^{th} \) sensor \[ [Pa] \]
\[ P \] Hydraulic power \[ [W] \]
\[ P_{11} \] Unit hydraulic power \[ [W] \]
\[ Q \] Volumetric flow rate \[ [m^3/s] \]
\[ Q_{11} \] Unit discharge \[ [m^3/s] \]
\[ v_i \] Velocity components \[ [m/s] \]
\[ \eta \] Hydraulic efficiency \[ [%] \]
\[ \chi \] Pressure recovery coeff. \[ [-] \]
\[ \sigma \] Root mean square value \[ [\ ] \]

References

[1] Arpe J and Avellan F 2002 Pressure wall measurements in the whole draft tube: steady and unsteady analysis Proc. 21st IAHR Symp. on Hydraulic Machinery and Systems, Lausanne, Switzerland 1 593–602
[2] Mauri S, Kueny J L and Avellan F 2004 Werlé–Legendre separation in a hydraulic machine draft tube J. Fluids Eng. 126 976
[3] Tridon S, Barre S, Ciocan G D, Leroy P and Ségoufin C 2010 Experimental investigation of draft tube flow stability IOP Conf. Ser.: Earth Environ. Sci. 12 012044
[4] Duquesne P, Fraser R, Maciel Y, Aeschlimann V and Deschênes C 2014 Draft tube flow phenomena across the bulb turbine hill chart IOP Conf. Ser.: Earth Environ. Sci. 22 032003
[5] Duquesne P, Maciel Y, Aeschlimann V, Ciocan G D and Deschênes C 2014 Power break off in a bulb turbine: wall pressure sensor investigation IOP Conf. Ser.: Earth Environ. Sci. 22 032014
[6] Escudier M 1987 Confined vortices in flow machinery Annu. Rev. Fluid Mech. 19 27–52
[7] Susan-Resiga R, Ciocan G D, Anton I and Avellan F 2006 Analysis of the swirling flow downstream a francis turbine runner J. Fluids Eng. 128 177
[8] Houde S, Carrier A, Buron J D and Deschênes C 2014 Numerical analysis of a measured efficiency hysteresis on a bulb turbine model IOP Conf. Ser.: Earth Environ. Sci. 22 022009
[9] Duquesne P, Maciel Y and Deschênes C 2016 Investigation of flow separation in a diffuser of a bulb turbine J. Fluids Eng. 138 011102
[10] Deschênes C, Houde S, Aeschlimann V, Fraser R and Ciocan G D 2014 Modern challenges for flow investigations in model hydraulic turbines on classical test rig IOP Conf. Ser.: Earth Environ. Sci. 22 022013
[11] Vuillemard J, Aeschlimann V, Fraser R, Lemay S and Deschênes C 2014 Experimental investigation of the draft tube inlet flow of a bulb turbine IOP Conf. Ser.: Earth Environ. Sci. 22 032010