Flow separation in a straight draft tube, particle image velocimetry

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Abstract. As part of the BulbT project, led by the Consortium on Hydraulic Machines and the LAMH (Hydraulic Machine Laboratory of Laval University), the efficiency and power break off in a bulb turbine has been investigated. Previous investigations correlated the break off to draft tube losses. Tuft visualizations confirmed the emergence of a flow separation zone at the wall of the diffuser. Opening the guide vanes tends to extend the recirculation zone. The flow separations were investigated with two-dimensional and two-component particle image velocimetry (PIV) measurements designed based on the information collected from tuft visualizations. Investigations were done for a high opening blade angle with a N11 of 170 rpm, at best efficiency point and at two points with a higher Q11. The second operating point is inside the efficiency curve break off and the last operating point corresponds to a lower efficiency and a larger recirculation region in the draft tube. The PIV measurements were made near the wall with two cameras in order to capture two measurement planes simultaneously. The instantaneous velocity fields were acquired at eight different planes. Two planes located near the bottom wall were parallel to the generatrix of the conical part of the diffuser, while two other bottom planes diverged more from the draft tube axis than the cone generatrix. The last four planes were located on the draft tube side and diverged more from the draft tube axis than the cone generatrix. By combining the results from the various planes, the separation zone is characterized using pseudo-streamlines of the mean velocity fields, maps of the Reynolds stresses and maps of the reverse-flow parameter. The analysis provides an estimation of the separation zone size, shape and unsteady character, and their evolution with the guide vanes opening.

1. Introduction

For a bulb turbine, like other low head turbines, the pressure recovery produced by the diffuser represents an important part of the total head. Important losses in the draft tube can lead to a sudden drop of efficiency and power. Bulb turbines are often designed with an aggressive and short diffuser because of dimensional constraints. Large flow separation occurs in this type of geometry and causes an important part of the losses in overload condition. A link between flow separation and efficiency/power drop is expected and has been observed in the present BulbT project [1].

Flow separation is a numerical and practical challenge. Among the various types of flow separation, tridimensional unsteady separation is certainly the most complex one but also an important one, since it can be found in a large spectrum of industrial applications, including turbine diffusers. Tridimensional unsteady flow separation is characterised by complex flow patterns with spatial and temporal unsteadiness. These characteristics make it difficult to predict it numerically. Moreover,
experimental data to compare and validate simulations is rarely available, in particular in complex geometries like turbine systems. Tridimensional separation has been mostly investigated with visualization methods in open area flows, which have led to its characterization with critical point theory [2] [3]. In confined flows the situation is more complex because the separated zones can interact with other flow structures. An example of a study of separated flow in a diffuser using magnetic resonance velocimetry can be found in [4]. This benchmark flow case was later investigated numerically with direct numerical simulations by [5].

The Consortium on Hydraulic Machines and the LAMH (Hydraulic Machine Laboratory of Laval University) launched the BulbT project in 2011 with the aim of improving our understanding of bulb turbine hydrodynamics. Part of the project focuses on the study of flow separation in the draft tube and its link to the power and efficiency sudden drop past the best operating point.

Previous pressure and visualization investigations of the BulbT turbine flow have revealed the presence of important unsteady tridimensional separation in overload conditions. An important reduction in turbine performance is observed when flow separation extends far upstream in the draft tube [6]. The present study aims at improving our knowledge of the flow dynamics involved with the help of various velocity fields obtained through two-component, planar PIV measurements. The experimental setup is presented at the beginning of the paper. The mean flow and velocity fluctuation characteristics at the beginning of the separation zones are analysed using four different planes for three operating points. Finally, an indicator of flow separation based on backflow is proposed and used to analyze the extent of flow separation in the present flow.

2. Experimental setup

2.1. Turbine setup

The test bench and performance measurements follow the IEC norm [7]. The bulb-shaped turbine is supported by two symmetric profiled piers. The model control and torque measurement are performed with an innovative eddy brake system inside the bulb [8]. The distributor is composed of 16 guide vanes and the runner has four directional blades.

As shown in figure 1a, the draft tube is composed of two parts. An acrylic cone, locate at the runner exit, has an opening half angle of 10.25° and a length of 1.4 runner shroud diameters ($D_{ref}$). The second section is a transition part that transforms the circular section into a rectangular section within a length of 2.3 $D_{ref}$. The transition section is not symmetric. Right and left sides diverge with an angle of 9.5°, while the top side is near horizontal and the bottom side diverges with an angle of 5°. This section is made of metal sheets but it can be fitted with numerous acrylic windows for optical access for the PIV measurements. The cross-sectional area of the draft tube increases approximately by a factor 4 within the length of the draft tube ($L_{db}$, $L_{db}$=3.7 $D_{ref}$). The draft tube divergence can be considered aggressive.

In this paper and as shown in figure 1, the reference Cartesian coordinate system is defined as follows: $z$ is the turbine axial axis pointing downstream, $y$ is the vertical axis pointing upward and $x$ is set to respect a right-handed coordinate system.

**Figure 1.** Respectively a) Bulb turbine sketch, b) 2D-PIV measurement planes and BulbT reference coordinate system. Blue, red, orange and green represent B1, B2 S3 and S4 planes.
The parameters $Q_{11}$, $N_{11}$, $P_{11}$ and $\eta$ are used to describe the operation points:

$$
Q_{11} = \frac{Q}{\sqrt{H D_{ref}}}; \quad N_{11} = \frac{N D_{ref}}{\sqrt{H}}; \quad P_{11} = \frac{P}{D_{ref}^{3/2}}; \quad \eta = \frac{P}{\rho g H Q}
$$

$where N$ is the model rotation velocity (rpm), $H$ is the net water head (m), $Q$ is the flow rate ($\text{m}^3/\text{s}$), $P$ is the mechanical power extracted (W), $\rho$ is the water density ($\text{kg}/\text{m}^3$) and $g$ is the gravitational constant ($\text{m}/\text{s}^2$).

The best efficiency point measured is at a runner blade angle of 22.5° and $N_{11}$=150 rpm. To produce significant but representative flow separation and efficiency drop, the runner blade angle is set at 30.2° and $N_{11}$ at 170 rpm. Three operating points were selected to investigate flow separation in the draft tube. The first operating point, OP 2, corresponds to the best operating point in terms of efficiency for the selected blade angle and unitary speed. For OP 2, tuft visualizations have shown that flow separation occurs in the transition section but remains relatively small [6]. The other two operating points, OP 4 and OP 5, correspond to overload conditions for which the turbine performance drops. In this case, the tuft visualizations revealed large separation zones extending upstream in the conical part of the draft tube. These operating points have the same $N_{11}$ as OP 2 but the guide vanes are more opened by 2.8° and 4.8° respectively. Figures 2a and 2b respectively present the efficiency and power curves for the three operating points. The unitary power $P_{11}$, the efficiency $\eta$ and the unitary flow rate $Q_{11}$ have been normalised by the corresponding values for OP 2.

2.2. PIV setup

PIV measurement quality is strongly affected by optical deformations viewed by the cameras and by the deformation of the laser sheet. Image deformations resulting from the different refraction indices in air, acrylic and water were corrected by a preliminary calibration stage with a checker board target. This correction is particularly important for the sections of the measurement planes viewed through the conical section of the draft tube. To generate inclined laser sheets located near the wall and almost parallel to it, prism-shaped windows have been designed.

The PIV system consists of a 200-mJ Nd:YAG pulsed laser (Litron Laser, Nano L200-15) to generate 532 nm laser sheets and two digital cameras (HiSense Cameras 1280 × 1024 pixels CCD array size) mounted with 28 mm Nikkor lenses. As shown in figure 1b, the cameras were not used in stereoscopic mode but rather side by side in order to obtain an extended field of view. The flow is seeded with 10 μm silver-coated glass spheres. The processing of the single-exposure dual-frame PIV images was done with version 3 of Dantec Dynamics DynamicStudio software. Image processing was
done using iterative multigrid interrogation with window offset, cross-correlation with fast fourier transform (FFT) and Gaussian subpixel interpolation. The iterative procedure comprises nine iterative steps with three interrogation window sizes. The final interrogation window size is $32 \times 32$ pixels. Interrogation windows are overlapped by $50\%$ in both directions. At each iteration, peak validation and local neighbourhood validation are performed. At the end of the iterative procedure, N-sigma and universal outlier validations are applied on the velocity fields. Invalid vectors were substituted with the median vector of the $3 \times 3$ neighbourhood vectors. The measurement parameters including the final interrogation window size, the laser sheet thickness and the estimated maximum out-of-plane displacement are given in Table 1 for each plane. At each operating point, for each plane the data set includes $10\,000$ velocity fields acquired at $4$ Hz.

The measurement zone has been selected with the help of tuft visualizations to coincide with the most upstream parts of the observed flow separations [1]. It is located at the end of the conical part and at the beginning of the transition part of the draft tube. The measurement planes have an axial range between $z = 0.20\,L_d$ and $z = 0.45\,L_d$. As shown in figure 1b, two measurement planes are located near the draft tube bottom ($y^-$), B1 and B2, respectively in blue and red. Two others planes are near the draft tube side ($x^+$), S3 and S4, respectively in orange and green. B1 is the only plane whose median line is parallel to the cone generatrix. The other planes are more inclined with respect to the $z$ axis than the cone generatrix. Angles between the median line of measurement planes and the cone generatrix are given in table 1.

The velocity fields obtained contain only the two in-plane components. As a consequence, the axes of the velocity components differ from one plane to another. For each plane, the $u$ component is along an axis that corresponds to the projection of the $z$ axis on the plane. The second component $v$ ($w$) corresponds to the velocity along the $x$-axis ($y$-axis) for bottom planes (side planes).

**Table 1.** Measurement plane position and orientation, velocity components, interrogation window size, laser sheet thickness and estimated maximum out of plane displacement. Plane 1 refers to downstream plane and plane 2 refers to upstream plane.

| Position | Angle (°) | $D_{ref}$ | Compo-nents | IW size ($10^{-3}\,L_d$) | Laser | Out-of-plane (%) |
|----------|-----------|-----------|-------------|---------------------------|-------|-----------------|
|          |           | $L_d$     |             | Plane 1     | Plane 2 | thick.(mm) |                |
| B1       | Bottom    | 0         | $-0.08\,(x=0)$ | $u_{B1}$, $v_{B1}$ | $4.1 \times 4.1$ | $4.1 \times 4.1$ | 1.5 | 5 |
| B2       | Bottom    | +6.7      | $-0.15\,(x=0)$ | $u_{B2}$, $v_{B2}$ | $4.1 \times 4.1$ | $5.3 \times 5.3$ | 2 | 11 |
| S3       | Side      | +9.8      | $-0.21\,(y=0)$ | $u_{S3}$, $w_{S3}$ | $5.7 \times 5.7$ | $6.5 \times 6.5$ | 2 | 8 |
| S4       | Side      | +14.8     | $-0.27\,(y=0)$ | $u_{S4}$, $w_{S4}$ | $6.5 \times 6.5$ | $6.9 \times 6.9$ | 2 | 15 |

Since the measurement planes do not follow the curved or multi-faceted wall surface, wall distance varies for each vector position. Firstly, the wall distance decreases with $z$ for all planes except for the line $x = 0$ of plane B1. At fixed $z$, the distance to the wall decreases as $|x|$ ($|y|$) increases for B1 and B2 (S3 and S4). In the conical part, the wall distance variation is symmetric relative to the plane $x = 0$ for B1 and B2. Similarly, for planes S3 and S4, the wall distance variation is symmetric relative to the plane $x = 0$. For the transition section, the wall distance variation is again symmetric for B1 and B2 but non-symmetric for S3 and S4. For these side planes, at fixed $z$, $y^+$ positions are closer to the wall than $y^-$ positions for the same $|y|$.

### 3. Results and analysis

Various instantaneous velocity vector fields were first visually analyzed in order to characterize qualitatively the separation zone. The characteristics found are in agreement with the previous studies based on wall pressure and tuft visualizations [1] [6]. The flow separation zone appears fluctuant in size and the siege of large structures. Flow separation size and frequency of occurrence increase with the guide vanes opening. The majority of observed backflow occurs on the $x^+$ side for the bottom planes and $y^-$ side for the side planes. The upstream part of the separation zone is thus concentrated in
the (x+,-y-) corner of the draft tube. Figure 3 shows two examples of instantaneous velocity vector fields with backflow for operating point OP5. Figures 3a and 3b correspond respectively to the downstream portions of planes B1 and S3. Note that apparent abrupt changes in direction of the velocity vectors are visual artefacts due to the fact that only one vector out of nine is plotted in these figures. Erroneous velocity vectors have been substituted. Pseudo-streamlines have been added to these figures to help visualize the instantaneous flow pattern. Since they are computed with only two velocity components in a plane, they are not the real instantaneous streamlines. These figures reveal complex flow patterns. Convergence of the pseudo-streamlines is found in both fields and the velocity field of figure 3b includes a vortex. Even if the measurement planes are above the wall and cannot reveal the real instantaneous streamlines, these features are consistent with those expected of the skin friction lines in the case of three-dimensional separation [9].

![Figure 3. Instantaneous velocity fields at OP5 with pseudo-streamlines colored with the magnitude of the u component. a) Downstream portion of plane B1, black line represents plane contour b) On downstream portion of plane S3. For clarity, only one vector out of nine has been represented. For clarity green zones correspond to a value of one of the backflow occurrence function.](image)

3.1. Mean flow
Figure 4 shows three superposed mean velocity fields for the downstream portion of plane B1. Magenta, blue and red vectors correspond respectively to OP 2, OP 4 and OP 5. The u velocity component is preeminent and decreases in the downstream direction. This decrease is due to three factors: global flow deceleration by the streamwise adverse pressure gradient, intermittent separation and the fact that the distance between the wall and the measurement plane decreases in the z direction, except for the line at x = 0 of this particular plane for which this distance is constant (see section 2.2). The flow angle increases in the downstream direction. When swirl is present in a diffuser, the flow angle is expected to increase near the wall. However, the flow angle increase for the two operating points with large separation zones (OP 4 and 5) is more important than that for OP 2. The variation of swirl due to the small change in guide vane orientation between OPs (that is not taking into account the presence of separation) cannot explain this difference in behaviour. This statement is supported by the fact that the swirl angle is roughly the same for all OPs in the upstream part of the fields. The more frequent occurrence and the larger extent of flow separation for OP 4 and OP 5 are responsible for the
more important increase in flow angle. In the $x^+$ and downstream part of the plane, framed in red in figure 4, the flow angle difference between OP 2 and OP 5 can reach 19°. This zone is where frequent flow separation occurs in this plane. In other planes, the $u$ velocity component is smaller for OP 4 and 5 than OP 2 but the flow angle is conserved.

**Figure 4.** Three superposed mean velocity fields in plane B1. Respectively: OP 2, 4, 5 in magenta, blue and red. For clarity, only one vector out of 64 has been represented.

Figure 5 shows average $u$ profiles for one line cut in each plane: along a constant $x$ line for planes B1 and B2 and along a constant $y$ line for planes S3 and S4. The line cuts have been chosen to be in the separated zone. These four line cuts are also represented by a grey dash line in figures 6 and 7. Velocities in figure 5 are normalized by $V_{ref}$:

$$V_{ref} = \frac{Q}{\sqrt{0.25 \pi D_{ref}^3}}$$  \hspace{1cm} (2)

OP 2, OP 4 and OP 5 are represented in magenta, blue and red respectively. All profiles shown in figure 5 are actually two profiles joined together since two measurement planes were used simultaneously. The agreement in the overlap region at the center of the profiles is seen to be very good. The absence of data near $z/L_{dt} = 0.38$ in figures 5a and 5b and near $z/L_{dt} = 0.27$ in figures 5c and 5d is due to localised light reflections in the PIV images, leading to erroneous velocity vectors. The aforementioned effect of separation on flow deceleration is clearly seen in figure 5. The $u$ decrease in the downstream part of the profiles becomes more pronounced when separation is more prominent, from OP2 to OP5. Figure 5a shows that separation can affect the mean flow even in the upstream conical part of the draft tube ($z/L_{dt}<0.38$).
Figure 5. Average profiles for OP 2, 4 and 5 in magenta, blue and red respectively: a) for plane B1 at $x/L_{dt} = 0.047$, b) for plane B2 at $x/L_{dt} = 0.046$, c) for plane S3 at $y/L_{dt} = -0.069$ and d) for plane S4 at $y/L_{dt} = -0.057$. These four line cuts are represented by a grey dash line in figures 6 and 7. Measured data (symbols) are not exactly on the line cuts. Lines represent values exactly on the line cuts, obtained with bilinear interpolation of neighbouring data points. Circle (triangle) symbols are for upstream plane (downstream plane) data points.

3.2. Standard deviation of velocity fluctuations

Figure 6 shows contours of the root-mean-square (RMS) of $u$ fluctuations normalized by the local mean of $u$. Contour values are 30%, 50% and 80% for all measurement planes. Each color of the contours corresponds to an operating point, with magenta, blue and red for OP 2, 4 and 5 respectively. For all cases, the global trend of an increase of $u$-fluctuation intensities on the sides of the planes (bottom and top of the planes in the plots) and on the downstream end is due to the fact that these locations are closer to the wall. Variations of fluctuation intensities therefore have to be interpreted with caution. For OP 2, $u$-fluctuation intensities exceeding 30% are found only at near-wall positions for these measurement planes. The fact that fluctuation intensities are higher on the $x^+$ side for the bottom planes supports the idea of flow separation in this zone. For OP 4 and 5, the $u$-fluctuation intensities have much higher levels, with zones having levels superior to 50% on all planes. The highest $u$-fluctuation intensities occur in one corner of the S3 plane, near the wall, where they exceed 80%. Like for OP 2, fluctuation intensities are higher on the $x^+$ side for the bottom planes. Overall, these contours suggest that the most upstream part of the flow separation zone extends azimuthally when going from OP 2 to OP 5. It begins at the bottom of the draft tube for OP 2 and expands toward the $x^+$ side of the draft tube for OP 4 and OP 5. This azimuthal direction of expansion is opposite to the runner rotation. This description of fluctuation intensity evolution is compatible with the spatial development of flow separation deduced from the previous studies based on wall pressure and tuft visualizations [1] [6].
Figure 6. Contours of the RMS of $u$ fluctuations normalized by the local mean of $u$. Contour values are 30%, 50% and 80% for all measurement planes. OP 2, 4 and 5 are shown in magenta, blue and red respectively. The dashed grey lines represent the locations of the $u$ profiles of figure 5.

3.3. Frequency of occurrence of backflow
An indicator of the occurrence of separation at a flow location does not exist for three-dimensional separation and it is difficult to define. After considering several options, the following backflow occurrence function based on the velocity component $u$ has been chosen

$$\delta(x, y, t) = \begin{cases} 1 & \text{if } u(x, y, t) \leq 0 \\ 0 & \text{if } u(x, y, t) > 0 \end{cases}$$

(3)

Note that the velocity component $u$ is defined in the reference frame of the measurement plane and it is therefore specific to the plane considered. Its sign is most of the time identical to that of the (unknown) wall-parallel velocity component in the axial direction, but not all the time.

Furthermore, contrary to two-dimensional separation, a point in space can be in a three-dimensional separation zone even if there is no backflow. Examples of such a situation can be found in the instantaneous velocity fields of figure 3, for instance close to the zones of pseudo-streamline convergence. Hence, the backflow occurrence function is not an exact indicator of the occurrence of separation at a point in space, but because it is simple and rigorously defined, it can be used for comparisons with numerical simulations.
Figure 7. Contours of the time average of the backflow occurrence function for the downstream portion of the four measurement planes. Contour values are 5%, 10% and 20%. OP4 and 5 are shown in blue and red respectively. The dashed grey lines represent the locations of the $u$ profiles of figure 5.

Figure 7 shows contours of the time average of the backflow occurrence function for the downstream portion of the four measurement planes, and for OP 4 and 5. OP 2 is not represented because backflow occurrence is negligible. Based on the tuft visualization study, it is known that the frequency of occurrence of instantaneous backflow at the wall is not negligible at these locations for OP2. But because the height of the instantaneous backflow zones is probably too small, it does not translate into significant backflow in the measurement planes. The evolution from OP 4 to OP 5 of the contours of averaged backflow occurrence confirms the aforementioned spatial development of the flow separation zone. In the bottom plane B1, the frequency of occurrence of backflow increases on the $x$ side, near the wall. For the bottom part of the side plane near the wall, plane S3, the frequency of occurrence of backflow is higher and can reach 42%. Even if the frequency of occurrence never exceeds 50% for these measurement planes, such high frequencies can exist very near the wall for these locations in the draft tube.

4. Conclusion

Velocity fields inside a bulb turbine draft tube have been obtained in four planes through two-component PIV measurements. The investigation focuses on overload conditions for which unsteady tridimensional flow separation is present in the draft tube. Earlier studies have revealed that a sudden drop of efficiency and power occurs due to flow separation.
The instantaneous velocity fields show that the flow separation zone appears fluctuant in size and the siege of large flow structures. Flow separation in the draft tube is definitely three-dimensional in character. In agreement with previous studies based on wall pressure and tuft visualizations, it is found that the flow separation size and frequency of occurrence increase as the guide vanes are opened. The front of the flow separation zone extends far upstream along one corner of the draft tube. This study is a first step to a better comprehension of flow dynamics in a bulb draft tube and it provides an excellent test case for numerical simulations.

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