Flow field investigation in a bulb turbine diffuser

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Abstract. An important drop in turbine performances has been measured in a bulb turbine model operated at overload. Previous investigations have correlated the performance drop with diffuser losses, and particularly to the flow separation zone at the diffuser wall. The flow has been investigated in the transition part of the diffuser using two LDV measurement sections. The transition part is a diffuser section that transforms from a circular to a rectangular section. The two measurement sections are at the inlet and outlet of the diffuser transition part. The turbine has been operated at three operating points, which are representative of different flow patterns at the diffuser exit at overload. In addition to the average velocity field, the analysis is conducted based on a backflow occurrence function and on the swirl level. Results reveal a counter-rotating zone in the diffuser, which intensifies with the guide vanes opening. The guide vanes opening induces a modification of the flow phenomena: from a central backflow recirculation zone at the lowest flowrate to a backflow zone induced by flow separation at the wall at the highest flowrate.

1. Introduction

In recent years, increased trading and cost of energy have pushed the hydropower industry to install hydraulic power plants in low head sites and to operate turbines in a more extended range of conditions. Some turbines operated at overload present an efficiency and power sharp drop after the best operating point [1–3]. One important cause of losses, when the turbine is operated in overload conditions, is the flow separation at the wall in the diffuser. This is particularly the case for low head turbines where the pressure recovery produced by the diffuser represents an important part of the total head [4].

Flow separation, described as the ejection of fluid from the boundary layer to the irrotational flow away from the wall, is a numerical and practical challenge. The majority of flow separations found in industrial applications, including in turbine diffusers, are complex because they are turbulent, three-dimensional and unsteady.

One of the main scope of the BulbT project launched in 2011 by the Consortium on Hydraulic Machines and the LAMH (Hydraulic Machine Laboratory of Laval University) is to investigate and document the flow separation zone in a bulb turbine diffuser. Significant experimental works have already been presented at the runner exit [5] and in the diffuser to characterize the flow separation zone [4,6,7]. Despite of these investigations some questions remain in particular because the investigation was not yet extended to the diffuser outlet.

This paper presents two LDV setups performed to obtain the velocity field in two sections of the diffuser transition part. The three selected operating conditions are representative of a bulb turbine operated at overload with important performance decreases after the best operating point. The analysis
shows three distinct flow behaviors in the diffuser transition part at overload, including one case with a large flow separation zone.

2. Experimental setup

2.1. Turbine setup

Bulb turbine performance and LDV measurements were performed on the LAMH test bench. The bulb-shaped turbine model is supported by two identical and symmetric profiled piers. The distributor is composed of 16 guide vanes and the runner has four blades. Both sets of blades have adjustable pitch angle. The bulb contains an eddy current brake to control the model rotational velocity and to measure the torque. The diffuser has been specially designed by the Consortium on Hydraulic Machines with one important but realistic divergence in order to produce a sudden drop in efficiency and power after the best efficiency point. As shown in figure 1, the diffuser is composed of two parts. An acrylic cone, located at the runner exit, has an opening half angle of 10.25° and a length of 1.4 times the runner shroud diameter ($D_{ref}$). 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 was fitted with numerous acrylic windows for LDV optical access. The cross-sectional area of the diffuser increases approximately by a factor 4 within the length of the diffuser ($L_{dt} = 3.7 D_{ref}$). As shown in figure 1, the reference Cartesian coordinate system is defined as follows: $Z$ is the turbine axis pointing downstream, $Z = 0$ is defined at the runner blade axis, $Y$ is the vertical axis pointing upward and $X$ is set to respect a right-handed coordinate system. The runner rotation direction is from $Y^+$ to $X^+$; in this paper the counter-rotating zone refers to the rotations opposite to the runner rotation direction (from $X^+$ to $Y^+$).

![Figure 1. Test bench schematic.](image)

The unit parameters $Q_{11}$, $N_{11}$, $P_{11}$ and the efficiency $\eta$ are used to define the operating points:

$$Q_{11} = Q \left( \frac{H^{1/2}}{D_{ref}^{3/2}} \right); \quad N_{11} = \left( \frac{N D_{ref}}{H^{1/2}} \right); \quad P_{11} = P \left( \frac{D_{ref}^{2} H^{3/2}}{\rho g H Q} \right); \quad \eta = P \left( \frac{\rho g H Q}{Q} \right)$$

(1)

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

The best efficiency point measured is at a runner blade angle of 22.5° and $N_{11}$=150 rpm [4]. To produce significant but representative efficiency drop and flow separation, the runner blade angle has been set at 30.2° and $N_{11}$ = 170 rpm. Five operating points were selected to investigate flow separation in the diffuser (OP 1 to 5). 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 part but remains relatively small and sporadic. At OP 1, where the guide vanes are more closed than at the best operating point (OP 2), the flow separation at the wall was not observed. For OP 3 to 5 the guide vanes are more opened and the flow separation is larger and more frequent.
Figures 2 presents the efficiency curve for these five operating points. In this paper only OP 1, 2 and 5 are presented for brevity reasons.

![Efficiency Curve](image)

**Figures 2.** Efficiency curve for selected points of the BulbT project. \( N_{1/1} = 170 \text{ rpm} \) and blade angle at 30.2°.

### 2.2. LDV setup

Figure 3 shows the two measurement sections. The upstream section, 5a, is represented with blue squares at \( Z = 1.8 \) \( D_{\text{ref}} \). A double axis displacement system has been used to define a 100 nodes grid with 20 lines and 5 columns, each point being separated by 5.8% \( D_{\text{ref}} \) in \( X \) and \( Y \) directions. This section gives information on the core flow at the \( Z \)-position where the flow separation front was previously observed [6]. Axial velocity component \( C_z \) and transversal velocity component \( C_x \) have been measured. Because of optical access limitations, the \( C_y \) component is not measured for some points of the grid.

Due to the divergence angle of the diffuser lateral sides and the dimension limitation of the optical access, three setups were needed to measure the three velocity components for the downstream plane at \( Z = 3.12 \) \( D_{\text{ref}} \). The three LDV probe positions are identified in figure 3. The position 5b’ used a double axis displacement system and a horizontal window at the diffuser top side. With this position, the axial velocity component \( C_z \) and transversal velocity component \( C_x \) have been measured. The two other positions, 5b’’ and 5b’’’, are on each lateral side of the diffuser, a three displacement system has been used to measure the last transversal velocity component \( C_y \). Because of optical access limitations, the last measurement grid has a central region with the three components (position with black dots in figure 3). For the upper and lower regions, only the two components \( C_z \) and \( C_x \) have been measured (red dots in figure 3). Also shown in figure 3, the distance between two points is not constant (about \( 23 \times 14\% \) \( D_{\text{ref}} \) for the central squares).

![Measurement Sections](image)

**Figure 3.** LDV measurement sections. Blue squares represents the measurement grid of the section 5a. Black and red dots represent the grid of the section 5b. Labels represent LDV probe positions and directions. Black lines represent the end of the conical diffuser and measurement sections.

The LDV system is a two-components with four laser beams operating in backward scatter on-axis collection mode. There are two LDA (laser Doppler Anemometer) inside the probe head and each LDA uses two laser beams at the same wavelength to measure one component of velocity. Bragg-cell shifting at 40 MHz is used to resolve directional ambiguity on a 5W Argon-ion laser. The particles used as a reflective medium are silver coated hollow glass spheres. Their diameter is 10 µm and the density 1.4 g/cm³. The focal length, measurement volume, velocities components, sample size and uncertainty estimation for all measurement campaigns are reported in table 1. The observation time is 90s per node on the measurement grid. The acquisition rate varies from 3 Hz to 5 kHz depending on the distance travelled by the laser in water and the local mean velocity. The given uncertainty corresponds to the
quadratic sum of the uncertainty of the LDV measurement considering the probe alignment ($B_c$) and the random uncertainty ($P_c$ estimated with the standard deviation and the student coefficient with a 95% probability).

Table 1. Focal, measurement volume, measured velocity components, minimum sample size, grid size and total uncertainty.

| Position | Focal (mm) | Meas. Volume (mm$^3$) | Velocity components | Samples (average) | Grid size (nodes) | Uncertainty p=95% ($V_{ref}$) |
|----------|------------|------------------------|---------------------|------------------|------------------|-----------------------------|
| 5a       | 402.5      | 0.0486                 | $C_x, C_z$          | 40 000           | 100              | $\sqrt{B_c^2 + P_c^2}$    |
| 5b'      | 1000       | 0.1204                 | $C_x, C_y, C_z$    | 45 000           | 116              | 0.7%                        |
| 5b'',5b''' | 402.5     | 0.0486                 | $C_x, C_y, C_z$    | 45 000           | 116              | 0.7%                        |

In this study, the velocity is normalized using a reference velocity:

$$V_{ref} = \frac{4Q}{\pi D_{ref}^2}$$  \quad (2)

3. Result and analysis
3.1. Backflow analysis

As an indicator of the intermittent backflow, the following averaged backflow occurrence function $\delta$ has been defined and calculated at each measured position:

$$\delta(x,y) = \frac{\sum\limits_{i=1}^{nb} TT_i(x,y) \cdot \text{if } (C_i \leq 0)}{\sum\limits_{i=1}^{nb} TT_i(x,y)}$$ \quad (3)

where $nb$ is the sample size and $TT_i$ is the transit time of the particle $i$ inside the LDV measurement volume. $\delta$ represents the fraction of the observation time where the axial velocity is negative. Some limitations are associated with this indicator. First, the velocity component $C_z$ is the axial velocity but with the presence of swirl, the flow is not only axial. It is not evident to define the backflow direction as there is not one main flow direction. In the case of a three-dimensional separation zone from the wall, a point in space can be in the separation zone even if there is no axial backflow. Hence, a negative axial velocity is only an approximate indicator of the presence of a separation zone near the point in space considered. Furthermore, the backflow occurrence function is not able to dissociate between backflow zones issued from a separation zone at the wall or issued from a central recirculation.

Figure 4 presents the normalized axial velocity and the averaged backflow occurrence function at the diffuser exit plane (section 5b) for OP 1, 2 and 5.

For OP 1, as shown in blue, an average backflow zone is present at the diffuser center. This average backflow zone is small and intermittent. It covers only around 1% of total section area and the average of the backflow function does not exceed 65%. The contours of the average backflow occurrence function at 1% defines a larger circular zone around. Neither averaged nor intermittent backflows is observed near the wall in the restricted measurement area. Therefore, the average backflow does not seem to be connected to the wall and the zone is associate to a central recirculation area and not to a flow separation at the wall.

At higher flow rate, OP 5, an average backflow zone is located in the ($X^+$, $Y^-$) corner. The exact size of the zone is not known due to the lack of information near the wall but can be roughly estimated to more than 5% of the total section area. At the opposite corner ($X^-$, $Y^+$) the flow velocity is increased to balance the flow rate. The difference between the two corners is up to 47% of $V_{ref}$. The contour values of the average backflow occurrence function increase with the proximity of the wall in the ($X^+$, $Y^-$) corner, up to 80%. These observations confirm the presence of a large flow separation in the ($X^+$, $Y^-$) corner already observed in previous experimental works as shows that [6]. This new data set brings complementary information on the flow separation description. The average reattachment line is located downstream the diffuser outlet. In despite of the previous remark and of the wall distance, the averaged
backflow occurrence has never reached 100%, therefore unsteady reattachment lines might be present at the end of the diffuser.

![Figure 4](image1)

**Figure 4.** Contour plot of the normalized axial velocity for the section 5b. Dashed lines represent the averaged backflow occurrence function [%].

For the best operating point, OP 2, neither averaged wall separation nor averaged core flow recirculation is present. In the core flow, a recirculation is detected with $\delta$ lower than 16%. The averaged backflow occurrence function occasionally points out a wall separation, with $\delta$ lower than 17%. The averaged backflow occurrence function might be higher near the wall where no measurement could be performed. If an average flow separation zone exists at OP 2, it would be smaller than the distance between the wall and the measured area.

Backflow zone in the diffuser acts as restrictions of the section, reducing the kinetic energy conversion into pressure. OP 2 presents a better pressure recovery in the diffuser compared to operating points with more closed guide vanes (OP 1) or more open guide vanes (OP 5).

![Figure 5](image2)

**Figure 5.** a, b and c, contour plots of the normalized axial velocity, section 5a. Vectors represent the $C_x/C_z$. d, swirl values ($C_x/C_z$) at $X = 0$.

Figure 5 shows the normalized axial velocity at the beginning of the transition part (section 5a) for OP 1, 2 and 5. All operating conditions present a similar global pattern with a central zone of low positive axial velocity. There is no averaged backflow in the core flow, with the lowest velocity of 15% $V_{ref}$ at OP 1. From OP 1 to OP 5, this zone size decreases. The averaged backflow occurrence function has been calculated (not shown in the figure) and its value decreases from 3.5% at OP 1 to 0.06% at OP 5. This central low velocity zone is probably induce by a combinaison of the hub wake and by the diffuser’s diverging shape. At OP 1, the central low velocity zone is larger and the flow rate is lower to the other OPs. But even in this case, no average backflow zone can be noticed. Therefore, the recirculation which has been found at the diffuser exit is not present at the beginning of the transition section. In rare cases, $\delta < 3.5\%$, the recirculation at the diffuser exit induces an instantaneous backflow and can be superimposed to the hub wake effect. In OP 2 and OP 5, the $\delta$ values are nearly null in the core region,
the backflow from the diffuser exit never extends that far upstream. Here, the central low velocity zone can be considered mainly induced by the hub wake and the diffuser diverging shape. With the guide vanes opening, the flow rate increases and tends to fill the velocity deficit in the core flow. At OP 1, the flow rate is insufficient to fill the velocity profile, the hub wake can propagate more downstream and a weaker zone in the center is present at the diffuser exit, which benefits to the central recirculation apparition.

3.2. Rotating zone analysis
At the diffuser transition part, section 5a, the flow rotation is analysed with the swirl ratio $C_v/C_r$ and with the $C_v$ vectors along the $Y$-axis at $X=0$. Figure 5d, presents the swirl ratio for all operating points. Here, for the positions with $Y/D_{ref}>0$, the positive values of the swirl ratio correspond to the runner rotation direction. Because swirl ratio is expressed in the cartesian reference frame, for the positions with $Y/D_{ref}<0$, the runner rotation direction corresponds to the negatives value. Figure 5d shows that all operating conditions present a central zone of rotating flow in the direction opposite to the runner rotation. With the guide vanes opening, from OP 2 to OP 5, the intensity of this counter-rotating zone increases. For example, the maximal swirl value increase at OP 5 is 218% in comparison with the maximum value of OP 1. The position of this maximum does not move with the guide vanes opening, suggesting a stronger vortex but with the same axis.

The spatial averaging magnitude of the $C_v$ velocity along $X=0$, named here $\overline{C}_v$, changes with the guide vanes opening, from $-0.05\%\ V_{ref}$ at OP 1 to $-4\%\ V_{ref}$ at OP 5. This means that at OP 1 and 2 the flow is not deviated. At OP 5, the negative value of $\overline{C}_v$ underlines the flow deviation due to the flow separation zone in the corner ($X+, Y-$). To underline the effect of the secondary flow, vectors in figure 5a, b and c represent the difference of the transversal component with the spatial averaging of this component ($\overline{C}_v - C_v$) along $X=0$. At OP 5, the magnitude of counter-rotating $\overline{C}_v - C_v$ vectors can be consequent, up to $11\%\ V_{ref}$, and underlines the high intensity of a counter-rotating region.

Previous LDV measurements at the runner exit exhibited also a counter-rotating zone issued from the runner with the same evolution over the OPs [5]. Therefore the counter-rotating zone from the runner is convected along the diffuser conical section. The flow at the runner exit in this case is composed by three annular rotating zones where the middle ring one is counter-rotating zone [5]. Similar flow patterns have been also observed and well characterized in Francis turbines [8]. So, the counter-rotating zone is annulus, a small backflow zone of co-rotating flow is present at the center, close to the hub and in its wake. It is seems that this small zone vanishes in the diffuser conical section.

As presented in figure 5d, the swirl ratio decreases from OP 2 to OP 5 at the top of the measurement section. This trend is in part due to the global flow deviation in the ($X-$) direction, previously mentioned. But also, this trend is due to the reduction of tangential velocity from the secondary flow, as shows in figure 5c for OP 5. The global decrease of the swirl in the measured zone suggests that the swirl decreases also at the wall with the guide vanes opening. A well know effect of the swirl is the prevention of flow separation at the wall [9]. Therefore the swirl reduction has an important contribution to the flow separation apparition in this case.

4. Conclusion
The complex flow in the transition section of a bulb turbine diffuser has been investigated. The turbine model has been operated at three operating conditions in the overload range, including the point with maximal efficiency for the selected blade angle and selected unitary velocity. The two other operating points have respectively a lower and a larger flow rate. Velocity measurements in the transition part have been performed using a 2-component LDV system at two cross-sections. The first section is located near the transition inlet. The second section is at the diffuser outlet.

The velocity field analysis suggests that the counter-rotating zone generated at the runner persists all along the diffuser for all OP. In opposition, the backflow in the wake of the hub seems to disappear in
the conical section of the diffuser. The central counter-rotating zone intensity increases with the guide vanes opening but the vortex position remains the same over the OPs.

For the operating condition with the smaller flow rate, in addition to the counter-rotating zone, a backflow central recirculation is present at the diffuser exit. This zone appears disconnected to the flow separation zone at the wall. This central recirculation is induced by the hub wake and the low pressure at the diffuser exit.

At the operating condition with the larger flow rate, a flow separation zone appears at the \((X^+, Y^-)\) corner with the help of a decreasing swirl level injected to the wall. In the opposite corner, the flow velocity is increased to balance the flow rate, this induces a zone of strong shear in the diffuser. The three-dimensional envelop of the flow separation zone appears to have an important size. The effects of the flow separation appear in the inlet to the transition part and the average reattachment line is downstream the diffuser. Surprisingly, the central counter-rotating zone, which is stronger for this operating point, seems not to be deviated by the flow separation.

For the best operating point, in terms of efficiency for the selected blade angle and the selected unitary speed, neither the wall separation nor the central recirculation is present in the averaged field. But an instantaneous wall separation or an instantaneous central recirculation might appear from time to time at the diffuser outlet.

This study complements the previous flow investigation in a bulb turbine diffuser operated at overload with flow description in the core flow. In the short term, these observations will be used to validate numerical simulation tools. The velocity measurements will provide a reference at the model outlet. Afterwards, the validated numerical tools will be used to design new diffusers and to predict performances with more confidence.

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