Analysis of the flow at a T-bifurcation for a ternary unit

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Abstract. The motivation of this research is to understand the flow behavior through a 90° T-type bifurcation, which connects a Francis turbine and the storage pump of a ternary unit, under different operating conditions (namely turbine, pump and hydraulic short-circuit operation). As a first step a CFD optimization process to define the hydraulic geometry of the bifurcation was performed. The CFD results show the complexity of the flow through the bifurcation, especially under hydraulic short-circuit operation. Therefore, it was decided to perform experimental investigations in addition to the CFD analysis, in order to get a better understanding of the flow. The aim of these studies was to investigate the flow development upstream and downstream the bifurcation, the estimation of the bifurcation loss coefficients and also to provide comprehensive data of the flow behavior for the whole operating range of the machine. In order to evaluate the development of the velocity field Stereo Particle Image Velocimetry (S-PIV) measurements at different sections upstream and downstream of the bifurcation on the main penstock and Laser Doppler Anemometrie (LDA) measurements at bifurcation inlet were performed. This paper presents the CFD results obtained for the final design for different operating conditions, the model test procedures and the model test results with special attention to: 1) The bifurcation head loss coefficients, and their extrapolation to prototype conditions, 2) S-PIV and LDA measurements. Additionally, criteria to define the minimal uniformity conditions for the velocity profiles entering the turbine are evaluated. Finally, based on the gathered flow information a better understanding to define the preferred location of a bifurcation is gained and can be applied to future projects.

1. Introduction
A competitive and compact solution for a ternary unit with low losses and cost requires that the T-bifurcation is located close to the inlet of the spiral case [1]. The minimal distance possible is that at which the flow entering the turbine is uniform and stationary enough to guarantee the normal operation of the turbine for all specified operating conditions. In order to decide on the final position of such a bifurcation comprehensive flow data has to be provided. The purpose of the studies performed was to supply this information.

2. Operating conditions
The following table summarizes the operating points considered for the model test and for the CFD calculations for each operating condition namely hydraulic short-circuit (k), pump (p) and turbine (t) operation. Also the locations where laser measurements were performed are provided normalized with the diameter of the main penstock (Dtu).
### Table 1. Operating points definition and measurements section for laser techniques.

| Operating Points | φ_r | PIV/LDA Measurements Locations |
|------------------|-----|--------------------------------|
|                  |     | Bifurcation - Turbine | Bifurcation - Reservoir | Inlet of bifurcation |
| Name             | CFD | [%]   | [Dtu] (PIV) | [Dtu] (PIV) | [z/Dtu] (LDA) |
| p06              | Yes | 0     | -           | 2.4, 5.0    | 0.94          |
| k01              | No  | 10    | 2.4, 3.7, 5.0, 6.3 | 2.4, 5.0    | -             |
| k02              | Yes | 25    | -           | -           | -             |
| k03              | Yes | 50    | -           | -           | -             |
| k04              | Yes | 75    | -           | -           | -             |
| k06              | Yes | 100   | -           | -           | -             |
| t06              | Yes | 100²  | 2.4, 5.0    | -           | -             |

φ_r = Q_turbine \cdot \frac{Q_{penstock max}}{}

2: distance considered from the axis of the main penstock to the measured section

### 3. CFD Analysis

As a first step a CFD optimization process to define the hydraulic geometry of the bifurcation was performed.

#### 3.1. Numerical model

The CFD computations were performed with the commercial code CFX from Ansys. In CFX, the three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations are solved. The Shear-Stress-Transport (SST) model was chosen as turbulence model. Steady state calculations were performed in prototype size. The computational domain for the T-Bifurcation was resolved by a mesh with about 4.000.000 nodes. At the inflow boundary (Pump), a uniform velocity distribution normal to the inlet was prescribed.

#### 3.2. Results

To analyse the flow distribution, the normalized projection of the velocity on the main penstock’s axis was used (U_axis):

\[
U_{axis} = \frac{u_{axis}}{Q_{axis}/A_{axis}} = \frac{u_{x_{axis}} + v_{y_{axis}} + w_{z_{axis}}}{Q_{axis}/A_{axis}}
\]  

Positive values of U_axis correspond to flow going into the reservoir direction. An overview of the flow for pump, turbine and short-circuit operation is presented in form of streamlines and contour plots of U_axis in Figure 1, Figure 2 and Figure 3 respectively.

![Streamlines (left) and U_axis distribution (right) for pump operation.](image-url)
As can be observed from the CFD results, especially under hydraulic short-circuit operation, the flow complexity is increasing with increasing turbine flow and it is strongly dependent on turbulence modelling. Therefore, it was decided to perform experimental investigations.

4. Measurements

4.1. Purpose of the tests
The purpose of the model tests was to investigate the flow development upstream and downstream the bifurcation, the estimation of the bifurcation loss coefficients and to provide comprehensive data of the flow behavior. The scope of the model testing included: S-PIV and LDA measurements and the determination of the bifurcation loss coefficients.

4.2. Description of the model
The model is homologous to the prototype bifurcation, the scale factor from model to prototype is 14.5. A setup of the model is shown in Figure 4 and the main geometrical dimensions in model size are presented in Table 2.

Table 2. Main geometrical dimensions (model size).
| Diameter | Description                        |
|----------|-----------------------------------|
| $D_{tu}$ | Diameter of the pipe connecting Turbine | 0.200 m |
| $D_{pu}$ | Diameter of the pipe connecting Pump | 0.165 m |
5. Model Test Results

5.1. Hydraulic similitude
To achieve dynamic similitude the Reynolds number for model and prototype should be the same. Since is not possible to satisfy this requirement, several tests were conducted in order to operate the model in the Reynolds range where the bifurcation loss coefficients remain constant. If the mentioned condition was not achieved then the model test results were corrected when transposing them to prototype conditions. The extrapolation procedure is explained in the following subsection. The present study was performed at Reynolds numbers (Re) between 1.0E+05 and 1.0E+06.

5.2. Bifurcation loss coefficients
The total head loss \( \Delta h_{\text{total}} \) between two arbitrary control sections \( i \) and \( j \) can be expressed as,
\[
\Delta h_{\text{total}} = \Delta h_{\text{local}} + h_{\text{friction}}
\]
(2)
where \( \Delta h_{\text{local}} \) is the local head loss and \( h_{\text{friction}} \) are the friction losses. The local head loss can be calculated with,
\[
\Delta h_{\text{local}} = \zeta_i \frac{v_{pu}^2}{2g}
\]
(3)
where \( \zeta_i \) is the local head loss coefficient for the branch \( ij \), \( v_{pu} \) is the averaged velocity in the pipe connecting to the pump and \( g \) is the gravity. Substituting (3) into (2), then the local head loss coefficients can be determined according to the following equation.
\[
\zeta_i = \frac{\Delta h_{\text{total, } i} - h_{\text{friction, } i} - h_{\text{friction, } j}}{\frac{v_{pu}^2}{2g}}
\]
(4)

The friction losses are estimating for a fully developed turbulent flow on equivalent straight pipes based on the Darcy-Weisbach equation. The friction coefficients where calculating according to Colebrook [2].

5.3. Extrapolation of the bifurcation loss coefficients
The model test results were corrected when transposing them to prototype conditions. In the present study a linear function was chosen to extrapolate the piezometric head difference between the control sections as a function of the quadratic discharge [3].

Using the obtained extrapolation laws allow to calculate the local head loss coefficients for discharges beyond the model maximum discharge. The local head loss coefficients are calculated according to (4) and shown in Figure 5 for the operating point k04. The coefficients are normalized with the maximum head loss coefficient (\( \zeta_{\text{max}} \)) due to data protection. As can be seen in Figure 5 the coefficients are independent of Reynolds for Reynolds numbers higher than 1x10^5.
The same procedure was applied for all operating points. A summary of the local head loss coefficients extrapolated beyond Reynolds $1 \times 10^6$ is presented as function of the discharge ratio $\Phi_p$ in Figure 6.

**Figure 5.** Local head loss coefficients measured and extrapolated for the operating point $k04$. The values are normalized with $\zeta_{\text{max}}$.

**Figure 6.** Bifurcation loss coefficients resulting from the extrapolation (extrapolated to $Re > 1 \times 10^6$) as a function of $\Phi_p$. The values are normalized with $\zeta_{\text{max}}$.

5.4. Laser Doppler Anemometry (LDA) measurements

LDA measurements were performed at the bifurcation inlet. The measurement section is located at $+188$ mm ($z/D_{tu} = 0.94$) from the axis of the main penstock (See Figure 7).

A 2D LDA system allows to measure two velocity components simultaneously on a point. In order to obtain all three velocity components it is necessary to perform measurements from two orthogonal directions. Therefore, the cross section was measured from a direction normal and parallel to bifurcation plane of symmetry for each operation point. A grid consisting of approximately 400 points was used for the measurements with an acquisition time of 10 seconds per point.
Whenever necessary, the Kriging interpolation was used to interpolate the measured velocity field in order to further post process the results. In figures 8 to 11 a summary of the main results obtained for operating point k03 are presented.

5.5. Stereo Particle Image Velocimetry (S-PIV) measurements
The S-PIV system allows to measure instantaneous 3D velocity fields of a whole section. Statistical values were obtained by measuring each section 1000 times. Vectors fields are calculated by the use of specified software which applies a cross correlation technique to obtain about 4500 vectors for a section. The Kriging interpolation was used to interpolate the measured velocity field whenever necessary. In figures 12 to 15 a summary of the main results obtained for operating point k03 for all measured sections are presented.
A summary of the main results obtained at the measurement section 2.4D for short-circuit operation are presented in figures 16 to 19.
To get an overview of the development of the flow for the whole operating range and for the all measured sections the following statistical parameters were calculated from the available measurements:

- Standard deviation of the axial velocity component ($v_{axial}$)
- Average of the cross velocity component ($v_{cross}$)
- Standard deviation of the temporal fluctuation of the axial velocity component ($v_{axial}'$)
- Standard deviation of the temporal fluctuation of the cross velocity component ($v_{cross}'$)

In Figure 20, Figure 21, Figure 23 and Figure 24 the aforementioned parameters have been normalized with the mean axial velocity component ($\bar{v}_{axial}$).