Discharge Flow Measurement of CNR's Low Head Bulb Turbine at Beaucaire Hydropower Plant

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Abstract

The production of renewable electricity has shown to play a crucial role in the last years, due both to the European energy market crisis and to the drop of the French nuclear electricity production. Being the first 100% renewable electricity producer in France, CNR is a key contributor to the power network by providing electricity mostly from water sources (3000 MW of installed capacity), while pushing forward wind and solar sources (1000 MW of installed capacity). In this frame, CNR's is working hard to make available as much hydro units as possible by optimizing the maintenance operations and by optimizing their performances.

An example is presented in this paper from unit 4 of the Beaucaire hydropower plant (HPP), where an intense program of flow measurements with an acoustic scintillation frame has been launched in September 2022. The objective is to measure the performance of the unit with the original runner blade design, before they will be replaced by a new set of blades with a modern profile end of 2023. Several months were necessary to build, transport, install and equip unit 4 with the acoustic scintillation device. The first results were obtained in January 2023 and served as a calibration for the Winter-Kennedy flow coefficient., which then were used to perform transient flow measurement during transition from turbine generating mode to sluice operating mode.

The measurement device and the associated method are presented in a first part, the calibration of the Winter-Kennedy and the turbine efficiency are detailed and discussed in a second part. Finally, a comparison of the flow measurement with the numerical simulation results during transition to the turbine sluicing mode is given in a third part.

1. Introduction

The Compagnie Nationale du Rhône (CNR) has 19 hydropower plants of which 18 are run-of-river plants. In the framework of improving knowledge of the flow rates passing through CNR's hydropower turbines, experimental and flow rate measurement qualification tests are performed by using Acoustic Scintillation Flow Measurement and Winter-Kennedy method. These operations were launched in 2009 for Kaplan turbines with steel frames designed to support the ASFM sensors, adaptable to several CNR hydropower plants equipped with Kaplan turbines; and launched in 2011 for Bulbs turbines with the design of a frame adaptable to several hydropower plant equipped with Bulb turbine [1] [2].

An intense program of flow measurements is planned over the next years to define the performance of CNR's hydropower turbines. This paper presents the measurements carried out at the Beaucaire hydropower plant, about 200 kilometers downstream of Lyon, along with a project of blade refurbishment. The objective is to measure the performance of the unit with the original runner blades design. The performance will again be measured with the new modern profile in 2024.

The measurements were made by using acoustic scintillation flow measurement (ASFM). This technique measures the velocity of the flow by analysing the deformation of the signal under turbulent flow. The results are used to define the efficiency of the original blades. The Winter-Kennedy method is also used to check the combination of blades and guides vane turbine [3].

Equipping a scintillation system requires time, space, and significant crane handling. These operations took place over several weeks. Handling the frame presented a challenge given the inability to roll the mobile crane with the load. A trolley was designed to transport the scintillation frame via the rails used to remove woods from grids. The mobile crane then approaches the opening of the cofferdam and manages the lowering operation into the cofferdam.

The presence of both methods on site made it possible to measure a particular mode of operation. Turbines can switch to a sluicing mode to let go of the flow when necessary. The flow measurement was measured using both techniques: WK for variations along the event and ASFM for absolute flow rate during sluicing mode. The measurements were used to confirm the numerical simulation.

2. **Measurement device and associated method**

2.1 Introduction

The two methods carried out during an on-site measurement campaign are the Winter Kennedy method and the Acoustic Scintillation Flow Measurement. The Winter-Kennedy method is an index method used to determine the optimum combination of blade and guides vane. The sensors used for WK are differential pressure sensors [3]. Other sensors are installed to collect information concerning level, power, and pressure loss.

To use the ASFM transductor, a metal frame (18 meters high and 12 meters wide) was designed in 2009 for the Vaugris hydropower plant measurement campaign. This frame was designed to be reused on the CNR facilities equipped with bulb-type turbines. It has numerous locations to adapt the position of the sensors depending to the water intake height. The instrumentation takes place flat on an area close to the plant. The frame is then placed in a vertical position by mobile cranes and brought above the water intake to be lowered into place.

2.2 Acoustic Scintillation Flow Meter

The ASFM method uses a technique called acoustic scintillation drift [5] [6] [7] to measure the flow velocity perpendicular to several acoustic paths established across the intake of the turbine, 30 paths are set in this study. Short pulses of high-frequency sound are sent from transmitting arrays on one side to receiving arrays on the other side. Fluctuation in the amplitude of those acoustic pulses result from the turbulence in the water carried along by the current.

The ASFM measures those fluctuations and from them computes the lateral average of the velocity perpendicular to each path. The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and flow. If the two paths are sufficiently close (Δx), the turbulence remains embedded in the flow, and the pattern of these amplitude variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay Δt. This time delay corresponds to the position of the peak in the cross-correlation function calculated for upstream and downstream signals. The mean flow velocity perpendicular to the acoustic paths is then $V = \Delta x/\Delta t$. The total flow rate is calculated by integrating the average horizontal component of the velocity at each level over the cross-sectional area of the intake. The measurement accuracy is a combination of systematic uncertainties estimated at 1% and random uncertainties given by the standard deviation of the measurements, which is about 0.5%. For more details see the standard [4].

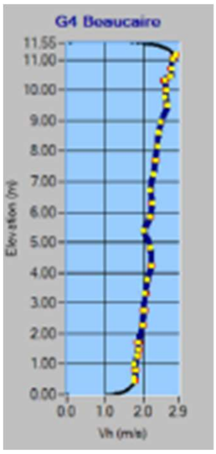

Figure 1: Results of computed velocity, Q=284.47m3/s

The turbine's efficiency is determined using the following equation:

$$\eta = \frac{P_e}{P_h} = \frac{P_e}{\rho\ g\ Q\ H_n}\ (1)$$

With Pe the electrical power, Ph the hydraulic power of the turbine, g the gravity
H_n the net head, Q the flowrate through the turbine, ρ the water density

For power and head values, sensors are installed in the plant in addition to those used for the operation of the plant. The regulator signals such as the opening of blade and guide vanes, the power produced are also recorded during all acquisitions as a means of comparison.

Figure 2: Frame located on the upstream platform on the left bank of Beaucaire plant and part of the trolley on the rails

The ASFM sensors were installed on a metal frame showed in figure 2. The bottom cross member is designed such that it rests on the sill and no water can pass under it. The side faces are designed to sit flush with the intake walls once the frame is lowered into place. It is equipped with 60 transducers which creates 30 acoustic paths. The position of the transducers was selected to correctly cover the flow where it was most needed at the bottom and the top. However, due to echoes issues, no scintillation measurements can be made on the last 40cm section at the top and the bottom of the frame. Therefore, in these two sections, a computational fluid dynamic (CFD) has been used to define the horizontal velocity profiles Un:

$$U_n = Z/T^{1/X} \quad (2)$$

With Z the elevation power, where Z is the elevation,
T is the boundary thickness, and X is the shape factor of the curve

The CFD gives X=3 at the bottom and X=18 at the top (considering T as the length between the last sensor and the top/bottom of the frame).

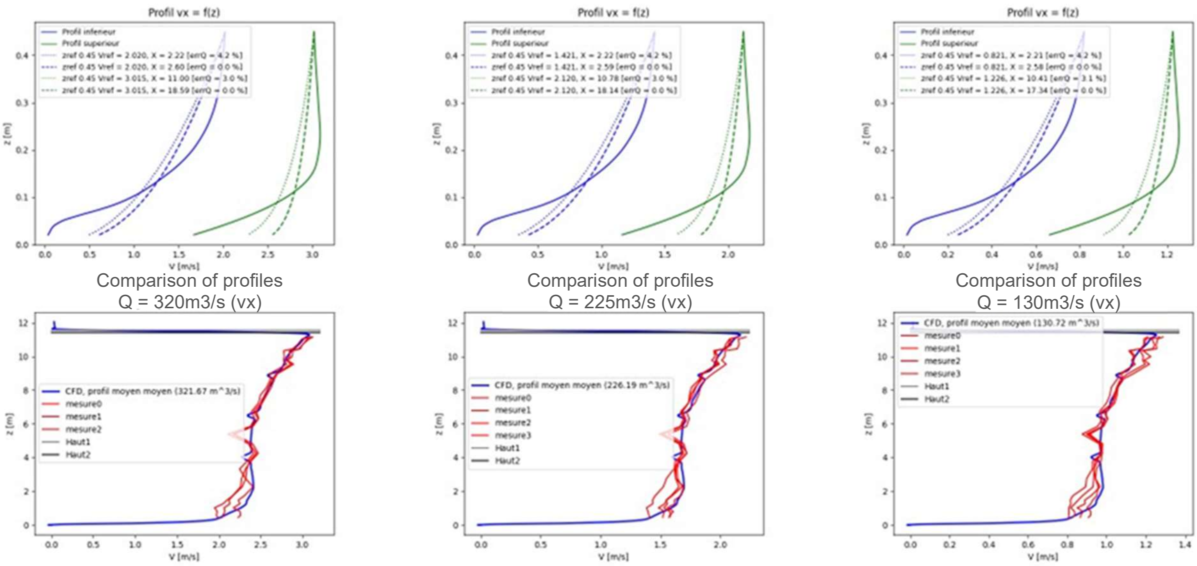

Figure 3: Results of the CFD simulation for 3 flows: 130, 225 and 320m3/s

The instrumentation takes place flat on an area close to the plant (figure 2). It requires several weeks to be fully equipped with transducers and vibration sensors. Every ten transducers, there is a canister on the receiver and the transmitter side. Then from the canisters only 3 cables are pulled out of the frame and connected to the data acquisition centre. This method reduces the number of cables handled, knowing that the cable length is around 50m each.

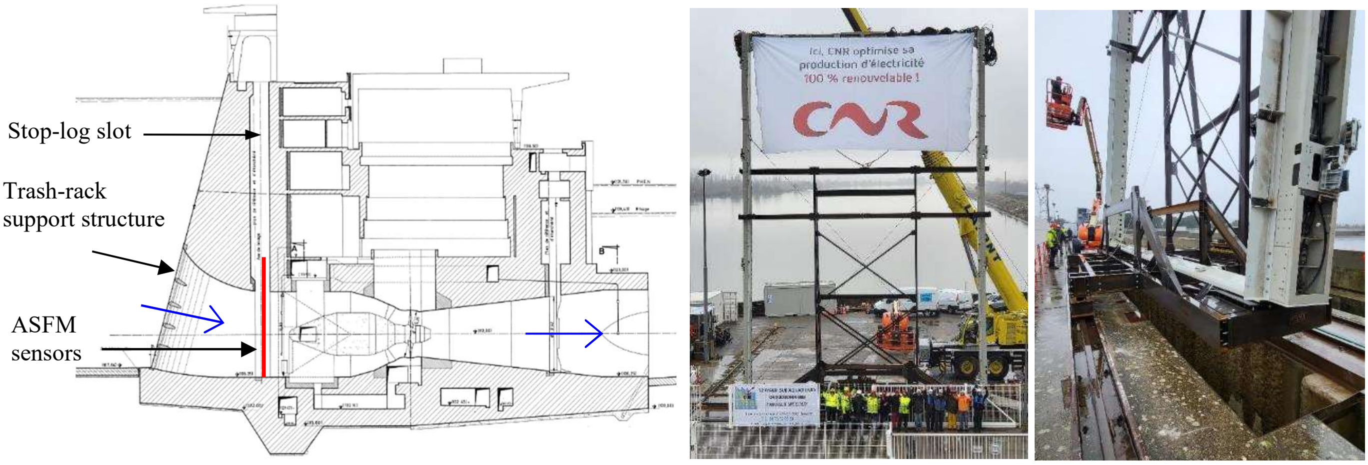

Figure 4: Vertical cross section of Beaucaire intake (left) – Frame positioned onto the trolley (center and right)

The final step is to introduce the metal frame fully equipped into the stop-log. On the Beaucaire plant it was not possible to move the frame horizontally because the width necessary is not sufficient. Therefore, a system was elaborated to slide the frame vertically above the stop-log. The system is a trolley able to move along the rails of the grid's cleaner. Two cranes were used to place in a vertical position the frame. The slings are then positioned only on one crane to install the frame onto the trolley. To conceive the trolley, wind and frame hold parameters have been considered. Finally, when the trolley is above the stop-log, the crane lifts the frame, and the trolley is put aside. The frame is lowered into place until it reaches the bottom.

As part of the work, divers are present to carry out checks on the installation of the frame inside the intake. They check the absence of wood before inserting the frame. Then, when the frame is installed, they make a marking along the ceiling of the water intake to measure the distance to the first transducer. The central unit is connected to check the proper functioning. Finally, the divers detach the slings from the frame.

2.3 Winter Kennedy method

The Winter Kennedy method is used to optimize the correlation between blades and guide vanes positions. The method relies on the correlation between the flow rate passing through the turbine and the difference in pressure between 4 taps located upstream (1' and 2') and downstream (3' and 4').

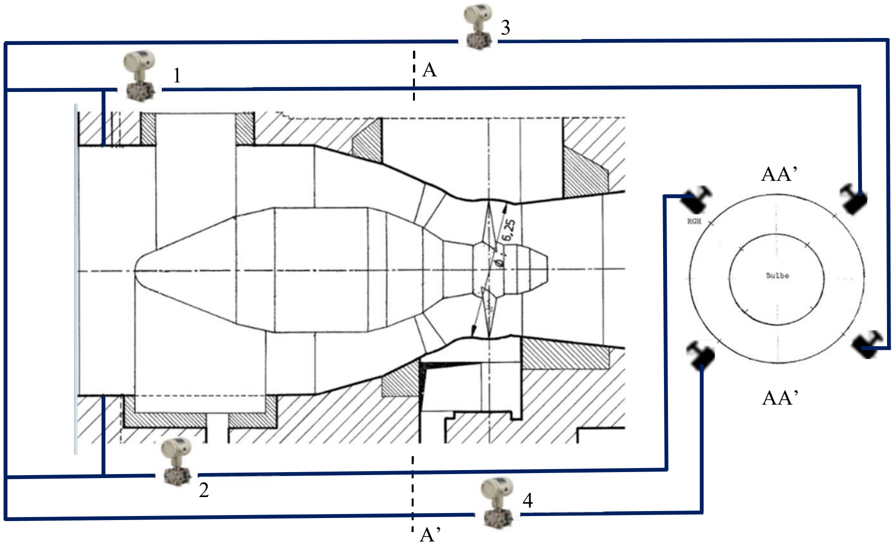

Figure 5: Localisation of WK pressure taps

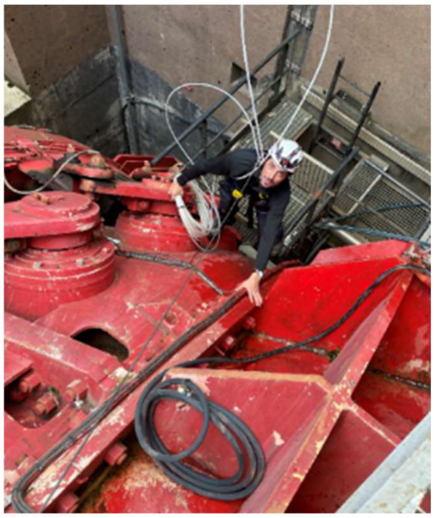

Figure 6: Equipment of downstream pressure taps on the outer belt (right)

The flow rate is expressed by the following relation:

$$Q = K\Delta P^n \approx K\sqrt{\Delta P} \qquad (3)$$

With ΔP *the differential pressure*
n *an exponent theoretically equal to 0.5, however the coefficient can vary from 0.48 to 0.52*

It is first necessary to determine the coefficients Ki for each differential pressure sensor. They are determined using the results of the ASFM on a range from 200 m^3/s to 300 m^3/s. On a bulb turbine it was observed that the Ki are quite constant. It was decided to use the average of all the tests.

The accuracy measurement is around 0.5%. This method is described in detail in international standard IEC 60041 [1].

2.4 Test protocol

The test campaign consisted of several on-site tests so that the operating plant head range is fully covered. The head target is determined according to the occurrence: 10%, 30%, 50%, 90%. For each head we target two scintillation measurement to assess repeatability in the measurements, and one WK measurement. Thus, one measurement campaign is theoretically 12 days.

Carrying out the tests depends on numerous parameters, among which the most restrictive is the hydrology of the Rhône River. Beaucaire plant being a run-of-river, there is only little margin for regulating the test conditions. For this reason, the tests at 10% head were not carried out because the incoming flow rate at the powerplant did not correspond during the instrumentation period. However, some measurements were launched without monitoring during flood event. From these measurements we keep only the constants parts of the measurements, but they allow to complete parts of the final efficiency curves. Also, the flow needs to be stable enough during 10h to be usable in the study. The WK standard [1] indicates that the variation of the net head should be lower than 2% in order to bring all measurements back to the mean net head.

During an ASFM measurement, the turbine is set at minimal flow (around 100 m^3/s) and is levelled up from 20 m^3/s until it reaches its maximal capacity (around 380 m^3/s, or maximal power output). Each measurement consists of 4 runs of 10 min. These runs are computed and give the velocity field as presented in figure 1. During the 10 hours of measurements, 13 results were recovered.

During a WK measurement, the turbine is set at several opening blades from 10% to 80% (or maximal output according to the head). The coefficients Ki are determined by using the ASFM measurement campaigns. For each blade opening, the turbine is driven manually to vary the guide vanes around the current on-cam set point. There are around 7 measurements per opening, which makes a total of 60 measurements during 10 hours. Each measurement is stabilised and then acquisition is done during 3 minutes long to finally be averaged.

The pressure losses of the grids are measured and removed from the results. The measurements take place between upstream and downstream of the turbine.

3. Calibration of the Winter Kennedy and the turbine efficiency

3.1 Calibration of the Winter Kennedy

It is first necessary to ensure that the turbine is well on-cam, meaning that the blade/guides vanes combination gives the optimal efficiency. Then the efficiency of the turbine is measured at the optimal cam. If a gain adjustment is needed, the cam must be changed in the regulator before carrying out absolute flow measurements. In the case of Beaucaire turbine no gap was found between the current cam and the optimal cam, meaning that the combination of blades and guide vanes positions was correct.

3.2 Results

The absolute flow measurement results for flow levels from 100 m^3/s to 370 m^3/s show a difference of around 10% with the regulator values. The flow references entered in the regulator must be changed in accordance with these on-site measurements to improve the calculation of the development flow for all flow conditions.

The combination of the two methods lead to determinate the efficiency curve of the Beaucaire plant. The figure 7 presents the efficiency according to the flow rate, each vertical tile representing an efficiency point. Depending on the net head the maximum efficiency differences are 1%. The characteristics of the turbine are quite similar despite the head.

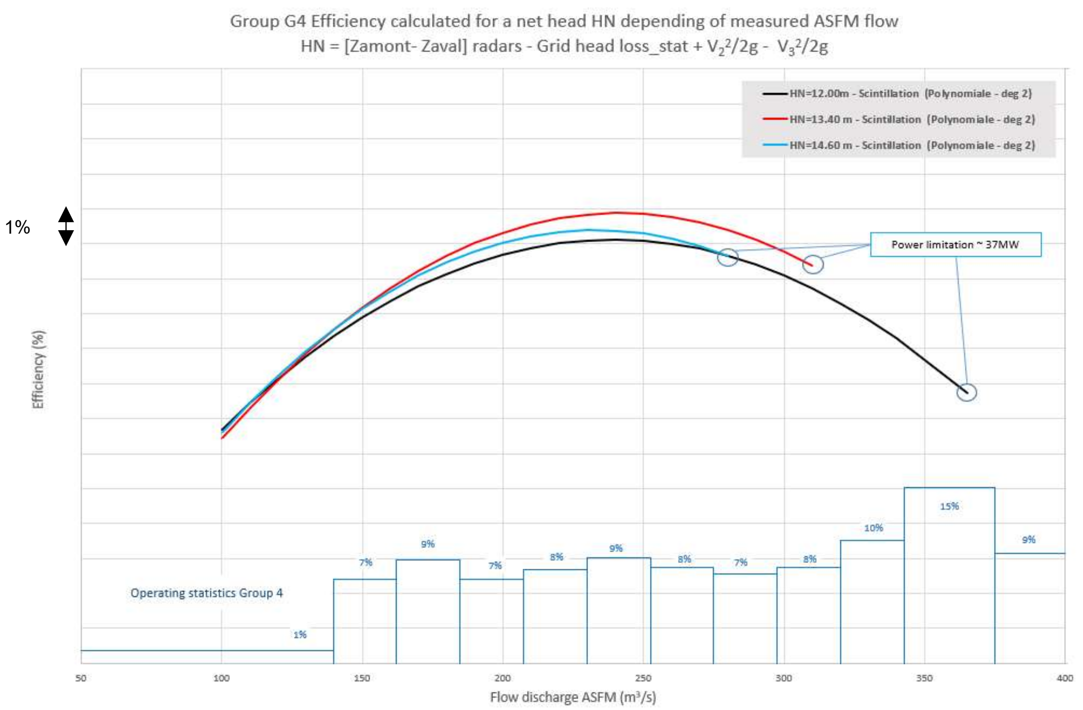

Figure 7: Efficiency results of the Beaucaire campaign for 3 net head: 12m,13.4 and 14.6m

This study serves as a baseline for the Beaucaire plant because the blades will be changed on this turbine. New measurements will take place during 2024 with the new blades using the same ASFM and WK process. This study will make it possible to quantify the efficiency gain obtained following this replacement, and to develop a strategy for replacing the blades of this same series on other plants in the event of a significant gain.

3.3 Monitoring

The ASFM campaign (January to March 2023) gives very stable values of the Winter Kennedy Ki coefficients. Figure 8 gives the recalculated WK efficiency and ASFM efficiency for a net head of 12.3m and 13.9m. The results are very close (difference of about 0.5%), and it could be interesting to install permanent Winter Kennedy pressure sensors to measure the turbine efficiency over time (predictive maintenance of the turbine).

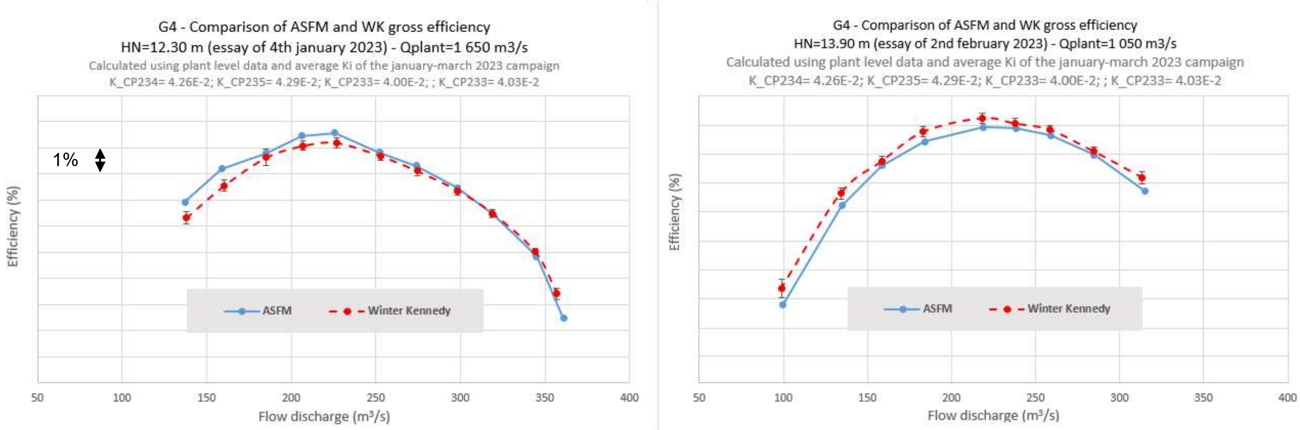

Figure 8: Comparison of efficiency with WK and ASFM results

4. Comparison with the numerical simulation during transition from the turbine to the sluice operating modes

Along with the goal of determining the hydraulic performance of the unit, one of the targets of the ASFM measurement campaign was to better know the flow discharge during transient events. One of the most interesting cases for CNR is the transition from the turbine operating mode to the sluice operating mode of the unit subjected to a load rejection.
The sluice operating mode of the low head Bulb units has been described in [8], which presents a numerical modelling of the Bulb unit transition from the turbine operating mode to the sluice operating mode. The same 1D-numerical modelling using the Simsen software has been used in the present study.

The sluice operating mode of Bulb units consists of making the turbine deliver a significant fraction of its nominal flow rate without the group supplying energy, after it has been desynchronized from the power network due to an external default. This sluice operating mode is of utmost importance regarding the incoming flow, to prevent the upstream and downstream channels to undergo disjunction waves, described in [9], and to ensure a discharge continuity in case of flood conditions. Until now, the 1D-numerical model was used to predict the unit discharge in such conditions, based on a calibration relying only on unit speed measurement. Using the flow transient measurements is a tremendous step forward to ensure the quality of the numerical model, since it is a particularly costly effort to setup and to calibrate, as shown in the previous chapters.

To access to the water flow measurement during the transition from turbine to sluice operating modes, ASFM were used during stabilized flows before and during the sluicing mode. WK were used during the transition to capture all the variations of the flow discharge, since the WK pressure transducers are more able to capture instantaneous variations in the flow compared to ASFM transducers. It is then possible to compare the numerical model not only with the unit speed but also with the WK flow discharge, by using the results from the calibrated WK pressure measurements.

Site tests were performed first in January 2023, when the total incoming discharge was rather high, leading to a medium gross head of around 12m. The first two comparison cases presented farther were targeting an initial unit flow rate of 210m^3/s and 368m^3/s under around 12m gross head. The third comparison case was performed later in February 2023, when the total incoming flow rate was much lower, leading to a gross head of 14m. This third comparison targeted an initial flow rate of 222m^3/s under 14m of gross head. The comparison graphs are available in Figure 9, 10, and 11, where the plain lines are measured values and the dashed lines are computed values. The unit discharge is on the right vertical scale.

In addition to the usual instrumentation, during the February 2023 set of measurements, a pressure transducer has been especially mounted in the draft tube cone shortly downstream the runner, to measure the static pressure at the runner outlet. Using an available pressure transducer mounted upstream the runner, both these static pressure measurements are combined with the flow discharge to compute a measured net head of the runner. This runner net head is then used to compare with the numerical results of the 1D transient model.

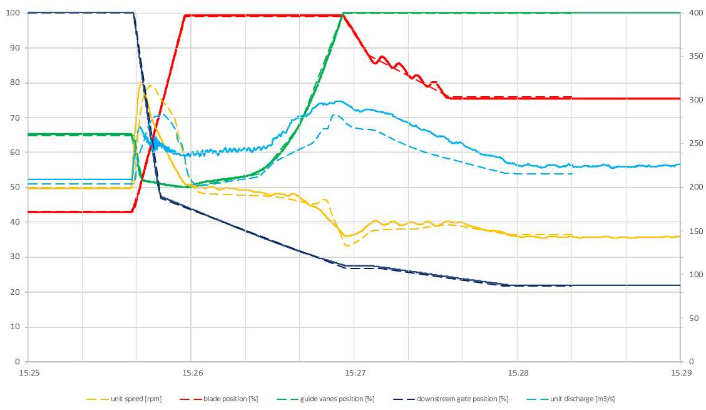

Figure 9: Flow transition from turbine mode to sluicing mode initial discharge 210 m³/s, gross head 12.2m. Comparison between measurements (plain lines) and computations (dashed lines)

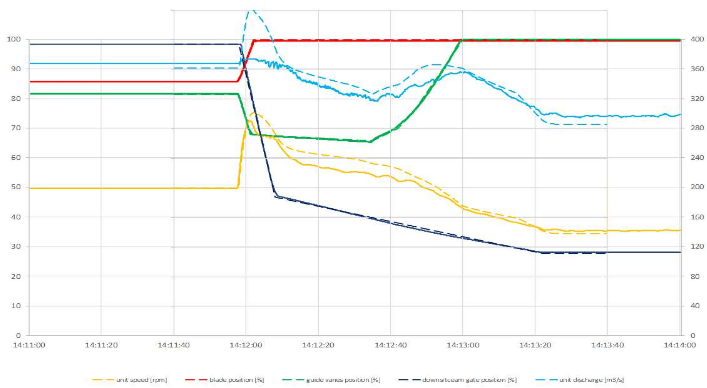

Figure 10: Flow transition from turbine mode to sluicing mode initial discharge 368 m³/s, gross head 12.3m. Comparison between measurements (plain lines) and computations (dashed lines)

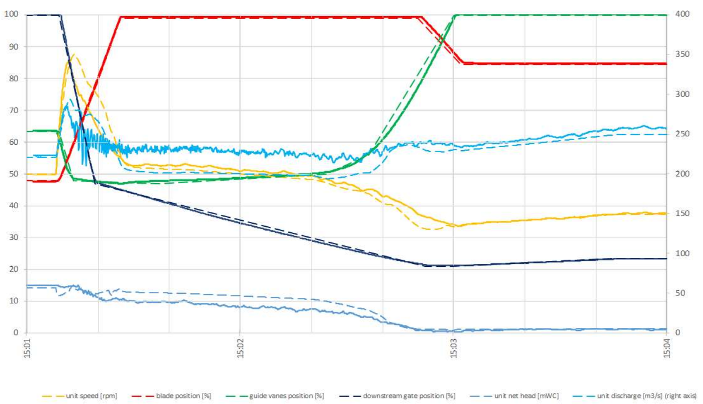

Figure 11: Flow transition from turbine mode to sluicing mode initial discharge 222 m³/s, gross head 14.5m. Comparison between measurements (plain lines) and computations (dashed lines)

The time evolution previously shown suggested that the 1D numerical model setup has successfully reproduced the transition from the turbine operating mode to the sluice operating mode. Usually, the quality of the numerical model is assessed through the monitoring of the unit speed only. By adding the flow discharge evolution as well as the turbine net head, it shows that the numerical methodology applied at CNR is sufficiently accurate as to reduce the computation error below 5% for all the values of interest, see Table.
Only one numerical value is not comparable to the measurements recorded in January 2023 at an initial unit flow rate of 368 m³/s. In this case, the maximum unit discharge has not been measured accurately, most probably due to the saturation of the Winter-Kennedy pressure transducer. More generally, even for the two other records, it seems that more reliable measurements of the transient flow rate may be achieved by defining Winter-Kennedy pressure transducers more sensitive to the dynamic of the hydraulic transient phenomena.

Table 1: Relative error between numerical results and measurements of speed and measurement of discharge using the Winter-Kennedy results (initially calibrated with ASFM measurement device)

		06.02.23 222m3/s	18.01.23 210m3/s	18.01.23 368m3/s
relative error (numerical Vs measurements)	overspeed [%]	3.1	-1.3	4.1
	intial discharge [%]	-0.2	-2.9	-1.7
	maximum discharge [%]	3.2	-4.6	N/A
	sluicing speed [%]	-0.9	2.5	-1.7
	sluicing discharge [%]	-3.2	-2.6	1.1

The very good matching between the numerical results and the unit discharge measurements for the three transition events is a very promising achievement. Indeed, this validates the numerical methodology used to predict the water flow discharge in numerous conditions. It is also a combined source of validation of the measurement methodology applied to calibrate the Winter-Kennedy coefficient based on the ASFM measurements done before and after the transition sequences.

5. Conclusion and perspectives

The ASFM on-site measurements between January and March 2023 allowed to characterize the performance of the turbine with the original runner blade design, as a zero state. The turbine efficiency is quite similar for the three net head measured (12.00m, 13.40m and 14.60m) with a maximum difference of about 1%. The efficiency results will be used to quantify the efficiency gain obtained with the new blades (measurement campaign in progress).

ASFM absolute flow discharge measurements allowed to calculate the Winter-Kennedy Ki coefficients. These values are very stable and will be used in the future to measure the turbine efficiency over time (predictive maintenance of the turbine).

The measurement carried out during sluice mode events during the campaign contribute to better know the flow discharge during transient events. The on-site tests were compared to the numerical model. The good matching of the numerical results and the discharge measurements validate the numerical methodology used to predict the water flow discharge in numerous conditions.

This type of campaign is planned for several plants in the coming years to improve the knowledge and adjustment of CNR units.

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