

Assessment of a CNR Bulb turbine flow: comparison of acoustic scintillation, ADCP, Winter-Kennedy tests with the current meters method (PENELOP2 project)

Pierre Roumieu, Gilles Pierrefeu
Compagnie Nationale du Rhône
Laboratoire Hydraulique et Mesures
4 rue de Chalon-sur-Saône
69007 LYON
France

Laurent Tomas, Xavier Cornut
ALSTOM Hydro France
Global Technology Center
82 Avenue Léon BLUM
38041 Grenoble Cedex 9
France

Karine Pobanz
Altran RA
1 place Verrazzano
69009 LYON
France

Carole Chaize
In Vivo
ZA La Grande
29940 LA FORET FOUESNANT
France

Dave Billenness
ASL AQFlow Inc.
1 – 6703 Rajpur Place
Victoria, BC V8M 1Z5
Canada

Olivier Bertrand
Artelia
6 rue de Lorraine
38130 Echirolles
France

1. Introduction

France has at its disposal a significant potential for developing renewable energy. In 2010, its rivers provided 12% of the country's electricity, and thus 80% of its renewable energy output. Given that locations for new developments are now increasingly few and far between, it is increasingly important that existing installations function at the highest possible level and benefit in particular from rehabilitation works to facilitate this.

The PENELOP2 project has been designed to respond precisely to these conditions, bringing together leading French organizations in hydraulics and hydropower, including Alstom Hydro France, CNR, Sogreah, LEGI (Grenoble INP), InVivo, Actoll and JKL. This collaborative effort is financed by the FUI (*Fond Unifié Interministériel*) and led by TENERDIS, the renewable energy competitive cluster. Its aim is to study the influence of various factors negatively affecting low-head turbine performance, in order to develop ways in which to optimize sites and production methods and thus increase production rates.

In the framework of improving knowledge of the velocity fields upstream of CNR's bulb turbines, on-site measurement tests were performed in December 2011 at Vaugris hydropower plant.

2. Vaugris hydropower plant

The Vaugris hydropower plant (see Figure 1) owned by CNR is located on the Rhône river about fifty kilometres downstream of Lyon. It is equipped with four Alstom bulb turbines of 6.25 meters runner diameter each delivering 18 MW under 6.70 meters head. The maximum discharge of each unit is about 350 m³/s.

The dam is equipped with six spillway gates. The maximum discharge of each gate is about 1 250 m³/s (Q₁₀₀₀= 7 500 m³/s)

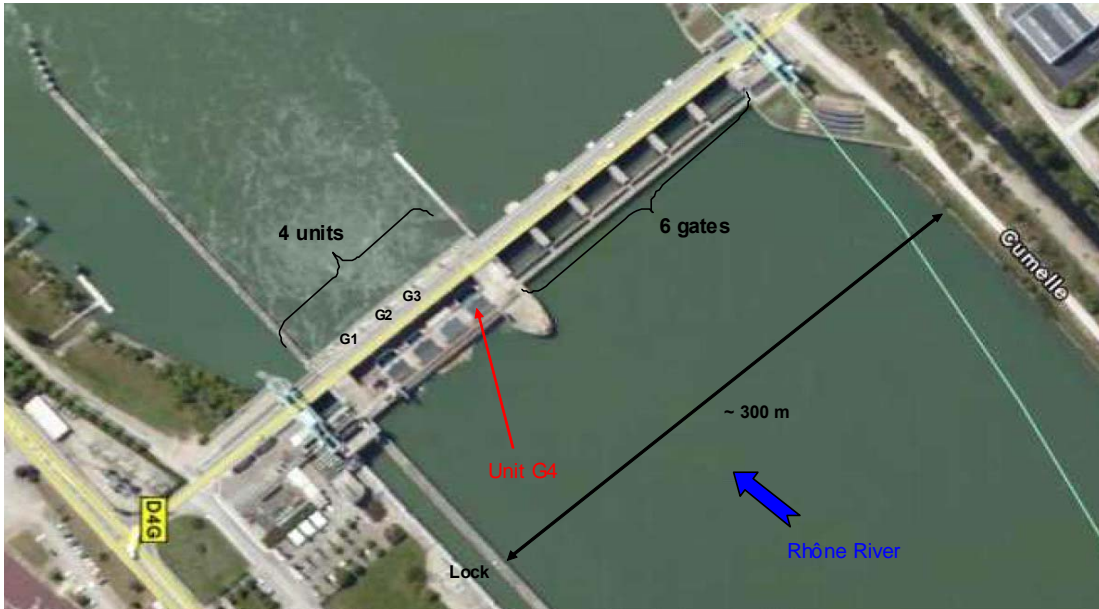


Figure 1: Plan view of Vaugris hydropower plant

3. Measurement Methods

3.1. Introduction

Three absolute methods were used to do the measurements: Current Meter (CM), Acoustic Scintillation Flow Meter (ASFM) and acoustic Doppler current profiler (ADCP) methods. In addition, the Winter-Kennedy relative method was used to verify the stability of the discharge during the comparative tests and also to compare the relative discharge value with the absolute ones.

Figure 2 gives the locations of intake flow measurements. Each method was applied without knowledge of the results obtained from the other methods (blind test).

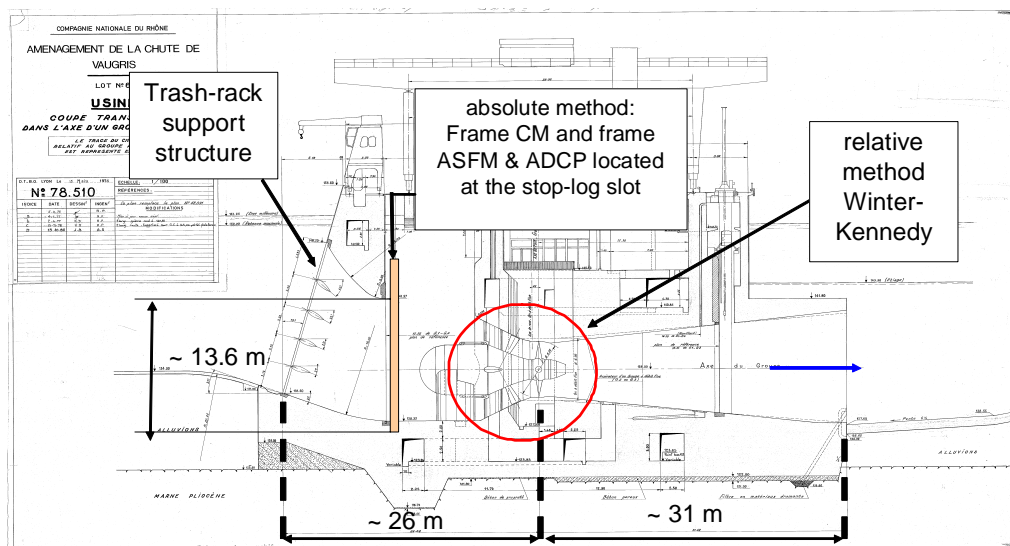


Figure 2: Location of intake flow measurements

About fourteen hydraulic configurations (various discharges of unit G4 and configurations of the adjacent unit G3 to test its influence on unit G4) were tested and compared.

The measurement required the fabrication of two steel frames. The first one (18 meters high and 12 meters wide), supporting the ASFM sensors (thirty acoustic paths) and the ADCP sensors (fourteen sensors), was fitted into the stop-log slot (see Figure 4). The second one, supporting the CM propellers (twenty-two propellers), was inserted vertically into the first one (see Figure 3).



Figure 3: Picture of the propellers frame



Figure 4: Picture of ADCP and ASFM frame

3.2. Initial CFD model

In order to prepare the in situ measurement campaign as efficiently as possible and set the various sensors in the best possible positions, Artelia has built a preliminary 3D numerical model of the hydraulic passage for unit G4. This model runs from 70m upstream of the inlet to unit G4 to the outlet from the draft tube downstream of the plant.

This model was built with the OpenFOAM CFD software. The grid consists mainly of cubic meshes, the size of which varies from 10 cm to 1 m depending on the area modelled. The grid is refined near the walls in order to properly model the boundaries layers. The grid consists of a total of over a million meshes.

The aim of this preliminary model was to produce results rapidly, even without having any calibration data available in order to analyse flows in the plane of the measurement frame (positioned in the stop-log slots upstream of the water chamber), where instruments would then be placed. It was therefore decided to take into account only the fixed components of the bulb unit. The rotating blades and their effects, which are in principle negligible in an area so far upstream of the bulb, were therefore not represented. The Figure 5 below showing a longitudinal section gives a clearer idea of the components taken into account in an upstream-downstream direction. These include the roundhead pier separating the power plant and the spillway (visible on the right side of this section), the floor, the main supports of the inlet screen, the water chamber, the bulb and its supports and finally the draft tube.

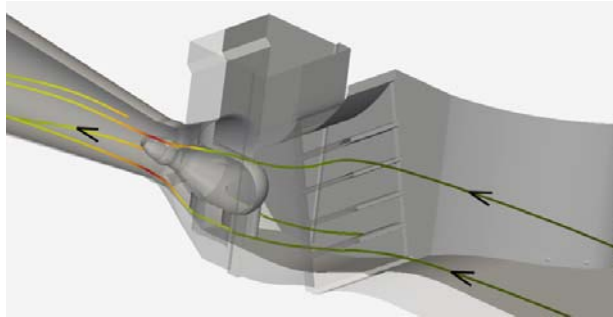


Figure 5 : Longitudinal section of the 3D model

3.3. Current meter method

The current meter method has been successfully used by Alstom for discharge measurement in power plants for decades. The main drawback of the method is the cost related to preparing the tests and the time taken for the measurements. However, the current meter method offers several advantages even today: the velocity is measured directly and not deduced from other physical values, it targets an area in the measurement section that we are particularly interested in and it allows an appreciation of changes in the velocity field with respect to the height and width of the measurement section.

The propeller bodies used are of Dumas-Neyrpic type, with 50 mm propellers for those closest to the wall and 120 mm self-compensating propellers for the others. They ensure a resolution of three tops per revolution and were calibrated for a velocity range of 0.4 to 3.2 m/s according to the preliminary CFD studies presented above.

Throughout the measurement process, the method was based on standard ISO 3354:1998 “Measurement of fluid flow in closed conduits”, which defines the necessary rules to ensure accurate measurement. As stated in this standard, even though some of the standard requirements were not met, such as the minimum length between the measurement section and any channel irregularity, the method can be used, though with slightly greater uncertainty.

According to the initial CFD results, it was considered that the mainstream line has an angle of 15° with the horizontal axis. This hypothesis has been used for the propellers calibration and confirmed with the ASFM on site measurements.

The calibration of the 22 propellers has been performed on a third-party installation specially designed for the purpose in conformity with the prescription of the ISO3455 “Calibration of the rotating-element current meters in straight open tanks”.

During testing, the frame was set at the desire elevation, and then the current meters were sampled for 2 min.

Figure 6 gives the location of the 4 x 22 = 88 measurement points:

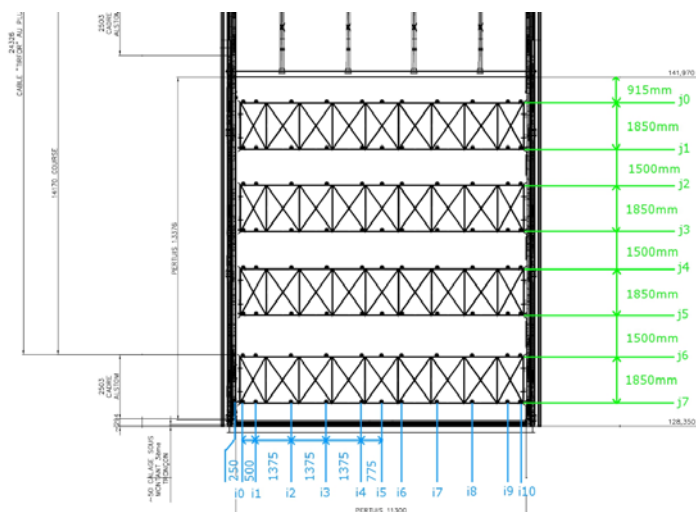


Figure 6 : Location of the CM measurements

The ISO3354:1998 standard defines two different methods for the velocity-area integration in a non-standard meshing. Those two methods are the graphical integration (in our case a midpoint rectangular integration) and the numerical integration based on the assumption of a mathematical form of the velocity distribution law (weighted according the velocity distribution). Both methods estimate the velocity in the peripheral zone by adding a defined function to the wall roughness, the velocity of the closest propeller to the wall and the distance between this propeller and the nearest wall.

3.4. Acoustic scintillation method

The ASFM uses a technique called acoustic scintillation drift (Clifford & Farmer, 1983; Farmer & Clifford, 1986; ASL, 2001) to measure the flow velocity perpendicular to a number of acoustic paths established across the intake to the turbine. Short (16 μ sec) pulses of high-frequency sound (307 kHz) are sent from transmitting arrays on one side to receiving arrays on the other, at a rate of approximately 250 pulses/second. Fluctuations in the amplitude of those acoustic pulses result from turbulence in the water carried along by the current. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e. along the acoustic path) of the velocity perpendicular to each path.. In its simplest form, two transmitters are placed on one side of the measurement section, two receivers at the other (Figure 7). The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and the 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 peak in the time-lagged cross correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic paths is then $\Delta x / \Delta t$. Using three transmitters and three receivers at each measurement level allows both the magnitude and inclination of the velocity to be measured. The ASFM computes the discharge through each bay of the intake by integrating the horizontal component of the velocity over the cross-sectional area of the intake. In a multi-bay intake, the discharges through each bay are summed to compute the total discharge.

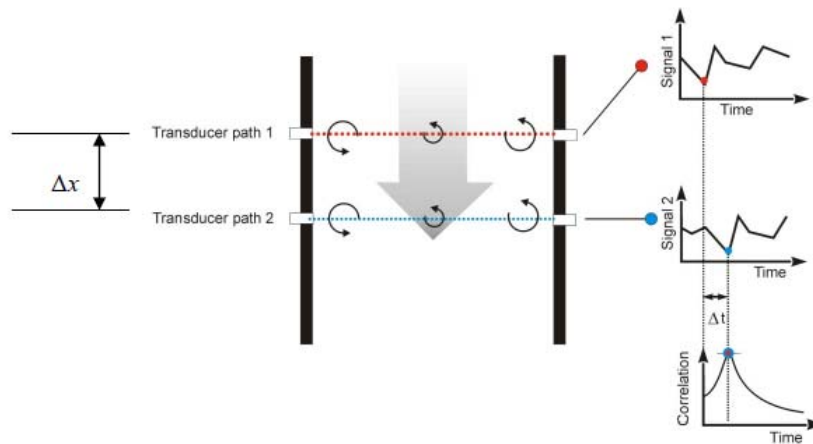


Figure 7: Schematic representation of acoustic scintillation drift

The magnitude and inclination of the flow velocity in the intake of Unit G4 was computed using 33-second measurements at each level. For most of the measurements, five individual repeat runs were made at each condition. An individual discharge was computed for each of the repeat runs, however, due to the larger than normal number of points removed, the individual discharge is not considered accurate. A mean discharge was computed by averaging the horizontal velocity at each level from the repeat runs and then integrating the average horizontal velocity profile. Roughly 30 minutes was necessary to obtain an individual discharge for each condition.

Final discharges were computed after an outlier removal and a thorough review of the data.

First, the raw acoustic amplitude series used in the acoustic scintillation method are band-pass filtered before computing the cross-correlations used to calculate the velocity. Since the band-pass depends on the velocity, an

iterative process is implemented. From this procedure, a quality index QI is computed and velocity outliers in the set of correlation peaks are identified and rejected using the Grubbs T-statistic.

Then, velocity profiles for each individual run are computed, any velocity component outliers are removed using the modified Thomson tau technique (ASME - PTC 19.1-2005) and the average velocity computation is performed.

Finally, the individual runs made at each condition allowed the repeatability of the ASFM flow measurements to be calculated.

3.5. ADCP method

An ADCP is a current profiler based on the Doppler effect. It is one of the techniques used to measure discharges by exploring velocity fields. Frequently implemented to measure discharges in rivers, it was used in a confined environment in the framework of the PENELOP2 project. Thirteen Workhorse Rio Grande type ADCPs with frequencies of 600 kHz and 1200 kHz and one V-ADCP with a frequency of 2400 kHz were used for this project. Several sensors were lent by government services and the manufacturer, complementing those of CNR and In Vivo to ensure the project was performed satisfactorily.

The Workhorse Rio Grande ADCPs are equipped with four beams located in orthogonal planes in pairs at an angle of 20° in relation to the axis of the ADCP. The V-ADCP sensor is also equipped with four beams: three set at an angle of 20° in relation to the axis of the ADCP to measure radial speeds; the fourth, in the axis of the ADCP, measures the height of the water column only.

The ADCP measures velocity components as a function of the axes of the beams. These radial velocities can be used with simple trigonometric formulae to estimate flow velocity in three dimensions, V_x , V_y and V_z , provided that the flow detected by the beams of the ADCP at a given distance (in a plane perpendicular to the axis of the ADCP) is homogenous.

Because of the inhomogeneity of the volume of water insonified at a given depth, the approach chosen for the estimation of the velocities consists of making the following hypotheses: the flow is homogeneous in the first three meters in front of the ADCP, the flow is parallel to the civil engineering structure near the edges of the sluice, the orientation of the velocity evolves linearly between the top and the bottom of the sluice and between the left bank and the right bank of the sluice.

3.6. Winter-Kennedy method

The principle of the method is based on the correlation between the flow rate passing through the turbine and the difference in pressure between two specific sections of the bulb (see Figure 8).

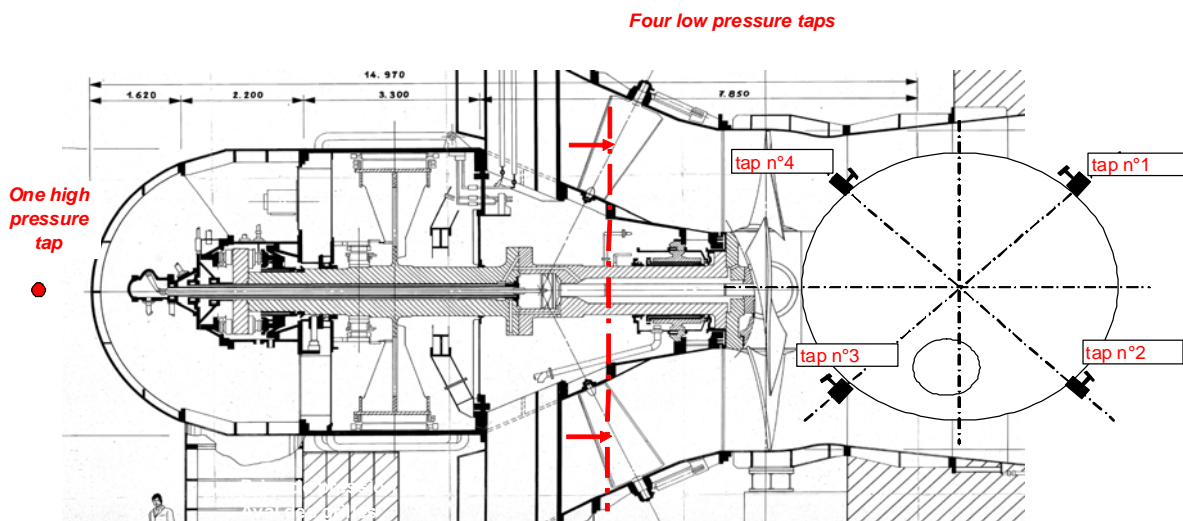


Figure 8: Location of WK pressure taps

The method assumes that the flow rate passing through the turbine is generally expressed with sufficient precision by relation $Q=K \Delta H^n$, where ΔH is the differential pressure and n is an exponent theoretically equal to 0.5. It should be noted that the standard indicates that this coefficient can vary from 0.48 to 0.52 under unfavourable conditions, such as low speed or in the case of semi-scrolls (cf standard IEC 60041/AC1).

In practice, it is first necessary to determine coefficient K . To do this, it is usual to start from the optimal output of the turbine unit. The output value is then determined on the output curve provided by the most recent tests or, failing these, it is taken as being equal to the value provided by the turbine supplier. The fact of setting an output for calculating K implies that this method only supplies a relative flow rate.

Since Unit G4 has four pressure taps, four K coefficients are calculated and at each test it is possible to determine four flow rate values (Q_1, Q_2, Q_3 and Q_4).

The homogeneity criterion of the flow rate values generally taken into account with the Winter-Kennedy method, i.e. difference between Q_1, Q_2, Q_3 and Q_4 less than 2% was observed for all the tests performed, and the average value was retained.

For all the tests the fluctuations of the measurement were calculated with the criterion (or variation coefficient)

$$\frac{\sigma(\textit{standard deviation})}{m(\textit{mean value})}$$

4. Measurement tests

The measurement campaign ran from Tuesday 6 December 2011 to Friday 6 January 2012. During this period fourteen tests were performed.

The article deals with the eight tests performed with all the methods described before:

Test n°10: Minimum flow rate on Unit G4

Test n°11: Maximum flow rate on Unit G4

Unit G4 in sluicing mode:

Test n° 8A: Unit G4 in sluicing mode n°1

Test n° 8B: Unit G4 in sluicing mode n°2

Test n°8C: Unit G4 in sluicing mode n°2

Test n° 8C_bis: Unit G4 in sluicing mode n°2

Sluicing mode n°1: the initial discharge of unit G4 is about the minimum value (110 m³/s). The sluicing discharge is about 150 m³/s.

Sluicing mode n°2: the initial discharge of unit G4 is about the maximum value (350 m³/s). The sluicing discharge is about 250 m³/s.

Influence test of the adjacent unit (Unit G3) on Unit G4 :

Test n° 6b: Maximum flow rate on Unit G4 (with Unit G3 in operation)

Test n° 5b: Maximum flow rate on Unit G4 (with Unit G3 stopped)

The duration of each test was about four hours. Since the reference method is the CM one, it was decided to proceed with the CM method at the beginning and at the end of each test as follows:

CM Method: one-hour duration

ADCP method: one-hour duration

ASFM method: half an hour duration

CM Method: one-hour duration

In order to make valid comparisons between the various methods, the hydraulic conditions (total head, total discharges, upstream level, and downstream level) were maintained as constant as possible during each test. In addition, it was verified by measurement that the blade positions and gate positions of the unit G4 were fixed during each test.

Table 1 gives the mean, minimum, and maximum values of the total head and the flow rate given by the Winter-Kennedy method for each test.

It can be seen that the hydraulic conditions were stable during each test since the maximum variation of the total head was less than 1.2% (7 cm) and the maximum variation of the flow rate given by the relative method of Winter-Kennedy was less than 0.9% (1.2 m³/s).

The maximum value of the criterion $\frac{\sigma (\text{standard deviation})}{m (\text{mean value})}$ calculated with the Winter Kennedy flow rate values is less than 0.85%. This indicates that the fluctuation of the discharge during each measurement was very low.

Date		Wednesday 14 decembre 2011	Thursday 8 decembre 2011	Wednesday 14 decembre 2011	Thursday 8 decembre 2011	Wednesday 14 decembre 2011	Monday 12 decembre 2011	Wednesday 14 decembre 2011	Monday 12 decembre 2011
Test		Test n°10	Test n° 8A	Test n° 8B	Test n°8C	Test n° 8C_bis	Test n° 6b	Test n°11	Test n°5b
		Minimum flow rate on Unit G4	Unit G4 in discharger mode n°1	Unit G4 in discharger mode n°2	Unit G4 in discharger mode n°2	Unit G4 in discharger mode n°2	Maximum flow rate on Unit G4 (with Unit G3 in operation)	Maximum flow rate on Unit G4	Maximum flow rate on Unit G4 (with Unit G3 stopped)
Total Head	Mean value (m)	5.95	6.02	5.87	6.23	5.99	6.25	5.94	6.30
	Minimum value (m)	5.92	5.98	5.86	6.21	5.98	6.23	5.91	6.29
	Maximum value (m)	5.99	6.05	5.88	6.24	5.99	6.27	5.97	6.30
	Range (m)	0.07	0.07	0.01	0.03	0.01	0.04	0.06	0.01
	Range (%)	1.2%	1.2%	0.2%	0.5%	0.1%	0.7%	1.0%	0.1%
Q Winter Kennedy	Mean value (m ³ /s)	129.8	128.8	219.7	233.2	237.8	310.8	315.0	311.1
	Minimum value (m ³ /s)	129.4	128.5	219.3	232.4	237.3	310.7	314.9	311.0
	Maximum value (m ³ /s)	130.5	129.3	220.1	234.3	238.3	310.9	315.2	311.1
	Range (m ³ /s)	1.14	0.87	0.72	1.90	1.01	0.12	0.21	0.15
	Range (%)	0.9%	0.7%	0.3%	0.8%	0.4%	0.0%	0.1%	0.0%
	Maximum fluctuation σ - (%)	0.55%	0.46%	0.45%	0.85%	0.49%	0.19%	0.16%	0.17%

Table 1: stability of hydraulic conditions during the tests

5. Results and conclusion

Table 2 gives the flow rates passing through turbine unit 4 of Vaugris measured by the four methods for the eight selected tests performed on 8 December, 12 December, and 14 December 2011.

It has to be noted that no correction were applied to these values since the variation of the total head during each test was very low. The maximum correction on the flow rate that vary as the square root of the total head will have a range of about 0.6% (since the maximum variation of the total head is less than 1.2%).

Date	Wednesday 14 décembre 2011	Thursday 8 décembre 2011	Wednesday 14 décembre 2011	Thursday 8 décembre 2011	Wednesday 14 décembre 2011	Monday 12 décembre 2011	Wednesday 14 décembre 2011	Monday 12 décembre 2011
Test	Test n°10	Test n° 8A	Test n° 8B	Test n°8C	Test n° 8C_bis	Test n° 6b	Test n°11	Test n°5b
	Minimum flow rate on Unit G4	Unit G4 in discharger mode n°1	Unit G4 in discharger mode n°2	Unit G4 in discharger mode n°2	Unit G4 in discharger mode n°2	Maximum flow rate on Unit G4 (with Unit G3 in operation)	Maximum flow rate on Unit G4	Maximum flow rate on Unit G4 (with Unit G3 stopped)
Total Head (m)	5.95	6.02	5.87	6.23	5.99	6.27	5.94	6.25
CM - Discharge (m ³ /s)	125	124	222	238	240	315	317	318
ASFM - Discharge (m ³ /s)	134	135	225	247	244	322	324	327
ADCP - Discharge (m ³ /s)	120	119	212	243	237	308	306	310
WK - Discharge (m ³ /s)	130	129	220	233	238	311	315	311
Difference of ASFM vs CM (%)	7.4%	8.8%	1.5%	3.8%	1.6%	2.2%	2.2%	2.8%
Difference of ADCP vs CM (%)	-4.0%	-4.0%	-4.5%	2.1%	-1.3%	-2.2%	-3.5%	-2.5%

Table 2: Comparison of flow rates determined by Current meters (CM), ASFM, ADCP, and the WK method

The results of the testing program are as follow:

- Except for low discharges, the values of the ASFM flow rates are very close to the absolute flow rate values measured by CM. The mean difference is less than 2.4% for medium and high discharges ($Q > 225$ m³/s), which is not surprising taking into account the uncertainty of each measurement; it can also be noted that ASFM method gives higher discharge values than CM method.
- The values of the ADCP flow rates are always under the values measured by CM (except for one point in sluicing mode). The mean difference is 3%, which is not considered as a high value (again taking into account the uncertainty of each measurement)
- The CM flow rate values are very consistent with the relative flow rate values provided by the Winter-Kennedy (WK) method
- The ASFM flow rate values are consistent (relatively constant deviation) with the relative flow rate values provided by the Winter-Kennedy (WK) method.
- There is no significant influence of the adjacent unit (G3) on the flow rate of unit G4.
- Using a 3D CFD model is very helpful to set the various sensors in the best possible positions (distribution within the frame and sensors directions).

References

1. **Emmert, R., Lomeland, J., Belleau, B., Buermans, J., Lampa, J.**, “Deployment methods for the acoustic scintillation flow meter”, *WaterPower* 2007.
2. **Vich Llobet, J., Lemon, D.D., Buermans, J., Billenness, D.**, “Union Fenosa Generation’s field experience with acoustic flow measurement”, *IGHEM* 2008.
3. **Lemon, D.D., Warren, P., Bell, W.**, “Measuring hydraulic turbine discharge with the acoustic scintillation flow meter”, *IGHEM Montreal* 1996.
4. **Reeb, B., Ballester, J.-L., Buermans, J., Lampa, J.**, “Case studies of discharge measurement using the acoustic scintillation flow metering technique”, *Hydro* 2007.
5. **Buermans, J., Billenness, D., Lemon, D.D.**, “Turbine Discharge Measurements by Acoustic Scintillation Flow Meter at CNR’s Vaugris hydropower plant, Penelop Unit 4”, December 2011
6. **Tomas L, Cornut X.**, “Penelop Project, 4 Horizontal Bulb Turbines, Flow Measurement By The Means Of propellers”, **Alstom internal report**, January 2012
7. **Schaguene J., Bertrand O., David E., Roumieu P., Pierrefeu G., Pobanz K., Cornut X., Tomas L.**, “The use of numerical modelling to optimize the placement of data-gathering equipment in low-head hydro production structures”, *Simhydro* 2012 – Nice- France
8. **Olivier, A., Blancart, B., Pierrefeu, G., Scotti, M.**, “Incertitude sur les mesures de débits issues d’un jaugeage à l’ADCP”, *Houille Blanche*, mars 2009.

The Authors

Pierre ROUMIEU: graduated in Hydraulics from the Ecole Nationale Supérieure d'Hydraulique et Mécanique de Grenoble. He is in charge of the CNR laboratory's physical modelling activity. He has designed a large number of hydraulic structures in river and torrential environments (with sediment transport) as well as in the field of pressure hydraulics. Over the last height years he has carried out detailed studies, diagnostics and designs for lock filling systems (Cremona lock, Panama Locks). Recently, he is in charge of specific hydraulic on-site measurement campaigns on CNR units (Winter Kennedy, ASFM,..)

Gilles PIERREFEU: graduated in Hydraulics from the Ecole Nationale Supérieure d'Hydraulique et Mécanique de Grenoble. A hydraulics engineer and hydrologist, he joined the Compagnie Nationale du Rhône in 1990. Since 1997, he has been in charge of the Hydrometry department that groups the supervision of the measurement network that provides data on the flow rates of the Rhone and its tributaries. Before 1997, he performed hydraulics studies on physical and mathematical models.

Karine POBANZ: graduated in Hydrodynamics from the University of Toulon and Var (ISITV). She worked for two years in a research institute on the determination of historic flood flows and on the extrapolation of stage-discharge curves by hydraulic modelling. She joined Altran in 2007 as a hydraulics engineer and hydrologist. In this capacity, she has contributed in particular to the design of small hydropower plants through physical models and took part in the tests of the physical model of the Post Panamax locks in 2008. She is now involved in hydrological projects in the Hydrometry department of the CNR since four years.

Laurent TOMAS: graduated from Ecole Centrale de Lyon in 1992 and holds a PhD degree in applied mathematics. He is an hydraulic design expert at the Alstom Global Technology Center (GTC) in Grenoble (France). After 12 years at the hydraulic design department as hydraulic engineer and two years in the site test team, he is now working in the mechanical design department of the GTC.

Xavier CORNUT: graduated in Mechatronics from the Ecole National d'Ingénieurs of Brest (ENIB), he has been working for the Laboratoire de Mecatronique de Brest (LMB), in the field of the memory of shape alloy. In 2008, he worked for STEELBRO ltd New Zealand (a sidelifter manufacturer) to develop embedded systems, aimed to improve speed and accuracy of the cranes. He joined ALSTOM Power in 2009, as a site measurement engineer, where he got specialized in hydraulic and mechanic measurements on hydraulic turbines.

Carole CHAIZE : graduated in Coastal Engineering from the University of Caen. She has been working in marine environment and oceanography since 2000. Over the last seven years, she has carried out detailed study on hydrodynamics and hydro sedimentary processes at IN VIVO. She is in charge of measurement campaigns at sea, and specializes in current and wave measurement using ADCP.

Dave BILLENNESS: graduated from the University of Victoria, British Columbia, in 1995 and has worked for ASL Environmental Sciences since 1997. He currently heads the flow measurement field program associated with the ASFM.”

Olivier BERTRAND: graduated from the University of Bordeaux in 1999, he has worked for Artelia since 2002. He is a specialist in hydraulic numerical modeling and has developed numerous computation codes in such varied fields as crystallogenesis, compression of petroleum fluids, oceanic and river modeling, transport of oil slicks. He participates in particular in expert appraisal and complex hydraulic studies concerning marine, lake and river environments. He provides his experience in hydraulic development and its impact on the environment at different levels, from simple advisory services to design and innovative modeling studies. In particular, he runs and coordinates research and development projects associated with these problems.