Turbine acceptance tests at Velle, Frieira and Castrelo plants, Spain, with the Acoustic Scintillation Flow Meter

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Introduction

In October 2007, Gas Natural Fenosa (formerly called Union Fenosa Generación) successfully made flow measurements with the Acoustic Scintillation Flow Meter (ASFM) to establish the operational efficiency of existing Kaplan turbines at their Velle, Frieira and Castrelo hydroelectric plants on the Miño River in north-western Spain. Following the 2007 tests, company personnel stipulated in the contract for replacement runners at these plants that the ASFM would be used in the field acceptance tests. Measurement with the current meters (CMs) would be done if the efficiency guarantees were not met. The first of these tests was carried out with both the ASFM and CMs at the Frieira plant. Subsequent acceptance tests at the Castrelo and Velle plants were performed exclusively with the ASFM. Because of the inflow and dispatch limitations, it was not possible to test all guaranteed weighted conditions.

Each of the three plants has two Kaplan units, with the nominal flow of 374 m^3/s and the net head of 13.0 m at Velle, 24.5 m at Frieira and 21.5 m at Castrelo. The first test with the ASFM and CMs took place at Frieira Unit 2 in June 2011. Personnel from ASL AQFlow attended the ASFM and personnel from W.E.S.T. attended the CMs and turbine efficiency measurements. Subsequent tests on Castrelo Units 1 and 2, and on Velle Unit 1 were performed by Gas Natural Fenosa personnel with the ASFM only.

The results of the testing are discussed in the paper in detail, along with the procedures for the installation of the instruments and data collection.

1 Background

1.1 Acoustic Scintillation

As there are no slots at these three plants which could be made available for the ASFM, the instrument was mounted on the walls of the intake bays downstream of the gate slot (Fig. 1, 2 and 3). As was the case in 2007 (Ref. 1), the following factors were considered in the design of the ASFM mounting system: minimum interference with the flow from protrusions into the flow area, accurate alignment of, and distance between, the transmitting and receiving transducers and ease of installation. Consequently, two-part portable frames were utilized: the fixed base plates were bolted to the walls in each intake bay ahead of the measurement, while the intake was dewatered during unit outage. The two sets of portable frames holding the transducers were fully instrumented in the yard and attached to the base plates under water by divers at Frieira and Castrelo plants and by climbers at Velle plant (Fig. 4). Each portable frame contained 15 holes on either side for 15 pairs of transducers (Fig. 5).

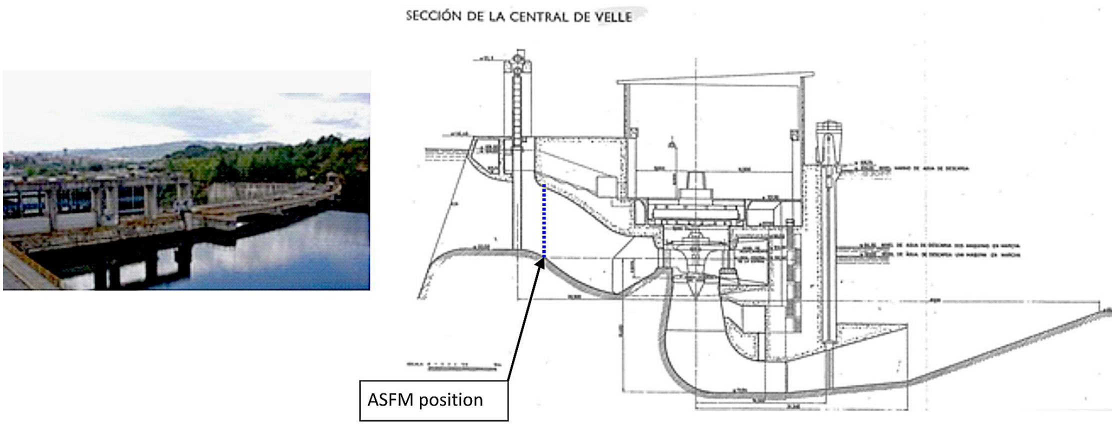

Fig. 1 – Velle HPP

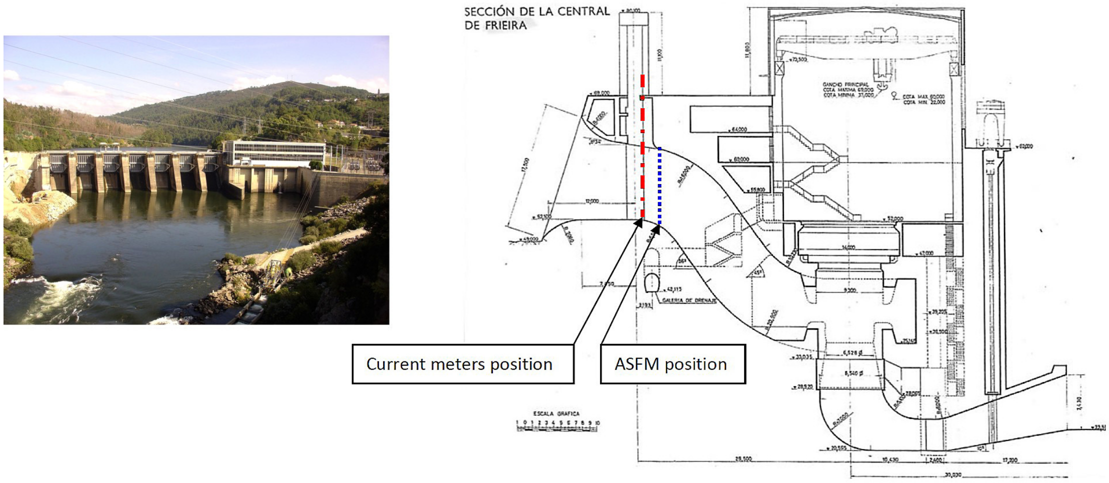

Fig. 2 – Frieira HPP

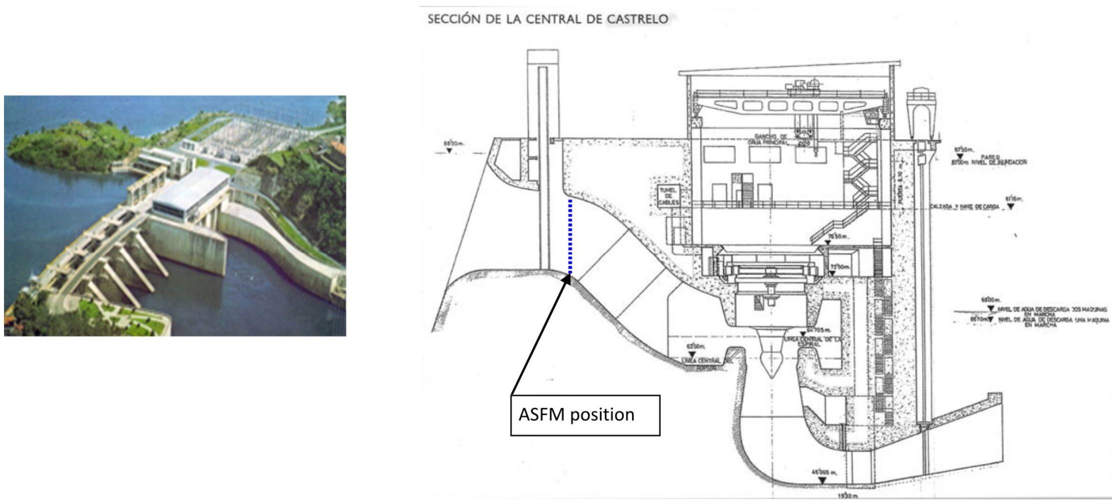

Fig. 3 – Castrelo HPP

Fig. 4 – ASFM frame in the yard (left) and in the intake bay (right)

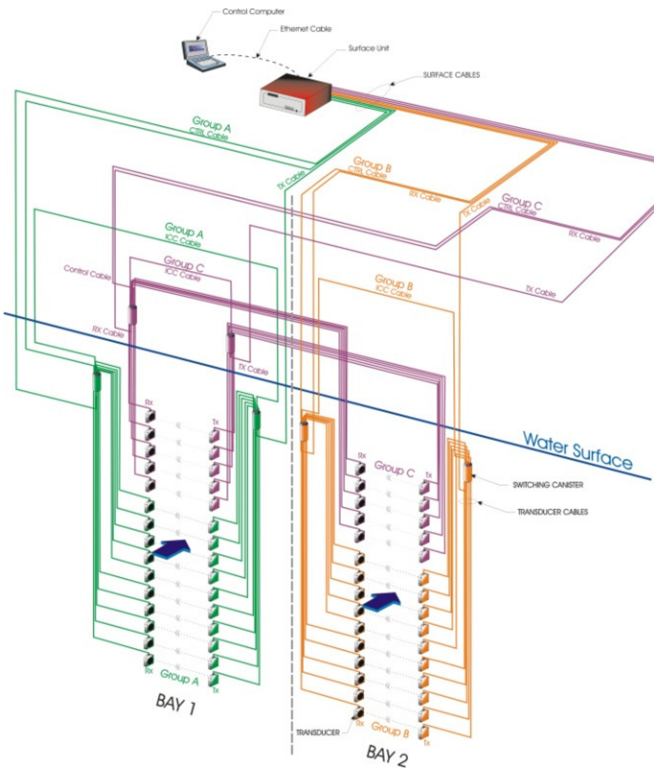

Fig. 5 – ASFM components

1.2 Current Meters

For the first test on Unit 2 at Frieira (Ref. 2 and 5) the flow rate was measured with sixty CMs mounted on two frames just downstream of the gate slot (Fig. 2), one for each intake bay. Each frame had two rods of ovoid profile, 35x105 mm, at a distance of 800 mm, to which the CMs were attached (Fig. 6).

Fig. 6 – CM frame (left) and lifting winches (right)

The lifting of each frame was performed with the use of three winches, positioned one at the center of the frame, and two at each side (Fig. 6). Two lateral guides, made with 100 x 100mm L-profiles and spaced 520 mm, were installed on the walls to allow vertical lifting of the frame through the full height of the intake and the measurement of the entire flow velocity field.

2 Test Program

2.1 Acoustic Scintillation

At Frieira Unit 2, the magnitude and inclination of the flow velocity in the intakes were computed using 33 second measurements at each level. Six to seven individual repeat runs were made at each guaranteed condition for which measurements were possible. Roughly 40 minutes were necessary to obtain individual discharges for each condition.

The basis of the ASFM velocity measurement is the time-lagged correlation of the time series of acoustic amplitude fluctuations recorded over two spatially separated paths. Six to seven sequential time series were collected at each level during the normal course of these tests; each sequence was treated as described in Ref. 3.

The horizontal velocities from the individual repeat runs at each level were averaged and the discharge was computed by integrating the average velocity profile using a quadratic interpolation scheme.

Sample horizontal velocity profiles are shown in Fig. 7 (the averaged velocities of the repeat runs are in red, the individual velocities in grey).

For Frieira Unit 2, preliminary discharge results were supplied for comparison with the current meter method as the tests were proceeding. The final values, provided after verification and checking, show only minor differences resulting from changes to the dimensional measurements of the intake, as supplied by Gas Natural Fenosa after the measurement. For all subsequent testing, Gas Natural Fenosa personnel performed the ASFM measurement and calculations using an identical methodology, but without ASL AQFlow personnel.

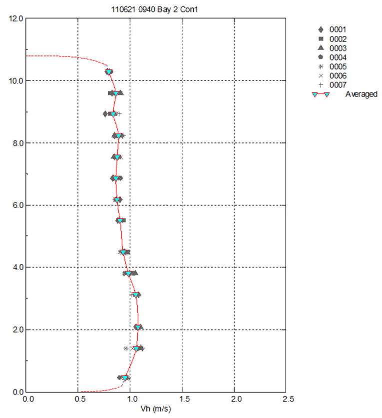

Fig. 7 – ASFM sample horizontal velocity plots, Frieira Unit 2

2.2 Current Meters

During each of the eleven tests at Frieira Unit 2, the frame with the current meters was moved vertically into eight positions, thus exploring the measurement section in sixteen different horizontal levels. Therefore, the flow in each intake bay was calculated from the flow velocity measurement at 240 points (16 levels with 15 points each), with an acquisition time for each local velocity of 180 seconds.

The determination of the flow rate has been achieved, as required by IEC 60041 and ISO 3354 codes, by integrating the flow field in the horizontal planes first, and then vertically according to the expression:

$$Q = \int_0^H \left(\int_0^L V \, dl \right) dh$$

The flow rate was calculated by using the method of cubic interpolation between the measured points (J. Coffin and the method of Spielbauer, Ref. 2) or by the method of trapezoids. The integrations were carried out directly by computer via numerical equations, as required by the codes, and extrapolation to the vertical side walls as follows:

$$V_x = V_a \left(\frac{X}{a}\right)^{1/n}$$

where 4 <n <10. The value of n was calculated from the average of the values obtained by extrapolating the trend in proximity to the wall derived from the flow velocity detected by the current meters closest to the wall. All sixty current meters worked properly during all tests: no foreign bodies in the water impacted the behavior of the propellers. The thruster control, carried out at the end of the tests, confirmed their smooth operation.

Figure 8 shows examples of the contours of the velocities measured in the two intake bays.

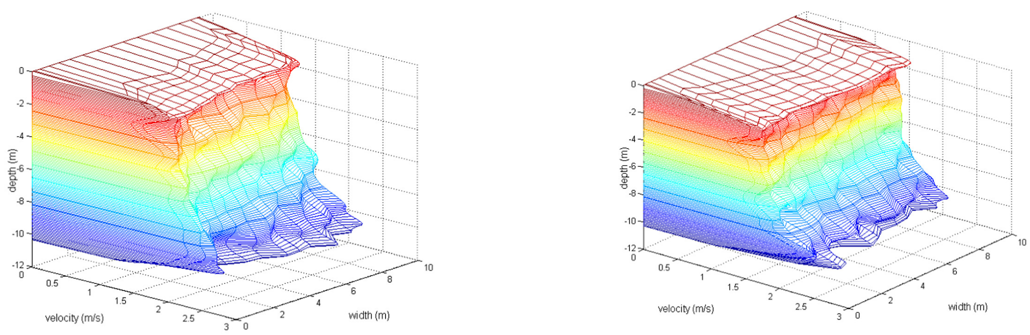

Fig. 8 – CM velocity contours Bay 1(left) and Bay 2 (right), Frieira Unit 2

3 Results

3.1 Frieira Unit 2

The average standard deviation of the individual ASFM repeat runs made at each condition at Frieira Unit 2 was 0.52% in Bay 1 and 0.78% in Bay 2 (Table 1).

Table 1:

Scintillation	
Bay 1_stdev	Bay 2_stdev
(%)	(%)
0.57	0.90
0.34	0.77
0.56	0.65
0.44	0.61
0.57	0.88
0.67	0.80
0.45	0.68
0.57	0.84
0.68	1.02
0.45	0.73
0.40	0.71

The results of the two methods at Frieira Unit 2 were all within 1% (Table 2).

Table 2:

	Current Meters		**Scintillation**		**Bay 1**	**Bay 2**	**Current Meters**	**Scintillation**	**Total flow**
	Flow – Bay 1	**Flow – Bay 2**	**Flow – Bay 1**	**Flow - Bay 2**	**Delta**	**Delta**	**Total flow**	**Total flow**	**Delta**
Condition	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(%)**	**(%)**	**(m^3/s)**	**(m^3/s)**	**%**
1	86.897	92.478	86.6	92.5	-0.31	0.05	179.375	179.153	-0.15
2	110.487	117.575	110.8	117.6	0.26	-0.01	228.061	228.339	0.15
3	128.827	138.128	129.9	138.4	0.84	0.20	266.955	268.305	0.50
4	149.100	157.013	147.7	158.8	-0.95	1.16	306.113	306.516	0.13
5	166.530	177.109	165.6	177.2	-0.54	0.06	343.639	342.842	-0.24
6	110.044	116.461	109.9	116.8	-0.09	0.25	226.505	226.694	0.09
7	130.202	137.726	131.3	138.6	0.87	0.61	267.928	269.911	0.74
8	136.210	143.524	137.8	144.3	1.15	0.53	279.734	282.067	0.85
9	154.684	162.283	153.8	163.0	-0.59	0.47	316.967	316.809	-0.05
10	107.773	114.137	108.3	113.8	0.45	-0.33	221.909	222.025	0.09
11	195.968	203.331	195.3	205.4	-0.34	1.00	399.299	400.666	0.35

Efficiency measurements at Frieira Unit 2 show that warranted values have been achieved once the estimated uncertainty of 1.5% has been taken into account (Fig. 9).

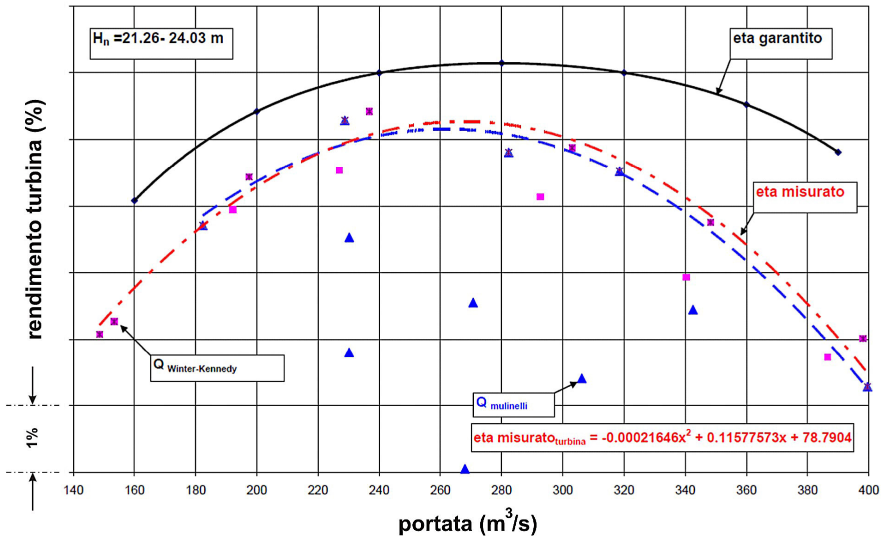

Fig. 9 – Frieira Unit 2 efficiency optimization (with Unit 1 stopped)

Cam curve optimization was performed using Winter-Kennedy method. A total of 23 stationary conditions were measured with the ASFM, with 11 of those also with the CMs (Ref. 5).

3.2 Castrelo Unit 1

ASFM acceptance tests for Castrelo Unit 1 included 40 stationary conditions measured in November 2011, 49 conditions in December 2011, and 53 conditions in March, April and May 2012.

The purpose of these tests was on one hand to measure the efficiency and on the other hand to improve the cam curve, if possible.

During the ASFM acceptance tests for Castrelo Unit 1 all guaranteed weighted conditions could not be field tested because of the inflow and dispatch limitations. The results were a little bit lower (Ref. 4) than the measurements made at Frieira Unit 2 and at Castrelo Unit 2.

During the cam curve optimization, significant improvements were obtained for all 3 conditions related to the operation of the Unit 2 (stopped, at half load, at full load) and the net head. Tests were used also to calculate and correct the net head value sent to the turbine governor. As an example, the efficiency increments achieved with the Unit 2 stopped are shown in Fig. 10: average 3.42%, maximum 5.87%. These results were obtained from the initial position of the rotor blade and the distributor, once the power set point was achieved, by varying the distributor position for the same rotor blade position.

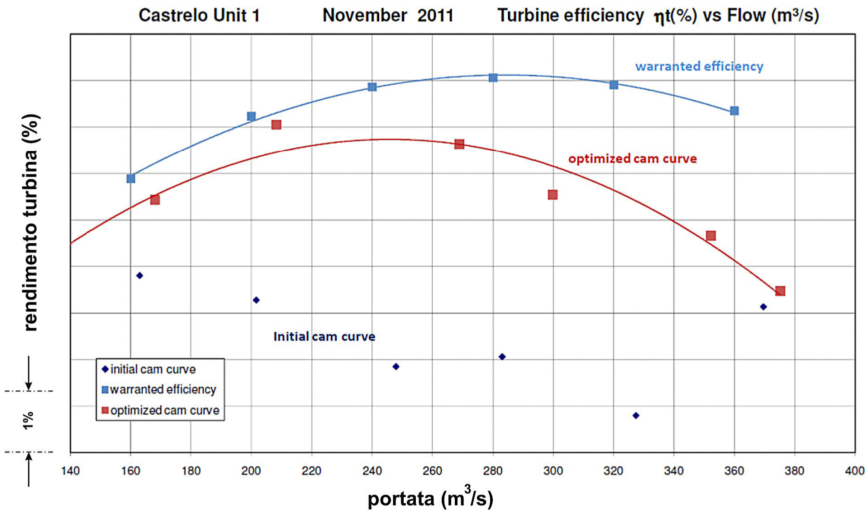

Fig. 10 – Castrelo Unit 1 efficiency optimization (with Unit 2 stopped)

The measurement uncertainties have been derived as follows:

Flow measurement uncertainty: Based on the existing experience with the ASFM for similar intakes, the systematic uncertainty has been estimated at ±1.2%. The random error has been calculated from the standard deviation of the measurement at ±0.5%.

Head measurement uncertainty: With the uncertainty of the pressure transducers at 0.1% , elevation gauge at 0.25%, the head measurement uncertainty is estimated at ±0.5%. With the potential energy uncertainty of 0.3%, the systematic uncertainty of head measurement will be $\pm\sqrt{0.5^2 + 0.3^2} = \pm 0.58\%$ and the random uncertainty 0.15%.

Power measurement uncertainty: With the power transformer uncertainty of ±0.5% and the calibration uncertainty of ±0.25%, the power measurement uncertainty is estimated at $\pm\sqrt{0.5^2 + 0.25^2} = \pm 0.56\%$ and the random uncertainty 0.20%.

Uncertainty in calculation of performance: $\pm\sqrt{1.2^2 + 0.58^2 + 0.56^2} = \pm 1.45\%$

Total uncertainty: $\pm\sqrt{1.45^2 + 0.65^2} = \pm 1.6\%$ (with the total random uncertainty estimated at ±0.65).

3.3 Castrelo Unit 2

ASFM acceptance tests for Castrelo Unit 2 were done in September 2011 when 62 stationary conditions were measured.

The results were very similar to Frieira Unit 2 measurements and the same conclusions apply. As an example, the efficiency increments achieved with the Unit 1 stopped were: average 2.09%, maximum 4.01% (Fig. 11).

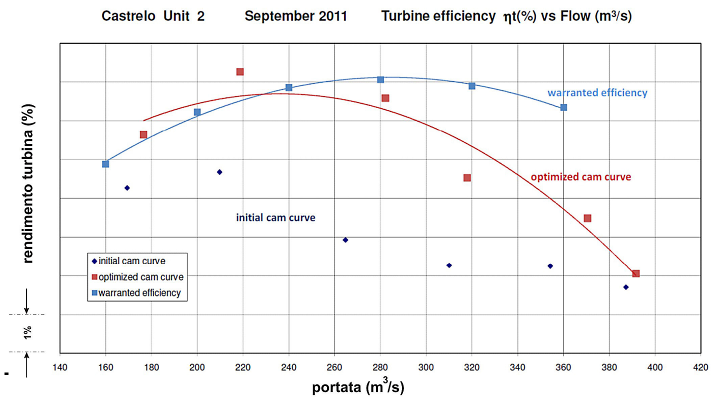

Fig. 11 – Castrelo Unit 2 efficiency optimization (with Unit 1 stopped)

3.4 Velle Unit 1

The initial measurements at Velle Unit 1 were made with the ASFM in January 2013, when 14 stationary conditions were measured. Once the differential pressure in the spiral case was calibrated, the following tests to check the efficiency and cam curve were performed using the Winter-Kennedy method in May 2013, when120 conditions were measured. The efficiency results were better than at all other units, even at maximum flows. In fact, in the case of the Velle Unit 1 the nominal efficiency at high flows as given by the initial cam curve is relatively low and close to the values actually measured at other units. The efficiency increments achieved with the unit 2 stopped are shown in Fig. 12: average 1.7%, maximum 2.94%.

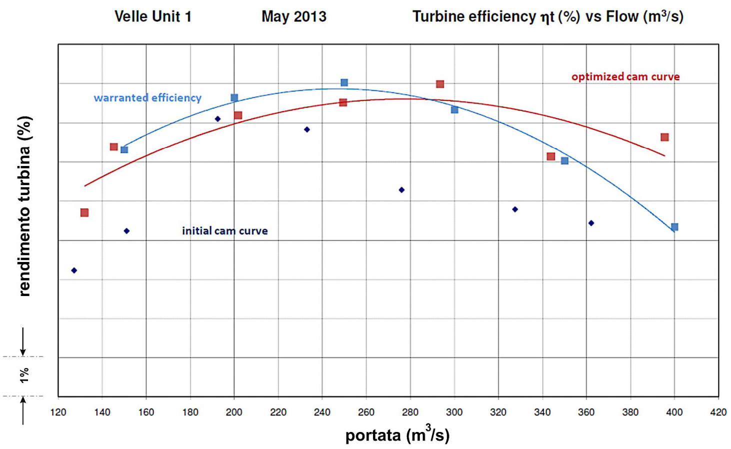

Fig. 12 – Velle Unit 1 efficiency optimization (with Unit 2 stopped)

4 Conclusions

The contract for the replacement of the runners at Velle, Frieira and Castrelo specified that the ASFM would be used for the flow measurement. If the warranted efficiency was not achieved based on the ASFM flows, CMs would be used for confirmatory flow measurement. As a result, both the ASFM and CMs were used at Frieira, but only the ASFM at Velle and Castrelo. The weighted efficiencies of all new units were warranted at 18 combinations of flow and net head as follows: 6 points with the other unit stopped, 6 points with the other unit at half load and 6 points with the other unit at full load.

At least 5 variations at each point were tested with the ASFM to carry out the cam curve optimization. In total, some 300 individual measurements were performed. After the first test at Frieira, all subsequent measurements were made by Gas Natural Fenosa personnel.

Measurement at all the warranted points was not possible because of the inflow and dispatch restrictions. The main difficulty has been that the cam curve optimization must be done under constant net head conditions while the weighted warranted efficiency points have different net heads.

The results of the first flow measurement at Frieira Unit 2, using the ASFM and CMs, were very close – all within 1%. By using the ASFM at other units, it was possible to significantly improve the cam curves, which was the responsibility of Gas Natural Fenosa. As a result, turbine efficiencies were improved and power outputs were increased for the same flows. Field efficiencies were measured to check the warranted values as much as the inflow and dispatch conditions allowed.

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