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Comparing acoustic scintillation and current meters discharge measurements at a mid-head HPP

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Abstract

This paper presents results obtained by EDF and WEST S.r.l. made a joint efficiency measurement test on a HPP in the South East of France, for the commissioning of a major 120 MW Francis turbine. Two absolute methods were implemented on this site: on one hand, current meters (CM), performed by WEST Company, as the code-approved method to be used to check the guarantees. On the other hand, the acoustic scintillation flow meter (ASFM) was implemented by EDF in the intake simultaneously. A large number of current meters (90) for this kind of operation were used, installed on a stationary frame made up of 9 hydraulically-profiled beams. Acoustic scintillation transducers were installed on steel plates mounted directly on the intake wall. Flow conditions were quite good for both methods. The entire efficiency/power range of the turbine was explored using both methods giving absolute discharge measurements. The benefit of using new algorithms derived from a previous PhD[1] work sponsored by EDF, even in these quite good conditions, will also be emphasized. A fairly good level of agreement was achieved between both absolute methods; the agreement was slightly improved when applying the new "SMASH" algorithms. The average difference between CM and ASFM discharge values lies beneath the combined uncertainties of the two methods.

I. Project history

The HPP is an underground Power Plant on the Durance river line (France, south-east), commissioned in 1975, consisting of 2 identical units (Francis turbines) supplied by a 32 km open channel, then 2 independent penstocks (140 m, ∅6 m), for a total installed capacity of 244 MW under 110 m of nominal net head.

After 35 years of operation, the hydro-mechanical equipment showed serious signs of wear linked to chronic disorders which made power generation more and more restrictive and risky. A general refurbishment was planned (table 1) in order to secure operation and upgrade the overall performances of the units.

The hydraulic profile of the new runner was designed specifically to produce a marked improvement in performance. Since the head race capacity is limited to 240 m^3/s, the new runner

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[1] Referred to as the « SMASH » algorithms

was designed with similar flow and output capacity to the existing ones (maximum unit flow and power: 130 m^3/s, 130 MW) but with a considerable increase in hydraulic efficiency.

Table 1: Disorders and scope of rehabilitation.

Issues to address	Scope of rehabilitation
High thrust bearing temperatures (pads and oil)	New thrust bearing
Low level of hydraulic performance of the runners confirmed by several series of measurements on site	New hydraulic components o New runner (new hydraulic design) o New guide vane profiles o Implementation of an axial aeration of the hydraulic vortex under the runner through the tubed hollow shaft line Air comes in at the top of the unit via an automatic air-supplying valve (opening as a result of the depressurization under the runner at partial loads)
Deformations of the distributor	New watertight distributor (except the existing head cover and bottom ring which are rehabilitated)
Vibrational state of the damaged shaft-line	Upgrading the shaft-line

The weighted average efficiency, allows understanding the turbine's overall performance. The different performance measurements and estimates since the initial commissioning show the expected gains (table 2; fig. 1).

Tests were carried out in 2011 on a scale model of 1/11 of the new runner. By scaling up the results to the real machine, the tests made it possible to forecast the future runner's hydraulic behavior: the weighted performance objective was achieved; the cavitation margins on the operation zone were sufficient; lastly, the need for an axial aeration on the runner that will allow the pressure fluctuations to be reduced was qualitatively confirmed.

Table 2: Estimates and measurements of hydraulic performances.

Record of estimates and measurements	Optimum efficiency	Weighted average efficiency	Measurement uncertainty
Original in-situ measurements (1979)	Reference	Reference	±2.0%
Predictive performances for the new runner (2010)	Ref. + 3.9%	Ref. + 5.1%	▨
Model tests (2011)	Ref. + 3.7%	Ref. + 5.4%	±0.24%

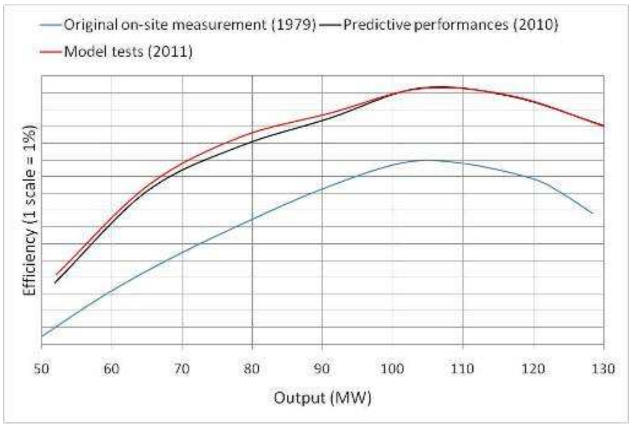


Figure 1: Hydraulic performance curves under maximum head

The considerable uncertainty of an *in-situ* performance measurement (between ± 1.2 % and ± 2 % with current methods) put the forecasts into perspective. However the potential gain remained positive even if the most unfavorable scenario was taken into account (*in-situ* measurements with increased uncertainty of 2%, and current guarantees reduced by a predictive uncertainty of 1.5%). The new runner was therefore supposed to lead to a minimum increase in overall hydraulic performance of 1.6%, which corresponds to an average gain of 11700 MWh/year for the 2 units.

II. Description of the flow metering techniques set-up

II. 1. Acoustic Scintillation Flow Metering (ASFM)

II. 1. 1. Measurement method

The ASFM uses a technique called acoustic scintillation drift to measure the flow velocity perpendicular to a number of acoustic paths established across the intake to the turbine. Short pulses of high-frequency sound are sent from transmitting acoustic arrays on one side to receiving arrays on the other, at a rate of approximately 250 pings/second [1]. Fluctuations in the amplitude of those acoustic pulses result from turbulence carried along by the flow.

These fluctuations (known as scintillations) are measured by the ASFM and from them the system 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). The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and with 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 Δx/Δt. 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.

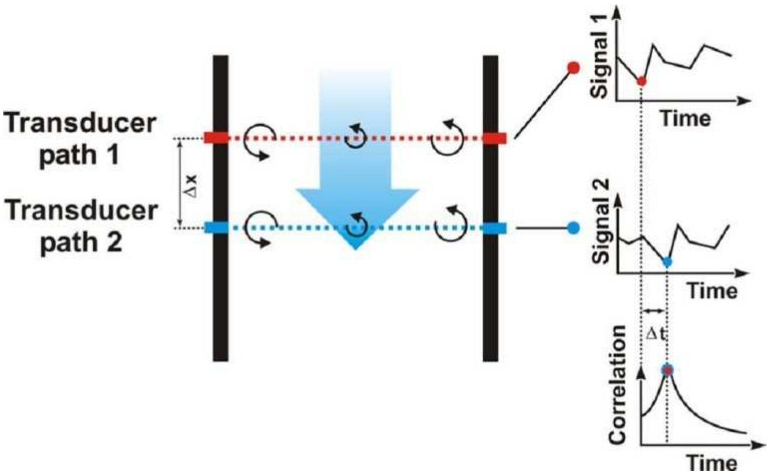


Figure 2: Schematic representation of acoustic scintillation drift.

II.1.2. Acoustic signal amplitude determination

In order to determine to acoustic signal amplitude, the ASFM measuring system determines the maximum value of each pulse’s envelope (named “ASFM Link” Software). Some recent works (“SMASH” project) have shown that another method to characterize the amplitude of the acoustic signal can improve the discharge measurement done in low turbulence conditions, which is the case when no trash racks is present upstream of the measurement section. This was possible only by recording the raw signals coming from the acoustic transducers from all paths. Advanced data recording tools were used, such as high speed streaming sampling cards. The amount of data gathered following on site tests, as well as laboratory measurements provided the basis of a long research into developing an algorithm that will extend the capabilities of the method (in terms of robustness and flow velocity range). In the case of low levels of turbulence, the new algorithms are capable of extracting enough information in order to compute a more accurate flow velocity and therefore a more accurate flow.

Since the quality/accuracy of the time delay between the time series depends on the quality of the time series, another energetic criterion had to be found in order to “boost” the turbulence footprint of the flow onto the signals, while removing/reducing the effects of unwanted interference. Since access to the raw data was possible, the researchers were able to perform a more in-depth analysis of the phenomena affecting the measurements.

The project had to take into account that the modifications must not have a large impact to the standard algorithm that is without having to change the ley parts of the system (acoustic transducers, electronics, etc.). Since the time series are obtained using an amplitude-based technique, the new tools would need to be based also on an energetic criterion. This was done by looking at the signal in a different representation (rather than the Amplitude-Time plane). This alternative representation has the advantage of separating the turbulence – related component from the unwanted ones which were overlapped in the time domain. Figure 3 shows a low turbulence time series and one with the boosted turbulence signature:

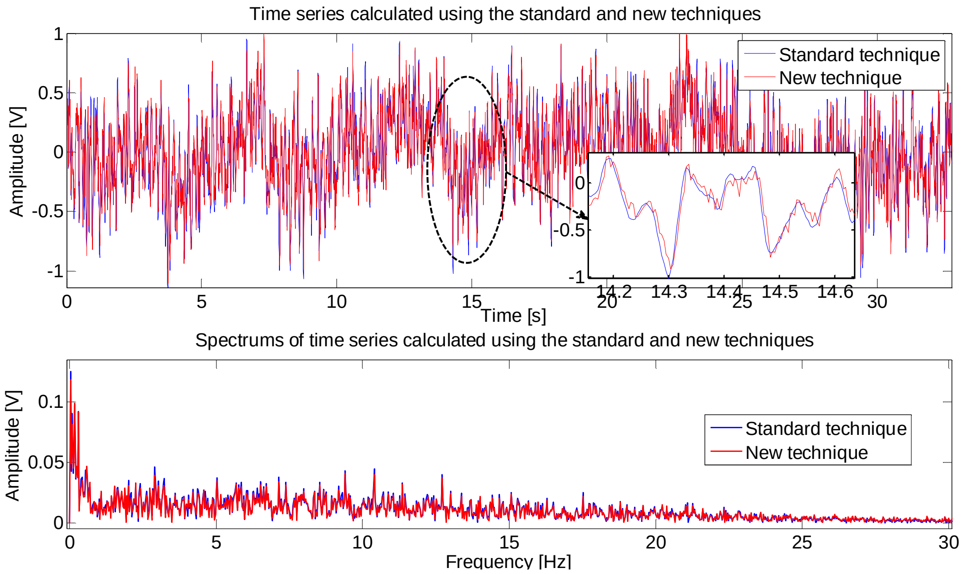


Figure 3. Boosted turbulence levels using the new algorithms.

The results show that the overall shape of the time series gets populated with more components specific to the embedded turbulence in the flow, resulting in a much higher correlation coefficient between the time series, and therefore to a better flow velocity accuracy.

II.1.3. ASFM set-up

Because of a previous mitigate experience with ASFM transducers on a traveling frame in this HPP, it was decided to install the transducers on two sets of steel plates, each plate being independent from the other, and installed into the intake using professional divers.
A total of 12 pairs of transducers was installed, providing a spatial resolution of around 0.5 m in the vertical dimension.

Figure 4 shows such a plate with 12 ASFM transducers mounted on it, before its installation in the intake by divers. Plates were meant to be mounted in front the stop-log gate slot, with fixations on either side of the slot so that they will be flush with the rest of the intake civil works, creating even better flow conditions for the CM just downstream (no recirculation in the slot, no wake reaching the current meters). Yet additional mounting devices had to be used on site, and some screws were added between the plates and the wall

This addition could seem negligible, but the screw heads were thick enough to create a small gap between the civil works and the ASFM plates in which water could flow during the tests. This was the origin of some vibrations of the plates, and probably the cause of some signal disturbances in the ASFM data which occurred for some operating points of the unit and especially for upper levels of acoustic transducers. These vibrations were partly cancelled out by the signal processing embedded in the SMASH algorithms but the residue accounts for some discrepancy between CM and ASFM measurements.

Basically the ASFM measurement section should have been “A+ grade”, because most following requirements of this system were met at the HPP:

- Trash rack elements were present upstream and with favorable design;

- Supporting beams of these elements were profiled and with enough distance so the wakes merged before reaching the measurement section;
- No transversal flow was expected, whereas the vertical flow component of around 7 % was well within the specifications.

The mere addition of screw heads on the back side of the plates was sufficient to downscale the measurement section from “A+” to “A-“ or even “B+”, as the ASFM is sensitive to flow-induced pulsations of the supporting plates in a certain range of low frequencies, between 5 to 37 Hz, where these artificial pulsations collide with the embedded turbulence used by the system to compute flow velocities.

Figure 4. Steel plate carrying 12 ASFM transducers.

The following figure shows the sections where instruments for both methods were installed in the intake:

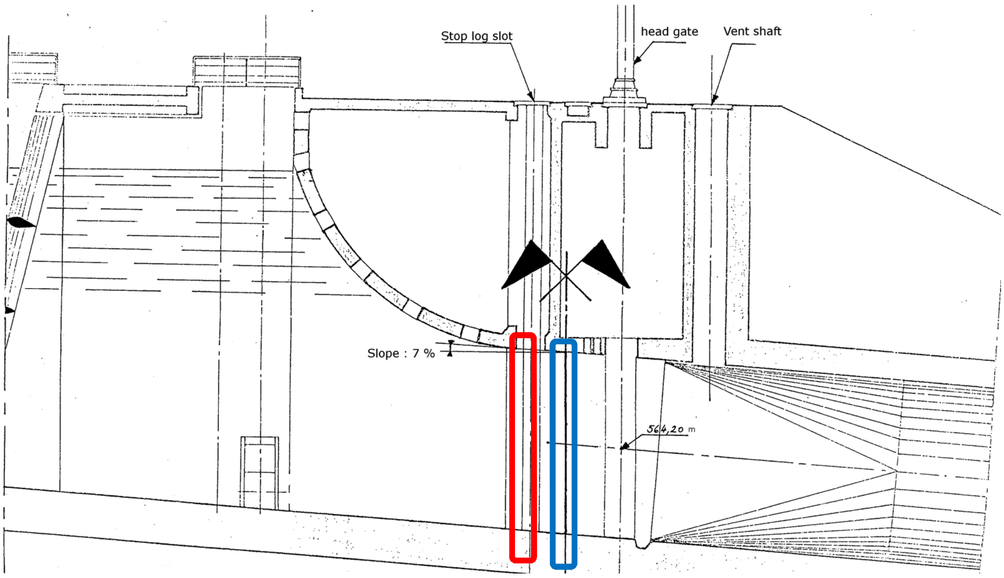


Figure 5. HPP schematic highlighting the sections for CM (blue) and for ASFM (red).

II. 2. Current meters (CM)

The CM measuring section was chosen in the intake between the flood gates and the head gate. A total of 90 current meters were placed on a support structure made of 9 horizontal beams (10 CMs/beam) having an oval cross section (75x35 mm) and two vertical reinforcing beams having the same section (figure 6) :

Figure 6. Current meters layout.

Each current meter is equipped with a reed and a magnetic cone that provide two pulses for each rotation of the C.M.'s propeller head (see figure 7). Three digital counters were used to record the pulses from the CMs during a 300 second period of acquisition.

Figure 7. One of the 90 current meters used in the tests and the mounting supports on the oval section beams.

The discharge is obtained, as indicated in the IEC Code EN60041 and ISO Standard 3354, integrating the flow field on the horizontal profile first and after on vertical profile by using the following expression:

$$Q = \int_0^H \left(\int_0^L V \, dl \right) dh \tag{1}$$

Extrapolation of the curve of velocities, the last measurement point to the vicinity of the side walls of the measuring section, was performed according to the formula:

$$V_X = V_a \left(\frac{x}{a} \right)^{1/n} \tag{2}$$

where the exponent ***n*** related to the roughness of the walls should lay in $4 < n < 10$; in this case the two current meters measurements close to the wall lead to the value $n=8$ that has been used for side walls, for the bottom floor and the top ceiling, as well.

A numerical calculation of the flow rate was made by the cubic method of J. Coffin and compared with the flow rate calculated using the numerical method of M.Spielbauer. This latter method is more difficult to implement in comparison to the method of Coffin, because the weight of the measured speeds are dependent not only by the geometry of the position of each single current meter in the measurement reticle but also by the relevant measured speeds.

The maximum discrepancy between the two numerical methods lays within 0.2%, therefore using the average between those methods the integration error can be assumed in the range of ±0.1%.

III. Results

III. 1. Current Meters – Scintillation results for Group 1

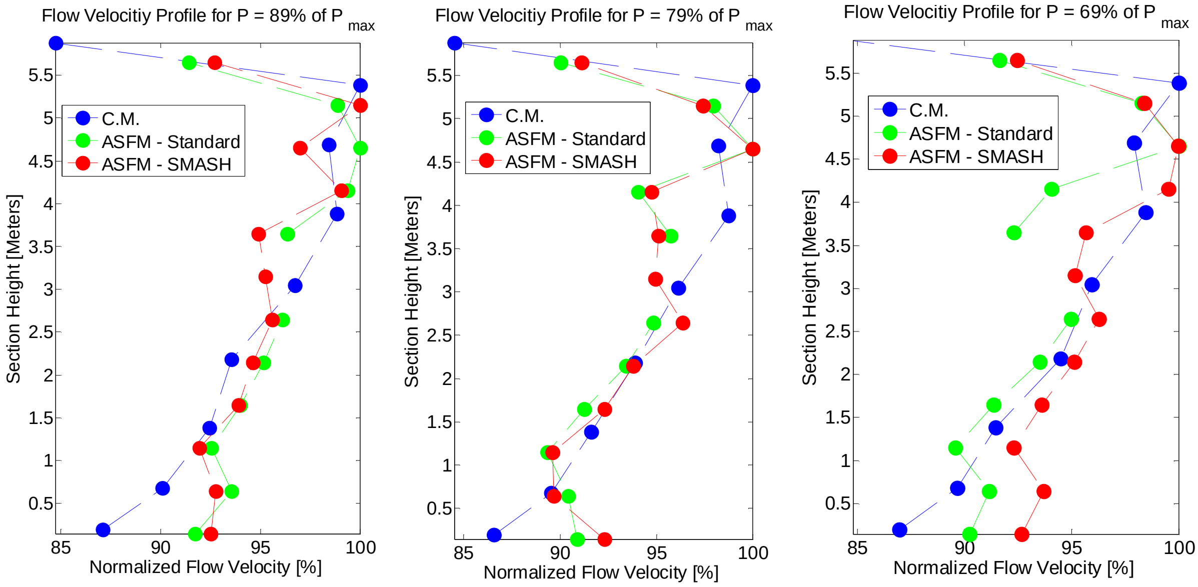
A relevant comparison between mean CM and ASFM flow velocities (standard and SMASH) was made. The results are illustrated in the following figures and tables:

Two consecutive CM measurements were performed during a 600 second period. For this time slot, three or four scintillation runs were made (although many more were possible, the recording of the raw scintillation pulses took time as well).

The averaged flow velocities for each method were then combined in order to compute the global flow velocity for each level in the 600 seconds time slot.

The signal quality for levels 7 – 12 was affected by unusual flow patterns, resulting in many signal level losses and higher than normal flow velocities (the reason for which the ASFM standard flow velocity for level 7 is not shown).

The following figure shows the averaged vertical flow profile obtained by both methods, whereas the following tables compare the averaged flow velocities obtained by both instruments for similar heights (only points with heights similar to ± 2 cm are shown).



(a) 89% of P_{max} (b) 79% of P_{max} (c) 69% of P_{max}

Figure 8. Flow velocities comparison for three different operating (power points).

Table 3. Relative error between CM, ASFM Standard and SMASH average flow velocities for P = 89% of P_{max}.

Section Height [m]	0,193	0,679	2,184	3,044	4,689
$\varepsilon_{CM/ASFM\ standard}$ [%]	-3,24	-7,94	-4,46	2,02	7,52
$\varepsilon_{CM/ASFM\ SMASH}$ [%]	-6,07	-10,6	-5,52	2,21	6,89

Table 4. Relative error between CM, ASFM Standard and SMASH average flow velocities for P = 79% of P_{max}.

Section Height [m]	0,193	0,679	2,184	3,044	4,689
$\varepsilon_{CM/ASFM\ standard}$ [%]	-3,86	-9,22	-0,05	0,52	9,13
$\varepsilon_{CM/ASFM\ SMASH}$ [%]	-5,40	-8,94	-1,05	0,91	8,61

Table 5. Relative error between CM, ASFM Standard and SMASH average flow velocities for P = 69% of P_{max}.

Section Height [m]	0,193	0,679	2,184	3,044	4,689
$\varepsilon_{CM/ASFM\ standard}$ [%]	-4,22	-9,21	0,35	6,07	9,35
$\varepsilon_{CM/ASFM\ SMASH}$ [%]	-3,87	-7,24	-2,94	2,58	7,88

III. 2. Measured Flow Comparison

Since two distinct CM flow measurements were made, it is interesting to see the relative errors between the CMs and the ASFM (both standard and SMASH). Tables 4 and 5 illustrate the computed relative errors for five relevant points on the efficiency scale.

Table 6. Relative measured flow error between CM, ASFM Standard and SMASH for several efficiency points – Run 1.

Output (% P_{max})	**59 %**	**69 %**	**79 %**	**89%**	**100%**
$\varepsilon_{CM/ASFM\ standard}$ [%]	1,11	1,25	0,67	1,34	1,13
$\varepsilon_{CM/ASFM\ SMASH}$ [%]	2,81	1,71	0,26	0,90	0,48
$\varepsilon_{ASFM\ standard/ASFM\ SMASH}$ [%]	3,96	0,46	0,94	0,45	0,66

Table 7. Relative measured flow error between CM, ASFM Standard and SMASH for several efficiency points – Run 2.

Output (% P_{max})	**59 %**	**69 %**	**79 %**	**89%**	**100%**
$\varepsilon_{CM/ASFM\ standard}$ [%]	1,21	1,65	0,42	1,17	N/A
$\varepsilon_{CM/ASFM\ SMASH}$ [%]	1,61	0,64	0,42	0,01	N/A
$\varepsilon_{ASFM\ standard/ASFM\ SMASH}$ [%]	3,96	0,46	0,94	0,45	0,66

III. 3. Measured efficiency

The graph shows the normalized efficiency obtained by both methods.

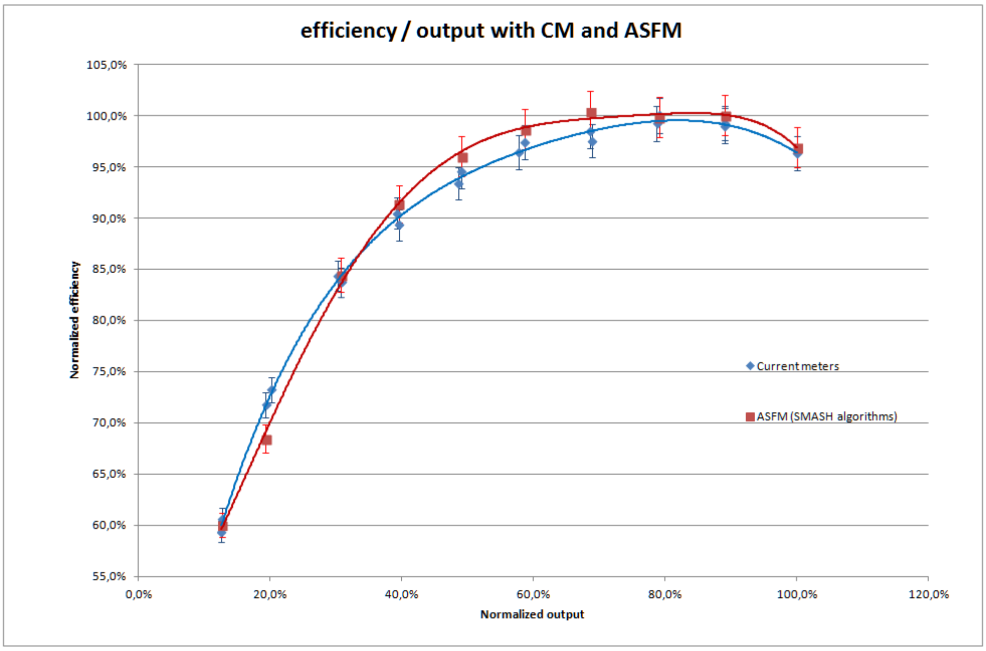


Figure 9. Efficiency / output with CM and ASFM.

The graph shows that there is a good overlapping of the intervals defined by the measurement points plus the uncertainty bars from both methods. At partial load there is a higher discrepancy but this may have be caused by higher flow variations and the methods should not be accounted for all of the bias.

III. 3. Uncertainty for each method

Current Meters

All the verifications performed by WEST show that the prescriptions of IEC 41 on current meters measurements were met during the tests. Consequently, for the uncertainty on the discharge, a value of the expanded uncertainty **W = ± 1.4 %** is associated to all CM discharges values, leading to a confidence level of 95 %.

ASFM

Acoustic scintillation is not present yet in the current issue of the IEC 60041 standard or in other international codes, although the latest projects under revision of these documents will mention this technique together with a typical level of uncertainty that can be reached in usual conditions. Hence, each user of the ASFM has to rely on its own experience and on published results in order to compute a plausible value for the uncertainty of these measurements.

Given the overall good quality of the measurement section, slightly degraded by fixation elements of the supporting plates, a tentative value of **W = ± 2.0 %** is chosen for the expanded uncertainty of all ASFM discharge measurements.

The field tests described in this article provide material to verify if the hypothetical value proposed for the uncertainty of ASFM measurements is confirmed or not. To do so, the normalized error, as per ISO/IEC Guide 43-1, is computed for each operating point using the following formula:

$$\epsilon_n = \frac{|Q_1 - Q_2|}{\sqrt{U_1^2 + U_2^2}} \tag{3}$$

where: Q_1 and Q_2 are the flow rates measured by the two methods (ASFM providing Q_1 and CM acting as reference method and providing Q_2);

U_i is the expanded uncertainty associated with the value of the flow rate Q_i with a coverage factor of 2, giving a 95% confidence level.

Table 8. Normalized errors for CM and ASFM (standard and SMASH).

Point	**59 %**	**69 %**	**79 %**	**89%**	**100%**
$\varepsilon_{\text{CM/ASFM standard}}$ [%]	0,34	0,45	0,27	0,62	0,60
$\varepsilon_{\text{CM/ASFM SMASH}}$ [%]	0,87	0,61	0,11	0,42	0,26

With this definition, the critical ϵ_n value is unity, and values below unity indicate insignificant bias between the measurements, i.e. the difference between the measurements is well within the combined total uncertainties of the two methods.

The ϵ_n values are listed in section III.2 of this chapter. Values are mostly below unity, showing that the agreement between CM and acoustic scintillation methods is small, compared to the combined uncertainty.

This constitutes a factual verification by field tests that for the present tests, an expanded uncertainty value of ± 2.0 % is appropriate for the acoustic scintillation measurements.

IV. Conclusions

These efficiency tests gave us the opportunity to compare two intake methods in relatively good conditions for each technique.

The current meter method was the primary method for guarantee verification, giving accurate and reliable results on Unit #1, although the installation proved cumbersome and time-consuming.

Acoustic scintillation was performed as a secondary method and as a transfer method on Unit #2 where CM were not used to estimate the efficiency of this other Unit, because of the cost for such an operation. ASFM proved easier and faster to install, although it does not compare exactly to the CM in terms of laterally averaged velocities. Still, the comparison on the discharge values computed by each method is within the overall uncertainty of both techniques, showing acceptable levels of overlapping values.

Results show that when a total uncertainty of ± 2.0 % is chosen for the acoustic scintillation measurements, statistical comparison values between CM and acoustic are good. This validates that for this given configuration, the value of ± 2.0 % is appropriate.

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