Case studies of discharge measurement
Using the acoustic scintillation flow metering technique

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Introduction

DTG is an engineering Division in EDF, in charge of performing discharge and efficiency measurements for the power plants run by the EDF Group. These can be hydraulic, conventional thermal or nuclear power plants, in France or abroad.

Concerning low head hydro plants, or other sites where the methods recognized by IEC 60041 can not be applied due to specific reasons, DTG has been looking for a method capable of being used instead of current meters, while generating less unavailability on plant operations.

In 2006 DTG decided to set up a full scale experiment of the Acoustic Scintillation Flow Meter (ASFM) in one of its hydro plants where a turbine refurbishment was to take place. In June 2006 discharge measurements were performed on Unit 1 at the Kembs hydro power plant, located on the Rhine River in France, near the cities of Mulhouse and Basel (Switzerland). The manufacturer of the ASFM was contracted by EDF to provide a 2-bay, 2-path system, on a rental basis, to perform the tests and to provide EDF with the analysis of the data and a comprehensive report of the measurement campaign.

Consequently to the Kembs testing which was found successful, DTG decided to purchase an ASFM in the same configuration, for performing its own discharge and efficiency measurements, especially where current meters used to be previously installed.

The first use of the ASFM by DTG on its own took place on Units 4 and 5 of the Pinet hydro power plant, located on the Aveyron River in the South West of France. Discharge measurements were made there while an internal intercomparison campaign was programmed, with three different flow metering techniques being bench marked : acoustic scintillation, acoustic time of flight and a chemical tracer method. The results of this campaign were used by DTG to set the uncertainty level to be associated with ASFM measurements.

1. Presentation of the acoustic scintillation technique

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 of the turbine. Fluctuations in the acoustic signals transmitted along the paths result from turbulence in the water carried along by the current. 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. A mean velocity perpendicular to the acoustic paths $V = \Delta x/\Delta t$ is then computed, and the total flow is obtained by integration of the velocity vectors measured in several locations covering the total cross-sectional area of the intake. See ref. [2] for a more comprehensive presentation of the ASFM features.

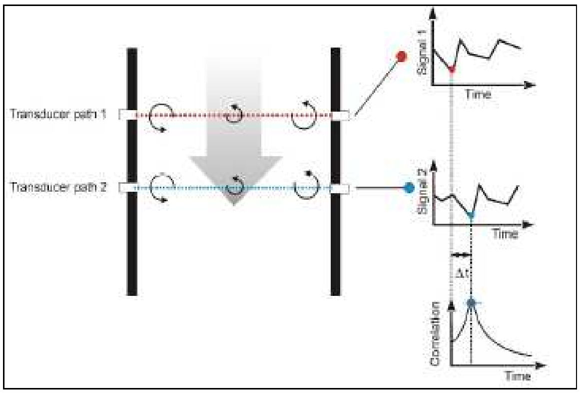

fig. 1 acoustic scintillation operating principle

2. Initial testing in Kembs

The Kembs hydro project comprises 7 low head units barring the Grand Canal d'Alsace which is fed by the waters from the Rhine River. DTG was contacted to perform efficiency measurements on Unit 1 Kaplan turbine before its complete refurbishment due to start in September 2006, so as to be able to verify the expected improvements in terms of maximal power output and efficiency once the refurbishment is over.

On this occasion, DTG contracted ASL AQFlow to assist in the installation and operation of a leased 2-bay, 2-path ASFM system.

2.1 Description of the measurement location

ASFM operation downstream of running turbines is not recommended by the manufacturer. The ideal location is far enough downstream of trash rack elements, generating smooth and isotropic turbulence in the measurement plane. No large vertical or horizontal elements should be present upstream of the ASFM, since they could induce a wake effect that would bias the flow indication from the ASFM.

In Kembs two slots were considered for ASFM installation :

- The stop-log slot
- The main intake gate slot

It must be noted that in Kembs, the intake is divided into two levels : the lower level leads to the turbine, while the upper level is used as a flood gate.

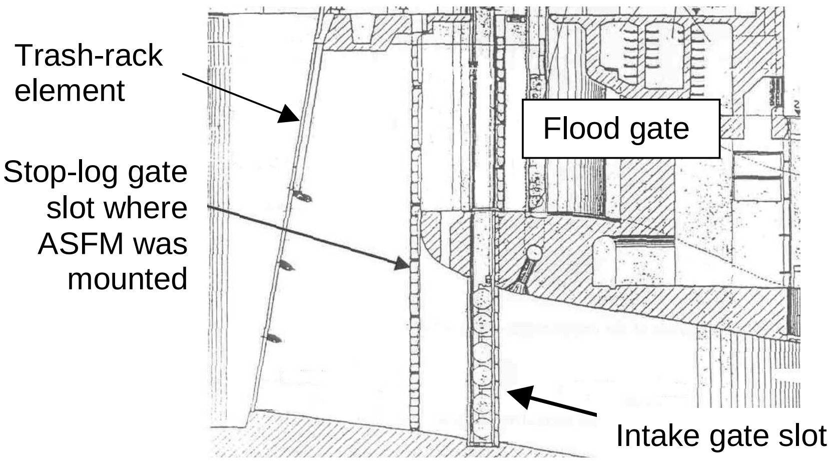

fig. 2 schematic of the intake bay (elevation)

Choosing the main intake gate slot would have meant several days of unit outage, so the stop-log slot was chosen as the measurement plane, after ASL validation. On a logistical point of view, frames could be lowered into this slot with the help of the trash-rack cleaner cranes, offering a good solution for frame handling.

2.2 Frame design

The frame was designed by DTG and a local contractor with remote assistance from ASL. The basic guidelines that must be followed are the same as those for a current meter frame.
Great attention was paid to minimize the disturbance created in the flow by the frame : once in the stop-log slot most parts of the frame, including the transducers, are hidden in the guide, with only two transversal beams present in the flowing fluid. The beams were designed so their obstruction effect would be reasonable, while keeping the frame as rigid as possible.
Two identical frame units were built, as each turbine in Kembs has 4 intakes, allowing simultaneous measurements in 2 bays at a time.

2.3 ASFM operation

After the transducers were mounted properly on the frame, and operational tests were successfully carried out, discharge measurements were performed for 3 days, at various wicket gate openings.
Each measurement lasted for approximately one hour, taking into account that two frames were manoeuvred at a time, in intakes #1 and #3 first, then switched to intakes #2 and #4 when the measurement process was resumed.
The plant conditions (gross head, output) proved quite stable over this period of time. Yet fluctuations in gate openings occurred over the one-hour long period of time necessary to achieve ASFM measurements. These fluctuations are taken into account through the global uncertainty associated with the results.

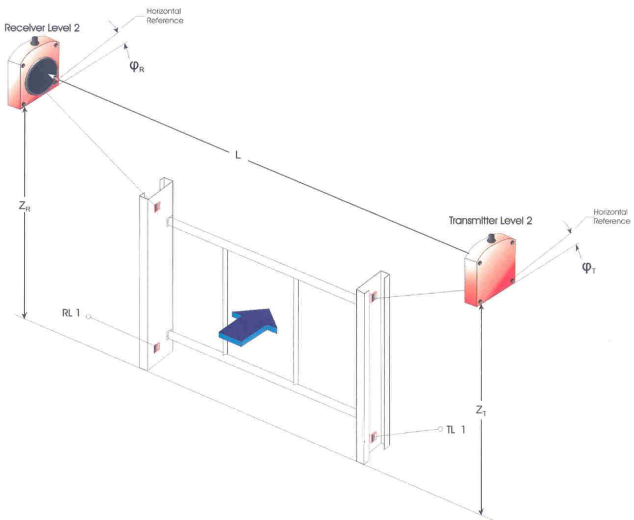

fig. 3 schematic of a frame with its transducers

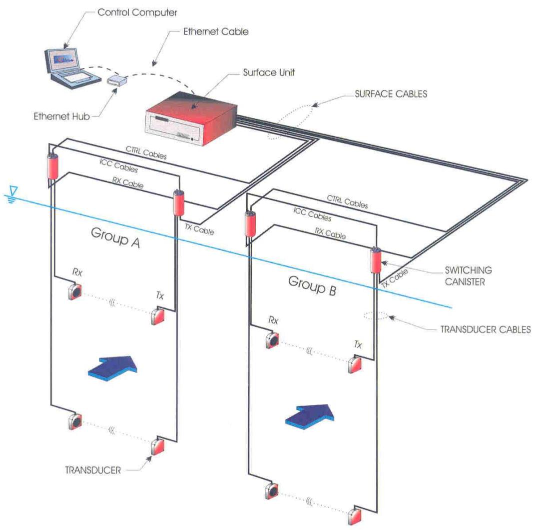

fig. 4 View of a 2-bay, 2-path ASFM system

2.4 Comparison between current meters and ASFM operation

The intake gate slot had been used for the last efficiency measurements performed in 1994 on Unit 1, with current meters installed on a moveable frame. Yet their installation had made it necessary to stop the unit for one whole week, to remove the intake gates, to dewater the intake during installation , and to set a temporary ceiling to isolate the intake level from the flood level (see fig. 2). Another week was needed to remove the devices, accounting for a two-week global unavailability of Unit 1.

On the other hand, in the 2006 measurements the ASFM transducers were mounted on the frame lying flat on the deck, then the frame was lowered into the gate while the Unit was running. Thus not a single day of unavailability was required for the ASFM mounting and operation. No ceiling was installed as the ASFM is able to measure both horizontal and vertical velocity components.

2.5 Results

The uncertainty of the ASFM measurements was calculated by the ASFM manufacturer : the expanded uncertainty determined with a coverage factor k=2, synonymous with a 95% confidence level, is **U = ± 1.8%.** It combines a 0.9% random component and a 1.5% systematic error component.
This figure is similar to the one given by IEC 60041 standard for the 1994 current meter measurements (±2% at best).

The results obtained with the ASFM in terms of turbine efficiency are plotted below, together with previous results from 1994 with current meters and a third curve showing the results of a Winter Kennedy (W-K) measurement operated in parallel to the ASFM measurements. All data are converted to a gross head of 13.45 m.
The W-K coefficients were derived from the three discharge measurements made with the ASFM concurrently.

According to ASFM figures, the efficiency measured in 2006 was about 6 % below that measured in 1994, near the optimal turbine operation. This deviation was found quite large, even when considering a 12-year operation impact. Indeed, previous measurements showed that between 1984 and 1994 a small degradation of only 1.5% had occurred then. Several possible causes are suspected to explain this 6% deviation :

- Unit 1 is a Kaplan turbine, whose cam efficiency was not checked during the tests. It could be that the current cam curve is no longer suited
- 1994 measurements by current meters may have given an underestimated value for the flow rate because of a possible oblique flow angle in the intake , leading to artificially large values of efficiency.
- Unit 1 has been in operation since 1946 ; both the turbine and the draft tube may have suffered from a degradation accelerating over the last 12 years
- The ASFM might have given overestimated values for the flow rate ; yet recent studies indicate that the ASFM used to suffer rather from a negative bias (see ref. [3])
- The gross head measurement includes the trash rack elements ; although they were cleaned before the measurements started, their blockage during the measurements is hard to estimate and might have induced an additional bias on head measurements.

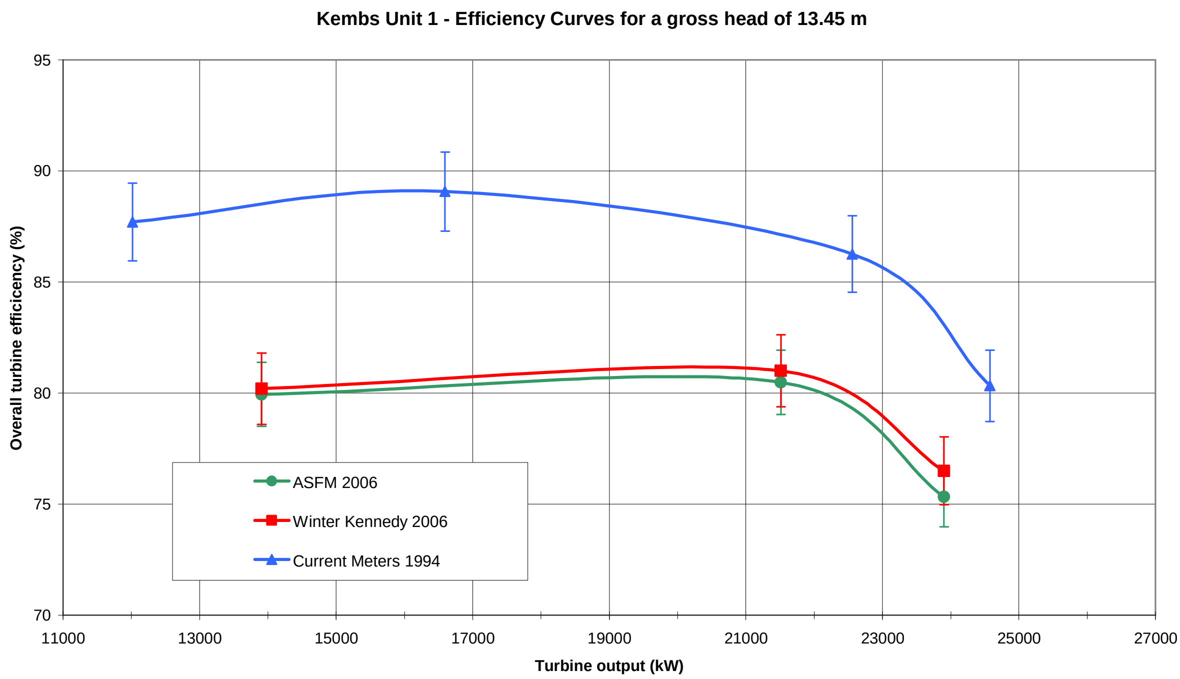

fig. 5 Efficiency curves obtained with current meters (1994) and acoustic scintillation (2006)

Kembs Unit 1 new turbine's acceptance will be determined through model tests this year. Future field measurements with the ASFM on the new turbine are already scheduled in early 2008 for index testing. Comparison between ASFM discharge measurements in 2006 and 2008 will provide DTG with more data about the reliability of the acoustic scintillation method for this site.

3. Discharge measurements in Pinet

Before starting to use the ASFM for contractual measurements, DTG planned an internal intercomparison of three different flow metering techniques, including acoustic scintillation. For this purpose, field acceptance tests of Unit 4 of the Pinet plant provided the occasion to compare acoustic scintillation with similar or concurrent techniques.
The Pinet plant comprises 5 units, each of approx. 9 MW output. Test were performed on Units 4 and 5, which are connected to a common penstock, fed by the waters of the Tarn River through 2 intakes.

3.1 The Time of Flight Acoustic meter arrangement

The ToF flow meter consisted of a 4-path internal flow meter, whose installation in the inlet tunnel had required the dewatering of the 5-meter diameter tunnel and penstock and the installation of an oblique scaffolding. The 4 paths were parallel to the flow and installed in two acoustic planes as shown in fig. 6.
The minimum code requirements in terms of straight lengths were met on site, as the meter was installed 60 D downstream and 6 D upstream of the nearest disturbances (code requirements are resp. 10D and 3D).
To assure a full compliance with IEC 60041 standard – Annex J, circularity was measured at the precise installation location and an exact diameter value was determined, by a Topography Expert team within EDF-DTG.
The diameter value retained for the calculations is the average of five equally spaced measurements of the diameter D in the measurement section, including one at each end and one at the centre. The average value found was D = 5003 mm ± 40 mm for a theoretical value of 5000 mm. Circular deviation was found equal to ± 30 mm, whereas path lengths were determined at ± 6 mm. Measurements were performed with a theodolite mounted on a heavy tripod in the centre of the measurement section.
The ToF meter was thus considered the reference meter for this intercomparison, as well as for the field acceptance tests of Unit 4.

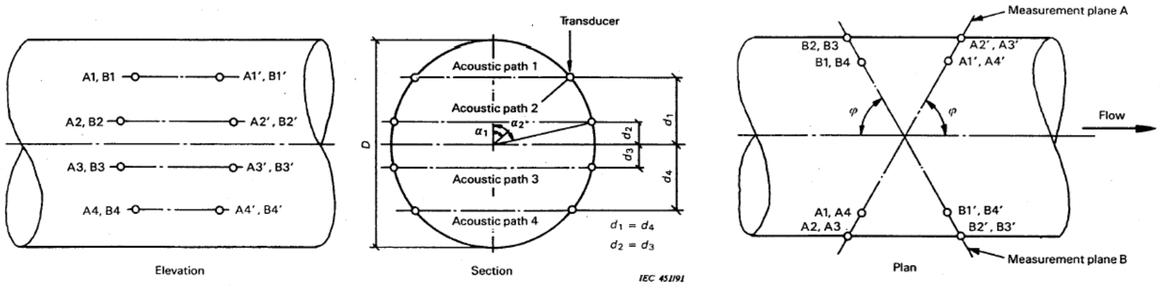

fig. 6 ToF meter arrangement (according to IEC 60041)

3.2 The chemical tracer method

The tracer method implied the use of Rhodamine WT as the chemical tracer. Rhodamine was injected in the middle of the conduit *via* a surge chamber (near the ASFM measurement plane) at a steady monitored rate, and its concentration in samples taken from the conduit via pressure taps was induced from fluorimetric analysis. The sampling location was located 75D downstream of the injection point, the duration of injection was adjusted to ensure a 30-minute stable concentration at the sampling location. Knowing the tracer concentration at the injection and sampling points, together with the injection flow rate, allows for the calculation of the water flow rate using the following formula :

$$Q_{water} = q_{injection} \cdot \frac{C_{injection}}{C_{sample}}$$

The measuring length of 75 D is in accordance with ISO 2975/1 fig.1. Three series of at least 400 individual fluorimetric measurements were collected over the 30-minute period at each sampling point.

3.3 The Acoustic Scintillation Flow Meter arrangement

Concerning the ASFM, once again “tailor-made” frames were manufactured for the Pinet intakes, with remote assistance from ASL AQFlow.
Two frame units were built to perform simultaneous measurements on intakes 1 and 2 with the ASFM, while the ToF meter was installed in the inlet tunnel common to units 4 and 5. There again the stop-log slot was used for ASFM operation, as it was conveniently located just downstream of the trash rack elements. Manual hoists mounted on a moveable portal were used for frame handling. Difficulties were encountered when first lowering the frames into the slot, as these had not been used in the recent years, thus delaying by several hours the operational status of the ASFM on site.

The arrangements for the three metering techniques are shown on fig. 7.

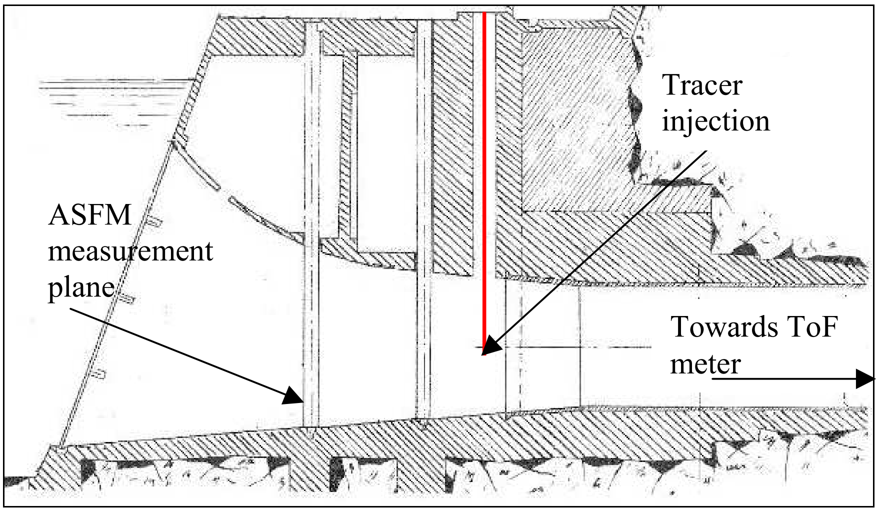

fig. 7 arrangement of the three meters involved in the Pinet experiment

3.4 Results

The intercomparison was performed in two steps : first measurements were made with the ToF meter and the tracer method in December 2006, then measurements with the ASFM and the ToF meter made in February 2007 completed the previous set of data.

The intercomparison was initially due to involve all three techniques at the same time, but the freshly commissioned DTG ASFM proved unsuited for measurements in a Pinet-like configuration. The ASFM electronics was sent back to the manufacturer for modification under warranty and the intercomparison resumed after its return – without the tracer method.

The three techniques have very different response times, from 8 seconds for the acoustic ToF, to 30 minutes for the tracer method and acoustic scintillation in this site configuration. Consequently, the ToF meter readings were recorded during the data collection of the other metering techniques, so as to estimate the stability of the flow rate. A component for the flow stability was included in the ToF expanded uncertainty (see below).

For a good understanding of the results, normalized errors E_n have been computed for each point of the comparison. The normalized error E_n is defined as such :

$$E_n = \frac{|q - Q_{ref}|}{\sqrt{U_q^2 + U_{ref}^2}}$$

where : q is the flow rate measured either by the tracer method or the acoustic scintillation
Q_{ref} is the flow rate obtained by acoustic ToF meter
U_q is the expanded uncertainty associated with the value of the flow rate q with a coverage factor of 2 (k=2) giving a 95% confidence level
U_{ref} is the expanded uncertainty associated with the value of the acoustic ToF flow rate with a coverage factor of 2 giving a 95% confidence level

The definition and use of normalized error is fully described in standards ref. [4] and [5].

The value of E_n is an image of the agreement between both flow rates : values of E_n between 0 and +1 are synonymous with a good agreement, compared to respective uncertainties. The closer E_n is to 0, the better the agreement. Values of E_n exceeding 1 indicate significant bias between flow meters.

Expanded uncertainties were computed for each point and for each metering technique, following the guidelines of IEC 60041 :

- An expanded uncertainty of **U ±1.7 % (k=2)** was determined for acoustic ToF flow rate values, including terms for acoustic path length, velocity, diameter and circularity determination, angle determination, transit time, and stability over a 30 minute-period
- For the tracer method flow rates, U was considered equal to **±2.3% or ±3.3% (k=2)**, depending on the point ; this figure combines standard deviation for the tracer concentration measurements, and the injection flow rate

- For the ASFM flow rates, a value of **U = ±3.5% (k=2)** was assumed. This figure combines a measured repeatability of 1.9%, a systematic error component of 1.5% from manufacturer, plus a 2.5 % systematic error after comparison with the ToF meter.

The following table shows the results in terms of flow rate values and normalized error values for each point :

Discharge measurement value (m3/s)			
Tracer	**ASFM**	**Acoustic ToF**	**En**
	37,38	36,53	0,52
	37,58	36,47	0,68
	36,41	36,76	0,22
	45,91	44,71	0,60
	47,52	44,49	1,47
	45,51	44,63	0,44
	53,93	51,84	0,89
	53,63	51,79	0,79
	53,77	51,57	0,94
30,37		30,65	0,34
24,98		25,20	0,25

table 1 - results of the intercomparison at Pinet 4 & 5 (comma is the decimal separator)

3.5 Comments

The comparison of acoustic Time of Flight ultrasonic meter and the chemical tracer method leads to very close flow rates on both parts : the normalized error does not exceed 0.35 which is a very good figure. These results give confidence in the proper installation of the acoustic ToF meter in the conduit and in its reliability.

Concerning acoustic scintillation compared with acoustic ToF, E_n values are slightly higher.
The one point leading to a value of E_n = 1.47 can be considered as an outlier, which would be rejected when compared to the other values obtained at the same flow rate. As for the other points, whose E_n values range from 0.22 to 0.94, they seem to validate the assumption of a total uncertainty of ± 3.5% (k=2) for the acoustic scintillation meter in the Pinet configuration.
In particular, data obtained around 38 m^3/s show a small bias (1%) compared to acoustic ToF. For this point a value of uncertainty lower than 3.5 % might be retained concerning acoustic scintillation,.

The Pinet site configuration was not optimal for such tests, as the number of intake bays (2) and the manual handling of the frames made it quite long (30 minutes) to obtain a full measurement by acoustic scintillation. Moreover all three techniques could not be compared at the same flow values for logistical reasons.

4 Conclusion

The initial test in Kembs was very interesting to us, as it provided EDF-DTG with a factual insight into the potential of acoustic scintillation, and an assessment of the main features of the ASFM device.
The intercomparison performed in Pinet between acoustic scintillation on one hand, and acoustic ToF and the tracer method on the other hand, gave promising results.
A very good agreement was found between the tracer method and the acoustic time of flight method, for relatively small flows.
The data collected show that a total uncertainty of ± 3.5 % (k=2) can be so far reasonably achieved by acoustic scintillation in a Pinet-like plant configuration. A lower level of uncertainty might be reached under better circumstances, especially when measurement duration can be reduced down to 5 or 10 minutes and when a single frame is sufficient. A careful attention is to be given to frame design, as it is dramatically important for the whole measurement success.
Both experiments increased EDF-DTG know-how in acoustic scintillation flow metering. Tests with this new technique will continue on other plants with other configurations. Another internal comparison with an IEC 60041 approved method is already sought to update the ASFM uncertainty level found in Pinet.

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The Authors

Bertrand Reeb, Eng, is a test engineer with EDF DTG. He has a 9 year experience in both liquid and gas flow metering, and has recently hold a position of technical manager of an accredited calibration laboratory within EDF. He performs discharge and efficiency measurements on EDF power plants, with various ISO 60041 accepted flow metering techniques. He is specialized in ASFM measurements within DTG.

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