Experience with comparative discharge evaluation in hydropower plants

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Abstract

The thermodynamic method is, at least for high heads, the most accurate method for testing the efficiency of hydropower plants. No discharge measurement is required to determine the hydraulic efficiency. On the other hand, the discharge flowing through the turbine or pump can accurately be evaluated from the hydraulic efficiency by measuring the electric power and knowing the mechanical and electrical losses.
This contribution presents the results of a series of comparisons of the thermodynamically determined discharge data with data from available flow meters owned by the hydropower plant operator.
Data of discharge measurement for comparison stem from acoustic transit time measurements (multipath, feed through or internal mounted sensors, or clamp-on sensors), from electromagnetic flow meters, from differential pressure measurements such as Venturi meters, or from turbine governor data (needle stroke of Pelton injectors).
It is especially essential to calibrate such installed devices with a view to long-term efficiency monitoring and optimization of machine operation. In addition, the long-term stability and the repeatability of the thermodynamic method and various discharge measuring methods are important and are discussed using examples.

1. Introduction

For the presented study 59 thermodynamic measurements carried out by our measurement team are analysed. The Figure 1 shows these measurements as a function of discharge and head. It becomes obvious that almost the entire recommended head and discharge range was measured. Most of the cases lie between heads of 250 and 750 m, in a range well suited for the thermodynamic method. In addition, some low head applications (head between 70 and 140 m) and some high head applications (above 1000 m) with the thermodynamic method are available as well. Special care and experience is required for the low head applications (for example [1] or [2]).

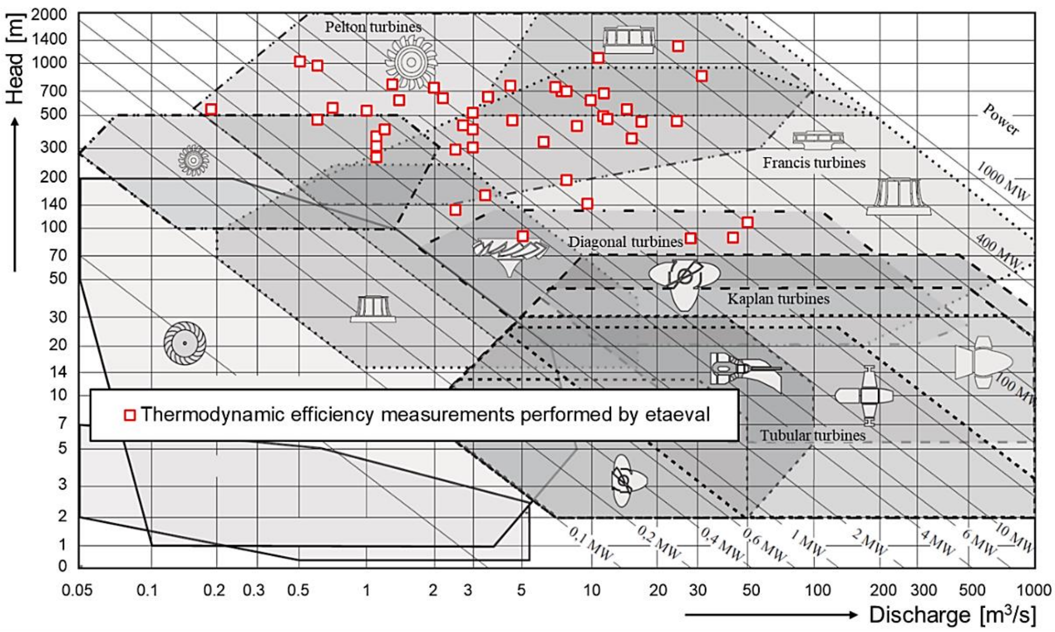

Figure 1: Thermodynamic efficiency measurements by etaeval for the presented case study, turbine classification according to Sulzer Hydro, Ravensburg, 1998.

The Table 1 show all types of discharge comparisons, resulting from the measurements in the hydropower plants (HPPs) shown in Figure 1, that were used in this study. The individual cases were assigned to four measurement methods. A total 59 discharge installations can be compared with the discharge resulting from the thermodynamic measurements. For the category of acoustic transit time (ATT) flow meters, a distinction is made according to the number of path and the type of installation (both categories result in 36 comparisons). Some further examples of different discharge measurement methods (such as Pitot tubes or volumetric gauge methods) are available, but the number of cases for the present study was set to a minimum of 3 examples.

Table 1: Number of comparisons with corresponding measuring methods.

	Acoustic transit time		Differential pressure		Electromagnetic flow meter	Turbine governor	
	2	1-path	1	Winter-Kennedy	3	11	
	16	2-path	8	Venturi			
	8	4-path					
	10	8-path					
	13	Clamp-on					
	19	Feed through					
	4	Internal mounted					
Total	36		9		3	11	59

In the most cases, comparisons are made with ATT flow meters (39 cases). In the past, a large number of differential pressure measurements in Switzerland were replaced by ATT flow meters. Electromagnetic flow meters are interesting, but the flow meter price seems to be too high for larger pipe diameters. This may explain the low number of installations. In many cases only turbine governor data are available. In this study, the examples of turbine governors come exclusively from Pelton turbines. That means, that they origin from measurements of the needle opening.

2. Procedure for comparative discharge evaluation

The principle chosen here for comparison is always the same. The reference discharge is the discharge resulting from the measurements of thermodynamic efficiency. Then the other measured discharge in the corresponding HPP is also plotted in the diagram. The relative deviation from the reference, resulting from the thermodynamic efficiency measurement to the measurement in the HPP is then plotted on the secondary axis (see Figure 2). The relative deviation is defined as follows:

$$\Delta Q = \frac{Q - Q_{\text{Reference}}}{Q_{\text{Reference}}} \,. \tag{1}$$

Q	[m^3/s]	measured discharge in the HPP control system
$Q_{\text{Reference}}$	[m^3/s]	reference discharge from the thermodynamic efficiency measurements
ΔQ	[%]	relative deviation

if ΔQ is positive → the discharge measurement of the HPP is too high → and vice versa

To compare different cases, it makes sense to normalize the discharge. Therefore, the maximum measured discharge is referenced to 100 %. The discharge range between 30 and 95 % is taken into account in order to obtain a mean value for the deviation, even if the deviations are not constant. The trend line and the corresponding equation are taken over this discharge range, the values are determined in increments of 5 % of the discharge range, and the mean deviation is then calculated. The mean deviation is calculated from the absolute values of the individual deviations.

In the following example at the HPP no. 3 (all cases were anonymized) three discharge measurements were available in the upstream waterway of the HPP:
- a crossed 4-path, feed through ATT flow meter upstream of the machine group
- a crossed 4-path, internal mounted ATT flow meter in the downstream part of the penstock
- and a crossed 8-path, internal mounted ATT flow meter in the upstream part of the penstock

The two ATT flow meters down- and upstream of the penstock are used for penstock leak detection. The ATT flow meter upstream of the machine group was installed for turbine efficiency monitoring purposes.

The example in Figure 2 shows different types of deviations. On the average, the ATTs in the penstock have almost constant deviations of -0.9 % (penstock upstream) and -1.3 % (penstock downstream) on average. The ATT upstream of the machine group has an almost constant deviation of -1.8 % at low discharge (part load), but the deviation increases towards full load and approaches -14 %. The reason for this is that the flow velocity (up to 17 m/s) at this measuring section obviously overloads the measuring system. The mean value between a discharge range of 30 and 95 % is -3.1 %.

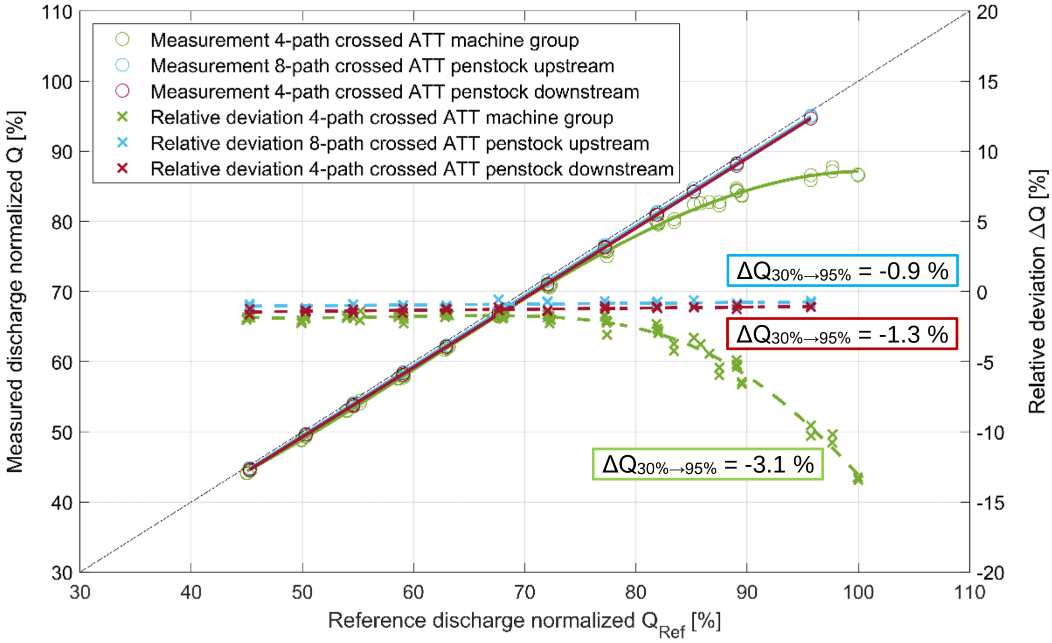

Figure 2: Example of a comparative discharge evaluation in a specific HPP.

It is important to point out that the present study is based neither on a theoretical foundation nor on a detailed analysis, but on the data as they are found in the HPPs. This is because a deviation or change could also have been submitted in advance by the HPP operator without the knowledge of the measurement team carrying out the thermodynamic efficiency measurements. One example for the deviation may be, that the HPP operator has corrected the water amount (discharge) due to government reasons (water taxes). Another reason may be that a flow meter for leak detection, which theoretically have 0 % deviation after commissioning, is corrected by 3 % because it corresponds to the measurement of an old flow meter that was already installed in the penstock at the time when the penstock leak detection system was put into operation. Another source of error can be the signal transmission (analogue and digital conversions), or even a simple signal manipulation due to any reason. With all this in mind, the following analysis can only give an idea of possible range of deviations found in HPPs for a given flow meter technology. With more and more examples in the future, the analysis will become statistically meaningful.

The present study shows comparisons with already installed flow meters. That flow meters from the HPP operators were neither installed nor verified by the measurement team. Comparative discharge evaluations between different methods have already been carried out in the past. In these evaluations, however, the measurement team usually installed the different discharge measurement techniques themselves, allowing higher quality of the measurements (see examples in [3], [4] or [5]).

3. Characterising the deviations

A simple way to analyse the deviations for a specific category is to first calculate a mean value of the deviation for a specific case (see chapter 2) and then determine the mean value of all available cases for a specific category. Only absolute values for the deviations will be considered. The mean value is subjected to statistical uncertainty. Therefore, the standard deviation with a confidence level of 95 % is used. As the various deviations or cases are purely random, the standard deviation of the different deviations is calculated according to [6]:

$$s_{\Delta Q} = \sqrt{\frac{\sum_{r=1}^{n}\left(\Delta Q_r - \overline{\Delta Q}\right)^2}{n-1}} \tag{2}$$

$s_{\Delta Q}$	[%]	standard deviation of the variable ΔQ (ΔQ is “a deviation of a specific case”)
$\overline{\Delta Q}$	[%]	arithmetic mean of n cases of the variable ΔQ
ΔQ_r	[%]	value obtained by the r^{th} measurement of the variable ΔQ
n	-	total number of cases (examples)

The standard deviation of the mean is calculated by dividing the standard deviation of the variable ΔQ by the square root of the number of available cases [6]:

$$s_{\overline{\Delta Q}} = \frac{s_{\Delta Q}}{\sqrt{n}} \tag{3}$$

In practice, the Student's t distribution is used to calculate the extended standard deviation of the mean with a confidence level of 95 %. The Student’s t value depends on the number of available cases according to [6]:

$$t = 1.96 + \frac{2.36}{\nu} + \frac{3.2}{\nu^2} + \frac{5.2}{\nu^{3.84}} \tag{4}$$

where

$$\nu = n - 1 \tag{5}$$

ν - degrees of freedom

The random uncertainty associated with the mean value of the deviations at the 95 % confidence interval, is then:

$$e_{r\_\overline{\Delta Q}} = \pm t \cdot s_{\overline{\Delta Q}} = \pm t \cdot \frac{s_{\Delta Q}}{\sqrt{n}} \tag{6}$$

The resulting uncertainty band for the mean of the deviations should not be confused with the uncertainty of a particular measurement system or a particular measurement method. The mean of the deviations with its uncertainty band is only used in this case to obtain a number with which the different evaluations can be compared with each other. Therefore, all following Figures have inserted the following value:

$$\overline{\Delta Q} \pm e_{r\_\overline{\Delta Q}}$$

4. Comparative discharge evaluation for the acoustic transit time method

The following Figure 3 shows all available comparisons with ATT flow meter installations.

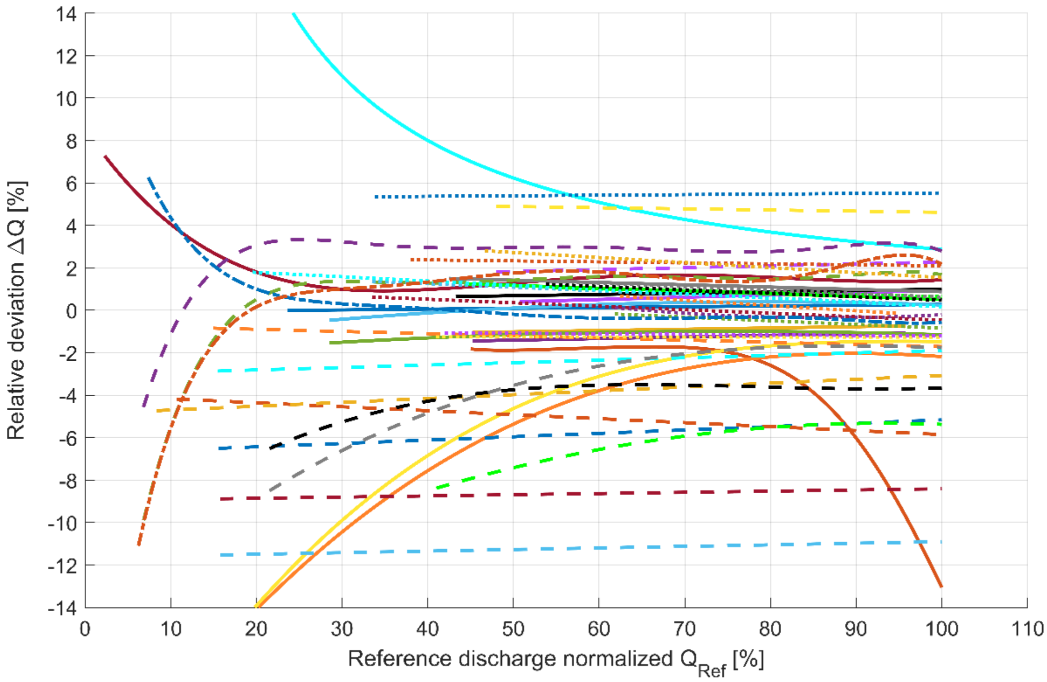

Figure 3: All comparative discharge evaluations for the ATT method.

The large range of deviations is obvious. It makes no sense to conclude that all ATT flow meters can have such a range of deviation. The deviations are mainly influenced by the number of paths (normally 1-, 2-, 4- or 8-path) and the type of mounting (internal mounting, feed through or clamp-on). We have therefore divided the available cases into the following two subsections.

4.1 Dependency on the number of paths

Figure 4 shows the deviations (only for ATT flow meter cases) as a function of the number of paths. It can be seen that there is a significant correlation between the range of deviations and the number of paths.

The number of 1-path cases (2 cases) is too low for a statistic behaviour. However, a sufficient number of examples can be provided for the 2-path (16 cases), the 4-path (8 cases) and the 8-path (9 cases) cases.

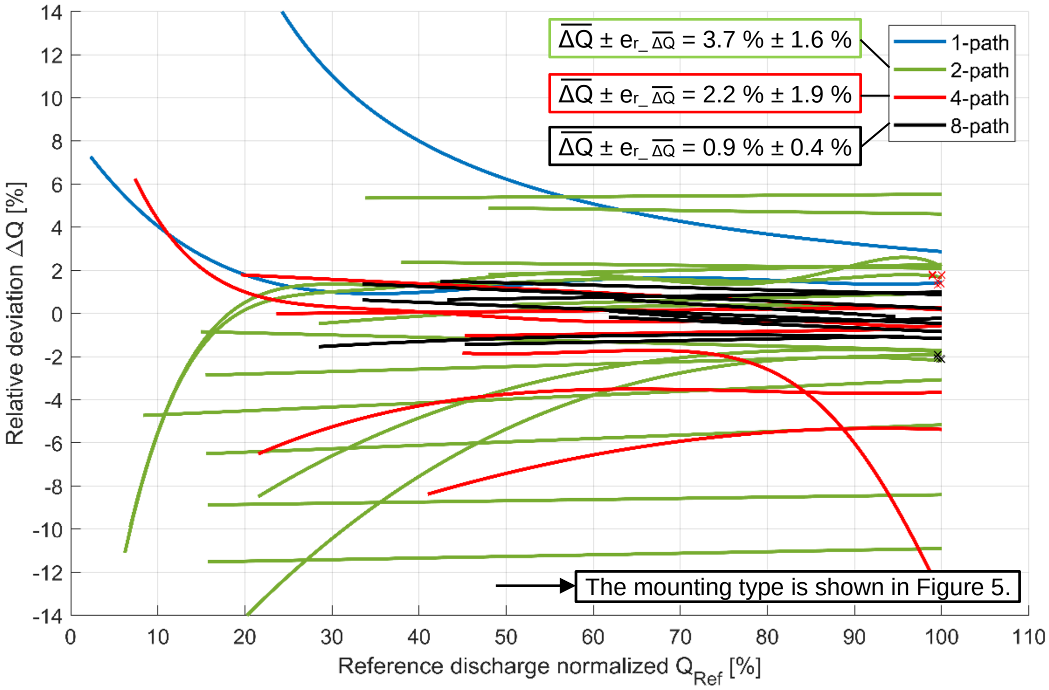

Figure 4: All comparative discharge evaluations for the ATT method separated into categories with different number of paths.

4.2 Dependency on the mounting type

Figure 5 shows the deviations (only for ATT flow meters) as a function of the type of mounting. It is clear that there is significant correlation between deviations and the type of mounting. Especially clamp-on examples show a large variation of deviations.

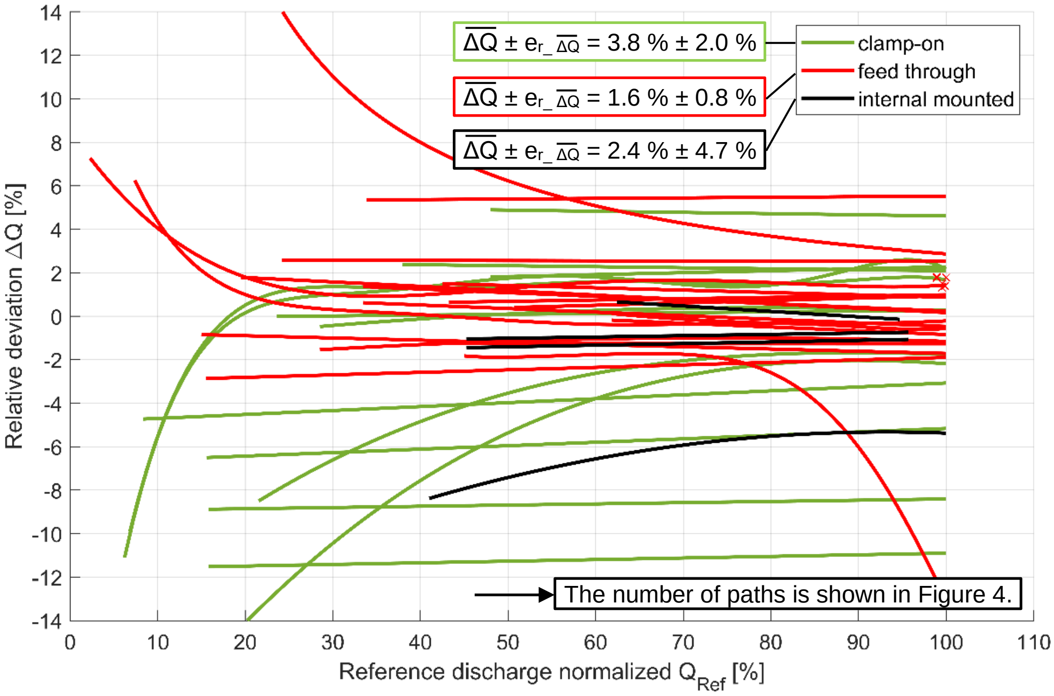

Figure 5: All comparative discharge evaluations for the ATT method separated into categories with different types of mounting.

5. Comparative discharge evaluation for the differential pressure method

Figure 6 shows the deviations in the measurements using the differential pressure method. Only one example is available, based on Winter-Kennedy differential pressure measurements in a spiral casing. The other eight cases are based on Venturi differential pressure measurements.

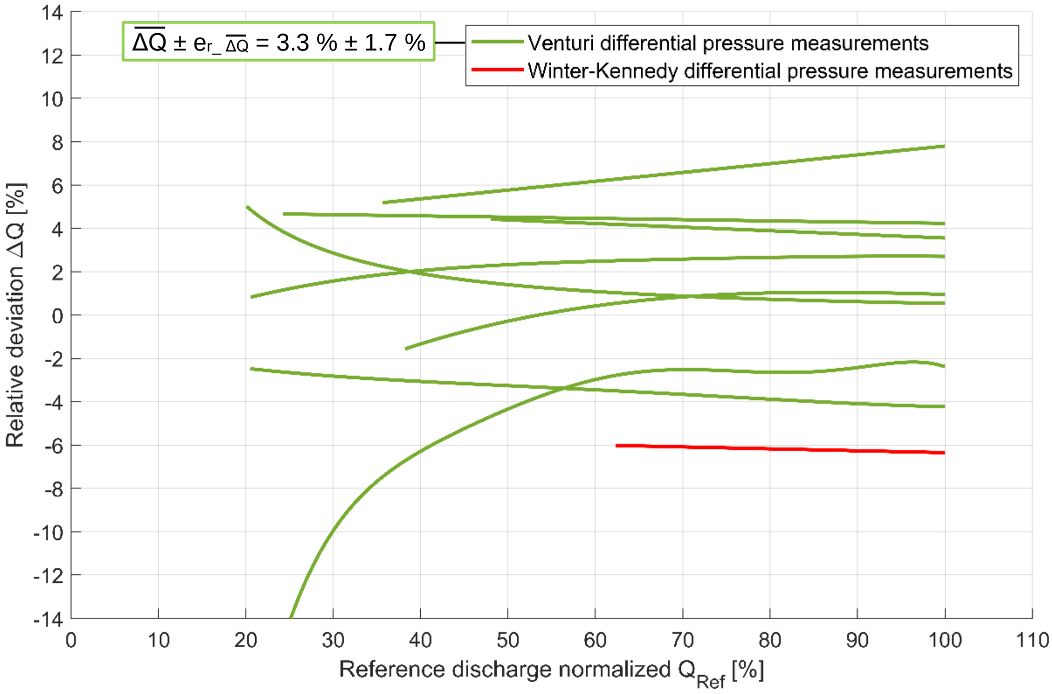

Figure 6: All comparative discharge evaluations for the differential pressure method separated into Venturi and Winter-Kennedy categories.

6. Comparative discharge evaluation for the electromagnetic method

Figure 7 shows the deviations for the measurements with electromagnetic flow meters. The three available cases show constant deviations in a range of ± 2 % over a wide range of application. But at part load, all three examples show a tendency towards higher deviations. The reason for this could be that the magnetic-inductive principle reaches its physical application limits at low flow velocities.

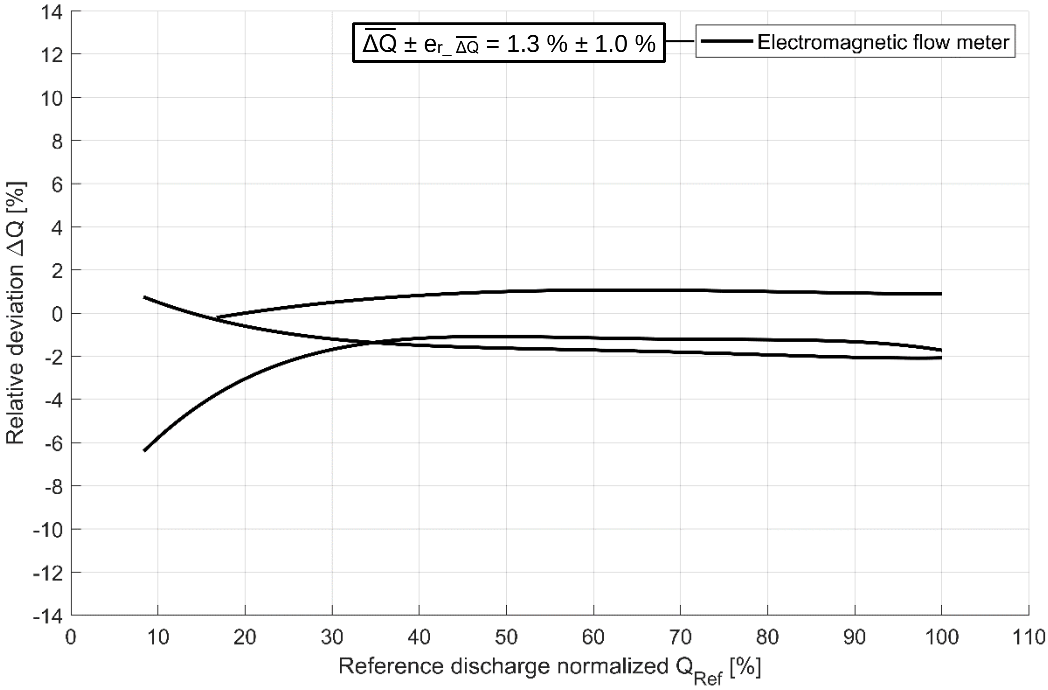

Figure 7: All comparative discharge evaluations for the electromagnetic flow meters.

7. Comparative discharge evaluation for the turbine governor method

Figure 8 shows the deviations for the measurements with the turbine governor (based on needle opening measurements).

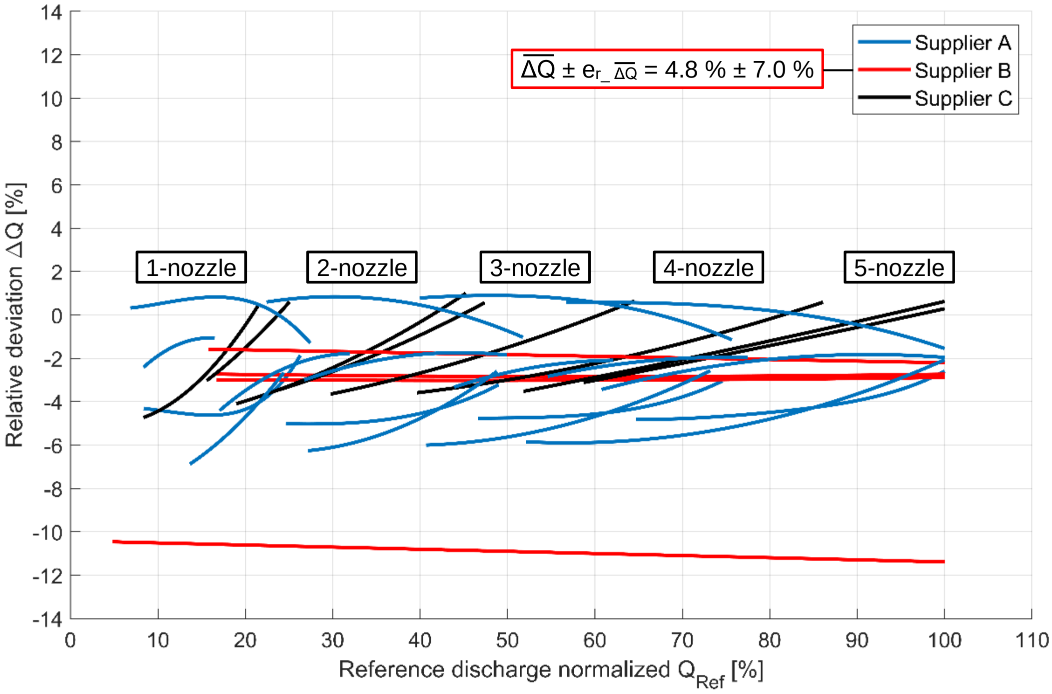

Figure 8: All comparative discharge evaluations for the turbine governor indications.

The deviations of the turbine supplier "B" are constant, for the other two suppliers they are not constant at all. The two suppliers with not constant deviations may have not a correct nozzle discharge coefficient curve. The prediction of the supplier with constant deviations is not depending on the number of nozzles in operation while the two others show a clear dependency on the number (all cases are with a minimum number of 4 nozzles per turbine, the maximum is 5 nozzles). A further reason can be, that the one supplier with constant deviations may have better experience with the transposition of the model tests to the prototype scale with using the dimensionless nozzle discharge coefficient.

8. Discussion of repeatability tests with the thermodynamic efficiency method

Based on [7], the meaning of the term "repeatability" is defined here as successive thermodynamic efficiency measurements with the same quantities under the same measurement conditions. This is valid in this case, where the same measurement procedure (thermodynamic efficiency method) is performed with the same observer and measuring instruments at the same location (in the same HPP). This is in contrast with the term "reproducibility", where a successive measurement is carried out with a different measurement procedure (e.g. current-meter measurements) or a changed observer (another measurement team would carry out the efficiency measurements).

Figure 9 shows all cases in which repetitions of the analysis of the deviations are available. The reasons for such repeated measurements were:

- The contractual efficiency values were not reached, so a second measurement campaign was required.

- Comparative efficiency measurements were carried out in order to quantify the difference in efficiency caused by a turbine revision, for example.

The first measurement campaign is shown with solid lines. The second measurement campaign is shown with dashed lines. The third measurement campaign (the maximum available number of cases) is shown with dotted lines.

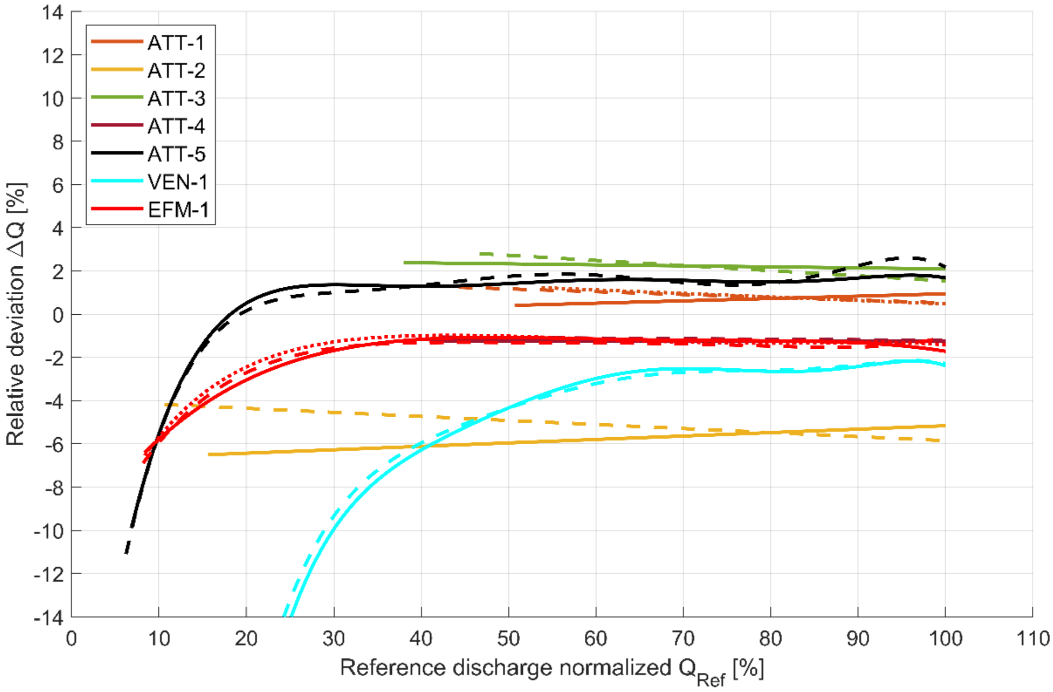

Figure 9: All comparative discharge evaluations for the analysis of the repeatability of thermodynamic efficiency measurements.

The differences evaluated for the available cases are listed in Table 2:

Table 2: Comparison of deviations for repeated measurement campaigns.

Case no.	Mean deviation 1st measuring campaign [%]	Mean deviation 2nd measuring campaign [%]	Mean deviation 3rd measuring campaign [%]	Max differences ("range of repeatability") [%]
ATT-1	0.64	0.88	0.92	0.28
ATT-2	-5.68	-5.25		0.43
ATT-3	2.24	2.31		0.07
ATT-4	-1.26	-1.14		0.12
ATT-5	1.50	1.64		0.14
VEN-1	-4.12	-4.05		0.07
EFM-1	-1.25	-1.40	-1.20	0.20
			Mean	0.19
			Standard deviation	0.13
			Student's t factor (7 cases)	2.4
			Standard deviation of the mean with a confidence interval of 95 %	0.12

The expected repeatability for the thermodynamic method with a confidence interval of 95 % is therefore (based on the cases of Table 2):

$$0.19\% \pm 0.12\%$$

This analysis is based on the assumption that no systematic changes have occurred in the measuring instruments (calibration, linearity, stability in time, influence of temperature, etc.) or in the control system of the HPP. The more cases are available the less influence the systematic changes have.

On the other hand, this analysis is also valid for the individual measurement methods and provides a practical estimate of the repeatability or long-term stability. As there is only one case for the differential pressure method (Venturi, VEN) and the electromagnetic flow meter (EFM), it makes no sense to provide statistics for these measurement methods. Only for the ATT method the number of cases (5 cases) is interesting to calculate more statistics.

The expected repeatability for the ATT method with a confidence interval of 95 % is therefore (based on the cases of Table 2):

$$0.21\% \pm 0.18\%$$

9. Conclusions

Primary measurement methods according to IEC 60041 [6] can be used to compare the discharge from the primary method as reference to the discharge measured by the HPP operator. In the present study the primary method was always the thermodynamic method. The following Table 3 summarizes the mean deviations of the different measuring methods installed at the HPPs and their standard deviations.

Table 3: Comparison of mean deviations and their standard deviations for the corresponding measuring methods.

Method	Subclass	Mean deviation [%]	Extended (95%) standard deviation of the mean [%]	Statistically substantiated yes / no
Acoustic transit time	2-path	3.7	1.6	yes
Acoustic transit time	4-path	2.2	1.9	no
Acoustic transit time	8-path	0.9	0.4	yes
Acoustic transit time	Clamp-on	3.8	2.0	yes
Acoustic transit time	Feed through	1.6	0.8	yes
Acoustic transit time	Internal mounted	2.4	4.7	no
Differential pressure	Venturi	3.3	1.7	yes
Electromagnetic flow meter		1.3	1.0	no
Turbine governor	Needle opening	4.8	7.0	no

The number of 1-path cases (2 cases), Winter-Kennedy cases (1 case) is too low for a statistic behaviour. Furthermore, if the extended standard deviation of the mean is higher than the mean deviation itself, the number of examples is too low. Therefore, the ATT internal mounted case and the turbine governor case do not seem to be statistically significant. On the other side, if the extended standard deviation is around half of the mean deviation itself, the number of examples seems to be sufficient for a valuable statement. With this probably non-scientific definition, the statement for the ATT 2-path, 8-path, clamp-on, feed through and for Venturi cases appears to be statistically substantiated.

The mean deviations for the ATT method show a clear dependency on the number of paths. The higher the number of paths the lower the mean deviations. In addition, feed through applications are significantly better then clamp-on installations. Internal mounting installations for large conduit diameters should be reliable as well, but up to now, the number of cases is too low to give a substantiated statement about the expected range of deviations. Venturi cases show a high scatter and seem to be not reliable. Electromagnetic flow meters have a low deviation, but the number of cases is also here too low at the moment.

Furthermore, a repeatability of 0.2 % with a corresponding standard deviation of only ±0.1 % for the thermodynamic method of efficiency measurements was analyzed. The low standard deviation of the mean implies, that enough cases were respected to be statistically significant.

The expected repeatability for the ATT method is 0.2 % with a corresponding standard deviation of ±0.2 %. The standard deviation is just slightly higher than the standard deviation of the repeatability for the thermodynamic method. This small number illustrates that the ATT method is a good measurement method for efficiency monitoring purposes. This is because long-term stability, which in turn is linked to a low repeatability of a measuring method, is of central importance for efficiency monitoring.

Whether this repeatability is independent of the number of paths and independent of the mounting type has not yet been investigated. Too few cases are available.

Within the ATT method, the repeatability of clamp-on applications is probably the most critical aspect, as the long-term stability of the contact paste between the sensors and the pipe wall, for example, can be called into question. In addition, the exact same positions must be maintained when disassembling and reassembling the clamp-on sensors. Furthermore, other internal diameters and layer structures may result due to revisions of corrosion coatings on the pipe walls. This can affect the sound path propagation and therefore the measured time differences.

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