NORTH SEA FLOW MEASUREMENT WORKSHOP
measuring for the energy transition

How to give specifications of a flow meter in a precise and useful way

Kjell-Eivind Frøysa, Western Norway University of Applied Sciences (HVL) and Norwegian Research Centre (NORCE)

1 INTRODUCTION

Flowmeters are essential parts of a metering station for custody transfer measurements of oil and of natural gas. Such measurements have a large focus from operator, partners, customers, transporters and authorities, because of the large monetary values involved. It is therefore critical to ensure that the flow meters are of a type with expected performance, and that the flow meters are maintained and operated as they should.

As an example, the Measurement Regulations of the Norwegian Petroleum Directorate [1] specify uncertainty limits at 95 % confidence level for oil metering for sales and allocation purposes of 0.30 % of standard volume. For gas metering for sale and allocation purposes the similar limit is 1.0 % of mass.

In order to document compliance with such uncertainty requirements, a combination of flow meter specifications, calibration results and field data are used, in addition to uncertainty from other instruments like pressure and temperature measuring units and online gas chromatographs.

In this paper, it will be shown that current vendor specifications of accuracy in flow meters do not comply with the international definition. Furthermore, the concept of repeatability is not uniquely defined in several of the vendor specifications. To complicate further, international standards for flow meters use different definitions of repeatability, in some cases also without specifying which definition they use. This makes compliance tests difficult, especially since repeatability is one of the properties that are in focus under such tests. In addition, this is also a challenge when measurement uncertainty is to be documented.

2 HOW ARE THE FLOW METERS SPECIFIED TODAY?

In this chapter, the vendor specifications of various flow meters are reported. The results are presented in an anonymous way, where the different brands are not in focus.

2.1 Ultrasonic gas flow meters

The specifications of ultrasonic gas flow meters from five different vendors have been reviewed. In all cases, the results from the top model from the vendor in question has been looked into. All five vendors specified two numbers.

The first number that was specified was denoted different things by each vendor:

- Nominal accuracy
- Measuring accuracy
- Accuracy (Error limits)
- Accuracy
- Typical uncertainty

For all vendors, the quantification of this was ±0.1 % of measured value. The condition this was specified on changed slightly between the five vendors, but four of the vendors stated that the specified number was valid after flow calibration flow calibration and also some vendors specified linearization of the meter.

The second number that was specified was repeatability. Here the quantification was given as 0.05 % or 0.1 %. Some vendors stated that this was percent of measured value and some specified a flow rate range.

2.2 Ultrasonic liquid flow meters

The specifications of ultrasonic liquid flow meters from three different vendors have been reviewed. In all cases, the results from the top model from the vendor in question has been looked into. Here, four different parameters were addressed.

Linearity: This was specified at a recommended installation by one vendor, specified at a given flow velocity range by another vendor, while one vendor did not specify linearity.

Uncertainty: All vendors specified this to be ±0.027 %. One vendor called this "uncertainty of meter factor".

Repeatability: One vendor defined this as ±0.02 %, one vendor as ±0.02 % (n=2) and one vendor did not specify repeatability.

Accuracy: one vendor specified this as 0.15 % - 0.20 % depending on velocity range, while two vendors did not specify accuracy.

2.3 Other types of flow meters

Specifications of two types of Coriolis flow meters and one type of turbine flow meter has also been looked into. Here, it can be seen that one vendor specifies accuracy, one vendor specifies measurement error, two vendor specifies repeatability and one vendor specifies linearity.

3 WHAT DO THE STANDARDS SAY, AND WHAT IS THE PROBLEM?

In this chapter, it will first be looked into how the concepts of accuracy and repeatability are defined, and thereby identify confusions and problems that arises by using these concepts. Thereafter, focus will be on repeatability, and how this concept is treated in relevant standards.

3.1 Definitions of accuracy and repeatability

In order to understand problematic sides with the specification of accuracy and repeatability, and how these specified numbers can be used, it is necessary to look into the basic definition of these two concepts. They have been taken from the "International vocabulary of metrology – Basic and general concepts and associated terms (VIM)" [2] by BIPM in cooperation with a series of organizations, among them ISO.

The term “*Measurement accuracy*” is there defined as
“*closeness of agreement between a measured quantity value and a true quantity value of a measurand*”.

Three notes are in [2] given to the definition. Note 1 states that
“*The concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error*”.

Furthermore, Note 3 states that
“*'Measurement accuracy' is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand*”.

From this, it can be deducted that accuracy is a qualitative term. It is possible to talk about low or high accuracy, but accuracy cannot be quantified with a number.

The term “*Measurement repeatability*” is in [2] defined as
“*Measurement precision under a set of repeatability conditions of measurement*”.

By taking in the definitions for “*Measurement precision*” and of “*repeatability conditions of measurement*”, the following definition is found for “*Measurement repeatability*”:
“*Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions under a set of condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time*”.

Note 1 under the definition of “*measurement precision*” states that
“*Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement*”.

This means that VIM does not give a unique definition of how repeatability is to be calculated. Various methods include calculation of standard deviation, variance or some coefficient of variation from the series of repeated measurements.

3.2 Repeatability as used in API MPMS

The use of the concept repeatability in API MPMS can be found several places in those publications. Most well known is maybe Chapter 5.8 which addresses “Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters” [3]. Here the repeatability is defined as “((High Counts – Low Counts)/Low Counts)x100”, see Table B.1 in [3]. This means that the repeatability is defined from the total spread (maximum minus minimum value) of the quantity in question. This quantity is originally thought of as number of pulses per run in a proving situation. Thus, the word “Counts” in the definition above. However, it can be used also for other quantities, like for example a meter factor.

Table B.1 in [3] states the repeatability (as defined here) that is required for a given number of runs (repeats) from 3 to 20. The table is generated in such a way that the uncertainty in a K-factor or meter factor generated by a proving situation shall be at most 0.027 %, which is given in the column to the right in Table B.1. This uncertainty is not the total uncertainty of the flow meter or of the K-factor (or meter factor), but the uncertainty contribution from the spread of repeated results. In addition, the uncertainty of the K-factor will also include other uncertainty contributions, for example the uncertainty of the volume reference (prover).

The relationship between the repeatability and the uncertainty contribution due to repeatability can be found from [3].

If w^* is the repeatability written in relative form

$$w^* = 100\ \% \cdot \frac{K_{max} - K_{min}}{K_{min}} \qquad (1)$$

the uncertainty contribution (relative expanded uncertainty at 95 % confidence level) is written as

$$U^* = \frac{T_{n-1}}{D_n \sqrt{n}} w^* \qquad (2)$$

where n is the number of runs, T_{n-1} the Student-T factor for 95 % confidence level and $n-1$ degrees of freedom, and D_n is a conversion factor for estimating standard deviation for n data points. See [3] for more details.

3.3 Repeatability as used in ISO 17089-1

In ISO 17089-1 [4], addressing ultrasonic meters for gas, the repeatability is defined as (in the notation from that standard):

$$r_p = k_{95} \sqrt{\frac{\sum_{i=1}^{n} (E_i - \bar{E})^2}{n-1}} \qquad (3)$$

This is the same as the standard deviation of n single measurement, multiplied with k_{95} which is the same factor as T_{n-1} above. This means that the repeatability here is the uncertainty contribution from repeatability to a single measurement in a measurement series consisting of n measurements.

Furthermore, the standard also defines *repeatability during calibration*, r_{cal}, which from the definition is

$$r_{cal} = \frac{r_p}{\sqrt{n}} \qquad (4)$$

This means that r_{cal} is the expanded uncertainty contribution at 95 % confidence level from repeatability, for the average of the n measurements. At accuracy class 0.5, the repeatability during calibration is required to be at most 0.17 %, for the highest flow rates.

The repeatability requirements to flow meters are in this standard given as a requirement to r_{cal}, see Table 5 in [4]. The uncertainty contribution to a meter factor or K-factor from repeatability will therefore here

$$U^* = 100\ \% \cdot \frac{r_{cal}}{\bar{E}} = r_{cal}^* \qquad (5)$$

Where r_{cal}^* is defined through Eq. (5) as the repeatability during calibration, med relative, and reported in percent.

3.4 Relationships between repeatability used in API MPMS and ISO 17089-1

As we have seen, the term repeatability is defined and specified differently in API MPMS and ISO 17089-1. In API MPMS, the repeatability w^* is specified for a given number of runs in order to obtain a certain upper limit of U^*, while in ISO 17089-1, the repeatability during calibration, r_{cal}^*, is specified. This is the same as U^*. By combining Eqs. (2) and (5), the relation between w^* and r_{cal}^* can be found as

$$U^* = r_{cal}^* = \frac{r_p^*}{\sqrt{n}} = \frac{T_{n-1}}{D_n\sqrt{n}} w^* \qquad (6)$$

In Fig. 1, the requirement of $U^* = 0.027\ \%$ in API MPMS is addressed. The graph shows how that is transferred into requirement to the repeatability as defined in API MPMS and to the repeatability and repeatability during calibration as defined in ISO 17089-1.

Similarly, in Fig. 2 the requirement of repeatability during calibration, $r_{cal}^* = 0{,}17\ \%$ is ISO 17089-1 is adressed. The graph shows how that is transferred into requirement to U^*, to the repeatability as defined in API MPMS and to the repeatability as defined in ISO 17089-1.

These two figures show how important it is to be precise on which definition of repeatability that is used and also how important it is to specify number of runs.

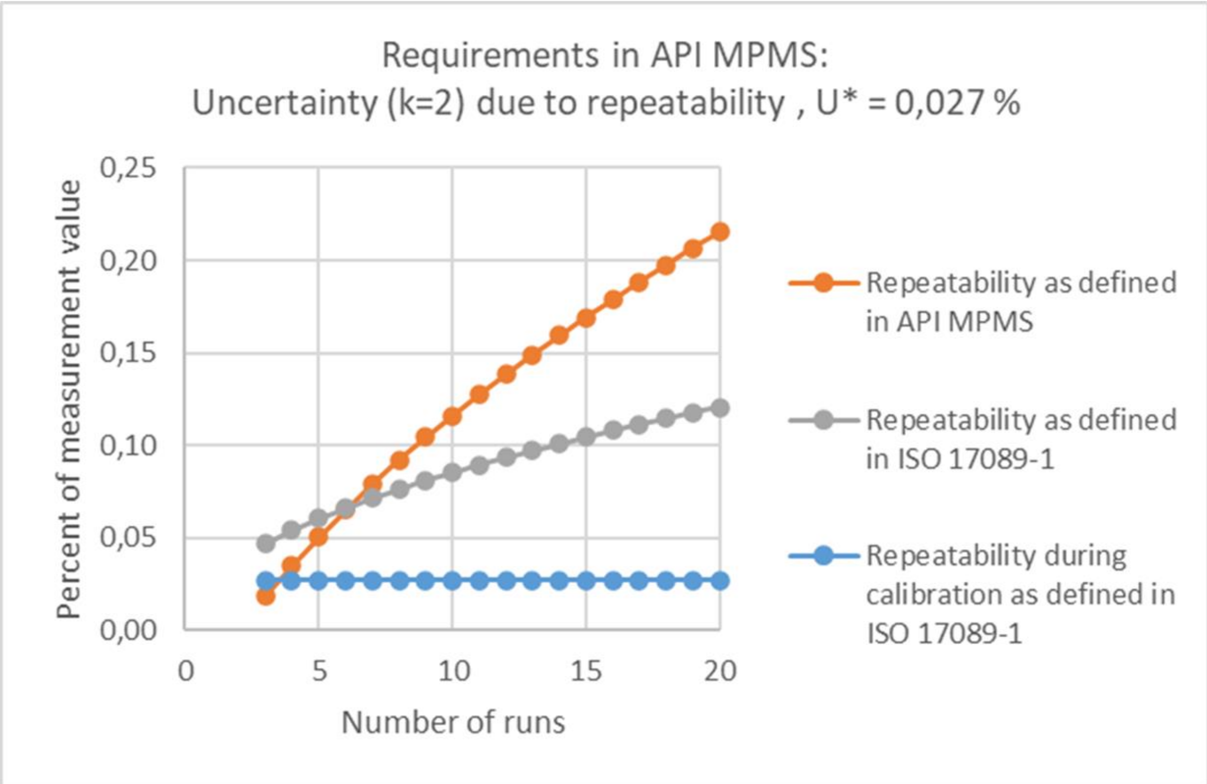

Fig. 1 – Repeatability as defined by API MPMS and repeatability and repeatability as defined by ISO 17089-1 for the uncertaintydue to repeatability requirement in API MPMS of 0,027 %

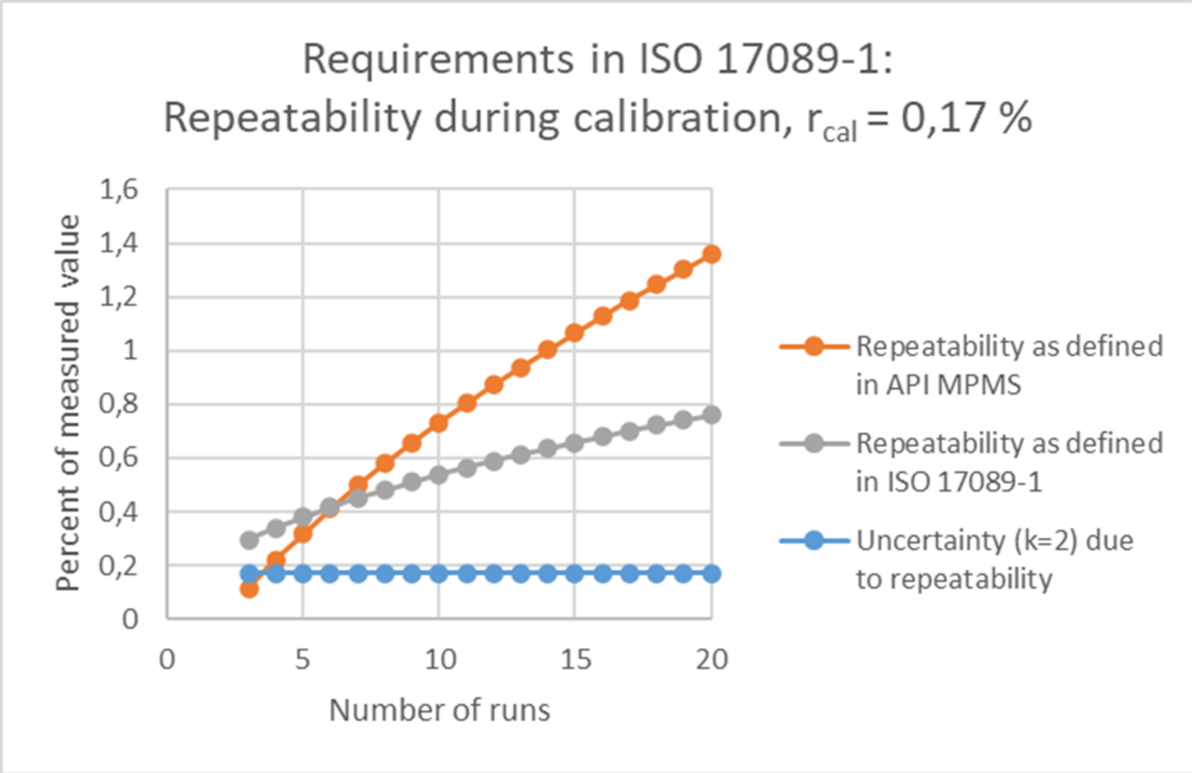

Fig. 2 – Repeatability as defined by API MPMS and by ISO 17089-1 and uncertainty due to repeatability for the requirement in ISO 17089-1 of repeatability during calibration of 0.17 %.

3.5 Repeatability as used by selected standards

So far, the focus has been on repeatability as defined in API MPMS and in ISO 17089-1. However, there is a series of other standards that may come into question, and where repeatability is addressed. A list of some of these relevant standards is given below, with their definition of repeatability:

API MPMS (oil flow meters) [3]:	Quantified, based on max-min
OIML R117 (oil flow meters) [5]:	Quantified, based on max-min
ISO 17089 (ultrasonic gas flow meters) [4]:	Quantified, based on standard deviation
ISO 10790 (Coriolis flow meters) [6]:	Not quantified, not specific on method
OIML R137 (gas flow meters) [7]:	Not quantified, not specific on method
AGA7 (turbine gas flow meters) [8]:	Quantified, probably based on max-min
AGA9 (ultrasonic gas flow meters) [9]:	Quantified, probably based on max-min

In many of these standards it is not specified how many runs/repeats that should be carried out. This indicates that in the next update of the standards, this issue should be lifted.

3.6 What is the problem?

Above, it has been shown that the terms accuracy and repeatability that are widely used in specifications of flow meters are not well defined.

Accuracy is often specified to be for example ±0,1 % of measured value, after flow-calibration and linearization. The problem is to interpret what this sentence means. It cannot be the total measurement error, because that also depends on for example the uncertainty (or measurement error) of the reference measurement during the flow test.

But can it be the deviation from reference value just after the flow test, before moving the meter? Or still valid after moving the flow meter. And under which conditions can it be valid over time? These questions are difficult to answer, but they are important when the total performance of the flow meter and the metering station shall be evaluated.

Repeatability is addressed above, and it is shown that specification of what is meant with repeatability (definition and number of runs) is important. A statement of repeatability without these specifications is to the author's understanding not meaningful.

4 IS THERE A SOLUTION?

In this chapter, some possible solutions and recommendations to solve the problem related to establishing measurement uncertainty based among other on meter specifications and requirements have been given.

4.1 Need for specification to establish measurement uncertainty

In order to assess the uncertainty of a volumetric flow rate measured by a flow meter, at least the following input is needed:

- Calibration reference
- Linearity
- Repeatability
- Installation effects
- Time since last calibration (aging, wear and tear)

For each of these keywords, an uncertainty contribution must be calculated. Based on these inputs, in addition to uncertainty related to the other instruments, like pressure and temperature measuring devices and online gas chromatographs, uncertainty analysis for standard volume, mass and energy flow rate can be carried out. Example of such an uncertainty analysis is shown in Fig. 3, where the three first bars in that plot matches the three first bullet points above. The two last bullet points ("Installation effects" and "Time since last calibration") are combined into the fourth bar ("Field uncertainty") in Fig. 3.

The uncertainty due to calibration reference is independent of the flow meter as delivered from the vendor. This uncertainty thus has to come from the calibration certificate and is a consequence of the choice of calibration method and calibration laboratory/site.

For the linearity, the vendor can specify maximum numbers. One way of specifying this is to do like in Table 5 in ISO 17089-1, where maximum peak-to-peak error is specified over a range of flow rates. This will give input as to expected uncertainty for a given type of flow meter, in the process of evaluating which type of meter to choose. After the calibration, this uncertainty estimate can be updated by using results stated in the calibration certificate. See for example the uncertainty programs that are available for free through www.nfogm.no for one way of carrying out such calculations.

The repeatability should be stated, but as addressed above, also the definition of the repeatability and the number of runs should be stated in order to be able to calculate an uncertainty contribution, and to evaluate compliance with selected standards.

Installation effects are often hard to estimate. These cover the added uncertainty from change in flow profile, pressure, temperature, and other external properties, for example caused by moving the flow meter from place of calibration to place of operation. Sometimes, we see specification of reproducibility. This can give a hint as to this uncertainty contribution. However, the concept of reproducibility is also somewhat loosely defined. Therefore, some of the same problems as found with the concept of repeatability will occur also for reproducibility. For differential pressure meters, we find in ISO 5167 (several parts, for example part two for orifice plates) tables stating how long straight pipe length that are required between the last upstream bend or obstruction and the flow meter, for various types of bends etc. This is hardly found for other types of flow meters.

For recalibration, there is generally lack of guidance, and the policy varies from country to country. The closest to something specific that is found in standards is the requirement in ISO 17089-1 of match between calculated and measured speed of sound in a ultrasonic gas flow meter. If this difference gets too large, it is an indication that re-calibration may be considered.

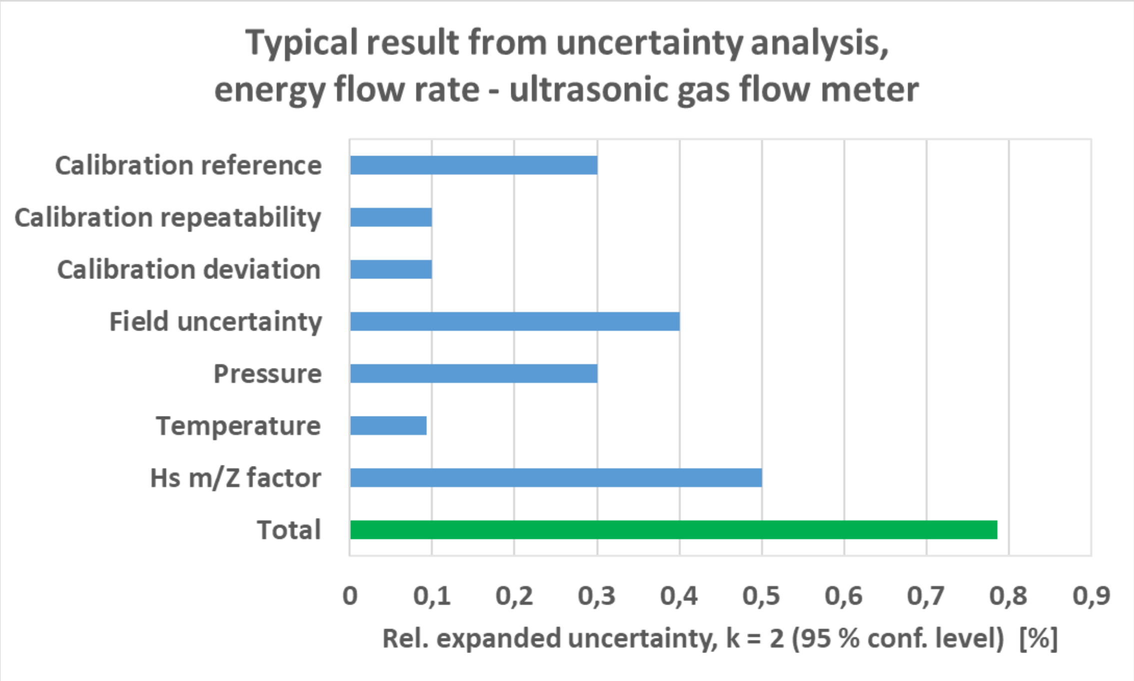

Fig. 3 – Example of results from an uncertainty analysis for the energy flow rate measured in a meter station consisting of an ultrasonic flow meter, pressure and temperature measuring devices and an online gas chromatograph.

4.2 …to the vendors

In order to obtain precise specifications, vendors should specify how the stated repeatability shall be understood and calculated. This includes the definition of the repeatability and also number of runs.

If the vendors use the concept of accuracy, they must explain what the quantification of accuracy means, since such a quantification is not defined in [2].

In case reproducibility is specified, the definition and interpretation of this concept should be defined better. This is because reproducibility definition contains the same weakness as the definition of repeatability. Also, it would be good to specify between which situations the reproducibility is valid (between same flow rig installation day by day, between tests in different flow rigs, between flow calibration and field installation, for how long time, etc…).

It would also be useful if the vendors could provide some more information on expected installation effects, such as additional uncertainties when a flow meter is moved to another location where the flow profile may have changes for example due to upstream bends.

4.3 …to developers of standards

When developing or updating a standard, it would have been good to get a unique definition on how repeatability shall be calculated. This must also include number of repeats/runs.

It would also be nice if different standards define repeatability in the same way. However, we must live with the fact that the different standards have different requirements on how small the repeatability should be in order to comply to the standard.

5 SUMMARY

In this paper it has been shown that the specifications of accuracy of flow meters is difficult to interpret and that it is not in compliance with definitions in BIPM-VIM [2]. Furthermore, the problem of different ways of calculating repeatability has been addressed.

6 REFERENCES

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[3] American Petroleum Institute (API) Manual of Petroleum Measurement Standards (MPMS) Chapter 5.8. *Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters*. Second edition, 2011.

[4] ISO International Standard 17089-1. *Measurement of fluid flow in closed conduits – Ultrasonic flow meters for gas – Part 1: Meters for custody transfer and allocation measurement.* Second edition, 2019.

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[9] American Gas Association (AGA) Report No. 9. *Measurement of Gas by Multipath Ultrasonic Meters.* 3rd edition, 2017.

[10] ISO International Standard 5167-2. *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 2: Orifice plates.* 2003.