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ISO 5167: Past and Present

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1 INTRODUCTION

ISO 5167 is the senior flow measurement standard. Its history goes back to national standards written before and during the Second World War. The first edition of ISO 5167, covering orifice plates, nozzles (and Venturi nozzles) and Venturi tubes was published in 1980. There were a small revision in 1991, a major amendment (with the new orifice-plate discharge-coefficient equation) in 1998, and a major revision in 2003. Additional parts for cone meters and wedge meters were added in 2016 and 2019, respectively. Throat-tapped nozzles were added to ISO 5167-3 in 2020.

Given these new parts there is a need to harmonize all the parts, incorporating all the research work on orifice plates and Venturi tubes since 2003 and including flow calibration of differential pressure meters. The revised edition of ISO 5167 is being published in the second half of 2022.

This paper gives a brief history of ISO 5167 and in more detail describes the changes to be made in 2022 and gives their justification.

2 BRIEF HISTORY

2.1 20th Century

There was a German flow measurement standard created in the 1930s. The first British differential-pressure flow measurement standards were as follows:

- BS 1042:1943 Flow measurement
- BS 1042-1:1964 Methods for the measurement of fluid flow in pipes, Part 1 Orifice plates, nozzles and Venturi tubes

The first ISO differential-pressure flow measurement standards were:

- ISO/R 541-1967 Measurement of fluid flow by means of orifice plates and nozzles
- ISO/R 781-1968 Measurement of fluid flow by means of Venturi

The Stolz Equation was introduced in 1980:

- ISO 5167:1980 Measurement of fluid flow by means of orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full

The 1991 revision made some minor revisions to the 1980 edition (see Stolz [1]):

- ISO 5167-1:1991 Measurement of fluid flow by means of pressure differential devices - Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full

The orifice-plate discharge-coefficient equation was changed to the Reader-Harris/Gallagher (1998) Equation [2, 3] by an amendment in 1998:

- ISO 5167-1:1991/Amd. 1:1998 Measurement of fluid flow by means of pressure differential devices - Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full. AMENDMENT 1

2.2 21st Century

A major revision of ISO 5167 was completed in 2003. It was divided into four parts:

- ISO 5167-1:2003 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 1: General principles and requirements
- ISO 5167-2:2003 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 2: Orifice plates
- ISO 5167-3:2003 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 3: Nozzles and Venturi nozzles
- ISO 5167-4:2003 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 4: Venturi tubes

A summary of the changes to ISO 5167 that were made in 2003 is given in [4], but the most important ones were:

- New upstream straight lengths for orifice plates based on new data
- Requirements and a compliance test for flow conditioners
- A revised expansibility equation for orifice plates
- Isenthalpic temperature correction from downstream to upstream
- Pipe roughness limits for orifice plates based on a new analysis of data
- Revised limits on steps in pipework upstream of orifice plates
- New upstream straight lengths for Venturi tubes
- Revised rule for surface roughness of Venturi tubes

Since 2003 work has been done on differential pressure meters but parts 1, 2 and 4 of ISO 5167 have remained unchanged until this year. Additional parts for cone meters and wedge meters were added in 2016 and 2019 as ISO 5167-5 and ISO 5167-6, respectively, and throat-tapped nozzles were added to ISO 5167-3 in 2020:

- ISO 5167-5:2016 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 5: Cone meters
- ISO 5167-6:2019 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 6: Wedge meters
- ISO 5167-3:2020 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 3: Nozzles and Venturi nozzles

Before the revision started the author looked at all the e-mail questions that he had received on ISO 5167 since 2003, many of which had come through BSI or ISO, and took account of them in the revision as Convenor of ISO/TC 30/SC 2/WG 11.

3 The 2022 Revision

3.1 In all or many parts

3.1.1 Uncertainty calculation

Previous revisions did not follow all the provisions of the GUM [5]; however, the 2022 revision is consistent with it.

What was previously called the uncertainty is now called the relative expanded uncertainty at $k = 2$ (approximately 95 % confidence level), but the values are unchanged.

The calculated flowrate uncertainty should now be calculated taking account of the probability distributions of the different components of the uncertainty. An example is provided in ISO 5167-1:2022 Annex E. In almost every case the calculated expanded uncertainty in 2022 will be very similar to the uncertainty calculated in accordance with the 2003 revision.

3.1.2 Improved wording of the rules for spacing of multiple fittings

In the rules for the spacing of multiple fittings in 2003 the text does not refer to the primary device and the fittings in a consistent order. In 2022 the primary device, fitting 1 (the fitting immediately upstream of the primary device) and fitting 2 (the next fitting upstream of the primary device and fitting 1) are referred to in that order in 6.2.8 of Parts 2, 3 and 4. Moreover, the wording has been clarified. However, the actual requirements have not been changed.

3.1.3 Flow calibration

If the uncertainty of an uncalibrated meter would be too high, then it can be calibrated. The rules are given in Section 7 of Parts 2 to 6.

3.1.4 Harmonization

Minor changes have been made to provide harmonization between the parts of ISO 5167.

3.2 ISO 5167-1 General principles and requirements

3.2.1 Setting a primary element as part of a metering system

ISO 5167-1:2022 5.5 describes how the primary element forms part of the whole metering system. A diagram is provided that gives a possible configuration. The aim is to provide a flow measurement standard, and not just a description of the primary element. Brief reference is made to orifice carriers, impulse-line isolation valves and valve manifolds, and flow computers.

3.2.2 Diagnostics and Condition-Based Monitoring (CBM)

ISO 5167-1:2022 5.6.4 provides a brief description of the merits of diagnostic systems. Listed diagnostic methods include:

- pressure transmitter internal diagnostic parameters
- use of multiple transmitters for the same measurement
- comparison of combinations of measurements across the flowmeter
- axial pressure profile analysis
- data reconciliation techniques.

Section 5.6.4 also describes the possibility of CBM.

3.2.3 Limitation on the use of 'the 5 % 2° rule' for an acceptable profile

ISO 5167-1:2003 7.3 states that acceptable flow conditions for a differential pressure flowmeter are achieved where, at each point across the pipe cross-section, the swirl angle is less than 2° and the ratio of the local axial velocity to the maximum axial velocity at the cross-section agrees to within 5 % with that which would be achieved in swirl-free flow at the end of a very long straight length (over 100D) of similar pipe. This criterion is called informally 'the 5 % 2° rule'.

Sets of data in which both velocity profiles and shifts in discharge coefficient are measured are rare: Reader-Harris et al. [6] was based on work done for the Headers Consortium [7]. In the report for the Consortium H is defined as the maximum percentage difference in u/u_{cl} from that in a fully developed flow over the range $r'/R \leq 0.96$, where u/u_{cl} is the ratio of the velocity at a point to that on the centre-line, r' is the distance from the centre line to a point and R is the pipe radius. CFD gave

$$\Delta C_{\mathrm{p}} \approx -0.50\beta^{3.5}H \tag{1}$$

where ΔC_{p} is the mean percentage shift in discharge coefficient and β is the diameter ratio. In the experimental data for the perforated plates the shifts were generally smaller in magnitude than those in Equation (1). It was then stated in [7] that 'from both experiment and computation it can be seen that $H \leq 5$ does not guarantee shifts less than 0.25 per cent for $\beta = 0.6$. It may be the case that limits on H and on turbulence levels are necessary to guarantee sufficiently small shift in discharge coefficient; nevertheless a rule that H should not exceed 5 is quite close to the required criterion for an acceptable velocity profile for orifice metering in installations where specific straight lengths have not been determined.'

On the basis of this work ISO 5167-1:2022 7.3 states that if 'the 5 % 2° rule' is satisfied, then the flow conditions are acceptable for primary devices of sufficiently small β.

In practice, measurements of velocity profile have very rarely been made to prove the acceptability of an installation; therefore, the revised text will be both more truthful and a very minor inconvenience.

3.2.4 Flow straighteners and conditioners

ISO 5167-1:2003 Annex C is a lengthy section on flow straighteners and conditioners, many of which have not been tested and shown to pass the compliance test for flow conditioners. ISO 5167-1:2022 Annex C is much shorter and more focussed on flow straighteners and conditioners for use with ISO 5167.

It is not required to use the Chevron swirler in the Flow conditioner compliance test; therefore, the Chevron swirler has been moved into Annex C.

3.2.5 Flow range and turndown

An extremely important development in the last 40 years has been the rapid improvement in differential pressure transmitters. Instead of approximately a 10:1 range in differential pressure (and a 3:1 range in flowrate) for a single transmitter, around 100:1 in differential pressure (and 10:1 in flowrate) are readily achievable. Figure 4.7 of [3] shows that when 5 fieldbus differential-pressure transmitters (all Yokogawa EJX110A) were calibrated at low static pressure at NEL the largest drift in reading between calibrations was 0.06% over a range of differential pressure from 50 to 5000 mbar. ISO 5167-1:2022 Annex D explores the consequences of this development for turndown.

3.2.6 Pressure loss

In ISO 5167-1:2022 Annex F permanent pressure losses for a piping installation including different differential-pressure meters are compared. The Venturi meter has much the smallest overall pressure loss. The impact of β is significant for all meter types. However, the point is made that that the permanent pressure loss caused by the primary element might or might not be a large component of the pressure loss of the whole piping installation.

3.3 ISO 5167-2 Orifice plates

3.3.1 Maximum orifice edge thickness (change only required for $\beta < 0.2$)

Husain and Teyssandier [8] measured the shift in discharge coefficient using an unbevelled orifice plate in a 6″ flange-tapped orifice meter from a baseline with $E = e = 3.2$ mm (1/8″) to tests with values of E (= e) up to 19 mm (¾″), where E and e are the orifice plate thickness and orifice (bore) thickness, respectively To do this the plate was initially 19 mm (¾″) thick and was successively machined thinner. The data are shown in Figure 1.

Beitler [9] collected the famous Ohio State University data in the 1930s on many plates, some used in more than one pipe. In some cases the plate was re-bevelled to change the value of e. It is then possible using the points with $e/d < 0.09$ as the baseline to plot the effect of e/D in Figure 1. d and D are the orifice diameter and pipe diameter, respectively. A point from Beitler (7585-T, $\beta = 0.12$, $D = 2″$, $e/d = 0.125$) was omitted because the spread of the deviations from the Reader-Harris/Gallagher (RG) (API) Equation for different Reynolds numbers was 1.39%, more than three times the spread of the deviations for any plotted points (except for the point from Beitler (7585-T), $\beta = 0.12$, $D = 2″$, $e/D = 0.0625$). Where no points are available with $e/d < 0.09$ the data are not plotted.

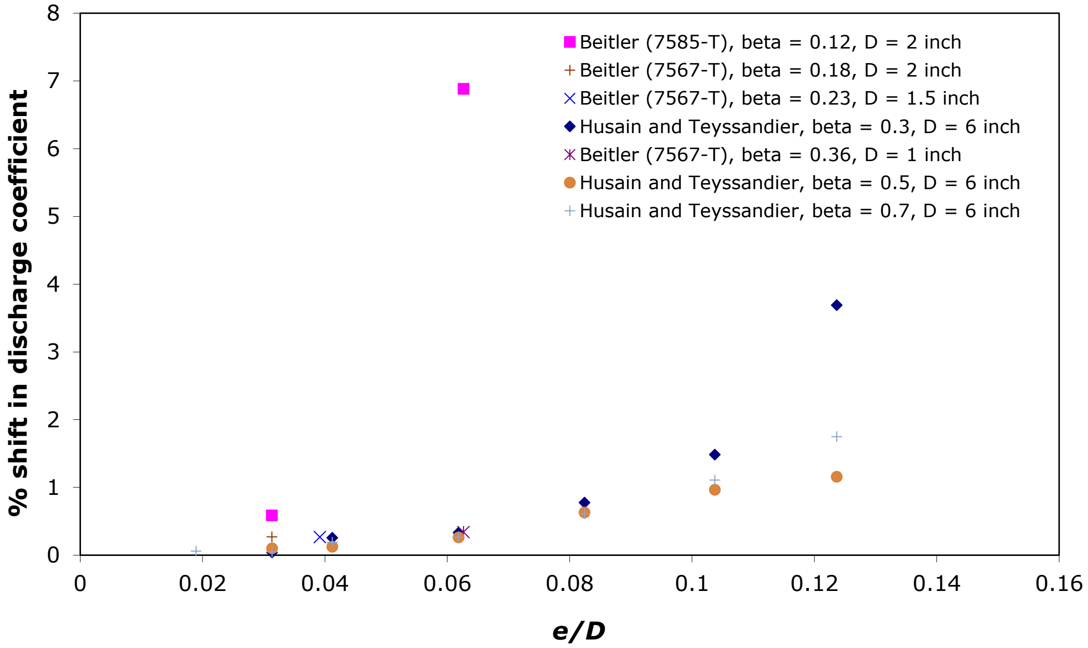

Figure 1 Effect on discharge coefficient of changing *e/D*

Figure 1 suggests that there is no problem with the limit of $0.005 \leq e/D \leq 0.02$ in ISO 5167-2: 2003 5.1.5.1 except for small β. Therefore, the data for β up to 0.4 are plotted in Figure 2, now against *e/d*.

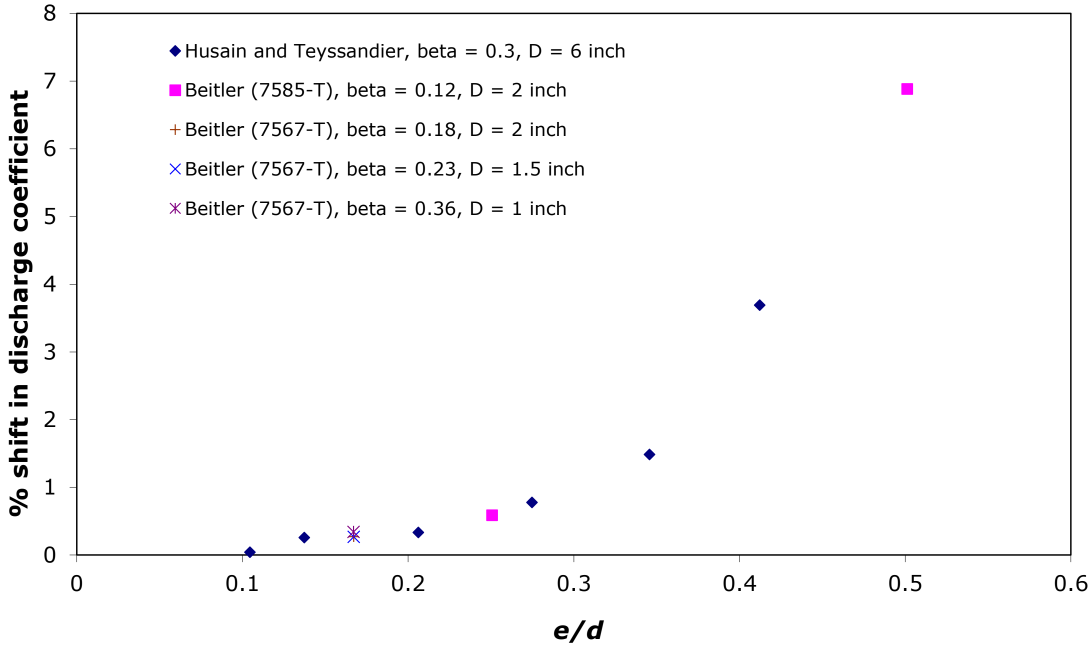

Figure 2 Shift in discharge coefficient on changing *e/d* from that obtained when $e/d < 0.09$; $\beta < 0.4$.

A common curve for all data as a function of *e/d* is obtained. The conclusions of Beitler are that there are two requirements: that $e/d \leq 0.125$ and that $e/h' \leq$

0.25, where h' is the dam height, the distance from the sharp edge of the orifice plate to the nearest point of the pipe wall (i.e., $h' = D(1-\beta)/2$).

ISO 5167-2:2022 has the two requirements: $0.005 \leq e/D \leq 0.02$ and $e/d \leq 0.1$. The second of these is an additional requirement to that of 2003. These requirements are more demanding than Beitler's and on the basis of the work here should prove adequate. The new requirement means that small β can be used with more confidence and more of the potential of orifice metering achieved: between the maximum flowrate at $\beta = 0.67$ and the minimum flowrate at $\beta = 0.1$ the flow range could be as high as 500:1 if the same static pressure is obtained throughout.

3.3.2 Correction to the required spacing between two 45° bends

In ISO 5167-2:2003 Table 3 there are straight lengths prescribed between an orifice plate and two 45° bends in the same plane in an S-configuration ($S \geq 2D$), where S is the separation between the two bends. The original data are given in GRI 99/0262 [10] where it is clear that the spacing between the two 45° bends was $22D$. '$S \geq 2D$' in 2003 appears to be an error. The straight lengths in ISO 5167-2:2022 Table 3 are therefore specified for two 45° bends in the same plane in an S-configuration ($S \geq 22D$).

3.3.3 Clearer specification for the tee in the table of straight lengths

In ISO 5167-2:2003 Table 3 of required straight lengths between orifice plates and fittings it is not clear how the tee is oriented relative to the straight length. Is there a blank flange on one of the arms of the tee? Even if there is a blank flange on one of the arms, is the blank flange parallel to the orifice plate or perpendicular to it?

Reference to the appropriate part of GRI 99/0262 [10] leads back to the original reports [11-13]: from these it is clear that the flow came from the branch (of equal diameter to the orifice run) into the run in which the orifice was located, with the far side of the run from the orifice closed (i.e. the blank flange was parallel to the orifice plate). ISO 5167-2:2022 Table 3 makes this clear with this wording: 'the data for configuration 7 came from using an equal tee with the flow from the branch into the run in which the orifice was located, with the other side of the run closed'.

3.4 ISO 5167-3 Nozzles and Venturi nozzles

No changes between the 2020 and 2022 revisions of Part 3 were made other than those required in all parts of ISO 5167.

3.5 ISO 5167-4 Venturi tubes

3.5.1 The use of single pressure tappings

In high-pressure gas flows using single pressure tappings is the normal way for measuring the flowrate using Venturi tubes. Permitting this simply recognizes reality.

The data described in 3.5.2 of this paper were taken with single pressure tappings. With a long straight upstream pipe and high-quality pressure tappings there is no difference in the discharge coefficient based on the number of tappings. Most of the installation-effects data used to determine the upstream straight lengths were taken with multiple pressure tappings, as indicated in ISO 5167-4:2022 Table 1 Note e: it is possible that with single tappings longer straight lengths might be required.

3.5.2 The discharge coefficient with a machined convergent for $Re_D > 10^6$

In 5.5.3 of ISO 5167-4:2003 the discharge coefficent for a Venturi tube with a machined convergent is given for $Re_D \leq 10^6$, where Re_D is the pipe Reynolds number. For higher Reynolds numbers information is provided in (informative) Annex B.

More data have now been collected and analysed and presented by Collins and Clark [14]. In ISO 5167-4:2022, on the basis of these data, the discharge coefficent for a Venturi tube with a machined convergent is given as 1.000 for $10^6 < Re_D$ with an expanded uncertainty of 1.8%. This discharge coefficient and this uncertainty are given in ISO 5167-4:2022 5.5.3 and 5.7.2, respectively, i.e. in the main body of the standard.

In ISO 5167-4:2022 the discharge coefficient and the uncertainty for $Re_D \leq 10^6$ are unchanged from 2003.

3.6 ISO 5167-5 Cone meters

3.6.1 Two corrections

Two corrections to ISO 5167-5:2016 have been made: in Figure 2 the key was inconsistent with the drawing; in 5.2.7 the frustum internal angles were incorrect.

3.6.2 Expansibility uncertainty

In ISO 5167-5:2022 the expansibility uncertainty is given as a relative uncertainty for ease of use with ISO 5167-1 and for consistency with the other parts. The calculated flowrate uncertainty is unchanged.

3.7 ISO 5167-6 Wedge meters

3.7.1 One corrections

A correction to ISO 5167-6:2019 Annex B has been made, as previously the definition of Kd^2 was incorrect.

3.7.2 Expansibility uncertainty

In ISO 5167-6:2022 the expansibility uncertainty is given as a relative uncertainty for ease of use with ISO 5167-1 and for consistency with the other parts. The calculated flowrate uncertainty is unchanged.

4 ORIFICE UNCERTAINTY: NO CHANGE REQUIRED

it is not simple to calculate the uncertainty for the orifice discharge-coefficient equation. Evaluating the uncertainty for that equation is different from most evaluations of uncertainty: a normal evaluation of uncertainty is for an instrument which is calibrated and itself subsequently used. However, the orifice discharge-coefficient equation is used for plates other than those used to collect the data.

Because the standard deviation in the original EEC/API database (see 5.3 of [3]) does not necessarily reflect the variability permitted by the standard it is not appropriate to evaluate the expanded uncertainty, corresponding to 95 % coverage, of the orifice discharge-coefficient equation as twice the standard deviation of the data in the EEC/API database about the equation.

Accordingly, the uncertainty of the orifice-plate discharge coefficient given by the Reader-Harris/Gallagher (1998) Equation was calculated in [15] taking account of the uncertainty of the data on which it is based and of the variability in manufacture permitted by ISO 5167-2. The work showed that using the correct method to determine the uncertainty in ISO 5167-2 made an insignificant difference to the value given in the standard.

5 CONCLUSIONS

This paper has listed the changes to ISO 5167 that have been made in the 2022 edition and will help readers to be up to date on differential pressure meters and their standards.

The changes are not very extensive, but the absence of major change suggests the standard is robust. Moreover, corrections, clarifications, greater consistency internally and with the GUM, and a broader focus are all valuable changes.

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7 NOTATION

D	pipe diameter
d	orifice diameter
E	orifice plate thickness
e	orifice (bore) thickness
H	profile deviation from fully developed (see 3.2.3)
h'	dam height
R	pipe radius
r'	distance from the centre line
Re_D	pipe Reynolds number
S	separation between two bends
u	point velocity
u_{cl}	velocity on the centre-line
β	diameter ratio (d/D)
ΔC_{p}	mean percentage shift in discharge coefficient

8 REFERENCES

[1] J. STOLZ The first revision of ISO 5167. In: Proc 6th North Sea Flow Measurement Workshop. East Kilbride, Glasgow: National Engineering Laboratory, Paper 3.1, 1988

[2] M. J. READER-HARRIS, J. A. SATTARY The orifice plate discharge coefficient equation — the equation for ISO 5167-1. In Proc 14th North Sea Flow Measurement Workshop, Peebles, Scotland. East Kilbride, Glasgow, National Engineering Laboratory, p. 24 [9], 1996

[3] M. J. READER-HARRIS Orifice plates and Venturi tubes. Springer, 2015

[4] M. J. READER-HARRIS ISO standards on differential-pressure flow measurement: developments. In: Proc 5th Int South East Asia Hydrocarbon Flow Meas Workshop, Kuala Lumpur, 2006

[5] ISO/IEC Guide 98-3, Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), 2008

[6] M. J. READER-HARRIS, J. A. SATTARY, E. WOODHEAD The use of flow conditioners to improve flow measurement accuracy downstream of headers. In: Proc 3rd Int Symp Fluid Flow Meas, San Antonio, Texas, 1995

[7] M. J. READER-HARRIS, E. WOODHEAD, J. A. SATTARY, D. McEWEN Flow conditions downstream of headers. Report HCP001 (223/94) for the Headers Consortium: National Engineering Laboratory, East Kilbride, Glasgow, 1995

[8] Z. D. HUSAIN, R. G. TEYSSANDIER The effects of plate thickness and bevel angle in a 150 mm line size orifice meter. In: Proc Flow Measurement in the Mid 80s. East Kilbride, Glasgow: National Engineering Laboratory, 1986

[9] S. R. BEITLER The flow of water through orifices. A study in 1-in., 1½-in., 2-in., 3-in., 6-in., 10-in, and 14-in. lines. Engineering Experiment Station Bulletin No 89. Ohio State University, 1935

[10] W. STUDZINSKI, U. KARNIK, P. LaNASA, T. MORROW, D. GOODSON, Z. HUSAIN, J. GALLAGHER White paper on orifice meter installation configurations with and without flow conditioners. White paper prepared for API 14.3 Part 2. GRI Report GRI 99/0262, Gas Research Institute, Chicago, 2001

[11] G. E. MATTINGLY, T. T. YEH Summary of NIST’s Industry-Government Consortium research program on flowmeter installation effects with emphasis on the research period February-December 1990: TEE, used as an elbow configuration. NISTIR 4753, National Institute of Standards and Technology, Gaithersburg, 1992

[12] T. B. MORROW, J. T. PARK Metering Research Facility program: Installation effects on orifice meter performance. Topical report. GRI Report GRI 93/0054.1, Gas Research Institute, Chicago, 1993

[13] T. B. MORROW Metering Research Facility program: Orifice meter installation effects: Ten-inch sliding flow conditioner tests. Technical memorandum. GRI Report GRI 96/0391, Gas Research Institute, Chicago, 1996

[14] A. COLLINS, S. CLARK Additional data supporting the 2022 updates to the ISO 5167 standards. Flow Measurement and Instrumentation, Vol. 86, Article 102193, August 2022

[15] M. J. READER-HARRIS, C. FORSYTH, T. BOUSSOUARA The calculation of the uncertainty of the orifice-plate discharge coefficient. Flow Measurement and Instrumentation, Vol. 82, Article 102043, December 2021