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Development of ISO Standards:

Orifice plates, comparison between ISO 5167 and AGA 3

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SUMMARY

The development of the standardisation of pressure difference devices and in particular the orifice plate is traced from its introduction at the end of the last century. In 1980 the USA were unable to support the adoption of the latest ISO Standard, ISO 5167, for their national use and so are continuing to use the American Gas Association Report No 3 for natural gas measurements especially.

The differences between these two documents are referred to and the progress being made on various test programmes in the USA and Europe to provide fresh data is described.

CONTENTS

NOTATION

C	Flow discharge coefficient
D	Pipe inside diameter
d	Orifice bore diameter
E	Velocity approach factor, $(1 - \beta^4)^{\frac{1}{2}}$
L_1	ℓ_1/D
L_2	ℓ_2/D
ℓ_1	Distance of the upstream tapping from the upstream face of the orifice plate
ℓ'_2	Distance of the downstream tapping from the downstream face of the plate
Δp	Pressure difference across the orifice plate
q_m	Mass flowrate
Re_D	Reynolds number
u_1	Mean velocity in the upstream pipeline
β	Diameter ratio, d/D
ε	Expansibility factor, dependent on fluid characteristics
ν	Kinematic viscosity
ρ	Mass density of fluid

1 INTRODUCTION

Familiarity with the ubiquitous orifice plate which, simply speaking, can be regarded just as a hole bored out of a standard piece of plate and inserted in the pipeline, has led many engineers to treat the measurements obtained from it quite casually. By contrast for example the use of a laser Doppler velocimeter to measure the velocity profile in a pipeline and integrate the results to get the flowrate would be regarded as highly complicated, requiring a great deal of care. In fact the latter is certainly true and even with such care there is a high probability that the results will show some anomalies and if checked against the true flowrate could easily be up to 2 per cent wrong.

The present notes are aimed at demonstrating that it is equally important that great care and attention should be paid to the manufacture, installation and use of orifice plate meters if good measurements are to result. The accuracy of the predicted discharge coefficients given in the Standards can only be obtained if strict observance of the requirements specified in the Standards is applied. Even more than this however is the need to understand better the fluid mechanics of the flow in pipelines and the flow through such devices so as to be able to avoid errors which can arise even after the user thinks that he has met all the requirements.

In a subsequent lecture, the assessment of the uncertainties in flow measurements will be studied and so the present lecture based on these notes will deal with this aspect only glancingly.

2 ORIFICE METERING

It has been estimated recently that over 50 per cent of industrial measurements are still being carried out using pressure difference devices despite the multiplicity of novel methods which have been introduced in the past 30 years. The orifice plate was originally developed in the 1890s for the measurement of natural gas flowing through pipelines from the wellheads in the USA. While pressure difference devices may be used for measuring the flow of virtually any fluid, this original application is still most important, certainly in terms of the value of the commodity being measured. Thus the buying and selling of natural gas from the North Sea at the custody transfer points in the UK and in Continental Europe, for example, or the measuring points along the proposed new gas pipeline from the Soviet Union to Western Europe are still made through orifice meter runs, as are nearly all the other measurement stations in the vast network which takes this energy resource in bulk from source to centres of use.

The first standards for orifice metering were produced by the instrument manufacturers but soon efforts were being made to codify the information since users were basing contracts for substantial sales on the measurements made. It was not practicable to calibrate every flowmeter in its operational location and so laboratory calibrations were undertaken to build up a data bank from which flow discharge coefficients (C) could be calculated.

The mass flowrate q_m, through an orifice plate is:

$$q_m = CE\varepsilon\frac{\pi}{4}d^2\sqrt{(2\Delta p\rho)}.$$

The way in which, for example, the diameters d and D were determined in practice varied from area to area while the location of the pressure tappings upstream and downstream of the plate was selected differently by different constructors. It became clear that some rationalisation was essential; national committees were set up in the 1920s and 30s to agree on the physical geometry to be used and, by the mid 1930s, this had progressed to the point where international agreement was possible and the ISA Bulletin Nos 9 and 12 were published$^{(1,2)}$. National committees, however, continued to publish their own codes which were far more detailed than the ISA Bulletins.

Naturally, these national codes reflected current practice in their own countries and so there were differences in detail between them. The German DIN Standard and the American ASME Fluid Meters Handbook were the first to be published and it was not until 1943 that the British Standard BS 1042 appeared. The International Organisation for Standardisation, which took over from the ISA in the late 1940s, created the ISO Technical Committee No 30: 'Measurement of the flow of fluids in closed conduits'. After many meetings two 'Recommendations', ISO R541 on orifice plates and nozzles and ISO R781 on venturi tubes were published in the late 1960s$^{(3,4)}$.

Essentially these two 'Recommendations' still presented national viewpoints, each being composed of sections taken from the national standards virtually in toto. Those from the USA were mainly adopted from the Fluid Meters handbook while the European attitudes were represented by details from the German Standard and to some extent the British Standard plus French and Belgian experience.

Efforts were being made, for example, to improve the presentation of available data on the basic discharge coefficients. The discharge coefficient depends on the relationship of the pressure difference as measured by a particular combination of upstream and downstream tappings, the density of the fluid flowing, the ratio of the bore to the pipe diameter, and the distribution of the flow approaching the orifice plate. In broad terms the latter can be identified by the Reynolds number Re_D where:

$$Re_D = \frac{U_1 D}{\nu}$$

This is, of necessity, a criterion which is modified for every individual case since the Reynolds number is calculated from the mean velocity and takes no account of the actual velocity profile in the pipeline or the turbulence level in practice. Variations arise from the upstream pipeline configuration and the internal surface finish to the pipe, as well as through the fluctuations caused by pumping or compressor stations etc.

In the late 1960s and early 1970s, attempts to rationalize the variety of discharge coefficient data available were mathematical. Equations using power series of the variables were evolved which, while excellent fits to the specific data on which they were based, were certainly complicated to use and were dangerously wrong if extrapolated. More important than this, however, was their mutual incompatibility with each other. Hence the user, by choosing which equation he adopted, could artificially derive a discharge coefficient which, when used in the flow equation, could give a resulting measurement favouring one or other of the parties to a contract.

3 THE PRESENT INTERNATIONAL STANDARD

J Stolz, the Chairman of the ISO/TC30 Sub-committee responsible for pressure difference devices, led the way to a new understanding of the problem.

He realised that improvement could only come by recognising that the discharge coefficients derived from different sets of pressure tappings must nevertheless be related to each other by physical laws. Thus the results for flange tappings and corner tappings must become identical for large pipe sizes since the allowable tolerances on their physical locations then overlap. Similarly flange and D and D/2 tappings must give the same results at very small sizes. Again all coefficients for all tappings and pipe diameters must approach each other as the diameter ratio decreases. An equation was then fitted to the pressure distribution just upstream and downstream of the orifice plate based on independent tests. Combining these boundary conditions to represent logically these laws with the two sets of data which were the best authenticated (the Beitler and Witte data discussed lated) he evolved an equation for calculating the discharge coefficient which was relatively straightforward(5). This was approved by the Subcommittee and was incorporated into the ISO Standard 5167 which was eventually published in 1980(6).

The Stolz equation (Table 1) is not necessarily valid for all time but can, with great confidence, be regarded as a satisfactory foundation for accommodating new data merely by altering the constants. In the author's opinion any updated correlations of data should be based on its principles.

The coefficients given by the Stolz equation are only applicable to the type of orifice plates specified in ISO 5167 (Fig. 1) and can only be applied when the conditions of use given in Table 3 are met (ISO 5167, clause 7.3.1). Another condition is that the upstream pipeline shall be smooth with an upper limit of relative roughness, dependent on the diameter ratio of the plate being used but generally less than $k = 0.001D$ (this is approximately equivalent to the surface obtained in a 50 mm (2 in) diameter new seamless cold draw steel pipe).

Inevitably there will be uncertainties both in the physical measurements to be entered into the flow equation and those associated with the discharge coefficient equation. All these sources of uncertainty must be taken into consideration when assessing the overall accuracy of a measurement and as stated earlier another ISO standard, ISO 5168, provides guidance on how to determine this overall uncertainty(7). The user must estimate the uncertainties associated with his own measurements, but those associated with the discharge coefficient, and the expansibility coefficient required when dealing with gases particularly at pressures near to ambient, have to be specified. The uncertainties published in ISO 5167 associated with the Stolz equation are given in Table 4.

Table 4 has such attractive simplicity and symmetry that its validity might easily be accepted as fundamental. This is not the case, since neither the predicted discharge coefficients nor the conditions of layout etc, to which they can be said to apply are universally accepted. Indeed the publication of ISO 5167 was long delayed while the drafting Committee of ISO/TC30/SC2 sought full agreement on all aspects. Eventually it was published on the basis of a consensus of support from the participating nations. The USA could not accept some of the requirements because they were at variance with the AGA Report No 3 which has long been established as a standard used for the measurement of natural gas by American companies nationally and internationally(8).

In a recently published recommendation that the Stolz equation be adopted in the USA, the ASME Fluid Meters Research Committee stated(9) that: "it is more convenient to use; it fits the Ohio State University data and the AGA and ASME equations; and it fits the newer high Reynolds number data better and the low Reynolds number data much better than AGA3".

4 OUTSTANDING PROBLEM AREAS NEEDING RESOLUTION

Difficulties nevertheless remain in both the use and interpretation of ISO 5167 itself, as well as the fact that there are major differences between it and the AGA3 document submitted to ISO/TC28/SC5. Clearly it will be some years before fresh authenticated data will become available; the publication of a radical revision of ISO 5167 is, therefore, still some years away. In consequence, urgent consideration is to be given to the publication of a supplement to ISO 5167 so that these areas of concern can be reduced as far as possible. The key problem areas fall broadly into two categories:

- the reliability, both in terms of absolute values and the uncertainties, of the discharge coefficient for the prescribed design of orifice plates;

- the installation configuration for which these basic coefficients can still be used when the upstream straight lengths between the particular pipeline fittings and the orifice plate are shorter than the 'ideal' long lengths thought to apply in the original tests. Fittings in this sense applies to bends, valves, changes of cross section etc, upstream of the orifice meter run itself.

Thus the various differences between the AGA and the ISO 5167 documents are many but in essence they can be considered as follows:

a It is impossible to retain forever the Bean and Buckingham coefficient equation which dates from the early 1930s and disregards all the work done since that time. Hence the AGA3 equation for the coefficient must be superseded. The latest version of the ASME Fluid Meters Standard, dated June 1983 which has been submitted to the American National Standards Institute for adoption as a US Standard gives the Stolz ISO 5167 equation.

b The uncertainties to be associated with the prediction of the discharge coefficients must be reconsidered. Various efforts have been made to move from the original values and the latest comes from the Federal Republic of Germany who would like to see the uncertainties broken down to get a better picture of the different sources of error. Thus edge sharpness, installation, flatness, diameter ratio are all factors. It is unlikely that any simple solution exists for all these effects are interdependent but it does mean that a slavish acceptance of a universal figure of, say, ±0.5 per cent will be unacceptable.

c At the moment, illogically, it would appear from the two standards that better accuracy would be achieved by following the AGA Report even though it tolerates much greater disturbances to the upstream flow. The installation configurations and lengths adopted many years ago by the AGA Committee have been proved to be inadequate. In other words tests have shown that errors can result which put the metering outside the specified tolerance limits. A recent paper given at Conference in Aberdeen in May 1983 showed in fact that for certain configurations even the ISO 5167 lengths are insufficient(10).

d There is a great need therefore to establish a stable but shorter pipeline configuration which could achieve the best accuracies already claimed. This approach has been the reason for many investigations from the work of

Sprenkle in the USA in the 1930s to that of Zanker at the British Hydromechanics Research Association in the UK in the 1950s and many other workers more recently$^{(11)}$. The most recent work is that using the Mitsubishi straightener and referred to at the IMEKO Conference in Tokyo in 1979.

A major study on this subject is underway at NEL in Scotland and we expect to be publishing results in the next two years. It has to be appreciated however that it is likely to take a further three or four years to accumulate enough data and confidence to be able to adopt such a major change in a revision of the International Standard.

5 NATIONAL EXPERIMENTAL PROGRAMMES: PAST AND PRESENT

As mentioned earlier, the data analysis for the development of the Stolz equation was based on only two sources because other data was of less well documented validity or acceptance in the standardisation world.

The greatest single series of experimental determinations of discharge coefficients was that carried out by Professor S R Beitler in the early 1930s at the Ohio State University Engineering Experimental Station$^{(12)}$. He studied water flowing in pipes from 2-14 inches (50-350 mm) diameter. In each of the seven pipe sizes orifice plates with a wide range of bore diameters were tested. While little is now known of the fine detail of the pipework condition or of the plates themselves, the considerable care with which these tests were undertaken is noteworthy. The well documented results were published in 1935.

In Europe a wide range of tests was carried out by Dr R Witte, in Germany, also in the early 1930s. These were made in water, air, steam and other fluids and covered a range of pipe sizes and orifice bore diameters. Instead of the original raw data and the derived values of the discharge coefficients and other parameters, which have been lost, there are only some very small diagrams contained in publications by Witte during the 1930s, the results of the tests being coalesced into tables and graphs published in the German standards in the late 1930s. These tables provided the framework for the publication of data in ISO R541 in 1967 and were used by Stolz in his overall assessment.

- When one considers the hundreds of thousands of orifice plates in use in the world, it may be considered remarkable that all the flow computations are based on the data of perhaps 600 test points.

While such past data may be reasonably well authenticated, insufficient is known about the actual devices or the pipe runs or the test conditions. In 1978 the API and AGA supported a joint experimental programme to obtain new basic discharge coefficients. They decided to construct two sets of orifice meter runs in a number of different pipe sizes. The pipe sizes were 50, 75, 100, 150 and 250 mm (2, 3, 4, 6 and 10 in) internal diameter and for each of these sizes two meter runs were constructed. For each of the pipe sizes two sets of orifice plates were manufactured in a range of diameter ratios from 0.2-0.75 thus making 70 different orifice plate/meter tube combinations. The intention at that time was to use the results from these tests to publish a revised edition of the AGA/API Manual 'Orifice Metering of Natural Gas'$^{(8)}$. In practice AGA and API have subsequently separately funded test programmes at the NBS, Colorado using gas and at NBS, Gaithersburg using water.

A study carried out for the EEC Commission's Directorate General XII for Research, Science and Education had resulted in a proposal being put forward to the Commission in October 1977 that a major project should be carried out to check and improve prediction of the discharge coefficients of orifice plates. An earlier report to the Commission had drawn attention to the demand, in the area of distribution of gas energy, for improvements in the level of measurement accuracy which could be obtained. The Commission gave its approval in January 1978 and, when it became clear that it would not be possible to operate a single collaborative scheme with the AGA/API project in the USA, it was decided to construct separate orifice meter runs in Europe.

The EEC project has three major differences from the original objectives of the USA project. First the EEC project is aimed at obtaining coefficient data on all three internationally recognised tapping arrangements (corner, flange and D and D/2) whereas the US project is solely concerned with the flange tap measurements. Secondly, the EEC project is aimed at resolving not only the question of the validity of the basic coefficient data, as is its US counterpart, but also with resolving doubts about the installation straight lengths required after various standard fittings and with the requirements associated with the use of straighteners. Thirdly, the EEC project is to be carried out using water, air and gas test facilities so that the range of Reynolds numbers over which the coefficient data would be established will be extended. The present API project does now envisage that at a later stage it will be extending to liquids and gases other than water.

The concept for a positive exchange of hardware across the Atlantic remains unchanged. It is vital to ensure that there should be full acceptance by standardising groups in the USA, Europe and elsewhere of the validity of all the results. It is therefore proposed that the tests carried out at NEL in Scotland should be replicated at the NBS in Washington on both the EEC and the US meter runs.

As stated earlier AGA separately decided that it should also initiate a project to develop new test data. The Gas Research Institute in the USA is sponsoring the programme of tests using the equipment manufactured originally for the AGA/API programme. These tests are being carried out in the modified test facility built for the NBS at Boulder, Colorado, USA, using liquid nitrogen. The advantage of this facility is that the liquid nitrogen can be diverted and weighed accurately whilst in the circuit the liquid nitrogen can be warmed up to ambient conditions and operate as a gas. The GRI programme, which is at present aimed at obtaining the basic discharge coefficient data in long straight pipelines, will include all the pipe sizes up to 150 mm (6 in) and hence will deal with some 60 orifice plate combinations.

The American programmes are still at such an early stage that it is difficult to predict when they will be completed. However, since they are aimed at developing the basic discharge coefficients and not investigating installation effects it seems likely that answers will be obtained by the early part of 1984. The EEC programme, which is already well underway and has obtained data both on installation effects and on basic discharge coefficients in water, high pressure air and high pressure gas is scheduled to be completed by mid-1984. A report on the first part of the work is planned to be presented in February 1984.

At NEL a separate test programme is being carried out to study small pipe sizes of 2 inches and below since the latter are not covered in ISO 5167. Daniel Industries Ltd, who also manufactured the meter runs for the API and AGA programmes and for the 100 mm size for the EEC programme, are collaborating with NEL in this project.

6 CONCLUSION

The experimental programmes now in operation will make it possible to resolve a number of critical questions which have remained unanswered for decades. Linked together, these major programmes should provide a sound data base on basic coefficients which will be established together with realistic determinations of the uncertainties associated with predicting these coefficients. In total over 100 orifice meter combinations have been manufactured and will be tested. On this basis the new evaluation of the Stolz equation can be expected to be much more reliable.

In addition a number of nodal points will be established on the effect on the coefficient of various upstream fitting configurations. Finally many more minor requirements in the specification of the design and use of orifice plate metering will be checked so that next full revision of the ISO Standard 5167 can truly meet the needs of the 1980s and 1990s. Meanwhile it is confidently hoped that interim modifications and additions can be published which will assist users of the present standard to conform with greater confidence and appreciate the true uncertainty with which their measurements are being made.

ACKNOWLEGEMENT

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LIST OF TABLES

LIST OF FIGURES

Table 1 The Stolz equation*

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^{8}$$
$$+ 0.0029\beta^{2.5}\left[\frac{10^{6}}{Re_D}\right]^{0.75}$$
$$+ 0.0900L_1\beta^{4}(1-\beta^{4})^{-1} - 0.0337L_2'\beta^{3}$$

If $L_1 \geqslant \frac{0.0390}{0.0900}$ (= 0.4333)

use 0.0390 for the coefficient of $\beta^4(1-\beta^4)^{-1}$

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* *As given in ISO 5167 (clause 7.3.2.1)*

Table 2 Values of L_1 and L_2'

Corner tappings	$L_1 = L_2' = 0$
D and $D/2$ tappings	$L_1 = 1$; $L_2' = 0.47$†
Flange tappings	$L_1 = L_2' = 25.4/D$‡

† *Hence coefficient of $\beta^4(1-\beta^4)^{-1}$ is 0.0390*
‡ *Where D is expressed in mm*

Table 3 Conditions of validity

	Corner taps	Flange taps	D and $D/2$ taps
d (mm)	$\geqslant 12.5$	$\geqslant 12.5$	$\geqslant 12.5$
D (mm)	$50 \leqslant D \leqslant 1000$	$50 \leqslant D \leqslant 760$	$50 \leqslant D \leqslant 760$
β	$0.23 \leqslant \beta \leqslant 0.80$	$0.2 \leqslant \beta \leqslant 0.75$	$0.2 \leqslant \beta \leqslant 0.75$
Re_D	$5000 \leqslant Re_D \leqslant 10^8$ for $0.23 \leqslant \beta \leqslant 0.45$ $10\,000 \leqslant Re_D \leqslant 10^8$ for $0.45 < \beta \leqslant 0.77$ $20\,000 \leqslant Re_D \leqslant 10^8$ for $0.77 \leqslant \beta \leqslant 0.80$	$\geqslant 1260\beta^2D$† $\leqslant 10^8$	$\geqslant 1260\beta^2D$† $\leqslant 10^8$

† *Where D is expressed in mm*

Table 4 Uncertainty associated with the Stolz equation*

When β, D, Re_D and k/D are assumed to be known without error, the uncertainty of the value of C is:

	Corner taps	Flange taps	D and $D/2$ taps
$\beta \leqslant 0.6$	0.6%	0.6%	0.6%
$0.6 \leqslant \beta < 0.8$	β%	—	—
$0.6 \leqslant \beta \leqslant 0.75$	—	β%	β%

* *ISO 5167 Clause 7.3.3.1*

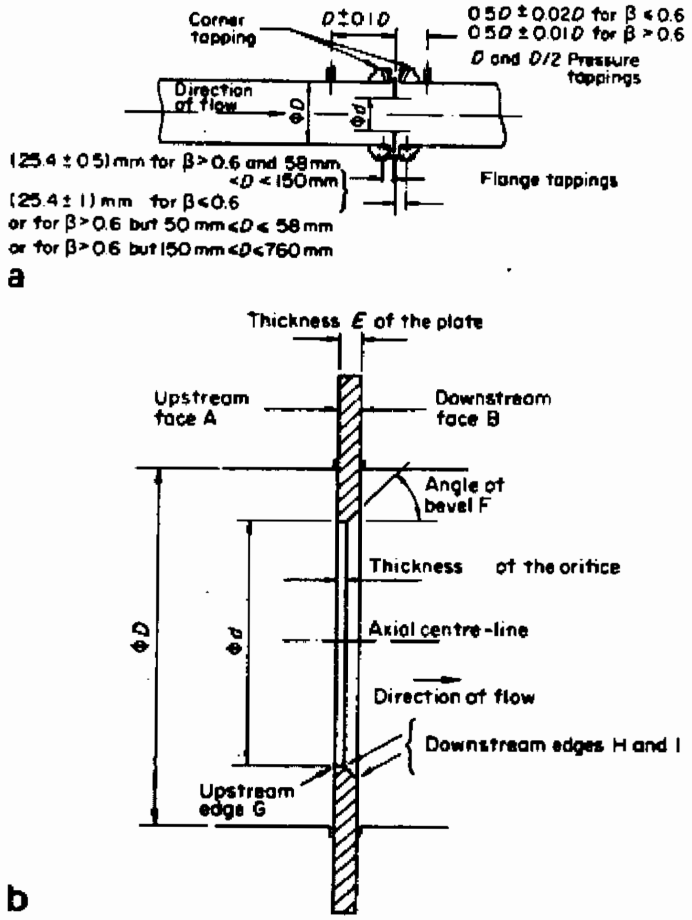

Fig 1 (a) Location of ISO 5167 pressure tappings upstream and downstream of orifice plate (b) Details of ISO 5167 orifice plate