The Stolz and ASME-AGA Orifice Equations Compared to Laboratory Data

R. W. Miller

Flow Consultant,
The Foxboro Company,
Foxboro, Mass. 02035
Mem. ASME

Today, technical experts in Europe and the U.S. are debating the merits of conducting new orifice flowmeter tests, establishing the effects of upstream disturbance and conducting other programs to improve orifice flowmetering accuracy. ISO has adopted a new "Universal" orifice equation proposed by J. Stolz. With over 1,000,000 orifice flowmeters in use today, any change in the coefficient value is of major concern.

There are now two equations for calculating flange tap coefficients, the ASME-AGA equation and the ISO equation. They differ in form, predict different coefficients, and have different overall uncertainties (tolerance value).

This paper presents a comparison between actual laboratory data and these two equations. The data were obtained in two high accuracy laboratories on flange tap orifice flowmeters fabricated by different manufacturers to AGA or ASME recommendations. Data plate dimensions were used in all calculations, and conformity to ASME or AGA requirements was the responsibility of the manufacturer. For this reason it is believed that the analysis more nearly represents what the user can expect if the in-site installation approached that of the laboratory.

Results indicate that over the same beta ratio range the ISO (or Stolz) equation form is significantly better than the present ASME-AGA form. The overall uncertainty (or tolerance), although smaller than the ASME-AGA, is still ±1 percent because of a 0.4 percent systematic error. Results of work by Miller-Kneisel, using data from three different laboratories, are presented to indicate that ±0.5 percent remains achievable; for betas up to 0.7 using the ISO (Stolz) equation form with modified coefficients.

Introduction

Accuracy (or the overall uncertainty) in the determination of the flow rate is directly dependent on the discharge coefficient. For best possible accuracy the flowmeter is calibrated to determine the coefficient, but this is often impractical, expensive, and unnecessary if confidence in published values based on dimensions and good installation practices exist. The coefficient is computed from basic orifice dimensions. When the orifice meter run is installed properly, the user expects to be within the stated coefficient's overall uncertainty.

The coefficient value is primarily a function of the orifice bore to pipe diameter ratio (β), pressure tap location, operating Reynolds number; and for flange tap meters, the pipe diameter. Other parameters also affect the coefficient, such as orifice bore to pipe diameter eccentricity, installed straight lengths of pipe following an upstream flow disturbance, edge sharpness, pipe roughness, etc. These effects are not well understood, but data exist that allow for limiting specifications for each.

The purpose of standards or recommended practices is to provide the user with the latest technical information on orifice flowmetering so that a flow measurement can be made to a specified overall uncertainty value. Examples of standards, or available literature, are: AGA Report No. 3 [1], ISO 5167 [2], ASME Fluid Meters [3], Spink's Handbook [4], the Shell Handbook [5], and BSI 1042 [6]. Many of these form the basis for custody transfer metering and cost accounting for feedstock, natural gas, etc. All of these attempt to guide the user through over 50 years of orifice flowmeter practice, theoretical considerations, and literally thousands of flow tests.

The present equation for flange tap orifice coefficients was empirically determined from data obtained at Ohio State University in the 1930's [7]. These data were cross plotted against the various known influence quantities (Bore Reynolds no., etc.) to arrive at the "Buckingham" equation; an equation adopted by ASME, AGA, and until recently, ISO. This equation has predicted uncalibrated flange tap orifice coefficients for over forty years.

The ASME Fluid Meters Research Committee, in the mid-1960's, began a study to reevaluate the original data and add new coefficient data obtained from several laboratories over the intervening thirty years. The program used regression analysis to obtain the coefficient values for a fitting equation. Two sigma ($\pm 2\sigma$) was selected by the committee as well as ISO, as the overall uncertainty of the data with respect to the equation.

Contributed by the Fluids Engineering Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS and presented at the Winter Annual Meeting, San Francisco, Calif., December 10-15, 1978. Manuscript received by the Fluids Engineering Division, August 2, 1978. Paper No. 78-WA/FM-2.

The 1930 data had an overall uncertainty of ± 1.85 percent with respect to the Buckingham equation and ± 1.56 percent with respect to a new fitting expression. Limiting line size, Reynolds number, and beta ratio range reduced the uncertainty to ± 1 percent, or approximately twice that published in Fluid Meters Fifth Edition.

When additional data from many laboratories were added, an uncertainty of ± 8.6 percent was calculated. By limiting line size, Reynolds number, beta ratio range, and eliminating substantial blocks of data, the uncertainty was reduced to ± 1 percent. This work was presented in a paper by Dowdell and Chen [8], published in the Transactions of ASME in December 1970.

A direct result of this analysis was a change in the Fluid Meters Sixth Edition's Uncertainty to ± 1 percent from ± 0.5 percent of the Fifth Edition, and to begin discussions for initiating a new test program that would repeat the 1930 tests using more refined procedures and equipment.

In 1973, flange tap orifice data, obtained in The Foxboro Company's hydraulic flow laboratories, was presented in an ASME paper by Miller and Kneisel [9]. This data was obtained on commercially available flange tapped meter runs fabricated to ASME or AGA specifications. This work indicated an overall systematic error of $+0.65$ percent in the Buckingham equation and a random uncertainty ($\pm 2\sigma$) of ± 1.5 percent with respect to the overall systematic error. Limiting the data to 4 in. and larger line sizes reduced the overall systematic error to $+0.34$ percent with a random uncertainty of ± 0.62 percent.

Subsequent regression analysis on the data from Foxboro and Columbus, and data supplied by Daniel Industries, showed it was possible to reduce the tolerance to ± 0.48 percent, with zero systematic error, for line sizes 4 in. to 24 in., and beta ratios of 0.2 to 0.7. This work, by Miller and Kneisel, was not published, but it was presented to various interested groups to show what was possible [10, 11].

In 1975, J. Stolz presented to ISO/TC30 [12] his conviction that there should exist a universal orifice equation for all three tappings, since the pressure drops were in all cases due to the same orifice. He derived an equation with which to calculate the coefficients for flange taps, D and $D/2$ taps, and for corner taps. Using selected Columbus data for flange taps and for D and $D/2$ taps, and published tabular values for corner taps, it has been refined to the point where it is now the equation for ISO/TC30 document 5167 [2], [22]. This work was done in cooperation with the joint AGA-API orifice study committee, with the computer and analysis work under the direction of Mr. Wayne Fling. The purpose of this paper is to compare flange tap data obtained in The Foxboro Company's laboratory to the ASME-AGA and the Stolz equation.

The Stolz Equation

The proposal for a universal orifice equation was presented to ISO/TC30/SC2 in 1975 [12], based on a paper presented by J. Stolz at an NEL (East Kilbride, Scotland) Flow Conference in Aril 1975. In it, logical "rules" are set forth for an equation that encompasses the major tapping arrangements; corner taps, flange taps, and D and $D/2$ taps (radius taps). Briefly these rules are:

1. Two or more identical orifice meters should have the same coefficients even when they are used with different names, for example, the flange tap meter in a 2 in. line size has essentially the same tap locations as D and $D/2$ orifice meter. Flange taps in large line sizes and corner taps approach the same tap locations and should, therefore, have the same coefficient.

2. Flange taps in any pipe size (≥ 2 in.) should have coefficient values that lie between D and $D/2$ taps and corner taps; especially when beta (β) is greater than 0.5 or where the upstream tap has the most influence.

The significant contribution by Stolz was to represent analytically the pressure drops in the immediate vicinity of the plate, which led to the simplicity of a (l/D) parameter and a function of $\beta^4(1-\beta^4)^{-1}$ for tap location parameter.

Using these "logical" rules, subset rules were applied to a specific equation form; using regression analysis on tabular values [7], and selected flange tap and D and $D/2$ taps data

Nomenclature

C = discharge coefficient-dimensionless
D = pipe diameter (inches)
d = orifice bore diameter (inches)
E = orifice plate thickness (inches)
EE = equation efficiency
e_s' = percentage systematic error for each orifice
$\bar{e}_s$ = overall systematic error for all orifices
$\bar{e}'$ = percentage estimated systematic uncertainty for all orifices
$(e_R')_{95}$ = percentage estimated random uncertainty for all orifices
F = F-distribution value based on ratio of standard deviations squared
$(F)_{95}$ = F-distribution tabular value at the 95 percent confidence level
$k_{1,2..}$ = constant coefficients in an equation form
L_1 = dimensionless ratio of upstream tap distance from the upstream face of the plate divided by the pipe diameter
L'_2 = dimensionless ratio of downstream tap distance from the downstream face of the orifice divided by the pipe diameter
R_D = Reynolds number based on pipe diameter (Stolz equation)
R_d = Reynolds number based on orifice bore diameter (ASME equation)
n = number of data points for each orifice
m = number of orifice flowmeters tested
t = students "t" value at the 95 percent confidence level
S = estimate of the standard deviation of all data points
$\bar{S}_s$ = estimate of the standard deviation of the means of the systematic error (e_s') of each orifice
β = dimensionless ratio of orificed bore diameter divided by pipe diameter
α_3 = coefficient of skewness
α_4 = coefficient of Kurtosis

Subscripts

1 = percentage
STOLZ = Stolz equation
ASME = Buckingham or ASME equation
95 = 95 percent confidence level
A = actual laboratory determined coefficient
E = equation calculated coefficient
S = overall systematic error
ASME/STOLZ = combined ASME and Stolz standard deviations
∞ = infinite Reynolds number coefficient value

from the Ohio test, the final equation was developed for flange, corner, and D and $D/2$ taps [13].

The equation form selected was:

$$C = C_\infty + \text{"Slope factor"}/R_D^n \qquad (1)$$

and the subset rules were:

1. The exponent (n) should be the same for all tapping.
2. The slope shall be the same for all tapping.
3. The slope term should equal zero for beta equal to zero.
4. The infinite Reynolds number coefficient (C_∞) should have the same limiting value for beta = 0 for all tapping.
5. The influence of the upstream impact pressure is linear with the parameter $(\beta^4)(1-\beta^4)^{-1}$.

The Stolz equation, as it appears in ISO/5167 [2], [13], is:

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.0029\beta^{2.5} [10^6/R_D]^{0.75} + 0.09L_1\beta^4(1-\beta^4)^{-1} - 0.0337L'_2\beta^3 \qquad (2)$$

When $L_1 \geq 0.4333$, use 0.0390 for coefficient term of $\beta^4(1-\beta^4)^{-1}$

In this dimensionless equation, the term L_1 denotes the location of the upstream pressure tap with respect to the upstream face of the orifice and L'_2 denotes the location of the downstream tap with respect to the downstream face of the orifice.

L_1 = 0 for corner taps

L_1 = $1/D$ for flange taps; where (D) is in inches

L_1 = 1 for D and $D/2$ taps
Note: with L_1 being greater than 0.4333 the coefficient of the $\beta^4(1-\beta^4)^{-1}$ term is to be taken as 0.0390.

L'_2 = 0 for corner taps

L'_2 = $1/D$ for flange taps; where D is in inches

L'_2 = 0.47 for D and $D/2$ taps

The determination of the constant coefficients for the terms in the equation and the "balances" of each set of tabular corner tap values and experimental data (flange taps and D and $D/2$ taps) has been well documented in numerous ISO publications and will not be expanded on by the authors.

The ASME-AGA Equation

Buckingham, working with the data from the Ohio State Test [7], derived the flange tap orifice equation that is presently used by ASME and AGA. This was a monumental task, being done by logarithm tables and French curves, and employed a greal deal of engineering judgment. The equation is well-known and is presented for information purposes.

The ASME-AGA orifice plate coefficient equation:

$$A = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + 530/\sqrt{D})$$

$$K_e = 0.5993 + 0.007/D + (0.364 + 0.076/\sqrt{D})\beta^4 + 0.4(1.6 - 1/D)^5[(0.07 + 0.5/D) - \beta]^{5/2} - (0.009 + 0.034/D)(0.5 - \beta)^{3/2} + (65/D^2 + 3)(\beta - 0.7)^{5/2}$$

$$K_0 = K_e[10^6 d/(10^6 d + 15A)]$$

$$K = K_0(1 + A/R_d)$$

$$C_{\text{ASME-AGA}} = K\sqrt{1-\beta^4}$$

Flow Laboratories and Test Procedures

All flow calibration work was performed in one of two flow laboratories in Foxboro, Massachusetts. Meter sizes up to 4 in. are tested in the Engineering Laboratory, and larger sizes, up to 24 in., tested in the Production/Engineering Laboratory [14]. This laboratory has a capability of 15,000 gallons per minute and offers a wide flow rate range capability. In both laboratories the static-weigh/time technique was used to determine the flow rate. Manometers or the Null Balance Integration (NBI) measurement system [15] was used to measure differential pressure. When manometers were used, at least 20 visual readings were taken and averaged to obtain the differential.

The orifice meter runs were all calibrated in a horizontal straight pipe section. The upstream piping, in both laboratories, consisted of straightening vanes followed by a minimum of 20 pipe diameters of straight pipe ahead of each test section, and a miniumum of 10 pipe diameters downstream. Flow was supplied from a head tank [16] or centrifugal pumps.

All measurements (mass, time, temperature, and differential) was corrected for known systematic errors of ±0.01 percent or larger, to standards traceable to the National Bureau of Standards.

A minimum of 8 calibration points were taken for each primary device following accepted ASME test procedures and computation recommendations.

Data Analysis

Two statistical quantities are of primary interest when evaluating data or agreement of data to an empirical equation. The first is the systematic error, sometimes called bias, offset, or shift. The second is the random error of the data with respect to the systematic error. This has often been called precision, repeatability, reproducibility, data spread, or tolerance. To be consistent, the terminology and statistical treatment outlined in ISO/5168 [17] will be used to evaluate these two errors.

A computer card was prepared for each data point which included the line size (D), discharge coefficient (C_A), bore Reynolds number (R_d), and orifice identification number. From this information, a computer program calculated the discharge coefficient (C_E) based on the equation; Buckingham (ASME, AGA, and Stolz (ISO 5167)). A high-speed line plotter plotted the percent difference between the laboratory determined coefficient (C_A) and the calculated equation coefficient (C_E) against bore Reynolds number. All data points were plotted and no runs omitted. The percent deviation was calculated as:

$$\% = \left(\frac{C_A - C_E}{C_E}\right) \times 100 \qquad (3)$$

The systematic error, for each orifice, was calculated as the average of the percent deviations calculated from equation (3) as:

$$\text{Systematic Error} = e_s{}' = \frac{\Sigma(\%)}{n} \qquad (4)$$

A positive systematic error ($e_s{}'$) indicates that, on the average, the laboratory determined coefficients were higher than the equation predicts.

If the equation predicts the coefficients well, the overall systematic error will be zero; the sum of the systematic errors divided by the number of orifices would approach zero. If there is an overall systematic error, the equation on the average would either be predicting the coefficients too high or too low. The overall systematic error can be defined as:

$$\text{Overall systematic error} = \bar{e}_s = \frac{\Sigma(e'_s)}{m} \qquad (5)$$

Since the overall systematic error ($\bar{e}_s$) is an average of a limited number of orifices (m), a range of values exists within the *true mean* would be expected to lie. This range can be estimated, for a given confidence level, using the Students "t" distribution [18].

$$\text{Range of Mean} = \bar{e}_s{}' = \pm \frac{t\bar{S}_s}{\sqrt{m}} \qquad (6)$$

Where $S_{\bar{s}}$ = Estimated standard deviation of the systematic errors.

($S_{\bar{s}}$), used above, is the standard deviation of the means and can be considered the "purely" random error, if a Gaussian distribution is assumed. It is computed as:

$$\text{Standard deviation} = \bar{S}_s = \left[\frac{\Sigma(e_s{}' - \bar{e}_s)^2}{m-1}\right]^{1/2} \qquad (7)$$

and the random uncertainty at the 95 percent confidence level, is:

$$\text{Random uncertainty} = (e_R{}')_{95} = \pm t\bar{S}_s \qquad (8)$$

Results can be considered to consist of three errors. An overall systematic error ($\bar{e}_s$), an uncertainty in the overall systematic error because of the limited number of orifices ($\bar{e}_s{}'$), and a random uncertainty with respect to the overall systematic error $(e_R{}')_{95}$.

In interpreting the results it is of interest to know if the equation has a mean shift ($\bar{e}_s$), and what is the overall uncertainty of the equation form. This is significant since the overall systematic error can be used to correct the equation, and the remaining uncertainties ($\bar{e}_s{}'$, $(e_R{}')_{95}$) would represent the best the equation form can be expected to fit the data. If the overall systematic error were zero, this would be the "tolerance" as specified in ASME [2], AGA [1], and is today called overall uncertainty (or accuracy) in the latest ISO-standards [2, 17].

Assuming the overall systematic error is zero, the remaining systematic uncertainty (assumed randomized) ($\bar{e}_s$) and the random uncertainty $(\bar{e}_R{}')_{95}$ can be combined using the Root Sum Square method to obtain an equation efficiency as:

$$\text{Equation Efficiency} = \text{EE} = [(\bar{e}_s{}')^2 + (e_R{}')^2{}_{95})]^{1/2} \qquad (9)$$

Equation Comparison

When two equations (Buckingham (ASME) and Stolz (ISO)) are used to calculate the discharge coefficient for the same set of orifice data, over a range of Reynolds numbers, four questions need to be answered to determine if one is better.

1. Does either equation have a more "normal" or Gaussian distribution?

2. If there is a difference in the overall systematic error and random uncertainties between equations, is it significant or due to chance, within a stated confidence limit?

3. Is there a significant difference between equations in predicting the coefficient change with pipe or orifice bore Reynolds number?

4. If there is a difference in Equation Efficiency (EE) or equation form, is the difference significant or due to chance, within a stated confidence limit?

Question 1 can be answered by calculating the Coefficient of Skewness (α_3) and the Coefficient of Kurtosis (α_4) of the data with respect to the mean. For a normal distribution, the coefficient of skewness is zero and the coefficient of Kurtosis is three. Values less than zero indicate skewness to the left, and values greater than zero, skewness to the right. The closer to zero, the more "normal" the distribution and hence the greater confidence one has in using the statistical treatment of the data presented, and the resulting overall uncertainty statements.

The coefficient of Skewness is calculated as:

$$\alpha_3 = \frac{\Sigma[\% - e_s{}']^3}{(n-1)\bar{S}^3} \qquad (10)$$

The coefficient of Kurtosis is calculated as:

$$\alpha_4 = \frac{\Sigma[\% - e_s{}']^4}{(n-1)S^4} \qquad (11)$$

Question 2 can be answered by using a "Difference in the Means and Proportions Test." The authors elected to use a "two" tailed, 0.05 level, test. This test essentially estimates a "combined" standard deviation based on the standard deviations calculated for both the Stolz and ASME equations. With this estimate, the (Z) range is calculated using the difference in the systematic errors divided by the combined estimated standard deviation. If the resulting (Z) value is greater than ± 1.96, then there is a significant difference at the 95 percent confidence level. These equations are:

$$\bar{S}_{\text{ASME/STOLZ}} = \text{Average Standard Deviation} = \left[\frac{(\bar{S}_s)^2{}_{\text{ASME}} + (\bar{S}_s)^2{}_{\text{STOLZ}}}{m}\right]^{1/2} \qquad (12)$$

and

$$Z = \frac{(\bar{e}_s)_{\text{ASME}} - (\bar{e}_s)_{\text{STOLZ}}}{\bar{S}_{\text{ASME/STOLZ}}} \qquad (13)$$

The authors elected to answer Questions (3) and (4) using the F-distribution significance test at the 0.05 level (95 percent confidence). In this test, the ratio of the standard deviation squared is computed and compared to a tabular value at the specified confidence level. If this tabular (F) value is greater than the ratio squared, then no significant difference can be attributed to the difference in the data spread (standard deviation). The equation for question 3 is:

$$F = \left[\frac{S_{\text{ASME}}}{S_{\text{STOLZ}}}\right]^2 \qquad (14)$$

for question 4:

$$F = \left[\frac{(\text{EE})_{\text{ASME}}}{(\text{EE})_{\text{STOLZ}}}\right]^2 \qquad (15)$$

These statistical tests are well covered in the literature [18, 19] and are summarized above using the previously defined statistical terms. A sample calculation is presented in the appendix given in reference (23).

Flange Tap Orifice Results

The 28 orifices (422 data points) were initially compared to the ASME (Buckingham) and Stolz (ISO) equations, and an overall systematic error of +0.65 percent for the ASME and +0.49 percent for the Stolz obtained. These results were similar to those obtained in reference [9], with the 2 in. data substantially shifting the entire set of data.

Three groupings of the data were made:

1. All line sizes and beta ratios

   2.067 in. $\leq D \leq$ 23.23 in.; $0.250 \leq \beta \leq 0.7499$

2. All line sizes except the 2 in. data and all beta ratios

   3.853 in. $\leq D \leq$ 23.23 in.; $0.250 \leq \beta \leq 0.7499$

3. All line sizes except the 2 in. data and all beta ratios equal to or less than 0.7000

   3.853 in. $\leq D \leq$ 19.493; $0.250 \leq \beta \leq 0.7000$

Individual plots and an analysis of each group was then made. All the data is plotted in Figs. 1 through 6 for the ASME and Stolz equation, and statistical results are presented in Tables 1 through 3. Individual data points are presented in reference [23].

Group 1: 2.067 ≤ D ≤ 23.23; 0.250 ≤ β ≤ 0.7499. The data for this group are shown plotted in Figs. 1 and 2 for the ASME and Stolz equations respectively, Tables 2 and 3 present the statistical results.

An overall systematic error ($\bar{e}_s$) of +0.65 percent for the

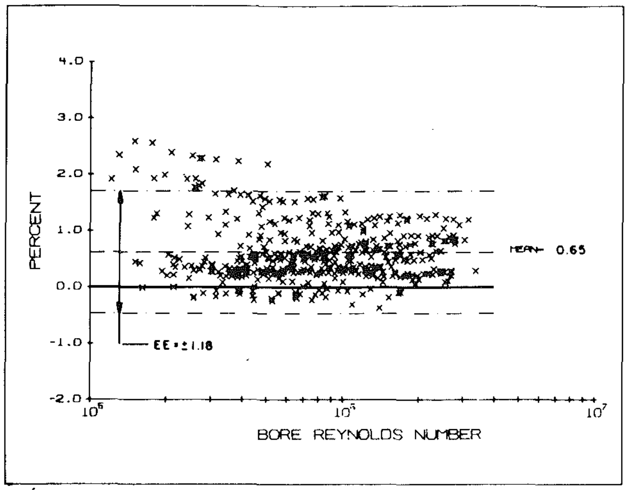

Fig. 1 Data compared to ASME-AGA equation: $2.067 \le D \le 23.250$, $0.250 \le \beta \le 0.750$

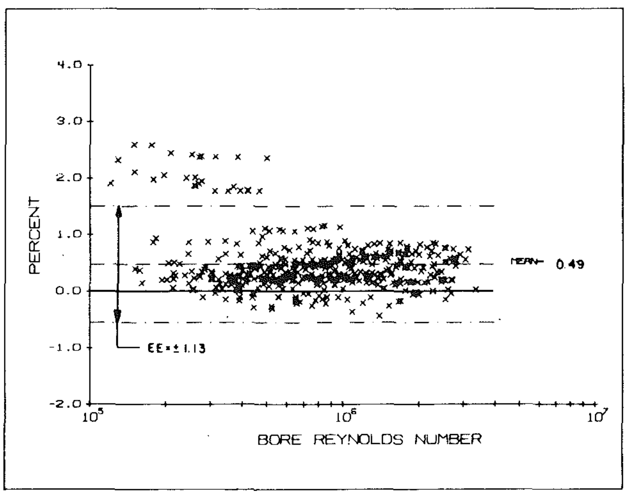

Fig. 2 Data compared to Stolz equation: $2.067 \le D \le 23.250$, $0.250 \le \beta \le 0.750$

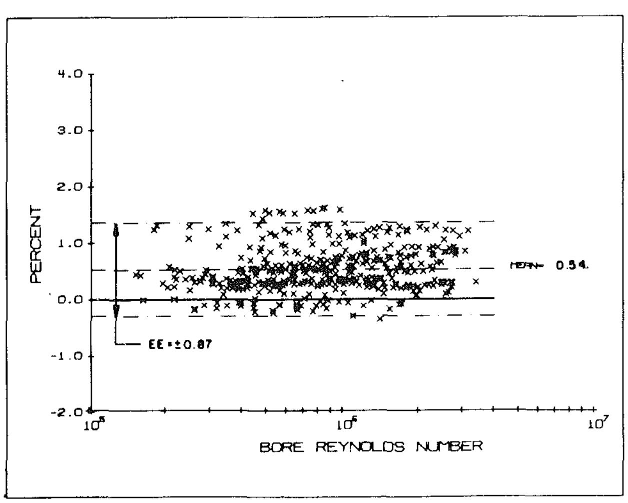

Fig. 3 Data compared to ASME-AGA equation: $3.853 \le D \le 23.250$, $0.250 \le \beta \le 0.750$

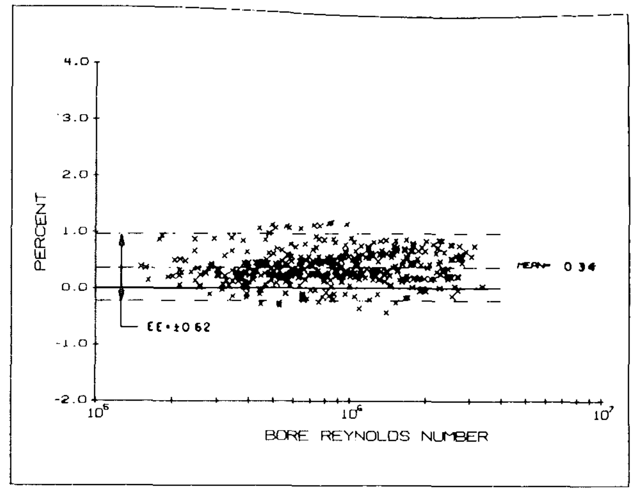

Fig. 4 Data compared to Stolz equation: $3.853 \le D \le 23.250$, $0.250 \le \beta \le 0.750$

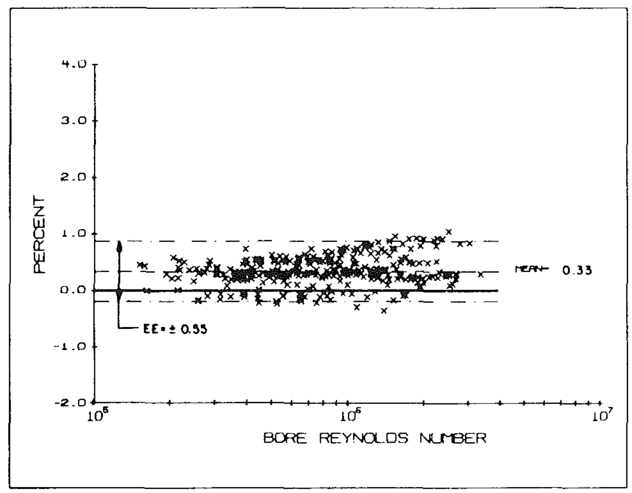

Fig. 5 Data compared to ASME-AGA equation: $3.853 \le D \le 19.493$, $0.250, \le \beta \le 0.700$

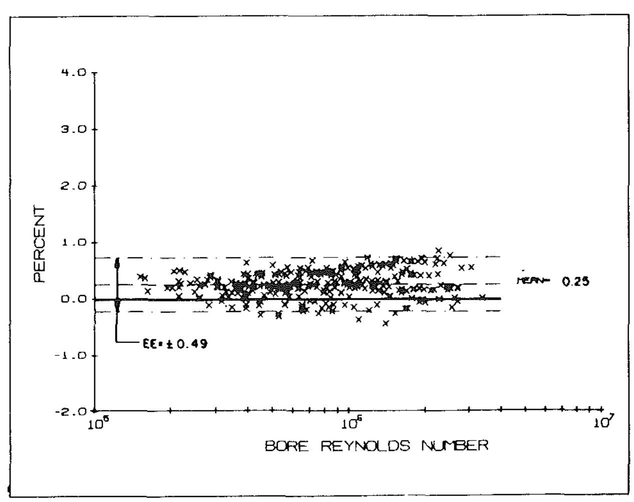

Fig. 6 Data compared to Stolz equation: $3.853 \le D \le 19.493$, $0.250 \le \beta \le 0.700$

Table 1 Flange taps summary

No.	Pipe Size D	Orifice Bore d	beta β	ASME Systematic $(e_s')_{ASME}$	ASME Std. Dev. S_A	STOLZ Systematic $(e_s')_{STOLZ}$	STOLZ Std. Dev. S_s
1	2.067	1.000	.4838	1.787	.148	1.881	.108
2	2.067	1.150	.5564	2.313	.179	2.385	.152
3	3.853	1.610	.4179	0.311	.055	.240	.052
4	3.853	2.0125	.5223	0.295	.006	.246	.060
5	3.853	2.416	.6270	0.141	.068	.071	.058
6	3.853	2.8178	.7313	0.800	.099	.323	.094
7	4.022	2.909	.7233	1.504	.107	1.050	.093
8	4.024	2.578	.6407	0.528	.040	.446	.044
9	4.025	2.578	.6405	0.473	.051	.391	.051
10	4.025	2.909	.7227	1.225	.092	.774	.093
11	4.026	2.848	.7074	0.948	.182	.572	.183
12	6.063	3.904	.6439	-0.104	.078	-.147	.122
13	6.063	4.486	.7399	1.059	.107	.635	.084
14	6.064	3.793	.6255	.37[illegible]	.088	.308	.085
15	6.065	4.082	.6730	.709	.065	.565	.064
16	6.068	4.486	.7393	.652	.055	.228	.050
17	8.092	4.044	.4998	.254	.103	.198	.109
18	10.046	5.319	.5295	.640	.135	.573	.125
19	10.050	6.209	.6178	-.044	.180	-.065	.161
20	10.053	6.209	.6179	-.036	.155	-.057	.145
21	10.055	2.514	.2500	.279	.088	.177	.097
22	10.055	4.022	.4000	.332	.061	.272	.063
23	10.055	5.650	.5619	.552	.098	.485	.102
24	10.055	7.038	.7000	.814	.138	.575	.099
25	10.055	7.540	.7499	1.198	.076	.784	.075
26	19.493	13.562	.6957	.218	.075	.021	.105
27	19.493	10.146	.5205	.296	.041	.225	.050
28	23.250	16.632	.7154	.727	.132	[illegible]	.095

Table 2 Flange tap statistical results

Range	Equation	(%) Overall Systematic Error $(\bar{e}_s)$	(%) Range Of Mean $(\bar{e}_s')$	(%) Random Uncertainty $\pm(e_{R'})_{95}$	(%) Equation Efficiency ±(EE)
2.067 ≤ D ≤ 23.23 0.250 ≤ β ≤ 0.7499 28 orifices 422 points	ASME	+0.65	±0.22	±1.16	±1.18
	STOLZ	+0.49	±0.19	±1.12	±1.13
3.853 ≤ D ≤ 23.25 0.250 ≤ β ≤ 0.7499 26 orifices 395 points	ASME	+0.54	±0.17	±0.85	±0.87
	STOLZ	+0.36	±0.12	±0.59	±0.62
3.853 ≤ D ≤ 19.493 0.250 ≤ β ≤ 0.7000 18 orifices 288 points	ASME	+0.33	±0.13	±0.53	±0.55
	STOLZ	+0.25	±0.11	±0.47	±0.49
Foxboro-Columbus-Daniels Data					
4.025 ≤ D ≤ 23.27 0.2 ≤ β ≤ 0.74 817 points	Miller-Kneisel	+0.003	±0.07	±0.63	±0.63
4.025 ≤ D ≤ 23.27 0.2 ≤ β ≤ .7000 716 points	Miller-Kneisel	-.03	±0.07	±0.47	±0.48

Table 3 Flange taps—significant tests

Range	Equation	Coeff. of Skewness (γ_3)	Coeff. of Kurtosis (γ_4)	F-distribution test: Reynolds Number $(F)_{R_e}$	F-distribution test: Equation Form $(F)_{EE}$	F_{95}	Differences in Means and Proportions: (Z)	Differences in Means and Proportions: $(Z)_{95}$
2.067 ≤ D ≤ 23.25 0.250 ≤ β ≤ 0.7499	ASME	+1.1	4.[illegible]					
28 orifices 422 points	STOLZ	+[illegible].95	7.59	1.4	1.08	1.91	1.11	1.96
3.853 ≤ D ≤ 23.25 0.250 ≤ β ≤ 0.7499	ASME	+0.52	2.78					
26 orifices 395 points	STOLZ	+0.19	2.98	1.24	1.97	1.93	1.85	1.96
3.853 ≤ D ≤ 19.493 0.250 ≤ β ≤ 0.7000	ASME	-0.02	2.84					
18 orifices 288 points	STOLZ	-0.24	2.70	1.29	1.27	2.28	1.04	1.96

ASME and +0.49 percent for the Stolz equation, and an Equation Efficiency of 1.18 and 1.13 were obtained.

In the tests for significance and difference in means and proportions, no significant difference between equations is apparent. Both equations poorly represent the data with respect to a normal Gaussian distribution, and there is insignificant difference between equations in predicting the slope factor (Reynolds number coefficient change) or in the equation form.

The Stolz equation is slightly better since the overall systematic error and Equation Efficiency are less than the ASME equation. But, both equations represent the data with severe skewness and a highly peaked (Kurtosis) normal curve.

Assuming the equations are corrected for the overall systematic error ($\bar{e}_s$), the overall uncertainty (EE), would be ± 1.2 percent in predicting the coefficient from dimensions. Without adjusting for the overall systematic error, the overall uncertainty would be -0.53 to $+1.73$ percent for the ASME equation, and -0.64 to $+1.62$ percent for the Stolz equation. Note that the overall uncertainty is what has been referred to as "tolerance" in prior ASME [3] and AGA [1] literature, and this has been changed from ± 0.5 percent to ± 1 percent in ASME [3] and remains ± 0.5 percent in AGA [1] for $0.15 \leq \beta \leq 0.7$ and is $\pm$ percent for $0.7 \leq \beta \leq 0.75$.

Group 2: 3.853 ≤ D ≤ 23.25; 0.250 ≤ β ≤ 0.7499. Data for this group are shown plotted in Figs. 3 and 4 for the ASME and Stolz equations, respectively.

Eliminating the 2 in. data has a marked effect on the ability of both equations to predict the coefficient. Although both overall systematic errors are reduced by only 0.1 percent, the equation efficiencies are reduced by more than ± 0.3 percent, and both equations represent the data to a more normal curve.

The Stolz equation does, however, represent the data better, having less skewness and a coefficient of Kurtosis of almost 3.0 (2.98). Additionally, the F-distribution test on the equation form indicates a significant difference at the 95 percent confidence level. While the Means and Proportions test does not show a significant difference at the 95 percent level, it is significant at the 87 percent level, and indicative that the Stolz equation does represent the data, both in mean and randomness, better than the ASME equation. Both equations equally predict the change in slope factor (Reynolds number effect).

With both equations corrected for the overall systematic error, the overall uncertainty (tolerance) would be ± 0.87 percent for the ASME equation, and ± 0.62 percent for the Stolz equation. Without adjustments, these values would be -0.33 to $+1.4$ percent, and -0.26 to $+0.98$ percent. Both are still well outside the ± 0.5 percent that has been used in the past and not inside the ± 0.6 percent shown in ISO 5167 [2] for the Stolz equation; the Stolz equation does predict the values within the ASME fluid meters tolerance values of ± 1 percent [3].

Group 3: 3.853 ≤ D ≤ 19.493; 0.250 ≤ β ≤ 0.700. If the range of beta is limited to 0.7, the results for both equations are further improved, as is shown in Figs. 5 and 6. The overall systematic error is reduced to 0.3 percent, and the equation represents the data to ± 0.55 percent or better.

The tests for significance indicate that the ASME equation is slightly better in representing the data to a normal curve, being less skewed and more peaked, but these values are only marginally different. Although there is no significant difference in slope factor and equation form, or in differences in Means and Proportions, the Stolz equation is slightly better in its form, (Equations Efficiency) and has less overall systematic error than the ASME equation. But these differences are all within 0.05 percent.

Adjusting the equations for the overall systematic error would result in ± 0.55 percent overall uncertainty (tolerance)

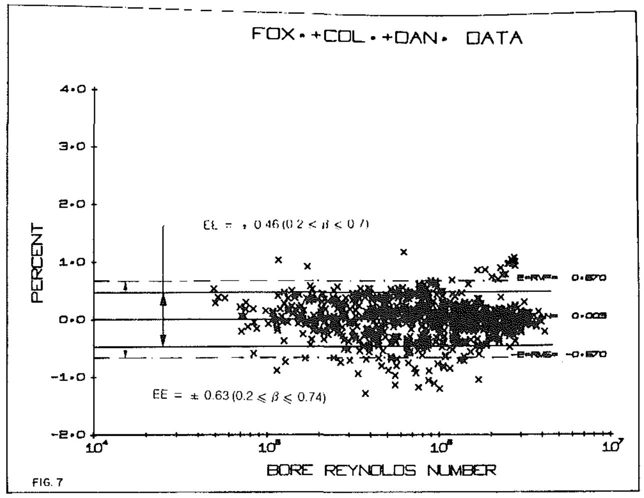

Fig. 7

for the ASME equation, and ± 0.5 percent overall uncertainty for the Stolz equation. These values would be -0.22 percent to $+0.88$ percent (ASME) and -0.24 to $+0.73$ percent (STOLZ) without this adjustment. Again both equations do not predict the data to within the ± 0.5 percent (or ± 0.6 percent) as shown in some standards. Both equations do lie within the ASME fluid meters [3] of ± 1 percent.

Miller-Kneisel Equation

In 1973, using 72 sets of flange tap orifice data, 26 from the Columbus test, and 20 from the Daniels test, Miller and Kneisel arrived at an equation for line sizes 4 to 24 inches over a beta ratio range of 0.2 to 0.74. This work was not published, but was presented to several interested groups [10, 11].

When work on this paper began, the authors did not intend to present this information, but because of the significance of the Stolz equation form have decided to outline this work, and publish a follow-up paper using this data to determine the regression coefficients in the Stolz equation form for flange taps only.

The main difference between this work and that of Stolz were:

1. Only flange tap data was used in the regression to determine the constants in the equation.
2. Random uncertainty and systematic errors of *three* laboratories are included in the overall uncertainty.
3. No attempt was made to include other tapping arrangements in the equation form.
4. The equation is based on flange tap data only, and "tabular" values from published standards, etc., were not used.
5. Subset rules were not used to ensure compatibility for all line sizes or slope Reynolds effects.

Modifying the technique outlined by Dowdell and Chen [8], a series expansion of β, βD, D, and powers of β and D were investigated using regression analysis.

A regression fit was first made to determine the constant regression coefficents (C_∞, b) for each orifice for the general equation form of the discharge coefficeint:

$$C = C_\infty + b/R_d^{0.5} \tag{17}$$

With the 72 values of (C_∞) and (b), two regressions were made to determine the two separate equations that relate (C_∞) to beta (β), and (D), and the slope factor (b) to beta (β), and (D). The general series form was:

$$C_\infty = k_1 + k_2\beta + k_3\beta^2 \ . \ . + k_4\beta D + k_5\beta D^2 + \ . \ . \ k_6\beta^2 D + k_7\beta^3 D + \ . \ . + k_8 D + k_9 D^2 + \ . \ . \tag{18}$$

and

$$b = k_1' + k_2'\beta + k_3'\beta^2 + \ldots k_4'\beta D + k_5'\beta D^2 + \ldots k_6'\beta^2 D + k_7'\beta^3 D + \ldots + k_8' D + k_9' D^2 + \ldots \quad (19)$$

Eliminating terms that had insignificant effect (<0.01 percent) on the final result, the equation in its final form is:

$$C_\infty = 0.5812 + 0.0933\beta + 0.00293D - 0.1929\beta^2 + 0.1641\beta^3 - 0.0251\beta D + 0.0660\beta^2 D - 0.054293\beta^3 D \quad (20)$$

$$b = 5.856 - 72.93\beta - 1.028D + 239.18\beta^2 - 204.17\beta^3 + 12.84\beta D - 39.16\beta^2 D + 33.29\beta^3 D \quad (21)$$

It should be noted that this is a dimensional equation where (D) is in inches, unlike the Stolz term which is dimensionless in (l/D).

The results for data groupings similar to two and three are presented in Table 2 and plotted in Fig. 7.

It is interesting to note that, except for the overall systematic error, the results are within 0.01 percent of those obtained with the Stolz equation. This implies that it is possible to combine data from three different laboratories into a single equation with an overall uncertainty (tolerance) of ±0.5 percent, with no systematic error. It also implies that a universal orifice equation is possible, since Stolz included other tapping arrangements in his equation form. Unfortunately, because these tapping arrangements data were lost, only published tabular values were used. And, of course, the Stolz analysis does not include the systematic errors that exist between testing laboratories [20, 21].

It should be noted that equation (21) is not recommended. The range is limited to 4 in. and larger and an inflection point in the slope factor term (b) occurs for the large line sizes, resulting in a "negative" term; or rising coefficient with pipe Reynolds number. Since for these line sizes the test meters Reynolds number is normally quite large, this had negligible effect on the statistics, however, for viscous fluids (lower Reynolds numbers), it could be important to the user. The equation is presented for information purposes only, and to indicate the level of work up to the point when the project was discontinued. These slope problems have been addressed by Stolz in his work by the inclusion of his rules and subset rules.

Conclusions

Based on a statistical treatment of the data presented in this paper and data available from Daniels and Columbus on flange tap orifice coefficients, the following conclusions and recommendations can be made regarding the Stolz and ASME orifice equations.

1. The form of the Stolz equation is significantly better than the ASME equation for 4 in. to 24 in. line sizes and beta ratios of 0.25 to 0.75, although the overall uncertainty is ±1 percent.
2. The form of the Stolz equation is easier to apply than the ASME.
3. The 2 in. data does not compare well with either the Stolz or the ASME equations.
4. Although the regression coefficients in the Miller-Kneisel equation can be adjusted to produce "zero" systematic error, as derived from three sets of data from different laboratories, its form is not as good as that of the Stolz equation in predicting the slope factor, and it does not have the normal distribution curve.

It is recommended that the regression coefficients be determined for the Stolz equation form using the combined data from Foxboro-Columbus-and-Daniels to arrive at a flange tap orifice equation.

Acknowledgments

The author gratefully acknowledges the computer work of J. T. Cullen of The Foxboro Company whose help and attention to detail greatly assisted in the timely publication of this paper at the ASME Winter Annual Meeting in San Francisco.

References

1 AGA Report No. 3, "Orifice Metering of Natural Gas," Gas Measurements Committee Report No. 3, American Gas Association, Apr. 1955.

2 ISO-5167 "Measurement of Fluid Flow by Means of Orifices, Flow Nozzles, and Venturies," 1978.

3 *Fluid Meters,* Sixth Edition, 1971, ASME.

4 Spink, L. K., *"Principles and Practice of Flow Meter Engineering,"* The Foxboro Company, 9th Edition, 1967.

5 *Shell Flowmeter Engineering Handbook,* Waltman Publishing Company, Delft, The Netherlands, 1968.

6 British Standard 1042: 1, 1974.

7 Beitler, S. R., "The Flow of Water Through Orifices," Ohio State University Engineering Experiment Station, Bull. 89, May 3, 1935.

8 Dowdell, R. B., and Chen, Yu Lin, "A Statistical Approach to the Prediction of Discharge Coefficients for Concentric Orifice Plates," ASME *Journal of Basic Engineering,* Vol. 92, No. 4, Dec. 1970, p. 752.

9 Miller, R., W., and Kneisel, O., "A Comparison Between Orifice and Flow Nozzle Laboratory Data and Published Coefficients," ASME *Journal of Fluids Engineering,* Vol. 96, No. 2, June 1974, p. 139.

10 Miller, R. W., Presentation to COGM (API) Meeting, Miami, Beach, Fla., Mar. 1974, not published.

11 Miller, R. W., Presentation to AGA Transmission Conference, Miami Beach, Florida, May 1974, not published.

12 Stolz, J., "An Approach Toward a General Correlation of Discharge Coefficients of Orifice Plate Flowmeters," ISO/TC30/SC2 (France 6) 645, June 1975.

13 Stolz, J., "Refitting of the Universal Equation for Discharge Coefficients of Orifice Plate Flowmeters," ISO/TC30/SC2 (France 12) 90E, Oct. 1977.

14 Miller, R. W., "A Large Hydraulic Laboratory Designed to Meet Today's Calibration Needs," ISA Paper 68-866.

15 Miller, R. W., "Precise Measurement of Differential Pressure When Calibrating a Head Class Flowmeter," ASME *Journal of Basic Engineering,* Vol. 92, No. 4, Dec. 1970, p. 742.

16 Spencer, E. A., Hayward, A. T. J., "The Accurate Calibration of Flow Meters with Water," *Transactions of the Society of Instrument Technology,* Vol. 9, No. 1, Mar. 1967.

17 ISO-5168, "Calculation of the Uncertainty of a Measurement Flowrate," 1978.

18 Fisher, R. A., and Yates, R., "Statistical Tables for Biological, Agricultural and Medical Research," Longman Group Ltd., London.

19 Experimental Statistics, Handbook 91, United States Department of Commerce, National Bureau of Standards, Chapter 17.

20 Spencer, E. A., and Neal, L. C., "The Reliability of Test Data from Flow Measurement Calibration Laboratories," *Flow - Its Measurement and Control in Science and Industry,* Vol. 1, ISA Publication 1974, p. 1225.

21 Levie, S. A., Clay, C. A., Miller, R. W., Spencer, E. A., Upp, E. L., "A Study of Interlaboratory Comparison on Ten Orifice Plates," Flomeko Conference, Groningen, The Netherlands, 1978.

22 Stolz, J. "A Universal Equation for the Calculation of Orifice Plates," Flomeko Conference, Groningen, The Netherlands, 1978.

23 Miller, R. W., Cullen, J. T., "The Stolz and ASME Equations Compared to Laboratory Data," ASME WAM, 1978 San Francisco, Paper No. WAM-FM-2.