On the Standardization of Elbow Flow Meters

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Abstract: Based on the operating principles of elbow flow meters, this paper states that the core of standardization of elbow flow meters is the standardization of hardware's structural dimension. On condition that the elbow flow meters' feature structural dimension parameters R/D are strictly kept the same, the flow coefficients of elbow flow meters with the same conduit diameter determined by experiments have good consistency. Comparison of the experimental results of several elbow flow meters with different conduit diameters shows that the flow coefficient increases as the conduit diameter decreases. The experiments and comparisons prove that the determination of hardware's structural dimension is essential in the standardization of elbow flow meters.

Keywords: elbow flow meters, standardization, feature structural dimension, *R/D*—ratio of elbow conduit's curvature radius to conduit diameter, reproducibility

1. Introduction

Through several years' experimentation and research, we can conclude that precisely processed elbow flow meters have good reproducibility. Professionals have been attempting to propel the standardization of elbow flow meters forward further, as their operating principles and mathematical models have great similarity with all kinds of differential pressure type flow meters now known, to apply it to precise flow measurement by dry calibration, like ISO 5167 differential pressure type flow meters, and meet the great demand of the market.

Fortunately，modern science and technology has made available the equipments and technology that can ensure the consistency of elbow flow meters' structural dimensions during manufacturing, which lay a firm foundation for the research and manufacturing of elbow flow meters whilst ending completely the chaos caused when various research results of elbow flow meters can not reach an agreement. This paper will introduce our achievements in the research on standardization of water medium elbow flow meters.

2. Operating principles of elbow flow meters

Modern computational fluid dynamics can calculate and display the variation of state parameter when fluid flows through an elbow conduit. [1] Fig.1 shows the formation, development, and disappearance of variation of fluid velocity when nonviscous fluid flows through a 90° elbow conduit.
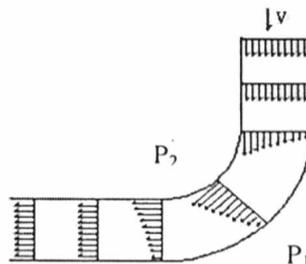

Fig.1 Variation of   nonviscous velocity when ideal fluid flows through a 90° elbow

It can be seen from Fig.1 that when fluid is 2 diameters of straight pipe on the upstream from the inlet of elbow conduit the inner side fluid velocity begins to accelerate from the average fluid velocity V in straight pipe to the maximum at 45°, then decreases gradually to the average fluid velocity as the fluid is 2 diameters of straight pipe away from the outlet. In the same range the outer side fluid experiences a reverse variation in fluid velocity. At 45°, the outer side fluid velocity reduces to the minimum while the velocity difference ΔV between the inner and outer side gets to the maximum. According to Bernoulli's Equation, the inner side fluid has a low static pressure p_2 and the outer side fluid has a high static pressure p_1. Fig.2 shows the fluid isopiestic distribution corresponding to the variation of fluid velocity illustrated in Fig.1.
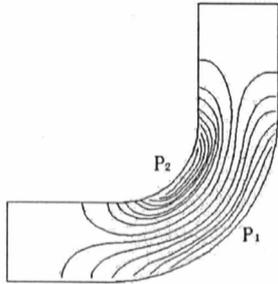

Fig.2 Fluid isopiestic distribution in elbow conduit

Fig.2 illustrates the fluid pressure distribution corresponding to fluid velocity. At 45° the Δp ($\Delta p = p_1 - p_2$) maximizes. As the flow changes the Δp varies correspondingly. Thus it can be deduced that elbow flow meters' operating principle is to obtain the value of flow through measuring the Δp and its relevant parameters.

Herbert Addison, after setting the trapezoidal distribution of fluid velocity at 45° elbow conduit as illustrated in Fig.3, gave the basic principles of elbow flow meters expressed by equation (1) (free-vortex flow equation). [2]

$$\overline{V} = \frac{(x^2 - 1)(x - \sqrt{x^2 - 1})\sqrt{2g}\sqrt{\Delta p}}{\sqrt{x}} \qquad (1)$$

Where $\overline{V}$ (m/s) is the average fluid velocity in elbow conduit, Δp ($\Delta p = p_1 - p_2$) is the pressure difference $m(H_2O)$, X ($X = 2R/D$) is elbow conduit's axis curvature radius to inside radius of elbow conduit, g (m/s^2) is acceleration due to earth's gravity
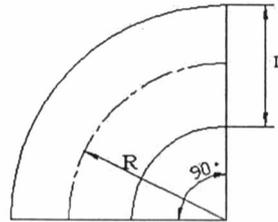

Fig.3 Trapezoidal distribution setting of fluid velocity at 45° under free-vortex flow equation

Equation (1) explains the principles of obtaining the value of flow through measuring the Δp and specifies the elbow flow meters' dependence on its physical model as well as embodies the dependence in a complex functional equation expressed by feature structural dimension parameter X, which denotes the degree of the curvature of elbow flow meters. The definition of X is illustrated in Fig.4.
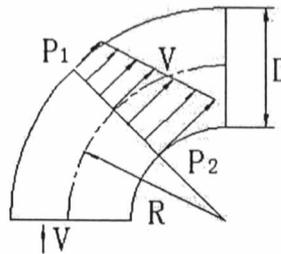

Fig.4 Definition of feature structural dimension parameter X

Based on previous researches, L.K. Spink adopted equation (2) (SI unit) in his book to specify the operating principles of elbow flow meters. [3]

$$\overline{V} = 0.961\sqrt{\frac{R}{D}}\sqrt{\frac{\Delta p}{\rho}} \qquad (2)$$

Where ρ (kg/m^3) is the mass density of fluid media, Δp (p_a) is the pressure difference ($\Delta p = p_1 - p_2$)

Equation (2) simplifies the complex functional

equation (1) that denotes the feature structural dimension parameter X.

To summarize, the standardization of elbow flow meters' feature structural dimension parameter R/D—ratio of elbow conduit curvature radius to conduit diameter—is the fundamental problem to be solved in the standardization of elbow flow meters.

3. Research on experimental results of elbow flow meters

Concentrating on the research on a fixed R/D parameter, the paper establishes a mathematical model expressed by equation (3) on the basis of equation (2) to find those factors affecting flow coefficients and their regularity.

The experiment consists of two parts. One is to compare the performances of elbow flow meters that have an identical conduit diameter with the purpose to determine the reproducibility distribution of flow coefficient a shown in equation (3), thereby to determine the consistency of elbow flow meters' performances after their feature structural dimension parameters are unified.

$$\overline{V} = \alpha \sqrt{\frac{R}{D}} \sqrt{\frac{\Delta p}{\rho}} \qquad (3)$$

Where a is flow coefficient

The second part aims at determining the conduit diameters' (D) effects on the performance of elbow flow meters and to deduce from experimental results the variation regularity of flow coefficient a correlating with the alteration of elbow conduit diameter after the feature structural dimension are unified, as displayed in equation (4)

$a = f(D)$ (4)

Since the relation between a and D has been determined, all the elbow flow meters mentioned here adopt a uniform feature structural dimension parameter $R/D=1.5$. Detailed conduit diameter

specifications and quantities of elbow flow meters are listed in Table.1

Table.1 Conduit diameter specifications & quantities of experimented elbow flow meters

Specifications	DN 50	DN 80	DN 100	DN 125	DN 300	DN 500
Quantity	6	6	10	6	1	1

To ensure these elbow flow meters listed have good geometric similarity, the location deviation of their tap holes are also strictly controlled.

Table.2 lists the actual structural dimensions of 10 DN100 elbow flow meters and their deviation from design.

Table.2 shows that according to the equation (3), the largest flow deviation of the 10 elbow flow meters caused by difference in feature structural dimension parameters R/D is 0.1%. They are shown to have good geometric similarity by analyzing the degree of consistency of their structural dimensions.

The diameters of tap holes in experiments are limited to two specifications—6mm (seven elbow flow meters) and 10mm (three elbow flow meters)—for further research on their effects. All the location deviations of these tap holes are less than $0.5°$, therefore a good consistency of location of these tap holes is ensured.

Relative standard deviation in Table.3 should be calculated by equation (5):

$$S_{cv} = \frac{1}{X} \sqrt{\frac{\sum\limits_{i=1}^{n}(X_i - X)^2}{n-1}} \qquad (5)$$

It can be seen from Table.3 that all the elbow flow meters can preserve a good reproducibility of performance in a spectrum of accuracy where the relative standard deviation is less than 0.4% on condition of a uniform feature structural dimension parameter R/D.

Table.2 Structural dimensions of 10 DN100 elbow flow meters

No.	Diameter of elbow conduit D(mm)	Curvature radius R(mm)	Ratio R/D	Diameter of the tap holes d(mm)	Deflection of the tap holes at the extreme inner side of the bend Δβ1＝β1-β2 (°)	Deflection of the tap holes at the extreme outer side of the bend Δβ2＝β3-β4 (°)
30125	95.968	144.274	1.503	10	-0.013	+0.460
30127	95.947	144.022	1.501	10	+0.115	+0.354
30128	95.961	143.763	1.498	10	-0.185	+0.296
30134	95.945	143.783	1.499	6.0	-0.414	+0.053
30135	95.936	143.763	1.499	6.04	0	+0.068
30136	95.942	144.161	1.503	6.05	+0.243	-0.049
40001	95.970	143.852	1.499	6.00	-0.405	+0.131
40002	95.903	143.802	1.499	6.05	+0.060	+0.100
40003	95.918	143.585	1.497	6.00	-0.150	+0.130
40004	95.865	143.782	1.500	6.00	-0.160	+0.154
Deviation from design	≤0.0015D	≤0.002R	Relative deviation ≤0.2%	≤0.1D	$-0.5° ≤ Δβ1 ≤ +0.5°$	$-0.5° ≤ Δβ1 ≤ +0.5°$

The definitions of symbols in Table.2 are illustrated in Fig.5

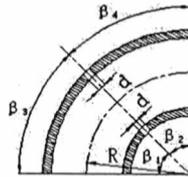**Fig.5** Definitions of parameters listed in Table.2

Fig.6 shows the flow coefficient distribution settled by actual values at different fluid velocities of the 10 DN100 elbow flow meters

Table.3 lists the actual flow coefficient and relative standard deviation analytical results corresponding to each fluid velocity of the 10 DN100 elbow flow meters.

Table.3 Actual values at each fluid velocity & relative standard deviation of the 10 DN100 elbow flow meters

| NO.	Standard fluid velocity	Flow coefficient values corresponding to each fluid velocity of each elbow flow meter										Relative standard deviation $Sc_α$
		30125	30127	30128	30134	30135	30136	40001	40002	40003	40004	
1	1.0 m/s	0.9712	0.9751	0.9726	0.9771	0.9726	0.9814	0.9756	0.9721	0.9710	0.9735	0.278%
		0.9711	0.9753	0.9738	0.9768	0.9726	0.9800	0.9768	0.9734	0.9716	0.9760	
		0.9722	0.9743	0.9713	0.9761	0.9724	0.9771	0.9783	0.9736	0.9716	0.9746	
2	1.5 m/s	0.9745	0.9807	0.9761	0.9787	0.9715	0.9798	0.9776	0.9743	0.9734	0.9778	0.266%
		0.9733	0.9795	0.9759	0.9782	0.9740	0.9801	0.9778	0.9742	0.9731	0.9781	
		0.9753	0.9805	0.9756	0.9791	0.9741	0.9775	0.9778	0.9746	0.9727	0.9774	
3	2.0 m/s	0.9775	0.9842	0.9777	0.9774	0.9733	0.9789	0.9728	0.9715	0.9738	0.9796	0.354%
		0.9755	0.9825	0.9775	0.9811	0.9729	0.9794	0.9752	0.9749	0.9736	0.9799	
		0.9782	0.9828	0.9780	0.9810	0.9733	0.9781	0.9730	0.9742	0.9725	0.9783	
4	2.5 m/s	0.9800	0.9848	0.9782	0.9817	0.9744	0.9813	0.9764	0.9744	0.9757	0.9808	0.362%
		0.9791	0.9843	0.9793	0.9831	0.9748	0.9809	0.9759	0.9725	0.9761	0.9802	
		0.9792	0.9849	0.9790	0.9823	0.9734	0.9785	0.9736	0.9749	0.9762	0.9799	
5	3.0 m/s	0.9830	0.9838	0.9803	0.9828	0.9747	0.9813	0.9772	0.9729	0.9776	0.9819	0.356%
		0.9819	0.9850	0.9778	0.9841	0.9753	0.9814	0.9761	0.9759	0.9785	0.9813	
		0.9828	0.9844	0.9789	0.9835	0.9746	0.9813	0.9770	0.9747	0.9778	0.9819	
6	3.5 m/s	0.9832	0.9855	0.9798	0.9828	0.9744	0.9804	0.9743	0.9736	0.9772	0.9808	0.386%
		0.9835	0.9850	0.9800	0.9826	0.9738	0.9813	0.9753	0.9760	0.9770	0.9791	
		0.9817	0.9855	0.9795	0.9830	0.9739	0.9812	0.9764	0.9752	0.9756	0.9785	
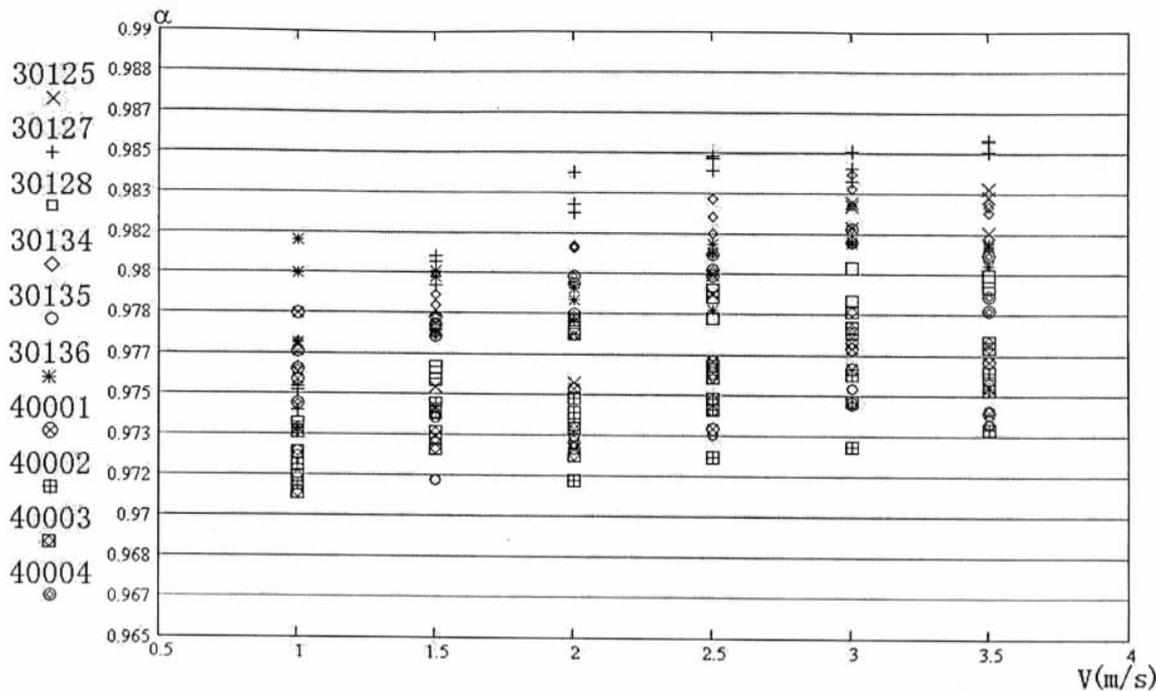
Fig.6 flow coefficient distribution at each fluid velocity of the 10 DN100 elbow flow meters

Further systematic experiments on elbow flow meters with different conduit diameters show that each conduit diameter specification has its specific corresponding flow coefficient a. Fig.7 shows the fitting curve between flow coefficient a and alteration of conduit diameter D.
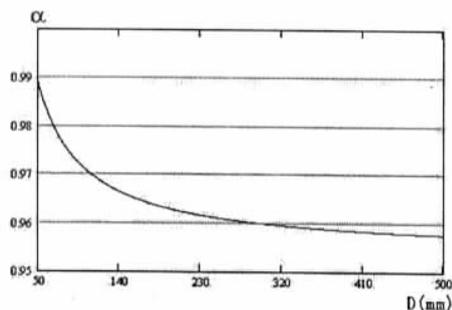

Fig.7 a—D fitting curve

The mathematical model of the a—D fitting curve can be settled by equation (6)

$$\alpha(D) = ae^{\frac{b}{D}} \qquad (6)$$

4. Conclusions

Three points can be derived from the above research.

4.1. High precision and good reproducibility can be achieved through a strict consistency of elbow flow meters' feature structural dimension parameter R/D.

4.2. Based on the same elbow flow meters' feature structural dimension parameter R/D and 45° tap holes, the precision of measurement higher than 1% can be obtained without calibration on each elbow flow meter. Yet it should be noted that each different conduit diameter has its specific flow coefficient a. So flow coefficient a must be adjusted according to conduit diameter and its regularity should be settled with high precision by additional experiments.

4.3.The determination of flow coefficient a follows the standardization of elbow flow meters' structural dimensions. It means that manufactured elbow flow meters can be applied directly to industrial metrology of high precision through dry calibration, like ISO5167 differential pressure type flow meters.

5. Epilogue

In the past 16 years we carried out comprehensive research on elbow flow meters, which resulted in success in water, steam, and natural gas media elbow flow meters successively. In addition we explored elbow flow meters' application to other media. Its good reproducibility and low energy

consumption together with its low requirement to the length of straight pipes in projects, resistance to abrasion and soiling, little maintenance, and long durability are favored by industries and enterprises. By the end of 2003, there had been about 5000 elbow flow meters applied in all trades. We expect this paper to inspire understanding, attention, and support from fraternity worldwide and hope to cooperate with those who are interested in this program to realize the standardization as early as possible. While lamenting those pioneers who toiled for this program all their lives, we hope this kind of elbow flow meters can make improvements to the world's industrial measurement.

6. Acknowledgement

References

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[3] Li Zhi, Zhang Jinfeng, etc, "Research on the Curved-Pipe flow meter", Acta Metrologica Sinica, 2003, Vol.24, No.3, p189-192