

Numerical Simulation and Experiment on Averaging Pitot Tube with Flow Conditioning Wing

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Abstract: Cross-section of Averaging Pitot Tube (APT) flow sensor is a determinant factor in meter performance. In order to improve the performance of the APT flowmeter, three different cross-sections with Flow Conditioning Wing (FCW) were put forward. It was shown by Computational Fluid Dynamics (CFD) numerical simulation and prototype test that the performance of the FCW II cross-section, such as the linearity, the repeatability, and the value of differential pressure generated, is better than those of traditional circle and diamond cross sections. It was shown by prototype test, in the case of the APT flowmeter with different length upstream straight pipe were fitted downstream a 90° bend, that, under the condition of non-fully developed turbulent flow velocity profile, the linearity and the value of differential pressure of the FCW II cross-section are better than those of the circle and the diamond cross sections, but there is not apparent difference at the repeatability.

Keywords: Averaging Pitot Tube (APT) flowmeter, Cross-section, Flow Conditioning Wing (FCW)

1. Introduction

Based on the principle of pitot tube flowmeter and approximately integral theory, Averaging Pitot Tube (APT) flowmeter describes the equation of fully developed turbulent flow velocity profile in pipe by several detecting points, and measures the average flow velocity in pipe cross-section by detecting the flow speed of many points in a line. APT flowmeter is widely used in large bore pipe flow measurement for its particular merits, such as, low pressure loss, easily fit and take down, simple structure, low cost, and so on.

Cross-section of the APT flowmeter is a determinant factor in meter performance, such as the linearity, the repeatability, the value of differential pressure generated. So it is always a important content of research since APT flowmeter appeared, and there are many different productions. Now, the cross-section of circle, diamond, streamline, T type, and Delta type are relatively popular. Abaciński and Pospolita[1] compared fifteen different cross-sections, and as the optimum design a two-profile cross-section was put forward. It was shown by the data that the differential pressure of that new cross-section is larger than that of other cross-sections. Wecel, Chmielniak and Kotowicz[2] compared the meter performance of eight different cross-sections. Dobrowolski, Kabaciński Pospolita[3] compared the meter characteristics of five different cross-sections, profoundly analyzed a streamline section, and put forward a mathematic model of it. Seshadri, Gandhi and et al[4] investigated the meter factor, the pressure loss, the flow fields around the probe of Annubar type APT flowmeter.

In order to improve the performance of the APT flowmeter, three different cross-sections with Flow Conditioning Wing (FCW) were put forward in this paper, by Computational Fluid Dynamics (CFD) numerical simulation and prototype test. It was shown by data that the linearity, the repeatability, and the value of differential pressure generated, of the FCW II cross-section, are better than those of the circle and the diamond cross sections.

2. Numerical Simulation of Flow Conditioning Wing Cross-sections

Verified by previous research works, there is a space for improving the performance of Averaging Pitot Tube (APT) flowmeter with different popular probe cross-sections. So there are lot of works to do for cross-section optimizing, to improve meter performance and enhance the ability of adaptive to many types complex flow fields. The new APT flow sensor should meet several points as below. (1) The differential pressure generated is larger than those of existing productions at the same applied conditions, is that, the meter factor K is smaller. (2) The linearity of $K-q_v$ curve is better that of existing productions. (3) The manufacture of flow sensor, and the installation and take down is easy.

Traditional circle, diamond, streamline, and 3 different new cross-sections with Flow Conditioning Wing (FCW) are shown in Fig.1. Numerical simulation of the six different cross-sections in Fig.1 was made by Computational Fluid Dynamics (CFD) software package Fluent. The conditions of simulation are as below. For the convenience of simulation and subsequent performance test, the diameter of pipe is DN50. Diameter of the circumcircle of the APT flow sensor probe is 8 mm, the diameter of the internal chamber in the probe is 3 mm, and the diameter of pressure detecting ports is 2 mm as shown in Fig.1. Two pairs of pressure detecting ports is symmetricly arranged relative to pipe center point according to the method of Chebyshev. The measured fluid is air, the pressure of it is 101 325 Pa, the temperature of it is 293 K, the density of it is 1.205 kg/m³, the kinematic viscosity of is 14.9×10⁻⁶ m²/s, the viscosity of is 18.1×10⁻⁶ Pa·s.

The meter factor and the linearity of six APT flowmeters with different cross-sections are shown in the Tab.1, which were calculated by numerical simulation in the flow velocity range from 5 m/s to 30 m/s. Conclusions can be gotten from the Tab.1. (1) The order of differential pressure value of different cross-sections from small to large is the circle, the streamline, the FCW I, the diamond, the FCW II, and the FCW III. (2) The order of linearity of different cross-sections from large to small is the circle, the streamline, the FCW I, the diamond, the FCW III, and the FCW II. The linearity of the FCW II is the best, its value is 0.45%. The meter factor of the FCW II is 0.623, it is smaller than all of the other cross-sections except for the FCW III, so the differential pressure value of it is relatively large. Comprehensively considering the meter factor and the linearity, the FCW II is the best one. so the prototype of it was manufactured. The meter performance of the FCW II is compared with those of the circle and the diamond by prototype test in the following parts of the paper.

Tab.1 Performance contrast of the APT flowmeters with six different cross-sections, in the flow velocity range of 5 m/s~30 m/s

Cross-sections	Circle	Diamond	Streamline	FCW I	FCW II	FCW III
Meter factor	0.75	0.63	0.69	0.64	0.623	0.577
Linearity (%)	4.07	1.27	2.11	1.36	0.45	1.54

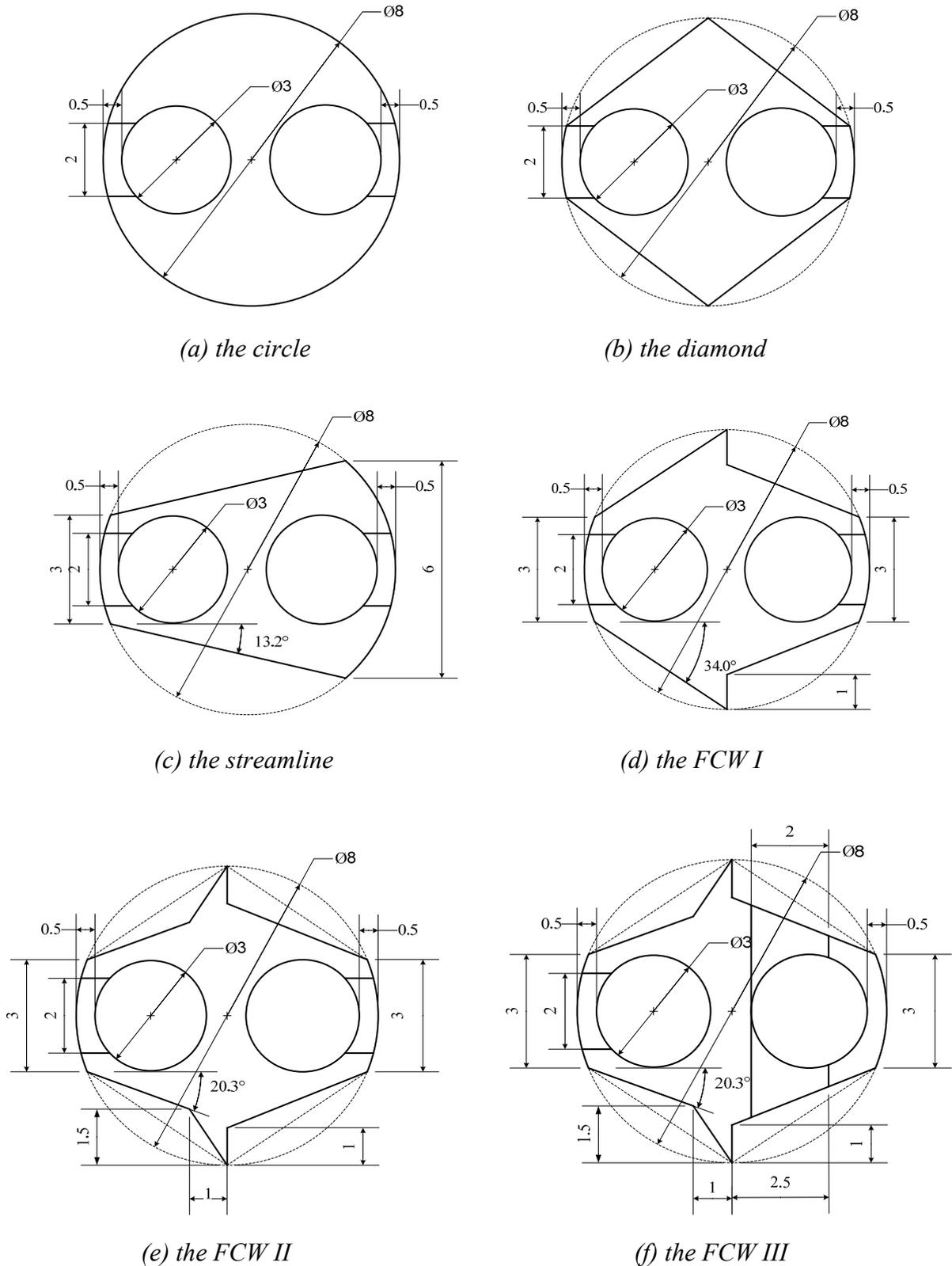


Fig.1 Six different APT flowmeter cross-sections

The method for calculating the meter factor, the linearity error, the repeatability in Tab.1 is as below. The relationship between the differential pressure value generated by the APT flow sensor and the volume flow rate in pipe is

$$q_v = K \frac{\pi}{4} D^2 \sqrt{\frac{2\Delta p}{\rho}} \quad (1)$$

in the formula, q_v is volume flow rate, m^3/h , K is dimensionless factor, D is the diameter of pipe, m , Δp is the differential pressure value generated by the APT flow sensor, Pa , ρ is density of the air, kg/m^3 . The formula (1) can be simplified as following

$$\bar{v} = K \sqrt{\frac{2\Delta p}{\rho}} \quad (2)$$

in the formula, \bar{v} is the averaging flow velocity in cross-section of pipe, m/s , the factor of flow rate or flow velocity can be obtained from formula (2) as below

$$K = \frac{\bar{v}}{\sqrt{\frac{2\Delta p}{\rho}}} \quad (3)$$

During the APT flowmeter performance experiment in following parts of paper, m is the number of the flow rate point, which were selected to be test in a certain flow rate range. The value of m is determined by the flow rate range and the accuracy of flowmeter. Three tests are continuously made at one flow rate point, and every time persists 15 seconds. The averaging meter factor K_i at every one flow rate point is

$$K_i = \frac{1}{n} \sum_{j=1}^n K_{ij} \quad (4)$$

in the formula, n is the number of test time at one flow rate, $n=3$ in this paper, K_{ij} is the meter factor of the test No. j at the flow rate point No. i .

The repeatability error of meter factor $(E_r)_i$ at every one test flow rate point is

$$(E_r)_i = \frac{1}{K_i} \left[\frac{1}{n-1} \sum_{j=1}^n (K_{ij} - K_i)^2 \right]^{1/2} \times 100\% \quad (5)$$

The repeatability error E_r of the APT flowmeter in the whole flow rate range is

$$E_r = \left| (E_r)_i \right|_{\max} \quad (6)$$

The meter factor K of the APT flowmeter in the whole flow rate range is

$$K = \frac{(K_i)_{\max} + (K_i)_{\min}}{2} \quad (7)$$

in the formula, $(K_i)_{\max}$ is the maximum of the K_i at all of the test flow rate points, $(K_i)_{\min}$ is the minimum of the K_i at all of the test flow rate points.

The linearity error E_L of the APT flowmeter in the whole flow rate range is

$$E_L = \frac{(K_i)_{\max} - (K_i)_{\min}}{(K_i)_{\max} + (K_i)_{\min}} \times 100\% \quad (8)$$

3. Performance Test of Flow Conditioning Wing Cross-section

For furtherly investigate the performance of the Averaging Pitot Tube (APT) flowmeter with different type cross-sections, three prototypes were made separately according to the circle, the diamond and the Flow Conditioning Wing (FCW) II cross-section, and marked in turn as 1'#, 2'#, 3'# as shown in Fig.2. For the convenience of meter performance test, the diameter of pipe is selected as DN50.



The external appearance of three different APT flow sensors



The circle

The diamond

The FCW II

Fig.2 Three APT flowmeters with different cross-sections, for DN50 pipeline

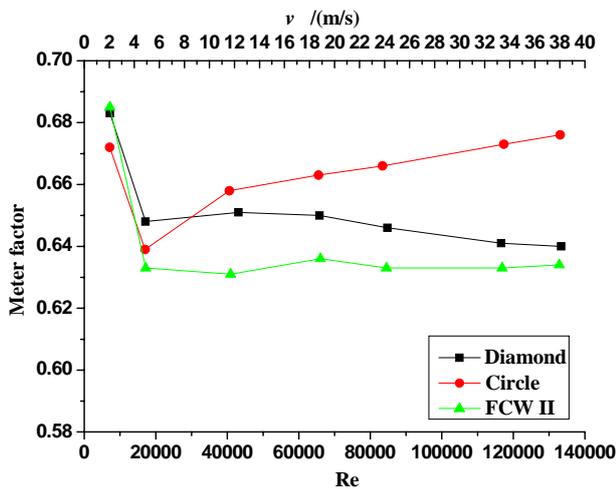
The experiments were carried out at a critical flow sonic nozzle air flow standard facility with negative pressure, the main parameters of the facility are as below. The expanded uncertainty of sonic nozzle is 0.2% ($K=2$). The expanded uncertainty of the whole facility is 0.3% ($K=2$). The range of pipe diameters is DN25~DN200. The flow rate range is 1~4000 Nm³/h. The test conditions are normal pressure and room temperature. Only the pipe of DN50 was applied in the process of APT flowmeter performance test. The

upstream straight pipe length of flowmeter is 20D, and the downstream of it is 10D. The measuring range of pressure transducer, applied in the experiments, is 0~10 kPa, and the accuracy of it is 0.075%FS.

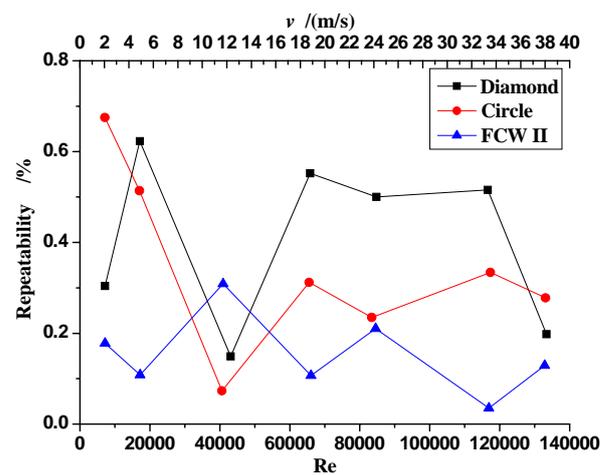
The meter factor and the repeatability error of three APT flowmeter with different probe cross-sections at each flow rate point are shown in Fig.3. The general performances of three APT flowmeter prototypes are shown in Tab.2. It can be concluded from the data that the meter factor of the FCW II cross-section is the smallest, is that, the differential pressure generated by it is the largest. This is a advantage for improving the precision of flow measurement. The linearity of the APT flowmeter with the FCW II cross-section is the best of three prototypes, in the flow rate range of 5 m/s~40 m/s, its value is 0.380%. The repeatability of the FCW II cross-section is the best also, the value is 0.308%.

Tab.2 Meter factor, linearity, and repeatability of three different APT flowmeters

Flow velocity		Circle	Diamond	FCW II
5~40 m/s	Meter factor	0.658	0.645	0.634
	Linearity (%)	2.850	0.830	0.380
	Repeatability(%)	0.514	0.623	0.308



(a) Meter factor



(b) Repeatability

Fig.3 Meter factor and repeatability of three different APT flowmeters

4. Installation Effect Test of Flow Conditioning Wing Cross-section

Generally, 20D~30D length upstream straight pipe is needed for the Averaging Pitot Tube (APT) flowmeter, to ensure the distribution of flow velocity in pipe is fully developed turbulent flow velocity profile. In the industrial scene, the APT flow sensor is often installed at the downstream of different kinds of pipe fittings. In many cases, the straight pipe length is only several times of pipe diameter, it is not enough for keeping the fully developed turbulent flow velocity profile, limited by the space of industrial fields. Bend is one of the most frequently used fittings in industrial scene. With different length of upstream straight pipe, the APT flowmeters with the circle, the diamond and the FCW II cross-sections were fixed downstream a 90° bend, for performance test and comparing with each other. For the bend applied in the experiment, the ratio of bend radius to pipe diameter (R/D) is 1.

The experiments were made at a critical flow sonic nozzle air flow standard facility with positive pressure, the main parameters of the facility are as below. The pipe diameters of test benches are DN50 and DN100. The DN50 was utilized in the process of test. The expanded uncertainty of sonic nozzle is 0.3% ($K=2$). The expanded uncertainty of the whole facility is 0.5% ($K=2$). The flow rate of the smallest sonic nozzle is 2.5 m³/h. The flow rate of the largest sonic nozzle is 203.58 m³/h. The maximum flow rate is 692.21 m³/h supplied by combined 11 nozzles. The test was conducted from February 20 to March 12 in 2010. For all of the test process, the range of temperature variation is 273 K~293 K, because there is a big temperature difference between the environment of outside and inside the room. But, the temperature fluctuation in a certain test at one flow rate point is below 1K. Similarly, the range of pressure variation is 220 kPa~250 kPa, the pressure fluctuation in a certain test at one flow rate point is smaller than 1 kPa.

Based on the performances under the condition of fully developed turbulent flow, the APT flowmeters were investigated as they were installed at different positions downstream the bend. The results of test are shown in Tab.3, when the APT flow sensor with 70D length upstream straight pipe and 40D length downstream straight pipe.

Two different ways of APT flowmeter fixing were adopted. One is the ATP flowmeter perpendicular to the bend plane as shown in Fig.4a, another one is the APT flowmeter and the bend in same plane as shown in Fig.4b. During the experiments, the length of the upstream straight pipe are 2D, 4D, 7D and 12D respectively, keeping the length of downstream straight pipe always is 5D.

Tab.3 APT flowmeter performance with 70D upstream straight pipe, and 40D downstream straight pipe

	Flow velocity 2~35 m/s			Flow velocity 3.5~35 m/s			Flow velocity 7.5~35 m/s		
	Meter factor	Linearity %	Repeatability %	Meter factor	Linearity %	Repeatability %	Meter factor	Linearity %	Repeatability %
Circle	0.663	3.705	1.709	0.658	2.996	0.623	0.658	2.996	0.378
Diamond	0.548	12.748	1.473	0.548	12.748	0.361	0.609	1.513	0.402
FCW II	0.550	12.181	0.527	0.576	7.087	0.372	0.609	1.267	0.152



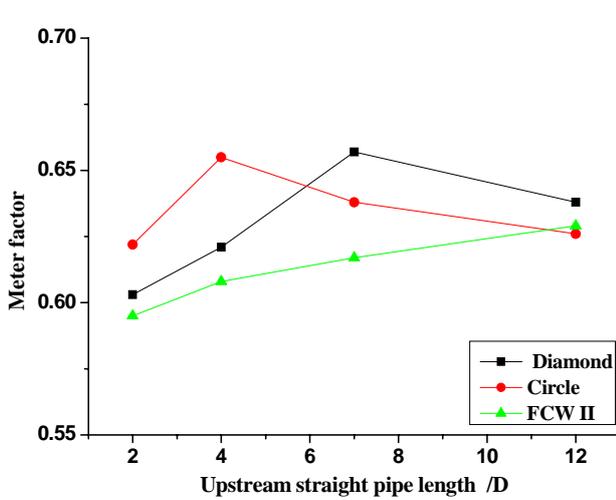
(a) ATP flowmeter perpendicular to the bend plane



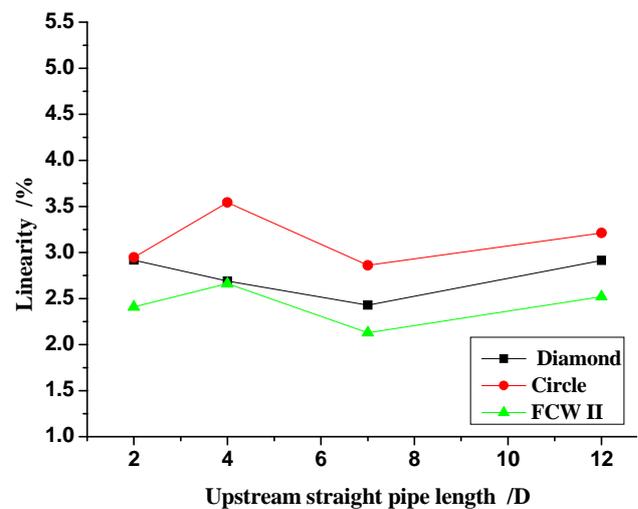
(b) APT flowmeter and the bend in same plane

Fig.4 Two different ways of APT flowmeter fixing

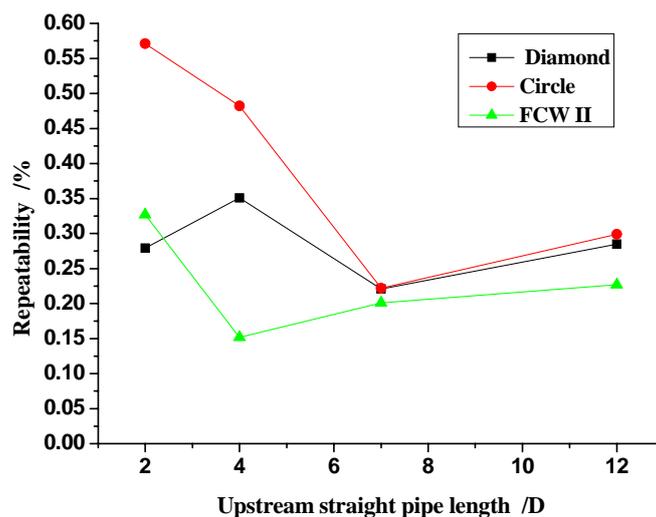
The results of test are shown in Fig.5, as the APT flowmeter is fixed perpendicularly to the bend plane, and they were test in the flow velocity range of 7.5 m/s~35 m/s. Similarly, the results are shown in Fig.6, as they were fixed in same plane of elbow. The characteristics of the APT flowmeters with different cross-sections can be found from the graphs. (1) Meter factor: The meter factor of the FCW II cross-section is the smallest, the diamond is the second, the circle is the biggest. It shows that the FCW II cross-section gains greater differential pressure than other two prototypes. This is a great help to flow measurement. (2) Linearity: For different length of the upstream straight pipe, the linearity of the APT flowmeter with the FCW II cross-section is the best, the diamond is the second, the circle is the worst. (3) Repeatability: There is no obvious superiority in all of the repeatabilities of the APT flowmeters with three different cross-section shapes. Considering the targets such as meter factor, linearity and repeatability comprehensively, the FCW II cross-section is the best one in performance.



(a) Meter factor variation

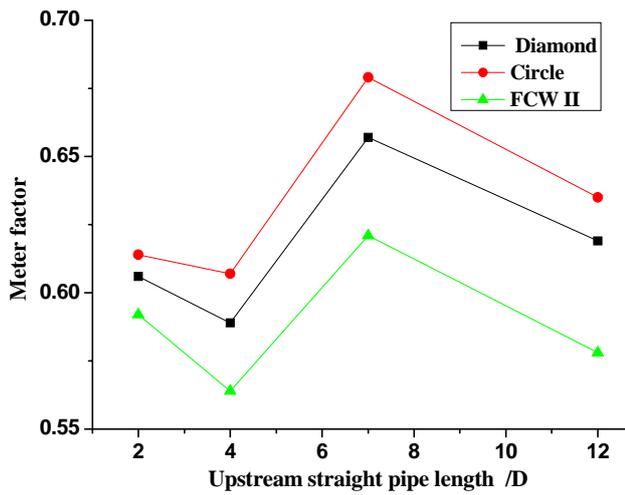


(b) Linearity variation

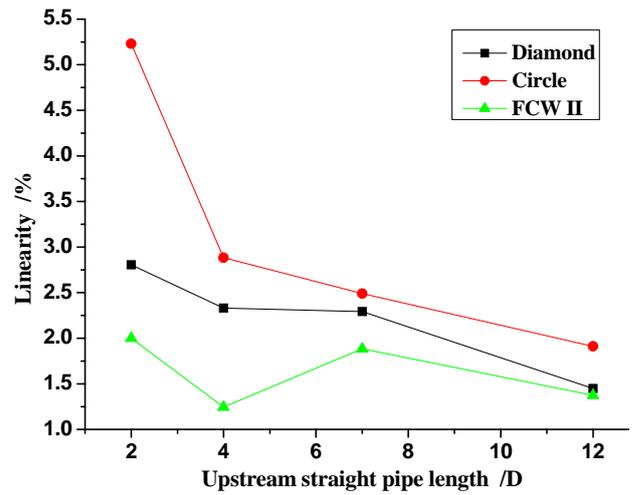


(c) Repeatability variation

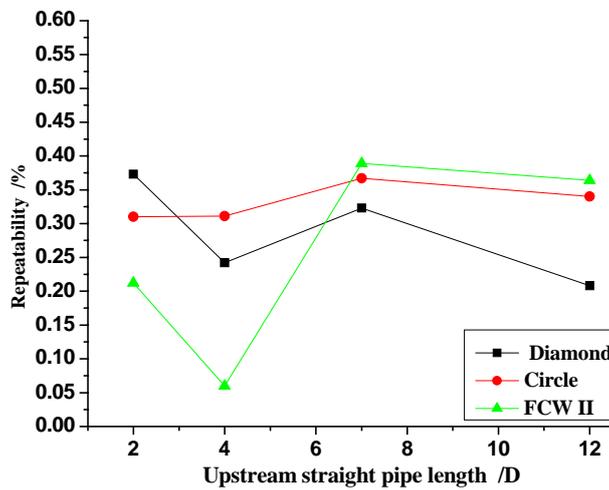
Fig.5 Meter performance variations according to the upstream straight pipe length change, as the APT flowmeter is fixed perpendicularly to the bend plane



(a) Meter factor variation



(b) Linearity variation



(c) Repeatability variation

Fig.6 Meter performance variations according to the upstream straight pipe length change, as the APT flowmeter is fixed in same plane of elbow

5. Conclusions

(1) Three different cross-sections with Flow Conditioning Wing (FCW) were put forward. It was shown by the numerical simulation results that the FCW II cross-section are better than the cross-section of the circle, the diamond and the streamline in the linearity and the output of differential pressure.

(2) The Averaging Pitot Tube (APT) flowmeter prototype test data shows that the FCW II cross-section is better than the cross-section of the circle, the diamond in the meter factor, the linearity and the repeatability.

(3) It was shown by prototype test, in the case of the APT flowmeter with different length upstream straight pipe were fixed downstream a 90° bend, that, under the condition of non-fully developed turbulent flow velocity profile, the linearity and the value of differential pressure of the FCW II cross-section are better than those of the circle and the diamond cross sections, but there is not apparent difference at the repeatability.

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