Pipe Flow Control and Flow Metering

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Abstract

This paper aims to reveal the relation between pipe flow control and accurate flow metering. Every flow meter is subject to installation effects, because it is calibrated in a fully developed pipe flow (standard pipe flow), that is usually different from the flow condition in the industrial application.

Dimensional analysis for flow meters identifies a set of similarity criteria. Kinematic similarity requires to keep the same velocity profile both for calibration and application, that is usually difficult.

In order to control the velocity profile of the pipe flow, a spindle-shaped central body, as a passive flow control device, is designed and installed aligned with the axis of the pipe. Numerical simulations indicate that any incoming flow will be conditioned to the same velocity profile in the annular channel.

The central body also functions as a throttle to generate differential pressure for a special type of differential pressure (DP) flow meter, which is named SPINDLE. To validate the numerical simulation, calibration experiments have been carried out in different facilities at different organizations worldwide, including NIM China, PTB Germany and CEESI USA. All the results of calibration experiments confirm the CFD analysis.

The performance of the SPINDLE flowmeter in critical flow is investigated by numerical simulation and experiment as well.

1. Introduction

Flow control is categorised into active control and passive control. Active flow control seems more attractive for scientific research, while passive flow control seems more attractive for industry applications.

Research on flow control for outer flows has achieved brilliant results. Sophisticated and effective flow control techniques are developed and successfully applied in aeronautical industry. For research on pipe flow control, less attention has been paid. However, pipe flow control is meaningful for flow metering. Flow separation destroys the flow fields in the pipe and hamper flow metering. On the other side, oil or gas flows in pipe line at every moment. Flow separation will eat away huge amount of energy.

The flow field in a pipe becomes very complicated when devices (valves, throttles, elbows, and etc.) are installed [1]. The velocity distribution can be completely different from so called fully development pipe flow. The disturbed flow fields result in marked errors for flow metering because the flow condition in the pipe is different from that in the laboratory facility where the flowmeter has been calibrated.

Every flow meter is subject to such installation effect. To overcome this disadvantage various types of straighteners or conditioners, see figure1, have been developed. From the flow control point of view, the conditioners may operate as passive control devices for pipe flow and strategies of flow control may be induced. The existing flow conditioners play a role just as mixers that disturb the coming flow and intensify the mixing in order to approach to a fully developed pipe flow in a shorter distance.

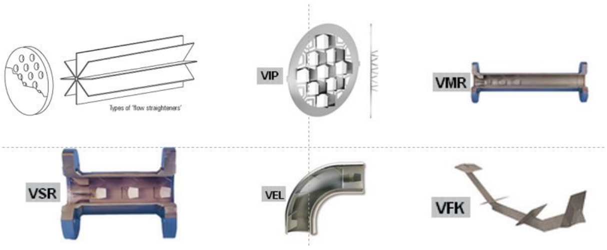


Figure 1: Flow conditioner

However, the flow condition (velocity profile) after a conditioner is still not the same as it has been during the calibration of the flow meter A lengthy pipe is still needed in front of the flow meter. Moreover, the conditioners always induce a large permanent pressure loss. This is another challenge for flow metering.

In addition, flow conditioners cannot satisfy the requirement for flow kinematic similarity between calibration and application, which is a prerequisite for accurate flow measurements.

The importance of dynamic similarity, Reynolds number for example, is widely accepted and practiced. However, the requirement of flow kinematic similarity is often neglected intentionally or unintentionally. Kinematic similarity requires to keep the same velocity profile (velocity distribution inside the flow meter) both for calibration and application, which is usually very difficult.

Low permanent pressure loss is also an important character for a flowmeter, especially for DP type of flowmeter, because a throttle like a DP flowmeter usually causes flow separation and vortices, and hence leads to a big pressure loss.

Moreover, flow separation and vortices generate strong turbulence which results in flow unsteadiness [2], so that the accurate flow measurement becomes difficult.

In this paper the authors intend to reveal the relation between pipe flow control and accurate flow metering. A new flow meter of DP type, named SPINDLE, is investigated [3].

In contrast to modern flowmeters, DP flowmeters are generally considered obsolete. To the authors, however, the DP flowmeter offers an excellent opportunity to control or condition the pipe flow for more accurate flow rate measurements with less pressure loss [4].

2. Dimensional analysis for DP flowmeters

All variables involved are included in f_1:

$$f_1(\Delta p, \rho_1, p_1, v_1, D, d, \mu) = 0 \qquad (1)$$

Take ρ_1, v_1, D as the basic variables and make dimensionless quantities:

$$\frac{p_1}{\frac{1}{2}\rho_1 v_1^2} = \frac{1}{\frac{1}{2}kM^2} \qquad \frac{d}{D} = \beta \qquad \frac{\mu}{\rho_1 v_1 D} = \frac{1}{Re} \qquad \frac{\Delta p}{\frac{1}{2}\rho_1 v_1^2} \qquad (2)$$

All the quantities in formula (1) are substituted by above dimensionless quantities, we have

$$\frac{\Delta p}{\frac{1}{2}\rho_1 v_1^2} = f_1(Re, \beta, kM^2) \qquad (3)$$

Therefore,

$$v_1 = f_2(Re, \beta, kM^2)\sqrt{2\,{}^{\Delta p}/_{\rho_1}} \qquad (4)$$

and then,

$$q_m = \rho_1 v_1 A_1 = f_2(Re, \beta, kM^2)\frac{\pi D^2}{4}\sqrt{2\rho_1 \Delta p} \qquad (5)$$

Or,

$$q_m = f(Re, \beta, kM^2)\frac{\pi d^2}{4}\sqrt{2\rho_1 \Delta p} \qquad (6)$$

Reynolds number Re and Mach number *M* imply viscosity effect and compressibility effect respectively. They are independent.

Comparing with the empirical flow rate equation,

$$q_m = \frac{C \cdot \varepsilon}{\sqrt{1-\beta^4}}\frac{\pi d^2}{4}\sqrt{2\rho_1 \Delta p} \qquad (7)$$

we may conclude that the discharge coefficient C depending on Reynolds number Re only and ε depending on Mach number *M* only.

3.Design of SPINDLE flowmeter

The primary element of the SPINDLE flowmeter is designed as indicated in Figure.2.

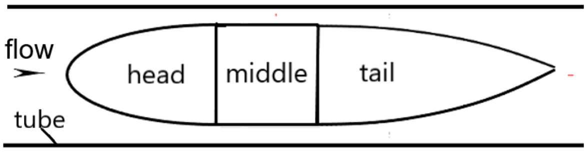


Figure 2: Primary element of SPINDLE flowmeter

The central body has a streamlined shape and consists of three segments: the head, the middle and the tail.

The structure of a SPINDLE flowmeter is indicated in Figure.3.

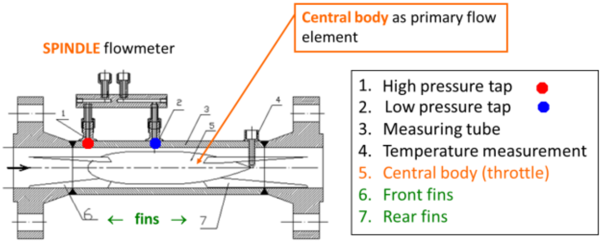


Figure 3: Structure of SPINDLE flow meter

3.1 The SPINDLE as throttle of a DP flowmeter

The central body as a throttle generates a pressure difference Δ*p* between the head and the middle. The flow staggers at the front of the head and the high pressure is tapped. Then the flow is accelerated passing the head and the low pressure is tapped in the middle. The tail is important for pressure recovery so that the permanent pressure loss will be minimized.

The central body is supported by front fins and rear fins as indicated in Figure 3.

3.2 The spindle as a device of passive flow control

The central body (spindle) also functions as a device for pipe flow control. The head of the spindle compresses the coming flow and provides a smooth transition of the flow field. The middle part stabilizes the flow further. The tail is shaped to avoid any flow separation.

4. Flow fields in the Spindle flow meter

Numerical simulation is carried out by using the commercial software FLUENT. The detailed numerical technique is evaded.

The overall flow field is indicated in Figure.4. The flow moves smoothly when passing the central body. No flow separation or vortices occur. The high velocity region is found in the annular channel of the middle segment, which implies lower pressure.

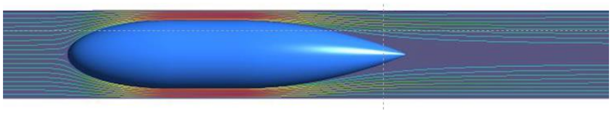


Figure 4: The overall flow field

4.1 Velocity distribution in the annular channel

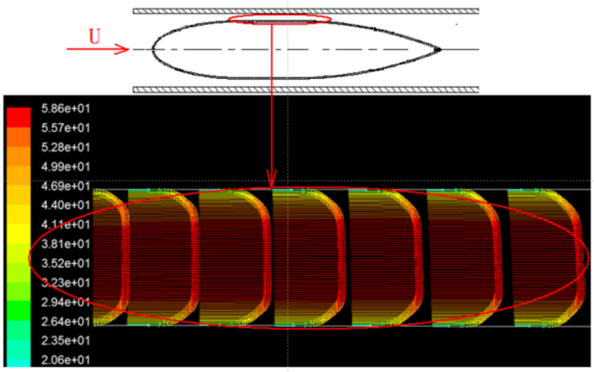


Figure 5: Velocity distribution in the annular channel

Figure 5 indicates that the velocity distribution in the annular channel is uniform except in the boundary layers on the both sides. With increasing flow (increasing Reynolds number), the boundary layers become thinner and the velocity profile is more uniform which means less viscous effects appear. The discharge coefficient may be expected to be a constant (see next chapter).

4.2 Flow conditioning for arbitrary coming flow

As mentioned above, the central body (the SPINDLE) also functions as a flow control device or flow conditioner. The numerical simulation is thus also carried out for arbitrary coming flow.

Figure 6 shows that an arbitrary flow is conditioned when passing the flowmeter. In the annular channel (the middle segment) the flow becomes uniform except for the boundary layers. Comparing with Figure 4, the flow control function can be identified.

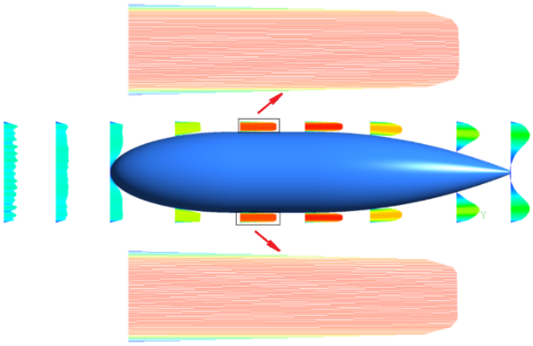


Figure 6: SPINDLE as a flow conditioner

4.3 Flow conditioning for an upstream bend

In industry, often bends and/or other disturbances of pipelines need to be placed in front of flow meters. It is necessary to investigate their influence on flow measurements.

A numerical simulation is carried out for the SPINDLE flowmeter with a bend upstream of the meter (see Figure 7)

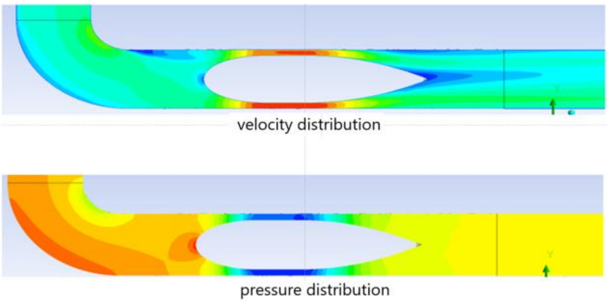


Figure 7: SPINDLE flowmeter with a bend upstream

It is shown clearly that the strong twisted flow, caused by the bend, is modified into an axis symmetrical flow pattern, close to the flow pattern at calibration condition.

It is also found that the wake of the central body is very short. This means less disturbance for the downstream equipment will appear (for detail, see section 4.5).

4.4 Pressure distribution

The pressure distribution along the meter is shown in Figure 8. The central body generates a large pressure difference for the flow rate measurement. The pressure in the middle segment (the annular channel) is minimum. However, the pressure recovery is significant at the tail, which results in a minimum permanent pressure loss. This is an important advantage of the SPINDLE configuration.

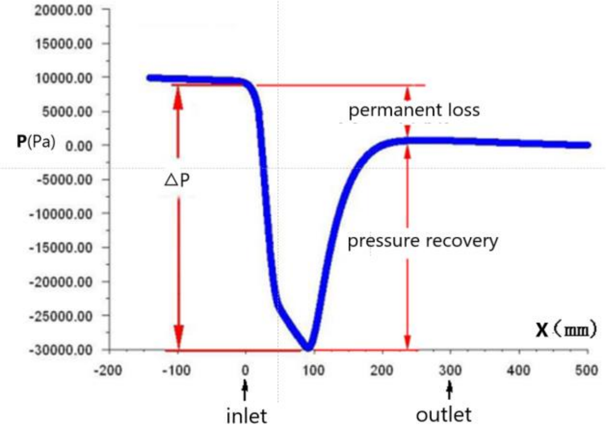


Figure 8: Pressure distribution along the flow meter

4.5 The wake characteristics

A throttle in the pipe has a wake that may influence the devices downstream. A short wake is expected, at which a shorter wake also implies less permanent pressure loss.

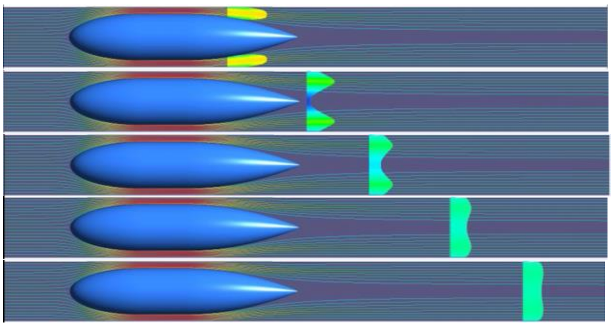


Figure 9: The wakes of the SPINDLE

Figure 9 shows the evolution of the wake of the SPINDLE. No flow separation is found, which implies lower permanent pressure loss. It is also recognized that the flow is very stable, so that a high accuracy is expected.
The wake flow is also investigated by experiments. Figure 10 shows the measurement set-up.

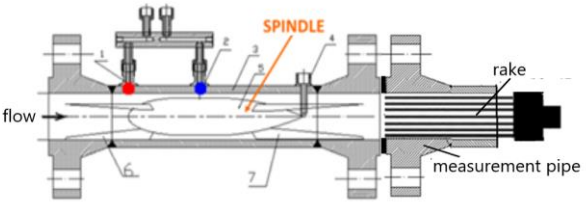


Figure 10: Set-up for wake measurements

The wake flow is measured by a rake that consists of seven total pressure tubes. Figure 11 indicates the evolution of the wake downstream the spindle.

The velocity profile is axis symmetrical and becomes flatter some distance further downstream.

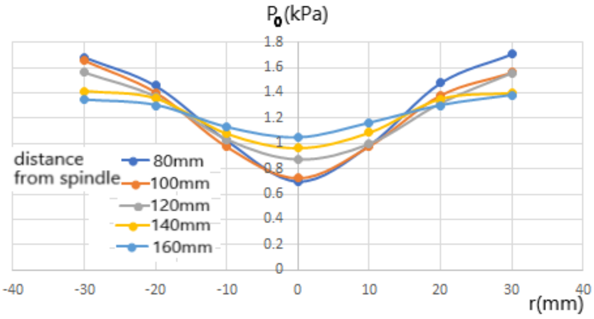
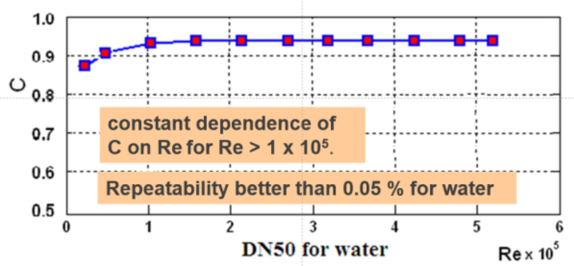


Figure 11: wake flow evolution

5. Calibration

Calibration experiments of a SPINDLE flowmeter have been carried out in different facilities of different organizations, including NIM China, PTB Germany and CEESI USA etc.

5.1 Calibration in water prover of NIM China



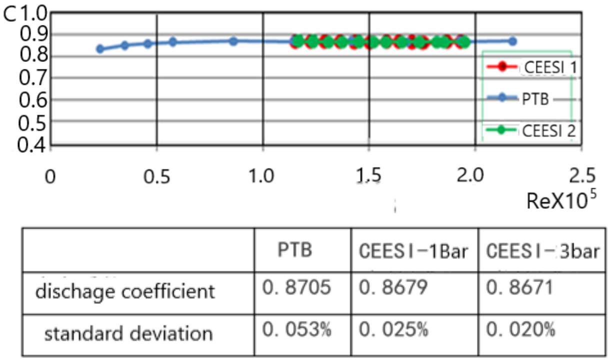
Flow Rate	Q_{max}	$0.7Q_{max}$	$0.4Q_{max}$	$0.3Q_{max}$
Uncertainty	0.13	0.09	0.14	0.12

Figure 12: Calibration results in water

The first calibration was conducted in the water prover of NIM, China. The flowmeter size is DN50 with throttle ratio of β=0.6. The results indicate that the discharge coefficient C is a constant when the Reynolds number is larger than 1x10^5 as indicated in Figure 12. A constant discharge coefficient C has an advantage in application, because no iteration is needed for flow rate calculation. Besides, the results show satisfactory uncertainty and repeatability.

5.2 Calibration in air standard bench

Calibration experiments of a SPINDLE flowmeter have been carried out in different facilities of different organizations, including NIM China, PTB Germany and CEESI USA etc.
Figure 13 shows the comparison of PTB calibration and CEESI calibration. As indicated, they are in good agreement.



	PTB	CEESI－1Bar	CEESI－3bar
dischage coefficient	0. 8705	0. 8679	0. 8671
standard deviation	0. 053%	0. 025%	0. 020%

Figure 13：Calibration results in PTB and CEESI

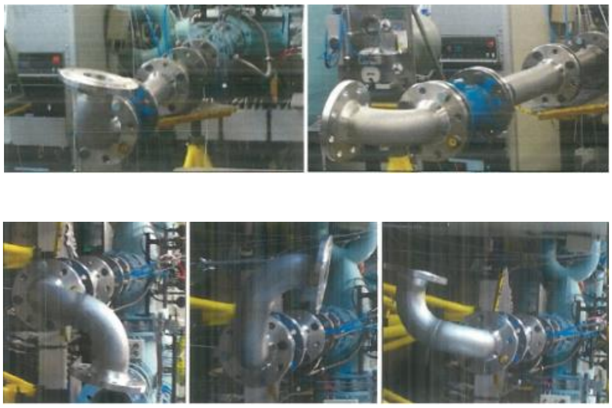


Figure 14: Calibration set-up in PTB Germany

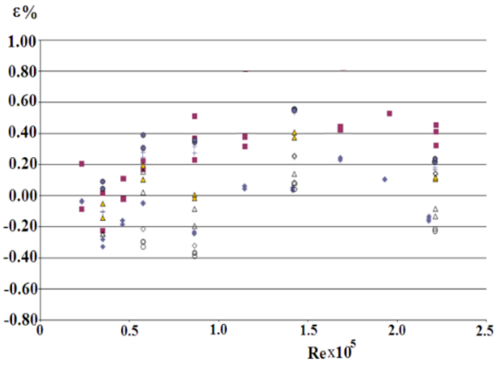


Figure 15: Influence of upstream bending

Flow measurements are mostly influenced by different disturbances upstream of the flow meter.To investigate these influences, single and double bendings at different azimuth angles are installed upstream the flow meter in PTB experiments, as shown in Figure 14. Figure 15 presents the relative errors for flow rate measurements with these bendings compared to the case without bendings. No errors exceed 0.6%. The data verify that the pipe flow controlling is effective and the SPINDLE flow meter has strong abilities of conditioning.

5.3 Calibration in different media

From dimensional analysis in chapter 2 we conclude that the discharge coefficient C depends on Reynolds number Re only.

The following experiments have been conducted with same SPINDLE flow meter of DN50 in different media that are water, air and natural gas.

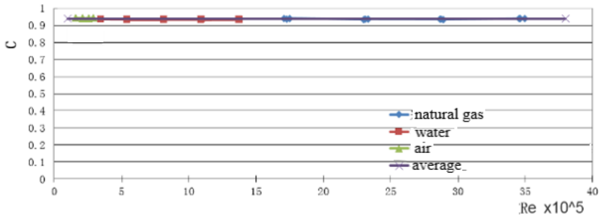


Figure 16: Discharge coefficient C in different media

The results in Figure 16 verify the finding, that the discharge coefficient C depends on the Reynolds number only, even for different media, which means that the SPINDLE flowmeter could be calibrated in water while applied in air or natural gas.

6. The performance in critical flow

The SPINDLE flow meter may even be applied in critical flow condition when the back pressure ratio is less a critical value. The velocity at the annular channel reaches local sound velocity in this case.

Numerical simulation reveals the flow characteristics as shown in Figure 17. When the pipe flow passes the central body, the velocity increases and reaches a maximum value in the annular channel. When the flow enters the tail segment, the flow velocity decreases after a shock wave. The flow is subsonic again.

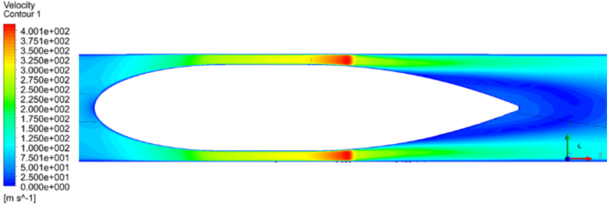


Figure 17: Critical flow in SPINDLE flowmeter

The numerical simulation shows that the discharge coefficient C is of constant dependence on the Reynolds number as indicated in Figure 18.

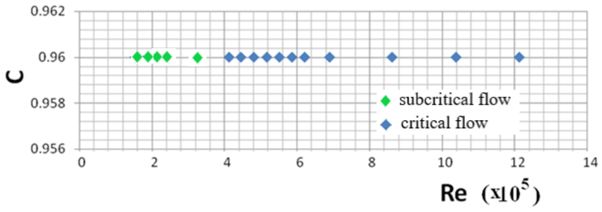


Figure 18: Performance at critical flow conditions

These results have been validated by experiments as indicated in Figure 19. A DN80 Spindle flowmeter is tested at both subcritical flow and critical flow. The discharge coefficient is kept constant even at critical flows.

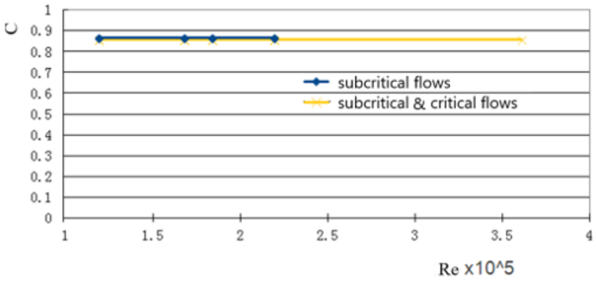


Figure 19: Validate of critical flow performance

7. Applications

Spindle flowmeter has been patented in Europe and China, and applied in industries. The sizes of the meter are covered from DN8 to DN200.
Figure 20 shows minimum size of ND8 and DN200 SPINDLE flowmeters for comparison.

Figure 20: DN8 and DN200 SPINDLE flowmeters

The application fields cover the important industries and research organizations.

High pressure (70 MPa) flow measurements and Two-way measurements of natural gas storage are Impressive by the clients.

8. Conclusions

Custody transfer and high-end process flow metering are still a challenge which requires developing flowmeters with high accuracy in any configuration.

1，A DP flowmeter is one of the most promising type of flowmeters that can modify or condition the incoming flows in applications, depending on the design of the primary flow element.

2，SPINDLE is a new type of DP flowmeter that modifies the pipe flow into annular channel flow inside the meter, so that the installation effects are minimized.

3，The shape of the primary flow element is optimized to avoid flow separation, so that a constant dependence of the discharge coefficient on the Reynolds number is achieved.

4，As the central body and the fins, which support the central body, are well streamlined, SPINDLE is also featured by low pressure loss, self-cleaning and reliability in structure,

5，Calibrations in highly qualified facilities (PTB and CEESI) and applications in complex industrial configurations indicate that SPINDLE is f suitable for custody transfer and inter-comparison flow rate measurements.

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