

Experimental Investigation to Measure the Natural Flow by Gas Laser Doppler Laser Doppler Velocimetry

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Abstract:

In order to solving the natural gas flow measurement problem about measuring flow under the complicated conditions and the measurement traceability of large diameter instruments, a set of optical natural gas flow metering devices based on Laser Doppler Velocimetry was established, translating the traditional flow volume measurement into pipeline section velocity field measurement to achieve the accurate measurement of natural gas flow. Results show that: the facility can achieve 1.45Mpa, 500m³/h the largest experiment measuring ability and the expanded uncertainty was 1.42% ($k=2$); The relative deviation between the experimental results and the standard flow based on the ultrasonic flowmeter was 0.09%~2.93%; The results verify the feasibility of optical method measuring natural gas flow, and the established experiment system can be used for broader flow range of the research of high pressure natural gas flow measurement.

Key words:

Metrology; Laser Doppler velocimeter; Natural gas; Flowrate measurement

1. Introduction

In recent years, with the continuous growth of natural gas trade, the accuracy of flow measurement is very important, and the accuracy of gas flow measurement is closely related to the calibration technology. For a long time, the field real - flow calibration of large diameter flowmeter is a difficult problem. Secondly, there are differences between physical parameters and gas composition parameters of natural gas, working conditions on the measurement site are different and installation conditions of flowmeter are relatively complicated, so that not only measurement errors are increased, but also increase the difficulty of real flow calibration of the large-diameter flowmeter. At present, the world's metrology experts are committed to solving the above problems, improve the natural gas flow measurement level^[1].

In order to solve the problems of natural gas flow measurement under complicated working conditions and traceability of large-caliber meter value and to promote the unification of measurement values of natural gas flow in China, Chengdu Branch of National Oil & Gas Large Flowrate Measurement Station (CVB) and National Institute of Metrology (NIM) established a set of natural gas flow metering device by optical method in 2015. The device adopted a laser Doppler velocimeter as a standard device to achieve a maximum experimental measurement capacity of 1.45 MPa and 500 m³/h, with an expanded uncertainty of 1.42% ($k=2$). In this paper, the

analysis of the establishment of the device and the traceability of value were analyzed, This paper focuses on the establishment of the analytical device and quantity value traceability, and verifies the feasibility of the optical method for measuring natural gas flow by comparing the flow measurement results with the verification flow meter (an ultrasonic flow meter).

2. Establishment of natural gas flow metering device

2.1 Working principles

The flow is the amount of fluid flowing through the cross section of the pipeline or the open channel per unit time, i.e. the integral of the flow velocity over the flow cross section^[2]. Due to the fluidity of the fluid, the movements of various units in each part of the fluid are not necessarily the same, but the relationship between the flow velocity and the flow can be established once flow velocity distribution on the flow cross section is accurately obtained, thereby realizing the measurement of the flow from flow velocity.

Hot-wire anemometer (HWA), particle image velocimeter (PIV) and laser Doppler velocimeter (LDV) are the main methods of measuring flow velocity at present. Compared with HWA and PIV, LDV has greater potential and advantages in measurement of a wide dynamic range of velocity at high spatial resolution. This is a non-intrusive, point-by-point method of measurement. At present, the resolution of LDV to measure the position in the

fluid pipeline has been very accurate. [3 ~ 4].

The working principle of LDV is shown in Figure 1. The measurement principle is explained with the fringe model: Two coherent Gaussian beams are intersected in air to form a measuring body in the intersection area and form alternately dark and bright interference fringes in the measuring body. When the scattered particles following the fluid pass through the measuring body, the Doppler frequency of the light intensity signal of the scattered particles is related to the motion speed of the particles:

$$v_{LDV} = \frac{\lambda}{2 \sin(\theta/2)} f \quad (1)$$

Where λ stood for wavelength of emitted light, θ stood for included angle between two beams of coherent light, and f stood for Doppler frequency.

In formula (1), $\frac{\lambda}{2 \sin(\theta/2)}$ characterizes the spacing between interference fringes in the measuring body, and f characterizes the transition time that the scattered particles pass through the measuring body.

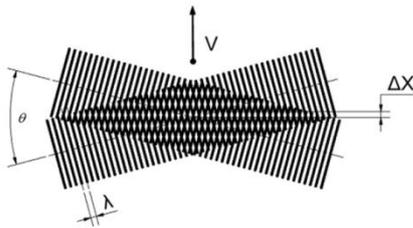


Figure 1: Working Principle Diagram of LDV

2.2 Composition of device

The natural gas flow metering device by optical method mainly consisted of a standard device, a window section, a particle source, a check meter, etc. The gas source came from the main pipeline of natural gas from CVB. The principle diagram of the device was shown in Figure 2.

The standard device is the key equipment of the device, which provides the standard measurement velocity. The standard device mainly including a laser Doppler velocimeter output power 150 mw, wavelength 532 nm), The LDV equipment includes one probe for 1D and one probe for 2D, and 1 set of lens with focal lengths of 250 mm and 400 mm respectively.

Due to the high requirement of light transmittance when LDV is used to measure pipeline velocity, it is not possible to directly measure natural gas pipeline, so it is necessary to set the measurement window section. The measurement window is a transparent round pipe of plexiglass (L= 500mm). The diameter

of the pipe in the measurement window is the same as that of the natural gas pipe being measured, so as to avoid the influence of disturbance caused by the change of pipe diameter on the flow field.

The particle source provides the standard tracer particle for the experiment, and was located at 30D upstream of the window section. The particle source mainly included a pressure Laskin particle generator, dioctyl sebacate (DEHS) particle liquid and nitrogen source. Nitrogen source pressure is higher than natural gas pipeline pressure..

By considering that the feasibility of measuring natural gas flow by optical method needed to be compared with traditional and reliable flow measuring methods, the device was provided with a DN 100 ultrasonic flowmeter which was adopted as a check table.

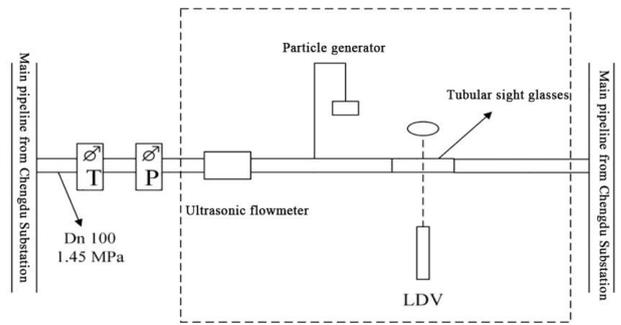


Figure 2: Structural Sketch of optical method gas flow facility

2.3 Calibration of LDV

In order to realize the traceability of measurement and ensure the reliability of the results, the value of the optical natural gas flow metering devices needed to be traced to the national measurement standard. a set of optical method gas flow facility Therefore, the actual value of fringe spacing in the measuring and distribution should be obtained through calibration. As an effective tool, turntable was widely used in calibration research through LDV. PTB of Germany, NIST of the United States and NMIJ of Japan have established their own turntable measurement systems respectively [6].

NIM has also established a turntable measurement system, which can be traced to the two basic quantities of length and time. Its technical parameters were shown in Table 1. Based on the above system, the LDV device of CVB was used to calibrate with a speed range of 1 m/s~25 m/s. The physical diagram and results were shown in Fig. 3 and Table 2. The calibration results showed that the maximum error between the measured value of LDV standard device and the indicating value of the standard value was 0.343%. The LDV was calibrated by PTB at the factory while being delivered, and the relative deviation between the

two calibrations was 0.11%, which also verifies the accuracy of the above calibration results.

Table 1: Technical Parameters of NIM Turntable Measurement System

Name	Parameters
Diameter of turntable	200.2848 mm
Range of linear velocity	(0.1~35) m/s
Diameter of tungsten filament	5μm

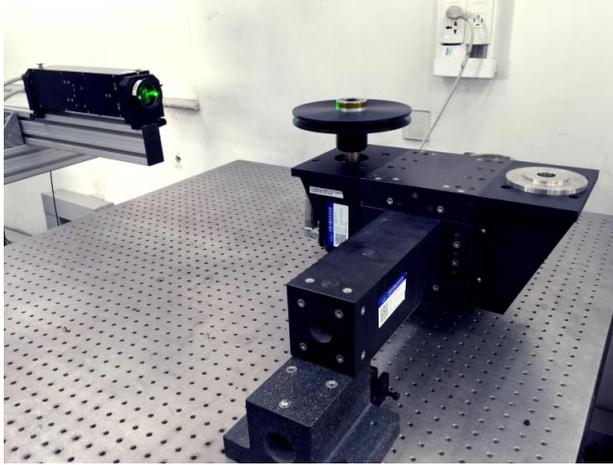


Figure 3: LDV of CVB for NIM Turntable System Calibration

Table 2: (1~25)m/s LDV fringe spacing in NIM measurement results (Green Light λ=532nm)

Doppler frequency [Hz]	NIM fringe spacing [μm]	Standard velocity [m/s]	LDV velocity [m/s]	Indicating value error [%]
2.257E+05	4.655	1.051	1.054	0.337
1.123E+06	4.668	5.253	5.248	-0.109
2.251E+06	4.668	10.507	10.515	0.076
3.365E+06	4.668	15.760	15.717	-0.275
4.514E+06	4.668	21.014	21.086	0.343
5.627E+06	4.668	26.267	26.285	0.068
Average error	0.073%			

2.4 Uncertainty

By considering comprehensively, the uncertainty composition of the optical natural gas flow metering devices was as follows:

$$u_r(Q) = \left\{ \begin{array}{l} u_{rel}^2(V_{LDV}) + u_{rel}^2(T) + u_{rel}^2(P) \\ + u_{rel}^2(Q_{center}) + u_{rel}^2(Q_{boundary}) + u_{rel}^2(V_p) \end{array} \right\}^{0.5} \quad (5)$$

Where, $u_{rel}(V_{LDV})$ is standard uncertainty of single point flow velocity measured by LDV; $u_{rel}(P)$ is standard uncertainty of pressure measurement; $u_{rel}(T)$ is uncertainty of temperature measurement; $u_{rel}(Q_{center})$ is standard uncertainty of flow integral of core area; $u_{rel}(Q_{boundary})$ is standard uncertainty of flow integral of boundary layer of pipeline wall;

$u_{rel}(V_p)$ stood for repeatability of flow velocity measurement at single point. Therefore, the uncertainty sources of optical natural gas flow metering devices are shown in table 3

Table 3: List of Uncertainty of optical natural gas flow metering devices

S/N	Symbol	Source	$c_r(x_i)$ [1]	$u_r(x_i)$ [%]	$u_r(x_i) \cdot c_r(x_i)$ [%]
1	$u_{rel}(V_{LDV})$	Flow velocity at single point of LDV measurement	1	0.15	0.15
2	$u_{rel}(P)$	Pressure measurement	1	0.1	0.1
3	$u_{rel}(T)$	Temperature measurement	1	0.1	0.1
4	$u_{rel}(Q_{center})$	Flowrate integral of core area	1	0.3	0.3
5	$u_{rel}(Q_{boundary})$	Flowrate integral of boundary layer of pipeline wall	1	0.6	0.6
6	$u_{rel}(V_p)$	Measurement of repeatability	1	0.1	0.1
Combined standard uncertainty $u_r(Q_{EMUT})=0.71\%$					
Expanded uncertainty $U_r(Q_{EMUT})=1.42\% (k=2)$					

3. Experimental results and analysis

During the experiment, the natural gas flow was adjusted by a flow regulating device. The flow field of nation gas flowrate was measured at 100 m³/h, 300 m³/h, 400 m³/h and 500 m³/h in pipe. The measuring points are selected in the radial section of the pipe, the center of the section is taken as the origin of the measuring point coordinates, and 5mm is taken as the distance between the measuring points. The distribution diagram is shown in figure 4. The LDV is fixed on a coordinate frame, and the origin of the measuring area is positioned with a tape measure and a coordinate frame. After the gas flow is stabilized, the measurement is carried out, and 20 particles are sampled at each measuring point.

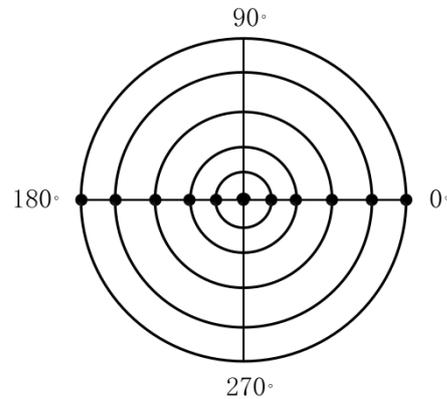


Figure 4: Distribution Diagram of LDV Measuring Points

3.1 Following feature of particles

According to the measurement principle of LDV, the

value measured by LDV is not the velocity of the fluid, but the velocity of the scattered particles in the flow field. The following problem of particles must be considered first in experiments. The common particle following property is generally solved by BBO equation. Based on the calculation results of the BBO equation, we calculated the particle following in the experiment, and the calculation results are shown in table 4. In the experiment, we use particles with a diameter of $5\mu\text{m}$ to obtain relatively good follow-through to the fluid.

Table 4 Solution of BBO Equation for Following Features of Particles with Different Particle Sizes

d_p [μm]	ω [l]	V_p/V_f [l]	T [ms]
0.50	130941.58	1.000000000000	0.000001
0.76	130941.58	1.000000000000	0.000002
1.01	130941.58	1.000000000000	0.000004
2.02	130941.58	0.999999999999	0.000016
4.00	130941.58	0.999999999418	0.000062
5.00	130941.58	0.999999997816	0.000097
6.00	130941.58	0.999999993551	0.000140
7.00	130941.58	0.999999983869	0.000190
8.00	130941.58	0.999999964278	0.000249
9.00	130941.58	0.999999927930	0.000315
10.00	130941.58	0.999999864912	0.000389
20.00	130941.58	0.999991505834	0.001554

3.2 Distribution of Axial Velocity at Section of Pipeline

In Fig. 5-8, v stood for the average velocity at the measuring point, and x stood for the radial distance from the measuring point to the center of the section. It could be seen that the axial velocity at the section of the pipeline was within the range of $X=-50$ to $X=-45$ and $X=45$ to $X=50$, i.e. there was a window period of measurement at the edge of the pipeline wall. With the increase of pipeline flow, the window period of measurement was expanded to $X=40$. The axial velocity was not symmetrically distributed at the axis of the section, but in a " ~ " shape, and it gradually developed into an irregular " S" shape. The degree of irregularity was proportional to the flow.

It showed that the flow measurement in circular tube was easily affected by turbulence intensity and boundary layer. There were three main reasons. 1. The size of the particle was close to that of the boundary layer. The internal velocity gradient was large, and the following features of the particles were decreased, so that the number of particles were influenced; 2. In actual flow, the thickness of the boundary layers on both sides of the pipeline wall were not completely equal, and the energy exchange between the boundary layer and the core area was changed while the flow position was changed along the pipeline; 3. The particles were added to the pipeline under high pressure on single side, which belonged to the problem of impact jet flow perpendicular to the mainstream direction. This

certainly disturbed the asymmetric distribution of number of the particles and the turbulence intensity of the mainstream.

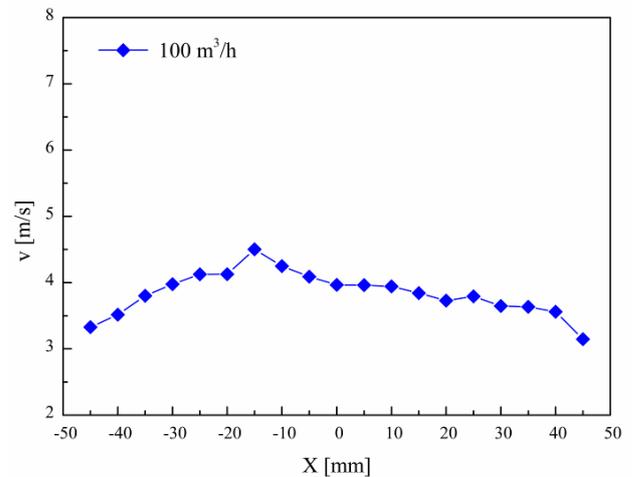


Figure 5: Distribution of Axial Velocity at Radial Section of Pipeline under $Q=100\text{ m}^3/\text{h}$

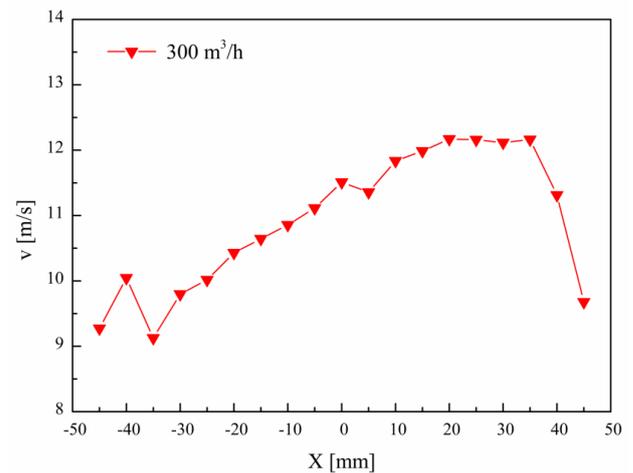


Figure 6: Distribution of Axial Velocity at Radial Section of Pipeline under $Q=300\text{ m}^3/\text{h}$

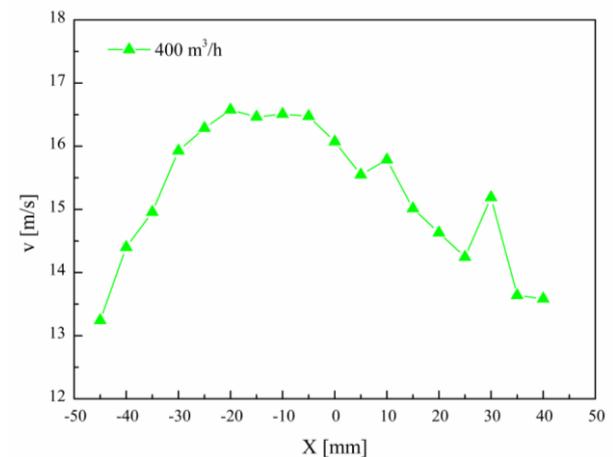


Figure 7: Distribution of Axial Velocity at Radial Section of Pipeline under $Q=400\text{ m}^3/\text{h}$

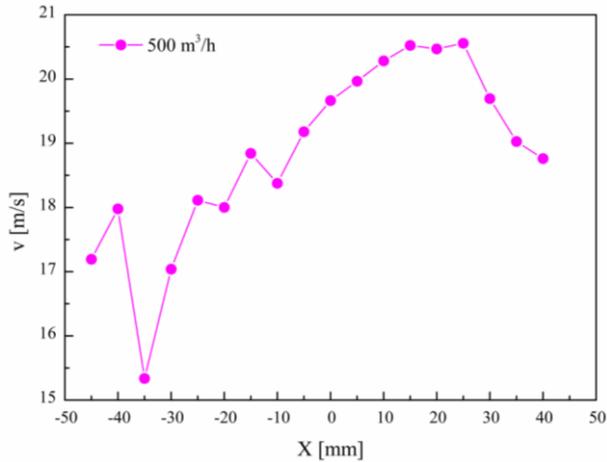


Figure 8: Distribution of Axial Velocity at Radial Section of Pipeline under $Q=500 \text{ m}^3/\text{h}$

3.3 Establishment of relationship between flow velocity and flowrate

Based on the above-mentioned distribution of axial flow velocity, the flow velocity was converted into the flow in an integral manner, so as to obtain flow of the pipeline.

According to fluid dynamics theory, pipeline fluid included two parts: core area and boundary layer.

Therefore, total flow Q_{total} was equal to the sum of the flow in the core area, Q_{centre} and the flow in the boundary layer $Q_{boundary}$, i.e. $Q_{total} = Q_{boundary} + Q_{centre}$. By considering the asymmetric flow of the measured fluid, we considered on both sides based on the center of the pipeline section which adopted as

benchmark, i.e. $Q_{total} = Q_{total_plus} + Q_{total_minus}$. The distribution of flow velocity obtained at under different flow rates was treated as shown in Fig. 9.

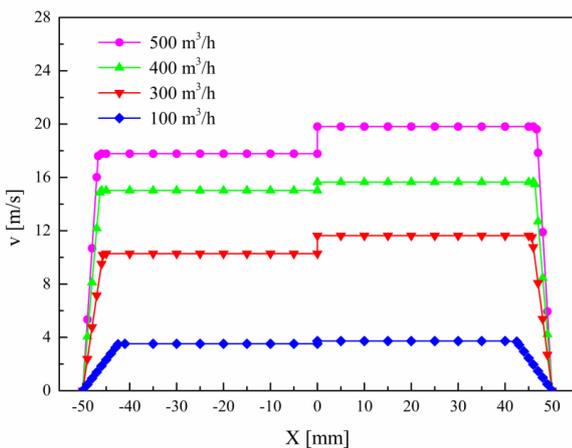


Figure 9: Measuring Results of Flow Velocity Treated at Different Flow Rates

Based on the measurement results of the flow velocity at the section of the pipeline processed in Fig. 6, the volume flow obtained at measured flow

section by integration was compared with the standard flow of the ultrasonic flowmeter as shown in Table 6. By considering that the window section was connected with the ultrasonic flowmeter through a straight pipeline section and the distance was short, the changes of pressure and temperature could be ignored. Therefore, the indicated volume flow of ultrasonic flowmeter could be directly compared with the integral flow based on LDV. It could be seen that the maximum deviation between the flow rates was -0.81% except that the deviation between the two was -2.93% at $100 \text{ m}^3/\text{h}$. This verified the feasibility of measuring natural gas flow by optical method.

Table 6: Correspondence of Measured Natural Gas Flow Rate and Standard Flow Rate Based on LDV

Flow point	Stepping direction	Average velocity in core area	Integral flow	Total integral flow	Standard flow	Indicating value error
Q (m^3/h)	/	m/s	m^3/h	m^3/h	m^3/h	%
100	Negative direction	3.52	42.64	87.71	90.36	-2.93
	Positive direction	3.72	45.07			
300	Negative direction	10.28	133.25	284.00	286.32	-0.81
	Positive direction	11.63	150.75			
400	Negative direction	15.02	197.17	402.62	402.25	0.09
	Positive direction	15.65	205.44			
500	Negative direction	19.81	261.99	497.14	499.45	-0.46

4. Conclusions

Chengdu Branch of National Oil & Gas Large Flowrate Measurement Station and National Institute of Metrology (NIM) established a set of natural gas flow metering device by optical method in 2015. In this paper, the establishment of the device and the traceability of value were emphatically analyzed, and experiments were carried out. Conclusions were as follows:

- 1) The natural gas flow metering device by optical method adopted the laser Doppler velocimeter as the standard device to achieve a maximum experimental measurement capacity of 1.45 MPa and $500 \text{ m}^3/\text{h}$, with an expanded uncertainty of 1.42% ($k=2$).
- 2) The feasibility of measuring natural gas flow by optical method was preliminarily verified through experiments. The established experimental devices could be used for the research on measurement of natural gas flow within a wider flow range.
- 3) Measurement in circular tube was easily influenced by turbulence intensity and boundary

layer, but the measurement reliability of the above method could be improved by reducing turbulence intensity and increasing the number of particles.

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