Research and application of ultrasonic gas flow meter performance on-line audit

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Abstract

Ultrasonic flow meter has become the mainstream measuring instrument in the natural gas trade because of its advantages of large measuring range, small pressure loss and high measurement accuracy. In the measurement of natural gas with high pressure and large flow, the advantage of ultrasonic flow meter is particularly obvious. Ultrasonic flow meter based on transit-time method can measure the speed of sound and the flow velocity of fluid at the same time. With the continuous improvement of on-site monitoring and diagnosis technology of ultrasonic flow meter, the on-line audit of flow meter based on speed of sound checking has attracted extensive attention. According to AGA No.10 report, the on-line audit based on speed of sound checking was carried out with a 4-path ultrasonic flow meter used in a natural gas station was studied. The studies showed that within 2 years, the signal quality indicators of the ultrasonic flowmeter were basically the same, the variation of flow velocity deviation was within ± 0.5%, and the variation of the speed of sound deviation of acoustic path was within ± 0.03%. With the comparison of the real flow calibration, it could be concluded that the metering performance of the flowmeter was stable and reliable, but the installation conditions should be checked to see if they meet the requirements. The results showed that the method of on-line audit can effectively monitor the performance of ultrasonic flowmeter and could be a powerful supplement to the real flow calibration.

1. Introduction

With the rapid development of the natural gas industry, the accuracy and reliability of metering have attracted more and more attention. As the most important measuring instrument in natural gas custody transfer, the flowmeter's equipment selection and performance characteristics are very important to the gas transmission station. Ultrasonic flowmeters have become the mainstream measuring instruments in natural gas custody transfer due to their high measurement accuracy, no moving parts, and no pressure loss, accounting for more than 95% [1,2]. In the measurement of high pressure and large flow of natural gas, the advantages of ultrasonic flowmeter are particularly obvious [3].

Ultrasonic flow meter based on transit-time method can measure the speed of sound and the flow velocity of fluid at the same time, which can be calculated by measuring the transit time of the sound wave [4,5]. By checking the speed of sound of the ultrasonic flowmeter, the accuracy of the speed of sound measured by the flowmeter can be audited, so as to determine the accuracy of the fluid flow rate and determine whether the performance of the flowmeter is normal [6-8]. With the continuous improvement of on-site monitoring and diagnosis technology of ultrasonic flow meter, the on-line audit of flow meter based on speed of sound checking has attracted extensive attention. on-line audit is the inspection of the measurement performance of the flowmeter during the calibration period when the flowmeter is in use, which can avoid metering disputes and eliminate potential safety hazards [9-11]. The development of on-line audit can not only protect the legitimate rights and interests of flowmeter users, but also save the high cost caused by frequent disassembly and calibration.

AGA Report No. 10, speed of sound in natural gas is based on a large database of high-accuracy gas physical parameters. With high-accuracy gas state equation and calculation program, the speed of sound of natural gas can be accurately calculated. According to AGA No.10 report, the on-line audit based on speed of sound checking was carried out with a 4-path ultrasonic flow meter used in a natural gas station was studied. The signal quality, flow velocity characteristics, speed of sound checking and other diagnostic information of the ultrasonic flow meter within 2 years were collected. At the same time, the changes of important parameters such as the flow velocity deviation and the speed of sound deviation of acoustic path of the flowmeter are studied according to the state of the flowmeter during the real flow calibration.

2. Experiment

2.1 Experimental device

A 4-channel transit-time ultrasonic flowmeter was studied, and its basic working principle is shown in Figure 1.

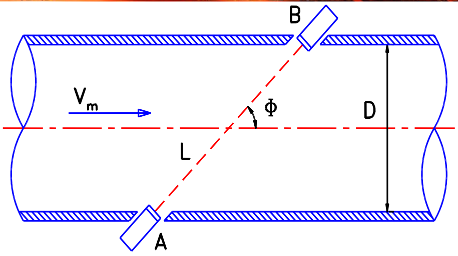

Figure 1: Basic principle diagram of ultrasonic flowmeter.

The acoustic pulse propagates along the sound path, and is transmitted by one transducer and received by the other transducer. The acoustic pulse transmitted downstream is accelerated by the air flow, and the acoustic pulse transmitted upstream is decelerated by the air flow. The transmission time difference is related to the axial flow velocity of the gas. The transmission velocity (C_f) of the acoustic wave in the gas flow can be calculated through the length of sound path (L), the downstream propagation time (t_1) and the upstream propagation time (t_2) of acoustic wave, as shown in formula (1); At the same time, the gas flow rate (V_m) of the ultrasonic flowmeter can be calculated, as shown in formula (2),

$$C_f = \frac{L}{2}\left(\frac{1}{t_1} + \frac{1}{t_2}\right) \quad (1)$$

$$V_m = \frac{L}{2\cos\emptyset}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \quad (2)$$

The multi-path ultrasonic flowmeter is based on the flow velocity measured by different paths, according to its corresponding weight coefficient (w_i) calculate the average velocity on the pipe section ($\overline{V_s}$). The 4-path transit-time ultrasonic flowmeter used in this study is designed as an opposite-type, which is the transmitting and receiving end of each other, and is distributed in parallel on the pipe section from top to bottom. The section of the acoustic path layout is shown in Figure 2.

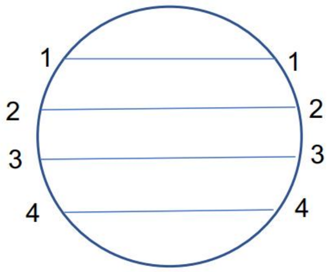

Figure 2: The acoustic path layout of 4-channel ultrasonic flowmeter.

The formula for calculating the theoretical average flow velocity of the fluid flowing through the flowmeter is shown in formula (3),

$$\overline{V_s} = \sum_{i=1}^{4} w_i V_i \quad (3)$$

where, V_i is the average flow velocity of i acoustic path, m/s； w_i is the weight coefficient of i acoustic path. The weight coefficients of each acoustic path of the 4-path ultrasonic flowmeter used in this paper are, $w_1 = 0.1382$，$w_2 = 0.3618$，$w_3 = 0.3618$，$w_4 = 0.1382$.

2.2 Technical Parameters

In order to facilitate the analysis of the state of the ultrasonic flow meter, the flow velocity deviation, the speed of sound deviation, and the speed of sound deviation of acoustic path of the flow meter were defined.

(1) **Flow velocity deviation:** the relative deviation between the average flow velocity measured by the ultrasonic flowmeter and the theoretically calculated average flow velocity, E_V.

$$E_V = \frac{\overline{V} - \overline{V_f}}{\overline{V_f}} \times 100\% \quad (4)$$

where, $\overline{V}$ is the average flow velocity measured by the ultrasonic flowmeter, m/s; $\overline{V_f}$ is the average flow velocity by theoretically calculated.

(2) **Speed of sound deviation**: the deviation between the average speed of sound measured by the ultrasonic flow meter and the calculated speed of sound, E.

$$E = \frac{\overline{C_f} - C}{C} \times 100\% \quad (5)$$

where, $\overline{C_f}$ is the average speed of sound measured by the ultrasonic flow meter，m/s； C is the speed of sound calculated with the gas state of equation，m/s.

(3) **Speed of sound deviation of acoustic path：** the relative deviation between speed of sound of acoustic path and average speed of sound measured by the ultrasonic flow meter，E_{Si}.

$$E_{Si} = \frac{\overline{C_i} - \overline{C_f}}{\overline{C_f}} \times 100\% \quad (6)$$

where, $\overline{C_i}$ is the average speed of sound measured by i^{th} acoustic path, m/s.

2.3 Data analysis

The signal gain value, average performance, signal-to-noise ratio, flow velocity characteristics, speed of sound checking and other diagnostic information of the ultrasonic flow meter within 2 years were collected by using the ultrasonic flowmeter diagnosis software. The flow velocity deviation, the speed of sound deviation, and the speed of sound deviation of acoustic path and other technical indicators of the flowmeter were studied and analyzed.

According to the relevant regulations and specifications of the ultrasonic flowmeter and in combination with the operation manual of the ultrasonic flowmeter, the threshold and judgment criteria corresponding to the technical indexes were determined, as shown in Table 1.

Table 1: Threshold value and judgment criterion of ultrasonic flowmeter.

No.	Parameters	Threshold value and judgment criterion
1	Signal gain value	（19～81）dB
2	Average performance	＞25%
3	Signal-to-noise ratio	＞20 dB
4	Profile Factor	1.12～1.22
5	Symmetry	near 1
6	Cross flow	near 1
7	Swirl angle	±2°
8	Speed of sound deviation	≤0.2%
9	Speed of sound deviation of acoustic path	≤0.35%
10	Speed of sound	（430～440）m/s
11	Maximum speed of sound path spread	≤0.5 m/s

2.3.1 Quality of signal

The signal gain value, average performance and the signal-to-noise ratio of each acoustic path of the ultrasonic flowmeter within 2 years were shown in figure 3 to figure 5. From figure 3, it could be seen that the average performance of the ultrasonic flowmeter was 100% within 2 years. Figure 4 showed that except for the 3^{th} acoustic path in February 2022 was higher, the signal gain value of acoustic path at other times was stable at about 40 dB. Figure 5 showed that the signal-to-noise ratio of acoustic path of the ultrasonic flowmeter was between 38db-41db within 2 years. The signal quality of each acoustic path was good.

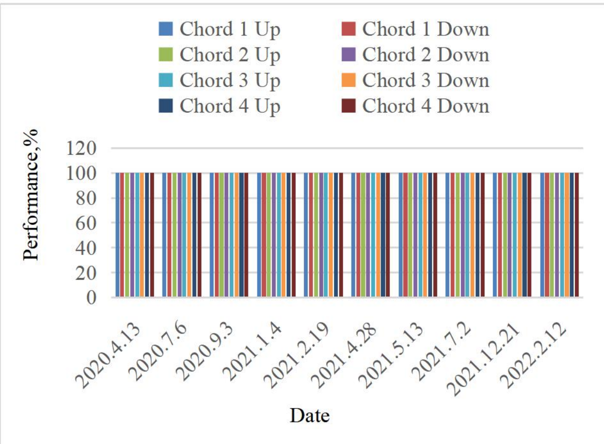

Figure3: Change of performance of ultrasonic flowmeter within 2 years.

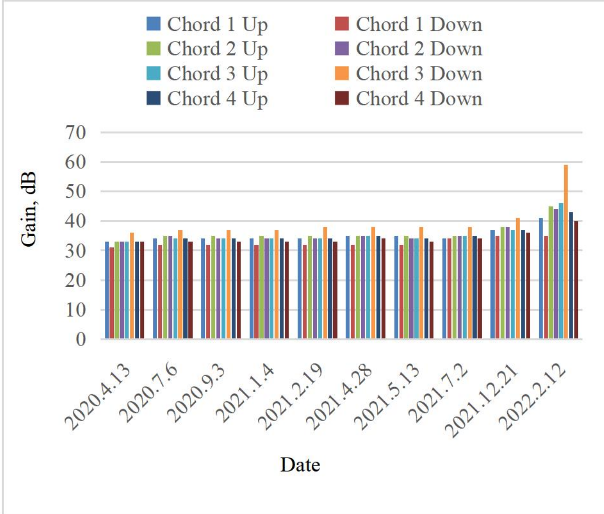

Figure4: Change of signal gain value of ultrasonic flowmeter within 2 years.

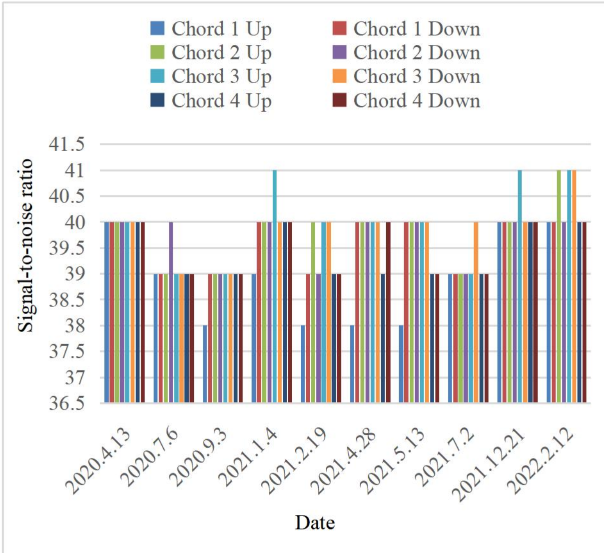

Figure5: Change of signal-to-noise ratio of ultrasonic flowmeter within 2 years.

2.3.2 Flow regime indicators

The flow regime indicators of the ultrasonic flowmeter are based on the collected data such as the flow velocity of acoustic path and the measured flow velocity. The relative deviation between the measured average flow velocity of each acoustic path and the theoretically calculated flow velocity should be within a reasonable range. The adopted flow regime indicators include flow velocity deviation, profile factor, symmetry, cross flow, swirl angle, etc.

The flow regime indicators such as flow velocity of acoustic path, profile factor, symmetry, cross flow and swirl angle were shown in table 2 to table 4. Compared with table 1, it could be seen that the changes of various flow regime indicators were within the threshold range specified by the manufacturer. Figure 6 showed the changes of flow regime indicators.

The average flow velocity, as well as the theoretical average flow velocity and flow velocity deviation calculated according to the weight coefficient of each acoustic path of the ultrasonic flowmeter were given in table 2. it could be seen that the deviation between the measured average flow velocity and the theoretical average flow velocity of the ultrasonic flowmeter was within ± 0.5%, and the flow velocity deviation in the calibration state (December 21, 2021) was the smallest.

Table 2: Flow velocity deviation of ultrasonic flowmeter within 2 years.

Date	Average flow velocity(m/s)	Theoretical average flow velocity(m/s)	Deviation (%)
2020.4.13	12.487	12.468	0.15
2020.7.6	13.404	13.379	0.18
2020.9.3	14.944	14.909	0.23
2021.1.4	12.519	12.501	0.14
2021.2.19	17.002	16.949	0.31
2021.4.28	15.371	15.333	0.25
2021.5.13	16.033	15.989	0.27
2021.7.2	9.099	9.089	0.11
2021.12.21 (calibration)	**13.911**	**13.914**	**-0.02**
2022.2.12	9.994	10.033	-0.39

Table 3 showed that, for the profile factor, the variation range was 1.12 ~ 1.14 within 2 years. According to the ideal value 1.17 of the profile factor (the flow velocity of path 1 and 4 is 0.89 times of the average flow velocity of the flowmeter, and the flow velocity of path 2 and 3 is 1.042 times of the average flow velocity of the flowmeter), the calculated relative deviation was within 4%; For the symmetry, the variation range was 0.97 ~ 0.99 within 2 years. According to the ideal value 1 of symmetry, the calculated relative deviation was within 3%.

Table 3: The profile factor, symmetry of ultrasonic flowmeter within 2 years.

Date	Profile factor		Symmetry	
	Measured value	Deviation (%)	Measured value	Deviation (%)
2020.4.13	1.133	3.20	0.974	2.63
2020.7.6	1.130	3.40	0.975	2.46
2020.9.3	1.127	3.66	0.993	0.74
2021.1.4	1.131	3.32	0.979	2.09
2021.2.19	1.132	3.23	0.973	2.71
2021.4.28	1.136	2.93	0.980	1.99
2021.5.13	1.136	2.91	0.978	2.24
2021.7.2	1.131	3.31	0.984	1.64
2021.12.21 (calibration)	**1.137**	**2.79**	**0.995**	**0.48**
2022.2.12	1.125	3.84	0.983	1.74

Table 4 showed that, for the cross flow, the variation range was 0.93 ~ 0.95 within 2 years. According to the ideal value 1 of cross flow, the calculated relative deviation was within 7%; For the swirl angle, the variation range was within ± 2 ° within 2 years.

Table 4: The cross flow and swirl angle of ultrasonic flowmeter within 2 years.

Date	Cross flow		Swirl angle
	Measured value	Deviation (%)	Measured value
2020.4.13	0.936	6.38	1.92
2020.7.6	0.937	6.33	1.80
2020.9.3	0.944	5.58	0.54
2021.1.4	0.937	6.31	1.53
2021.2.19	0.936	6.40	1.98
2021.4.28	0.936	6.36	1.45
2021.5.13	0.936	6.39	1.64
2021.7.2	0.938	6.25	1.20
2021.12.21 (calibration)	**0.942**	**5.805**	**0.35**
2022.2.12	0.939	6.149	1.27

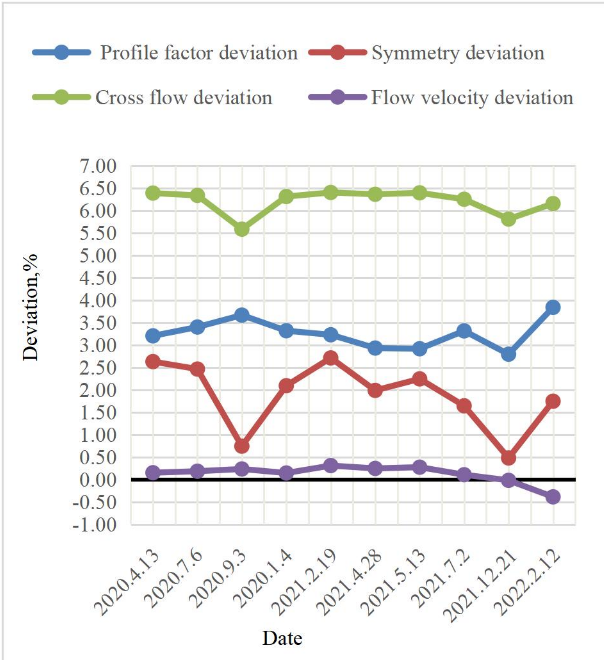

Figure6: Change of flow regime indicators of ultrasonic flowmeter within 2 years.

It could be seen from the changes of the above indicators that, in addition to the calibration time, the flow velocity of the fluid passing through the path 1 and 2 of the flowmeter was asymmetric with that of the path 3 and 4 during running in the gas transmission station. The flow velocity of the upper half of the pipeline was lower than that of the lower half, indicating that there may be a problem with the flow regulator when the flowmeter was installed, which was also the reason for the deviation between the measured average flow velocity and the theoretical average flow velocity of the ultrasonic flowmeter in table 2.

2.3.3 Speed of sound indicators

The speed of sound indicators of ultrasonic flowmeter mainly includes the measured speed of sound of acoustic path, the measured average speed of sound, and the technical indicators of speed of sound checking of ultrasonic flowmeter. The speed of sound checking was based on the working condition temperature, pressure and component data at the ultrasonic flowmeter, the theoretical speed of sound was calculated, the speed of sound deviation was calculated by using the theoretical speed of sound and the measured speed of sound, and the maximum speed of sound path spread, speed of sound deviation of acoustic path, and other data were investigated. The change of indicators should be within the range specified in table 1.

The speed of sound of acoustic path, average speed of sound, and speed of sound deviation of acoustic path of the ultrasonic flowmeter within 2 years were shown in table 5 and table 6. Compared with table 1, it could be seen that the changes of various speed of sound indicators were within the threshold range specified by the manufacturer. The variation of speed of sound deviation of acoustic path of the ultrasonic flowmeter were shown in figure 7.

Table 5: The speed of sound of acoustic path and average speed of sound of ultrasonic flowmeter within 2 years.

Date	speed of sound(m/s)				
	1	2	3	4	Average
2020.4.13	418.6	418.5	418.5	418.6	418.6
2020.7.6	431.4	431.4	431.4	431.5	431.4
2020.9.3	412.6	412.6	412.6	412.6	412.6
2021.1.4	411.0	411.0	411.1	411.1	411.1
2021.2.19	405.7	405.6	405.7	405.8	405.7
2021.4.28	417.6	417.5	417.6	417.7	417.6
2021.5.13	415.5	415.4	415.4	415.6	415.5
2021.7.2	429.8	429.8	429.8	429.9	429.8
2021.12.21 (calibration)	**424.9**	**424.9**	**424.9**	**425.0**	**424.9**
2022.2.12	406.2	406.2	406.2	406.3	406.2

Table 6: The speed of sound deviation of acoustic path and speed of sound deviation of the ultrasonic flowmeter within 2 years.

Date	Speed of sound deviation of acoustic path				Speed of sound deviation
	1	2	3	4	
2020.4.13	0.002	-0.019	-0.005	0.022	-0.04
2020.7.6	-0.002	-0.016	-0.002	0.019	-0.09
2020.9.3	-0.007	-0.017	-0.007	0.005	0.01
2021.1.4	-0.005	-0.012	0.000	0.019	-0.09
2021.2.19	-0.002	-0.020	-0.002	0.025	-0.01
2021.4.28	0.002	-0.022	-0.007	0.024	0.04
2021.5.13	0.000	-0.022	-0.007	0.024	0.06
2021.7.2	0.000	-0.012	0.000	0.016	0.05
2021.12.21 (calibration)	**0.000**	**-0.016**	**-0.002**	**0.021**	**0.03**
2022.2.12	-0.005	-0.012	0.000	0.020	0.03

It could be seen that within 2 years, the maximum speed of sound path spread of the ultrasonic flow meter was within 0.5 m/s, the speed of sound deviations of the ultrasonic flow meter was within ± 0.1%, and the speed of sound of acoustic path of the ultrasonic flow meter was within ± 0.03%. With the comparison of the real flow calibration (2021.12.21, see Figure 8), it could be seen that the change of relative speed of sound deviations of the same acoustic path of the ultrasonic flowmeter were ± 0.02% within 2 years. The results were indicating that the metering performance of the flowmeter within 2 years was stable and reliable.

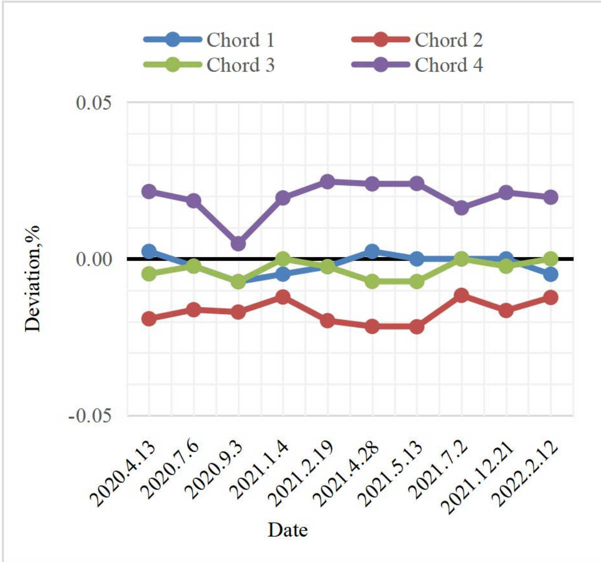

Figure7: Variation of speed of sound deviation of acoustic path of the ultrasonic flowmeter within 2 years.

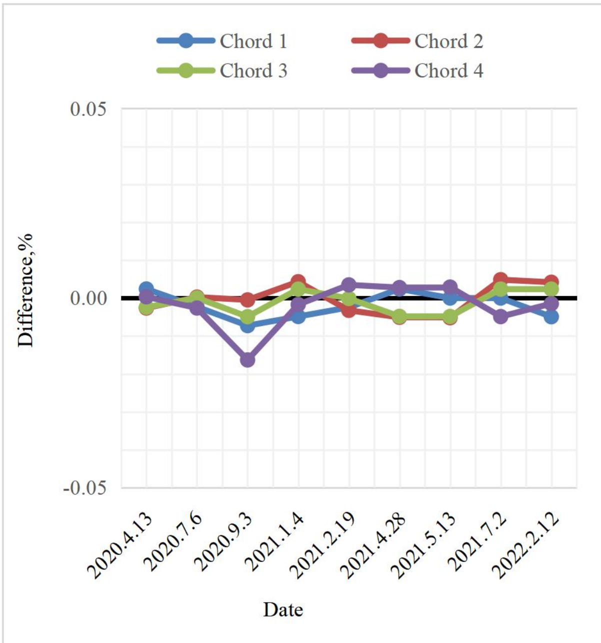

Figure8: Change of speed of sound deviation of acoustic path compared with the real flow calibration.

3. Conclusion

In this paper, the on-line audit based on speed of sound checking was carried out with a 4-path ultrasonic flow meter used in a natural gas station was studied. The technical indicators such as signal quality, flow regime indicators and speed of sound indicators of the flowmeter within 2 years were collected and analyzed. Combined with the status of the flowmeter during the real flow calibration, the changes of important parameters such as the flow velocity deviation and speed of sound deviation of the flowmeter were compared and analyzed. The conclusions and recommendations are as follows:

(1) The signal gain value, average performance and the signal-to-noise ratio of each acoustic path of the ultrasonic flowmeter within 2 years were basically the same, and the signal quality of each acoustic path was good.

(2) The deviation between the measured average flow velocity and the theoretical average flow velocity of the ultrasonic flowmeter was within ± 0.5%, the deviation of the profile factor was within 4%, the symmetry deviation was within 3%, and the cross flow deviation was within 7%; Combined with the change trend of the flow regime indicators, and compared with the real flow calibration state, it was indicating that there may be a problem with the flow regulator when the flowmeter was installed, and the troubleshooting should be focused on the installation conditions to reduce additional installation errors.

(3) The speed of sound deviations of the ultrasonic flow meter was within ± 0.1%, and the speed of sound of acoustic path of the ultrasonic flow meter was within ± 0.03%. With the comparison of the real flow calibration, it could be seen that the change of relative speed of sound deviations of the same acoustic path of the ultrasonic flowmeter were ± 0.02%. The results showed that the metering performance of the flowmeter was stable and reliable.

(4) The on-line audit could be used as an effective means to monitor the metering performance of ultrasonic flow meter. For the ultrasonic flow meter with stable performance, the method of on-line audit could be adopted as a powerful supplement to the real flow calibration.

(5) Based on the above finding, it can further clarify the significance of the technical indicators of the on-line audit of the ultrasonic flowmeter for the flow measurement accuracy, establish the flow deviation prediction model, and ensure the measurement accuracy of the ultrasonic flowmeter in use through the field test in the natural gas station and calibration of the flow standard device.

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