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The Effect of Stagnation Pressure on the Critical Back-Pressure Ratio of Sonic Nozzle by Positive Pressure Method

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Abstract

A test system for the critical back pressure ratio (CBPR) of sonic nozzle was built in Hubei Institute and Measurement and Testing Technology, which was based on the high pressure sonic nozzle gas flow standard facility. The system used a gas volume flowmeter to judge the CBPR. A pressure reducing valve was installed upstream of the gas volumetric flowmeter and the back pressure ratio was adjusted by the valve downstream of the sonic nozzle. The experimental study on the CBPR at different Reynolds numbers was carried out. The results showed that for a nozzle with the positive pressure condition, the CBPR at different flowrates was different. It increased with the increase of the stagnation pressure. During the operation of the standard facility, special attention should be paid to the effect of this difference on the state parameters to ensure the quality and accuracy of gas flowmeter calibration at high pressure.

1. Introduction

As the simple structure, stable performance and high accuracy, sonic nozzles are usually used as master meters for gas flow standards. There are two kinds of sonic nozzle gas flow standard facilities: positive pressure method and negative pressure method, and the latter is widely used at present. However, the working pressure of most flowmeters is higher than the local atmospheric pressure, the experimental conditions of positive pressure method are closer to the actual working conditions. So, the positive pressure sonic nozzle gas flow standard facility can not only calibrate the flowmeter under the actual working pressure, but also study the influence of gas pressure as well as density on the flowmeter performance because the pressure at the tested meter is adjustable [1].

The premise of using sonic nozzle is to maintain the critical flow state of gas flow, that is, the back pressure ratio of nozzle cannot exceed the critical back pressure ratio, which is referred to as CBPR. ISO 9300 [2] stipulates that when the throat Reynolds number is great than 2×10^5, the CBPR is a function of the area ratio of the diffusion section. The throat Reynolds number is less than 2×10^5, it is recommended to maintain a back pressure ratio of 0.25 or conduct CBPR test. In the past, the research on nozzle CBPR basically focused on the negative pressure condition. there are few domestic high pressure standard facilities, there are few studies on the influence of nozzle CBPR under positive pressure.

Hu Heming et al. [3] carried out experimental study on sonic nozzles with throat diameter of 5 ~ 15 mm in series. The results showed that the smaller the throat Reynolds number of the sonic nozzle, the lower the critical back pressure ratio. When the throat Reynolds number is less than 5×10^4, the preunchocking phenomena may occur, resulting in a further reduction of the critical back pressure ratio. Due to the appearance of the phenomenon, the upstream installation conditions have a significant impact on the CBPR of small throat diameter nozzles. Therefore, it is best to measure the CBPR under its actual use conditions during the use of nozzles.

Cao peijuan et al. [4] experimental studied the effect of stagnation pressure on the discharge coefficient of sonic nozzle by the pVTt high pressure gas flow primary standard facility, in which 18 nozzles with different throat diameters was used. The experimental results showed that the variation of the discharge coefficient of the sonic nozzle can reach up to 2.3% under different stagnation pressures, which cannot be ignored.

The influence of stagnation pressure on nozzle CBPR is rarely involved in previous studies [5, 6]. When the sonic nozzle with small throat diameter is used in the high-pressure micro gas flow standard facility, the sonic nozzle must meet the requirements of maintaining the back pressure ratio of critical flow to ensure the mass flow, that is, the accuracy level of standard flow measurement. Because the pressure at the upstream meter under test is higher than the atmospheric pressure and adjustable, when the stagnation pressure before spraying changes, the Reynolds number changes. The difference of the CBPR under different Reynolds numbers significantly affects the facility state parameters during operation, which may lead to large errors in the standard flow.

In this paper, a test system for critical back pressure ratio (CBPR) of micro positive pressure sonic nozzle was established. The CBPR of nozzle was studied under different gas pressure and Reynolds number through the change of flowrate of standard flowmeter.

2. Experimental system and measurement method

2.1 Experimental system

In order to meet the traceability requirements of the gas flowmeters with high pressure but small flow, the high pressure sonic nozzle gas flow standard facility was built. The 6 sets of the sonic nozzles with different throat diameters were used as the reference meters in the facility. The throat diameters were 0.439mm, 0.620mm, 0.862mm, 1.362mm, 1.926mm and 2.720mm respectively. The flow range was within (2~120) L/min and the pressure range was within (0.1~0.6) MPa, while the Reynolds number range was within (5746~211600).

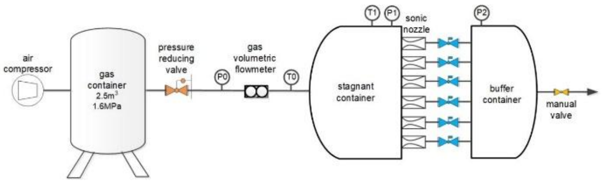

Figure 2: Experimental system diagram

In order to ensure the accuracy level and fine regulate the operation state parameters of the standard facility, a test system for the critical back pressure ratio (CBPR) of sonic nozzle was designed based on the standard facility, which was shown in Figure 1. The system included gas volumetric flowmeter, sonic nozzle, pressure reducing valve, gas container, air compressor, temperature sensors, and pressure sensors. The gas volume flowmeter in the system was used to judge the CBPR. A pressure reducing valve was installed upstream of the gas volumetric flowmeter and the back pressure ratio was adjusted by the valve downstream of the sonic nozzle. The critical flow state of the sonic nozzle was judged by the gas volume flowmeter, and the experimental study of nozzle CBPR at different Reynolds numbers was realized.

2.2 Sonic nozzles

There are three sonic nozzles used in the experiment, and the throat diameter is (1.362 ~ 2.720) mm, which was shown in Table 1.

Table 1: The detailed information of the sonic nozzles and the gas volume flowmeters.

Sonic nozzle		Gas volume flowmeter
No.	**Throat diameter [mm]**	**Type: TYLZ-G10-DN25-V**
		No. 00622030362050
210312	1.362	Flow range: (0.4~16) m^3/h Accuracy level: 1.0
210333	1.926	
210291	2.720	

In order to study the influence of stagnation pressure on the CBPR of sonic nozzle, three test pressures were set in the experiment: 0.2MPa, 0.3MPa and 0.4MPa. A single nozzle is selected for each test.

2.3 The determination of CBPR

By adjusting the pressure reducing valve which was installed upstream of the flowmeter, set the upstream pressure to the specific value. The downstream of the sonic nozzle was a valve, which was connected with the atmosphere when it was fully opened, so as to ensure that the sonic nozzle could reach the critical flow state. Open the regulating valve, and the air flowed through the gas volumetric flowmeter and sonic nozzle from the surge tank, and finally be discharged to the atmosphere.

Since the pressure loss of the flowmeter was small, it was taken as the upstream pressure of the sonic nozzle. Adjust the pressure downstream of the sonic nozzle by adjusting the opening of the valve downstream of the nozzle, so as to change the back pressure ratio of the sonic nozzle. With the increasing pressure downstream of the nozzle, the critical flow state was finally destroyed. The critical flow state of the sonic nozzle was judged by the flow change of gas volume flowmeter, and the CBPR of the sonic nozzle at different Reynolds numbers was obtained.

During the experiment, the output frequency of the gas volumetric flowmeter was obtained and the flowrate at the corresponding frequency was calculated. For the convenience of analysis, the experimental data measured each time are normalized and the parameters were defined.

$$y = \frac{Q - \overline{Q}}{\overline{Q}} \times 100\% \qquad (1)$$

Where, $\overline{Q}$ was the average flowrate of the experimental data measured by the sonic nozzle under the critical flow conditions. The normalized experimental data of each upstream pressure of each nozzle were sorted to obtain CBPR. Typical experimental results were shown in Figure 3. The abscissa represents the back pressure ratio of the nozzle, and the ordinate represents the flow after normalization and averaging.

Due to the expanded uncertainty of the high pressure sonic nozzle gas flow standard facility is 0.15% (*k*=2), the uncertainty of *y* is 0.15% (k=2).

- When $E = \left|\frac{y}{U_{rel}}\right| < 1$, the sonic nozzle was in critical flow state.
- When $E = \left|\frac{y}{U_{rel}}\right| = 1$, the back pressure ratio of the sonic nozzle is CBPR.
- When $E = \left|\frac{y}{U_{rel}}\right| > 1$, The critical flow state of the sonic nozzle is destroyed

During the experiment, because the increase of back pressure was not continuous, the maximum back pressure ratio when *E*<1 was selected as CBPR.

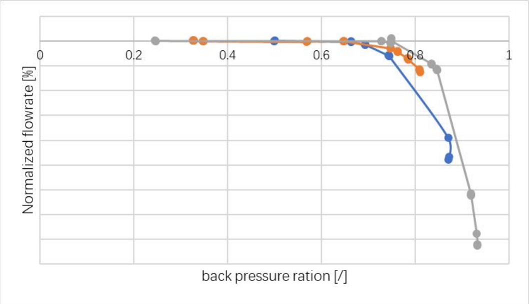

Figure 3: The experimental results of the sonic nozzle (*d*=1.362 mm)

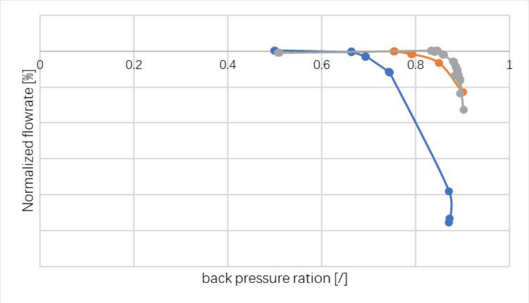

Figure 4: The experimental results of the sonic nozzles under 0.2 MPa (*d*=1.362 mm, 1.926 mm and 2.720 mm)

3. Experimental results

The Experimental results of CBPR obtained by three nozzles under different upstream conditions were shown in Table 2.

Table 2: The experimental results of CBPR under different upstream conditions.

Upstream pressure	210312 (*d*=1.362 mm)	210333 (*d*=1.926 mm)
0.2MPa	0.66	0.79
0.3MPa	0.65	0.80
0.4MPa	0.74	0.83

From the Table 2, it can be found that:

- For nozzle No. 210312, when the upstream pressure increased from 0.2MPa to 0.3MPa, the CBPR was not change significantly. When it increased to 0.4MPa, the CBPR began to increase.
- For nozzle No. 210333, when the upstream pressure increased from 0.2MPa to 0.3MPa, the CBPR was not change significantly. When it increased to 0.4MPa, the CBPR began to increase.
- Under the pressure of 0.2 MPa, the back pressure ratio increased with the increase of throat diameter. The CBPR of the numbered 210312 was 0.66, the numbered 210333 was 0.79, and the numbered 210291 was 0.85.

4. Uncertainty analysis

The CBPR of the sonic nozzle was judged by the *E* value, which was based on the change of the standard flowrate according to the gas volume flowmeter and calculated by the experimental data after processing. Therefore, the uncertainty of the CBPR was mainly composed of two parts, one was the introduce of the flowmeter measurement and the other was the uncertainty caused by data processing.

- The flowrate measurement *u*(*y*)

The flowrate was measured by the high pressure sonic nozzle micro gas flow standard facility and the expanded uncertainty of the facility is 0.15% (*k*=2). The standard uncertainty of the flowrate measurement *u*(*y*) was 0.075%.

- The data processing *u*(*dp*)

The maximum value of the experimental standard deviation of each upstream pressure condition was taken as the uncertainty of data processing. From the experimental data, *u*(*dp*) was 5.10%

So, the uncertainty of the measured CBPR *u*(*CBPR*) was expressed as shown in Equ. (2).

$$u(\text{CBPR}) = \sqrt{u^2(y) + u^2(dp)} = 5.11\% \qquad (2)$$

The results showed that the CBPR under different flowrates was different for a single nozzle under positive pressure. With the increase of stagnation pressure, the CBPR increased. There is a close relationship between stagnation pressure and CBPR under positive pressure.

5. Conclusion

A test system for the critical back pressure ratio (CBPR) of sonic nozzle was built in Hubei Institute and Measurement and Testing Technology, which was based on the high pressure sonic nozzle micro gas flow standard facility. The critical flow states of the sonic nozzles were judged by the gas volumetric flowmeter, and the CBPR of the sonic nozzles under different Reynolds numbers was obtained.

- When the stagnation pressure in front of the sonic nozzle changed, the Reynolds number changed. When the stagnation pressure increased to a certain value (0.4MPa in the experiment), the Reynolds number at the sonic nozzle throat was greater than 7.4 × 10^4, and the critical back pressure ratio showed an increasing trend. The difference of CBPR significantly affected the setting of state parameters of the facility during operating, thus affecting the error of standard flow.

- The sonic nozzles used in the facility were all small throat diameter. When the small throat diameter sonic nozzle was used in the high pressure micro gas flow standard facility, the sonic nozzle must meet the requirements of maintaining the back pressure ratio of critical flow to ensure the accuracy level of mass flow.
- For a single nozzle under positive pressure, the CBPR at different flowrates was different. With the increase of stagnation pressure, the CBPR increased. During the operation of the device, special attention should be paid to the influence of this difference on the state parameters to ensure the quality and accuracy of gas flow calibration under high pressure.

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