The upstream installation effect on the CBPR of sonic nozzle

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Abstract

The test for the critical back pressure ratio (CBPR) of a sonic nozzle by using an orifice plate is established, and six types of upstream conditions are set up. Preliminary experimental results show that the upstream conditions have almost no effect on the CBPR at throat Reynolds number larger than 1.1×10^5, but better upstream conditions or the longer lengths of upstream straight pipe can improve flow stability; when throat Reynolds number smaller than 1.1×10^5, the upstream installation condition would have a significant impact on the CBPR, because of the occurrence of the premature unchoking phenomenon. Therefore, it is necessary to measure the CBPR in use for small throat diameter nozzle.

Keywords: Gas flow, Sonic nozzle, CBPR, Orifice plate

Introduction

Compared with other flow meters, sonic nozzle is featured with simple structure, stable performances, high accuracy and other advantages, and therefore it is commonly used for measuring other types of gas flow meter as a standard. The premise for the use of the sonic nozzle is that the back pressure of the nozzle cannot exceed the critical back pressure ratio, which is called CBPR for short. It is specified in ISO 9300 [1] that the CBPR of the nozzle of which the reynolds number of throat part is more than 2 * 100000 is the function of diffusion section area ratio, while the suggested back pressure ratio of the nozzle of which the reynolds number of throat part is less than 2 * 100000 shall be controlled in 0.25 or subjected to CBPR test. However, the nozzle with small throat diameter and low reynolds number is commonly used for inspecting the gas meter as a standard, and the use thereof is wide. Therefore, during recent years, the research in the CBPR of this type of nozzle is more and more [2-5].

Park[2] et.al. measured the CBPR of the nozzle with 2×10^4~3.4×10^5 Reynolds Number Range. When the spread half angle is 2°~6°, the change of the spread angle has no so much effect on CBPR; but if the spread angle is 8°, CBPR reduces to 0.85. Besides, for nozzles with less than 4.48mm throat diameter: even if the areas are the same, the CBPR will change according to the changes of the Reynolds Number.

Nakao[3] et.al. carried out experiments for nozzles having the Reynolds Number within the range of 40~3×10^4. The results show that: CBPR is only the function of Reynolds Number and has no relation with the size of the throat diameter; when the Reynolds Number is 40, CBPR is only 0.05.

Lavante[4], et.al carried out experiments for the standard nozzles with (0.15~2.0) mm throat diameter and 1.7×10^3~5×10^4 Reynolds Number which proved that the CBPR is far lower than the theoretical value.

In the past, the research in the CBPR of the nozzle is concentrated in the physical dimension of the nozzle, such as throat diameter and diffusion angle. When the nozzle is in the working standard, the upstream installation condition is always very complicated due to the limitation of on-site environmental conditions, but the impact of these changes on the CBPR of the nozzle has never been involved in previous researches. This paper researches the impact of six types of different upstream conditions in the reynolds number range of 5.25 * 10000 to 1.81 * 100000 on the CBPR of the nozzle by simulating the upstream disturbance through the pore plate installed in the front of the nozzle.

Structure and Measurement Method of Experimental Facility

Experimental Facility The experimental system is shown in Fig.1, and composed of pore plates, rectifiers, critical flow nozzles, volume tanks, vacuum pumps, and temperature and pressure sensors. In the system, the pore plate, which is used as a flow meter for judging the CBPR, is also used as a local disturbing member for generating the upstream disturbance. The upstream of the pore plate is directly connected to the atmosphere, and the downstream is provided with the sonic nozzle to be tested. The pore plate and the nozzle can be provided with a straight pipe or rectifier therebetween according to the requirements.

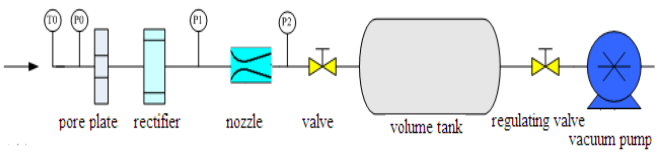

Fig.1 Diagram of experimental system

Sonic Nozzles Totally, there are 9 experimental sonic nozzles designed according to ISO 9300[6], and the pore plates of two apertures are processed according to the flow rate design of the nozzle. As shown in Table 1:

Table 1 Experimental sonic nozzles and pore plates

sonic nozzles				pore plates
number	throat diameter	flow	reynolds number	apertures
	[mm]	[m^3/h]	[/]	[mm]

8601	4.0250	8.80	5.25×10^4	18.218
8602	5.9090	19.20	7.76×10^4	
8603	7.0020	26.90	9.14×10^4	
8604	7.9820	35.30	1.05×10^5	30.708
8605	9.0855	45.30	1.19×10^5	
8606	9.9360	54.50	1.31×10^5	
8607	11.0320	67.50	1.46×10^5	
8608	12.4440	85.00	1.64×10^5	
8609	13.6740	104.00	1.81×10^5	

The rectifier is divided into two types, i.e. tube bundle type of rectifier and plate type of rectifier [7], wherein the thickness of the tube bundle type rectifier is 100 mm, the outer diameter of the tube bundle is 10 mm, the wall thickness is 1 mm, and the total number thereof is 19. For the plate type rectifier, the thickness is 6.25 mm, and the 5 different apertures are as follows: 12.5mm、28mm、37.5mm、42.5mm、45mm.

In order to research the impact of upstream conditions on the CBPR of the nozzle, the specific upstream conditions set in the experiment are as follows:

The nozzle and the pore plate do not be provided with a rectifier therebetween, and the lengths for the straight pipe section upstream the nozzle are 5D (referred to as no-5D) and 10D (referred to as no-10D**).**

The nozzle and the pore plate are provided with a plate type rectifier therebetween, and the lengths for the straight pipe section upstream the nozzle are 5D(referred to as plate-5D) and 10D (referred to as plate-10D).

The nozzle and the pore plate are provided with a tube bundle type rectifier therebetween, and the lengths for the straight pipe section upstream the nozzle are 5D(referred to as tube -5D) and 10D (referred to as tube -10D).

Determination of CBPR The pressure within the volume tank is vacuumized to 100Pa and below through the vacuum pump, so that the back pressure of the nozzle is sufficiently low, the critical flow state of the nozzle can be realized, and the pressure regulating valve can be closed. With the accumulation of gas within the volume tank, the pressure within the tank is increased continuously, and the critical flow state of the nozzle is damaged finally. According to the temperature and pressure measured, the change of the flow rate can be obtained as well as CBPR.

In the experiment, the density of the gas within the pipe between the pore plate and the nozzle is not more than 1.5%, the change for the mass of gas within the pipe is small without considering the change of pipe volume, and it can be considered that the mass flow rate flown through the pore plate and nozzle is equal. The calculation formula for the mass flow rate of the pore plate is $Q=K'\sqrt{\frac{\Delta P\cdot P_0}{T_0}}$, in which K' refers to a constant. In order to facilitate the analysis, the experimental data measured every time shall be subject to further treatment of normalization, and the parameter thereof is defined as y. y is shown in Eq.(1):

$$y=\frac{Q-\overline{Q}}{\overline{Q}}\times100\% \qquad (1)$$

$\overline{Q}$ refers to the average of the experimental data measured in the critical flow conditions of the nozzle. The experiment of each upstream condition of each nozzle is repeated for 9 times, and the normalized experimental data of 9 times is sorted and equalized to obtain the CBPR. The typical experimental results are shown in Fig.2, in which the horizontal ordinate refers to the back pressure of the nozzle, vertical coordinate refers to the flow rate value normalized and averaged.

In order to minimize the impact of temperature on the change of flow rate, the whole back pressure ratio range is divided into certain sections. In the selected section m, y_m refers to the data flow of this section, $\overline{y_m}$ refers to the average of all data in the section, $y_m-\overline{y_m}$ refers to the difference between the flow rate data and average of the section, $\overline{y_m-\overline{y_m}}$ refers to the average of the section. The uncertainty of the nozzle is U = 0.15% (k = 2), and the uncertainty of y is u_y=0.075%.

- When $E=\left|\frac{\overline{y_m-\overline{y_m}}}{u_y}\right|$ is less than 1, the nozzle is in the state of critical flow;
- When $E=\left|\frac{\overline{y_m-\overline{y_m}}}{u_y}\right|$ is equal to 1, the back pressure ratio thereof is CBPR;
- When $E=\left|\frac{\overline{y_m-\overline{y_m}}}{u_y}\right|$ is more than 1, the critical flow state of the nozzle is damaged.

In the experiment, the maximum back pressure ratio in the condition that $E=\left|\frac{\overline{y_m-\overline{y_m}}}{u_y}\right|$ is less than 1 is CBPR as the increase of back pressure is discontinuous.

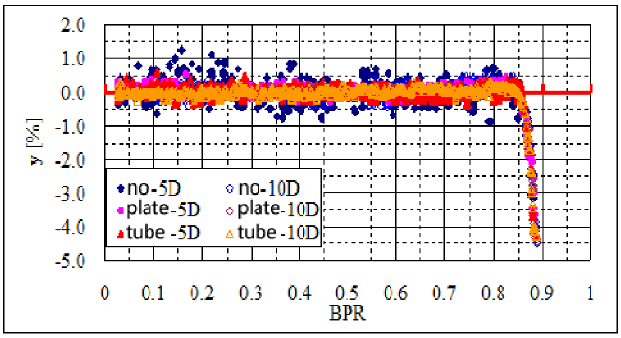

Fig.2 Experimental result of 8605 nozzle（d=9.0855mm）

Experimental Result

Fig.3 represents experimental results on the CBPR of nozzles(8601 to 8609) in different upstream conditions:

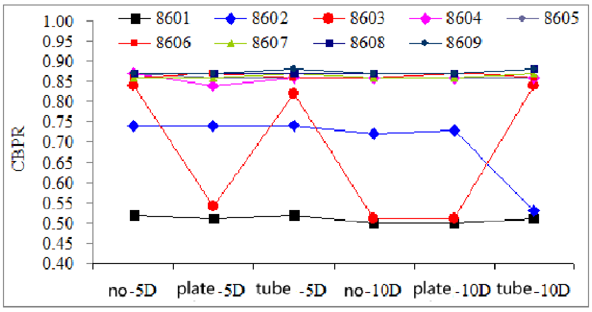

Fig.3 The influences of upstream conditions on the CBPR

According to Fig.3, it can be seen that:

For the nozzle of 8604 to 8609: The CBPR is more than 0.84 (including) and above, and the change for the results of CBPR is not more than 0.01 in case of the change of upstream conditions.

For the nozzle of 8601 to 8604: The range of variation for the CBPR of 8601 and 8604 is small, all the CBPRs of 8601 is 0.52 (inclusive) and below, and the CBPR of 8604 is about 0.86. The range of variation for the CBPR of 8602 and 8603 nozzles is large. When the upstream condition of 8602 is tube-10D, the CBPR is 0.53. In case of other conditions, the CBPR is more than 0.72 (inclusive). When the upstream condition of 8603 is no-10D, plate-5D or plate-10D, the CBPR is reduced to 0.54 (inclusive) and below, and the CBPR in case of other conditions is more than 0.82 (inclusive).

Uncertainty Assessment

CBPR is determined by E value on the basis for the change of flow rate of the pore plate after a certain processing on the data. Therefore, the uncertainty is mainly composed of two parts, of which is the uncertainty due to the measurement of flow rate of the pore plate, and another part is the uncertainty due to the data processing.

Differential Pressure Measurement, $u(p)$ The orifice plate pressure difference is the pressure difference between sensors on both sides of it. The tolerance of the instrument is 0.01%FS. The measurement range is （0-110）kPa、（0-700 ）kPa. Considering the uniform distribution, the introduced standard uncertainty of these two pressure sensors is $u_{11}=\frac{0.011\%}{\sqrt{3}}=0.006\%$，$u_{21}=\frac{0.070\%}{\sqrt{3}}=0.040\%$.

The maximum pressure change of one experiment shall not be over ΔP=0.01kPa. The 100kPa measured value, considering the uniform distribution, so the pressure fluctuation referenced standard uncertainty is $u_{12}=u_{22}=\frac{0.01}{100\sqrt{3}}=0.006\%$. Thus the standard uncertainty induced by pressure measurement is $u_1=\sqrt{u_{11}^2+u_{12}^2}=0.008\%$, $u_2=\sqrt{u_{21}^2+u_{22}^2}=0.040\%$. the standard uncertainty induced by pressure difference is shown in Eq.(2):

$$u(p)=\sqrt{u_1^2+u_2^2}=0.041\% \tag{2}$$

Temperature Measurement, $u(T)$ The tolerance of the adapted temperature transmitter is ±0.05℃. The 19.5℃ temperature measurement value, considering its uniform distribution, the introduced standard uncertainty is $u_1(T)=\frac{0.05}{292.65\sqrt{3}}=0.099\%$. The maximum temperature change of one experiment shall not be over 0.5℃. The 19.5℃ measured value, considering its uniform distribution, the standard uncertainty introduced by temperature fluctuation is $u_2(T)=\frac{0.5}{292.65\sqrt{3}}=0.099\%$. Then the standard uncertainty induced by temperature measurement is shown in Eq.(3):

$$u(T)=\sqrt{u_1(T)^2+u_2(T)^2}=0.140\% \tag{3}$$

Experiment step size, $u(step)$ The back-pressure in each experiment changes gradually from small to large. Its step size (space between the adjacent back-pressure) shall not be over 0.04 and take the relevant CBPR value 0.86 (this is the maximum step size/CBPR value). Considering its uniform distribution, the standard uncertainty induced by step size is shown in Eq.(4):

$$u(step)=\frac{0.04}{0.86\sqrt{3}}=2.65\% \tag{4}$$

Data processing, $u(dp)$ CBPR judges by the E value and E value is based on the normalizing equalization experiment data. The disparity of experiment data causes the uncertainty of processing data. Here we treat the median of every upstream condition experiment standard deviation as the uncertainty under this condition.

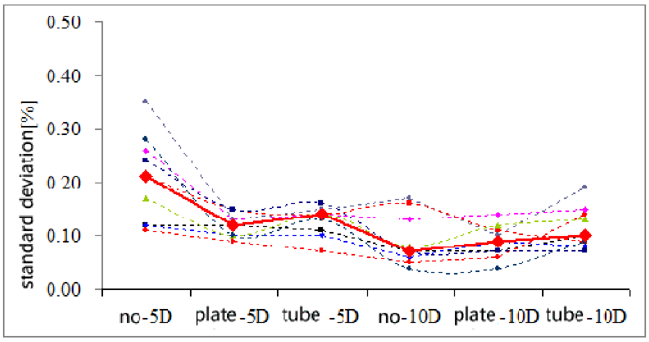

Fig.4 Uncertainty of data processing

As Fig.4, when the upstream condition is without a rectifier-5D, disperity of the measuring data is bigger, 0.21%. The other kinds of measured data under the upstream condition, the disparity is about the same, (0.07～0.14)%. Above all, the uncertainty of CBPR by measurement $u(CBPR)$ is shown in Eq.(5):

$$u(CBPR)=\sqrt{u(p)^2+u(T)^2+u(step)^2+u(dp)^2}=(5.30\sim5.32)\% \tag{5}$$

The uncertainty plays a leading role in uncertainty evaluation, and the upstream condition changing doesn't affect too much the measured uncertainty.

Influence of Advanced Non-Congestion Phenomenon to CBPR

Experimental results show 8601-8604 nozzles occur non-congestion phenomenon[3,4,8,9]. As shown in Fig.5:

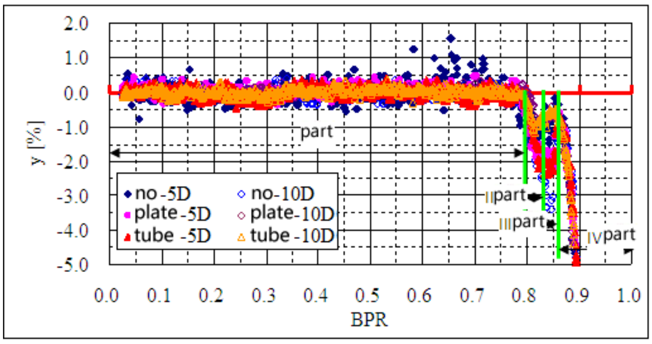

Fig.5 Experimental result of 8604 nozzle- advanced non-congestion phenomenon

In I part, the back-pressure of nozzle is lower than CBPR and the flow through the nozzle keeps stable.

In □part, when the back-pressure ratio of the nozzle exceeds the CBPR, its throat critical flow will be broken, and the flow of the nozzle will reduce.

In □ part, with the increasing of the back-pressure ratio, within the range of this back-pressure ratio, the flow of the nozzle will increase again, even to the maximum flow.

In □ part, with the increasing of the back-pressure ratio, the flow of nozzle will continuously decrease.

The advanced non-congestion phenomenon doesn't influence the size of CBPR. Fig.6 is the experimental result of 8601 nozzle:

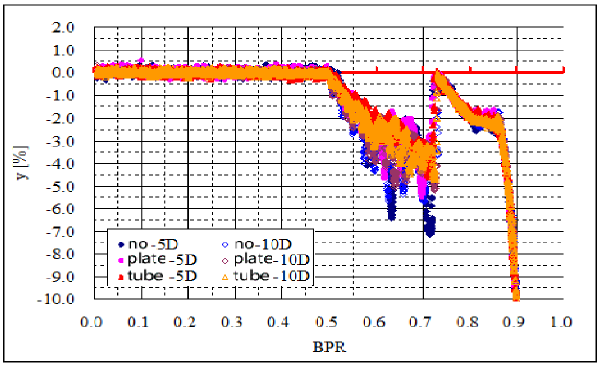

Fig.6 Experimental result of 8601 nozzle（d=4.0250mm）

We can see the nozzle will occur the obvious advanced non-congestion phenomenon under different upstream conditions. This phenomenon will keep the CBPR of the nozzle of only 0.52. Between the back-pressure ratio of 0.52 ～0.73, the use of rectifier or increase the length of the straight section, it can reduce the flow reduction. But in the retest experiment of 8604 nozzle, the advanced non-congestion phenomenon doesn't occur which means the advanced non-congestion phenomenon may be related with the installation conditions. To 8601 and 8604 nozzle, the advanced non-congestion phenomenon doesn't have influence on CBPR size.

The advanced non-congestion phenomenon decrease the size of CBPR. Fig.7 is the experiment result of 8602 nozzle. When the upstream is the tube-10D, the back-pressure ratio is 0.52, and the first advanced non-congestion phenomenon occurs. But under other conditions, the advanced non-congestion phenomenon will occur when the back-pressure ratio is over 0.72 which make the CBPR under this condition will obviously decrease than under other conditions.

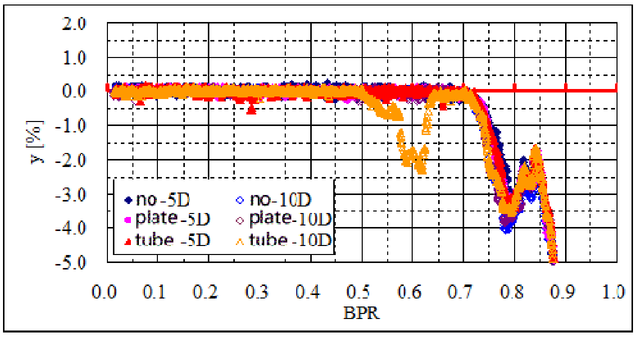

Fig.7 Experimental result of 8602 nozzle（d=5.9090mm）

Fig.8 is the experiment result of 8603 nozzle. When the upstream conditions are no-10D, plate-5D or plate-10D and when the back-pressure ratio is 0.52, the advanced non-congestion phenomenon will occur.

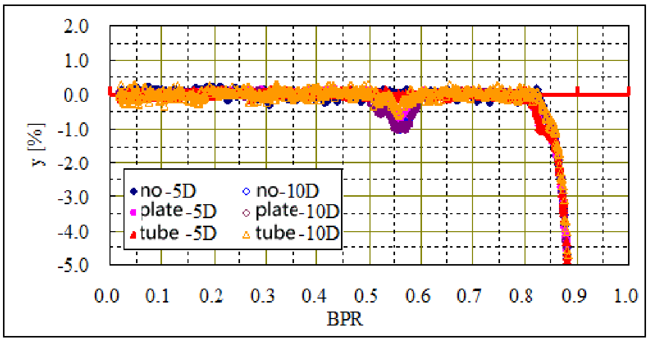

Fig.8 Experimental result of 8603 nozzle（d=7.0020mm）

To 8602、8603 nozzle, after the retest of CBPR, the result is similar with Fig.7 and Fig.8. The appearance of the advanced non-congestion phenomenon will decrease obviously the CBPR compared with other upstream conditions.

Conclusion

With the characteristics of real-time measurement of orifice plate, use the flow change of the orifice plate to monitor the flow change of the nozzle to get the CBPR of the nozzle. Connect the orifice plates (and rectifiers) in series before the nozzle to simulate the disturbance of upstream and research the nozzle CBPR influencing factors through six different kinds of upstream conditions, it is concluded that:

When the nozzles of throat Reynolds number over 1.1×10^5(8605-8609), the trend flow changing with the back-pressure curve will become smooth. Different upstream conditions have little influence on CBPR. But setting the rectifier in the upstream of nozzle or increase the straight length will increase the flow stability.

When the nozzles of throat Reynolds number below 1.1×10^5(8601-8604),the appearance of advanced non-congestion phenomenon makes the CBPR influenced by the upstream conditions. It can be classified into two cases: To 8601 、 8604 nozzle, the advanced non-congestion phenomenon doesn't influence the size of CBPR; To 8602、8603 nozzle, the advanced non-congestion phenomenon will decrease CBPR obviously.

Because the appearance of advanced non-congestion phenomenon will make the upstream installation conditions having obvious influence on the CBPR of small-throat-diameter nozzles. Therefore, when using the nozzles, it’s better to test the CBPR under its actual using condition.

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