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Influence of wall temperature distribution on discharge coefficient of sonic nozzle

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Abstract

To investigate the influence of complex body temperature distribution, especially the temperature drop near the throat on the discharge coefficient C_d of sonic nozzles, an adiabatic sonic nozzle with the throat of 2 mm and temperature acquisition systems including insulation sleeve with 15 mm Polytetrafluoroethylene (PTFE) and 5mm pearl cotton, multichannel data collector, three T type thermocouples, were established. Moreover, this system can be directly installed on the 100 L pVTt facility with or without insulation sleeve at National Institute of Metrology of China (NIM), to obtain these characteristics of body temperature distribution near the throat and C_d for sonic nozzle. Then, the influence of temperature distribution at throat on the C_d was qualitativelyanalyzed.

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1. Introduction

The critical flow venturi nozzles (known as sonic nozzles or nozzle) can be used not only as a flowmeter to measure the gas flow, but also as a master standard to calibrate other industrial flowmeters, due to their excellent performances. When the nozzle is used as the flowmeter or transfer standard, it is necessary to obtain its discharge coefficient, C_d, which is defined as the ratio is a dimensionless ratio of the actual flow-rate to the ideal flow-rate, and can be gotten through experimental calibration $C_{d,\mathrm{exp}}$ or theoretical calculation $C_{d,\mathrm{th}}$. Due to special structure of nozzle, when the gas expands and accelerates through it with a large temperature drop, the heat exchange between the cold gas and the nozzle body will affect the displacement thickness of the boundary layer, the thermal expansion of throat diameter, and the measurement accuracy of stagnation temperature T_0, which finally results in the changes of the discharge coefficient C_d. The series of complex phenomena results from the heat transfer between the sonic nozzle body and the fluid is generally called the “thermal effect”.

Firstly, the influence of T_0 on the C_d was much smaller than that of stagnation pressure P_0, so it was often ignored. In 2015, Wright[1] measured the stagnation temperature at the inlet of the sonic nozzle by using different axial and radial methods, and found that the error of T_0 at different positions was not more than 0.3 K, which would cause the uncertainty of the C_d to be about 0.05%. In 2019, Hou[2] studied experimentally that a deviation of C_d was about 0.2%, due to the different measurement methods of T_0, and the reason for the deviation needs to be further verified.

Secondly, the influence of thermal expansion and thermal boundary layer on the C_d of sonic nozzle caused by the wall temperature distribution and wall temperature drop had also attracted the attention of experts. In 1988 and 1995, Jones[3], and Caron and Carter[4] found that the thermal expansion was related to the adiabatic body temperature distribution of sonic nozzle. In 1996, Thomas and Richard[5] used thermocouples to measure the steady and unsteady wall temperature distribution of the sonic nozzle with the throat diameter d = 25 mm, and found that the maximum wall temperature drop ΔT is 11 ℃ and the thermal equilibrium time of the wall could be longer than 1700 s. In 2013, Ünsal[6] combined with experiment and simulation to investigate the effect of wall temperature distribution on the C_d for two toroidal nozzles of d = 5 mm with different body weight and geometry. The results indicated that thermal inertia alters the C_d especially for higher Reynolds number Re.

In 2015, Wright[1] found that C_d was affected by the sampling error of the wall temperature and the effect of the thermal boundary layer, and proposed a new correction coefficient against the thermal boundary layer experimentally, which can reduce measurement uncertainty. He also found that the traditional correction formula of thermal expansion corrects the C_d to make the results more deviate from the experimental data. In the same year, Ünsal[7] also obtained numerically the relationship between C_d and ΔT for the sonic nozzle with d = (1 ~ 30) mm. The results showed that the effect of the wall temperature with a smaller throat diameter was more significant.

In 2016 and 2018, Wang and Ding[8]-[10] found the dynamic temperature distribution through 12 sampling points in the body of sonic nozzle and revealed the position of shock wave was the main influence on body temperature distribution, and obtained the maximum body temperature drop of 16.5 ℃. Preliminarily, some isotherm maps of sonic nozzle body were obtained with the simple Kriging interpolation method (SKIM). Based on temperature distribution results, they proposed the correction factors of the thermal boundary layer and the thermal expansion, and pointed out that the constrained thermal deformation could not be simplified as free expansion to correct the d C_d, and the C_d at Re = 1.0×10^3 would increase by 0.408% for typical body temperature drop was 10 ℃, which could not be ignored. Unfortunately, the results of SKIM showed that the isotherm was closed cycle, that was, “bull’s eye” phenomena, indicating that there was an internal heat source in the temperature field, which was not consistent with the actual situation. In addition, they found that the experimental conditions and the structure for sonic nozzle of wall temperature distribution and thermal expansion correction are relatively simple. The C_d of sonic nozzle was usually calibrated under the constant temperature environment in the laboratory, but in practical applications, it is difficult to maintain the same ambient temperature and stagnation temperature, such as natural gas transmission pipe or aero engine test site. Even in the laboratory, the T_0 of the gas changed as high as nearly 20 ℃ in different seasons of one year, resulting in poor repeatability of the C_d. As for the analysis of thermal effect phenomenon, most studies focused on the wall temperature distribution under single conditions. However, under different working conditions (including stagnation and environmental parameters), the wall temperature at throat T_{tr} after heat balance was not consistent, and the law of wall temperature distribution at throat and its impact on flow characteristics were lack of more accurate experimental verification.

To solve the above problems, an adiabatic sonic nozzle with the throat diameter of 2 mm and the temperature distribution measurement systems including insulation sleeve with 15 mm Polytetrafluoroethylene (PTFE) and 5 mm pearl cotton, multichannel data collector, and T type thermocouples were designed to further research the influence of the T_{tr} or ΔT on C_d of sonic nozzle. T type thermocouple probes with accuracy of 0.2 ℃ to measure temperature at throat of nozzle and were implanted into the blind holes with 1 mm diameters for temperature acquisition. And, the blind holes were filled with thermally conductive silicone to satisfy boundary condition at the external surface. At the same time, this system can be directly installed on the pVTt gas flow standard facilities with or without insulation sleeve at National Institute of Metrology of China (NIM), to obtain these characteristics of ΔT and C_d for sonic nozzle.

2. Temperature distribution measurement system

2.1 Sonic nozzle with the thermocouple

To study the wall temperature at throat T_{tr}, a sonic nozzle was machined as toroidal nozzles according to the ISO 9300, whose geometric characteristics are shown in Table 1. The throat diameters and the diffusion angles are 2 mm and 4.0º respectively, and the outer diameter is 36 mm. The overall length is about 50 mm.

Table 1: The geometric characteristics of the sonic nozzle.

Nozzle	Throat diameter (mm)	Outer diameter (mm)	Overall length (mm)	Diffusion angle (°)
No.1	2.00	36.0	50.0	4.0

This sonic nozzle sensor with the 3 T type thermocouple probes is used to calibrate temperature near throat and divergent section, as shown in Figure 1 and seen in No. 5#, 6# and 7#, where x = 0 mm denotes the position of the throat for sonic nozzle.

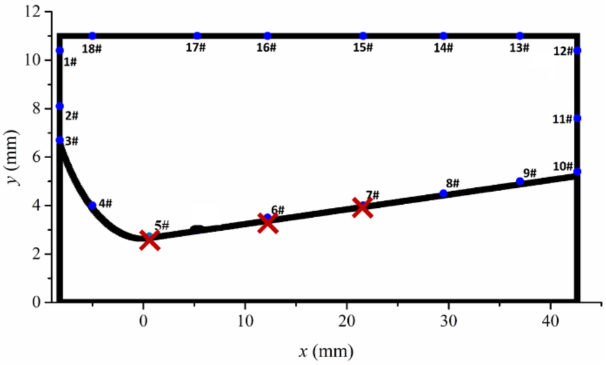


Figure 1: Sonic nozzle with three T type thermocouple probes.

The material of this sonic nozzle is AISI 304 whose thermal conductivity is λ = 16.27 W·m^{-1}·K^{-1}, and this is installed in polytetrafluoroethylene (PTFE) sleeve and pearl cotton. PTFE with 15 mm thickness and pearl cotton with 5 mm thickness are used to insulate the external heat of this sonic nozzle, as shown in Figure 2. The blind holes are filled with thermally conductive silicone to reduce the influence of hole on temperature distribution, and the thermal conductivity of silicone λ = 9.5 W·m^{-1}·K^{-1}.

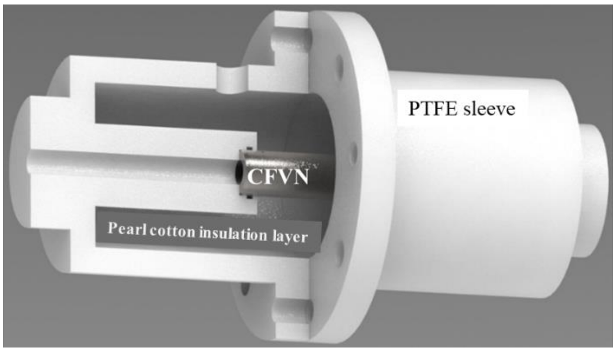


Figure 2: Sonic nozzle and insulation fixture.

And then, to investigate the influence of complex body temperature distribution, especially the temperature drop near the throat ($\Delta T = T_0$ - T_{tr}) on the C_d of sonic nozzles, a temperature acquisition systems including insulation sleeve with 15 mm PTFE and 5mm pearl cotton, multichannel data collector, and T type thermocouples, were established. 3 T type thermocouple probes with accuracy of 0.2 ℃ to measure temperature near throat and divergent section of sonic nozzle. The signals of thermocouples are filtered and amplified by using Tp1000 multi-channel data recorder.

2.2 Experiment system of C_d

This temperature acquisition systems can be directly conducted on the 100L pVTt gas flow standard facilities with or without insulation sleeve at National Institute of Metrology of China (NIM). The scheme of the experimental platform is shown in Figure 3. The facility includes a pure air generation device, pressure regulating valves, gas holder, acquisition system, and collecting tank. The dry compressed air is utilized to calibrate C_d of sonic nozzles covering flow range from 0.019 to 1367 kg/h, and the stagnation pressure range from 0.1 to 2.5 MPa. The uncertainty of calibrated discharge coefficient for sonic nozzle was 0.08%~0.10% (k=2). A detailed description of experimental system is introduced in references [11].

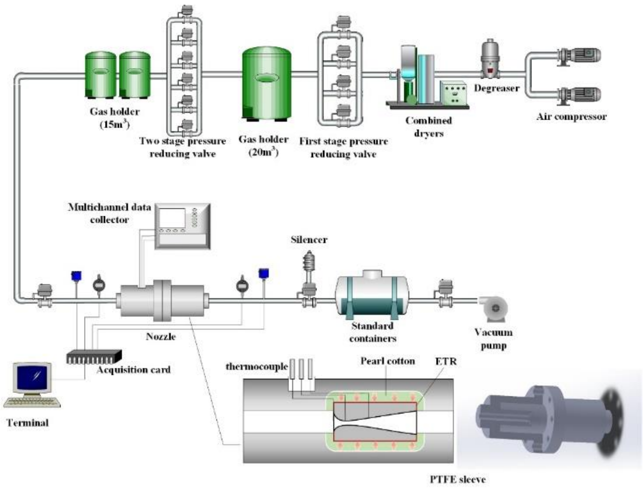


Figure 3: pVTt experimental system with temperature acquisition of adiabatic sonic nozzle.

3. Experimental results and analysis

3.1 Results of the C_d

The experimental $C_{d,exp}$ of this sonic nozzle with or without insulation sleeve at different stagnation pressure p_0 from 0.2 to 0.6 MPa were conducted under different times, as shown in Figure 4, in which a total of 43 $C_{d,exp}$ of this sonic nozzle were plotted.

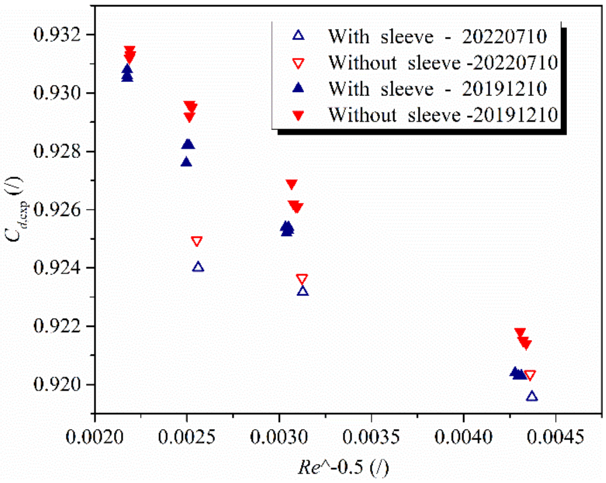


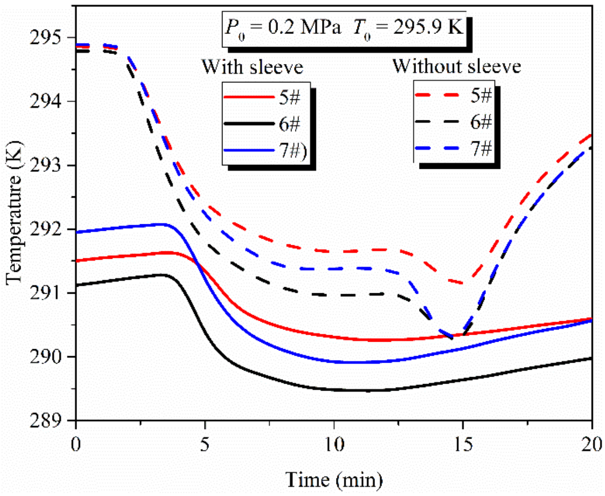
Figure 4: $C_{d,exp}$ of this sonic nozzle under different conditions.

As shown in Figure 4, at different stagnation pressure, $C_{d,exp}$ could be changed up to 1.3% for this sonic nozzle,. In order to get a higher accuracy of the C_d, it is necessary to carry out the actual measurement or accurate prediction of it under different stagnation pressure. The uncertainty of the results (reproducibility) in 2019 and 2022 was about 0.60%. Due to calibration made in the different seasons, the stagnation temperature T_0 was different from 288.67 to 296.48 K, resulting in poor reproducibility. And then, the deviation of $C_{d,exp}$ with and without insulation sleeve in 2019 and 2022 were 0.15% and 0.10% respectively. Therefore, the effect of ambient temperature and stagnation temperature on C_d should be paid attention to.

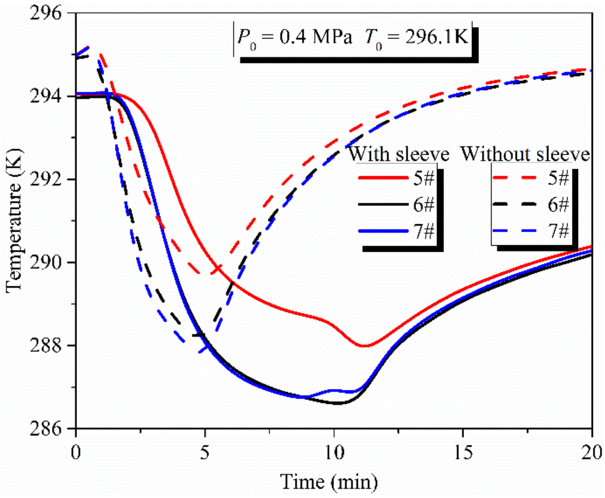
3.2 Variation law of the T_{tr} or ΔT and C_d

While measuring the C_d, the wall temperature changes near and after the throat with different conditions were collected at ambient temperature of about 296.0 K. The distribution curve of steady temperature near the inner surface (5# to 7# temperature measured) for d = 2 mm sonic nozzle at p_0 = 0.2 MPa, 0.4 MPa and 0.6 MPa with or without insulation sleeve were presented in Figure 5.

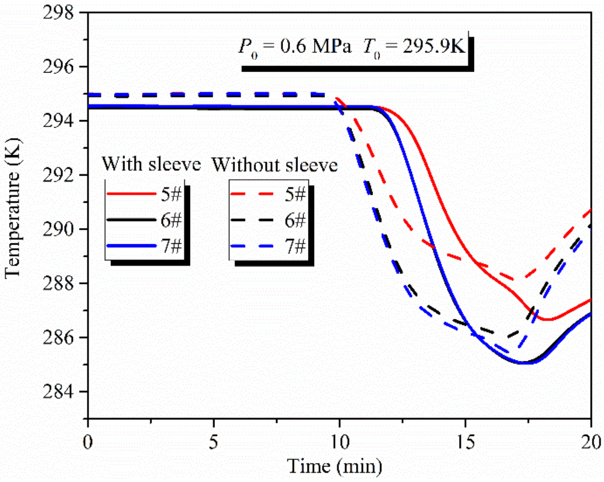
Figure 5 revealed that the cool gas have a longer and greater influence on the wall temperature for the smaller and bigger p_0, respectively. Under the three p_0, the wall temperature reached the lowest behind the throat (such as 6#), which is consistent with our previous research results [12].



(a) p_0 = 0.2 MPa, T_0 = 295.9 K;



(b) p_0 = 0.4 MPa, T_0 = 296.1 K;



(c) p_0 = 0.6 MPa, T_0 = 295.9 K;

Figure 5: The measured temperature for d = 2 mm sonic nozzle under different conditions with the 5#, 6# and 7# points.

And the initial wall temperature of sonic nozzle with insulation sleeve was relatively low, and the temperature drop ΔT was large. Combined with Figure 4 and Figure 5, it can be found that when the ΔT was large, the C_d will decrease. Unfortunately, the sampling time of 30s for measured temperature was a little too long to not conduct quantitative analysis, and the sampling time will be further shortened for measurement later.

5. Conclusion

The complex thermal effect affects the flow field and the C_d of sonic nozzles greatly. In order to understand this phenomenon very well, especially for the body temperature distribution, several important works were accomplished.

1) An adiabatic sonic nozzle with the throat diameter of 2 mm and the temperature distribution measurement systems were established, including insulation sleeve with 15 mm PTFE and 5mm pearl cotton, multichannel data collector, and T type thermocouples.
2) The experimental $C_{d,\mathrm{exp}}$ of this sonic nozzle with or without insulation sleeve at different p_0 from 0.2 to 0.6 MPa were conducted under different times. The calibration results showed that the $C_{d,\mathrm{exp}}$ could be changed up to 1.3% for the same nozzle at different stagnation pressure.
3) The results uncertainty of the $C_{d,\mathrm{exp}}$ (reproducibility) in 2019 and 2022 was about 0.60%. Due to calibration made in the different seasons, the T_0 was different from 288.67 to 296.48 K, resulting in poor reproducibility.
4) And then, the deviation of $C_{d,\mathrm{exp}}$ with and without insulation sleeve in 2019 and 2022 were 0.15% and 0.10% respectively.

5) Under the three p_0, the wall temperature reached the lowest behind the throat (such as 6#). Figure 4 and Figure 5, it can be found that when the ΔT was large, the C_d will decrease.

Unfortunately, the sampling time of 30s for measured temperature was a little too long, which will be further shortened for measurement later in order to qualitatively analyse the influence of wall temperature distribution on C_d of sonic nozzle.

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