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CHARACTERISTICS OF SMALL SONIC NOZZLES

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Abstract

Small sonic nozzles (throat diameter 0.28 4.48 mm) were tested in the gas flow standard system. This standard system is composed of two bell provers and 5 colum piston provers, compressor, filters, and dehumidifier. The discharge coefficients of small sonic nozzles are obtained and correlated as a function of throat Reynolds numbers with 0.33 % uncertainty at a confidence level 95 %. The tested high Reynolds number was the lower limit of ISO 9300 specifications. The data are useful as data base for revision of ISO 9300.

Key Words: Sonic Nozzle, Throat Diameter, Discharge Coefficient

1. INTRODUCTION

The necessity for measuring a very small mass flow-rate increases in various areas such as semiconductor, medicine, chemical industry, and environmental area etc. Sonic nozzles among other flow-meters are getting used more widely to precisely measure and control gas flow-rates especially in the aerospace field and gas industries.

Because the maximum flow-rate of a sonic nozzle is restricted by the inlet pressure range, in order to use sonic nozzles for a wide range of flow-rates, many nozzles of different throat diameters should be used. However, in spite of this demerit, sonic nozzles have the following merit. That is, the mass flow-rate through a sonic nozzle is not affected by its downstream flow disturbance or pressure fluctuation, and thus in order to calculate a flow-rate we need to measure its upstream temperature and pressure only.

In addition to the advantage, because of easy operation, easy movability, high efficiency, high reproducibility, and low uncertainty, sonic nozzles are also getting used more widely. A sonic nozzle is used as a reference flow-meter calibrating many flow-meters such as household gas-meters, area type flow-meters, and so on.

In order to use any sonic nozzle as a reference flow-meter we have to obtain the data for the discharge coefficient which is defined as the ratio of its corresponding real flow-rate to the ideal flow-rate. The flow characteristics of a sonic nozzle can be theoretically anticipated by using the equation of one-dimensional isentropic flow of an ideal gas. According to Hillbrath[1] and ISO 9300[2] a discharge coefficient is a function of Reynolds number.

Studies on the discharge coefficients for the Toroidal throat Venturi nozzle and the cylindrical throat Venturi nozzle were carried out by Grace & Lapple[3] and Kastner et al[4], and they reported that the actual flow-rate approaches the theoretical flow-rate.

Stratford[5] stated that the optimum curvature radius of a sonic nozzle should be twice the throat nozzle diameter, because the variation of discharge coefficients is small, when the boundary layer changes from laminar to turbulent, if the curvature radius is about twice the nozzle throat diameter.
Sparkes[6] reported that the discharge coefficient is 0.995±0.25 % when $Re_d=10^6$ and 0.9965±0.2 % when $Re_d=10^7$, from sonic nozzles manufactured according to the shape suggested by Stratford.

The objective of this investigation is to fulfill insufficient parts of the previous studies on the characteristics of small sonic nozzles and also to obtain useful data necessary to supplement ISO 9300.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 Experimental Apparatus

The measuring system (Fig. 1) for discharge coefficients of sonic nozzles is set up in the Korea Research Institute of Standards and Science (KRISS). We used the standard gas flow-rate measuring system designed for atmospheric pressure level in the KRISS, piston provers and bell provers. The measuring system consists of an air compressor, air storage tanks, air filters, air dryers, pressure regulators, platinum-resistance thermometers, pressure gages, a universal counter and a sonic nozzle package.

As for the air compressor used in this experiment, it has the power of 30 HP (22 KW) with air flow-rate of 3.1 m^3/min, one-stage screw rotary and air cooling type. The humidity and impurities in the compressed air are eliminated through the air dryers of both cooling and suction type. The compressed air with high temperature of about 38ºC and high humidity from the air compressor enters an air dryer of cooling type and is cooled below the dew point 4ºC and the condensed water is discharged outside into the atmosphere.

The drain rate of saturated air of the dryer is 4.25 Nm^3/min, with the maximum tolerable pressure limit of 1.05 MPa, and its cooling style is air-cooling type. The air dryer of suction type removes fine moisture, minute oil particles, and impurities smaller than 5μm in the air. The dried and compressed air with the dew point -60ºC through the air dryer is stored in the air tank of 4m^3 capacity. The allowable maximum pressure limit of the tank is 1 MPa. To stabilize the temperature of the compressed air at the entrance of sonic nozzle, 10 temperature-stabilizing pipes with 100 mm diameter, 6 m length, and 0.0471 m^3 volume, are connected in a row.

To safely control mass flow-rates of the air in the testing pipe of sonic nozzles, one pressure regulator for the 1st pressure control and two pressure regulators for the 2nd pressure control are set up. The sonic nozzle package is shown in Fig. 2 and was manufactured based on the regulation suggested by ISO 9300.

A platinum-resistance thermometer is set up 500 mm upstream the nozzle package to measure the stagnation temperature and the stagnation pressure is measured at a distance of 1 D upstream of the nozzle. Fig. 3 shows the details of the sonic nozzle installed within the testing pipe, manufactured according to ISO 9300. The amount of the air through the testing pipe is measured by the prover.

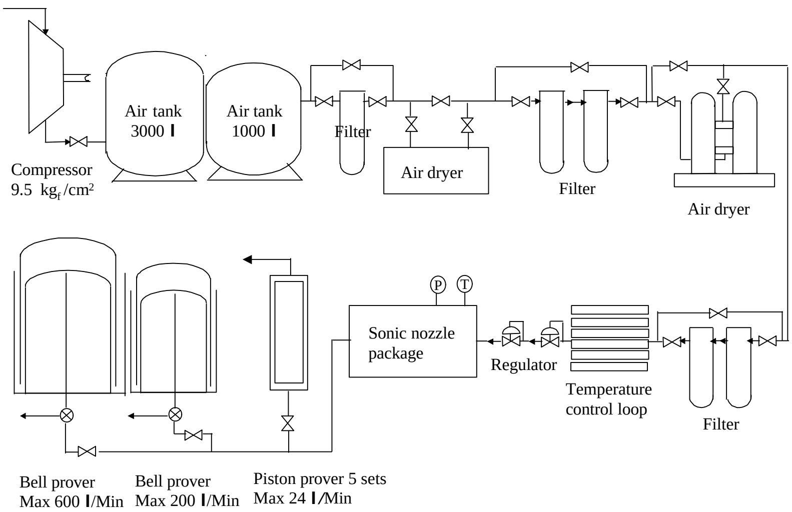
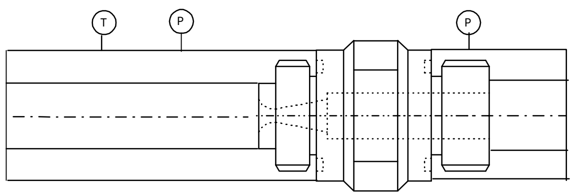


Fig. 1 Schematic diagram of gas flow measurement standard system



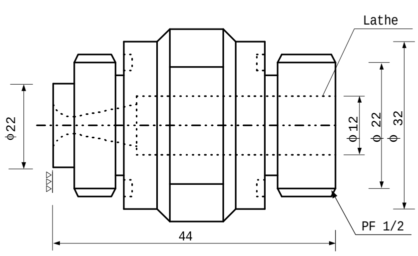


Fig. 2 Sonic nozzle package

Fig. 3 Sonic nozzle shape

2.2 Experimental Method

If the composition of the gas through a sonic nozzle is constant, the most efficient way to change the mass flow-rate is to vary the nozzle throat area and if we combine the nozzles with the area ratio twofold, continuous variation of the flow-rate can be attained.

The 9 kinds of different sonic nozzles (total 43 nozzles) designed by the regulation of ISO 9300 from 0.28 mm to 4.48 mm throat diameter were tested for the calibration and characteristics testing. They were all manufactured in the KRISS and one set of 9 nozzles is in the KRISS, and the rest are in the other companies and they are being used currently as reference flow-meters.

We can carry out experiments for the stagnation pressure ranging from the minimum of 0.2 MPa to the maximum of 0.65 MPa within sonic nozzle package of 100 mm diameter. To confirm the reproducibility, experiments are carried out three times.

The collection time of gas through the nozzle is more than 60 seconds and the amount of gas collection was measured by piston provers for the nozzles with their throat diameters of 0.28 mm to 0.4 mm and by bell provers for the nozzles of 0.56 mm to 4.48 mm.

3. Results and Discussions

Experiments of 9 nozzle throat diameters such as 0.28 mm, 0.4 mm, 0.56 mm, 0.8 mm, 1.12 mm, 1.6 mm, 2.24 mm, 3.2 mm, 4.48 mm were carried out and their discharge coefficients are shown in Fig. 4. The experimental data in Fig. 4 show somewhat different trend from those of ISO 9300 and it's because the nozzle throat diameters are too small to precisely measure them. Only the nozzle of 4.48 mm diameter in Fig. 4 has the same trend as ISO 9300.

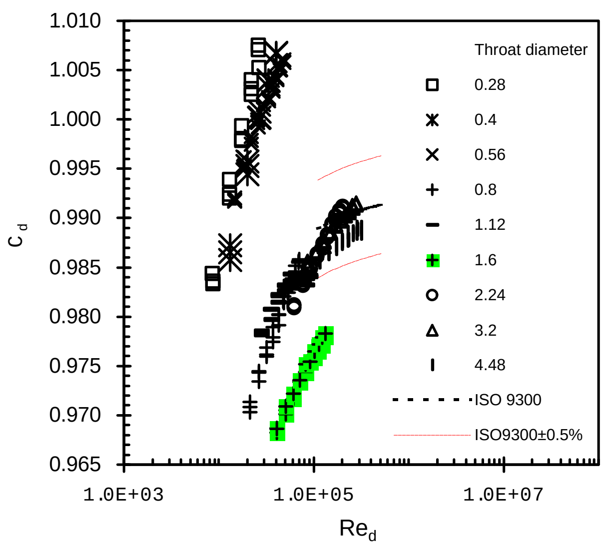


Fig. 4 Discharge coefficients as a function of Reynolds number

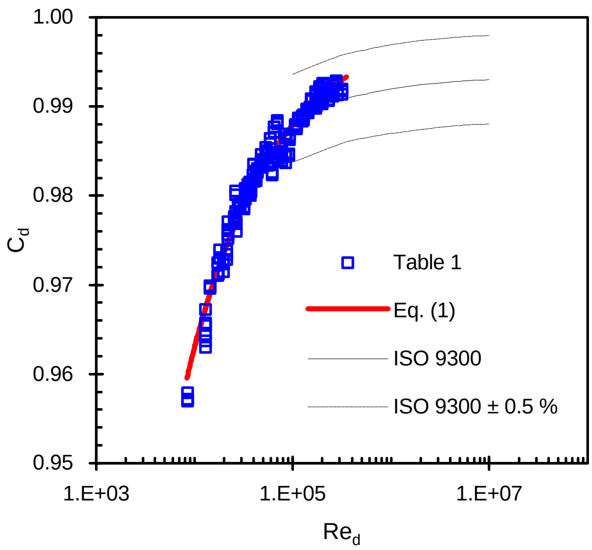


Fig. 5 Discharge coefficients using modified throat diameters(9 nozzles)

Since the discharge coefficient is a function of Reynolds number, the discharge coefficients for both cases at the same Reynolds number must be equal. Therefore, if the throat diameter is properly adjusted, the same discharge coefficient can be obtained for the same Reynolds number and thus we can conjecture this adjusted diameter is the correct one.

In this way, we can get a discharge coefficient as a function of Reynolds number. The discharge coefficient of the nozzle with 4.48 mm diameter is in agreement with the result obtained previously at the KRISS[7] and also with ISO 9300. Therefore, the throat diameter of 3.2 mm is modified so that the change of its discharge coefficient might have the same trend as that of 4.48 mm and likewise the nozzle diameter of 2.24 mm was modified according to the trend of 3.2 mm.

In the same way, the diameter of another nozzle with smaller value is modified by means of the nozzle with next larger diameter and thus all the small nozzles are adjusted for their correct diameters and by means of these newly modified diameters is depicted the discharge coefficient in Fig.5. The nozzle diameters used in Fig. 4 and Fig. 5 are compared in Table 1.

Table 1 Modified sonic nozzle throat diameters

Nominal	Measured (mm) used in Fig. 4	Modified (mm) used in Fig. 5
0.28	0.3372	0.3418
0.40	0.5110	0.5171
0.56	0.5708	0.5773
0.8	0.8441	0.8430
1.12	1.1159	1.1156
1.60	1.6316	1.6215
2.24	2.4102	2.4285
3.20	3.3455	3.3385
4.48	4.4624	4.4559

The discharge coefficient in Fig. 5 is curve-fitted as in the following equation of the first degree of $Re_d^{-0.5}$ within 95% confidence level in according to the theoretically suggested relation.

$$C_d=0.9995-3.6601Re_d^{-0.5}, \quad \text{uncertainty} : \pm 0.316\% \qquad (1)$$

The coefficient of $Re_d^{-0.5}$ in Eq. (1), 3.6601 is greater than the value suggested by ISO 9300, 1.525 and thus the discharge coefficient decreases rapidly as the Re_d is getting smaller.

Because it's difficult to precisely measure the throat diameter of very small sonic nozzles, as for the sonic nozzles which are used in calibration-service organizations, the modified throat diameters by adjusting the discharge coefficients by means of Eq. (1) from their nominal throat diameters which were used when they were manufactured are shown in Table 2 and their discharge coefficients are shown in Fig. 6

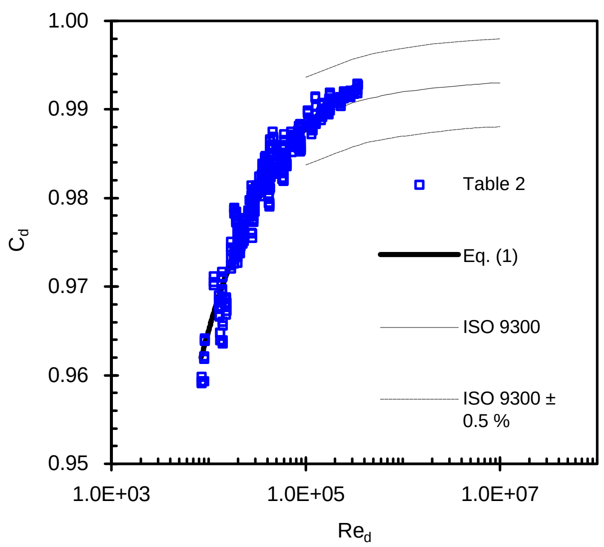


Fig. 6 Discharge coefficients using modified throat diameters(43 nozzles)

Table 2. Modified sonic nozzle throat diameters

Nominal throat diameters (mm)	D*(mm)				Nominal throat diameters (mm)	D*(mm)			
	K.Co.	J.Co.	HI.Co.	E.Co.		K.Co.	J.Co.	HI.Co.	E.Co.
0.28	0.3610	0.3420	0.4495	0.3680	1.60	1.6561	1.6405	1.6251	1.6663
0.40	0.5556	0.5281	0.5181	0.5632	2.24	2.3285	2.2603	2.3170	2.3325
0.56	0.6029	0.5907	0.6082	0.5561	3.20	3.2653	3.3115	3.2565	
0.80	0.7598	0.7902	0.7651	0.7275	4.48	4.4523	4.4630	4.4628	
1.12	1.1165	1.1241	1.1468	1.1080					

The discrepancy between discharge coefficients by using Eq. (1) and modified diameters is ± 0.36 % in the range of 95 % confidence level. Therefore, if we use Eq. (1), we can obtain correct throat diameters for incorrect nominal diameters

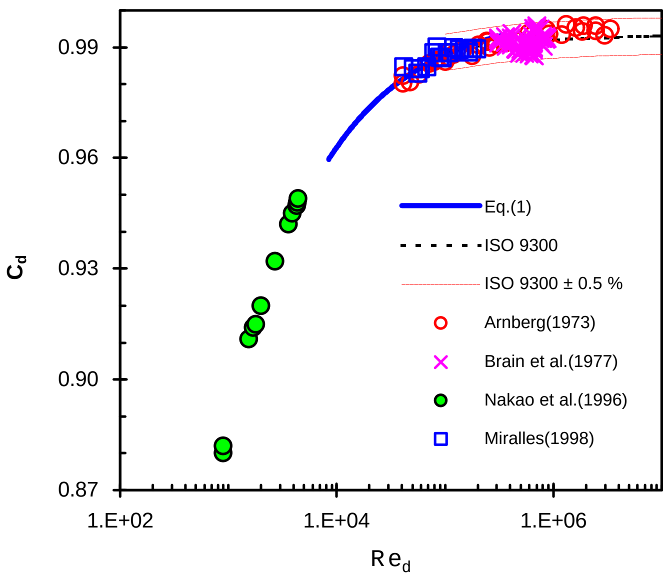


Fig. 7 Companion with published data

Fig. 7 compares Eq (1) with the results of Amberg[8], Brain and Macdonald[9], Nakao, Yokoi and Takamoto[10], and Miralles[11]. Nakao et al. carried out experiments for the range of Reynolds number $9.0\text{x}10^2$ Re_d $4.4\text{x}10^3$ and obtained the data for a range which is out of the range in this investigation. The lower Reynolds number range of Nakao than this investigation which used the same throat diameters is due to the difference of flow generation methods.

This study used blow-down method, that is, the upstream pressure of the nozzle is higher than 0.2 MPa and downstream pressure is atmospheric pressure, while Nakao et al. used suction type method which has 0.1 MPa upstream pressure and downstream vacuum pressure. Therefore, the Reynolds number will be different even for the same size of nozzles.

The nozzle diameters used by Amberg are 17 kinds ranging from 0.15 mm to 1.37 mm. Those data show the same trend of discharge coefficient change within the same Reynolds number range as this investigation and we verified that the gradient of the discharge coefficient change for the larger Reynolds number range than this study is the same for both cases.

Brain and Macdonald carried out an experiment for the range of $3.1\text{x}10^5$ Re_d $8.7\text{x}10^5$ by the experimental system of the error ±0.3 %. For the case of Re_d 10^5, the data are in agreement with ISO 9300 within the error ±0.4 % and they had the data for larger Reynolds number range than this study.

Miralles conducted an experiment with sonic nozzles without their expansion portions, whose diameters are 1.165 mm, 1.5555 mm, 2.080 mm and the results were compared with those of this study in Fig. 7.

Table 3. Comparison with published correlations of C_d

Table 3 shows the comparison of the equations of discharge coefficient used in Fig. 7. Eq (1) is in good agreement with the other results published previously and thus the validity of the prediction for the throat diameters in Eq (1) was confirmed.

If we put the results of this study and those of Nakao et al together, then the trend of discharge coefficients for the lower range of Reynolds number than ISO 9300 can be predicted and we can confirm the generality of the results of this study by comparison with previously published data.

Since the equation for the discharge coefficients suggested by ISO 9300 is only for the range of 10^5 Re_d 10^7, further study has to be proceeded in order to include the lower Reynolds number range than 10^5 or in order to get the international acknowledgement by rearranging equations of discharge coefficients for each different range of Reynolds numbers.

4. CONCLUSION

Some characteristics of 43 sonic nozzles which have 9 kinds varying from 0.28 mm to 4.48 mm and which were manufactured in accordance with ISO 9300 were studied by using the standard gas flow-meter system designed for atmospheric pressure level, which is set up in the KRISS.

The discharge coefficients of small sonic nozzles are in agreement within ±0.37 % at the Reynolds number around which is in the range of ISO 9300 and were correlated as a function of throat Reynolds number, as was suggested by ISO 9300. The correlation data by this investigation show the same trend as the results published previously and thus this confirms the generality of this investigation data. We suggested the trend of discharge coefficients out of the ISO 9300 Reynolds number range, that is 10^3~10^5.

The data from this study are expected to be used as some data base for the revision or supplement of ISO 9300.

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Laboratory	Nozzle Throat (mm)	C_d	Re_d	Deviation from ISO 9300 (Re_d 10^5)
Fig. 5	Table 1	$0.9985-3.3436\ Re_d^{-0.5}$	$8.5x10^3$ Re_d $3.1x10^5$	±0.37 %
Arnberg	0.15-1.37	$0.99738-3.3058\ Re_d^{-0.5}$	$4.1x10^4$ Re_d 3.4x106	±0.5 %
Brain et al.	1.26-3.82	$0.99692-6.2453\ Re_d^{-0.5}$	$3.1x10^5$ Re_d $8.7x10^5$	±0.4 %
Nakao et al.	0.5, 0.3	$1.007-3.195\ Re_{th}^{-0.5}$ $1.006-3.783\ Re_{th}^{-0.5}$	$9.0x10^2$ Re_d $4.4x10^3$	-
Miralles	1.165 1.555 2.080	$0.996473-2.673217\ Re_d^{-0.5}$	$4.0x10^4$ Re_d $2.0x10^5$	±0.3 %

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