Sizing Effects on Silicon Micro Sonic Nozzles

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Abstract

Four types of silicon sonic nozzles are examined with different sizes to unveil their macro properties as a metering device. The throat dimensions are 38 to 140 µm for nozzles of types A and D and 75 to 184 µm for nozzles of types B and C. According to the experimental results, it is found that the discharge coefficient is proportional to the throat dimension for the four types of nozzles. With a perfectly etched geometry, the critical back pressure ratio for type B or C can reach the level of 0.4. With a micro thermal sensor attached on the surface at the nozzle exit of type A, the temperature measured shows that the silicon nozzle reaches thermal equilibrium with sonic flow in about a minute.

Key words

Silicon Sonic Nozzle, Micro Sonic Nozzle, Sizing Effect, Micro Thermal Sensor

1. Introduction

In the regime of gaseous flow calibrations, sonic nozzles are frequently employed as standard meters. For Reynolds number greater than 2.1×10^4, the measurement using sonic nozzles can follow the standard ISO 9300 [1]. On the other hand, the usage of small sonic nozzles, for which throat diameters are less than 200 µm or Reynolds number below 2.1×10^4, has been found more and more in laboratorial or industrial applications [2-5]. However, due to the difficulty of machining, the flow passages of small sonic nozzles are hardly conformed to toroidal or cylindrical Venturi nozzle specified in ISO 9300 [1,3]. Hence, small sonic nozzles are usually of non-ISO type. For example, Bignell [3] examined a shrinking glass tube, a water-cutting head, and a nozzle with rectangular throat. Nakao and Takamoto [6] tested a quadrant nozzle, i.e., an ISO-typed nozzle but without its divergent part. Their results indicated that the non-ISO-typed nozzles are able to serve as standard meters [3,6].

In addition to conventional machining, MEMS technique has been applied to fabricate small sonic nozzles. Mammana et al. [7] used an electrochemical etching process to form a diamond nozzle with a throat diameter of 217 µm. Preliminary test of the diamond nozzle implied the possibility of practical application. MEMS technique has also been found in the fabrication of micro thrusters for micro satellites [8-9].

In the previous study of the present authors [10], the technique of KOH anisotropic etching technique was applied to fabricate four types of silicon sonic nozzles with square cross sections, as shown in Figs. 1 and 2. The dimensions of the nozzle throats were in the order of 90 µm by 90 µm. Reynolds numbers examined ranged from 6×10^2 to 8×10^3. With a specially designed clamping holder, the silicon nozzle was able to withstand an operation pressure of 1380 kPa at least. For nozzle types of B and C, the critical pressure ratio for choking was about 0.36 and 0.32, respectively, while those for types A and B are around 0.2. Before reaching thermal equilibrium with sonic flow, the maximum deviation of the discharging coefficient was less than 0.05%. The silicon nozzle also bears a very good long-term stability.

In this study, the silicon nozzles are further made in different sizes. Referring to Table 1, the throat dimensions range from 38 to 140 µm for nozzles of types A and D, and 75 to 184 µm for nozzles of types B and C. The sizing effects on the silicon nozzles are studied experimentally.

Table 1 Throat dimensions of the silicon nozzles

<table>
<thead>
<tr>
<th>Unit: µm</th>
<th>Type A &amp; D</th>
<th>Type B &amp; C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>94</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
<td>135</td>
</tr>
<tr>
<td>4</td>
<td>188</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 Types of nozzle configurations examined.

2. Fabrication of Silicon Sonic Nozzles

In this study, KOH anisotropic etching technique is applied to fabricate silicon sonic nozzles. With the square openings on Si3N4 deposited on a <100> silicon wafer, the KOH etchant would recess along the <111> crystalline planes of the wafer [12]. Instead of having a circular cross section normal to the flow direction, the achieved silicon nozzle bears a square cross section, as shown in Fig. 2, similar to a pyramidal orifice. The slopes of the side walls with respect to the wafer surface are 54.7°, i.e., a 35.3° half angle for the nozzle. The thickness of the silicon wafer is 505 µm, denoted by l. For installation concern, the nozzle chip was cut from the silicon wafer in a dimension of 6 mm by 6 mm.

The sizes of the nozzle throats examined in this study are listed in Table 1. For types A and D, the nozzle throats...
are 38, 90, and 140 µm. On the other hand, the throat dimensions for types B and C are 75, 94, 135, and 188 µm. During experiments, the nozzle chip of type D is just an inverse installation of the type A with respect to the flow direction. Likewise, the nozzle chip of type C is an inverse of type B. The length of the convergent section is about 2 times of the divergent section for type B.

In addition, by using surface micro machining, a micro thermal sensor is integrated with the nozzle of type A. As seen in Fig. 3, platinum, Pt, is deposited surrounding the nozzle exit. This Pt sensor has a line width of 20 µm, and a thickness of 0.1 µm. Hence, the temperature at the nozzle exit can be measured. Calibration of the sensor resistance with respect to the temperature was carried out beforehand. The temperature coefficient of resistance is $1.4 \times 10^{-3}(1/\degree C)$.

In this study, experiments are focused in the lower range of Reynolds numbers, i.e., below $8 \times 10^3$. For most cases, the upstream pressure, $P_{in}$, of the nozzle is not greater than 300 kPa.

4. Experimental Results

Discharge coefficient of a sonic nozzle represents the ratio of real mass flow rate to ideal mass flow allowed to pass through the nozzle. There are several factors that can block the real mass flow rate. The most apparent one is the existence of viscous boundary layer that reduces the effective throat area. Also, due to strong heat exchange with the nozzle body, thermal boundary layer in sonic flow makes the flow density lower than its isentropic state; subsequently, a lessened mass flow rate. The throat area would also contract in this cooling process. The discharge coefficient, $C_d$, can be expressed as follows [1].

$$ C_d = \frac{q_m}{q_{mi}} \quad (1) $$

where $q_m$ denotes the real mass flow rate measured during experiments, and $q_{mi}$ is the ideal mass flow deduced from isentropic relations. For toroidal or cylindrical sonic nozzle specified in ISO 9300, $C_d$ is expressed as a linear function of Re, where Re represents the real Reynolds number, based on $q_m$ and the dimension of the nozzle throat, $d$. For toroidal type, $C_d$ is formulated as $\left( a_1 - b_1 \cdot \text{Re}^{-0.5} \right)$, and $\left( a_2 - b_2 \cdot \text{Re}^{-0.2} \right)$ for cylindrical type, where $a_1, b_1, a_2, b_2$ are constants. Hence, for ISO-typed nozzles, the $C_d$ value gets lower as Re becomes smaller, which is a phenomenon mostly due to viscous boundary layer.

Figure 5 gives the results of discharge coefficient for type A and D nozzles. The upstream pressures for each nozzle are in the range between 60 to 300 kPa. Nozzle under higher upstream pressure will exhaust more mass flux, leading to a larger Reynolds number. For convenience, each of the nozzle chip listed in Table 1 is coded with a number. As an example, the throat dimension of 38 µm for type A is labeled as A_1, 90 µm as A_2 and so on.

Firstly, the results corresponding to type A are discussed, referring to the hollow symbols in Fig. 5. As seen, the $C_d$ values for the three cases of type A don’t collapse into a single curve, and the smaller the nozzle size the lower the $C_d$ curve. For example, the $C_d$ values for A1, shown by the rhombic symbols, are about 0.814, while downstream of the nozzle to provide a controllable back pressure.
0.851 and 0.877 for A_2 and A_3, respectively. It is noted that nozzle A_1, A_2, and A_3 don’t satisfy the condition of geometry similarity, though the nozzles all have a 35.3° half angle. As mentioned, the wafer thickness, l, are fixed to 505 µm. The ratios of l/d for A_1, A_2, and A_3 are about 13.3, 5.6, and 3.6, respectively. Therefore, it is speculated that in the case of A_1 the flow travels a relatively longer distance in the nozzle as compared with the others. Consequently, the viscous boundary layer in A_1 occupies a relatively larger portion of the throat area and results in lower Cd values.

Fig. 5 Cd versus Re for types A and D.

On the other hand, it is also observed that the Cd curves for the three cases are gradually bended up in the lower Re regime as l/d gets smaller. For A_1 and A_2 the Cd distributions are similar to those of traditional sonic nozzles. That is to say, the Cd value is smaller for lower Re. However, the Cd value evolves in a different way for A_3; the Cd value gets a little higher as Re decreases. Specifically, the Cd value at the highest Re is about 0.8763, yet its value at the lowest Re is 0.23% higher in this case. The reason is speculated as follows. As l/d gets smaller and smaller, the flow would be difficult to accelerate to sonic condition inside the convergent section of the nozzle. Instead, the flow passing over the throat will continue to accelerate to reach a minimum area of potential flow, usually called the plan of vena contracta, which is smaller than the actual size of the throat. The situation becomes similar to the flow of an orifice plate. Due to inertia of airflow, the plan of vena contracta gets larger as Re gets smaller, an inverse tendency to viscous boundary layer effect.

As a counterpart, the solid symbols in Fig. 5 present the results of type D nozzles. Unlike type A nozzle, type D nozzle does not provide a convergent passage for airflow. As seen, the Cd distributions for these three cases are much more like that of an orifice plate. That is to say, the Cd value increases as Re gets lower. The results imply that type D nozzle behaves like the flow through an orifice plate operated with sonic condition. Hence, the Cd distributions can be directly related to vena contracta phenomenon, as mentioned above. On the other hand, since types A and D are actually the same nozzle chip, a comparison of the results suggests that the effective throat area of type A is about 10% larger than type D for the corresponding cases.

The results for types B and C are depicted in Fig. 6. These two types of nozzles bear convergent and divergent parts for the flow. The hollow symbols represent the cases for type B and solid symbols for type C. It is observed that the Cd values for type C are slightly larger than those of type B. Whether it implies a thinner viscous boundary layer in the throat region needs further investigation. For B_1 and B_2, the experimental data have good linearity to Re -0.7 with an acceptable error less than ±0.1%; on the other hand, it is Re -1 for B_3 and B_4. For type C, the fitting curves for all of the four cases examined can match well with Re -0.7.

Fig. 6 Cd versus Re for types B and C.

Fig. 7 Deviations of Cd versus pressure ratio for types A.

As known, the mass flow rate through a sonic nozzle is not influenced by the downstream conditions as long as the nozzle is at choking condition. The ratio of downstream pressure to upstream pressure of the nozzle is employed as a choking parameter. In this study, the critical back pressure ratio, denoted as CBPR, is defined as the pressure ratio when discharge coefficient becomes 0.1% below its initial value at choking condition [6]. As an example, Fig. 7 gives the deviations of the discharge coefficient for type A. Here, P_b denotes the downstream pressure of the nozzle, and P_u is the upstream pressure. For each of the nozzle chips, P_u is operated at 100 and 300 kPa, respectively, while P_b is adjusted from low to high. By the line marking the threshold of -0.1%, the CBPR for
each case is identified. Figure 8 gives a collection of CBPRs with respect to Re. As seen, the CBPRs for types A and D fall in the region between 0.1 and 0.2. Also, the CBPR for type D, as shown by the solid symbols, deteriorates slightly as Re increases, while type A, the hollow symbols, shows an inverse tendency. For reference, the CBPR values for the quadrant nozzles in the study of Nakao and Takamato [6] were 0.24 to 0.4.

Figure 9 shows the CBPR results for types B and C. As seen, the values seem to be insensitive to Re, and for most cases the values are between 0.33 and 0.36. Apparently, the CBPR values for types B and C are superior to those of types A and D, evidencing a common situation that a convergent-divergent nozzle could choke at a greater back pressure than a convergent or a divergent nozzle [15]. Interestingly, it is noticed that the CBPRs for B_1 and C_1 are especially higher than the others, which are about 0.39 to 0.41 at the Reynolds numbers examined. The reason for this is due to a fabrication problem. For type B or C, the silicon wafer is etched from both upper and lower surfaces simultaneously. The total time of etching has to be estimated very carefully. If the etching time is too short, the etching wouldn’t be completed, and conversely would over-etching occur. Figure 10a shows an example of over-etching. Unfortunately, this is the one corresponding to the cases of the lower CBPRs in Fig. 9, except B_1 and C_1. Undercut can be observed in the throat, which makes the throat become irregular and rough. As a counterpart, Fig. 10b shows the case of B_1 or C_1, which is just perfectly etched. Hence, one can say if the perfect etch can be obtained, the CBPRs for the other cases shown in Fig. 9 can be improved for about 15%.

To clarify the transient behavior of silicon nozzles due to internal energy transferring to kinetic energy [3,12,15], a micro thermal sensor is integrated to type A nozzle by using surface micro machining to measure nozzle temperature, see Fig. 3. During experiment, the surface temperature at the nozzle exit is measured by monitoring the resistance of the sensor element. The throat dimension for this case is 141 µm. Before starting the test, the standard meter is warmed up through a bypass circuit to prevent any unpredicted drift. Once the flow is switched to the nozzle system, the temperature of the Pt sensor is recorded.

Figure 11a shows the temperatures recorded in a time length of 120 seconds. The Reynolds number is $6.2 \times 10^3$. The temperature upstream of the nozzle is shown by rhombic symbols and the surface temperature of the nozzle exit is shown by triangular symbols. As seen, both of the temperatures are initially at 22.43°C, and then increase rapidly while the flow starts. Later, they fall down gradually. After about 50 seconds, the upstream temperature returns to the initial room temperature. However, the nozzle temperature takes longer to reach equilibrium. In order to clarify the response of nozzle temperature, the difference between the nozzle and upstream temperatures, $\Delta T$, is given in Fig. 11b. It is
observed that the nozzle temperature is a little higher than the upstream temperature at the beginning stage and then it is cooled down quickly by sonic flow within the first 5 seconds. Finally, it reaches an equilibrium state with the flow at the time of 70 second, which is 20 seconds behind and 0.68°C below the upstream temperature.

Correspondingly, the deviation of the Cd value is given in Fig. 11c. The deviation is referred to the Cd value taken at the time instant of 120 second. The Cd data in the first 5 seconds are neglected due to drastic pressure change. As seen, the deviation decreases very fast to a negligible level, saying 0.05%, in a time length less than 20 seconds. For reference, the glass nozzle of Bignell [3] required about 1 hour. This result indicates that the silicon nozzle reaches its thermal equilibrium much faster than traditional nozzles. The reasons are that the thermal inertia of the nozzle chip is tiny and also the chip is isolated from the nozzle holder; hence, heat exchange between sonic flow and nozzle body is quite less.

5. Concluding Remarks
In this study, macro properties of silicon sonic nozzles with different sizes and four types of configurations are examined. According to the results, it is found that regardless of the nozzle types, the larger the nozzle size is, the higher the discharge coefficient will be. Due to the special geometry of the present nozzles, not only viscous boundary layer but also vena contracta phenomenon can influence the discharge coefficient.

Experimental results also show that types B and C have higher critical back pressure ratios, CBPR, than types A and B, implying that silicon nozzles with a convergent-divergent geometry would give better performance. Furthermore, if type B or C is made with perfect etch, the CBPR can be in the level of 0.4, which is comparable and even better than traditional small sonic nozzle in the same size.

With a micro thermal sensor made around the exit of type A nozzle, the temperature variation of the nozzle is measured, showing that the silicon nozzle responses to the sonic flow very quickly, saying in a few seconds. Also, in a time length less than 20 seconds, the deviation of Cd can decrease to a negligible level, saying 0.05%.

In the near future, the flow physics in the silicon nozzles will be carried out numerically.

Acknowledgements
The authors would like to acknowledge the funding support of National Science Council, Taiwan, on this work, under the contract number of NSC96-2221-E-244-002-.

References