DESIGN AND EXPERIMENTAL CONSIDERATION FOR GASDYNAMICS OF MEMS BASED MICRO SUPersonic NOZZLE

Tomoaki Fujii, Shuichi Furuya, Hideaki Tsukahara, Hiroshi Kawabata, Naoki Takaano and Toshiyuki Toriyama
Department of Micro System Technology, Ritsumeikan University, Japan

Abstract: This paper describes design and experiment for an internal flow in a micro supersonic nozzle. The micro supersonic nozzle has a throat with a 100μm-thick and a 300μm-depth, and a converging-diverging channel with a 138μm-length. The maximum design discharge isentropic Mach number is 1.37. The design expansion ratio is 3:1. The design mass flow rate is 0.024g/s. Isentropic flow Mach number distribution along the converging-diverging channel was directly measured by static wall pressure distribution via micro-fabricated wall surface vents. The flow Mach number distributions, which are predicted from a method of characteristics for an inviscid core flow with a boundary layer correction and CFD analysis, were compared with experimental data to demonstrate the validity of a first approximate design on a basis of the method of characteristics.

Key Words: micro supersonic nozzle, converging-diverging channel, flow Mach number, MEMS

1. INTRODUCTION

The concept of MEMS-based supersonic micro-nozzle was first proposed by Breuer [1]. Breuer investigated aerodynamic performance of hot and cold supersonic micro-nozzles. Thrust and specific impulse, which are required for micro-spacecraft application, were experimentally measured and compared with theoretical prediction. Since then, various researches concerning to the micro-scale nozzles have been investigated inspired by Breuer’s concept [2,3]. Previous studies, however, have not clarified internal flow field along the nozzle section, i.e., flow Mach number and static pressure distributions.

This paper tries to measure isentropic flow Mach number distribution along a converging-diverging channel of a micro supersonic nozzle. The isentropic flow Mach number distribution can be evaluated from a direct measurement of static wall pressure distribution via wall surface vents. The nozzle structure and the vents were fabricated on a basis of MEMS process. The proposed experimental configuration has possibility for direct measurement of a various branch of micro-scale expansion flow phenomena such as a static pressure recovery subsequent to shock formation.

2. DESIGN CONSIDERATION

The method of characteristics with weak expansion is applied to a design of a micro supersonic nozzle [4,5]. Internal flow is expanded from M = 1 at a throat to M = 1.37 in an exhaust section. We have chosen the Prandtl-Meyer function as v=8, which corresponds to M=1.37. The Prandtl-Meyer function v(M) is given by,

\[ v(M) = \frac{\gamma+1}{\gamma-1} \tan^{-1} \left( \frac{\gamma-1}{\gamma+1} \left( M^2 - 1 \right) - \tan^{-1} \sqrt{M^2 - 1} \right), \]  

(1)

where \(\gamma\) is ratio of the specific heats.

The brief design procedure is as follows [4].

(1) The throat dimension

The throat with a 100μm-width and a 300μm-depth are selected for a preliminary design.

(2) The initial expansion

The section of the initial expansion is divided into segments with 1 degree deflection angles at the corners. The maximum value of the wall deflection is \(\theta_{\text{max}} = 4\) degree.

(3) The wave reflection

We choose the symmetrical nozzle with respect to the centerline. Thus, the waves are reflected from the centerline.

(4) The region of cancellation

In this region, the reflected waves are cancelled by deflecting the wall 1 degree. The value of the
initial expansion (the maximum wall deflection) is given by \( \theta_{\text{max}} = (1/2)v \).

(5) The final section
The section height agrees with the value \( A^*/A_T = 0.91 \) which corresponds to \( v = 8 \) and the mass flow rate \( \dot{m} = 0.024 \text{g/s} \). \( A^* \) and \( A_T \) are areas of the throat and exhaust section, respectively.

The method of characteristics treats the inviscid core flow. Therefore, effect of the viscous dissipation such as observed in the boundary layer does not take into account. We adopt the boundary layer correction to evaluate the effective exhaust nozzle area. The typical Reynolds number of the core flow is estimated to be \( \text{Re} \approx 2000 \). A two-dimensional laminar flow on a flat plate is assumed to calculate a thickness of a boundary layer. This is given by [4],

\[
\delta(x) = \int_0^l \left( 1 - \frac{\bar{u}(x_1, x_2)}{U} \right) dx^2,
\]

where \( x_i \) is a distance from an origin, \( U \) is a core flow velocity, and \( \bar{u}(x_1, x_2) \) is a two-dimensional flow velocity distribution within a boundary layer.

The shape of the nozzle obtained from the method of characteristics is corrected applying the thickness of the boundary layer calculated using eqn. 2. Afterward, aerodynamic performance for the corrected shape of the nozzle is analyzed using CFD (CFX-5.7.1). The turbulence model is the shear stress transport model. The boundary conditions specified for the wall flow is no slip and the heat transfer is adiabatic.

Fig. 1 shows comparison of Mach number distributions predicted from the method of characteristics and CFD analysis. The Mach number obtained from the method of characteristics is inserted in the figure with the Mach lines and that from CFD analysis is shown in the gradation of numerical contour. Difference of the thickness of the boundary layers obtained from eqn. 2 and CFD analysis falls within a few %.

3. FABRICATION

Figure 2 shows cross-sectional and schematic views of the nozzle, respectively. The nozzle structure is composed of three layers. The top layer is a Pyrex glass and middle and bottom layers are silicon. The upper side of the middle silicon layer has the micro converging–diverging channel with wall surface vents. The under side of the middle silicon layer has the static pressure monitoring channels directly connected to the wall surface vents on the opposite side. The bottom silicon layer has through ports to connect the wall surface vents with external pressure sensors. These layers with the exception of the Pyrex glass layer are fabricated using a similar process.

![Fig. 1: Comparison of Mach number obtained from method of characteristics and CFD analysis.](image1)

![Fig. 2: Cross-sectional (a) and schematic (b) views of the micro supersonic nozzle.](image2)
Fig. 3 shows a schematic of the microfabrication process of the micro supersonic nozzle. A silicon wafer with a 500μm-thick layer is selected as a starting substrate. Both side of the silicon wafer are patterned by ultraviolet (UV) lithography and etched to fabricate the channels by inductively coupled plasma-reactive ion etching (ICP-RIE) (Fig.3(a and b)). Fig. 4 shows SEM micro-image of the wall surface vents along the micro converging-diverging channel. These vents are fabricated by FIB (focused ion beam) milling (Fig.3(c)). The diameter and depth of these vents are approximately 5μm and 30μm, respectively. Each silicon layer is aligned and bonded together by Au-Si eutectic bonding. Finally, the Pyrex glass layer and the multilayer supersonic nozzle are aligned and bonded together by anodic bonding. Fig. 5 shows external view of the fabricated nozzle.

4. EXPERIMENT

To demonstrate the validity of the aerodynamic design method of the micro supersonic nozzle, the static wall pressure distribution along the converging-diverging channel is measured. Fig.6 shows a photograph of the experimental instrument. The air is supplied from the external gas-line to the micro supersonic nozzle via a mechanical interface. The micro supersonic nozzle is mechanically mounted into the interface as shown in Fig.6. The interface connects the small-scale nozzle to the large-scale external system, which includes the pressure sensor, air supply and discharge lines. The interface has several through ports with mechanical seals. One of the ports is connected to the external gas-lines in order to supply the air to the micro supersonic nozzle, and another is connected to the exhaust port of the nozzle. The remaining ports are directly connected to the pressure sensors, which are used for measuring the static pressure distribution along the converging-diverging channel. The stagnation pressure of the air, which is supplied to the nozzle, is set to be 200kPa (gauge pressure), and the exhaust port of the nozzle is open to the atmosphere (101.3kPa).
5. RESULTS AND DISCUSSION

Figure 7 shows the static pressure distribution obtained by the experiment. Fig. 8 shows a comparison of experimentally obtained isentropic Mach number $M_{is}$ with two kinds of theoretical predictions, i.e., the method of characteristics (Prandtl-Meyer function) with the boundary layer correction and the CFD analysis. $M_{is}$ can be deduced from the inlet stagnation pressure and the wall static pressure using the isentropic relation. As shown in this figure, theoretical value of the flow Mach number obtained from the method of characteristics is overestimated against the experimental result. It is mainly due to the inviscid flow assumption that the kinetic dissipation of the viscous flow does not take into account. On the contrary, CFD gives better interpretation that the stagnation pressure loss due to the kinetic dissipation of the viscous flow along the channel reduces the flow velocity.

The difference between the theoretical value obtained from the method of characteristics and the experimental value falls within 20%. In the case of CFD, the difference falls within 10%. The true flow Mach number may be slightly smaller than the experimental $M_{is}$ because of the kinetic dissipation. This evidence slightly increases a discrepancy between prediction and experimental results. However, these agreements can be estimated as an acceptable level from the viewpoint of engineering design.

The experimental results suggest that the method of characteristics is valid for the supersonic internal-flow calculation even if we reduce the flow scale from the macroscopic to the microscopic order. Therefore, the method of characteristics with the boundary layer correction is a good candidate for preliminary design choice before we perform CFD design.

Fig. 8: Comparison of isentropic Mach number obtained from experiment and predictions.

REFERENCES