Development of Large-entrainment-ratio Micro Ejector for Catalytic Combustor

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Abstract

We have developed a large-entrainment-ratio micro ejector to supply fuel-air mixture for a catalytic combustor. As the key component of the ejector, an axisymmetric convergent-divergent nozzle having a throat diameter of 42 μm is fabricateed by electro-discharge machining. Operating conditions and geometric parameters of the ejector are systematically changed, and their effects on volume flow rate ratio are investigated in the experiment. The experimental data are compared with analytic solutions and numerical results. It is shown in experimental evaluations that the present micro ejector has achieved a maximum air-to-butane volume flow rate ratio of 43 when the back pressure of ejector is set as 11.6 Pa.

Keywords: Micro Catalytic Combustor, Axisymmetric Convergent-divergent Nozzle, Supersonic, Ejector, Back pressure

1 INTRODUCTION

In order to produce portable power generating devices from hydrocarbon fuels, various concepts such as MEMS gas turbine, micro rotary IC engine, micro fuel cell, and micro thermoelectric generator have been proposed. Since most of these systems take the approach of converting thermal energy to electric energy, micro combustors and consequent fuel and air feeding devices are the key components in micro power generation.

Figure 1 shows the configuration of the present micro heat generation system. A micro nozzle is plugged into the inlet tube of a catalytic combustor to form an ejector. This ejector pumps ambient air to the combustion chamber by utilizing the vapor pressure of liquified fuel. Catalytic combustion of the fuel then takes place, and heat generated is used in various micro power devices such as reformer and thermoelectric generator attached to the combustor. Suzuki et al. [1] developed a micro ceramic combustor with Pt/Al_2O_3 catalyst using high-precision tape casting technology. This combustor employs butane as the fuel because it has both high energy density (13300 Wh/kg) and favorable storage properties due to its moderate vapor pressure at room temperature (0.24 MPa).

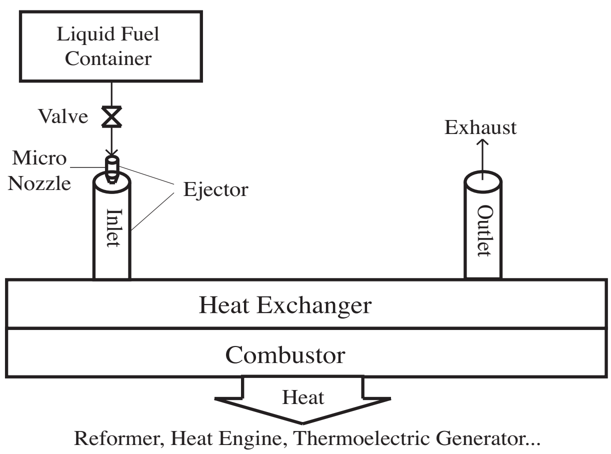

Figure 1. Configuration of micro heat generation system.

Ejector, also known as jet pump, is a pumping device that exchanges velocity and pressure between high velocity primary flow and low velocity secondary flow to produce a mixed flow with intermediate velocity. The increase of the secondary flow velocity results in the emergence of a low pressure area downstream the inlet of secondary flow, and ambient fluid is continuously introduced into the ejector by the positive pressure gredient. The requirement of designing an ejector for a butane combustor is to achieve an air-to-butane volume flow rate ratio of 31 for the stoichiometry condition for butane combustion. The advantage of using ejector is that air-entrainment is achieved without additional air container or micro pump, and thus the system should be simple, safe, and reliable.

2 MICRO EJECTOR

2.1 Supersonic Primary Flow

In order to have large entrainment ratio, the ejector should be designed in such a way that the flow velocity of the primary flow becomes very large. In the present study, an axisymmetric convergent-divergent nozzle having a small throat diameter is used to produce a supersonic primary flow.

Figures 2 and 3 show the schematic and SEM images of the micro nozzle. The throat diameter of the nozzle is designed to be 42 μm and fabricated by electro-discharge machining of stainless steel. The exit diameter of the nozzle is designed to be 60 μm, so that the supersonic nozzle has a moderate expansion angle of 18°. While it is commonly known that a large expansion angle will lead to serious flow seperation, a small expansion angle also has a problem of degraded expansion due to a thick boundary layer. The Knudsen number at the throat is around 0.002, so that the rarefied gas effect can be neglected.

If compared with MEMS ejectors having a flat chamber [2, 3], the ejector with the present nozzle has a truly 3-D shape, which can be made without complicated fabrication process. In addition, by utilizing an axisymmetric structure, the present design minimizes the viscous loss at the wall. However, the wall surface of the present prototype nozzle is somewhat rough, and the cross-sectional shape is not a perfect circle. This is partially because electro-discharge machining from the both inlet and outlet sides is needed.

Figures 4 and 5 respectively show the experimental results of the primary volume flow rate with increasing gauge total pressure for butane and air as the primary flow source. It is shown in quasi 1-D analysis that the primary flow can reach a supersonic state when the total pressure is larger than 0.071 MPa for butane, and 0.090 MPa for air. At low total pressure, the experimental data are somewhat lower than the results of the quasi 1-D calculation probably due to the viscous effect. However, both experimental data asymtotically approach the calculation results, when the effective throat diameter is estamated to be 43.15 μm. The throat Reynold number in the present experimental condition for supersonic flow is around 3600.

2.2 Large-entrainment-ratio Micro Ejector

The experimental setup for ejector is shown in Fig. 6. Firstly, experiment has been conducted when butane is supplied from a gas cylinder as the primary flow source.

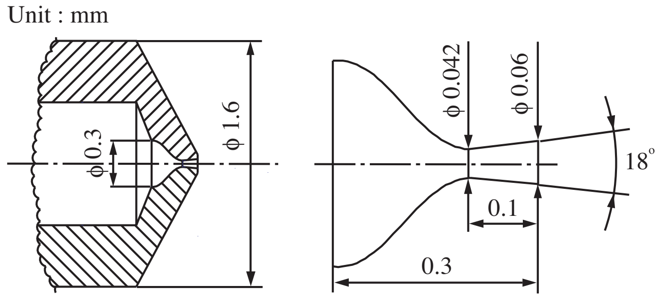

Figure 2. Schematic drawing of the micro nozzle.

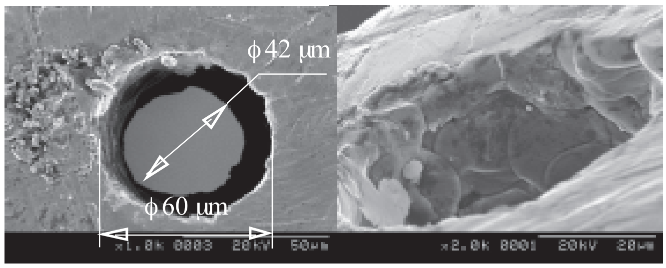

Figure 3. SEM images of the nozzle tip; a top view (left) and a magnified view (right).

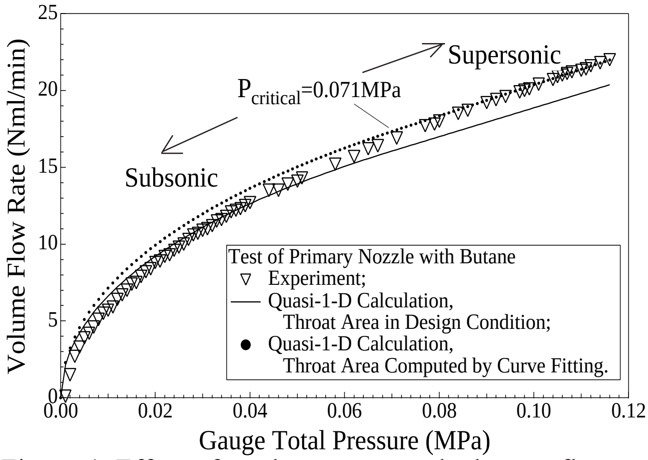

Figure 4. Effect of total pressure on the butane flow rate produced by the micro nozzle.

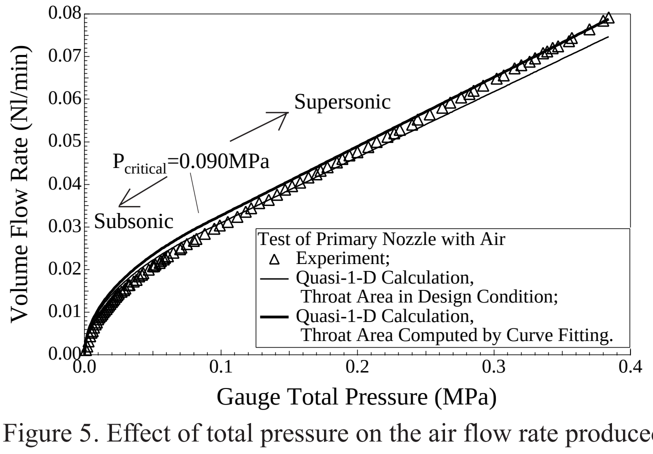

Figure 5. Effect of total pressure on the air flow rate produced by the micro nozzle.

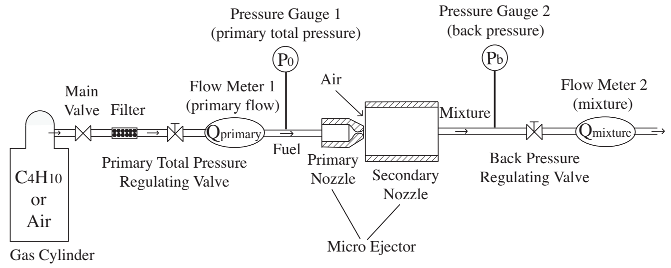

Figure 6. Experiment setup for micro ejector.

Table 1. Area ratio of micro ejectors. Unit: mm

Exit diameter of primary nozzle	0.060						
Inner diameter of secondary nozzle	1.00	1.10	1.70	2.00	2.45	3.18	4.20
Area ratio	277	335	802	1110	1666	3116	4899

Ambient air is sucked in from the inlet of the secondary nozzle. The primary total pressure and back pressure are measured by two pressure gauges. The primary flow rate and the flow rate of air-butane mixture are respectively measured by a thermal mass flowmeter and a soup film flowmeter having a low pressure drop. The area ratio is defined as the ratio of the cross-sectional area of the secondary nozzle to the exit area of the primary nozzle, and is changed by using straight circular tubes with different inner diameters (Table 1). The primary total pressure and back pressure are regulated by two valves.

Figures 7 and 8 show the effect of back pressure on the volume flow rate ratio, defined as the ratio of the secondary flow rate to the primary flow rate. The flow rate ratio reaches a maximum of 43 at a back pressure of 11.6 Pa, but the ratio repidly decreases with increasing back pressure. The ejector with a small area ratio produces a higher volume flow rate ratio for larger back pressure as shown in Fig. 7, but it produces a lower volume flow rate ratio for small back pressure. On the other hand, the ejector with a large area ratio produces a higher volume flow rate ratio for smaller back pressure, but it produces a lower volume flow rate ratio for larger back pressure. It is shown in Fig. 7 that the increase in total pressure leads to a better performance.

CFD (Fluent 6) simulations of compressible flow in the ejector is conducted in a 2-D axisymmetric computational domain. Detailed dimensions of the domain are taken from the actual ejector. Grid dependency is examined systematically, and finally a grid system of 230*120 is adopted. Spalart-Allmaras one-equation turbulent model [4] and species transport model are employed. The gauge total pressure of butane at the inlet of primary nozzle and gauge static pressure

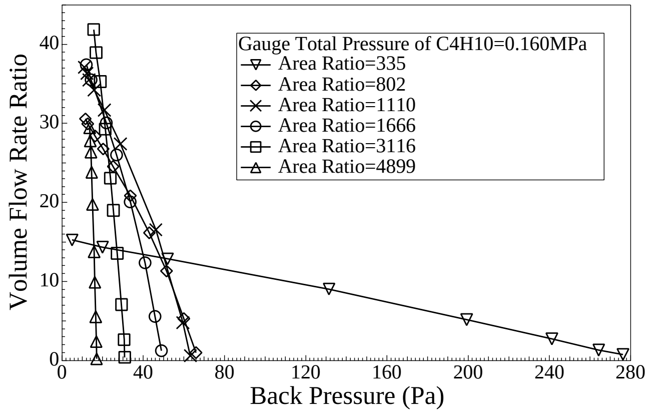

Figure 7. Effect of area ratio.

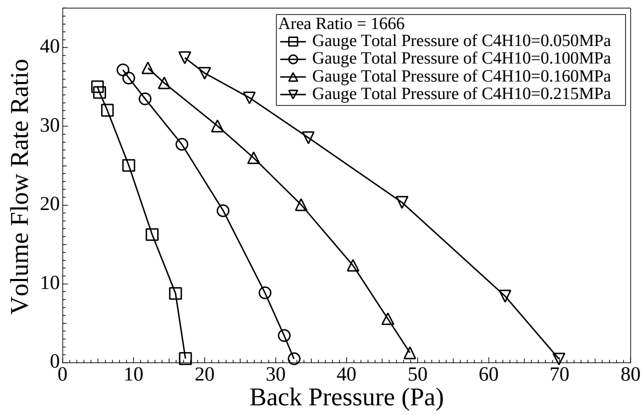

Figure 8. Effect of primary total pressure. (Butane)

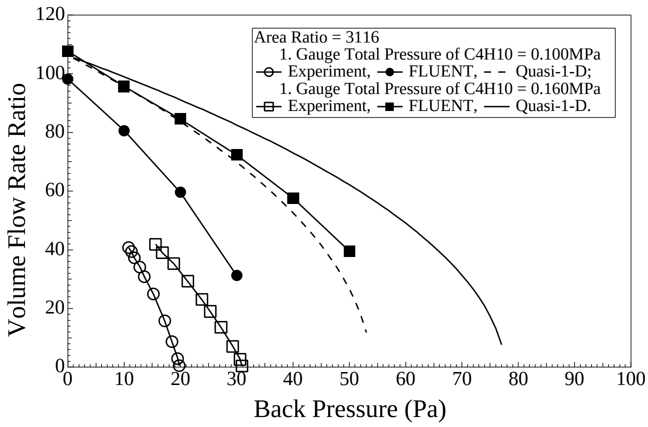

Figure 9. Comparison of volume flow rate ratio between CFD results and experimental data.

of air at the outlet are given as boundary conditions. Air at the inlet of the secondary nozzle is set as the atmospheric pressure. The wall temperature is kept at 300 K.

Figure 9 shows comparison of volume flow rate ratio between the CFD results and the experimental data. Although their trends are qualitatively similar, the present experimental data are much smaller than the CFD result. This is partially due to the rough inner surface of the present micro nozzle

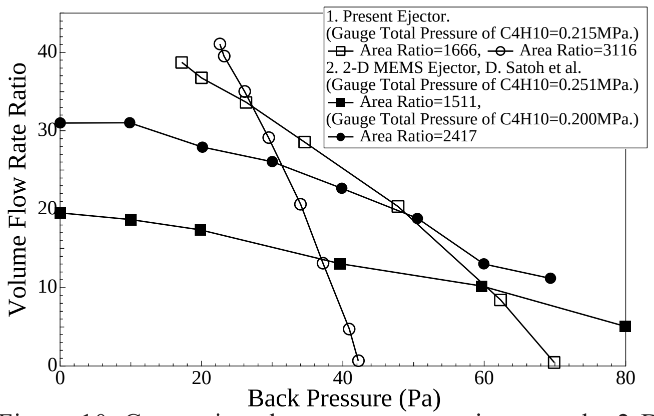

Figure 10. Comparison between present ejector and a 2-D MEMS ejector [3]. (Butane)

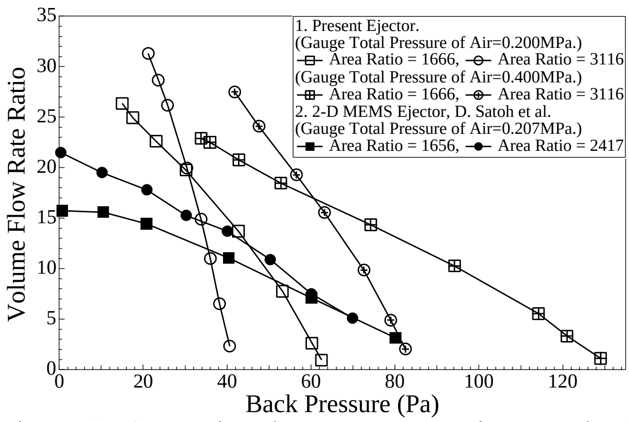

Figure 11. Comparison between present ejector and a 2-D MEMS ejector [2]. (Air)

as shown in Fig. 3.

If compared with the 2-D MEMS ejector [3] having area ratio of 1511 and 2417, the present ejector produces higher volume flow rate ratio for small back pressure as shown in Fig. 10, although the ratio is more rapidly decreased with the increase of back pressure. It is conjectured that the volume flow rate ratio for higher back pressure can be larger if the secondary nozzle of present ejector has a diffuser for pressure recovery.

It has been found in the present simulation that the butane concentration is almost uniformly distributed in the radial direction at the exit of a 5 mm long secondary nozzle, when the gauge total pressure is 0.1 MPa. The tube length required for complete mixing becomes larger with increasing gauge total pressure (not shown).

To explore the possibility of applying other kinds of fuels having relatively lower molecular weight and higher vapor pressure as the primary flow source, a preliminary test with air has been conducted. A maximum volume flow rate ratio of 35 has been achieved for an ejector having area ratio of 3116 when back pressure is 12.2 Pa. The value is reasonably lower than butane due to its lower molecular weight. Theoretically, butane has the capability of producing a maximum volume flow rate ratio 1.4 times larger.

Figure 11 compares experimental data of the present ejector with 2-D MEMS ejectors [2] for air as the primary fluid. When the gauge total pressure is set as 0.2 MPa, the present ejector yields larger volume flow rate rate for small back pressure, although the ratio is more rapidly decreased. The data for gauge total pressure of air at 0.4 MPa indicates the potential of using low-molecular-weight gases for large back pressure conditions, because they can provide larger volume flow rate ratio for large back pressure.

3 CONCLUSION

We have developed a micro ejector having an axisymmetric convergent-divergent nozzle to supply fuel-air mixture for a catalytic ceramic combustor. A volume flow rate ratio as large as 43 is acheived for a back pressure of 11.6 Pa, but it rapidly decreases with increasing the back pressure. The volume flow rate ratio obtained in the present experiment is much smaller than the CFD results. This is partially because the nozzle wall surface is somewhat rough.

ACKNOWLEDGEMENT

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