A Micro Power Generation System with Gas Turbine Engine and Piezo Converter

-- Modeling, Fabrication and Characterization --

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Abstract
This paper reports the concept design of a micro power generation system based on gas turbine engine and piezoelectric converter. The system design is implemented using an iterated computation process between geometry formation and flow behavior. A silicon-based micro combustor, in which a hairpin-shaped design of fuel/air recirculation channel is adopted for prolonging the gas flow path, is fabricated and characterized. Both the computational simulation and experimental results showed that this prolonged gas path is effective in improving the performance of micro combustor. A modeling and design of proposed piezoelectric converter are also presented.

Key words: micro gas turbine engine, combustor, CFD, piezoelectric converter

1 INTRODUCTION

Miniaturization of gas turbine engine using MEMS-based technology was proposed by MIT [1, 2]. Tohoku University has also fabricated three-dimensional micro turbines using micro milling [3]. In micro heat engine system, both the heat loss and chamber wall cooling in the combustor are critical problems. A design of recirculation gas flow jacket in micro combustor was reported in [1, 2]. However, the design in [1, 2] had limited effects in preheating the fuel/air mixture or cooling the combustor sidewall.

Our research aims to develop a micro power generator. As illustrated in Fig. 1, it consists of a micro gas turbine engine and a piezoelectric power converter. The micro gas turbine engine is composed of a centrifugal compressor, a combustor and a radial inflow turbine. The piezoelectric converter is to produce electricity from the rotation of the turbine, which will be linked with the piezoelectric element.

In this paper, we will present our research on a new silicon-based micro gas turbine engine for power generation, which consists of a micro combustor, a compressor, a turbine and a piezoelectric converter. The total system design, device design, fabrication and characterization are introduced. The micro combustor consists of seven layers of silicon structures. A hairpin-shaped design for fuel/air recirculation channel is applied to prolong the gas flow path. Comprehensive computational simulation based on CFD (Computational Fluidic Dynamics) showed that this prolonged gas path is effective to sustain high temperature in combustion chamber and at the same time, cool the sidewall of the chamber. Experimental results show that such design improves the efficiency and performance of the micro combustor. The modeling and design of proposed piezoelectric converter will also be presented.

2 SYSTEM DESIGN OF THE TURBINE ENGINE

The preliminary configuration of our micro gas turbine engine is shown in Fig 2. The design of the engine is based on the stacking of 7 wafers [4]. Both of the compressor and turbine consist of centrifugal blades with two-dimensional profiles. Fuel is injected through a hole-array on the 2nd wafer, and mixes with air and preheated as it flows through recirculation channel made up of the 3rd to 6th wafers. A novel hairpin-shaped channel on the 6th wafer is designed to prolong the gas flow path in order to (1) preheat the fuel/air mixture well, (2) efficiently cool down the outer wall of combustor, (3) reduce heat loss via outer wall and (4) sustain a stable flame. Then the mixture is injected into the combustion chamber through a set of flame holders on the 5th wafer, reacts in the annular combustion chamber, and finally exhausts through the turbine vans on the 4th wafer.

In the design, some parameters are preset according to the proposed working conditions and the requirements on system performance. These parameters include inlet airflow, compressor ratio, expected rotation speed and consumption rate of hydrogen fuel, which are 0.36 g/s, 4:1, 1.2M rpm and 17 g/h, respectively. Based on thesees preset parameters and experienced database, the adiabatic
efficiencies of compressor and turbine are estimated to be 0.65 and 0.75, respectively. The efficiency and pressure recovery coefficient of combustor are predicted to be 0.74 and 0.92, respectively. The temperatures at the inlet and outlet of combustor are calculated to be 774 K and 1600 K, respectively; and the temperatures at inlet and outlet of turbine are 1600 K and 1300 K, respectively. The net power output of the designed power generation system is expected to be 39 watts.

![Fig. 1 Concept design of micro power generation system based on a gas turbine engine and piezo converter](image1)

Considering the silicon micromachining process, the blades heights of compressor and turbine, as well as the height of airflow path, are limited by the thickness of the wafers. If 0.8 mm thick wafers were used in fabrication, the heights of blade and flow path would be 0.4 mm. However, the blade profiles of compressor and turbine can be optimized. The geometrical design of flow path and blade profile is based on an iterated CFD computation between geometry formation and cascade flow field analysis. Through several cycles of iterative computation, the following parameters, as shown in Table 1, are finalized. Fig. 3 shows the blade profiles of compressor and turbine. The capability and limitation of silicon microfabrication process have been considered in determining the dimension of compressor and turbine. The rotors of both compressor and turbine are design to have the same outer diameter. Both of the compressor and turbine will be figured out from a single wafer together with the critical micro journal bearing. This single-wafer process can get ride of the assembly (or bonding) process with compressor and turbine, and therefore, avoid the possible misalignment.

![Fig. 2 Implementation of the micro gas turbine engine](image2)

### Table 1. Parameters of the designed gas turbine engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor inlet air flow (g/s)</td>
<td>0.360</td>
</tr>
<tr>
<td>Compressor pressure ratio</td>
<td>4.0</td>
</tr>
<tr>
<td>Rotating speed (million rpm)</td>
<td>1.2</td>
</tr>
<tr>
<td>Compressor rotor o.d. (mm)</td>
<td>4.1</td>
</tr>
<tr>
<td>Compressor diffuser i.d / o.d. (mm)</td>
<td>4.17 / 5.15</td>
</tr>
<tr>
<td>Rotor / diffuser blade No.</td>
<td>11 / 13</td>
</tr>
<tr>
<td>Turbine rotor o.d. (mm)</td>
<td>4.11</td>
</tr>
<tr>
<td>Turbine guide van i.d / o.d. (mm)</td>
<td>4.27 / 5.32</td>
</tr>
<tr>
<td>Rotor / Guide van No.</td>
<td>17 / 23</td>
</tr>
<tr>
<td>Combustor Height (mm)</td>
<td>0.8 / (1.2)</td>
</tr>
<tr>
<td>Combustor volume (mm³)</td>
<td>126 / (188)</td>
</tr>
<tr>
<td>Estimated fuel consumption (g/h)</td>
<td>18</td>
</tr>
<tr>
<td>Engine output (Watts)</td>
<td>39</td>
</tr>
</tbody>
</table>

Comprehensive CFD simulations have been applied to investigate the combustion characteristics of non-premixed hydrogen and air. Since the accurate measurement within the micro combustor is hard to implement, such CFD modeling can be very helpful in understanding the flow behavior and chemical reaction mechanism in combustion chamber. The simulation takes into account the coupling of fluid dynamics, heat transfer and detailed chemical kinetics. Fig. 4 illustrates the CFD model of one part of the combustor with a sector angle of 12°. The fluid dynamics and heat transfers within the micro engine are simulated by commercial CFD code Fluent 6.0, and the detailed chemical kinetics of hydrogen/air combustion is expressed by DETCHEM as the user-defined functions of Fluent. The detailed gas-phase mechanism involves 19 reversible steps reaction model and 9 species [5].

The combustor performance is evaluated by predicting the temperatures at exit gas and the outer wall of the micro turbine engine. The size effects of combustion chamber and recirculation channel towards combustion efficiency and temperature distribution are investigated as well. Fig. 5 shows the simulation result of temperature distribution.
inside the combustor, where the flow rate and equivalence ratio were set to be 0.15 g/sec and 0.6, respectively. The heights of combustor chamber in results (a) and (b) are 0.6 mm and 1.0 mm, respectively. It was found that, when the equivalence ratio is as high as 0.6, the flame can be stable in the combustor for the cases (a) and (b). The temperature peak of flame and wall temperature, and the combustion efficiency are very similar in these two cases. However, when the equivalence ratio is set at 0.5, the flame can not be sustained in the combustor with chamber height being decreased to 0.6 mm. The CFD simulations also show that the hairpin-shaped design of recirculation channel is effective for sustaining higher temperature inside combustion chamber and for cooling the outer walls.

4 FABRICATION AND CHARACTERIZATION

DRIE (Deep Reactive Ion Etching) is the major process in the fabrication of micro combustor. Process parameters have been optimized to realize deep etching and to obtain straight sidewalls. A refined bias power generated an appropriate electric field in the plasma sheath, which provided perpendicular ion-bombardment to the bottom surface of the features. The 7-layer micro combustor with a hairpin shaped recirculation channel has been successfully fabricated from silicon wafers. Wafers of 0.4 mm thick are used for the 1st, 2nd and 7th layer, while wafers of 0.8 mm thick are used for the 3rd to 6th layers. The eventual assembled structure has a size of 21×21×4.4 mm³. The height of the combustor chamber is 0.8 mm. This height can be increased to 1.2 mm or 1.6 mm by adding extra wafers in order to investigate the size effects of combustor chamber.

Fig. 6 shows the cross-section of the assembled combustor. Seven dies are clamped together using a stainless steel fixture, which also facilitates the connection with fuel/air supply and pressure monitor through 3 metal tubes. Fig.7 shows an IR figure of combusting prototype assembled in the fixture for testing. To investigate the temperature profile during combustion, various thermal measurements at different points of the exit of combustor are made using a 0.5 mm diameter K-type thermal coupler. Fig. 8 shows the tip positions of thermal coupler during recording the exit temperature. The temperature at the exit center #1, as well as the temperature at the edge positions #0, #2-#4 of the exit port, is measured. Fig. 9 depicts the recorded temperature vs. mass flow rate of air/fuel mixture when the equivalence ratio is kept constant at 0.8. Results in Fig. 9 illustrate that stable combustion can be sustained when mass flow rate is over 0.04 g/sec. However, relative low temperature (about 1000 K) is recorded at the central part of exit port, shown as point #1 in Fig. 8. In the meantime, the temperatures measured near the edge positions of the exit port, shown as points #0, #2-#4 in Fig.8, are much higher and keep constant at around 1300-1600 K. The reason behind this thermal distribution could be related to the flow path in combustor device. Further systematic investigation on thermal phenomenon of the designed micro combustor is ongoing through fluidic dynamic simulation and experimental evaluation.

Fig. 5 Temperature distribution inside the combustor with a different chamber height

Fig. 6 The cross-section of the assembled combustor
The conversion from the mechanical rotation to electric energy will be made through piezoelectric materials. The structure is similar to a traveling wave ultrasonic motor but with the role reversed. The rotation motion will be transferred to a piezoelectric material via a linkage and then used to produce electricity. For a mechanic-electric converter examined in this research, the concept design of the linkage for transferring rotation from the micro gas turbine to piezoelectric materials is shown in Fig. 10. A prototype of a piezoelectric laminated beam generator with a resonance-frequency-adjusting seismic mass is shown in Fig. 11 (a), and the simplified modeling and analysis of the ‘31’ transverse mode type piezoelectric generator are conducted, as depicted in Fig. 11(b). The energy conversion efficiency of the generator, which is dependent on the operation frequency, can be expressed in the frequency domain, and the output power is taken as the indicated parameters of the generator. Case studies of laminated cantilever type micro-generators using PZT-PIC 255 for MEMS applications is given in Fig. 12 and the use of single crystal PZN-8% PT is also studied for comparison [6]. The performance of PZT-PIC255 is more sensitive to external resistance. However, PZN-8% PT is more sensitive to operational frequency, and increasing the frequency can improve the output power.
6 SUMMARY

As part of an effort to develop MEMS-based power generation system, the design, fabrication, assembly and test of a micro combustor with 7-layer stacking structure are presented in this paper. Fuel and air are injected, mixed, pre-heated and ignited in the combustor. A specific stainless steel-made assembly jig is developed to house the micro combustor and provide fuel/air injection. Hydrogen-air combustion is sustained in the micro chamber and the exit gas temperature up to 1700 K has been observed. The device and assembly jig are all passed 20-hour combustion experiment with elevated temperature. Investigation on compressor, turbine and piezoelectric power converter are also introduced in this paper. These results show a significant step towards establishing a MEMS-based micro power generation system.

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