Development of Micro Cogeneration System with a Porous Catalyst Microcombustor

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Abstract. The self-standing micro cogeneration system by coupling a microcombustor, thermoelectric modules and an air supply device was developed. The microcombustor has a porous monolithic Pt catalyst layer and the combustion efficiency of 90% was attained. A micro-blower was used to supply air to the combustor, and it was driven by a part of the electricity from the Bi-Te TE modules through a DC-DC converter. We investigated the optimal point where the output became maximal and the system stood by itself. At the optimal point, the input fuel enthalpy was 13.2W and the electricity of 403mW was generated from the TE modules. The micro blower used 280mW and the net electricity was 123mW. Therefore the final thermal efficiency was 0.93%. The efficiency was the same magnitude of the world smallest model plane engine TeeDee01 (COX Co. Ltd.) although the thermal input was less than its 1/20.

1. Introduction

Recent increase of portable electric devices and/or development of UMVs, such as micro drones, demands higher energy density power sources. Hydrocarbon fuels have large energy density compared with those of conventional batteries, which are attractive for large power/weight ratio generators or heat engines [1]. However, in order to use the combustion heat of hydrocarbon fuels in a small volume, it is necessary to overcome the huge heat loss due to large surface/volume ratio to sustain combustion.

In our previous research, we developed a micro-combustor, which has porous Pt catalyst layer inside a narrow ceramics tube whose inner diameter was 0.8mm [2]. The catalyst layer, which was built up by sintering technique, had a monolithic mesh structure and had a large surface area, and could sustain combustion with the aid of the surface reaction. We coupled our microcombustor with Bi-Te thermoelectric (TE) modules and succeeded in generating electricity with final efficiency of 3.5% [3, 4]. The corresponding energy density was about 420Wh/kg, which was 2.4 times that of typical Li-ion battery. The developed generation system was also able to provide heat of 5W, therefore it was expected to use as an emergency personal energy resource used in catastrophic situation right after natural disaster, for example.

However, the efficiency above did not take account of fuel/air supply system. Some of hydrocarbon fuels, such as butane, can be condensed by compression. Therefore, the supply of fuel to the combustor is not so difficult. On the other hand, the supply of sufficient air is critical issue to solve because the amount of air is more than that of fuel and the entrainment force of fuel is very small due to its small flow rate. In the present article, we drove air supply system with using the electricity from TE modules and discuss the feasibility of self-standing cogeneration system.

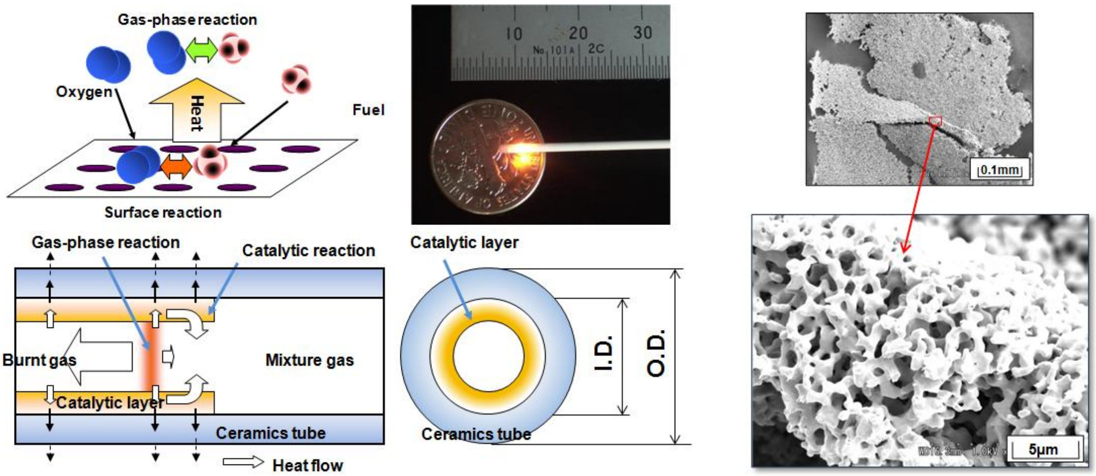

Figure 1. Concept of microcombustor and SEM image of the catalyst layer.

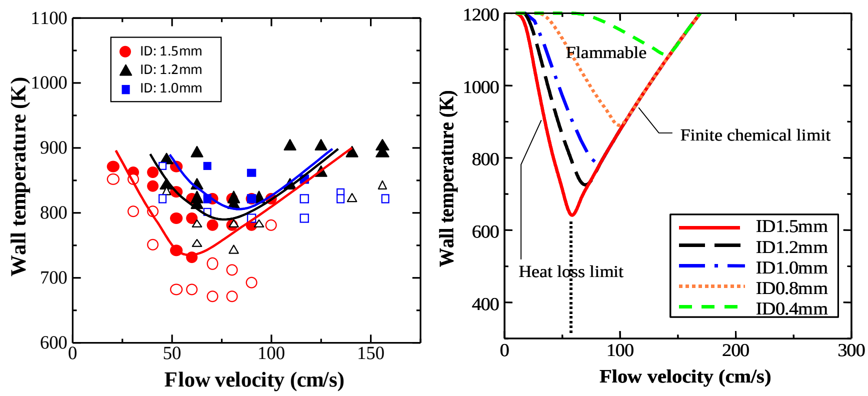

Figure 2. Limiting wall temperature for methane-air mixture in a narrow tube (left: exp., right: prediction).

2. Experimental setup

2.1 Microcombustor

The microcombustor used in the article is shown in Fig. 1. The combustor was a mullite ceramics tube and had a porous Pt catalyst layer on the inner wall. The length of the catalyst layer was 5mm, and the thickness was less than 50μm. The concept of sustaining combustion even in a narrow tube whose diameter is smaller than the quenching diameter is as follows. A part of the supplied mixture reacts on the catalyst later and increases the wall temperature. The rest mixture reacts in the core of the combustor with the aid of heated wall. The combustion limit in a narrow tube is determined by the blow-off limit due to high velocity, and quenching limit due to heat loss to the wall. In our previous scale analysis and experiments [5], the limiting wall temperatures are expressed as follows.

$$T_{w,q} = T_i - \frac{\eta_c T^*_{f,ad}}{(1+\theta)(1+2\Omega^*)} \quad \text{where } \theta = \frac{2h\alpha}{\rho c_p {V_g}^2 r} = 4Nu\,\mathrm{Re}^{-2}\,\mathrm{Pr}^{-2} = 4NuPe^{-2},\ \Omega^* = \sqrt{Nu}\,\frac{\delta}{r}$$

$$T_{w,b} = 300\left(\frac{V_g}{C_4}\right)^{\frac{1}{1.68}} \quad \text{where } C_4\text{=0.33}$$

The η_c, r, δ, V_g are the combustion efficiency, the radius of the tube, flame thickness, and flow velocity in the tube, respectively. Figure 2 shows the experimental results and analytical prediction of the combustion limit in a heated narrow tube. The same mullite ceramics tubes were used. It is found that both too high and too low flow velocity cannot sustain combustion.

The typical combustion efficiency with the inner diameter of 0.8mm is shown in Fig. 3. The fuel was methane and butane, respectively. It is found that the combustion efficiency of 90% was achieved

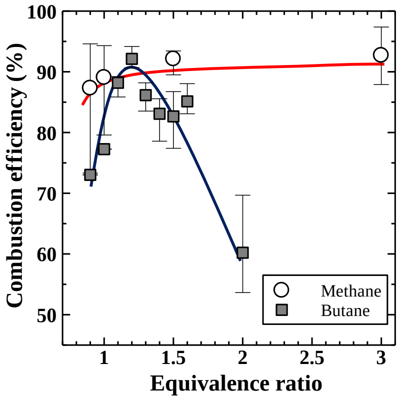

Figure 3. Combustion efficiency in the microcombustor.

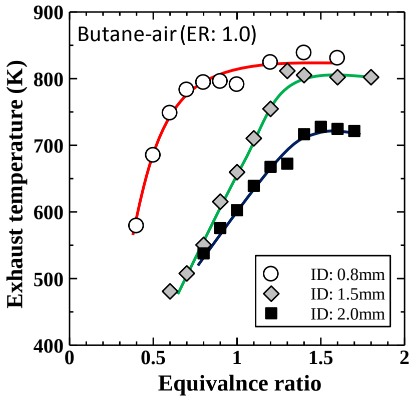

Figure 4. Exhaust temperature with varying the inner diameter.

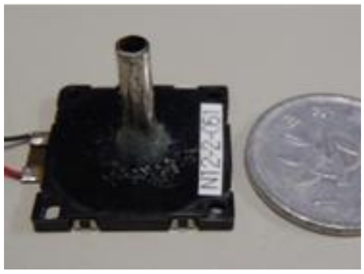

Figure 5. Micro-blower.

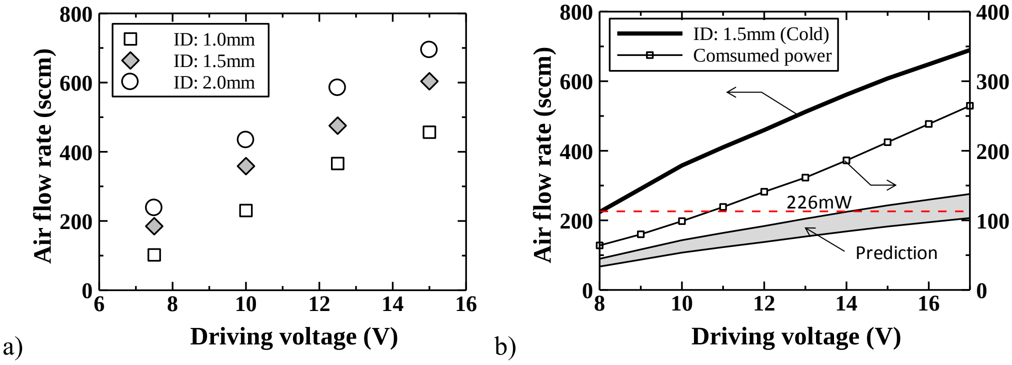

Figure 6. a) Air flow rate vs. driving voltage in cold condition for different ID, b) prediction of air flow rate during combustion for ID of 1.5mm.

near stoichiometric condition. Figure 4 shows the effect of the inner diameter on the exhaust gas temperature from the combustor when the total mixture flow rate is fixed at 70sccm (at 293K). The fuel was n-butane and the equivalence ratio was 1.0. The temperature was measured by a thermocouple whose diameter was 0.1mm. It is found that the larger the inner diameter is, the lower the exhaust temperature is. This means that the combustion efficiency becomes lower when the inner diameter is large. As shown in Fig. 2, the higher wall temperature was required to sustain combustion if the flow velocity was low. The result implied that mixture in the core of the tube did not react when the diameter was large. Therefore, it is found that relatively high velocity is required in order to sustain high combustion efficiency.

2.2 Setup of air supply system

In the present article, we set up air supply system by using a micro blower (Murata Manufacturing Co., Ltd.) shown in Fig. 5. The necessary air flow rate depends on the total mixture flow rate, which determines the combustion heat. Therefore, if the final conversion efficiency is the same, the larger the mixture flow rate is, the larger the generated electricity becomes. On the other hand, the required electricity becomes larger if the air flow rate is large. Hence, we first investigated the relation between flow rate and the driving voltage in the ceramics tube of different diameter with a differential pressure sensor (no catalyst, no burning). The result is shown in Fig. 6a. It is found that the micro blower consumes 100-250mW, and the air flow rate range significantly depends on the tube diameter. In Fig. 6a, even in the tube whose inner diameter is 1.0mm, the air flow rate of 450sccm was achieved with the voltage of 15V. This air flow rate corresponded to the combustion heat of 26W if the stoichiometric mixture was supplied. However, in actual, the flow rate reduced if catalyst later was set up. Additionally, if the mixture reacted in the tube, it increased the viscosity, and finally the flow rate was expected to be reduced in 30-40% of that in cold condition. Therefore, in order to avoid too much

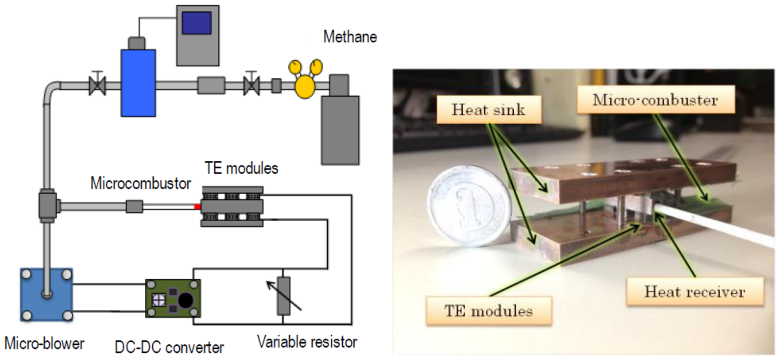

Figure 7 Schematic of experimental setup and micro-cogenerator.

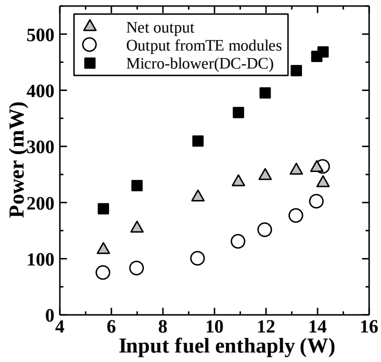

Figure 8. Output from TE modules vs. input fuel enthalpy.

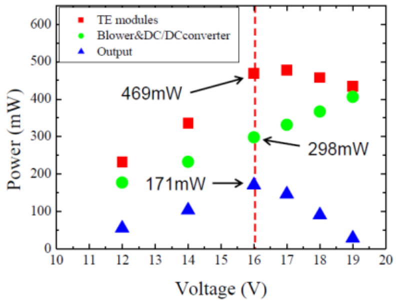

Figure 9. Net output vs. driving voltage of micro-blower.

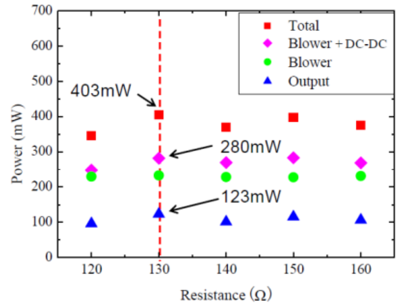

Figure10. Net output of self-standing system with varying load resistance.

Table 1. Specifications at design point.

Input fuel enthalpy	13.2W
Inner/outer diameters	1.5/2.5mm
Methane/air flow rate	23.8/226sccm
Size and number of TE modules (17 pairs)	4mm x 4mm 6 (in series)
Matching load resistance	130Ω
Output voltage	4.0V
Gross electricity from TE modules	403mW
Efficiency of TE modules	3.35%
Consumed power at micro-blower	247mW
Consumed power at DC-DC converter	33mW
Net output electricity	123mW
Final thermal efficiency	0.93%

pressure loss and to keep high combustion efficiency, we chose the inner diameter of 1.5mm in the present article. The expected flow rate vs. driving voltage is shown in Fig. 6b.

The schematic of the self-standing generation system is shown in Fig. 7. In order to generate the electricity from the heat of the exhaust gas, Bi-Te TE modules (1MD04-017-1, RMT Ltd.) were attached on the copper hot block with a hole, in which the microcombustor was inserted. The number of TE modules was changed from 2 to 6 according to the magnitude of the output heat from the combustor not to heat the copper block above 550K. The cold side of the TE modules were copper slabs, heat-sink type coolers. A part of generated electricity was supplied to DC-DC converter (LM2735: Strawberry Linux Co., Ltd.), whose conversion efficiency was 90%, and the output voltage was adjusted to drive the micro blower. The rest electricity was supplied to the load, which was variable resistor. The fuel was methane, which was supplied by a mass flow meter. The supplied air and fuel were mixed at the inlet of the combustor.

3. Results and Discussion

We first discussed the optimal input enthalpy to maximize the output electricity. Figure 8 shows the expected generated electricity, consumed electricity for the blower including DC-DC converter, and the net output electricity with varying the mixture flow rate, namely the input enthalpy of the fuel. The necessary electricity for the blower was predicted from the result in Fig. 6b. In Fig, 8, the generated electricity from TE modules was calculated assuming that the average final conversion efficiency was 3.3% according to the previous research [3]. The generated electricity increased with the input enthalpy, but the consumed electricity significantly increased when the input enthalpy was more than 14W. Hence we chose 13W as the input enthalpy for the experiment. According to the chosen input enthalpy, the number of TE modules attached on the copper block was selected as 6, and they were connected in series. The generated electricity was changed by the load resistor, and the matching load to maximize the output was 30Ω. The champion output was 533mW for 13.2W input enthalpy, which corresponded to the conversion efficiency of 4.0%.

Then, we investigated the optimal driving voltage for the blower by experiments. First, the micro-blower was driven by the separate power source not from the TE modules so that we could measure the consumed power and stabilize the system. The fuel flow rate was fixed at 23.8sccm, which corresponded to the enthalpy of 13.2W. In order to make stoichiometric mixture, the air flow rate of 226sccm was required. In Fig. 6b, the required air flow rate can be supplied in the range of voltage from 14V to 17V. Figure 9 shows the experimental result varying the driving voltage of the blower when the fuel flow rate was fixed. The output electricity from the TE modules was measured by setting the matching load as 30Ω. The result shows that the electricity has a peak of the output from the TE modules at 16V. It means that the stoichiometric mixture was supplied at the driving voltage of 16V. Therefore, we chose 16V as the driving voltage of the blower for 13W input condition. As the prediction, the net electricity was expected 170mW, which corresponded to the conversion efficiency of 1.3%

Finally, we found the optimal point for the self-standing generation system. The fuel flow rate was fixed at 23.8sccm, which corresponded to the input enthalpy of 13.2W. The driving voltage of the blower was set at 16V. We first drive the micro blower with a separate power source. After the micro combustor attained the steady state, we switched the power source to the output from the DC-DC converter. Then we adjust the load resistor and found the condition where the net output became maximal. Figure 10 shows the measured electricity with varying the load resistor. When the load resistor was 130Ω, the maximal net output 123mW was measured. The specifications at the optimal point are listed in Table 1. The final conversion was about 0.93%. The obtained efficiency was less than the expected one, but it was due to the lower thermal output caused by the individual difference among the developed combustors. If the output from TE modules were 500mW, the net output had increased to 200mW. The model plane engine, Tee Dee01 by OCX is known as the world smallest reciprocal engine [6]. Its displacement volume is 0.163cc and the input fuel enthalpy is about 300W. The net output is 5W, which corresponds to the thermal efficiency of 1.6%. Generally, the thermal efficiency is drastically reduced if the size of the engine becomes small. The developed system achieved the efficiency of the same magnitude whereas the thermal input was less than 1/20 of that of TeeDee01.

4. Summary

We developed a small self-stand generation system in which the air supply system was driven by a part of the generated electricity. The thermal input was 13.2W and the final output was 123mW; thus the final thermal efficiency was 0.93%. The magnitude of the efficiency was close to the world smallest conventional reciprocal engine TeeDee01although the power size was less than its 1/20.

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