Development of a Micro Cyclone Combustor for the Thermoelectric Power Generation

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Abstract

A 30 W class, square-pillar-shape cyclone combustor was developed for a 1 W class thermoelectric power generation. The combustor was fabricated to burn the fuel stably inside the combustor by forming an air swirl flow. The combustion stability of the developed micro cyclone combustor was investigated. The temperature distribution of the combustor wall was also measured using the infrared thermal image analyzer. The developed micro combustor (Model 1) burns the supplying fuel with a wide range of stability inside the combustion chamber, and it has been proven to be feasible for the thermoelectric power generator (TPG). Another smaller combustor (Model 2) was also developed for a 1 W class TPG. The flame stabilization characteristics were examined to check the feasibility of the Model 2 for a 1 W class thermoelectric power generation.

Keywords: Micro combustor, Cyclone combustor, Combustion stability, Thermoelectric module, Power generation

1 - INTRODUCTION

Recently, needs for the development of alternative, portable power generation system have been increasing because the advance of battery technology is approaching the limit in the respect of energy density, although many of portable devices use batteries for their power supply. Thus, many feasibility studies that focused on the development of new portable power generation system using a chemical fuel as an energy source have been performed during last decade [1-3]. Among such power generation systems, thermoelectrics, combined with a combustor represent one potential possibility of portable power generation technology [4,5].

The final objective of this study is to develop a 1 W class unit thermoelectric power generator. The main two elements of TPG are a thermoelectric module and a combustor that can supply thermal energy to the TE module. As a first step, a 30 W class micro cyclone combustor was developed in this study to supply heat to the thermoelectric module. The combustion stability is one of important factors in the designing of a micro combustor. In addition, the temperature distribution of the combustor wall is another important factor in optimizing the thermoelectric power generation system integrated with a combustor.

In this study, we investigated the combustion stability and flame shapes of developed micro cyclone combustor experimentally to identify the combustion performance of the combustor. The surface temperature distribution of the micro combustor outer wall was also measured by the infrared thermal image analyzer. The feasibility of the developed micro combustor for the TPG was discussed.

2 - THERMOELECTRIC POWER GENERATOR

The concept of TPG with a combustor has been already well known. However, the optimal performance of TPG depends on the arrangement and the performance of its components. We conceptually propose a TPG integrated with a micro combustor. Figure 1 shows the schematic of the unit TPG designed.

The TPG consists of a thermoelectric module, a micro combustor, a cooling fan, a storage capacitor, cooling fins and an outer housing. The micro combustor is designed to be square pillar so that the thermoelectric modules can be attached to the combustor surface as much as possible. Although not shown in the figure, the thermoelectric module is attached to the upper part of combustor. The cooling fins and the cooling fan are installed to increase the efficiency of thermoelectric power generation by increasing the temperature difference between the hot and cold surfaces. The unit power generator can be easily linked with another one to increase the output

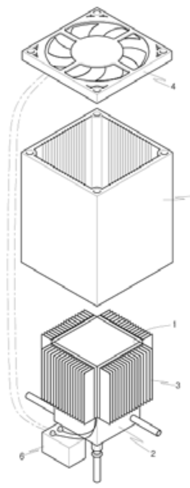

Figure 1 - Schematic of the unit thermoelectric power generator integ-rated with a combustor; 1 : thermoelectric mod-ule, 2 : combustor, 3 : cooling fins, 4 : cooling fan, 5 : outer housing, 6 : storage capacitor.

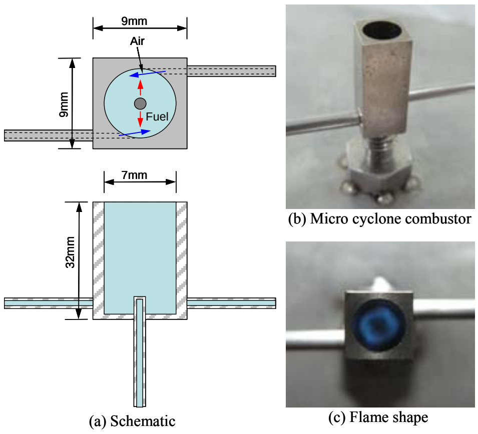

Figure 2 - Schematic and photo of the micro cyclone combustor (Model 1); (c) : Q_{fuel} = 52.3 sccm, Φ=1.0.

power level double because the outer housing is also hollow square pillar.

3 - DESIGN OF MICRO COMBUSTOR

The final objective of this study is to generate an electricity of 1 W using a TPG. Supposing that the total system efficiency of thermoelectric power generator ranges 2.5~5%, the needed combustor output power is 20~40 W based on the lower heating value of fuel (CH_4). In this study, thus, we developed a 30 W class, square-pillar-shaped micro cyclone combustor which is suitable for the TPG shown in Figure 1. The dimensions of the square-pillar-shape combustor are 9 mm × 9 mm × 32 mm and the diameter of the inner combustion chamber is 7 mm (Model 1). The micro combustor was made of a typical stainless steel.

The schematic and photo of the developed micro cyclone combustor are shown in Figure 2. The outer shape of the combustor was designed to be a square pillar so that thermoelectric modules are easily attached to the hot combustor surfaces but the inner side of combustor was designed to be a simple circular shape with two air ports and a fuel supplying tube. The air ports (i.d. = 1.6 mm) are machined to be tangential to the inner surface of the combustor and the air was injected tangentially to the inner combustion chamber. The fuel supplying tube (o.d. = 3.2 mm, i.d. = 1.6 mm) is intruded into the inside combustion chamber along the axisymmetric centerline combustor. The top of the fuel supplying tube is clogged and the fuel was laterally injected into the air stream through two fuel ports near the top of the tube. The arrangement of the fuel and air supplying tubes and the photo of the fabricated micro cyclone combustor are shown in Figure 2 (a) and (b), respectively.

Air is supplied from a compressed air cylinder to the micro combustor and forms a swirl flow inside the combustor. The swirl flow of the air enhances the mixing with the fuel and stabilizes the flame inside the combustor. For a 30 W class combustion test, the Reynolds number is less than 250 for all

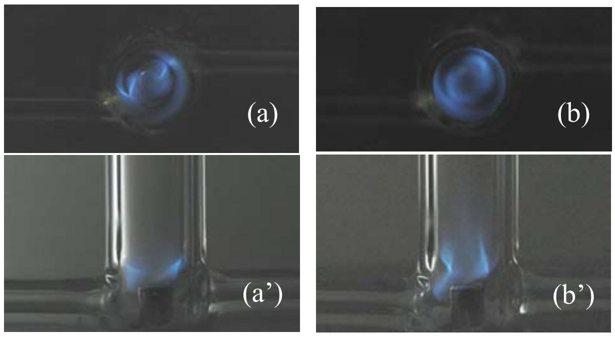

Figure 3 - Photos of the flame shape inside the micro cyclone combustor; Upper : top view, Lower : side view; (a) and (a') : Q_{fuel} = 52.3 sccm, Φ=1.0, (b) and (b') : Q_{fuel}= 52.3 sccm, Φ=0.8.

the equivalence ratio (Φ) conditions. The photo of Figure 2 (c) shows the top view of the flame shape stabilized circumferentially around the fuel supplying tube inside a micro cyclone combustor. For this condition, the fuel flow rate (Q_{fuel}) is 52.3 sccm, which corresponds to 33 W output.

Figure 3 shows the top and side views of the flame shapes stabilized inside a micro cyclone combustor. For visualization of the flame inside a combustor, the combustor was made of quartz tube. The overall flame shape varies with the equivalence ratio, that is, the air flow rate (Q_{air}). A fan-shape luminous reaction region appears at higher equivalence ratio. As lowering the equivalence ratio, the luminous reaction region spreads around the fuel supplying tube and the reaction intensity decreases. In the side views, it is seen that the flame is stabilized upper part of the fuel supplying tube top. At lower equivalence ratio, the flame tip is lifted upward because the air flow velocity increases. The flame stabilization characteristics and the flame shape vary with to the equivalence ratio (the air flow rate).

4 - COMBUSTION STABILITY

Figure 4 shows the combustion stability diagram of the micro cyclone combustor (Model 1). Each stability limit was

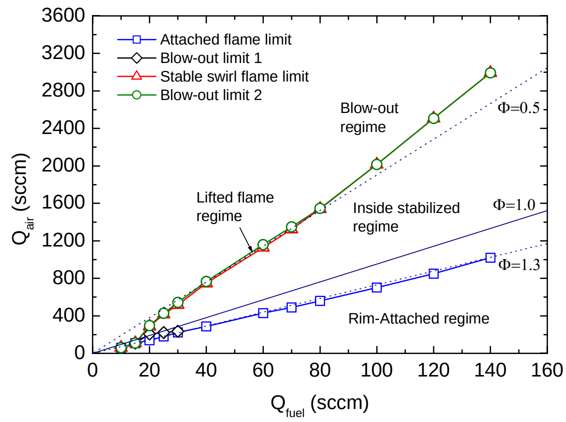

Figure 4 - Combustion stability diagram of the micro cyclone combustor.

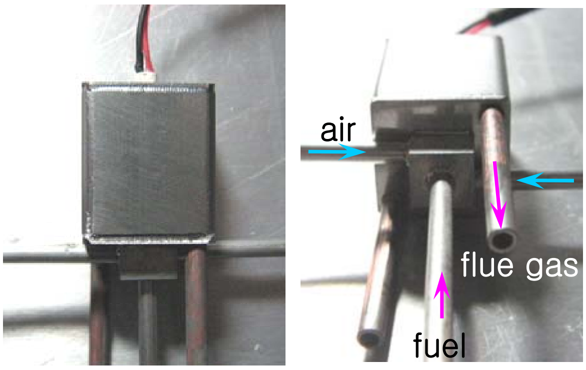

Figure 5 - Photos of the micro cyclone combustor integrated with the outer housing.

measured by increasing the air flow rate while the fuel flow rate was fixed. Before each measurement, the combustor was sufficiently cooled by electric cooling fan to obtain accurate stability limit. It is found that the stable combustion regime is extended when the combustor wall is initially heated.

It is seen that the attached flame limit is approximately coincides a condition of $\Phi = 1.3$. In the rim-attached regime, the flame is not stabilized inside the combustor but attaches the combustor outlet rim because the air velocity is not sufficiently large to form a swirl flow. In the inside stabilized regime (ISR), the flame can be stabilized inside the combustor due to an air swirl flow. However, in a rich condition of $1.0 < \Phi < 1.3$, only the primary combustion zone (flame) exists inside the combustor and the secondary combustion zone is formed when a part of the supplied fuel is oxidized with ambient air because the amount of air supplied is not sufficient to oxidize all the fuel in the primary combustion zone. In the respect of practical use of a micro combustor, it is not suitable to operate the micro combustor in a region of $\Phi > 1.0$. Thus, the ISR, the region between the blow-out limit and a line of $\Phi = 1.0$, is the most interesting region for the practical operation of the micro cyclone combustor. In this region, a stable swirl-type flame can be maintained inside the micro cyclone combustor.

Although the combustion stability limits were not measured for the conditions of $Q_{fuel} > 140$ sccm due to the limitation of our flow control system, it is presumed that the developed micro cyclone combustor (Model 1) can be sufficiently operated up to more than 100 W.

5 - DESIGN OF OUTER HOUSING

As shown in Figure 2, considering the micro cyclone combustor part, it is seen that a high-temperature flue gas of 1,250 K is exhausted from the combustor outlet without any

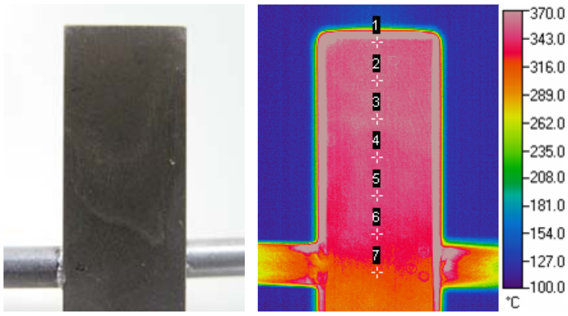

Figure 6 - Real and thermal images of the micro cyclone combustor wall without the outer housing.

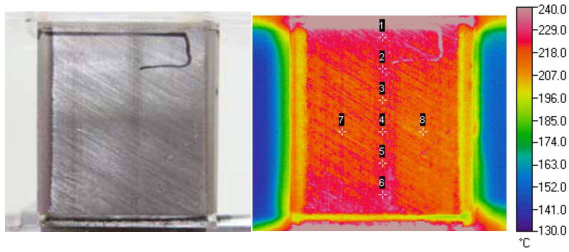

Figure 7 - Real and thermal images of the outer housing wall of the micro cyclone combustor.

heat exchange. In this case, the amount of the heat loss from the flue gas may be significant, and this situation is not good for the system efficiency. Thus, the outer housing that covers the micro cyclone combustor was installed. To exhaust the flue gas, two tubes was attached the bottom surface of the outer housing. The fabricated micro cyclone combustor integrated with an outer housing is shown in Figure 5. The igniter was inserted from the upper plate of the outer housing to the inner cyclone combustor. It is identified that the temperature of flue gas at the immediate exit of the exhaust tube is 385 K when the outer housing is installed.

6 - TEMPERATURE DISTRIBUTION OF COMBUSTOR WALL SURFACE

In the geometry shown in Figure 5, the thermoelectric modules can be attached to the four sides of outer housing. The wall area to where the thermoelectric modules can be attached increases, but the surface temperature of the housing wall may be lower comparing with that of the inner cyclone combustor part. The relationship among the power generation efficiency, the area and the temperature magnitude of a hot combustor wall will be investigated in detail in the future works.

In the thermoelectric power generation system coupled with a combustor, the temperature distribution and its magnitude of combustor wall are very important parameters for the

Table – 1 Temperatures for the selected points of the infrared thermal images (unit : K)

Point	1	2	3	4	5	6	7	8
Inner combustor	627.8	628.8	632.7	623.3	623.5	610.1	592.2	
Outer housing	499.1	495.8	490.0	488.4	493.5	505.2	491.9	485.4

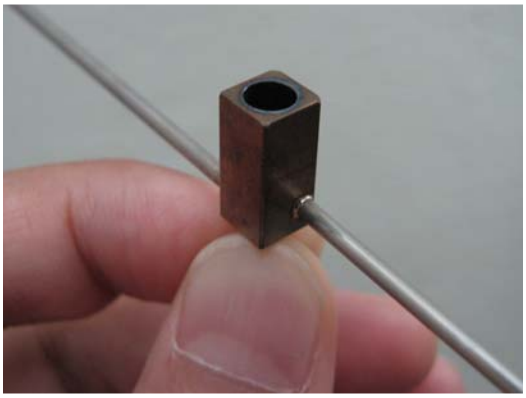

Figure 8 – Photo of micro cyclone combustor (Model 2).

generation of the electricity by the thermoelectric module. Figure 6 and 7 show two-dimensional infrared thermal images for the inner cyclone combustor wall and the outer housing wall which covers the inner cyclone combustor. Before the final infrared thermal images were captured, the emissivity of the combustor wall was calibrated using the temperature data obtained by the K-type thermocouple.

In Figure 6, the horizontal temperature distribution of the inner cyclone combustor wall is uniform and the vertical temperature distribution is also nearly uniform in the upper part of the combustor. The temperature of lower part the inner combustor is lower than that of upper part because a flame is stabilized downstream than the location of two air ports and high-temperature flue gas flows upward as shown in Figure 3. The temperature ranges 610~630 K in the upper region of the inner combustor wall.

In Figure 7, it is seen that the overall temperature of the outer housing wall is lower comparing with that of the inner combustor wall. The temperature of the outer housing wall ranges 485~505 K except the upper and lower parts of the wall. It is identified that the temperatures of the upper and lower parts of the wall are similar to those of other parts of the wall using the K-type thermocouple. The upper and lower high temperature parts represent welding regions between the upper or lower plate and the side walls. In these regions, the emissivity is different to that of other part. Thus, the colors (temperatures) of the upper and lower parts look to be different with those of the other parts.

7 - MINIATURE OF MICRO COMBUSTOR

As shown in Figure 4, a micro combustor (Model 1) can burn up to Q_{fuel} = 140 sccm. The Model 1 seems to be more appropriate to larger combustion capacity than 30 W class combustor. Thus, we developed another smaller micro cyclone combustor which dimensions are 7 mm × 7 mm × 25 mm and the diameter of the inner combustion chamber is 5 mm (Model 2). Figure 8 shows the photo of Model 2. It is identified that the Model 2 combustor can produce 20~40 W output stably based on the lower heating value of fuel (not shown). The wall temperature of the Model 2 seems to be higher than that of Model 2 because the size of Model 2 is smaller than that of Model 1. Consequently, a smaller TEG can be fabricated using the Model 2. It also seems that the Model 1 is more appropriate to rather the other systems which generate much higher power, such as a micro gas turbine.

8 - SUMMARY AND CONCLUSIONS

A 30 W class micro cyclone combustor was developed to supply heat to the thermoelectric module. The combustion stability of the developed micro combustor was investigated. The temperature distribution of the combustor wall was also measured using the infrared thermal image analyzer. The developed micro combustor (Model 1) burns the supplying fuel stably inside the combustion chamber, and the micro combustor has been proven to be feasible for the TPG. However, the combustion capacity of this combustor is somewhat large for a 1 W class electricity generation. Another smaller combustor was also developed for a 1 W class TPG. In the future works, the detailed combustion characteristics of Model 2 will be investigated, and the integration of the micro cyclone combustor with a thermoelectric module will also be performed.

ACKNOWLEDGMENTS

This work was supported by the 2006 basic research program of the Korea Institute of Machinery and Materials (KIMM) of South Korea. The authors gratefully acknowledge this support.

REFERENCES

[1] Epstein, A.H., *et al.*, “Micro-Heat Engines, Gas Turbines, and Rocket Engines - The MIT Microengine Project,” AIAA Paper 97-1773, *28th AIAA Fluid Dynamics Conf.*, Snowmass Village, pp. 1-12, 1997.
[2] Isomura, K., *et al.*, “Experimental Verification of the Feasibility of a 100 W Class Micro-scale Gas Turbine at Impeller diameter 10 mm,” *Power MEMS 2005*, pp. 25-28. 2005.
[3] Fu, K., *et al.*, “Design and Fabrication of a Silicon-Based MEMS Rotary Engine,” *Proc. ASME Int’l Mech. Eng. Congress and Expo.*, New York, Nov. 11-16, 2001.
[4] Posthill, J., *et al.*, “Portable Power Sources Using Combustion of Butane and Thermoelectrics,” *2005 Int’l. Conf. on Thermoelectrics*, pp. 517-520, 2005.
[5] Vican, J., et al., “Development of a Microreactor as a Thermal Source for Microelectromechanical Systems Power Generation,” *Proc. Combust. Inst.* Vol. 29, pp. 909-916, 2002.