

Non-uniform Heat Generation in Micro Catalytic Combustor

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Abstract

We developed a micro catalytic combustor using high-precision ceramic tape-casting technology and nano-porous alumina catalyst layer. It is found that failure of the ceramic combustor occurs due to steep gradient of the wall temperature in the streamwise direction. This is because heat generation is also highly non-uniform. Based on a series of CFD analysis of heat and fluid flow and surface reaction in micro channels, catalyst arrangement that gives much smaller temperature gradient is proposed.

Key Words: Catalytic combustion, Ceramic combustor, Thermophotovoltaic, Temperature distribution, CFD

1. INTRODUCTION

In micro energy conversion systems [1], combustion in small scale is one of the key technological issues [2]. Heterogenous catalytic combustion rather than homogenous gas phase reaction is preferred in order to obtain stable combustion in various operating condition.

The final target of the present research is to develop a high-performance micro catalytic combustor, which can be employed in a micro thermophotovoltaic (TPV) system as shown in Fig. 1. The combustor is packaged in a vacuum chamber, and equipped with a selective emitter for radiation spectra control [3, 4]. The PV cell generates electricity from the thermal radiation from the emitter. Since palladium catalyst is employed, the upper temperature limit of the combustor is about 900 °C. Rough estimates of the overall energy conversion efficiency and the power generation density are 5 % and 0.3 W/cm², respectively. Therefore, TPV systems using catalytic combustion can generate relatively large power with no moving parts, although the combustor temperature is somewhat low.

For combustors in TPV systems, uniform wall temperature distribution is of concern, since thermal radiation heat flux is proportional to the temperature quad. In addition, temperature gradient in combustors may cause failure due to thermal stress. However, it is not straightforward to design such combustors, because the wall temperature, surface reaction rate, radiation heat flux, and heat conduction in the wall are all coupled in a nonlinear manner.

Recently, Okamasa *et al.* [5] developed a ceramic combustor prototype using high-precision tape-casting technology for LSI packaging. The advantages of the tape-casting technology are three folds. Firstly, ceramic devices can be used at higher temperature than 900 °C. Secondly, high-precision three-dimensional structures can be fabricated by stacking and firing multiple ceramic tapes with an alignment error within 30 μm. Thirdly, since multilayer electrodes in ceramic packages are already used in industry, ignition heaters are easily integrated into the plates.

In the present study, we examine durability of our previous ceramic combustor, and propose more suitable design for minimizing temperature distribution.

2. EXPERIMENT WITH A COMBUSTOR PROTOTYPE

Figure 2 shows a prototype of the ceramic combustor [5], in which combustion channel height is 0.3 mm. Nano-porous

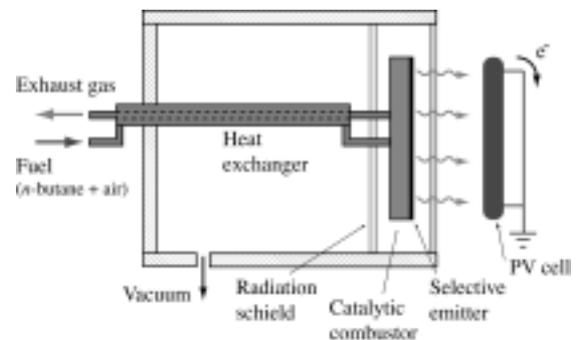


Figure 1. Schematic of the micro TPV system.



Figure 2. Micro ceramic combustor fabricated with ceramic tape-casting [5].

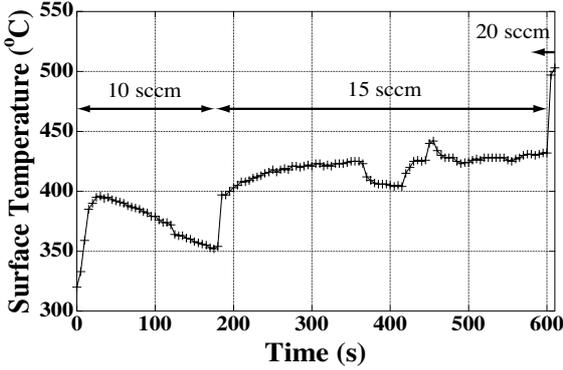


Figure 3. Experimental results with a combustor prototype.

alumina catalyst support is formed onto the inner surface of the bottom plate through anodic oxidation of spray-coated Al layer. The pore diameter and spacing are respectively about 20 nm and 50 nm. After anodic oxidation, Pd catalyst is impregnated and calcinated. The bottom plate has an embedded ignition heater and electrodes for the anodic oxidation.

Figure 3 shows combustion results in air for butane fuel. Premixed gas is introduced into the inlet tube. Temperature at the center of the bottom surface is measured with a radiation thermometer. Combustion is quenched for the butane flow rate at 10 sccm, but self-sustained combustion is achieved when the butane flow rate is larger than 15 sccm. When the butane flow rate is 20 sccm, the combustor temperature becomes over 500 °C, and failure of the bonding between the ceramic plates occurs at 530 °C. The temperature difference between the leading/trailing edges of the catalyst layer is approximately 150 °C. With a simple analysis based on 1-D plug flow model [5], it is found that heat generation density near the inlet is very large and rapidly decreased in the streamwise direction. Therefore, the highly non-uniform heat generation results in the large temperature gradient and the failure of the bonding between the ceramic structures.

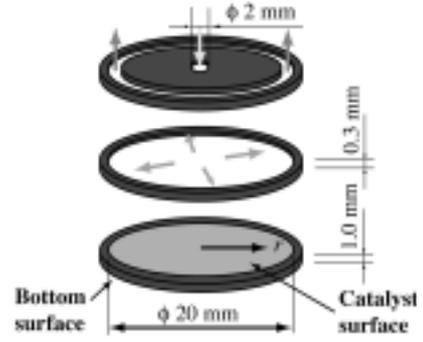


Figure 4. Exploded view of a radial-flow-type combustor.

3. RADIAL-FLOW-TYPE COMBUSTOR

In the present study, a radial-flow-type combustor shown in Fig. 4 is considered. Unlike our previous duct-flow-type combustor shown in Fig. 2, the premixed gas first impinges onto the catalyst wall, and then flows along the catalyst in the radial direction.

According to the first-order estimation with the 1-D plug flow model, this change of the flow geometry has little impact on reduction of the temperature gradient. However, combustors with axisymmetric configuration should be more robust for the failure. In the following section, we examine the effect of catalyst area and its arrangement on the heat generation density and the wall temperature distributions using numerical analysis.

A series of three-dimensional CFD analysis with Fluent 6 (Fluent Inc.) is carried out. In addition to the Navier-Stokes and the energy equations, species transport equations and the heat conduction equation in the ceramic wall are solved. We employ the one-step irreversible reaction model, in which the reaction rate is proportional to the butane concentration [5, 6]. Then, the surface reaction rate of butane R_B can be expressed as

$$R_B(r) = C_{B,s}(r) \cdot A \exp\left(-\frac{E}{R_u T}\right), \quad (1)$$

where $C_{B,s}$, A , E , R_u , and T are respectively molar concentration at the catalyst surface, pre-exponential factor, activation energy, universal gas constant, and catalyst temperature. The reaction constants in Eq. (1) are obtained in our previous study under isothermal conditions as follows: $A = 6.181 \times 10^8$ (m/s) and $E = 1.163 \times 10^8$ (J/kmol) [5]. Note that present activation energy is in reasonable agreement with the previous data of $0.9 \pm 0.05 \times 10^8$ (J/kmol) [7].

As shown in Fig. 4, the height and radius of the combustion channel are respectively set to 0.3 mm and 10 mm. Diameter of the inlet, thickness of the bottom plate, and radius of the ceramic walls are respectively 2 mm, 1 mm, and 15 mm. At the inlet, a uniform velocity profile of butane-air mixture is assumed. Unless otherwise noted, the volumetric flow rate Q is kept at 10 sccm with the equivalence ratio of unity, which corresponds to the heat generation of 20 W at complete fuel conversion.

Heat recovery using a heat exchanger is assumed as shown in Fig. 1, and the inlet mixture temperature is set to 630 °C. Temperature dependency of density, specific heat, and mass diffusivity is considered. Since the Reynolds number is 10-120, the flow inside the channel remains laminar. For thermal boundary condition at the bottom surface, only radiative heat transfer is assumed. Its emissivity is set to 0.3 based on the emission spectra of tungsten selective emitter [3]. Adiabatic wall is assumed for other external surfaces. Thermal conductivity of the ceramics material is set to 14 W/(mK).

In Case 1, Pd catalyst area is assumed to be $0 < r < 10$ mm. On the other hand, the catalyst area is $2 < r < 10$ mm in Case 2. Figure 5 shows radial temperature profiles at the catalyst surface. In Case 1, temperature at the center is as

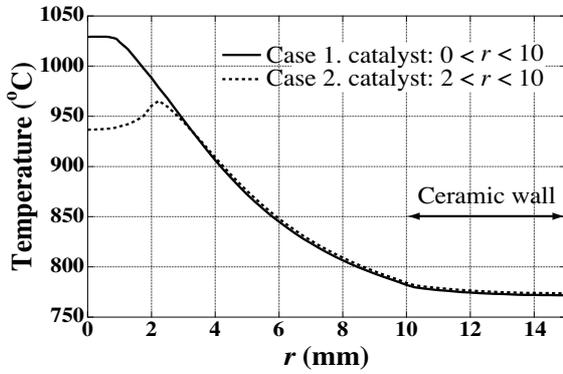


Figure 5. Temperature distribution of the catalyst surface.

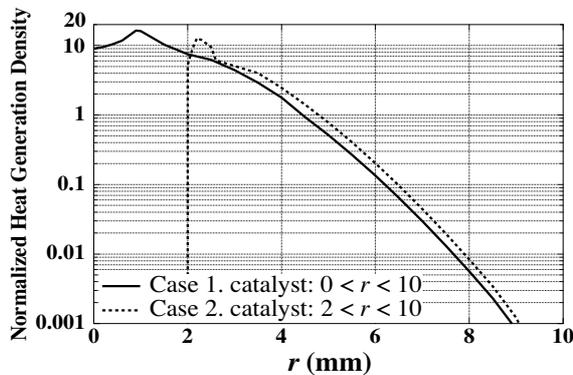


Figure 6. Heat generation density along the radial direction.

high as 1030 °C, where the fuel-air mixture impinges the catalyst surface. The temperature difference is as large as 260 °C, which may cause failure of the combustor. Figure 6 shows heat generation density profiles. The vertical axis is non-dimensionalized with its value for uniform heat generation. The heat generation density is rapidly decreased in the radial direction, and is lower than 50 % of its mean value at $r > 5$ mm. Near the trailing edge of the catalyst region, i. e., $r > 8$ mm, the heat generation density is below 1 % of its mean value. This is because most fuel has been converted upstream and the bulk mean concentration is very small.

Figure 7 shows the Sherwood number along the radial direction. The Sherwood number Sh can be written as follows;

$$Sh = \frac{C_{B,s}}{C_{B,b} - C_{B,s}} \cdot A \exp\left(-\frac{E}{R_u T}\right) / (D_B / H), \quad (2)$$

where $C_{B,b}$, D_B , and H are respectively bulk mean concentration of butane, mass diffusivity of butane, and the channel height. At the center, Sh is also large, but decreased in the radial direction due to large mass transfer coefficient near the stagnation point. Since the overall reaction at high catalyst temperature is diffusion-limited [5], the heat generation density and thus the catalyst temperature have large radial gradient. The Sherwood number is slightly increased in the radial direction, probably because of the deceleration of the flow in the radial direction.

On the other hand, in Case 2, a high-temperature peak near the stagnation point levels off, since no surface reaction occurs at $r < 2$ mm (Fig. 5). As shown in Fig. 6, heat generation density is somewhat larger than that of Case 1, but there still exists large temperature gradient of 200 °C. Note that the Sherwood number profiles for Cases 1 and 2 collapse onto a single curve except near the leading edge of the catalyst layer.

As depicted in Fig. 6, large temperature gradient is attrib-

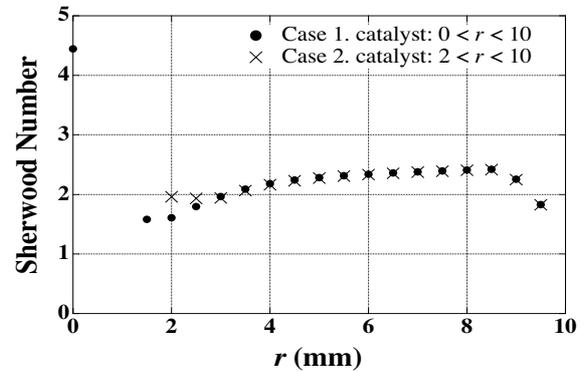


Figure 7. Sherwood number along the radial direction.

uted to very small heat generation density near the trailing edge. Therefore, we try to minimize the heat generation density distribution by optimizing the catalyst arrangement. In Case 3, the catalyst layer is assumed only at $7 \text{ mm} < r < 10 \text{ mm}$. The temperature distribution and the heat generation density are shown in Fig. 7. Although the catalyst area is half of that of Case 1, the fuel conversion efficiency is above 99 %. Heat is generated in the catalyst area at $7 \text{ mm} < r < 10 \text{ mm}$, and transferred to the bottom surface and also in the inner and outer radial directions. The catalyst temperature has its peak at around $r = 7 \text{ mm}$, and the temperature difference becomes as small as $60 \text{ }^\circ\text{C}$.

Figure 8 shows the detailed design of the radial-flow-type ceramic combustor. The catalyst surface is formed at $7 \text{ mm} <$

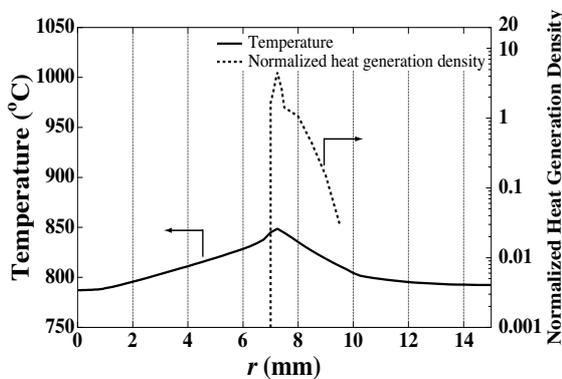


Figure 7. Temperature distribution and heat generation density of Case 3.

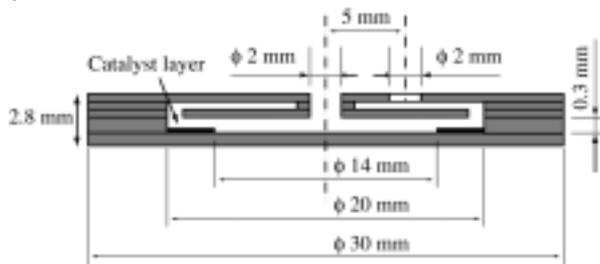


Figure 8. Schematic of the detailed design of the radial-flow-type combustor.

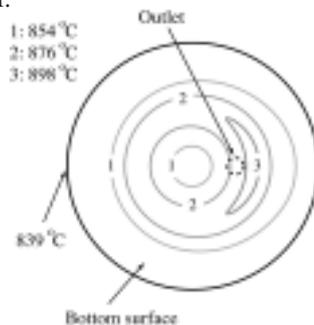


Figure 9. Temperature distribution of the bottom surface for $Q = 13 \text{ sccm}$.

$r < 10 \text{ mm}$. The outer diameter and height of the combustor are respectively 30 mm and 2.8 mm . The outlet port is located slightly off-center, and its diameter is 2 mm .

Figure 9 shows temperature distribution of the bottom surface for $Q = 13 \text{ sccm}$. Due to the asymmetry of the combustor geometry, the temperature distribution is also slightly asymmetry. The maximum temperature is $920 \text{ }^\circ\text{C}$, and the temperature difference at the bottom surface is about $65 \text{ }^\circ\text{C}$. Therefore, the radiation heat flux in the area of $\phi 30 \text{ mm}$ is within 25 %, which is enough small to be used in micro TPV systems.

4. CONCLUSIONS

Catalytic combustion in ceramic combustors for micro TPV systems is investigated. With the duct-flow-type combustor, wall temperature difference between the leading/trailing edges of the catalyst layer is as large as $150 \text{ }^\circ\text{C}$, and failure occurs due to the steep temperature gradient. In order to obtain combustor geometry and catalyst arrangement with much smaller temperature distribution, a series of CFD analysis has been made for radial-flow-type combustor. It is found that, by optimizing the catalyst arrangement, the wall temperature difference can be reduced to $65 \text{ }^\circ\text{C}$ with a maximum wall temperature of about $900 \text{ }^\circ\text{C}$.

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