A Study on Energy Conversion Efficiency of Direct Flame Fuel Cell Supported by Clustered Diffusion Microflames

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Abstract. The micro power generator based on clustered diffusion microflames and a direct flame fuel cell (DFFC) is proposed and its energy conversion efficiency is evaluated to investigate the optimum state of combustion. The clustered diffusion microflames are established on the 2.5 mm pitch 3-by-3 array of fuel jets with a diameter of 0.07 mm and a velocity of 24 m/s at the outlet by the interaction with other microflames around. The clustered diffusion microflames is more suitable for micro power generator than microflame array because of suppression of soot formation without air supply system. Although the conversion efficiency of the system with clustered microflames is quite sensitive to the separation distance between the burner and the cell, compared with the microflame array, it has attained the same level of conversion efficiency with microflame array, i.e. 0.45 %. The results of cell temperature suggest that the rapid decrease of conversion efficiency with increasing separation distance is caused by the decrease of species supply such as CO and H₂ rather than the decrease of heat supply. The observation of the secondary flame suggests that the reason of high sensitivity to the separation distance is because the cell position changes the flowrate of entrained ambient air and hence the flame equivalence ratio.

1. Introduction
One of potential micro power source that replaces conventional secondary batteries is a power generation system that uses a micro combustor as a heat source. The research and development on this kind of power generation system have been conducted in recent years [1-4]. The interest of this kind of power generation systems exists in the high thermal energy density (kJ/kg) of hydrocarbon. Since its thermal energy density is several ten times larger than the electric energy density of secondary batteries, its electric energy density is expected to overtake that of conventional batteries like Li-ion battery even at low energy conversion efficiency. In the power generation system that uses a micro combustor, there are a few kinds of approach, for example, the system based on thermal engines miniaturized by MEMS technology [1] or thermoelectric transducer [2, 3].

The present approach is different from them, that is, the system based on direct flame fuel cell (DFFC)[5], which uses solid oxide cell operated by a flame [6-8]. The way of power generation by DFFC is generally considered as follows; ideal fuels like CO or H₂ are supplied to the cell as intermediate products from hydrocarbon flame while the cell temperature is kept high enough by heat from the flame. If thermal efficiency attains more than 3 %, it will overtake the electric energy density of Lithium-polymer battery, assuming that the weight of device is a half of fuel weight and that fuel is dimethyl ether (DME)[5].

There are a few previous studies on DFFC [6-8], where they report the power density of cell but no energy conversion efficiency. However, evaluation and improvement of the conversion efficiency is necessary in the development of DFFC to make it a valuable micro power source. Therefore, the present study evaluates its energy conversion efficiency and aims to improve it with the improvement of combustion by use of microflames.

In order to improve conversion efficiency, decreasing the fuel consumption rate are important as well as increasing the electric power output. Thus, microflame array (MFA), which establish each
flame with low fuel flowrate with high heat release density, is selected as one of potential flames to operate a solid oxide cell. Clustered diffusion microflames (CMF) established on the burners with tens of micrometers [9], is another potential flame to operate a solid oxide cell. CMF are established by the interaction with other microflames around because the diameter of each burner is too small to establish a single flame. CMF is suitable for micro power generator because it is able to suppress soot formation without air supply system. In the present study, therefore, the optimum condition to improve the conversion efficiencies of DFFC supported by MFA and CMF are investigated.

2. Experimental Setup
The experimental setup is shown in figure 1. Two types of burners are used for the experiments; one is for MFA and the other is for CMF. The MFA burner has an array of 2-by-2 coaxial double tubes, which issue fuel from the inner tube and air from the outer tube. The CMF burner has an array of 3-by-3 square poles with a 0.07 diameter fuel outlet. There is no air outlet in the CMF burner. Methane is used as fuel for all cases in the present study. The fuel flowrate for MFA burner is fixed at 60 sccm and air flowrate is adjusted to meet the equivalence ratio of mixture of fuel and air jet becomes 1.27. The fuel flowrate for CMF burner is fixed at 50 sccm.

Temperature of the cell surface (thin silver film) has been measured by using a type R thermocouple with wire diameter of 25 µm and thermography (FLIR, T390). The emissivity of thin silver film is determined to be 0.06 based on those results. After this calibration, temperature of cell cathode surface has been measured by using the thermography.

Two solid oxide cells with collector electrode areas of 0.66 cm² and 0.67 cm² are used for experiments, which are afterward called #6 and #7, respectively. It has been verified in advance that the difference of performance between those cell are negligibly-small.

![Figure 1. Schematic drawing of experimental setup](image)

3. Results and Discussion

3.1. Influence of cell position on power generation
The power densities (W/cm²) at the solid oxide cell above MFA and CMF are measured at various distances between cell and burner tip, h, and those value as well as evaluated conversion efficiencies based on a lower heating value are shown in figure 2. During those measurements, the load resistance is fixed at 2 Ω. No measurement result of power are obtained at h = 4 mm and below because flame goes around to cathode of the cell.

For burners of MFA and CMF, both the power density and the conversion efficiency shows maximum at h = 5 mm. At this distance, while there are no large difference between MFA and CMF, a little higher power density is attained at MFA and a little higher conversion efficiency is attained at CMF. The reason why CMF shows higher conversion efficiency at even at lower power density is
simply because lower fuel flowrate supplied to the CMF burner. CMF shows a rapid decrease of power density and conversion efficiency at 6 mm and above, which is different from MFA. The direct photographs of MFA and CMF at various cell positions are shown respectively in figures 3 (a) to (d) and figures 3 (e) to (h) to investigate what causes this rapid decrease.

The position of MFA flame-base does not change with cell position. This is because the mean velocity of fuel at the burner exit is 0.29 m/s, which is slow enough for diffusion microflames to be held regardless of cell position. Therefore, the influence of cell position on combustion state of MFA is smaller, which results in smaller change in conversion efficiency.

On the other hand, CMF is lifted a little at $h = 8$ mm, and flame base position decreases with decreasing cell position from $h = 8$ to 6 mm. These CMF behavior and its mean velocity of fuel at the burner exit as high as 24 m/s suggests that flames are held in a stagnation flow where the cell works as a stagnation plate.

Thus, the decrease of cell position slows down the main flow velocity with divergence of the flow, which results in the decrease of flowrate of entrained ambient air, and hence attains the fuel rich condition. Consequently, the secondary flame is brightly observed at $h = 5$ mm. The maximum

Figure 2. Effect of distance between cell and burner tip, $h$

Figure 3. Direct photograph of MFA and CMF at various distance between burners and cell, $h$ (MFA:(a)～(d), CMF:(e)～(h))
conversion efficiency has been attained when the secondary flame is brightly observed, which suggests that this combustion state is suitable for cell operation.

3.2. Influence of cell position on cell temperature
The surface temperature of cell is measured to specify what causes the rapid decrease of power density and conversion efficiency at \( h = 6 \text{ mm} \) and above, specifically, whether the decrease of species supply such as CO and H\(_2\) or the decrease of heat supply. The results are shown in figure 4 together with results on the conversion efficiency shown in figure 2. The comparison of the result of CMF between \( h = 5 \text{ mm} \) and 6 mm shows that the change of cell temperature is negligibly small but the change of conversion efficiency is quite large. In addition, although the cell temperature decreases gradually in the range of \( h = 6 \) to 8 mm, the cell temperature is still larger than that of MFA. Therefore, it must be the decrease of species supply such as CO and H\(_2\) that causes the power density and the conversion efficiency reduced largely at \( h = 6 \text{ mm} \) and above.

![Figure 4. Effect of cell position on cell temperature](image1)

3.3. Influence of load resistance on power generation
The load resistance connected to the solid oxide cell above CMF is varied at \( h = 5 \text{ mm} \), and its influence is evaluated. The influences on cell voltage and current are shown in figure 5 (a) and influences on power density and conversion efficiency are shown in figure 5(b). The dashed line in figure 5(a) indicates electromotive force.

![Figure 5. Effect of load resistance](image2)
As the load resistance decreases, the cell voltage and hence voltage efficiency are reduced but the current increases. Since the fuel in DFFC is supplied and consumed at constant rate regardless of the electric power output, the increase of current means increase of fuel utilization. Therefore, the reduction of load resistance directly leads to improvement of conversion efficiency unless the voltage efficiency becomes too low.

The conversion efficiency decreases rapidly with decreasing from 2 $\Omega$ and decreases gradually with increasing from 2 $\Omega$. It is found that the conversion efficiency attains the maximum around 2 $\Omega$, which means that it is the optimum value of load resistance on the present solid oxide cell.

4. Concluding Remarks

It is demonstrated that the clustered diffusion microflames properly supports the power generation of DFFC without air supply system. Although the conversion efficiency of the system with clustered microflames is quite sensitive to the separation distance between the burner and the cell, compared with the microflame array, it has attained the same level of conversion efficiency with microflame array, i.e. 0.45% at a separation distance of 5 mm and load resistance of 2 $\Omega$. The results of cell temperature suggests that the rapid decrease of conversion efficiency owing to the change of the separation distance is caused by the decrease of species supply such as CO and H$_2$ rather than the decrease of heat supply. The observation of the secondary flame suggests that the reason of high sensitivity to the separation distance is because the cell position changes the flowrate of entrained ambient air and hence the flame equivalence ratio. Since the burner of clustered diffusion microflames works as an injector as well, designing of fuel jet will be a key to control the combustion state to be suitable for cell operation.

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