Development of a portable power system with meso-scale vortex combustor and thermo-electric device

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Abstract. In this study, a small scale power generation system with a meso-scale vortex combustor has been developed. The system was consisted of a couple of thermo-electric device and a heat medium. The medium was made of duralumin, 40 × 40 × 20 mm and 52 g weight, and the vortex combustion chamber of 7 mm inner diameter was embedded in it. It was found that a stable flame could be established in the narrow 7 mm channel even the mean axial velocity reached 1.2 m/s. And furthermore, the vortex flow significantly enhanced the heat transfer from the burned gas to combustion chamber, and as a result, the medium was heated to 300 °C quickly (within 5 minutes) by the combustion of propane / air mixture for 145W input energy. The system could successfully generate 1.98 W (4.3 V and 0.46 A), which corresponded to the energy conversion rate of 0.7 % per unit thermo-electric device.

1. Introduction
Due to strong demands for small-scale power sources, meso- and micro- scale combustors have received considerable attention [1,2]. On such small scale combustors, the thermal and chemical quenching effects of the wall become significant due to its large surface to volume, hence, large heat loss to heat release, ratio. Flame quenching is an unavoidable issue for small-scale combustors.

One solution for the flame stability issue on the micro combustor is using the “vortex flow”. Recently, we found that the flame could be easily stabilized in 3.6 mm tube for methane/air and propane/air mixture if the flow was rotating. In figure 1, appearance of flames in 3.6 mm tube for non-rotating flow (A) and rotating flow (B) are shown. In figure 1B, it can be seen that a large surface flame can be established in a vortex flow although the tube diameter (3.6mm) is close to the so-called “quenching diameter” of the mixture (3.5 mm). Even with vortex flow, the flame could not be stabilized in “μm” scale channels for those mixtures, however, it was found that the stable combustion range in a few millimeter scale channel was considerably extended. For example, in 3.6-mm tube, the stable combustion range of methane/ air mixture was \( \Phi = 0.75 \) to 1.2 , even for the high mixture flow rate 8.0 L/min (corresponding mean axial flow velocity is 13 m/s).

According to these results, it can be said that the vortex combustor be the powerful energy source for the portable devices. And due to these high stability nature of the vortex Fig. 1 Appearance of CH₄ / air flames in (A) non-rotating and (B) rotating flow (A: mixture flow rate \( Q_{\text{mix}} = 0.22 \), mean axial velocity \( V_x = 0.35 \) m/s. B: \( Q_{\text{mix}} = 2.0 \) L/min, \( V_x = 3.3 \) m/s).
Combustor, meso-scale vortex combustors have been successfully developed not only for gaseous fuels [3,4] but also for the liquid fuels [5-7].

However, the power system with the vortex combustor has never been developed. Then, in this study, a powerful portable power system with a meso-scale vortex combustor has been developed. On the system, a couple of thermo-electric devices (TED) and the vortex combustor are used. It is known that TED has poor conversion efficiency from heat to the electric power, however, it is promising device to generate the electric power from the heat of combustion. In this study, the temperatures of the gas and the heat medium as well as the system output are examined. The degree of the heat transfer from the burned gas to the combustor wall is also evaluated based on the obtained surface / gas temperatures.

2. Experimental

Figure 2 shows the appearance of the power system designed for 100 ~ 200 W input based on the heat of combustion of fuel (propane). Its weight is less than 400g and scale is comparable to a conventional fuel cell as shown in figure 2A. The schematic of the system is shown in figure 3. The system consists of a heat medium (figure 3A), thermo-electric device (figure 3B) and cooling plate and fan (figure 3C). The heat medium is 40 × 40 × 20mm and 52g weight, of which appearance is shown in Fig. 2B. The heat medium is directly heated up by the vortex combustion chamber (7mm i. d.) embedded in itself. The electric power can be obtained by a couple of thermo-electric devices placed on the surface of the heat medium. Note that, in this study, the cooling fan is powered by an outer power source to examine the maximum output of the system. The variable resistance (0 ~ 20 Ω) was installed in the circuit, and the electric current and voltage on the resistance were measured (see, lower part of figure 3). The obtained electric power can be a measure of the electric power that can be used by the actual electronic devices.

![Figure 2. Appearance of the power generation system (A: the system, B: the heat medium).](image1)

![Figure 3. Schematic of the power generation system with a vortex combustor.](image2)
In figure 4A, the channel inside of the heat medium is shown. A homogeneous propane / air mixture enters into the medium from the two inlets. The channel is connected to the gas line (1 mm i. d.) in right-angle at the Z – Z’ position, and then, the unburned gas is ejected tangentially into the combustion chamber (see figure 4B). In the experiment, the mixture is ignited by a torch at the opened “ignition port” shown in figure 4A. The flame appearance obtained with opened ignition port is shown in figure 4B. After the ignition, the port is closed by a stainless steel plug, and thus, the hot burned gas flows in one direction. The combustion chamber is 7 mm in inner diameter and 27 mm in length. As the flame length is estimated to be less than 10 mm in the experimental range of this study (input energy < 200W, mixture flow rate < 3 L/min), the half of the combustion chamber is expected to be occupied hot burned gas. The gas outlet channels are equipped to be close to the unburned mixture line to enhance the flame stability by the preheating of the unburned mixture.

During the power generation experiments, temperatures both on the heating side and cooling side of TED were measured by 250 μm K-type thermocouple. The measurement positions are shown in figure 3. The gas temperature was also measured by a series of R-type silica coated thermocouple installed in the gas channel. The measurement positions are shown in figure 4A, and each temperature is denoted as (1) $T_f$: flame temperature, (2) $T_b$: burned gas temperature and (3) $T_{out}$: exhaust gas temperature. Separately to the power generation experiment, the surface temperature profile on the heat medium was measured by a thermo graphic camera (Nihon avio, TSV-200EX) without TED.

In the experiment, the mixture was ignited under the stoichiometric condition of the air flow rate $Q_a = 3.0$ L/min which corresponds to input power of 200 W. When the medium surface temperature reaches the upper limiting temperature of the TED (260°C), the mixture condition was changed to $\Phi = 0.8$ of $Q_a = 2.7$ L/min (145 W) to achieve the steady state.

3. Results and discussion

Figure 5A shows the variations of the heating side ($T_{Hot}$) and cooling side ($T_{Cold}$) temperature of TED as well as the output voltage obtained with the system. After the ignition ($t = 0$ min), the hot side of the TED was heated up to 200°C within 5 minutes. At $t = 7$ min., the input was decreased to 145 W from 200W because the limiting temperature of the TED (260°C) was reached. After that, the $T_{Hot}$ takes almost constant of 250°C which indicates that the input energy is balanced with TED output and the heat loss to the surroundings. The cooling side temperature also increases with $T_{Hot}$ and takes almost constant of 100°C after $t = 7$ min.

As for the output voltage, the maximum of 4.7 V was reached at $t = 7$min., and the steady output of 4.3 V could be obtained. As the output of the TED depends on the temperature difference between
the hot side and cold side of TED, the temperature difference $T_{\text{Hot}} - T_{\text{Cold}}$ is also shown in figure 5A by (+). It is clear that the output voltage traces the tendency of the temperature difference.

Next, the medium surface temperature was measured by thermography. In the experiment, the wall temperature was measured directly without TED. The obtained two-dimensional temperature profile is shown in figure 6A, and the temperature distribution along the $A - A'$ line in figure 6A is shown in figure 6B. In figure 6A, the gas flow line is also indicated by dashed line. Results show that the difference between the maximum temperature ($T_{\text{max}} = 260°C$) and the minimum temperature ($T_{\text{min}} = 246°C$) is $14°C$, which is within $\pm 3\%$ of average temperature of $T = 253°C$. It is also seen that the position of $T_{\text{max}}$ is not centered but exists around the tangential injection.

Figure 5B shows the variations of the output voltage, electric current and the power of the system. The result shows that the maximum output of 2.3 W (4.7V × 0.49A) could be tentatively obtained at $t = 7$ min., and 1.98 W (4.3V × 0.46A) could be obtained continuously over 20 minutes.

The system output was examined for various internal resistances under the steady output state (after $t = 15$ min. in figure 5B). Results are shown in figure 7. It can be seen that the voltage monotonically increases whereas the electric current monotonically decreases with resistance. The output power takes its maximum of 1.98 W when the resistance is 10Ω. These results confirmed that the vortex combustor power system could successfully generate 1.98 W continuously. The conversion rate of input heat of
combustion to the electric output per unit TED, defined as,

\[
\text{TED} = \frac{\text{Output} [\text{W}] / \text{number of TED}}{\text{Input} [\text{W}]} \times 100\%,
\]

was calculated to be 0.68%. This low conversion rate comes from the inefficient cooling. As shown in figure 5A, \( T_{\text{Cold}} \) reaches 100°C continuously. The optimization of the cooling side of TED will lead to the drastic increase of the output of the system.

Finally, the heat transfer from the burned gas to the combustor wall is discussed. The variations of the flame temperature \( T_f \), burned gas temperature \( T_b \) and the exhaust gas temperature \( T_{\text{out}} \) are shown in figure 8. It can be seen that the temperature shows complicated behavior. The points are;

1. The exhaust gas temperature 250°C is enough lower than \( T_f \), and furthermore, it is almost same as the combustor wall temperature (\( T_{\text{Hot}} \) in figure 5A). This indicates that the heat of the burned gas was effectively transferred to the combustor wall.
2. The distance between the measurement position of \( T_f \) and \( T_b \) is only 27 mm and the residence time of the burned gas is estimated to be less than 20 ms, however, the maximum temperature difference between \( T_f \) and \( T_b \) is about 1000 K. This indicates the heat of the burned gas was rapidly transferred to the wall. Then, the Nusselt number was calculated for the 27 mm combustion chamber at \( t = 7 \) min using conventional heat transfer model in a cylindrical tube [10]. Resulting Nusselt number is 7, which is enough larger than that for the developed laminar flow (\( N_u = 3.7 \)), although the Reynolds number on the experimental condition is about 100 (based on the mean axial velocity). Thus, it can be said that the heat transfer from the burned gas to the combustor wall is drastically enhanced by the vortex flow.

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