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Effect of Heated Microcombustor Specific Surface Area-to-Volume Ratio on Heat Loss Intensity for Micro Power Generation

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Abstract: Microcombustors that burn hydrogen or hydrocarbon fuel as an energy source are difficult to sustain due to high heat loss to surroundings. This paper presents the experimental and numerical simulation of the effect of specific surface area-to-volume ratio of heated cylindrical stainless steel microcombustor on heat loss intensity. The results show that microcombustors with large surface area-to-volume ratios experience low heat loss and high heat loss intensity, whereas microcombustors with small surface area-to-volume ratios have high heat loss and low heat loss intensity. In addition, the difference between microcombustor and ambient temperature also increases the magnitude of both heat loss and heat loss intensity.

Key words: Microcombustor · Convective heat transfer · Heat loss · Micropower generator · MEMS

INTRODUCTION

Micropower generation has been extensively developed to fulfill the demand on compact power systems which are small in size, lightweight, of long duration, high density, robust and safe. Microcombustors that burn hydrogen or hydrocarbon as fuel offer several advantages over batteries such as high energy storage per unit mass and large power generation per unit volume [1]. However, the combustion reaction in a microcombustor is difficult to sustain due to extremely high heat loss to the surroundings caused by the high surface area-to-volume ratio which tends to suppress ignition and quench the reaction [2]. The surface-to-volume ratio is proportional to the inverse of the hydraulic diameter of a combustor [3]. According to the cubic-square law, when the size of a combustor is decreased by a factor of 100, the surface-to-volume ratio will increase by a factor of 100 [4]. With the same heat flux density per unit surface, the heat losses via walls will increase by a factor of 100 per unit volume [5] which will result in rapid flame quenching [6]. Besides that, the physical time available for combustion (residence time) inside the microcombustor is shorter than the time required for the chemical reaction to occur (combustion time) and this makes the complete combustion reaction difficult [7].

In this paper, experimental simulation of the effect of specific surface area-to-volume ratio of heated microcombustors on heat loss intensity for micro power generation is presented. The objective of this study is to understand experimentally the effect of surface-to-volume ratio on heat loss in the microcombustor.

Methods and Procedures

Experimental: In this study, a stainless steel cylindrical microcombustor with an outer diameter of 16mm and length of 28.7 mm was fabricated. The resulting volume and the total surface area-to-volume ratio (a_v) is 5770.5 μL and 0.3, respectively. Stainless steel is used because it endures high temperature, highly strain resistant, durable and has a long useful life [8, 9]. Previous researchers also used stainless steel for microcombustors [1, 10, 11,].

Figure 1 shows the schematic diagram of the experiment setup. The main objective is to determine the heat transfer coefficient (h), heat loss and heat (Q) loss per unit area (Q/A) of the microcombustor. In this experimental simulation, an electric heater is used to heat the microcombustor. The experiment was done in a controlled environment to avoid force convection heat transfer. K-type thermocouples with sensitivity 41 μV/°C are placed at the center and along the walls of the microcombustor. The microcombustor is filled with air and

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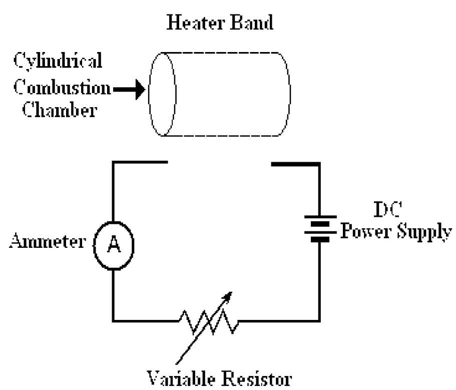

Fig. 1: Schematic Diagram of Experimental Setup

Table 1: Dimensions of the Fabricated and Simulated Microcombustors

a_v	Diameter (mm)	Total surface area (mm2)	Volume (µL)
0.6	7.6	728.2	1211.2
0.9	4.8	408.7	447.0
1.2	3.6	277.1	231.1
1.5	2.8	194.4	127.5
1.8	2.4	150.0	84.6
2.1	2.0	111.2	52.5

the air was heated to 50°C. When air temperature reaches 50°C, the electric heater was turned off and the microcombustor was kept cool by free convection. Temperature along the microcombustor walls and the surrounding region of the walls are measured by using a Fluke thermal imaging camera. The experimental procedure is repeated by heating the air inside the microcombustor from room temperature to 100, 150, 200, 250, 300 and 350°C, respectively.

Numerical Simulation: Numerical simulation is conducted to investigate the effect of microcombustor a_v to heat transfer coefficient (h), heat loss (Q) and heat loss intensity (Q/A). There are five dimensions simulated for the microcombustor (Table 1). The simulated microcombustor a_v is higher compared to that of the fabricated microcombustor because the objective of this experiment is to investigate the behavior of heat loss and heat loss intensity as microcombustor size is scaled down. The surface-to-area ratio is inversely proportional to the microcombustor size. In this simulation, the simulated microcombustors were assumed to have the same material, the same measured walls and the same fluid temperatures with the fabricated microcombustor in the experimental section. The heat transfer coefficient, heat loss and heat loss intensity for each simulated microcombustor were numerically calculated.

RESULTS AND DISCUSSION

Microcombustor Temperature vs. Heater Power: Figure 2 depicts the required heater power to heat the air inside the microcombustor. Power consumed by the heater increases as air temperature increases. A similar trend was observed by Federici *et al.* [5] for microcombustors coupled with thermoelectric element. This is due to the law of conservation of energy. The temperature of the microcombustor can be increased by increasing fuel-to-air ratio [10]. Therefore, increasing the fuel flow velocity will result in higher wall temperature [12]. One important observation shown in Figure 2 is that micropower generators produce a large amount of heat to generate electricity.

Temperature of Fluid Inside the Microcombustor Vs. Microcombustor Wall Temperature: Figure 3 depicts that the temperature at the outer wall surface is lower than air temperature inside the chamber. It is obvious that a temperature gradient exists between these two regions [1, 12-14]. This is attributed to a significant amount of heat absorbed and stored as kinetic or potential energy by molecules of the microcombustor material. According to the result, the overall system efficiency of the microcombustor is always reduced. To reduce the temperature difference between these two regions, the microcombustor walls should be made as thin as possible and the microcombustor should be fabricated from a highly (heat) conductive material.

Effect of Surface Area-to-volume Ratio to Heat Transfer Coefficient: The heat transfer coefficient values were calculated from the dimensionless Nusslet number (Equation 1).

$$h = \frac{Nu\lambda}{d} \quad (1)$$

Figure 4 demonstrates that the magnitude of heat transfer coefficient increases as the microcombustor a_v and temperature increases. It is also worth noting that the heat transfer coefficient is inversely proportional to microcombustor diameter. The increase in temperature difference between the microcombustor and the surroundings owes to the increase of the Grashof number (Equation 2). Consequently, the Nusselt number increased along with the heat transfer coefficient. These variables (Grashof and Nusslet number) are directly proportional with each other (Equation 3).

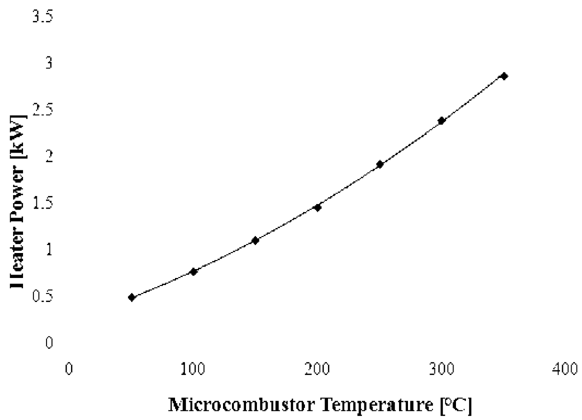

Fig. 2: Heater Power vs. Micro-combustor Temperature.

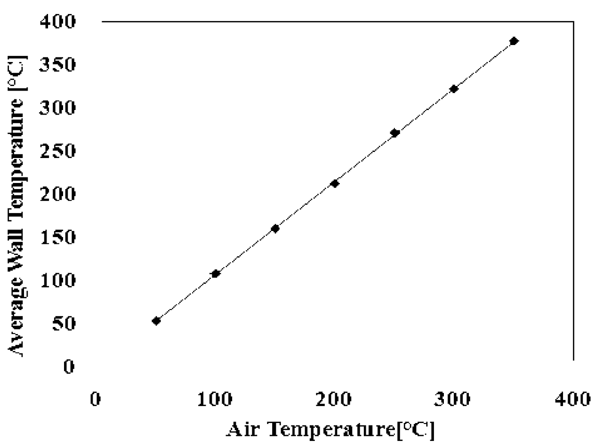

Fig. 3: Microcombustor Walls temperature vs. Air Temperature.

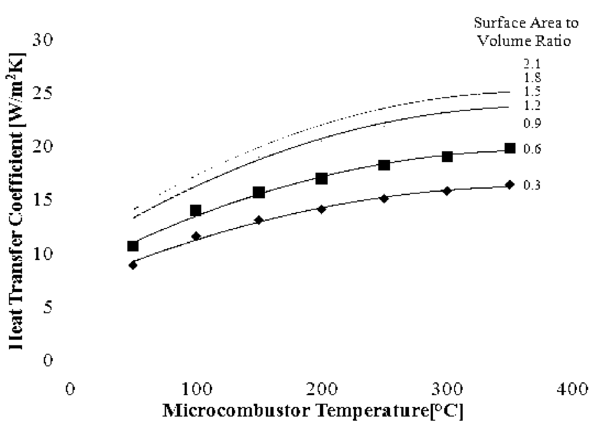

Fig. 4: Heat Trasnfer Coefficient vs. Microcombustor Temperature.

$$Gr = \frac{\beta g \Delta t d^3}{\upsilon^2} \qquad (2)$$

$$Nu = 0.53(GrPr)^{1/4} \qquad (3)$$

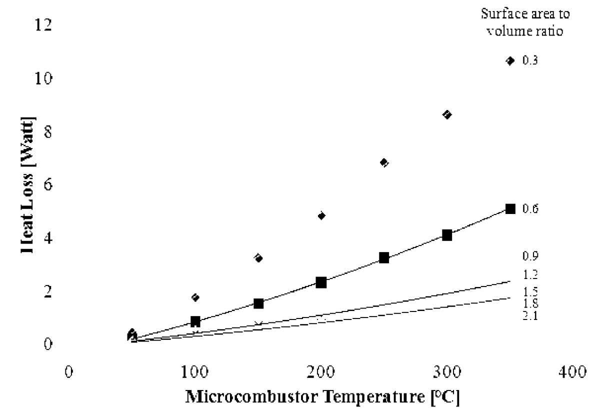

Fig. 5: Heat Loss vs. Microcombustor Temperature.

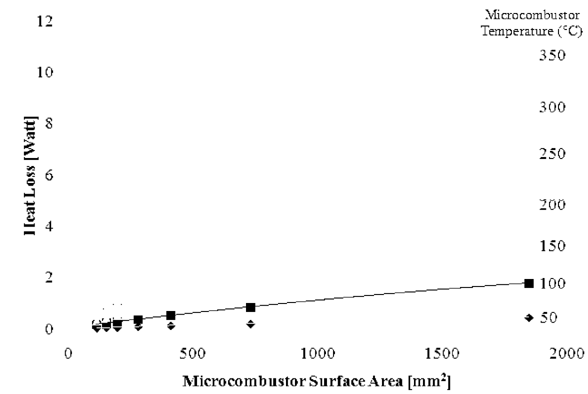

Fig. 6: Heat Loss vs. Microcombustor Total Surface Area.

Effect of Surface Area-to-volume Ratio on Heat Loss: Heat losses from the microcombustors were calculated using Newton's law of cooling as shown in Equation 4:

$$Q = hA(t_0 - t_s) \qquad (4)$$

Figure 5 depicts heat loss of the microcombustor. Microcombustors with low a_v experience higher heat loss compared to those with high a_v. Moreover, heat loss increases with the increase of microcombustor temperature. One reason for this is that the magnitude of heat loss is directly proportional to the heat transfer coefficient, total surface area and temperature difference between microcombustor walls and the surroundings. Figure 6 is plotted to give a better illustration of this relationship. The magnitude of heat loss increases as the size and temperature of microcombustors increase.

Effect of Surface Area-to-volume Ratio on Heat Loss Intensity: Heat loss intensity was calculated by dividing both sides of Equation 4 with the microcombustor total

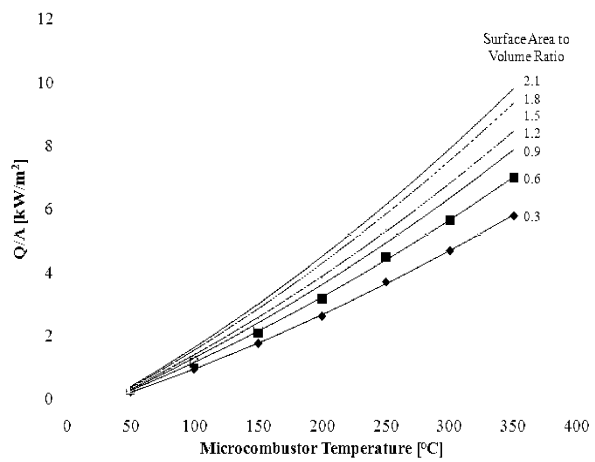

Fig. 7: Heat Loss Intensity vs. Microcombustor Temperature.

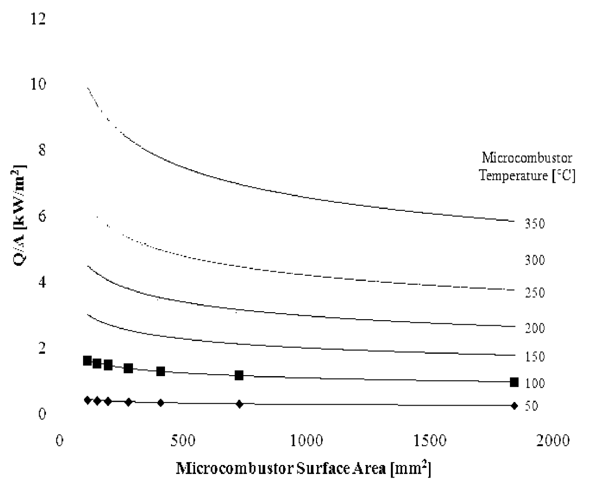

Fig. 8: Heat Loss Intensity vs. Microcombustor Total Surface Area.

surface area. Figure 7 illustrates heat loss intensity of the microcombustors. A consistent trend shows that increasing the temperature and surface area-to-volume ratio increases heat loss intensity. However, a significant increase is observed for high surface area-to-volume ratios. This may be due to a high heat transfer coefficient value. This argument is supported by Figure 8. The smaller surface area has higher heat loss intensity. The possibility of combustion to sustain over a long period of time in microcombustors (burning hydrogen or hydrocarbon) is very difficult due to the quenching effect.

CONCLUSION

A cylindrical stainless steel microcombustor was designed, fabricated and tested. Six microcombustors with various a_v were numerically studied. Based on the results of both experimental and numerical studies, microcombustors with small a_v result in higher heat loss to the surroundings compared to those that have large a_v. However, heat loss per unit area for the microcombustor with a small a_v is higher than those with a large a_v. Heat loss intensity is linearly proportional to surface area-to-volume ratio and inversely proportional to heat loss.

One important observation is that the temperature difference between the microcombustor and the surroundings greatly affect the magnitude of heat loss and heat loss per unit area. It is obvious that increasing the temperature will result in the increase of heat loss and heat loss per unit area.

The major contribution of this study is that the demonstration of heat loss from the surface area of microcombustors is greatly undesirable but cannot be avoided since miniaturization is the main goal. As a general solution to reduce heat loss, good insulation should be introduced.

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Nomenclatures:

a_v *Surface area to volume ratio*
A *Surface area*
β *Cubical expansion, 1/T*
d *Diameter*
g *Gravitational acceleration*
Gr *Grashof number*
h *Heat transfer coefficient*
Nu *Nusselt number*
Pr *Prandtl number*
Q *Heat loss*
t_o *Microcombustor temperature*
t_s *Surroundings temperature*
Δt *Temperature difference between microcombustor and the surroundings*
υ *Kinematic viscosity of the surroundings fluids*
λ *Thermal conductivity of the surroundings fluids*

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