Standalone portable micro power generator using stepped micro combustor

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1. Introduction

The global requirement for miniature, portable sources of power has propelled the demand for devices powered by microcombustors. Power sources based on combustion have an edge over their counterparts due to their high energy density, light weight and short recharging time [1]. However, two major areas of concern regarding the flame stabilization in microcombustors are related to its thermal and radical quenching, which can be attributed to its large surface to volume ratio [2]. The problems faced due to quenching/extinction of the flame can be addressed by adopting more efficient thermo-chemical management techniques. Presence of catalysts, employing porous media in the combustors, and designing stepped/bluff body/cavity combustors are some strategies used to ensure proper flame stabilization [3]. A hydrocarbon fueled power source, 5 % efficient in conversion, has an energy density that is six times higher than that of a conventional chemical cell. The breakthrough work carried out in the Massachusetts Institute of Technology's Gas Turbine Lab marked the beginning of the significant progress that was to be made in the field of micro-power generation methods [4]. An experiment was carried out by Lee at al. [4] to study the possibility of using thermophotovoltaic cells (TPV) as a power generating source by using an ammonia-hydrogen mixture which, due to its low temperature, gave rise to a secondary flame on the micro-emitter and reported an efficiency of 2.1 %. Schaevitz et al. [5] carried out combustion in the presence of a catalyst for generating micro electro-mechanical systems (MEMS) thermo-electric power. It was 2 % conversion efficient and reported to operate steadily up to 500 ^{0}C with an output voltage of 7 V. A meso-scale vortex combustor, with a 0.7 % conversion efficiency, was proposed by Shimokuri et al. [6]. Yadav et al. [7] utilized rearward facing stepped micro-combustor which had a heat recirculation cup attached to it. By using four modules at 6.5 m/s, the system was found to be 4.6 % efficient. Water-cooling is generally adopted method for thermoelectric generator (TEG) due to its high cooling efficiency. Even though water-cooled systems have a higher efficiency than their air-cooled counter parts, the utilization of air-cooled heat sinks in micro-aerial vehicles and unmanned aerial vehicle (UAVs) is more pragmatic mainly due to the ready presence of airflow with high flow-rate and low temperatures at heights. This system, in fact, has a higher heat transfer coefficient and a lower temperature on the module's cool side, which could lead to greater power output than the corresponding water-cooled system. Water would also significantly increase the payload. The present study is carried out with the objective of developing an autonomous micro power generator using air cooling. Air-cooled systems are preferred over the corresponding water-cooled systems because of the increase in the weight and volume of the system, despite the former having a slightly lower conversion efficiency due to its relatively weaker cooling effects.

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Limited research [6, 8] has been conducted in the design of air-cooled microcombustors while studies have also been undertaken on imitating the microcombustor through external electric heaters [9]. An air-cooled system, without the use of catalysts, has been proposed as a source of power in this study. The uniqueness of the proposed design are its compact size and high power density. Due to the requirement of obtaining a higher performance from this system than the water-cooled one, various air-cooled configurations were tried and tested and the one with the highest output was adopted. For water-cooled microcombustors, the main obstacle lay in optimizing the output through efficient designing of the heat sink and source. Chen et al. [10] and Aravind et al.[11] displayed that the heat source was more pivotal than the patterns of flow of the heat sink and the flow rates of the coolant for micro-combustor-based power generators. Thus, to obtain highly efficient thermoelectric power generators on a micro-scale, the ideal design requires the maximum heat transfer from the combustion products to the TEG module to take precedence.

In the present study, a dual combustor-based thermoelectric power generator with different modes of air-cooling heat sinks, such as a cooling fin with natural cooling, fin-fan combination with forced convective cooling are investigated and presented. Detailed experimental investigations on flame stability limits in the micro-combustor systems are carried out initially to understand the effect of various heat sinks on thermal characteristics of the combustor. Further, two thermoelectric modules are integrated into the combustor along with different active and passive cooling sinks for electric power generation. Finally, a standalone micro power generator system is developed, which consists of a power supply unit and mixture supply unit.

2. Details of microcombustor and power generator

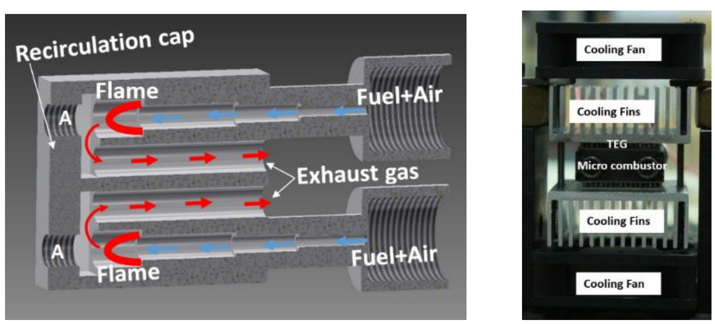


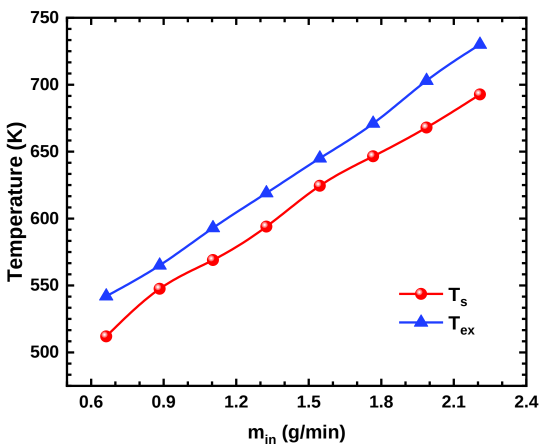
Figure 1. left: Cross-sectional view of the dual micro combustor; right: Power generator prototype.

The microcombustor consists of two rearward facing stepped combustors with two recirculation holes (which are used for exhaust gas feedback) of 4 mm diameter in an aluminium chamber with a total volume of $32 \times 32 \times 10$ mm^3. Each set of combustor consist of three rearward facing steps located at tube diameters of 2 mm, 3 mm, 4 mm and 6 mm from inlet to the outlet direction.The rearward facing steps assist in increasing the residence time of the mixture in the combustor by forming local recirculation zones near the steps, which also helps in stabilizing the flame. The recirculating holes aid in transferring the enthalpy of the exhaust gas to the fresh charge and help in preheating it. Overall, the strong flow recirculation and heat recirculation helps in enhancing the flame stabilization limits of the combustor. In addition to that, the presence of two combustion zones in the dual combustor setup offers a better thermal performance compared to the single combustor due to the enhancement of the intensity of combustion by the improved flame to wall and flame to flame interaction. The combustor used in this study is identical to our previous study [11]. Figure 1(left) shows the CAD drawing of the micro combustor designed for a 100 W thermal input based on the chemical energy input to the combustor (for propane fuel). While its weight is below 200 g, the size of the whole power generator unit is comparable with conventional electrochemical batteries as shown in Fig. 1 (right). Combustion of the air-fuel mixture releases heat, which is utilized by the two thermoelectric generators placed on the sides of the combustor to convert the heat into electric energy. The cold side of the generator is maintained at low temperature with the help of an aluminium fin and a fan placed on the top and bottom bare sides of the microcombustor. To test the output power of the system, an auxiliary source has been utilized to supply power to the fan. A regulated DC power supply system (TESTRONIX 92B) is used to power the fan for different rotational speeds based on the input power. For instance, a voltage of 3.98 V and current of 95 mA (corresponding to 0.38 W) is required for running the fan at 3000 rpm.

3. Result and Discussion

A detailed thermal analysis has been carried out for the proposed microcombustor and the power output characteristics of the power generator have been studied and discussed in the following sub-sections.

3.1 Thermal performance



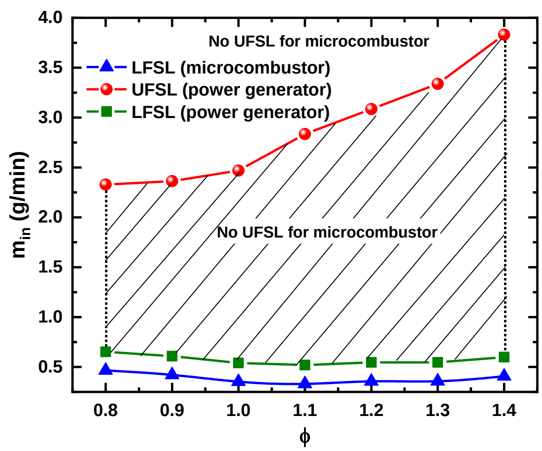


Figure 2. left: Variation of the average wall and exhaust gas temperatures with mixture flow rate; right: Flame stability limit of the combustor and the power generator.

The variation of average wall temperature (T_s) of the combustor with the mass flow rate of the mixture has been studied. The T_s in the study is calculated by averaging the wall temperature of eight equidistant points along the central line of the combustor wall. The temperature is measured with the help of k type thermocouples. It is found that a uniform surface temperature (T_s) has been achieved and the combustor was able to extract maximum enthalpy from the exhaust gas for all the mixture velocities experimented as shown in Fig. 2 (left). The reason for this can be attributed to the highly intense combustion of the propane-air mixture in two different zones of the system. The performance characteristics of the microcombustor and the power generator are obtained by initially varying the equivalence ratio and velocity of the inlet mixture. The upper flame stability limit (UFSL) of the combustor is found by increasing the mixture velocity at an increment of 0.5 m/s for equivalence ratios ranging from 0.8 to 1.4 as shown in Fig. 2 (right). The UFSL of power generator is measured while integrating the TEG and cooling jacket to the micro combustor. It is noted that the UFSL is lowered when the rate of heat transfer to the module is increased. However, experimentally, no UFSL is obtained for the micro combustor within the experimental limits (0-5 g/min). To avoid melting of the aluminum combustor (melting point of Aluminum is ~875 K), the experiments are limited to a maximum mixture flow rate of 5 g/min. Thus, it is noted that the microcombustor can operate at high flow rates across all the investigated equivalence ratios.

To study the effect of heat recirculation, the ignition plugs are closed after ignition. This allows the exhaust gases to pass through the recirculation chamber. The effect of HR has been observed and plotted in Fig. 3 (left). Recirculating hot combustion products improve the UFSL and lead to a rise of almost 80-100 K in the average wall temperature when compared with the no heat recirculation case. This can be justified by a remarkable increase in heat transfer to the walls due to increased turbulence of the recirculating flow. It is noteworthy that despite the mass flow rate of the inlet mixture approaching 2.3 g/min, the temperature on the hot side does not exceed 250 ^{o}C-which is the maximum operating limit of the TEG.

Furthermore, a micro power generator is developed by mounting two thermoelectric generators on a dual micro-combustor, along with the aluminium fin as a heat sink (active cooling). The thermoelectric generator used in the study is TEG1-127-30-30T250HP from Nippon Pvt. Ltd. India. The properties of the material of construction of the module are difficult to obtain because of the proprietary rights of the manufacturer. To improve the performance of the power generator, a cooling fan is placed above each set of cooling fins. This helps in maintaining a low temperature through the passive cooling. Three different power ratings of 0.07 W, 0.19 W, and 0.38 W are given as an input for the auxiliary source of power, with corresponding fan speeds of 500 rpm, 1500 rpm and 3000 rpm. A high accuracy optical tachometer is utilized to measure the speed of the fan. It is noted that as the mixture flow rates increases, there is a sharp rise in the hot side and cold side temperatures of the fin system (P_{aux} = 0.0 W). As the thermal input increases from 29 W (0.70 g/min) to 58 W (1.4 g/min), the hot side temperature increases from 384 K to 470 K and cold side temperature increases from 323 K to 400 K respectively for the fin system. The rapid rise in the temperature of the cold side is observed because of the heat transfer (due to conduction) taking place directly from the combustor to the fin through the modules. It can also be attributed to a lack of forced convection-which reduces heat transfer from the module's cold side to the surrounding air. Experiments are carried out up to mixture flow rate of 1.4 g/min as there is no significant improvement in the temperature difference (T_{Hot} – T_{Cold}) across the module. A significant drop in the cold side temperature can be observed for fin-fan system (P_{aux} = 0.38 W) as shown in Fig. 3 (right).

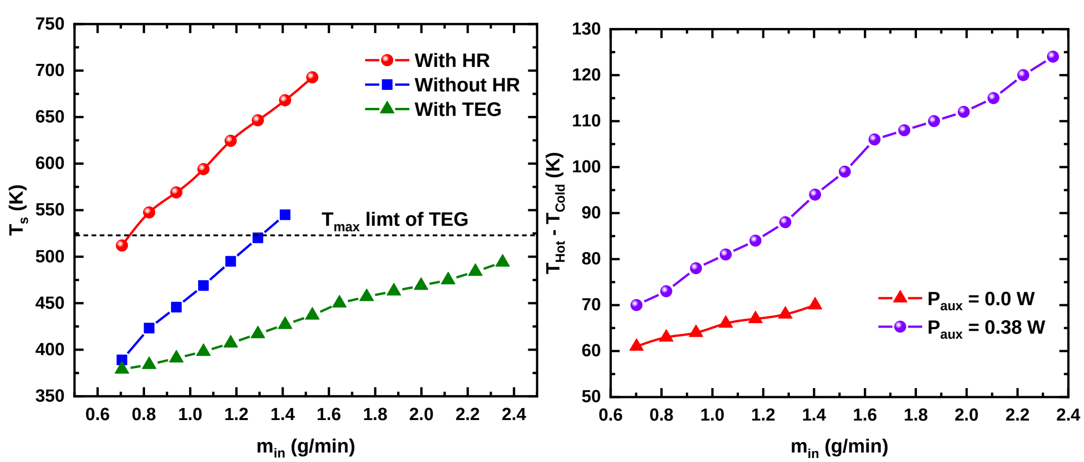


Figure 3 left: Various surface temperature measurement with mixture flow rate; right: variation of T_{Hot}-T_{Cold} for different auxiliary power inputs.

3.2 Power performance

A graph is plotted between the output power and the mass flow rate of the inlet mixture for different auxiliary power inputs (0-0.38 W) as shown in Fig. 4 (left). The 0 W of auxiliary input corresponds to natural convection, while the other readings correspond to forced convection. The conversion efficiencies and the output power are found to increase with a rise in the fuel input for the fin-fan system, but a drop is observed with a fuel input for the fin system-mainly due to the poor cooling. A maximum power output of 1.3 W, 2.0 W and 2.4 W with conversion efficiencies of 1.4 % and 2.1% and 2.5 % respectively were achieved for P_{aux} = 0.07 W, 0.19 W, and 0.38 W as shown in Fig. 4 (left) and Fig. 4 (right).

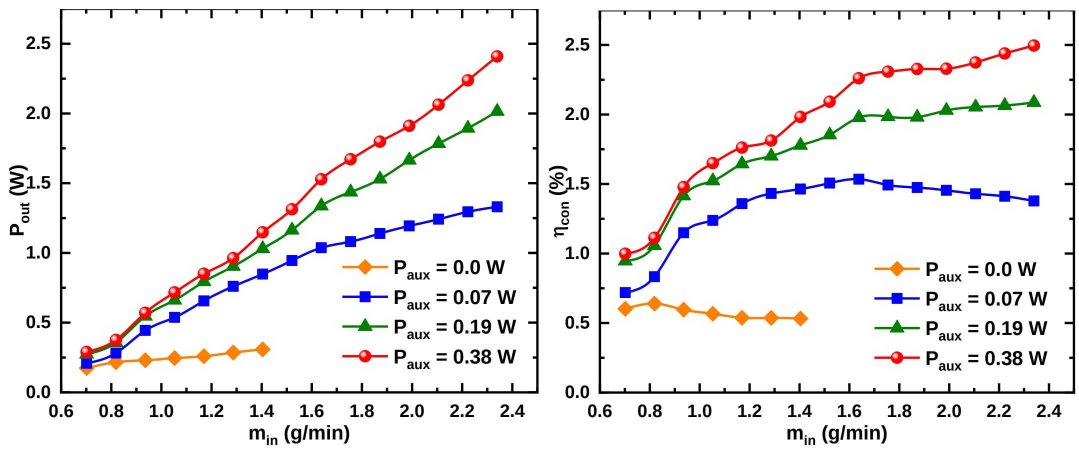


Figure 4. Variation of (left) output power and (right) conversion efficiency with mixture flow rates.

If analyzed from a manufacturing perspective, the auxiliary requirements for the system like the fan, micro-blower, electronic circuits and valves are insulated and usually have a lifespan of 8-10 years. These parts are not only inexpensive, but also readily available and can be easily replaced too -making the product durable and efficient for long-term operations. The proposed power generator is observed to be more efficient than its counterparts -in terms of conversion efficiency and power density. Regarding applications, a small fuel reservoir of ~180 g can be utilized for a 24-hour operation, while the air used for the purpose of combustion can be obtained by using a micro-blower. The recharging process involves replenishment of fuel in the fuel reservoir. Experiments and research on reducing weight, using self-aspirating combustors, is underway. Nevertheless, Faniculli et al. [12] and Shimokuri et al. [13] has obtained positive results for the above-mentioned study fields. This provides assurance of the fact that the proposed generator can be optimized for manufacturing operations.

4. Development of a standalone micro power generator

With reference to the results discussed above, a standalone micro-power generator is designed,which is capable of producing approximately 1 W power output, as depicted in Fig. 5. Acrylic is used as the material of construction for the outer body and it has a total weight of 400 g with an overall volume of 120 × 95 × 75 mm^3 (full power generator system). The system relatively heavy and bulky as it is not completely optimized, but this may be the first microcombustor based portable power system across the globe up to the author's knowledge. The system consists of a power supply unit which includes two thermo-electric modules integrated to the micro-combustor, with aluminum fins used for cooling along with a CPU fan (perpendicular to the direction of the fin) and an additional unit to deliver the premixed fuel-air mixture. In the mixture supply unit, fuel from a small butane cartridge injected to the combustion air from a micro blower. A potentiometer is used to vary the mass flow rates and equivalence ratios of the mixture. The power supply unit is supposed to be portable, but the presence of a water reservoir will render it difficult to carry around. Moreover, the output wattage of the current system can be improved significantly. Different fin arrangements and dimensions can be used to obtain an optimum output. Moreover, using a device similar to a miniature flow valves will give greater control over the flow rate of the fuel and could give an increased output.

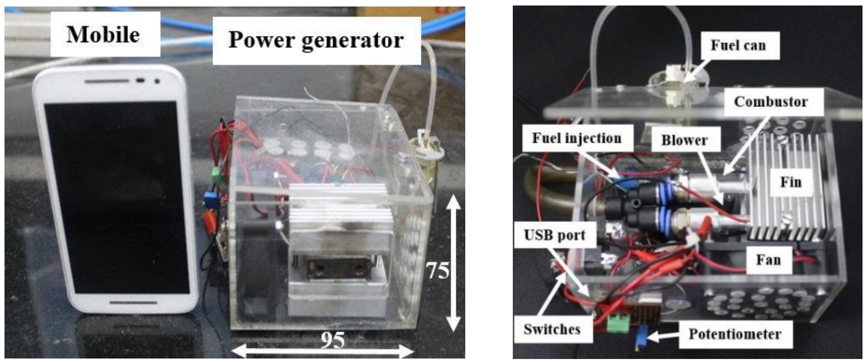


Figure 5. Variation of (left) Size comparison of the prototype; (right) inside view

5. Summary

An in-depth analysis of the thermal performance of the proposed microcombustor has been performed in the given study. Due to the formation of a dual combustion zone, dual combustor provides better performance than the single combustor. Furthermore, a thermoelectric generator was integrated with the combustor and a comparison study was carried out for different kinds of air-cooled systems and a water-cooled system. As a final step, the prototype "autonomous micro power generator" to charge the mobile electrical devices has developed. Using 250 g butane cartridge, ~1 W output can be obtained over 24 hours with running all assisting devices such as micro blower for the combustion air or fans for cooling air of TEG.

6. References

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