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Experimental investigations on a new high intensity dual microcombustor based thermoelectric micropower generator

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HIGHLIGHTS

- Developed a novel dual micro combustor for portable thermoelectric power gen.
- The proposed system size is compatible with a conventional electrochemical battery.
- Thermal characteristics & flame stability limits of the micro combustor presented.
- Thermoelectric modules were integrated to the combustor for the power generation.
- Micropower generator having high power density (0.14 mW/mm^3) is prototyped.

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ABSTRACT

A new concept of dual microcombustor based thermoelectric micropower generator with high power density (~0.14 mW/mm^3) and high conversion efficiency (4.66%) is reported in this work. A new configuration with a dual microcombustor system is experimentally investigated with two thermoelectric modules and operates with liquefied petroleum gas as fuel. The dual microcombustor is fabricated using a rectangular aluminium metal block and detailed investigations on flame stability limits and thermal characteristics were carried out. Dual microcombustor configuration helps to significantly improve the flame stability limits and thermal characteristics over the single combustor configuration due to increased flame-surface interaction and enhanced heat recirculation through solid walls. Maximum power point tracking (MPPT) algorithm is applied to achieve a maximum power output of 4.52 W with a maximum conversion efficiency of 4.66%. The application of porous media significantly helped improve the upper flame stability limits with a maximum conversion efficiency of 4.32%, and 4.66%, at $\phi = 1$ and 0.9 respectively at 10 m/s mixture velocity. The system compactness and high output power with significantly improved conversion efficiency shows the possibility of its application in various portable micro-scale power generators for remote, stand-alone, military and aerospace applications.

1. Introduction

There is a strong motivation to develop combustion-based portable power systems in the past few decades due to the rapid development and implementation of micro electromechanical systems (MEMS) in various platforms and small power requirement by these systems for their efficient operation. The usage of conventional electrochemical batteries as a power source is limited in various military, aerospace and standalone applications due to its inherent disadvantages such as long recharging time, heavy weight, low energy density and adverse environmental impacts [1]. Hydrocarbon fuel-based power source with a conversion efficiency of ~5%, would result in six times higher power density than advanced electrochemical battery concepts as illustrated in Fig. 1a. Therefore, combustion-based systems for power generation are considered to be a viable alternative to conventional electrochemical batteries owing to their high-power density, light weight and compact size [2]. The power delivered by various conventional electrochemical batteries has a sloping discharge curve and it falls progressively throughout its discharge cycle as shown in Fig. 1b. This could give rise to various problems in the system performance, particularly those requiring a constant voltage supply throughout their operation. Therefore, the combustion-based micropower generators could provide a better alternative as they are capable of providing a constant power throughout the operational time with minimum recharge time as shown

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Nomenclature

I	current (A)
m^*	inlet mixture flow rate (kg/s)
P_{in}	input power (W)
P_{aux}	pumping power (W)
P_{out}	electrical power output (W)
Q_s	heat supplied to module (W)
Q_r	heat rejected from module (W)
R_i	internal resistance of module (Ω)
R_L	load resistance (Ω)
t_p	porous media thickness (m)
T_{Cold}	cold side temperature (K)
T_{Hot}	hot side temperature (K)
$T_{surface}$	average surface temperature (K)
U_{in}	inlet mixture velocity (m/s)
V_w^*	volume flow rate of coolant (lpm)

Greek symbols

ϕ	equivalence ratio
Ω	unit of electric resistance
η_{con}	conversion efficiency

Abbreviations

LFSL	lower flame stability limit
MPPT	maximum power point tracking
TEG	thermoelectric generator
UFSL	upper flame stability limit

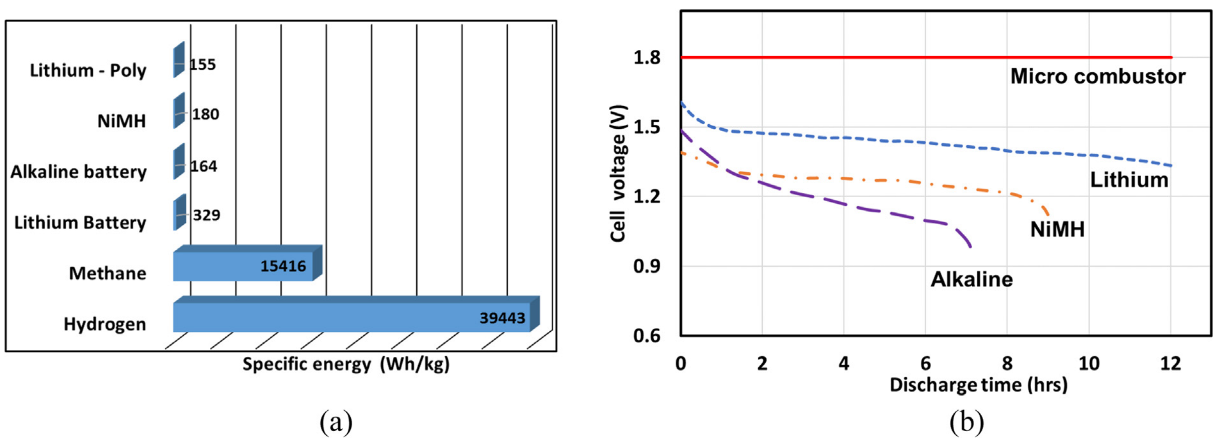

Fig. 1. (a) Comparison of the energy density of hydrocarbon fuels with conventional electrochemical batteries. (b) Comparison of discharge curve of different battery systems and microcombustor based power generation system.

in Fig. 1b. The hydrocarbon fuels have 50–100 times higher energy density than conventional electrochemical batteries [3]. Therefore, various innovative methods to use combustion-based power generators for such applications have been pursued by researchers all over the world [4,5]. Flame stabilization in such small-scale combustors continues to be a challenging task due to its increased surface to volume ratio [6]. The strong thermal-wall coupling together with the reduced residence time results in increased tendency of flame quenching through radical and thermal quenching routes [7]. Researchers have implemented various innovative techniques of excess enthalpy combustion [8–10] and catalytic combustion [11,12] to resolve the flame quenching issues at such small scales. Chou et al. [10] studied the effect of porous media on micro combustor performance. Their results show that higher and superior uniform temperature distribution along the combustor wall can be achieved with the application of porous media. Vijayan et al. [11] studied the importance of heat recirculation on meso scale combustor by performing a detailed parametric study on combustor performance by varying the combustor material, inlet conditions etc. Thorough investigations on various aspects of flame stabilization in swiss roll combustor by Shirsat and Gupta [13] and Wierzbicki et al. [14] indicate that extended extinction limits and combustion stability can be achieved with proper thermal management in the swiss roll combustors. This concept in the context of thrust generation for various applications such as small robotics and nanosatellites also explored by same research group using methanol as fuel [15]. Numerous numerical studies have been performed to understand the flame stabilization and its dynamics in microchannels in past decade [16–20]. Wan and Zhao [17] investigated the flame dynamics in a novel preheating micro combustor suitable for portable power applications. They observed a wide stability and various instability regimes due to the interplay between flame speed and flow velocity. Alipoor and Saidi [18] and Akhtar et al. [20] performed a numerical study on curved micro combustors suitable for photovoltaic power generation applications. The result shows a significant increase in the flame stability limits and combustor wall temperature for the curved micro combustor compared to the straight channel micro combustors. They observed a wide stability and various instability regimes due to the interplay between flame speed and flow velocity. Zuo et al. [21] used rectangular rib in the micro-cylindrical combustor for better flame stabilization. They conducted a detailed parametric study on the geometry of ribs to achieve maximum wall temperature and uniform temperature distribution. Since, the conventional chemical batteries are outperformed due to aforementioned issues, several combustion-based micropower generation systems such as micro gas turbine [22], micro thermophotovoltaic generators [23,24], fuel cells [25] and thermoelectric generators [26–30], were recently proposed and investigated. Although, heat engines could be commonly proposed, their significant heat and friction losses due to the presence of moving parts make them impractical for various applications at such small scales because of strong noise and low conversion efficiencies. Thermoelectric and thermophotovoltaic power generators are simple systems and subjected to less maintenance issues due to the absence of moving parts [31,32]. Cho et al. [33] have reviewed several micropower generation systems and provided deep insights into recent advancements of such systems.

Several efforts have been made by researchers on TPV [23,24] and fuel cell [25] based micropower generators. Yang et al. [23] developed a micro thermophotovoltaic power generator using backward stepped combustor with 0.113 cm^3 volume. The system delivered 1.02 W power