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Compact design of planar stepped micro combustor for portable thermoelectric power generation

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ABSTRACT

An efficient prototype of a micro power generator with integrated micro combustor has been developed in the present study. The proposed design of the integrated micro-combustor provides high surface temperature with superior temperature uniformity and enhanced flame stability limits, a prerequisite for a thermoelectric power generation system. This novel micro combustor configuration consists of three backward facing steps with a recirculation hole fabricated in a rectangular heating medium of aluminium material. Parametric studies are carried out by varying the mixture inlet velocity, equivalence ratio and coolant flow rate to obtain the optimized operating conditions for maximum power generation. Two thermoelectric modules are mounted on the system operating with liquefied petroleum gas as fuel. A maximum conversion efficiency of 3.3% is obtained at ϕ = 0.95 with a mixture velocity of 7.5 m/s and a load resistance of 4 Ω across the thermoelectric generator. The effect of porous media is investigated to enhance the flame stability limits in the micro combustor. Porous media significantly enhances the upper flame stability limits and maximum conversion efficiencies (3.8%, 4.03%, and 3.73% at ϕ = 1, 0.9 and 0.8 at 10 m/s). A significantly higher power density (~50% higher than existing systems) of 0.12 mW/mm^3 of system volume is achieved. A compact design of the prototype system with high conversion efficiency shows the possibility of its application for various systems requiring portable power for remote, stand-alone, military and aerospace applications.

1. Introduction

Combustion driven micro devices are receiving increased attention and interest from the research community due to their intense demand for the development of small-scale portable power sources. Combustion based power devices can be considered as a competitive alternative to conventional electrochemical batteries because of their high energy density, high power density, compact size, small recharging time and long working time, [1–3]. These devices have wide applications in micro satellite thrusters, MEMS, chemical sensing, and micro air vehicles (MAV) [4,5]. High precision fabrication techniques such as stereo-lithography and rapid prototyping helped in the faster development of micro and nano scale devices. Thermal and radical quenching are two key issues associated with flame stability in micro combustors due to high surface area to volume ratio [6]. Proper thermochemical management techniques have been adopted to minimise the quenching problems and significantly improve the flame stability limits [7,8]. Many researchers have come up with innovative techniques to solve the flame stability issues through excess enthalpy combustion [9,10]. Catalytic combustion [11–13], Porous media combustion [14–17] and use of stepped combustors [18–20] are some of the useful strategies proposed and successfully implemented to circumvent the flame quenching issues in small scale combustion devices. Hydrocarbon fuel based systems with a conversion efficiency of ~5%, would result in 6 times higher power density than a conventional high efficiency electrochemical battery, because of its high energy density [10] as shown in Fig. 1. Fig. 1 shows that combustion based systems have significantly (50–100 times) higher power densities as compared to various advanced electrochemical battery concepts. Such power generation systems with higher conversion efficiencies are yet to be explored in detail.

One of the earlier breakthrough in the field of micro combustion and micro power generation was reported by MIT gas turbine laboratory, USA, which provided a clear insight into the micro power generation methods [21]. Moving components in these types of conversion devices are frequently subjected to maintenance problems, resulting in very low conversion efficiencies. Therefore, many researchers focussed on direct conversion devices such as thermophotovoltaic (TPV) based devices [22–28], thermo electric generators (TEG) [29–34] and fuel

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Nomenclature

A_m	surface area of TEG (m^2)
A_s	bare surface area of the combustor (m^2)
h_c	wall heat transfer coefficient (W/m^2 K)
I	electric current (A)
K_m	thermal conductivity of TEG (W/m
L_m	width of the TEG (m)
$\overline{m}$	mass flow rate (kg/s)
N	number of TEGs
R_i	internal resistance (Ω)
R_L	load resistance (Ω)
S	seebeck coefficient (V/K)
SD	standard deviation

Greek symbols

ϕ	equivalence ratio
Ω	unit of electric resistance
S_J	uncertainty
T^C	cold side temperature (K)
T^H	hot side temperature (K)
T_∞	ambient temperature (K)
T_f	combustor wall temperature (K)
U	uncertainty (%)
U_{in}	mixture velocity (m/s)
V_L	load voltage (V)
V_o	open circuit voltage (V)
X_i	measured data
$\overline{X}$	mean value of measured data

Abbreviations

CV	calorific value (kJ /kg)
TEG	thermoelectric generator

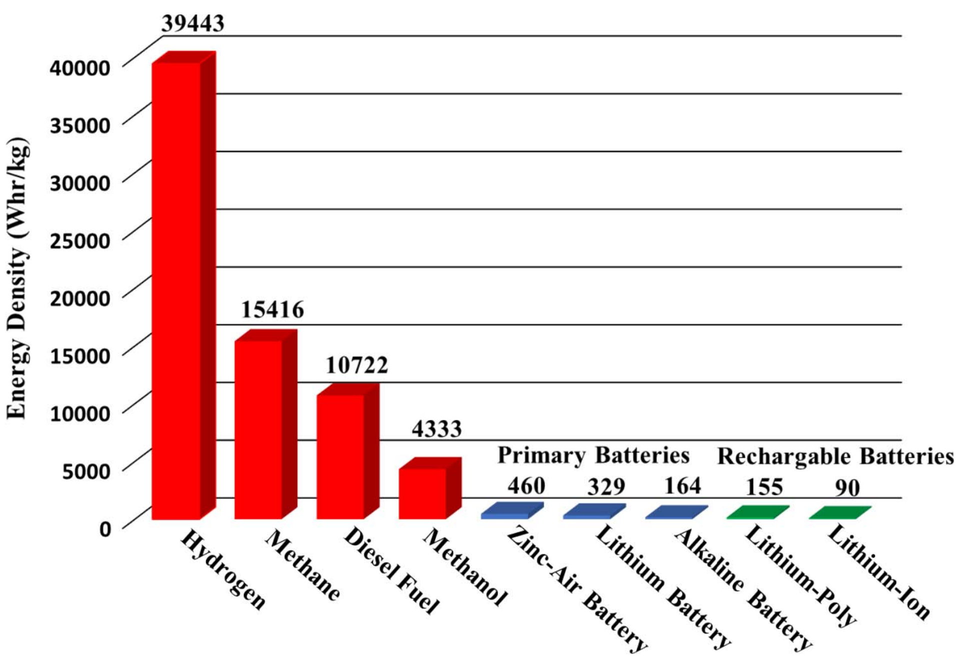

Fig. 1. Comparison of the energy density of hydrocarbon fuels with conventional electrochemical batteries.

cells [35,36] integrated to the micro combustors.

Yang et al. [23] proposed a thermophotovoltaic (TPV) based micro power generation system by integrating it with a backward facing step combustor. They observed that channel diameter and step size are crucial factors affecting the performance of the system. The increase in step height enhanced the heat recirculation near the combustor wall, thereby facilitating complete and stable combustion. Jiang et al. [26] fabricated a planar combustor suitable for microTPV, which facilitated a higher wall temperature (above 1300 K) with superior uniformity in the temperature profile and high combustion efficiency. Lee at al. [28] developed a micro combustor with a heat recuperator to extract electric power using TPV. They used a blend of ammonia and hydrogen as fuel which generated a secondary flame at the micro emitter due to its low temperature. They reported an overall conversion efficiency of 2.1%. Lei et al. [27] recently developed a model to estimate the power generation using micro TPV integrated to an annular micro combustor. They achieved a maximum conversion efficiency of 3.15% for a 1 mm annular micro channel. Further various numerical efforts on different microcombustor configurations have been made to enhance the uniformity and surface temperature suitable for thermophotovoltaic application [37–39]. One of the earliest development in TEM by Schaevitz et al. [29] reported MEMS based thermo electric power generation system using catalytic combustion. This generator was stable up to 773 K and achieved a conversion efficiency of 2% with an output voltage of 7 V. Similar work has been reported by Yoshida et al. [30], with a conversion efficiency of 2.8% and a power output of 184 mW. Jiang et al. [31] fabricated and tested a micro plate flame combustor for power generation with DME as fuel. Shimokuri et al. [32] prototyped a meso scale vortex combustor for thermo electric power generation. Vortex flow helped enhance the heat transfer from burnt gas to the combustion chamber. This led to a significant improvement in the conversion efficiency to 0.7%. Yadav et al. [34] developed a micro power generation system using a rearward facing stepped micro combustor with heat recirculation cup. A conversion efficiency of 4.56% is reported with four modules at 6.5 m/s mixture velocity. Qiu et al. [40] developed a power generation system by cascading the TEM (Thermoelectric modules) and TPV (Thermophotovoltaic modules) to increase the system efficiency. Their investigations successfully proved that higher efficiencies from a TE-TPV integrated system can be achieved over a TPV or TE power generator alone. Walther et al. [41]