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Development and investigation of a non-catalytic self-aspirating meso-scale premixed burner integrated thermoelectric power generator

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ABSTRACT

Portable electrical power generation using hydrocarbons presents significant potential owing to their higher power densities and negative environmental factors associated with chemical cell batteries. Small scale combustors have been widely developed and tested for power generation purposes, employing thermoelectrics and thermo-photovoltaic conversion of combustion heat into electricity. This experimental study is concerned with development and investigation of a novel non-catalytic meso-scale self-aspirating premixed burner with integrated thermoelectric generator which can be used in remote places to generate electricity for a continuous period of one month. Flame stabilisation has been one of the main issues in small scale combustion systems due to higher surface to volume ratio associated with small size of the combustor. Previous research has shown that catalytic combustion is one way of improving flame stabilisation, however employing a catalyst into the system increases the manufacturing cost which can be a significant downside. This research work studies flame stabilisation mechanisms in meso-scale burner which mainly focuses on backward facing step and secondary air addition into the combustion chamber. The first phase of the research was involved development of the burner which included optimisation of the design to achieve a stable enclosed premixed flame as per the design and operational requirements. The second phase of the research focused on the integration of the burner with thermoelectric power generators. This involved investigation of various configurations to optimise the electrical power output when limited amount of heat is available. The relationship between ambient temperature and thermoelectric power generation using an environmentally controlled chamber has also been presented in this experimental study.

1. Introduction

Thermoelectric power generation using small scale combustion of hydrocarbons is a promising alternative to conventional means of generating electricity. It is reported that hydrocarbons have notably higher energy density when compared to chemical cell batteries. For example, propane has a specific energy of 40 MJ kg^{-1} whereas a lithium-ion battery has 0.5 MJ kg^{-1} [1]. Batteries require long recharging durations and there are several environmental issues associated with their disposal. It is estimated that less than 3% of lithium-ion batteries are recycled, the rest being landfilled [2]. There are several benefits of thermoelectric power generation such as high reliability, noiseless operation, inexpensive maintenance and long life [3,4]. This research work involves a detailed study of integration of thermoelectric power generation modules with small combustors. The principle of thermoelectric power generation is based on Seebeck effect which states that a voltage is generated when there is a temperature difference at the two junctions of semiconductors joined together [5]. Modern thermoelectric generator (TEG) modules are fabricated using n-type and p-type semiconductors connected electrically in series. In the thermoelectric-burner integrated systems, combustion of hydrocarbons such as propane provides the heat required to raise the temperature of the hot side of a TEG module while cooling is provided at the cold side via heat exchangers or cold water recirculation.

A small scale thermoelectric power generation device employing combustion is presented in this work. The application of this device is in remote areas where mains electricity is not easily available. An application can be found in pest control industry where insect traps can be powered in gardens or farms by such unit while subsequently using the combustion exhaust (carbon dioxide and water) to attract insects [6]. Other applications can be in military and in parts of developing countries where electricity is not

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Nomenclature

Symbol	Definition
P	power output ,Watt (W)
P_1	power output of primary power generator, Watt (W)
P_2	power output of secondary power generator, Watt (W)
P_{max}	maximum power, Watts (W)
R_I	internal resistance of TEG, Ohms (Ω)
V_L	matched load voltage, Volts (V)
V_{L1}	matched load voltage of primary power generator ,Volts (V)
V_{L2}	matched load voltage of secondary power generator, Volts (V)
ΔT	average temperature difference across the TEGs, Kelvin (K)
ΔT_1	average temperature difference in primary power generator, Kelvin (K)
ΔT_2	average temperature difference in secondary power generator, Kelvin (K)
T_H	average hot side temperature of TEGs, Kelvin (K)
T_{H1}	average hot side temperature in primary power generator, Kelvin (K)
T_{H2}	average hot side temperature in secondary power generator, Kelvin (K)
T_C	average cold side temperature of TEGs, Kelvin (K)
T_{C1}	average cold side temperature in primary power generator, Kelvin (K)
T_{C2}	average cold side temperature in secondary power generator, Kelvin (K)
V_f	fuel flow rate, Litres per minute (L min^{-1})

Abbreviations

TEG	thermoelectric generator
HE	heat exchanger
IHS	internal heat sink

available. The device was developed with a focus on low cost and realistic stand-alone design having potential for commercialisation. The device was designed to operate continuously for a month when connected to a 13 kg propane gas bottle, which means that it can provide small electrical power without any disruption for 30 days and the user would only have to change the gas bottle once in a month. The emphasis was given to eliminate the requirement of moving parts such as pumps and combustion air compressors because of the electricity required to operate them and to reduce the manufacturing cost, therefore, making it a practical design solution.

Various small scale power generators, employing thermoelectrics and combustion, have been reported in the past. Yadav et al. [7] performed experimental investigation on a micro power generator consisting of thermoelectric power generation (TEG) modules integrated with a micro-combustor (thermal input ∼ 5 W). Their non-catalytic micro-burner were designed to preheat inlet reactants and employed multiple backward facing steps for flame stabilisation. The maximum power generation using two and four modules is reported to be 1.56 W and 2.35 W respectively. Nortan et al. [8] developed and tested a micro catalytic burner for power generation using thermoelectrics having a thermal output of 150 W and 0.5 W electrical power generation. A catalytic combustion based thermoelectric power generator is reported by Xiao et al. [9], the thermal output of the burner was around 500 W and generated ∼8 W of electrical power using eight thermoelectric modules. A catalytic propane burner is developed by Merotto et al. [10] for integration with commercially available thermoelectric modules. The combustion efficiency is reported to be 96% and the electrical power generation 9.86 W using two TEG modules [11]. Mustafa et al. [12] developed and investigated a hexagonal shaped porous gas (butane) burner, thermal output of ∼1.6 kW, for power generation using six thermoelectric modules. The maximum power output reported is 1.05 W. In another research, Mustafa et al. [13] used liquid fuel, kerosene–vegetable cooking oil, in a porous catalytic burner which had 10 TEG modules attached to it. The power generation was in a range of 4–21.9 W, depending upon the operating parameters. Mueller et al. [14] conducted a research on employing super-adiabatic porous catalytic burner in thermoelectric generators. The maximum power was recorded to be around 0.3 W after 5 h of operation using one TEG. An example of integration of thermoelectric to a comparatively larger scale of combustion (thermal output of up to 150 kW) can be seen in the work of Aranguren et al. [15] where they attached 48 TEG modules to the chimney of a combustion chamber. The electrical power generated is reported to be 21.56 W. In order to achieve high power densities, new thermoelectric modules were developed by Zhang et al. which consisted of nanostructured bulk half-Heusler alloys [16]. They have reported a power output of 94.5 W using 8 TEG modules integrated into a residential boiler. A thermoelectric generator hybrid system consisting of direct-carbon-fuel-cell is reported by Zhao et al. [17]. Hasani and Rahbar [18] reported a waste heat recovery system using thermoelectrics from a ∼5 kW PEM (proton exchange membrane) fuel cell, employing four TEG modules, they were able to produce 0.5 W of electrical power at a temperature difference of 20 K.

Some recent experimental work carried out in recovering waste heat from combustion appliances, such as stoves, using TEG modules can be found in the study of Montecucco et al. [19] and O'Shaughnessy et al. [20]. The former reported 27 W electrical power output using four TEG modules at a temperature difference of 250 K; and the later around 5 W using one TEG.

The scale of the burner presented in this study has been classified based on the previous work done by various authors in small scale combustion. Kariuki and Balachandran [21] developed a burner having combustion chamber made up of 5 channels, it was operated at a thermal output of 25–250 W and has been classified as a micro-combustor. Nortan et al. [8] developed and tested a catalytic burner having a thermal output of 150 W and termed it as micro-burner. Similar examples of combustors classified under micro-scale are the burners developed by Kania and Dreizler [22] (burner rating 50 W), US government [23] and Li et al. [26]. In the work of Wu et al. [24], a clear differentiation among micro and meso-scales has not been shown and their thermal outputs are between 25 and 170 W. Therefore, based on the operating range or burner thermal output, the burner developed and tested in the present study can be classified as micro-scale combustor as their thermal output is ⩽250 W, which is similar to the above discussed micro-combustors. However, a comparison based on the dimensions showed that the combustion chamber in present study was significantly bigger than those developed by the other investigators. The micro burner developed by US government had a characteristic length of just 1 mm, also the combustion chamber in Kania and Dreizler's burner was 25 mm long and the diameter was just 4 mm and the micro combustors of Kariuki and