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Experimental studies on a micro power generator using thermo-electric modules mounted on a micro-combustor

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ABSTRACT

In this paper, experimental investigations on micro power generation using thermoelectric modules installed around a microcombustor are studied. The work is aimed at developing a combustion based micro power generator as an alternative to low power density electrochemical batteries. A three step micro-combustor is fabricated with mild-steel as the material. Liquefied petroleum gas (LPG)–air mixture is used as fuel–air mixture to operate the microcombustor. A heating cup is used to increase the heat recirculation from hot combustion products thereby enhancing the flame stability limits. The heating cup is fabricated using aluminum material to obtain uniform temperature distribution for improved power generation at smallest scales. The overall conversion efficiency of the micro power generator has been observed to increase with the number of modules mounted on the micro-combustor system as compared to two and one modules. An overall conversion efficiency of 1.2% for one module, 2.56% for two modules and 4.6% for four module configuration was achieved. The overall conversion efficiency reported in the present work is highest for such small scale combustion based micro power generators in comparison to earlier work reported in the literature. A maximum power of 1.56 and 2.35 W respectively is obtained for two and four module configurations.

1. Introduction

In the recent times, micro-combustion has attracted the attention of researchers due to various challenges involved in stabilizing a flame at small scales. Recent advancements in the field of nano- and micro-fabrication technologies have led to miniaturization of various devices. Even the most efficient Li-ion electrochemical batteries have very low power densities compared to hydrocarbon fuels. Batteries require several hours of charging and their life is limited to finite and limited rechargeable cycles. Battery disposal after usage causes severe environmental issues.

Lithium-ion batteries have a power density of 0.2 kW h/kg, almost 1/60th of the power density of fossil fuels (such as methane and diesel). The power density of a Li-ion battery is approximately 1/20th of a typical diesel fuel based engine (200 kW power output with approximately 400 kg weight of engine), and 1/8th of the main engine of space shuttle (SSME, Thrust = 1.8 MN, with 730 tons of propellant weight and a jet exit velocity greater than 4000 m/s for over 500 s) [1,2]. It is clear from this comparison that using either liquid or gaseous hydrocarbon fuels, even with a mere 10% of overall energy conversion efficiency, the power density of a micro power generator would be approximately six times higher than that of advanced Li-ion batteries [1–3]. Due to higher power density of hydrocarbon fuels, combustion based devises are expected to help overcome the difficulties of lower power density and longer recharging times required by the electrochemical batteries.

Park et al. [4] have experimentally reported an electric power output of 2.35 W with an overall conversion efficiency of 2.12% using the concept of thermophotovoltaics. They used a step combustor with an internal diameter of 5 mm and a length of 42 mm along with propane–air mixtures. Thermophotovoltaic (TPV) modules were used to convert the thermal energy to electric power. In a similar work, Lee et al. [5] have reported an electric power output of 4.4 W, with an overall conversion efficiency of 2.3% with propane–air mixtures and 5.2 W electric power output with an overall conversion efficiency of 2.1% with $NH_3 + H_2$–air mixtures. They used a microcombustor of 8 mm diameter and length of 70 mm. Chan et al. [6] in MIT have used the thermophotovoltaic concept and shown that an overall efficiency of 2.5% can be achieved with such micro power generators. Li et al. [7] have used a TPV system to produce electric power and reported an electric power output of 8.3 W with an overall conversion efficiency of 1.47%. They used liquid n-heptane and pentane as fuels with a combustor diameter of 9.5 mm and length 60 mm. A recent work of Yadav et al. [8] has

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shown that by combining four thermoelectric modules in such a configuration, the overall conversion efficiency can be further improved.

To improve the overall thermal efficiency and flame stability limits in micro-combustors, various efforts were made toward the optimization of micro-combustion systems and thermal management through heat recirculation or use of a catalyst to sustain the combustion reaction at smallest scales [9–25]. The *excess enthalpy* based concept has been widely used in the design and development of micro-combustors. In one such concept, Swiss roll combustors were proposed [2,9–14] where a significant heat from hot combustion products is recirculated to unburned fuel–air mixture through solid walls. This results in increased flame temperature and enhanced flame stability limits as compared to those achieved with standard operating conditions.

Yang et al. [20,23] and Khandelwal et al. [26] have reported detailed studies on flame stabilization in micro-scale cylindrical combustors with and without backward facing step microcombustor configurations. Their work showed that a significant improvement in the flame stability limits can be achieved by introducing a backward facing step as this helped in rearrangement of flow near the step and enhanced mixing of hot combustion products with fresh mixture due to the formation of a recirculation zone at the step. Significant amount of work on flame stabilization using these multi-step microcombustor configurations have been reported by Khandelwal and coworkers [26–29]. They have reported detailed investigations to understand on the effect of various parameters on flame stability limits and wall temperature profiles.

The objective of the present work is to develop a microcombustor based micro power generator system to produce electric power from the heat released due to combustion of the fuel–air mixtures in these microcombustors. Detailed investigations have been carried out for one and two module configurations to understand the effect of various operating parameters on flame stability limits, temperature distribution on heat recirculating cup, overall conversion efficiency, and heat losses to the surroundings from these configurations. These investigations on one and two module configuration would help in understanding various important issues related to the development of optimized configurations with higher number of modules more clearly in such micro power generators as reported in the present work. Thermoelectric modules have been identified as one of the possible options to convert the heat energy from combustion to electric power with improved overall conversion efficiency. Thermoelectric modules work on the principle of Seebeck effect that convert the heat transferred through these modules due to temperature difference into an electro-motive force. A heating cup is placed on the outer side of the combustor to maximize the recirculation of heat from hot combustion products to reactants, thus helping in enhancing the limits of flame stabilization. On the cold side, a water jacket based cooling system is placed to maintain uniform and low temperature of the module. A three step backward facing microcombustor is used for carrying out the experiment. Pre-determined flow rates of fuel and air are given to the combustor and ignited with the help of an igniter. After the flame stabilizes, a recirculation cup is placed around the micro-combustor.

2. Experimental set-up

2.1. Micro-combustor configurations

Fig. 1 shows the dimensional details and photograph of an actual micro-combustor used for present investigations. The micro-combustor is designed from previous work reported by the author's research group earlier [26–28]. In their earlier work, Taywade et al. [29], have investigated the effect of various dimensions of heating cup on wall temperature and it was observed that an optimum sized heating cup achieves maximum temperature. A sudden expansion in backward step microcombustor creates a recirculation zone that helps in enhancing the flame stability limits. A premixed fuel–air mixture is ignited at the exit plane of the combustor.

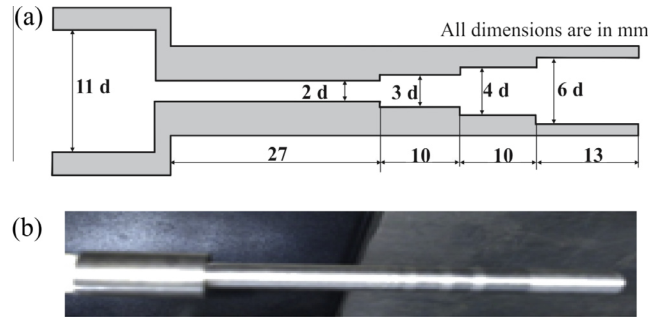

Fig. 1. (a) Dimensional details (mm) of a three step cylindrical micro-combustor considered for experimental investigations in the present work and (b) actual photographs of the combustor.

2.2. Details of the experimental method

A schematic diagram of the experimental setup employed for present investigations is shown in Fig. 2. During the experiments, air and fuel are supplied from pressurized fuel and air storage tanks through fuel and air feed systems. The experimental setup consists of a computerized mass flow control system, command module, valves, regulator and a backward facing micro-combustor. The mass flow rates of fuel and air are controlled using electric mass flow controllers (AALBORG-GFC) connected to a computer through a command module. The maximum flow capacity of the air and fuel MFCs (mass flow controller) is 1 SLPM and 500 MLPM respectively. The accuracy of the measured mass flow rates is within ±1.5% of the full scale. Soap bubble based method is used to calibrate the mass flow controllers. The required flow rates of the air and fuel are used to achieve different flow velocities at different mixture equivalence ratios.

An aluminum cup of dimensions 45 mm $\times$ 30 mm $\times$ 16 mm is used to ensure increased heat recirculation from hot combustion products to the heating cup. Part of the heat is transferred to the unburned mixture through solid walls of microcombustor (as shown in Fig. 3). The temperature on the outer walls of the cup is measured with k-type thermocouples of 0.5 mm bead diameter connected to a digital temperature indicator.

2.3. Details of the thermoelectric modules (TEM)

A thermoelectric module (HZ-2) (photograph shown in Fig. 4) works on the principle of Seebeck effect which converts heat into electricity. A thermoelectric module consists of many elements of p- and n-type doped semiconductor materials connected thermally in parallel and electrically in series. A thermoelectric module is a solid state device without any moving parts; hence it is extremely reliable power generation source. The electrical interconnects of these thermoelectric modules are mounted between two ceramic wafers. The thickness of the ceramic wafer is 0.25 mm. The purpose of these wafers is to hold the overall mechanical structure together and electrically insulate individual elements from one another as well as from external mounting surfaces. A schematic of the arrangement of thermoelectric module for two module