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Research Paper

Combustion and direct energy conversion inside a micro-combustor

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HIGHLIGHTS

- The flammability range of micro-combustor was broadened with heat recirculation.
- The quenching diameter decreased with heat recirculation compared to without recirculation.
- The surface areas to volume ratio was the most important parameter affecting the energy conversion efficiency.
- The maximum conversion efficiency (3.15%) was achieved with 1 mm inner diameter.

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ABSTRACT

Electrical energy can be generated by employing a micro-thermophotovoltaic (TPV) cell which absorbs thermal radiation from combustion taking place in a micro-combustor. The stability of combustion in a micro-combustor is essential for operating a micro-power system using hydrogen and hydrocarbon fuels as energy source. To understand the mechanism of sustaining combustion within the quenching distance of fuel, this study proposed an annular micro combustion tube with recirculation of exhaust heat. To explore the feasibility of combustion in the micro annular tube, the parameters influencing the combustion namely, quenching diameter, and flammability were studied through numerical simulation. The results indicated that combustion could be realized in micro- combustor using heat recirculation. Following results were obtained from simulation. The quenching diameter reduced from 1.3 mm to 0.9 mm for heat recirculation at equivalence ratio of 1; the lean flammability was 2.5%–5% lower than that of without heat recirculation for quenching diameters between 2 mm and 5 mm. The overall energy conversion efficiency varied at different inner diameters. A maximum efficiency of 3.15% was achieved at an inner diameter of 1 mm. The studies indicated that heat recirculation is an effective strategy to maintain combustion and to improve combustion limits in micro-scale system.

1. Introduction

The micro-electromechanical systems (MEMS) experienced growing interest during the past few years. The combustion of hydrogen or hydrocarbon fuels such as methane in MEMS to produce electrical power has several advantages over the batteries because of high specific energy of liquid fuels. The specific energy of liquid hydrocarbons is 35–300 times higher than that of batteries built on latest technology [1]. For example, the specific energy of methane is 50 MJ/kg whereas for an alkaline battery it is only 0.6 MJ/kg [1]. Thus, the direct conversion from chemical to electrical energy even at 10% efficiency is attractive.

The hydrocarbon fuel based MEMS were found promising for application in micro combustion. The MIT gas turbine laboratory developed MEMS based on gas turbine power generator with an approximate total volume of 300 mm^3 to produce 10~20 W of electric power [2]. At the Combustion laboratories of UC Berkeley, research was conducted to develop a liquid hydrocarbon fueled internal combustion rotary engine on millimeter scale [3]. A centimeter magnitude thermoelectric (TE) power generator integrated with plat-flame micro combustor system was developed by Jiang et al. [4] The maximum power output reached was 2 W, and the maximum overall chemical-electrical energy conversion efficiency was 1.25% [4]. In addition to electric power generation, a micro-combustor was employed to recirculate heat to produce hydrogen from ammonia [5]. Also, a thin-film-coated combustor and a packed-bed combustor were designed and fabricated to operate as a heat source for a methanol micro-reformer [6].

Even though the micro-power systems hold promise, the primary issue in them is obtaining sustainable combustion in a micro-combustor. As the combustor size decreases, the surface area to volume ratio increases. Because of the high surface area to volume

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ratio for micro-combustor, there is a high amount of heat loss (proportional to area) compared to heat energy generated (proportional to volume). Thus, the quenching and flammability problems are more critical in a micro-scale combustor. On the other hand, the high surface area to volume ratio characteristic of the micro combustor is most suitable for TPV systems. The TPV system consists of three main parts: a heat source (combustor), a selective emitter, and a photovoltaic array. The photovoltaic array converts the heat radiation absorbed from combustion to electricity. Thus smaller system will have higher energy conversion efficiency due to its relatively larger surface area to volume ratio as long as the combustion is sustainable. To maintain an optimal balance between the sustainable combustion and maximum heat output is the main issue for micro TPV system.

The above concern necessitates innovative schemes to improve the performance of micro-combustor. Several energy management methods including external heating, backward-facing step, catalyzed combustion, and heat recirculation were employed to improve the combustion in the MEMS [7]. The gas flow rates, equivalence ratio, and wall material are the main parameters which affect the combustion characteristics and heat loss in a micro-combustor. Li et al. found that maximum heat was released when equivalence ratio was slightly greater than one (and stainless steel wall resulted in more heat loss than ceramic wall) [8]. Leach et al. investigated the effect of structural heat exchange and heat loss on the power density and flame stability in order to optimize the design of silicon micro-combustors [9]. Moreover, the geometry of combustor also has an important role in the flame stability. Zhong et al. conducted experiments on micro Swiss-roll combustors with premixed CH_4/air mixture [10]. The combustion stability in the central regions of the combustors was enhanced and the extinction limits of methane/air mixtures were significantly extended [10]. Li et al. used backward-facing step in the combustor to effectively stabilize the flame position [11]. Fan et al. found that a triangular and semicircular bluff bodies significantly increased blow-off limit of hydrogen/air flame in a planar micro-combustor [12]. Yang et al. investigated the effect of wall thickness on the performance of three micro-cylindrical SiC combustors and found that wall thickness of 0.4 mm gave maximum power output from micro-thermophotovoltaic power generator [13].

Li et al. used porous medium in a 1 mm planar micro-combustor to enhance the flame stability which included flame flashback, blow-off, and heat transfer [7]. Recently, catalysts were employed to improve the combustion and heat transfer in a micro-combustor. Wang et al. found that catalyst can effectively inhibit extinction and actively promote air-hydrogen lean mixture reaction in the combustor [14]. In order to improve the efficiency and performance of mico-combustors, the exhaust gas was recirculated to heat the outer wall of the micro-combustor and the incoming cold reactants. As result, the mean wall temperature, total radiation energy emitted and useful radiation energy were improved [15].

In addition to experimental studies, extensive numerical simulations were developed by various investigators to evaluate the combustion and heat transfer performance of the micro-combustor. The flame stability in different numerical models was studied at different Reynolds and swirl numbers for MEMS [16,17]. Fanaee et al. used a two-dimensional model to investigate the effects of reaction zone thickness, maximum temperature and quenching distance on combustion phenomenon in micro-combustors under catalytic and non-catalytic conditions and obtained acceptable agreement between the analytical and experimental data [18]. Pan et al. investigated the effects of porous media, hydrogen to oxygen equivalence ratio, porosity and fuel mixture flow rates on the performance of the micro-combustor [19]. Li et al. found that in 1D cylindrical micro-combustor model hydrogen was superior to methane and propane as a fuel owing to its higher flame temperature and lower flame thickness [20]. Tang et al. conducted studies on premixed hydrogen/air combustion in 3D model of a micro planar combustor and found enhancement in heat transfer and increase in mean temperature of the radiation wall by inserting plates in the micro-combustor chamber [21].

The effect of cross-sectional geometry on the ignition/extinction behavior of catalytic micro-combustors using CFD models was studied by Benedetto [22]. He found that square cross-section channel was more resistant to extinction compared to circular channel [22]. Moreover, heat recirculation from the post-flame to the pre-flame in a micro combustor improved the flame stabilization and enhanced burning rate on a 2D mode [23].

The objective of this work is to develop a one-dimensional numerical model using FORTRAN code to explore the feasibility of CH_4/air combustion in a micro-combustor (straight tube combustor with heat recirculation) and investigate on its application to TPV power system. The effect of heat recirculation of a micro-scale counter flow combustor on the lean flammability, quenching diameter, and overall energy conversion efficiency were investigated in this study.

2. Numerical modeling and its formulation

2.1. Physical model of the micro-combustor

Fig. 1 illustrates the physical model of the micro combustor used in this study. It includes a combustion tube made of carbon steel with inner diameter varying from 1 mm to 3 mm and a concentric outer tube of same material which served as a counter flow heat exchanger. The incoming cold mixture in the inner tube was preheated by the hot combustion gases in the outer tube resulting in reduction of the chemical reaction time and helping complete combustion. For a micro-size combustor, the reduced diffusion time resulting from small size has a crucial effect on making the concentration distributions uniform near the flame in the combustor. In addition, the laminar flow prevented rapid mixing between fuel and air due to the low mass and heat transfer coefficients in the combustor. Therefore, a premixed combustion instead of diffusion combustion was assumed in this study. The flame propagation in the current model is two-dimensional in nature. However, if interest is limited to micro-scale burners with tube diameter and wall thickness much smaller than the tube length, the problem could be simplified to one-dimensional. This study assumed one dimensional laminar plug flow in the model.

The baseline micro-combustor configuration consisted of two annular tubes with an inner tube of 3 mm in diameter and 30 mm in length and an outer tube of 4.2 mm in diameter and 30 mm in length. Cold premixed fuel mixture which passes through inner tube will be ignited by hot gases in outer tube. In the mean time the heat radiation from high temperature outer tube wall will reach TPV system and be converted to electricity.

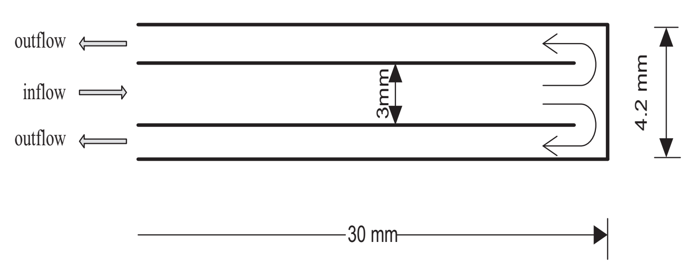

Fig. 1. Baseline micro-combustor in the theoretical model (carbon steel).