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Performance assessment of catalytic combustion-driven thermophotovoltaic platinum tubular reactor☆

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HIGHLIGHTS

- H_2 is injected in the inner tube to assist CH_4 catalytic combustion in the outer tube.
- The prototype TPV system comprises the micro-TPV reactor with GaSb PV cell array.
- Radiant efficient of a metal oxide–deposited quartz tube is behind the expectation.
- The system with a recirculating cap and a reflecting mirror are employed.
- The overall efficiency of the micro TPV system is measured under various conditions.

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ABSTRACT

This study is aimed to enhance the overall efficiency of micro-thermophotovoltaic (micro-TPV) reactor by collecting radiations from emitter and combustion chamber. However, the proper fuel deployment and fluid design for the micro-TPV reactor are strongly associated with combustion stability and radiant intensity of the micro-TPV reactor. Therefore, the system performance of the micro-TPV reactor was investigated with regard to combustion, thermal radiation, and electrical output. A platinum tube with a ring of perforated holes was utilised with specific fuel deployment, that is, hydrogen employed in the inner chamber for facilitating induction of methane catalytic combustion in the outer chamber. Because of the inherently high diffusivity of hydrogen, the heat and radicals could be delivered to the other chamber through the perforated holes; in this manner, the methane catalytic combustion could be successfully initiated. The flame-stabilizing mechanism of micro-TPV platinum tubular reactor was addressed and interpreted through the simplified simulation of segmented platinum tubular reactor with a gap. The effective power efficiency of the TPV system was 3.24% when $ER_{in\text{-}H_2} = 0.7$ and $ER_{out\text{-}CH_4} = 0.9$. With a mirror and a recirculating tube, effective power efficiency was enhanced to 6.32%.

1. Introduction

With the rapid development of electrically powered devices, the need for portable power systems is steadily growing. Electrically powered vehicles, unmanned aerial vehicles (UAV), and unmanned submarines exemplify the importance of power systems that deliver electricity with low noise and high reliability [1]. Long-endurance reconnaissance drones have been developed and can be applied in security and monitoring situations that require persistent flight, such as aerial reconnaissance, border patrol, forest fire observation, and battlefield management. A solar-powered UAV travelled 336 h continuously; electric UAVs can fly at stratospheric altitudes all over the world, and have wide-area military and civil potential, because they offer capabilities far beyond those of existing satellites and aircraft. The power of an electric UAV ranges from 100 W to 10,000 W. However, using a solar energy power generator results in climatic and topographical limitations. The combined heat and power (CHP) generators can generate heat and electricity simultaneously [2]. In high-altitude countries, the use of a heater or stove for heating a house is common. Qiu and Hayden [3] demonstrated the feasibility of TPV generation in boilers/furnaces for micro-CHP application in residential building. A Stirling engine can be connected to a micro-CHP for electricity generation with an output range of 10–1000 W. Although micro-CHPs can be used in daily life, engine operation is noisy because of the moving

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parts. Furthermore, the concept of one-person-portable power was proposed because of military demand to surpass logistical difficulties and the heavy weight of traditional power generators. Originally, JX Crystals Inc. designed a 230 W propane-firing recharger for the U.S. Army. In addition to military applications, one-person-portable power generation also had potential in civilian life because of the prevalence of electronic devices. The aforementioned applications all require power systems that have a small volume, light weight, uninterrupted power capability, adaptability to different environments, and high power density [4].

Microscale power generation systems are implemented in various forms, including the micro gas turbine [5], micro free-piston engine [6], micro thermoelectric device [7,8], and micro thermophotovoltaic (micro-TPV) system [9,10]. Although the current versions of these microsystems have low efficiency levels, these microsystems exhibit the potential to generate power on the order of a few watts within a volume of several cubic centimetres. Nevertheless, the concept of micro-TPV systems is straightforward: they directly convert thermal energy to electric energy through a photovoltaic (PV) array. The primary micro-TPV configuration comprises a heat source, an emitter, and a PV array [11,12]. Heat is absorbed by the emitter, which then emits radiation. The PV array converts the radiation into electricity. The heat source of TPV systems can be solar energy, nuclear energy, or chemical combustion. Compared with solar energy and nuclear energy, the combustion approach is not limited by climate, geographic conditions, and regulatory requirements. Combustion of hydrocarbon fuels is also regarded as a potential and feasible method to satisfy the power demands of present-day miniature devices thanks to the high energy density of hydrocarbon fuels (45 MJ/kg), which offer 10 times more power than sophisticated batteries do (0.5 MJ/kg) [13]. Additionally, micro-TPVs are compact, can be robotically assembled, and have neither moving components nor intricate structures that might produce friction and thus cause energy loss. Because micro-TPV systems offer high reliability and maintainability, this study centres on the development of micro-TPV power systems.

When combustor volume decreases, the ratio of surface area to volume increases, and the problems associated with heat loss appear. Heat loss through combustor walls tends to suppress ignition and leads to thermal quenching. When the temperature drops, the chemical reaction rate also declines due to thermal quenching, resulting in incomplete combustion. Therefore, very careful design is necessary in order to enhance stability and robustness of these systems and to improve combustion efficiency. Yang et al. [14] employed a backward-facing step in the microchannel. In this manner, flow recirculation was induced and anchored in the channel to improve the fuel–air mixture and overcome incomplete combustion [10]. Akhtar et al. [15] numerically discussed the flow and flame behavior in a micro TPV-reactor with different combustor geometries, and pointed out that the combustors with trapezoidal and triangular cross-section have better heat transfer capacity. Kim et al. [16] investigated the effect of Swiss-roll combustor configuration on the flame stabilization, and discussed the heat transfer behavior in a small Swiss-roll combustor. Ahn et al. [17] used a Swiss-roll burner to enhance the flame limit by using the exhaust gas to preheat the fresh fuel–air mixture. Zuo et al. [18] numerically investigated the thermal performance of counterflow and coflow double-channel combustor. Mujeebu et al. [19] adopted a porous medium burner to enhance the adiabatic flame temperature and effectively stabilise the flames in a microscale combustor. Additionally, Li et al. [20] designed a segment catalyst with cavities to successfully stabilise flames in a microscale combustor. The catalyst reduced activation energy and facilitated overcoming the thermal and radical quenching in the microchannel [21]. The cavities also provide a region of low velocity for stabilising the flame. According to the Stefan–Boltzmann law, photons produced at higher temperatures are more powerful, and so the radiation efficiency of the emitter can be enhanced. Therefore, increasing surface temperature of the emitter is necessary. Lu et al. [22] the effects of catalytic walls on the homogeneous combustion were investigated via varying catalyst segment layouts and sizes. Su et al. [23] pointed out that wall temperature of double-cavity combustor is more uniform and higher than that of single-cavity combustor. The radiation efficiency increases from 1.25% (single-cavity combustor) to 1.53% (double-cavity combustor). Yang et al. [24] investigated the effects of catalytic wall on combustion in the cylindrical micro-combustors, and found that the output electrical power of the system with platinum as catalyst is increased by 11–23.8% compared with that without platinum. Yang et al. [25] employed a silicon carbide (SiC) tube with heat recirculation to preheat the fresh mixture by the heat of exhaust gas; by means of heat recuperation, increased wall temperature and radiation of the emitter resulted. Lee and Kwon [26] designed a 1–10 W power-generating micro-TPV system and improved the performance of micro-TPV system with heat-recirculation concept. Park et al. [27] design a heat-recirculating micro-emitter fuelled with propane/air mixture. The output power and overall efficiency of the micro-TPV are 2.9% and 3.8 W. Because of the favourable management of heat exchange, the radiation and wall temperature of the emitter significantly improved. Alipoor and Saidi [28] discovered that the establishment of secondary flows and better preheating in the curved tube of micro-TPV reactor tends that the flammability limits to be at least four times in comparison with straight tubes.

The emitter's emitting material must be suitable for absorbing heat from the heat source and then transforming it into light. Several considerations must be taken into account [19]: First, optimal thermal stability and thermal shock resistance for tolerating the impact of high combustion temperatures, usually exceeding 1000 K. Second, a high thermal conductivity that leads to a uniform wall temperature over the emitter. Third, high emissivity to achieve a high radiative heat transfer rate. However, the most crucial requirement is that the radiative spectrum of the emitter matches the bandgap of the PV cells. Given the aforementioned considerations, ceramic is an appropriate candidate material for an emitter. Several studies have used oxide-based ceramics, such as Al_2O_3, ZrO_2, and MgO, as emitters for TPV systems; unfortunately, performance was insufficient because of poor thermal shock resistance and low emissivity. Silicon carbide (SiC) is employed as an emitter for non-oxide-based ceramics and boasts high temperature tolerance (approximately 1600 °C) and large emissivity similar to, for example, a black body. It is considered as a broadband emitter, for which the spectral range of radiation is 1000–3000 μm [29]. Most photons at near-infrared wavelengths cannot be transformed into electricity through PV cells, and unusable photons turn into heat and damage the PV cells. Alternatively, several studies have developed selective emitters that are based on transition metal oxides, such as ytterbia and erbia [30]. Owing to high-temperature stability and selective radiation [31], the wavelengths of ytterbia and erbia are approximately 900–1100 nm and 1300–1750 nm, respectively, at a surface temperature of 1373 K.

Currently, GaSb PV cells are regarded as the most plausible choice for TPV generators because of their low bandgap and maximal region of spectral conversion that can exceed 1800 nm. Compared with silicon-based PV cells (300–1100 nm), GaSb PV cells (250–1800 nm) transform a wider range of photons, from visible light to near-infrared light, into electricity. Most photons generated by the TPV systems congregate at the near-infrared portion of the spectrum. Consequently, using GaSb PV cells improves the quantum efficiency of the TPV system. Amano et al. [29] found that although Si cells generated only 0.11 W power, GaSb cells generated 0.25 W if flow velocity and equivalence ratio conditions were identical. Thus, GaSb PV cells are more appropriate for TPV systems than conventional silicon-based PV cells. Alternatively, Yang et al. [32] proposed the micro-combustor with SiC porous medium, and the corresponding overall efficiency is 0.92% when InGaAsSb PV cells are employed. Wu et al. [33] designed a radiant porous burner integrated with water-cooled GaSb PV cells, and the electrical output power