Chemical Engineering Journal 304 (2016) 485–492

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Combustion characteristics of a micro segment platinum tubular reactor with a gap ☆

Yu-Ting Wu [a,c], Yueh-Heng Li [b,c,*]

[a] Department of Engineering Science, National Cheng Kung University, Tainan 701, Taiwan, ROC
[b] Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan, ROC
[c] Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan 701, Taiwan, ROC

HIGHLIGHTS

- Flame-anchoring mechanism of a micro-TPV rector is numerically investigated.
- The gap on the platinum can provide a low-velocity region to stabilize micro flames.
- It allows to trade fuels and radicals from the inner and outer streams through gap.
- The catalytically induced combustion can be anchored on the micro-TPV rector.

ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 19 June 2016
Accepted 22 June 2016
Available online 23 June 2016

Keywords:
Catalytic combustion
Platinum
Small-scale reactor
Heterogeneous and homogenous reaction
Thermophotovoltaic

ABSTRACT

The present study proposes a conceptual design for a combustion chamber for overcoming critical heat loss and flame instability in a micro-thermophotovoltaic power system (micro-TPV). In the design, a platinum tube is used simultaneously as a catalyst reactor and an emitter. The flame-stabilizing mechanisms of a TPV reactor are numerically investigated regarding the effects of reactor configuration and fuel concentration. The interaction of heterogeneous and homogeneous reactions between the inner and outer chamber of the TPV reactor is also examined. Results indicate that the catalytically induced combustion can be anchored in the gap between two segmented platinum tubes by inheriting thermal energy and radicals from the upstream section of the segmented catalyst. The gap not only provides a low-velocity region for stabilizing flames, but also enables the exchange of fuels and radicals from the inner and outer streams.

1. Introduction

With the rapid progress in electromechanical and electronical consumer devices such as laptop computers, mobile phones, and aerial drones in recent years, the demands on micro power sources with high power densities are increasing. Characteristically, required power densities range from 10 to 1000 W/kg and energy densities from 500 to 5000 Wh/kg [1]. State-of-the-art battery technology (e.g., Li-ion batteries) is unable to deliver the levels of power and energy densities required for future portable electronic and electromechanical applications. In addition, batteries have a considerable environmental impact, high cost, and long recharging time. An alternative is the utilization of hydrocarbon fuels in combustion-driven micro-scale power sources. A number of notable theoretical and experimental works have exemplified and demonstrated the benefits of scaled-down power generating devices onvolving combustion-driven thermal cycles with the use of internal micro-combustion engines, micro gas turbine engines, and micro piezoelectric devices. Because of substantial technical difficulties in maintaining structural integrity and minimizing heat dissipation through the various system components, the development of micro thermophotovoltaic (micro-TPV) devices has drawn attention to capitalize on direct energy conversion without moving parts [2]. Therefore, thermophovoltaics utilize photovoltaic cells to generate electricity from the radiation of a high-temperature source. TPV conversion employs a variety of heat sources that heat an emitter to a typically incandescent temperature to provide radiation. For providing a stable and controllable heat source in a TPV

☆ This paper is submitted for publication in Chemical Engineering Journal. Material in this manuscript has neither been published in nor submitted to a journal previously, nor will it be submitted to another journal during the Chemical Engineering Journal review process.

* Corresponding author at: Department of Aeronautics and Astronautics, National Cheng Kung Univ., Tainan 701, Taiwan, ROC.

E-mail address: yueheng@mail.ncku.edu.tw (Y.-H. Li).

http://dx.doi.org/10.1016/j.cej.2016.06.112
1385-8947/

power system, burning fossil fuel is a straightforward and reliable approach with the benefits of inherently high energy density, immediate use, and ease of supply.

In miniaturization processes, the increasing surface-to-volume ratio of a micro-TPV reactor causes difficulty in maintaining the heat generated from the combustion process because of the heat loss to the wall, and concurrently enhances the possibility of radical termination through wall reactions. Consequently, a major challenge in the design of micro-TPV reactors is maintaining sustainable combustion and maximizing radiation heat output from the TPV emitter. To overcome these challenges, stabilization of flames in a micro-TPV system can be achieved through several methods. The most common method is to use simple configurations such as a backward-facing step, a bluff-body, or a cavity to induce flow recirculation and stabilize flames in a confined chamber. Wan et al. [3] employed a cavity in a micro combustor to generate a recirculation zone and stabilize flames in the cavity. Yang et al. [4] and Yadav et al. [5] used a backward facing step to anchor flames inside the micro reactor. In addition, a porous inert medium (PIM) is employed in a micro-TPV combustor to enhance the heat transfer capability between high-temperature combustion products and the combustor wall by capitalizing on the high thermal conductivity and emissivity of the solid matrix. PIM micro-combustion can yield high power density and increase the power and operational range of lean flammability. Yang et al. [6] and Chou et al. [7] have used SiC porous medium foam employed in a micro modular combustor to augment the combustion stability and radiation uniformity of an emitter. Alternatively, catalytic combustion is a plausible solution for overcoming the challenges associated with increasing surface-to-volume ratios. Platinum is also considered a selective material for delivering the radiation congregated in a short wavelength spectrum, and it is advantageous for maximizing the overlapping area between the radiant spectrum of the emitter and the bandgap range of PV cells. Therefore, catalytic materials are engaged on the micro-reactor walls to reduce the impact of thermal quenching [8,9]. Li et al. [10,11] have demonstrated that the deployment of catalyst segmentation and a cavity in a micro-channel can significantly stabilize catalytically-induced combustion in the reactor. The heterogeneous reaction in a prior catalyst segment produces chemical radicals and catalytically induced exothermicity, and the homogeneous reaction can be subsequently ignited and anchored in the following cavity. The concept of micro-channel design was adopted to design a tubular platinum reactor with perforated holes was fabricated and assessed with hydrogen fuel, and the corresponding combustion behaviors and operational ranges were subsequently examined [12].

Except for the radiation from an emitter, flames are regarded as an alternative radiation source to be further collected and converted into electricity through photovoltaic cells. It is feasible to manipulate the intensity of flame radiation by adjusting the fuel composition of gas mixtures [13] or by adding various volumetric concentrations of iron pentacarbonyl into liquid hydrocarbon fuels [14]. Unlike the flames confined in the combustion chamber and expected to heat only the emitter, Li et al. [13,14] have used high-luminescent flames to encompass and heat the emitter in a micro-TPV system. The results demonstrated a significant increase in the radiation efficiency of the TPV system engendered by the simultaneous collection of radiation from flames and the emitter.

The aim of the present study was to improve the radiation intensity of micro-TPV reactors by simultaneously converting radiation from flames and an emitter into electricity. The corresponding high surface-to-volume ratios at the microscale engender flame stabilization difficulty because of thermal and radical quenching on the combustor walls. Accordingly, the concept of micro-TPV combustor design originates from the aforementioned flame stabilization mechanism of the micro-channel with catalyst segmentation and cavities [10,11] and the heat recirculation mechanism of Swiss-roll combustors [15]. The configuration of the proposed micro-TPV combustor comprises two platinum tube segments with a gap. The gap has a function similar to a cavity for decelerating the flow in localized spaces, as well as a channel to trade and collect the fuel and radicals from two sides. The distribution of different equivalence ratios of fuel–air mixtures through the inner and outer chamber of the reactor is a deliberate strategy for sustaining maximal incandescence over platinum tubes with minimal fuel consumption. The catalytically-induced flames are anticipated to be stably anchored on the outer surface of the reactor, and the purpose of radiation integration is achieved in the design of the segmented TPV reactor. Therefore, this study numerically investigated the functionality of a gap between the segmented catalytic tube in terms of flame stabilization and combustion behaviors.

2. Numerical method

To demonstrate and validate the aforementioned concept that is feasible in a micro-TPV combustor, a numerical simulation was performed with a commercial CFD-ACE + program [16]. Fig. 1 shows the schematic configuration of the proposed micro-TPV combustor that consists of two platinum tube segments with a gap of 1 mm. The dimensions of the two platinum tube segments are 5.3 mm (ID) × 6 mm (OD) × 4.5 mm (L) and 5.3 mm (ID) × 6 mm (OD) × 44.5 mm (L), respectively. The platinum tubes are coaxially placed in a quartz tube with a dimension of 8 mm (ID) × 10 mm (OD) × 50 mm (L), and this coaxial reactor constitutes the central (inner) and annulus (outer) chambers. The cross sections in the central and the annulus are approximately identical. In this study, different equivalence ratios of H_2–air mixtures were individually introduced to the inner and outer chamber of the TPV reactor. The inlet temperature was 300 K and a uniform velocity profile (20 m/s) was specified at the inlet. At the exit, a constant ambient pressure of 101 kPa was specified, and an extrapolation scheme was used for species and temperature. Chemical reaction mechanisms are used in the gas phase as well as on the catalyst surface. The homogeneous reaction mechanism proposed by Miller and Bowman [17] was used for hydrogen–air combustion, and this mechanism comprises of 9 species and 19 reaction steps. The surface reaction mechanism was compiled primarily from that proposed by Deutschmann et al. [18]. These reaction mechanisms have been used in previous studies [19] and the comparisons with experimental results are satisfactory [20]. In this study, the effects of reactor configuration, fuel concentration, and flow velocity on the flame stabilization mechanism were addressed and discussed. This study emphasizes the thermal and chemical effects in the vicinity of the gap between the catalyst segments, not the optimization of reactor dimension.

3. Results and discussion

3.1. Effect of reactor configuration

Regarding the effect of reactor configuration, two identical platinum reactors, plain and segmented platinum tubes with a gap, were employed to investigate the effects of the reactor configuration and fuel–air distribution on the performance of the micro-TPV reactor. Fig. 2 shows the local distributions of OH mass fractions overlaid with velocity vectors and local equivalence ratio (LER) level lines for the two catalyst configurations at a fixed inlet velocity of 20 m/s in the inner and outer chambers. The upper panel of Fig. 2 shows the numerical results for the segment