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Stable flame limits for optimal radiant performance of porous media reactors for thermophotovoltaic applications using packed beds of alumina

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HIGHLIGHTS

- 3 different porous media combustion designs for thermophotovoltaics were analysed.
- Reflectors shift stable flame regimes increasing the radiant efficiency up to 63%.
- Superadiabatic temperature (1538 °C) was reached matching gallium antimonide bandgap.

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ABSTRACT

Porous media combustion (PMC) is characterized by intense heat exchange from the combustion gases to the solid media, enabling higher temperatures at the outer surface of the solid matrix. This paper, for the first time, experimentally investigates how to control combustion inside a porous media matrix to take advantage of its hot outer surface for active emission to a thermophotovoltaic (TPV) system. This 'coupled porous media combustion-based thermophotovoltaic (PMC-TPV) system' requires a stable flame over (only) the narrow height where the photovoltaic cells are mounted. Thus, this study reports a systematic flame stability analysis for lean Air/methane mixtures to optimize the radiant performance of three different porous media combustor designs for thermophotovoltaic applications. In this study, the equivalence ratio was set at 0.7 and the firing rates were varied in order to find the stable and unstable regimes of each reactor. Results indicate that the use of a radiant reflector shifts the stable flame regimes and increases the radiant efficiency to 63% at an operating temperature of 1356 °C. Superadiabatic conditions were also found to be possible in this system, with a maximum temperature of 1538 °C, which improves the radiant emission spectrum for the photovoltaic (PV) cells. These fundamental combustion findings will help to define the operating parameters and improve the electrical conversion efficiency in future PMC-TPV systems.

1. Introduction

Porous media combustors (PMCs) have a lot of design freedom since they are able to burn a wide variety of fuels, from ultra-lean to ultra-rich mixtures, due to the intense heat exchange from the combustion zone throughout the solid. This form of combustion produces an excess enthalpy flame [1], where the solid porous matrix acts as a means of recirculating the heat from the hot combustion products to the incoming air-fuel mixture [2]. The regenerative heat transfer of PMCs leads to higher flame speeds, higher temperatures and lower nitric oxide (NO_x) and carbon dioxide (CO_2) emissions compared to a free flame [3]. Internal heat recirculation also enables high power densities and the (aforementioned) capability to burn a wide variety of fuels. As one example, porous media combustors have been studied under rich combustion to obtain syngas—mainly composed of hydrogen (H_2) and carbon monoxide (CO)—in the flue gases, which is useful in the production of synthetic natural gas, ammonia and other chemical products [4]. As an alternate example, lean combustion has also been studied as a pathway towards more efficient combustion processes [2]. Low energy density fuels can also be burned in PMCs, since they can reach higher and more uniform temperature along the porous matrix [5]. Their fuel flexibility makes PMCs suitable for a variety of applications, such as radiant burner stoves, hydrogen generation, combined heat and power (CHP), and—as is investigated in this paper—thermophotovoltaic (TPV) applications [3].

Thermophotovoltaics offer a means of converting radiant energy

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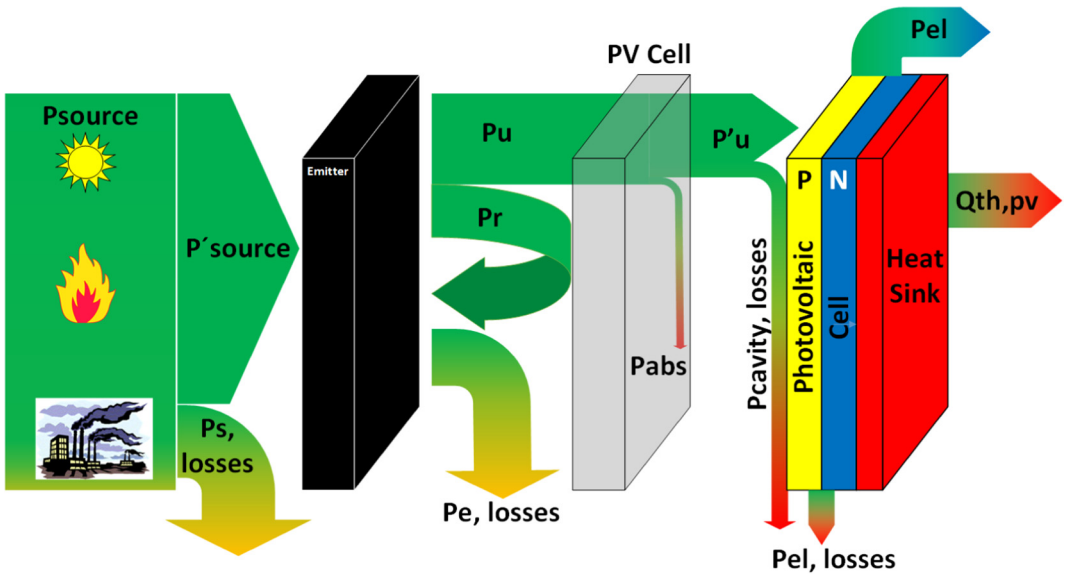

Fig. 1. Working principle of TPV system.

from any heat source directly into electricity through the spectral control of thermal radiation which—at high temperature—can theoretically achieve high efficiency [6,7]. The main components and the working principle of a TPV system are shown in Fig. 1. The system consists of a heat source, an emitter, a filter and a photovoltaic cell (PV cell). The heat source is used to heat up the emitter which re-emits infrared (IR) radiation towards the PV cell. The radiation is transmitted from the emitter and filtered by a selective filter, such that only the radiation wavelengths which match the response band of the PV cells, pass through the filter. Any radiation outside of the band gap of the PV cells is reflected back to the emitter, thus recycling the energy that cannot be converted by the PV cells. The PV cells, in turn, harvest the spectrum above the band gap and convert it into electrical energy.

Recently, several articles related to TPV technology have been published. Daneshvar et al. [7] presented an overview of combustion-driven thermophotovoltaic (CTPV) systems, describing the challenges and prospects of the critical components. Ferrari et al. [6] explained the fundamentals of the physical relationships of each component and summarised the state of art of CTPV prototypes. Bitnar et al. [8] also reported the most recent development and detailed analysis of CTPV applications. In order to achieve higher efficiency, Basu et al. [9] investigated the application of near-field radiation in micro-thermophotovoltaic systems. Regarding solar-powered thermophotovoltaics (STPV), Liao et al. [10] provided a parametric study for a STPV system at maximum efficiency, while Veeraragavan and Shum [11] and Veeraragavan et al. [12] modelled the performance of a storage integrated solar thermophotovoltaic (SISTPV) system. Finally, Bermel et al. [13] explored the use of a photonic crystal as radiant emitter for both micro-CTPV and micro-STPV.

Thermophotovoltaic systems require high driving temperatures, since they are effectively trying to replace sunlight (a ~5800 K blackbody emitter) with a terrestrial radiation source. In conventional hydrocarbon fuel-driven TPV systems, a large portion of the input energy (primarily the chemical energy of the fuel) is typically lost through convection in the flue gases. This can be overcome, to some extent, by using porous media combustion which essentially recycles some of the heat from the combustion gases to the solid media (via conduction), enabling higher surface temperatures of the solid matrix. If designed and operated correctly, a porous media matrix surface can also provide a relatively uniform high surface temperature, which represents an ideal emitter for TPV systems [5].

One of the major challenges in a coupled porous media combustion-based thermophotovoltaic (PMC-TPV) system, however, is obtaining a stabilized flame at the location of the thermophotovoltaic cells (e.g. to deliver radiative flux to where it is needed). One flame control technique, described by Trimis and Durst [14], utilises the fact that the flame tends to stabilize at the interface of two porous media materials inside the reactor. This is possible when one medium has a modified Péclet number greater than 65, while the other medium is less than 65. (Note: The Péclet number is defined as $Pe = \frac{S_L d_m c_p \rho_g}{\lambda_g}$, where S_L is the free laminar flame speed, d_m the pore diameter of the material, c_p, ρ_g, λ_g the specific heat, density and thermal conductivity of the gas respectively.) Thus, the pore diameter plays an important role in flame stabilization. This interface stabilization concept has been shown in a few PMC studies. Bubnovich et al. [15] studied flame stabilization for lean mixtures between two packed beds of alumina spheres with diameters of 5.6 mm and 2.5 mm, respectively. They observed stabilized flames with low pollutant emissions for a range of flow velocities from 10.3 [cm/s] to 27.9 [cm/s]—i.e. volumetric flow rates from 7.01 [l/min] to 19.00 [l/min]—at equivalence ratios (ϕ) between 0.6 and 0.7. Mathis and Ellzey [1] reported the stability limits and pollutant emissions on yttria-stabilized zirconia/alumina composite (YZA) and zirconia-toughened mullite (ZTM) porous media burners for equivalence ratios from 0.6 to 0.75, with an upstream ceramic foam of 23.6 ppcm and a downstream pore size of 3.9 ppcm. They found that the YZA burner stabilized the flame effectively near the interface; however, the ZTM reactor did not achieve the stabilization effectively. Mathis and Ellzey [1], Mendes et al. [16] and Barra and Ellzey [17] analysed the dependence on the ratio between the effective flame speed and the laminar flame speed with the stable flame regimes. The flame stabilizes when the incoming flow velocity is equal to the effective flame speed. When the flow velocity is lower, the flame propagates upstream (flashback) and when it goes downstream (blowoff) when the velocity is greater [2]. Wang et al. [18] analysed the dependence of the pore diameter and mass flow rate on temperature. The results show that the temperature decreases at the preheating zone and increases at the reaction and post-reaction zone with an increase in mass flow rate. Additionally, the peak temperature decreases at the reaction zone and increases at the preheating zone and post-reaction zone with an increase in pore diameter.

Porous media combustors have also been used as radiant burners due to their high solid surface temperatures [3]. That feature makes these systems suitable for TPV applications. In one approach, Khanna et al. [19] measured the radiant output, the radiant thermal efficiency,

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