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Micro-combustor performance enhancement using a novel combined baffle-bluff configuration

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HIGHLIGHTS

- A novel combined baffle-bluff micro-combustor is proposed for MTPV applications.
- At the optimal baffle thickness, the average temperature improves by 6% and uniformity by 87%.
- The combustion efficiency is most sensitive to the baffle length.
- The wall conductivity predominantly affects the entropy generation rate.

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ABSTRACT

This research is aimed at investigating a novel planar micro-combustor with combined baffle and bluff configuration for Micro-Thermo-Photo-Voltaic (MTPV) applications, numerically. It is shown that the novel combustor outperforms the similar configurations with only baffle or bluff, in terms of the flame stability, efficiencies, and emission. In addition, it is observed that the baffle thickness plays the key role in determining the flame location and, as the result, is the most important design variable controlling the temperature distribution and uniformity since the balance of heat transfer rates across the walls in different regions is significantly affected by this thickness. Moreover, small values of the bluff diameter and bluff-to-baffle distance result in performance improvements while the lower limit of these variables is set by the appearance of flame instability. In addition, for the optimal baffle thickness, the concurrent increase of 6.3% in the average wall temperature and 87.5% in the temperature uniformity are achieved. Finally, the sensitivity analyses reveal that the most effective parameter changing the combustion efficiency and entropy generation are the baffle length and wall conductivity, respectively.

1. Introduction

In today's industry, there is a huge demand for the use and improvement of portable electronic systems. The traditional energy sources for these systems are lithium-ion batteries with the limitations such as a relatively short lifetime, low energy density, heavy weight, long recharging time, and short charging duration. A reliable alternative to the batteries is the use of Micro-Thermo-Photo-Voltaic (MTPV) systems with a much more durability and power density and easier manufacturing. However, MTPVs possess a lower efficiency, and many research studies have been devoted to enhancing MTPV system efficiency.

MTPV systems consist of three main parts: the micro combustor, PV cell, and optical filter. The MTPV low efficiency is mainly originated from the low combustion efficiency of the micro-scale combustors. This is due to the higher heat loss from the combustor walls (due to the large surface-to-volume ratios) and the residence time mitigation, which become more critical by the reduction of the size of the combustor. Stable combustion can only occur in a combustion chamber when the reactant residence time is larger than the chemical reaction time. Also, combustion may be stable only when the chamber size is large enough compared to the adiabatic flame thickness (Hua et al., 2005). The flame stability and non-uniform wall temperature distribution are the most challenging issues of the MTPV micro-combustors.

Two main types of micro-combustor geometries are micro tubes and micro-planar channels. Compared to the micro tube combustor, the planar combustor offers the advantage of normal radiation flux to the PV cell (Li et al., 2009a). Different approaches are used to increase the combustion efficiency, wall temperature

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uniformity, and flame stability of the micro-combustors. Among the most important studies on the influence of the geometrical design parameters on the combustor performance, the work by Tang et al. (2015a) can be cited. They studied the micro planar geometry with parallel separating plates, called baffles, numerically and proved that baffles raise the efficiency of the combustor.

Bluff bodies can also improve the micro-combustor performance, especially the stability of the flame. Bagheri et al. (2014) investigated the effect of the bluff body shape on the micro planar combustor performance and concluded that the geometry with the wall-blade bluffs has the highest wall temperature and a more stable flame. Other design parameters can also influence the performance of micro-combustors. A review of the recent important studies on this topic is given in Table 1.

Note that the studies on micro-combustion and micro-combustors of other applications, like micro-turbines, etc., have

Table 1
Recent studies on micro combustors of MTPV systems.

Authors (year)	Design parameters	Geometry	Fuel	Main findings
Li and Zhong (2008)	Geometry, wall material	Tube	Methane	Stainless steel results in a higher temperature uniformity than ceramic. However, the heat loss from the walls are larger due to the larger wall emissivity
Li et al. (2009b)	Combustor size and geometry, inlet velocity profile	Planar and tube	Methane	The planar geometry represents higher flame temperatures than the tube geometry
Yang et al. (2012)	Fuel supply configurations	Modular	Hydrogen	Multiple fuel feeding inlets improve the temperature uniformity
Wan et al. (2012)	Inlet velocity, equivalence ratio, bluff	Planar with bluff	Hydrogen	Blow-off limit is enhanced by the use of bluffs
Zarvandi et al. (2012)	Hydrogen ratio, wall conductivity, inlet temperature	Tube	Methane	The flame instability imposed by using higher wall conductivities can be controlled by the hydrogen addition
Jiang et al. (2013a)	Inlet velocity and equivalence ratio	Tube	Hydrogen	Higher flow velocities and equivalence ratios increase the entropy generation rate which can be mitigated with the use of recuperator
Jiang et al. (2013b, 2014)	Baffle height and location	Planar with baffles	Hydrogen	Baffles extends the blow-off limit. Higher baffles lead to greater entropy generations
Fan et al. (2013) Hosseini and Wahid (2014)	Bluff body size	Planar and tube	Hydrogen, Methane	With all geometries and fuel types, increasing the bluff size increases the flame stability by the formation of stronger recirculating regions
Bagheri et al. (2014)	Bluff body shapes	Planar	Hydrogen	Wall-blade bluffs result in the highest wall temperature and a more stable flame
Wan et al. (2014)	Velocity, equivalence ratio, cavity size	Planar with wall cavity	Hydrogen	At a specific inlet velocity, the flame splits in the middle which leads to the efficiency drop. Increasing the length-depth ratio of the cavity extends the splitting limit
Tang et al. (2015a)	Number of parallel separating plates	Planar	Methane	Parallel separating plates (baffles) increase the average wall temperature
Zhang et al. (2015)	Hollow hemispherical bluff	Cube micro combustor	Methane	With hollow hemispherical bluff bodies, the blow-off limit is 2.5 times greater than that without the bluffs
Tang et al. (2015b)	Hydrogen fraction	Planar	Methane-Hydrogen blend	Hydrogen addition improves the flame stability
Ran et al. (2015)	Geometry (straight, concave, convex)	Planar	Methane catalytic combustion	The convex wall improves the efficiency by enhancing the methane contact with the catalyst and formation of the hot recirculating zone on the wall
Wan et al. (2015)	Wall conductivity	Planar with cavity	Hydrogen	The flame-splitting limit exhibits a non-monotonic variation with the change in conductivity.
Pan et al. (2015)	Porosity, equivalence ratio, flow rate	Porous tube	Hydrogen	With the appropriate value of the porosity, based on the other parameters, combustion efficiency increases significantly
Yang et al. (2015)	External surface emissivity	Planar with wall cavity	Hydrogen	The flame-splitting limit reduces with increasing the emissivity
Wenming et al. (2015)	Geometrical modification	Planar	Hydrogen	A properly designed insert block would change the flow pattern and enhance the heat transfer, resulting in a higher and more uniform wall temperature
Wan and Fan (2015) and Wan et al. (2016)	Wall material, flame holder length	Planar	Methane	The extent of the blow-off limit is mainly attributed to a good heat recirculation, which relies on the conductivity and surface emissivity of the solid material. An optimal length was reported for the flame holder.
Zuo et al. (2016)	Rib position and height, mass flow rate, equivalence ratio	Tube with rectangular rib	Hydrogen	The optimum rib height increases with the increase of the inlet mixture velocity
Giovannoni et al. (2016)	Mass flow rate, equivalence ratio, inlet temperature, conductivity, porosity	Tube	Methane	At low flow rates, a high amount of heat is dispersed through the flame holder since the burning velocity is much higher than the incoming flow velocity. To limit this loss, a low conductivity/high porosity is beneficial for the flame stability
Liu et al. (2016b) and Liu et al. (2016a)	Inlet velocity, equivalence ratio, tube diameter, wall conductivity	Tube	Methane	For a channel filled with fibrous porous media, the fuel leakage from the wall-flame "dead space" grows with the reduction of the channel diameter and the increase of the wall conductivity
Jiaqiang et al. (2016, 2017)	Geometry	Tube	Hydrogen (Non-premixed)	A novel geometrical configuration was proposed to improve the mixing and combustion efficiency
Zuo et al. (2017b)	Wall thickness variation	Tube	Hydrogen	Gradually reducing the wall thickness can result in a higher and more uniform wall temperature distribution depending on the wall material
Zuo et al. (2017a)	Coflow and counter flow configurations	Double-channel	Hydrogen	The outer wall temperature non-uniformity of the counterflow configuration is greatly lower than that of the coflow one
Fan et al. (2017)	Bluff body, wall material	Swiss-roll	Methane	The bluff body can greatly extend the flame blow-off limit by reducing the flame stretch