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Numerical study of hydrogen-air combustion characteristics in a novel micro-thermophotovoltaic power generator

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HIGHLIGHTS

- A micro combustor for thermophotovoltaic (TPV) devices is proposed.
- By utilizing the 3D CFD model, combustion characteristics are studied.
- Establishment of secondary flows causes better preheating in the curved tubes.
- Flammability limits is four times more for curved tube compared to straight tube.
- Secondary fluid can create a thermal equilibrium in the micro-combustor.

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ABSTRACT

In the present work, a micro combustor for thermophotovoltaic (TPV) devices is proposed which is included a U-shaped microtube in a box with a secondary fluid in space between U-shaped microtube and box walls. By utilizing the three-dimensional CFD model, combustion characteristics of the premixed lean hydrogen-air mixture in the present micro combustor are studied numerically with detailed chemistry and transport taking into account heat transfer through the wall. The results show that the establishment of secondary flows and better preheating in the curved tubes is caused the flammability limits to be at least four times in comparison with straight tubes. Combustion characteristics are studied for different parameters, namely inlet velocity, wall thermal conductivity, heat loss conditions, tube curvature and number of U-shaped tubes. By increasing inlet velocity up to 16 m/s, flame front moves toward downstream, the maximum temperature is increased and rate of reactions is intensified. The highest efficiency for thermophotovoltaic devices is calculated at 4 m/s inlet velocity. A wall thermal conductivity of 3 W/m K creates a better condition for flame stability. It is shown that the secondary fluid with higher thermal diffusivity could improve combustion characteristics. Energy conversion efficiency (η_Q), emitter efficiency (η_{Rad}) and total energy conversion efficiency of the TPV (η_{total}) is utilized to investigate the simulated cases for the present geometry. This type of micro combustor is well fitted for thermophotovoltaic applications.

1. Introduction

With the advances in the fabrication technologies, efforts are moving toward the design of devices in small scale. These devices require a compact, long lifetime, and instantly rechargeable power supplies [1]. Nowadays, these portable devices use lithium ion batteries, but the energy density of the existing batteries is very low. Since hydrogen and most hydrocarbon fuels have higher energy densities compared with the most advanced Li-ion batteries saying 20–50 times [2], hence, widespread application of power generating devices based on combustion in small scale is expected to expand in a near future [3].

To produce electric energy from thermal radiation released from the combustion process, micro-thermophotovoltaic (TPV) devices are suggested, since they are simple, efficient, without moving parts and scalable for different geometries. A typical micro-TPV system includes three main components namely fuel source, emitter and a PV cell array [4]. Several works have been done on developing TPV systems based on micro combustion. Durisch et al. [5] reported a small TPV system for butane flame as an emitter. Yang et al. [6] developed a prototype micro-TPV power generator for H_2-air combustion which was able to deliver a 0.92 W output electrical power for micro-combustor with

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Nomenclature

Dim	average diffusivity of the ith species (m^2/s)
Dij	binary diffusion coefficient of the ith species in jth species (m^2/s)
h	enthalpy (J/kg)
$\dot{m}_{H_2}$	mass flow rate of the fuel
p	pressure (Pa)
$\dot{Q}_{wall}$	heat transfer rate from the external walls
$\dot{Q}_R$	chemical heat release rate
Q_{LHV}	lower heating value of hydrogen fuel
$\dot{Q}_{Rad}$	radiation heat transfer rate
Ru	universal gas constant (J/kmol K)
T	temperature (K)
u	velocity vector (m/s)
$\overline{W}$	mean molecular weight of the mixture
Xi	mole fraction of specie i
Yi	mass fraction of the ith species

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity
λ	thermal η_{Rad} diffusivity
Φ	equivalence ratio
σ_i	collision diameter (A)
ε_α	Lennard-Jones energy
$\dot{\omega}_I$	rate of reaction of the ith species
Ω_D	collision integral
η_Q	energy conversion efficiency
η_{Rad}	emitter efficiency
η_{total}	total energy conversion efficiency of the TPV
σ	boltzmann constant
ε	surface emissivity

Subscripts

f	fluid
wall	wall
in	inlet
i	ith species
ij	ith species in jth species
im	ith species in the mixture
s	surface
sur	surrounding

0.113 cm^3 volume. Later on, they studied the effect of micro combustor configuration on the performance of micro-TPV power generators [7]. They suggested using of backward facing step in a micro combustor for increasing the output power of the system. Chia and Feng [8] reviewed different micro-TPV power generators by concerning the overall efficiency of the TPV systems. Yang et al. [9] introduced a modular micro-TPV system which has the advantages of easier fabrication and assembly.

Since the micro-combustor is an essential component of the micro-TPV system, maximum output power and high and uniform temperature distribution along the external surface of the micro-combustor are desirable. Hence, considerable efforts have been devoted to design different micro combustor with the purpose of improving the overall efficiency of the TPV systems.

For developing a micro combustor with the aforementioned conditions, it is required that the problems due to reducing the combustor scales be addressed carefully. Since the area-to-volume ratio in microscale devices is significantly large, heat release rate from external walls is high, and it is necessary to use thermal management to attain stable combustion. Different approaches have been introduced to increase combustion stability and thermal management in meso/micro scale combustors. The coating of the inner surface of the micro-combustor with catalytic and using of excess enthalpy concept are two main strategies for overcoming the flame extinction.

In the first strategy, Pizza et al. [10] numerically investigated the effect of inlet velocity and catalytic reactivity on the dynamics of lean hydrogen/air flames in a 2 mm height planar channel with platinum-coated walls. They showed that the rich flame dynamics could be suppressed by choosing suitable catalyst. Zhou et al. [11] compared the performances of catalytic micro-combustors made of different materials (quartz glass, alumina ceramic, copper). According to their experimental results, the combustors had high stability by coating inner wall of the combustor with the catalyst. Qazi Zade et al. [12] showed the importance of surface reactions in the stability of hydrogen-air combustion. Lucci et al. [13] explained that heat transfer from the hot catalytic wall laminarizes the flow. Yan et al. [14] elucidated characteristics of catalytic methane-air combustion in a plate type micro-combustor. They demonstrated that hydrogen addition into fuel has a significant influence on lowering the methane ignition temperature and shortening ignition time. Brambilla et al. [15] simulated lean hydrogen-air combustion in a planar channel coated with platinum. They performed a numerical parametric study where the influence of wall material, inlet velocity and inlet temperature on the startup process, from light off to gas-phase ignition, was investigated. Jiaqiang et al. [16] studied numerically the effects of inlet pressure on wall temperature and exergy efficiency of the micro-cylindrical combustor having a step geometry. They reported that the best performance is occurred at P_{in} = 0.1 MPa due to its potentiality to obtain better energy conversion efficiency and higher exergy efficiency.

Based on the concept of excess enthalpy combustion, different geometries have been proposed for combustor by researchers in the recent decade. Yang et al. [17] suggested using backward facing step in cylindrical micro-combustor. They experimentally measured the temperature at the exit and along the wall of the combustor for hydrogen-air combustion. Their results showed that the backward facing step could widen the operational range of flow rate and equivalence ratio. Chen and Buckmaster [18] developed a two-dimensional numerical model to simulate combustion and heat transfer in 'Swiss roll' combustors including the coupling of heat transfer and chemical reaction in the gas and heat diffusion in the conducting walls. They investigated the effect of the Reynolds number, equivalence ratio, wall thermal conductivity, and wall emissivity on the extinction limit. They reported that increasing Reynolds number and equivalence ratio causes reaction rate increase and moving toward upstream. Kim et al. [19] studied experimentally combustion characteristics of the propane-air mixture in various Swiss-roll combustors. They stated that flame could be stabilized for a broad range of inlet velocity and equivalence ratio due to heat recirculation from burned gas to unburned gas. They also noticed that blow-off limit was not observed in that conditions, and it can be a practical result for designing combustors in micro scales. In later years, Kim et al. [20] developed their experimental works on Swiss-roll combustors. Their result illustrated that the effect of design parameters such as the diameter of the combustor, top plate thickness, channel size, and combustor material could be substantial in the practical development of micro-combustors.