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Research Paper

Orthogonal Experimental Design and Fuzzy Grey Relational Analysis for emitter efficiency of the micro-cylindrical combustor with a step

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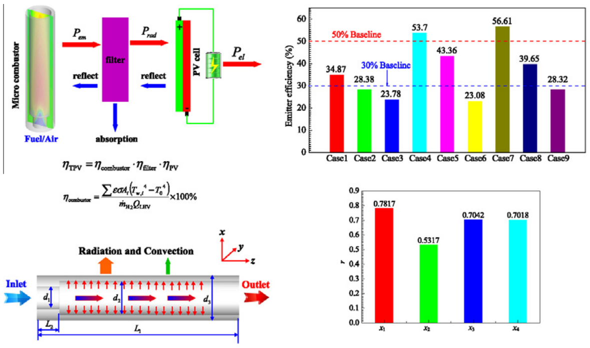
HIGHLIGHTS

- An efficient method combining OED and FGRA for evaluating impacts is proposed.
- Emitter efficiency under various conditions is obtained.
- Fuzzy grey relational grades are employed for comprehensive evaluation.
- H_2/air equivalence ratio affects emitter efficiency greatly.

GRAPHICAL ABSTRACT

Evaluate the impact of four factors for the emitter efficiency of the micro-cylindrical combustor with a step in the MPTV system.



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ABSTRACT

The micro combustor is the key component in the micro thermophotovoltaic (TPV) system. Moreover, emitter efficiency is the most important performance parameter of micro combustors. In this work, a method for evaluating the effects of various factors on the emitter efficiency of micro combustors is proposed. Firstly, the Orthogonal Experimental Design (OED) is employed for obtaining the simulation conditions of test cases. Then, the impacts of four factors (H_2/air equivalence ratio, H_2 flow rate, wall thermal conductivity and wall emissivity) on emitter efficiency are evaluated by fuzzy membership grades and Euclidean grey relational grades, respectively. Finally, Fuzzy Grey Relational Analysis (FGRA) was employed to make a comprehensive evaluation. Results show that the fuzzy grey relational grades of the four factors are 0.7817, 0.5317, 0.7042 and 0.7018, respectively, meaning that the impacts of the four factors are ranked from the most important to the least important as H_2/air equivalence ratio, thermal conductivity, wall emissivity and H_2 flow rate. This work offers us great reference value for optimizing micro combustors.

1. Introduction

Micro Power Generation Systems (MPGS) have many merits, including high energy density, small volume and long working

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Nomenclature

A_i	surface area of grid cell i (m^2)
d_1	inner diameter of the micro combustor at the inlet (mm)
d_2	inner diameter of the micro combustor at the outlet (mm)
d_3	outer diameter of the micro combustor (mm)
E_f	total fluid energy (J/kg)
h_j	enthalpy of species j (J/kg)
I	unit tensor
$\vec{J}_j$	diffusion flux of species j (kg/(m^2 s))
k_{eff}	effective conductivity (W/(m K))
k_w	thermal conductivity of wall (W/(m K))
l	resolution coefficient, $l \in [0,1]$
L_1	total length of the micro combustor (mm)
L_2	step length of the micro combustor (mm)
$\dot{m}_{H_2}$	H_2 flow rate (kg/s)
p	pressure (Pa)
P_{em}	total radiation power (W)
Q_{LHV}	lower heating value of hydrogen, 119.96 MJ/kg
R_j	net production rate of species j by chemical reaction (kg/(m^3 s))
r	fuzzy grey relational grade
r_1	fuzzy membership grade
r_2	Euclidean grey relational grade

S_f^h	fluid enthalpy source term (W/m^3)
T	temperature (K)
T_0	ambient temperature, 300 K
$T_{w,i}$	temperature of grid cell i on the wall (K)
$\vec{u}$	velocity vector (m/s)
u	specific internal energy (J/kg)
x	comparison matrix
y	reference matrix
Y_j	mass fraction of species j
z	axial coordinate (mm)

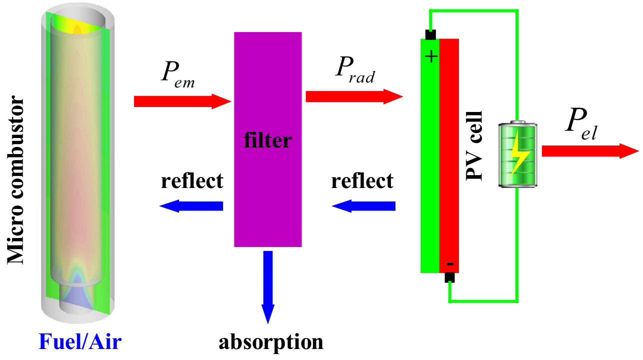
Greek letters

$\Delta_{\min}$	minimum absolute difference, $\Delta_{\min} = \min\lvert y(k) - x_i(k)\rvert$
$\Delta_{\max}$	maximum absolute difference, $\Delta_{\max} = \max\lvert y(k) - x_i(k)\rvert$
$\Delta(k)$	absolute difference, $\Delta(k) = \lvert y(k) - x_i(k)\rvert$
ε	wall emissivity
$\eta_{\mathrm{combustor}}$	emitter efficiency
η_{filter}	filter efficiency
η_{filter}	PV cell efficiency
μ	molecular viscosity (Pa s)
μ_j	chemical potential of species j (J/kg)
ξ_i	relational coefficient
ρ	density of gas (kg/m^3)
σ	Stephan–Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4)

time [1–4], which make them to be promising energy resources for micro-electromechanical systems (MEMS). Among the MPGS, the micro-TPV (MTPV) system has drawn lots of attention because of its simple energy conversion process [5,6], which is shown in Fig. 1 [7,8]. The chemical energy of the fuel is converted into thermal energy by combustion. Then, it is transferred to the PV cells through the filter. Finally, PV cells generate electricity due to photoelectric effects. In the energy conversion process of the MTPV system, the emitter efficiency of the micro combustor should be attached to great importance, which significantly affects the overall energy conversion efficiency of the MTPV system.

As it is well known that wall temperature is the most related parameter with the emitter efficiency, lots of experimental and numerical investigations are conducted. Yang et al. [9] studied effects of wall thickness on combustor wall temperature, showing that the performance of the combustor with a wall thickness of 0.4 mm was the best. Li et al. [10] investigated the effects of the combustor diameter, combustor length, flow velocity and fuel–air equivalence ratio on the wall temperature distribution, finding that the optimum efficiency was obtained at the fuel–air equivalence ratio of 0.8, independent of the combustor dimensions and the flow velocity. Then, they [11] investigated the effects of combustor size and geometry, inlet velocity profile and slip-wall boundary condition on the flame temperature, suggesting that a larger combustor led to a higher flame temperature. Tang et al. [12] conducted a comparative study on combustion characteristics of methane, propane and hydrogen fuels in a micro-combustor, showing that the wall temperature of methane case was the most uniform and highest among the three fuels. Akhtar et al. [8] researched the impact of different channel geometries on wall temperature distribution and energy conversion efficiency. It was found that combustors with trapezoidal and triangular cross-sections had better performance. Besides, the effects of inlet pressure on wall temperature were investigated in our previous study [13]. The wall temperature can be improved by adjusting the inlet pressure of the micro combustor.

Moreover, in order to increase the wall temperature, much excellent work has been done. Yang et al. [14] investigated the stainless cylindrical micro-combustor with or without a backward facing step. Results suggested that the micro-combustors with a backward facing step achieved a high and uniform temperature distribution. Jiang et al. [15] investigated the micro-combustor with and without baffles, showing that the baffle increased the mean wall temperature. Tang et al. [16] proposed a micro planar combustor with parallel separating plates. It was found that compared to single-passage combustor, the new combustor can achieve a higher mean temperature of the radiation wall due to the enhancement of heat transfer. Yang et al. [7], Vijayan et al. [17,18], Shirsat et al. [19], and Lei et al. [20] applied different recirculation methods to improve wall temperature and combustion limits of the micro-scale system. Bagheri et al. [21] employed bluff bodies to improve flame stability and wall temperature. Also, porous media is an effective material to enhance the heat transfer



$$\eta_{\mathrm{TPV}} = \eta_{\mathrm{combustor}} \cdot \eta_{\mathrm{filter}} \cdot \eta_{\mathrm{PV}}$$

$$\eta_{\mathrm{combustor}} = \frac{\sum \varepsilon \sigma A_i \left(T_{\mathrm{w},i}{}^4 - T_0{}^4\right)}{\dot{m}_{\mathrm{H2}} Q_{\mathrm{LHV}}} \times 100\%$$

Fig. 1. Energy conversion process of a MTPV system.