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Flame-anchoring mechanisms of a micro cavity-combustor for premixed H_2/air flame

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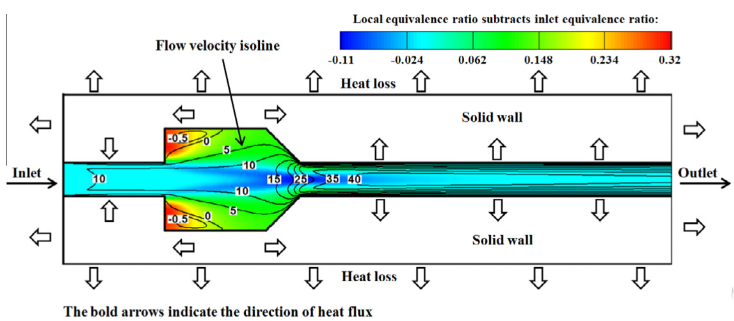
HIGHLIGHTS

- Flow recirculation zone anchors flame root and expands at smaller equivalence ratios.
- Heat recirculation via the solid wall leads to earlier initiation of chain reactions.
- A local equivalence ratio for premixed H_2/air combustion was defined.
- The preferential transport effect increases local equivalence ratio near flame root.

GRAPHICAL ABSTRACT

The major flame-anchoring mechanisms of the cavity in a micro combustor include the recirculation zone, low velocity zone and higher local equivalence ratio formed in the cavity and the heat recirculation effect via the upstream wall.



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ABSTRACT

Our recent work demonstrated that flame blow-off limit of microscale and mesoscale channels can be greatly extended by using wall cavity. In the present paper, we numerically investigate the flame-anchoring mechanisms of H_2/air flame in terms of interplays between flow field, heat recirculation, chemical reaction and preferential transport of species. The results show that obvious recirculation zone and low velocity zone are formed in the cavity, and the flame-anchoring location is near the vertical cavity wall. Moreover, the incoming fresh mixture is gradually heated by the upstream inner wall (i.e., heat recirculation effect), which leads to earlier initiation of chain reactions and more intense reaction near the flame-anchoring location. Furthermore, the preferential transport effect, which is caused by the differences in mass diffusivities of various species and two-dimensionality of the flow field, can change the local equivalence ratio (ϕ_{local}). It is shown that ϕ_{local} increases in the recirculation zone and low velocity zone in the cavity. More importantly, ϕ_{local} is much larger in the vicinity of the flame root, which is beneficial for flame-anchoring. In summary, the cavity can simultaneously provide a recirculation zone and low velocity zone, a better heat recirculation effect, and a high ϕ_{local} region, which are the main flame-anchoring mechanisms of the micro cavity-combustor for premixed H_2/air flames.

1. Introduction

Microscale and mesoscale combustions have been widely investigated in the past decades, largely due to the much higher energy densities of hydrocarbon fuels as compared with chemical

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Nomenclature

c_p	Specific heat capacity of the solid material, J/(kg K)
C_{in}	Mass fractions of hydrogen at the inlet of the micro-combustor
C_{out}	Mass fractions of hydrogen at the outlet of the micro-combustor
h_0	Natural convection heat transfer coefficient, W/(m^2 K)
K_n	Knudsen number
L_0	Total length of the combustor, *m*
L_1	Distance from the channel entrance to the vertical wall, *m*
L_2	Length of the cavity, *m*
L_g	Mean free path of gas, *m*
L_c	Characteristic scale of combustor, *m*
q_o	The total heat-loss rate to the surroundings, *W*
Q_1	Heat transfer rate from the upstream inner wall to incoming cold mixture, *W*
Q_2	Heat transfer rate from the hot flame in cavity to the upstream solid wall, *W*
Q_3	Heat transfer rate from the downstream solid wall to the upstream solid wall, *W*
$T_{w,o}$	Outer wall temperature, *K*
T_∞	Ambient temperature, *K*
V_{in}	Inlet velocity of mixture, m/s
W_0	Width of the combustor, *m*
W_1	Gap distance of the combustor, *m*
W_2	Depth of the cavity, *m*
W_3	Thickness of combustor wall, *m*
x	Horizontal distance of the combustor, *m*
y	Vertical distance of the combustor, *m*
Δx	Horizontal distance between two contiguous grids, *m*
Δy	Vertical distance between two contiguous grids, *m*
Greeks	
ε_s	Emissivity of the solid surface
θ	Apex angle, °
λ	Thermal conductivity of the solid material, W/(m K)
ρ	Density of the solid material, kg/m^3
σ	Stephan–Boltzman constant, W/(m^2 K^4)
ϕ	Inlet equivalence ratio of mixture
ϕ_{local}	Local equivalence ratio

batteries [1,2]. However, it is challenging to remain a broad range of stable flame as the combustor chamber is scaled down. This is mainly because of the increased heat-loss thanks to the large surface-area-to-volume ratio of small combustors [1,2]. Another critical issue is the reduced residence time of gaseous mixture in miniaturized combustors. Various flame dynamics have been reported hitherto [2]. For instance, flames with repetitive extinction and ignition (FREI) were observed in heated micro-tubes [3,4]. Later, these flame dynamics were theoretically interpreted [5]. In addition, a variety of non-stationary flame patterns, such as rotating Pelton-wheel-like flames, spiral-like flame, were observed in heated radial micro-channels [6–10].

Tremendous efforts have been made to improve flame stability in microscale and mesoscale combustors. Heat recirculation is a frequently adopted method in the design of small combustors. The “Swiss Roll” structure is a good example of such kind of burners [11,12]. Yang et al. [13] developed modular micro-combustor with porous media which demonstrated that self-sustained combustion can be achieved. Jiang et al. [14] studied combustion characteristics of a miniature cylindrical combustor with porous wall. Their experiments showed that flame can be stabilized in the combustor chamber due to reduction of heat losses and preheating effect of the fresh mixture.

Catalytic combustion has also been demonstrated to be viable in micro channels because catalyst can accelerate reaction and suppress radical depletion on the walls [15–17]. Boyarko et al. [18] investigated the catalytic combustion behaviors of hydrogen–oxygen mixture in micro-tubes coated with platinum. Leu et al. [19] studied the catalytic combustion of methanol in micro-channel reactor. Choi et al. [20] examined the combustion features in a catalytic combustor of sub-millimeter scale. It was shown that the activated region increased with the decreasing equivalence ratio.

To form a recirculation zone or low velocity zone via structural design is another effective way to anchor flame in small flow reactors. Yang et al. [21] developed micro-combustors with backward facing steps. Their results revealed that stable flames can occur in step-based micro-combustors over wide ranges of inlet velocity and equivalence ratio. Akram and Kumar [22] experimentally studied combustion behaviors of methane–air mixture in mesoscale diverging channels, which showed an enhancement of flame blow-off limit compared to the straight channel. Wan et al. [23] developed a micro bluff-body combustor which can expand the blow-off limit by several times compared to the straight channel. Effects of the bluff-body dimension and shape on flame blow-off limit of this micro-combustor were investigated recently [24–26].

It is well known that the cavity has been widely used for flame stabilization in supersonic combustion [27]. Lately, Li et al. [28] applied the cavity flame holder to micro-channels with segmented catalyst on the inner walls. They focused on the interactions between homogeneous and heterogeneous combustions. Nehe and Kumar [29] investigated methanol reformation for hydrogen production in a channel with cavities. Their results showed that the methanol conversion rate was enhanced in this design. Very recently, Wan et al. [30] investigated flame behaviors of CH_4/air mixture in a mesoscale channel with cavities experimentally and numerically. The small cavity-combustor could be potentially used for micro thermo-photovoltaic (TPV) systems or micro propulsion systems. Blow-off limits of this combustor are several times larger than the corresponding burning velocities of incoming CH_4/air mixtures, which indicates that cavities have a strong ability to extend the operational range of inlet velocity. Wan et al. [31,32] also explored lean H_2/air combustion in a micro-channel with cavities and confirmed the “flame-tip opening phenomenon”. In the present work, we aim at revealing the anchoring mechanism of micro cavity-combustor for premixed lean H_2/air flame. The underlying mechanisms are analyzed in terms of interplays between flow field, heat recirculation, preferential transport and chemical reaction.

2. Numerical methods

2.1. Geometric model

The schematic diagram of the micro cavity-combustor is shown in Fig. 1. In our previous study [31], we have investigated the influences of some geometrical parameters on the combustion characteristics of H_2/air flames. Thus, in this paper, we selected a fixed configuration and focused our concentration on analyzing the flame-anchoring mechanisms. The total length is L_0 = 18.0 mm