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Impacts of inner/outer reactor heat recirculation on the characteristic of micro-scale combustion system

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ABSTRACT

Flame stability and thermal performance of two different heat recirculation micro-combustors (inner reactor heat recirculation (IHR) and outer reactor heat recirculation (OHR)) are investigated using computational fluid dynamics (CFD) and compared together. A two-dimensional steady state CFD model including temperature dependent properties, laminar flow and transport, one step chemical reaction, surface-to-surface radiation, and heat conduction within solid walls has been carried out to assess flame propagation velocity, flame thickness, excess enthalpy, heat loss, and emitter efficiency. It is observed that both cases significantly extend flammability and blow-off limits due to preheating of the reactive mixture. The maximum flame propagation velocities of IHR and OHR in stoichiometric mixture are predicted 160.2 cm/s and 126.1 cm/s, respectively. It is found that super-adiabatic flame temperature takes place when dimensionless excess enthalpy is positive and it is maximum in the stoichiometric equivalence ratio. Heat loss can be varied from 245.8 to 248.6 W for IHR and from 249.6 to 254 W for OHR configuration. Therefore, there is a relative improvement in the Thermal quenching limit of IHR. It is concluded that IHR micro-combustor profoundly affects flame characteristic and stability, but OHR presents a higher range of emitter efficiency.

1. Introduction

It is evident that hydrocarbon fuels have a capacity for ≈ 100 times more energy–density than the most advanced batteries. Thus devices generating electricity from fuel at $> 1\%$ energy conversion efficiency demonstrate improvements over batteries for micro-scale systems [1,2]. These aspects of combustion based micro-power devices are deemed to find applications to fabricate compact, portable, and lightweight decentralized power generators [3,4].

Homogeneous combustion is a challenging issue at the micro-scale combustors due to the higher surface-to-volume ratio, thermal and radical quenching [5]. It was reported that the quenching distance is proportional to the flame thickness, that the flame thickness is inversely related to the burning velocity [6]. Therefore, to decrease the size scale of the combustor, the flame thickness should be reduced first. Several approaches can be employed for flame thickness reduction such as, reducing the molecular distance by increasing the pressure, the application of specific oxidants or fuels with characteristic of higher burning velocity, and the catalytic reaction combustors to preserve the chemical chain reaction of termination [7–10]. However, the mentioned methods are not directly associated with combustor configuration design. They can be applied to various combustors after determining the best configuration design. Consequently, several configurations have been suggested to overcome the ordinary quenching limits such as; vortex combustor [11,12], bluff-body [13–15], micro flameless combustor [16], and heat recirculating or excess enthalpy combustors [1,17,18].

In the heat recirculating combustor, because of the thermal energy transferring from combustion products to the reactants without mass transfer, the total enthalpy of reactant can reach a higher level than incoming cold reactants. In other words flame propagation would sustain under the conditions of low heating value fuel, lean mixture, and large heat losses that would quench without heat recirculation [19,17].

On the application side, Kim et al. [20] experimentally analyzed the propane–air mixture combustion in various configurations of swiss-roll combustor and different conditions of wall heat transfer. They pointed out that flames can be successfully propagated for a considerable extent of flow rates and mixture equivalence ratios by transferring heat of products to preheat the incoming cold reactants across solid walls. Several studies on combustion

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performance and flame stabilization in other small scale systems such as radial micro combustor [21,22] and backward facing step combustor [23,24] were implemented.

A spiral counterflow heat recirculating combustor was studied numerically by Kuo and Ronney [19] to understand the effects of viscous flow, temperature-dependent gas and solid properties and surface-to-surface radiative heat transfer. Extinction limits were predicted for a broad range of Reynolds numbers ($2 < Re < 5000$) and it was found that at $Re > 500$ turbulent modeling was required to obtain reasonable agreement with experiments. They emphasized that heat conduction along the walls and radiative heat transfer between the walls have a major impact in extinction limits, but the relative significance of such effects is remarkably dependent on *Re*. A computational fluid dynamic study of a single-pass heat recirculation micro combustor was developed by Federici and Vlachos [25]. It was shown that heat recirculation has a minimal effect on extinction but profoundly affects blowout. It was concluded that compared to the outer wall of heat recirculation, the inner wall more strongly impacts stability.

Park et al. [26,27] have developed a configuration of a 1–10 W micro-thermophotovoltaic device with a heat recirculating micro-emitter numerically and experimentally. They found that the heat recirculation concept and an expended exhaust outlet facilitate ignition, accomplish stable flame propagation in small confinement and uniform temperature distribution along the wall; hence, the generated heat from combustion emitted uniformly, providing significant overall efficiencies. Numerical and experimental investigations of a three-step micro combustor with external heating cup were conducted by Taywade et al. [3]. It was observed that stable X-shaped spinning flame exists for small flow rate with minimum thermal input of 2.2 W at $\varphi = 0.5$ and heat recirculation intensified the mean wall temperature of the combustor by 100–400 K.

Two common configurations of excess enthalpy combustors are inner reactor heat recirculation (IHR) and outer reactor heat recirculation (OHR) (Fig. 1). In IHR, the inlet is placed at the center of the reactor and the hot product sent over the entering chamber in a counter current direction for trapping heat within the reactor. Several studies [25,3] developed different size scale of this mode to expand flammability limit of the system compared to the simple micro combustor. In the OHR configuration, the combustor is fed by reactive mixture from the outer side and products of combustion exit from center of the reactor. Previous researches [26,27] documented that this design guarantees stable flame in the micro-burner with effective heat transfer into the incoming fuel–air mixture. Although the aforementioned studies have successfully explained the overall effect of heat recirculation in flame stabilization, the performance and efficiency of these two different configurations are not compared yet.

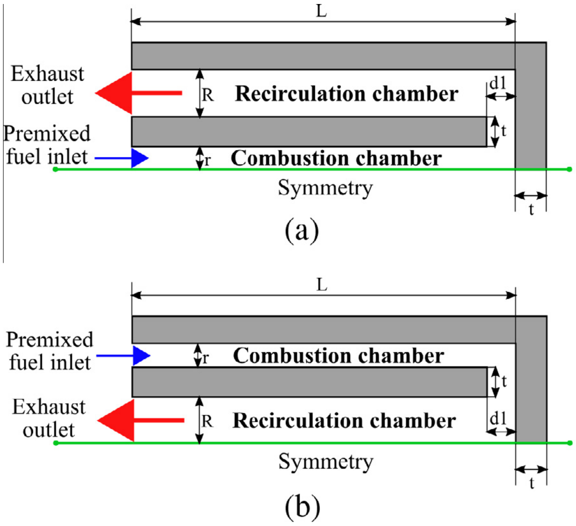
Consequently, the objective of present work is to predict the effect of IHR and OHR combustors on the flame stability limits. These two configurations enhance the average combustor wall temperature and consequently improve thermal performances of micro combustors. In this paper, the effect of incoming fuel–air mixture preheating in IHR combustor is delineated and compared with an OHR combustor. Parametric study has been carried out to understand the effects of heat recirculation model on flame position in micro combustor, flame speed and thickness, excess enthalpy and thermal performance of the combustors.

2. Model description

2.1. Micro-combustor configurations

Fig. 1 demonstrates the dimensional details of the micro-combustor configurations employed for numerical studies. These micro-combustors were designed based on presented geometries in [25,3,26,27]. There are two inner walls and two outer walls in which all walls have the same thermal conductivity and thickness.

Fig. 1(a) provides the dimensional details of an IHR micro-combustor. In order to maintain a uniform temperature on the combustor wall surface, a cylindrical configuration was chosen for the basic geometries. As indicated in Fig. 1(a), premixed air–fuel mixture is entered with a uniform flow velocity into the central chamber with a diameter of 0.6 mm. The hot products of combustion are split into two streams in recirculation chambers with a gap size of 0.6 mm. Fig. 1(b) shows the micro-combustor with OHR configuration and its major dimensions. In order to adopt the heat recirculation concept: products of combustion burned between inner and outer walls ($r = 0.3$ mm) turns around the closed end of the micro-combustor; the combustion products then preheat the incoming air-mixture supplied into the micro-combustor across the inner walls. The combustion products outlet is 1.2 mm in diameter. For both configurations, the combustion length *L*, wall thickness *t* and closed end gap *d*1 are 10, 0.5 and 0.6 mm, respectively.



	size(mm)
R	0.6
r	0.3
L	10
t	0.5
d1	0.6

Fig. 1. Description of heat recirculation geometries (not drawn to scale) (a) inner reactor heat recirculation (IHR) (b) outer reactor heat recirculation (OHR).