Combustion and Flame 171 (2016) 152–161

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Numerical study on heat recirculation in a porous micro-combustor

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ARTICLE INFO

Article history:
Received 5 January 2016
Revised 19 February 2016
Accepted 7 June 2016

Keywords:
Micro-combustion
Filtration combustion
Porous medium
H_2/air
heat recirculation
Numerical study

ABSTRACT

Heat recirculation is crucial to sustaining and stabilizing flames in micro-combustion in which a strong thermal coupling between the combustor wall and gas mixture exists through thermal conduction. Filtration combustion, on the other hand, is able to recirculate heat through the solid matrix to the unburned gas mixture, representing a promising potential to further enhance heat recirculation, if applied in micro-combustion. A numerical study on heat recirculation in premixed H_2/air filtration combustion in a planar micro-combustor with the channel height of $H = 1$ mm is carried out. Thermal non-equilibrium between the gas mixture and solid matrix is considered in the 2D numerical model. A parametric study is undertaken to examine the effects of key parameters on the two pathways of heat recirculation in the porous micro-combustor, they are, heat conduction in the combustor wall and conduction and radiation through the solid matrix. The porous micro-combustor has the low-velocity extinction limits as low as $\sim$0.2 m/s and the blowout limits in terms of critical equivalence ratios increase with increasing inlet flow velocity. Flame position and wall temperature are greatly influenced by the porosity (ε) and solid matrix thermal conductivity (k_s) of the porous medium, but interestingly, the flame temperature seems unaffected within the velocity range studied. Upon quantifying the two pathways of heat recirculation, it is found that convective heat exchange between the gas mixture and solid matrix plays the dominant role, while thermal conduction in the combustor wall the secondary role in preheating the gas mixture. The gas-to-solid convection efficiency ($\eta_{g\text{-}s}$) increases with the decrease of ε or equivalence ratio (Φ), and the increase of k_s. In contrast, the gas-to-wall convection efficiency ($\eta_{g\text{-}w}$) increases with the increase of ε or Φ. Careful selection of the wall material is important to ensure efficient heat recirculation through the combustor wall.
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1. Introduction

As a key component, micro/meso-scale combustors (referred to as ‘micro-combustors’ hereafter) were used as the heat source in a variety of miniaturized power systems, such as the micro gas turbine [1], the micro-thermoelectric device [2], the micro-thermophotovoltaic (TPV) system [3] and many others. The fact that hydrogen and many hydrocarbon fuels offer much higher energy densities than electrochemical batteries [4] motivated the prototyping, testing and development of those systems. Refs. [5–7] gave comprehensive reviews on the key progress in the research of micro-combustion and development of micro power systems. Despite the remarkable advances, the operation of micro-combustors still encounters technical challenges, for example, narrow flammability limits, poor flame stability, low combustion efficiency and so on.

Micro-combustion differing from its macro-scale counterpart is basically attributed to the reduced physical dimension. Norton and Vlachos [8,9] performed CFD simulations of methane/air and propane/air combustion in 2D micro-channels, showing that heat recirculation through the combustor wall is key to sustaining combustion in the micro/meso-scale. Leach and Cadou [10] established a 1D model with conjugate heat transfer between the gas and combustor wall, and found that the reaction zone thickness is broadened due to axial heat conduction through the combustor wall. Veeraragavan and Cadou [11] developed a more sophisticated 2D model that eliminates the assumption of a constant Nusselt number used in Ref. [10], and their results reaffirmed that heat recirculation is the primary parameter that determines the flame speed. Recently, Kang and Veeraragavan [12] employed a novel wall material with orthotropic thermal conductivity to investigate its effects on flame stability limits. A theoretical analysis based on that

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http://dx.doi.org/10.1016/j.combustflame.2016.06.007
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Nomenclature

d_s	Fiber diameter, m
D_{im}	Diffusion coefficient of the ith species into the mixture, m^2/s
$D^d_{\parallel}$	Thermal conductivity due to dispersion, m^2/s
h	Enthalpy, J/kg
h_c	Convective heat loss coefficient (non-insulated wall), W/m^2-K
h_i	Enthalpy of the ith species, J/kg
h_v	Volumetric heat transfer coefficient between solid and gas, W/m^3-K
H	Combustor height, m
k_g	Thermal conductivity of gas mixture, W/m-K
k_{rad}	Equivalent thermal conductivity due to radiation heat transfer, W/m-K
K_s	Thermal conductivity of solid matrix, W/m-K
$k_{s,eff}$	Effective thermal conductivity of solid matrix, W/m-K
k_w	Thermal conductivity of wall, W/m-K
l_0	Characteristic path length of the light quantum, m
L	Combustor length, m
p	Pressure, Pa
Q_c	Heat of combustion, kW
$q_{g\text{-}s}$	Convective heat transfer from gas mixture to solid matrix, W/m^3
$q_{g\text{-}w}$	Convective heat transfer from gas mixture to wall, W/m^2
q_w	Heat loss from non-insulated wall, W/m^2
t	Wall thickness, m
T_0	Inlet flow temperature, K
T_a	Ambient temperature, K
T_g	Gas mixture temperature, K
T_s	Solid matrix temperature, K
T_w	Wall temperature, K
T_{wo}	Outer wall temperature, K
u_g	Streamwise (x) velocity, m/s
U_0	Inlet flow velocity, m/s
v_g	Transverse (y) velocity, m/s
W_i	Molecular weight of the ith species, kg/mol
Y_i	Mass fraction of the ith species, kg/kg
Greeks	
α	Interfacial heat exchange coefficient, W/m^2-K
α_g	Thermal diffusivity, m^2/s
ε	Porosity of porous medium, -
ε_r	Emissivity of non-insulated wall, -
ε_s	Emissivity of solid matrix, -
η_{g-w}	Gas-to-wall convection efficiency, -
η_{g-s}	Gas-to-solid convection efficiency, -
μ	Dynamic viscosity, N-s/m^2
ρ_g	Density of gas mixture, kg/m^3
σ	Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2-K^4
Φ	Equivalence ratio, -
ω_i	Production rate of the ith species, kmol/m^3-s
Dimensionless numbers	
Nu	Nusselt number
Pe	Peclet number based on d_s ($\mathrm{Pe} = \mathrm{Re} \cdot \mathrm{Pr}$)
Pr	Prandtl number ($\mathrm{Pr} = \mu c_p/\alpha_g$)
Re	Reynolds number based on d_s ($\mathrm{Re} = \varepsilon d_s \rho_g u_g/\mu$)

particular configuration showed that the allowable heat losses to the ambient from the micro-combustor increased for a higher axial thermal conductivity of the wall [13]. The above-mentioned results consistently indicate that heat recirculation via thermal conduction in the combustor wall is necessary for stabilized and self-sustained flames in micro-combustors. To harness thermal energy in exhaust gases, Swiss-roll micro-combustors were constructed and tested [14,15], based on which simplified theoretical models were established and the results suggested that heat recirculation from exhaust gases to the unburned mixture was effective in increasing flame speed and extending flammability limits [16,17], manifesting the importance of transferring heat from the reaction zone to the unburned mixture in the case of micro-combustion.

One of the unique features of porous medium combustion, also known as 'filtration combustion', is the capability of recirculating heat through the solid matrix. Weinberg [18] first proposed the concept of excess enthalpy burners by a theoretical analysis. Takeno et al. [19] showed that superadiabatic combustion could be realized by inserting a porous, highly conductive solid into the flame zone. Barra and Ellzey [20] studied heat recirculation and heat transfer in two-section porous burners by employing the thermal non-equilibrium model, and found that the enhancement of flame speed is determined by the amount of heat recirculated through the solid matrix. Filtration combustion of CH_4/air mixture in high-porosity micro-fibrous medium was experimentally studied [21] and numerically modeled [22,23], with a standing-wave regime clearly identified which does not exist in macro-scale filtration combustion but suitable for stable operation. Because heat recirculation is highly desirable in micro-combustion, applying porous medium inside a micro-combustor could greatly enhance its performance. Some examples of porous micro-combustors could be found in the literature. A planar micro-combustor partially/fully filled with stainless steel (SS) mesh was experimentally tested by Li et al. [24], and the thermal equilibrium assumption was used in their CFD simulations to study the fundamental flame characteristics [25]. Marbach and Agrawal [26] constructed a cylindrical mesoscale combustor with annular porous medium for heat recirculation and SiC-coated carbon foam inside the combustion chamber for flame stabilization. Their follow-up CFD study [27] on heat transfer in the annular porous combustor, based on the thermal equilibrium model, identified design features with minimum heat losses. Chua *et al.* [28] conducted an experimental study on a micro-combustor filled with SiC foam, with the thermal equilibrium model based CFD study examining the effects of solid matrix properties on the wall temperature. However, the assumption of thermal equilibrium between the gas mixture and solid matrix adopted in previous CFD studies [25,27,28] on porous micro-combustors might render some inherent deficiency to their numerical models.

In the case of filtration combustion in micro-combustors, there are basically two pathways for heat recirculation, one is the solid matrix, same as the macro-scale counterpart, and the other is the combustor wall. It is practically important and theoretically meaningful to examine the significance of each pathway in a quantitative manner. In order to do so, both the conjugate heat transfer between the gas mixture and the combustor wall and the heat exchange between the gas mixture and the solid matrix need to be considered. Hence, the present study is to numerically model a porous micro-combustor combining the energy conservation equation of the combustor wall to account for the former with the thermal non-equilibrium model with thermal dispersion effects, similar to those in Refs. [20,22,23], to address the latter. The primary objective of the present study is, therefore, to reveal the effects of various key parameters on the two pathways of heat recirculation.

2. Modeling

The numerical model is based on a planar micro-combustor with the channel height of 1 mm. Figure 1 shows the direct photo,

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