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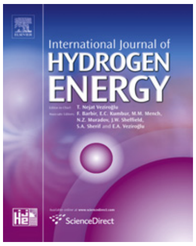

Flame stability studies in a hydrogen–air premixed flame annular microcombustor

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ABSTRACT

Flame stability in an annular heat recirculating microcombustor burning stoichiometric hydrogen–air mixture was explored by means of a rigorous thermal analysis. The analysis is based on computational fluid dynamics model of reacting fluid flow accounting for interactions in flow, species, and conjugate thermal field in fluid and solid. Consideration of thermal diffusion effects in the model was necessary for realistic predictions in all the cases. Flame stability under different inlet velocity and wall thermal conductivities was studied. Results showed that a stable flame could stabilize in this combustor in the velocity range of 3–35 m/s. However, the upper stability limit widened for lower wall thermal conductivity. Low velocity flashback and high velocity blowout bounded the stability region with respect to inlet velocity for lower thermal conductivity wall material. Lower flame stability limit was influenced by thermal design of the microcombustor that prevented flame extinction and ability of flame to stabilize at the heated wall even at higher inlet velocity controlled the upper flame stability limit. Flame established well within the combustor for the lowest wall thermal conductivity without blowout and approached flashback for the highest conductivity when wall thermal conductivity was varied at constant inlet velocity. Relative importance of axial and radial wall heat conduction in flame stabilization was explored at the extremes of operating conditions. Both the components played equally important roles in flame stabilization by influencing heat recirculation and losses within the microcombustor. A suitable combination of structural materials could provide a stable flame with high surface temperatures in a lightweight system.

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1. Introduction

In microcombustion, flame may quench thermally since the rate of heat release may not be able to compete with the rate of heat losses. Heat losses from microcombustors are especially significant since walls are in close thermal contact with the combustion zone.

Early studies by Chen and Churchill [1,2] revealed that wall conduction is an important mode of heat transfer to reactants in microcombustors apart from radiation and forced convection. In the recent past, experimental and numerical studies have focused on the effect of wall thermal properties on flame stability in a microcombustor. Junwei and Beijing [3] used SS 316 and alumina microtubes to burn CH_4–O_2 mixtures and found that lower thermal conductivity (k_{wall}) of alumina was detrimental to axial heat transfer and flame stabilization. However, higher emissivity (ϵ) of steel resulted in higher heat losses. Hence, material of high k_{wall} and low ϵ was recommended, in contrast to the requirement imposed by thermoelectric applications, which require materials of low thermal

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Nomenclature

C_P	specific heat
e_a	approximate error
e	extrapolated error
h	heat transfer coefficient
k	thermal conductivity
N	number of cells
n	normal vector
P	static pressure
p	apparent order of accuracy
$\dot{Q}''$	heat flux, W/m^2
$\dot{Q}'''$	heat release rate, W/m^3
R	radial coordinate
r	molar reaction rate, $kmol/m^3s$
r_N	grid refinement ratio
T	static temperature, K
V	velocity magnitude, m/s
X_{flame}	flame position, mm
X	longitudinal coordinate, m
Y	mass fraction
ϵ	emissivity
ϕ	equivalence ratio
φ	generic primitive variable
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, 5.6704e–08 W/m^2K^4
g	gage pressure, Pa
∞	ambient condition
1,2,3	grid levels (fine, mid, coarse, respectively)

conductivity [4]. Thermophotovoltaic applications depend upon heat losses by radiation and hence require materials of high emissivity. Zhou et al. [5] conjectured that outer layer of the wall should be of ceramic and inner one should be steel based on the results of Norton and Vlachos [6]. Their numerical studies [6] identified that lower k_{wall} would lead to lesser heat recirculation to reactants by axial heat conduction, thus causing flame blowout. Higher k_{wall} on the other hand would lead to extinction since heat losses would increase. Their results indicated k_{wall} ~3–5 W/mK as "optimal" thermal conductivity range allowing largest external heat transfer coefficient that would still sustain the flame. Kaisare and Vlachos [7] reported similar findings about the optimal range of k_{wall}. Recently, Khandelwal et al. [8] conducted parametric studies on methane–air flame stability in a 2 mm diameter dump microcombustor using quartz, steel, brass, and copper as wall materials. Their results showed that the stability limits narrowed for high thermal conductivity materials. Although, no stable flame occurred for copper, it was possible to stabilize the flame at the minimum flow rates for quartz walls.

Relative balance of axial and radial heat conduction in the walls [6] governs preheating of the reactant mixture. Kuo and Ronney [9] studied a related case of Swiss-roll microcombustor and discussed the effect of k_{wall} on the extinction limit. Optimal thermal conductivity in their case permitting the widest possible extinction limits turned out to be smaller than k_{air}. They proposed that k_{wall} could be low enough (in the sub-optimal range) until wall thermal resistance is comparable to thermal resistance between gas and wall. The perceived difference in optimal conductivity is due to different view about transverse heat conduction. Transverse heat conduction ultimately promotes heat losses [6,10] in large aspect ratio straight microchannel combustors. However, in heat exchanger microcombustors (Swiss-roll or other multiple fluid pass designs), it is the primary mechanism of heat exchange between hot products and cold reactants. In fact, studies [11,12] indicate that streamwise conduction along the wall may lead to extinction at low *Re*.

Inlet velocity is another operating condition influencing the flame stability in microcombustion [1–3,5–7]. Chen and Churchill [1,2] obtained stability maps of heat recirculating preheated microcombustor under adiabatic operating conditions. Classical flashback and blowout stability limits were observed. They also gave experimental and theoretical evidence for the existence of multiple steady states at a given inlet flow rate and fuel–air ratio. Numerical studies by Vlachos and co-workers [6,7] showed that high velocity blowout and low velocity extinction bounded methane–air flame stability with respect to flow rates. In both the extremes, the flame location moved downstream. Junwei and Beijing [3] studied effect of velocity on heat losses under fuel-lean conditions. They showed that wall temperatures increased with flow rates and enhanced the amount of heat losses by radiation. It was also reported that wall temperatures reached steady state distributions faster at higher flow rates. To summarize, the effects of operating conditions on flame stability are not always the same in microcombustion and vary from design to design.

Takeno and Sato [13,14] explored the possibility of producing an excess enthalpy flame by inserting porous solid in the flame, which was adopted and refined further [15,16] in a multi-tube combustor in which heat loss was prevented by recirculating the products around the combustor before purging (first counter-current; then co-current). Effective heat recirculation by conduction, convection, and radiation [13–16] was a key requirement for flame stabilization in this configuration and results indicate that stability limits widened with the help of heat recirculation under adiabatic conditions. However, adiabatic conditions seldom exist in practice because insulations cannot be applied at all the structural locations and thermal contact among different components cannot be eliminated. In fact, inability to separate hot and cold regions is a limiting factor for performance in a microcombustor. Thus, although a part of heat released in combustion conducted towards cold reactant mixture by a thermal pathway comprising of gas phase convection and solid phase conduction [1], heat loss through combustor walls was a limiting factor in flame stabilization in practice [15]. Additionally, other disadvantages of this configuration are; complicated structural arrangement for controlling heat losses and flame stabilization increased overall weight, and greater pressure losses in narrow tubes/passages in porous materials.

Hence, there is a need to devise a heat recirculating microcombustor that addresses above disadvantages by

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