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Prediction of flame speed and exergy analysis of premixed flame in a heat recirculating cylindrical micro combustor

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An interaction between wall heat recirculation, flame speed and thermodynamic irreversibility has been established from an analytical model based on flame sheet assumption pertaining to a premixed flame in a cylindrical micro combustor. The total rate of heat recirculation through the combustor wall and the flame speed depict global maxima depending on the wall to gas thermal conductivity ratio. The optimum value of wall to gas thermal conductivity ratio for maximum flame speed bears an inverse relation with the ratio of wall thickness to combustor radius and the outer wall *Nusselt* number. The proportional change in heat recirculation is more than that in heat generation with wall to gas thermal conductivity ratio, wall thickness to combustor radius ratio and outer wall *Nusselt* number. The exergy loss at outer wall is around 5–7% of inflow exergy while the exergy destruction in the process of heat recirculation and combustion is around 40–45% of inflow exergy. The second law efficiency is found to be almost constant around a value of 58%.

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1. Introduction

The rapid growth of micro scale devices brings about the development of miniaturized combustors, which are compact in size and competent to deliver power of the order of few Watts. Miniaturized combustors utilize chemical energy of fossil fuels to produce thermal energy which may further be utilized as compact and portable source of power. Because of high energy density of fossil fuels, miniature combustors are being considered as potential substitutes to the conventional chemical batteries [1]. The practical aspects and challenges associated with development of micro combustors have been reviewed in recent literature [2–4]. The characteristics length scale of a typical micro combustor is of the order of quenching distance. At this length scale, due to high surface area to volume ratio, heat loss becomes so severe that heat conduction through gas phase from flame to fresh mixture alone cannot establish a self sustained flame. One of the important characteristic features of combustion in small scale device is recirculation of heat from post flame region to pre-flame region via combustor wall which promotes the flame to get established even under severe heat loss condition. A good deal of attention has been paid to understand the characteristics of excess enthalpy flame by several researchers [5–9] in resent past. The pioneering effort to model an excess enthalpy flame is due to Jones et al. [10], where extinction and blow off limits were predicted by a global energy balance with a specified minimum flame temperature. Leach et al. [11] predicted extinction and blow off limits considering axial heat conduction in gas and structure using thermo electrical analogy. Ju and Choi [12] developed a thermo diffusive model using two infinitely long counter flow channels separated by a thin wall. Fast and slow burning regimes were observed along with the dependence of extinction limit on external heat loss. Schoegl and Ellezy [13] studied a model similar to Ju and Choi [12] considering wall to be conducting. They studied both counter flow and co-flow configurations and concluded the superiority of counter flow configuration over co flow in terms of higher flame speed and broader flammability limits. Veeraragavan and Cadou [14] predicted the speed of flame stabilized in an infinitely long micro channel. Their analytical model incorporated conjugate heat transfer between gas and combustor wall. In a subsequent analytical work, Veeraragavan [15] reported the influence of orthotropic wall material on flame speed in a micro-channel combustor.

Numerical studies [16–19] and Experimental investigations [20–23] have been made in the recent past in order to elucidate the influence of wall thickness and wall thermal conductivity on the performance of micro channel combustors with heat recirculating

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Nomenclature

$\bar{a}$	Molar chemical exergy (J/mol)
A	Exergy (W)
A^*	Non dimensional exergy (A/A_{free})
A_{free}	Flow exergy based on freely propagating flame speed (W)
D_g	Mass diffusivity of gas (m^2/s)
$\bar{h}$	Partial molar enthalpy (J/mol)
h_∞	Convective heat transfer coefficient
I	Irreversibility (W)
I^*	Non dimensional irreversibility (I/A_{free})
k	Thermal conductivity ratio (k_s/k_g)
k_s	Thermal conductivity of solid ($W/m.K$)
k_g	Thermal conductivity of gas ($W/m.K$)
Le	Lewis number
$\dot{m}$	Mass flow rate (kg/s)
Nu_E	*Nusselt* number at the outer wall of combustor
P	Pressure (N/m^2)
Pe	*Peclet* number
$Q_{gen,free}$	Heat generation corresponding to a freely propagating flame (W)
Q_R	Heat Recirculation through combustor wall (W)
Q_R^*	Non dimensional heat recirculation ($Q_R/Q_{gen,free}$)
Q_L	Heat loss in the pre-flame zone (W)
Q_L^*	Non dimensional heat recirculation ($Q_L/Q_{gen,free}$)
r	Dimensional radial coordinate
r^*	Non dimensional radial coordinate (r/R)
R	Radius of the combustor (m)
R_u	Universal gas constant ($J/mol.K$)
$S_{L,}$	Flame speed (m/s)
S_L^*	Dimensionless flame speed ($S_L/S_{L,free}$)
$S_{L,free}$	Freely propagating flame speed (m/s)
$\bar{s}$	Partial molar entropy ($J/mol.K$)
t	Wall thickness (m)
t^*	Wall thickness ratio (t/R)
T	Temperature (K)
y_f	Fuel mass fraction
Y_f	Dimensionless fuel mass fraction
z	Dimensional z-coordinate
z^*	Non dimensional z-coordinate (z/R)
Z_e	*Zeldovich* number $\left(\frac{T_a(T_{ad}-T_{-\infty})}{T_{ad}^2}\right)$
x^i	Mole fraction of species i
Greek Symbols	
α_{th}	Thermal diffusivity of gas (m^2/s)
λ_n	Eigen values in the pre-flame zone
β_n	Eigen values in the post flame zone
δ	*Dirac* delta function
δ_f	Flame thickness
γ	Heat release parameter $\left(\frac{T_{ad}-T_{-\infty}}{T_{ad}}\right)$
θ	Non dimensional temperature
φ	Pre-flame temperature filed along r-direction
ψ	Post-flame temperature filed along r-direction
ω	Reaction Rate
η_{II}	Second law efficiency
Subscript	
f	Fuel, flame
$free$	Associated with freely propagating flame
gen	Generation
g	Gas
opt	Optimum value
s	Solid

wall. Numerical study pertaining to repetitive extinction-ignition characteristics of lean H_2-air flame in a heated micro channel has been reported [24] in the literature. It is observed that the frequency of repetitive extinction-ignition increases with inlet flow velocity. In a recent numerical work Zuo et al. [25] made a comparison of coflow and counter flow double channel micro combustor for micro-TPV system. The results showed that the counter flow double-channel micro combustor has better thermal performance compared to coflow double-channel micro combustor. Pan et al. [26], from their experiments on micro combustor for thermo photovoltaic (TPV) power generation, predicted that the ratio of nozzle to combustor diameter had a key role in the determination of wall temperature distribution and flame location. In a subsequent experimental study, Pan et al. [27] reported that combustion efficiency in a sub-millimetre channel combustor is significantly influenced by nozzle geometry and fuel flow rate. Vijayan and Gupta [28] experimentally studied the premixed flame dynamics in a meso-scale heat recirculating combustor. The study demonstrated the existence of stable self-sustained flame at high mean flow velocities within a meso-scale Swiss-roll combustor. Propagation of excess enthalpy flame in small adiabatic heat recirculating tubes have been numerically investigated by Gauthier et el [29]. It is observed that with increase in tube diameter and inflow velocity, burning rate enhances due to flame stretching effects. Whereas, with decrease in tube diameter two-dimensional effects become less significant and heat recirculation controls the burning rate. In a more recent work [30] Gauthier and Bergthorson investigated the influence of external heat loss on flame propagation in micro and meso-scale tubes. The values of external heat loss coefficients at the limit of extinction and blowout are fund to increase with tube diameter.

The combustion of hydrocarbon fuels involves various irreversible physical processes which lead to destruction of energy quality. The growing need for the development of energy efficient combustors motivates for thermodynamic analysis of a combustor in a perspective of exergy (energy quality) preservation and its dependence on pertinent controlling parameters. The work on thermodynamic irreversibility and exergy analysis pertaining to combustion processes have been well documented in a comprehensive review of Som and Datta [31]. They identified the major sources of irreversibility as heat conduction, chemical reaction and mass diffusion in order of merit in almost all combustion process. However, determination of irreversibility components and subsequent exergy analysis in micro combustors have not yet been adequately addressed in literature. Li et al. [32] determined the entropy generation from a simplified model of entropy balance and correlated the entropy generation with the radius of a cylindrical micro combustor tube. They considered a laminar flame in deriving the flame temperature. Jejurkar and Mishra [33] determined the entropy generation based on entropy transport equation from CFD simulation of a reacting flow in a micro combustor.

The recent work of Rana et al. [34] has reported an exergy based

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