Energy 68 (2014) 510–518

Contents lists available at ScienceDirect

Energy

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

Thermodynamics of premixed combustion in a heat recirculating micro combustor

Uttam Rana, Suman Chakraborty, S.K. Som*

Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur 721302, India

ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
13 February 2014
Accepted 18 February 2014
Available online 15 March 2014

Keywords:
Micro-scale combustion
Heat recirculation
Thermodynamic irreversibility

ABSTRACT

A thermodynamic model has been developed to evaluate exergy transfer and its destruction in the process of premixed combustion in a heat recirculating micro combustor. Exergy destruction caused by process irreversibilities is characterized by entropy generation in the process. The entropy transport equation along with the solution of temperature and species concentration fields in the wake of flame sheet assumptions have been used to determine the different components of entropy generation. The role of thermal conductivity and thickness of combustor wall, and *Peclet* number on transfer and destruction rate of exergy is depicted in the process of flame stabilization via heat recirculation. The entropy generations due to gas phase heat conduction and chemical reaction are identified as the major sources of exergy destruction. The total irreversibility in pre-flame region is confined only within a small distance upstream of the flame. It has been observed that the local volumetric entropy generation is higher near the axis than that near the combustor wall. The second law efficiency is almost invariant with heat loss from the combustor, *Peclet* number, and thermal conductivity and thickness of combustor wall.

1. Introduction

The rapid growth of micro devices brings about a strong demand for small-scale power sources. This necessitates the development of micro and mesoscale combustors for power generation in small scale devices like micro gas turbine, micro air vehicle, micro thruster, micro actuator *etc*. The scientific issues and challenges pertaining to micro and mesoscale power generating devices in practice have been addressed in recent reviews [1–3]. The geometry of a micro scale combustor corresponds to a length scale which is close to quenching distance. The ratio of heat loss to heat generation becomes significant due to high surface area to volume ratio of such combustors. As a result, flammability limits get narrowed down and sometimes it becomes very difficult to stabilize a flame within the combustor. There are different approaches for stabilizing flame in micro combustors like heat recirculation via combustor structure [4–12], maintaining high wall temperature of combustor [13–16], use of catalytic combustor [17], use of pulsed micro wave energy [18], use of stepped tube combustor with inserted wire [19]. The addition of hydrogen [20] as an additive to methane–air mixture enhances the concentration of certain radicals which in turn increases the blow out limit. Amongst the different approaches, heat recirculation has gained considerable interest due to its natural occurrence in small scale structures. The studies on the influence of wall thermal conductivity and wall thickness on the performance of micro channel combustors with heat recirculation [21–24] reveal that an increase in wall thermal conductivity leads to a better heat recirculation thus increasing the flame speed and broadening the flammability range, while increasing the heat loss to the surrounding.

In the wake of growing concern for efficient utilization of natural energy resources, both micro and macro combustors should be thermodynamically efficient in preserving the energy quality while enhancing the burning rate and hence the flame speed. Recirculation of heat from post flame region via combustor wall to the fresh charge in enhancing the flame speed may cause higher entropy generation in the premixed gas phase region due to higher values of local temperature gradient. The increase in entropy generation may also be attributed to enhancement in species diffusion and chemical reaction. Therefore optimal utilization of energy resources should essentially be based on a compromise between the apparently contradicting aspects of entropy generation and the rates of thermo mechanical and thermo chemical transport processes. The importance of exergy based thermodynamic analyses for the performance evaluation of thermal systems has been reported in literature [25–29]. Khu et al. [30] developed a thermodynamic

* Corresponding author. Tel.: +91 3222 282978; fax: +91 3222 282278.
E-mail address: sksom@mech.iitkgp.ernet.in (S.K. Som).

http://dx.doi.org/10.1016/j.energy.2014.02.070
0360-5442/

Nomenclature

$\bar{a}$	molar chemical exergy
$\dot{A}$	exergy (thermodynamic availability)
c_p	specific heat capacity of gas
D_g	mass diffusivity of species in gas phase
$\dot{e}_{ch}$	volumetric entropy generation rate due to chemical reaction
$\dot{E}$	total entropy generation
E_a	activation energy
$\bar{h}$	partial molar enthalpy
H	channel half width
I	irreversibility
I^*	non dimensional irreversibility ($=I/Q_{gen,free}$)
k	thermal conductivity ratio
k_s	thermal conductivity of solid
k_g	thermal conductivity of gas
Le	Lewis number
$\dot{m}$	mass flow rate
Nu_s	Nusselt number at outer surface
P	pressure
Pe	Peclet number
Pr	Prandtl number
Q_R	heat recirculation through combustor wall
Q_R^*	non dimensional heat recirculation ($=Q_R/Q_{gen,free}$)
Q_L^*	non dimensional heat loss
$Q_{gen,free}$	heat generation in freely propagating flame
Re	Reynolds number
R_u	universal gas constant
S_L^*	dimensionless flame speed
$S_{L,free}$	freely propagating flame speed
$\bar{S}$	partial molar entropy
t	wall thickness
T	temperature
U	flow velocity
x	dimensional x-coordinate
x^*	dimensionless x-coordinate
y	dimensional y-coordinate
y^*	dimensionless y-coordinate
y_f	fuel mass fraction
Y_f	dimensionless fuel mass fraction
Ze	Zeldovich number
x^i	mole fraction of species i

Greek symbols

α_{th}	thermal diffusivity of gas
λ_n, β_n	eigen values in the pre flame and post flame zones respectively
δ	Dirac delta function
γ	heat release parameter
τ	geometric wall thickness ratio
θ	dimensionless temperature
ρ	density of gas
ϕ	pre-flame temperature filed along y-direction
ψ	post-flame temperature filed along y-direction
ω	reaction rate
η_{II}	second law efficiency

Subscript

a	activation
ad	adiabatic
ext	extinction
f	fuel, flame
free	associated with freely propagating flame
gen	generation
g	gas
r	reference state
s	solid

model, considering finite heat leakage and heat input through finite temperature difference to a micro heat engine and evaluated theoretical maximum power output, power density and thermal efficiency. Some of the recent works [31–33] have focused on the cost and environment impact associated with the thermodynamic efficiencies of combustion process. These works identified avoidable and unavoidable exergy destruction in different components of a plant and also made an exergy cost analysis of the plant. Caton [34] examined the availability destruction during combustion process in an adiabatic constant volume system with specific application to internal combustion engine. His analysis was based on equilibrium approach of exergy balance [35] and depicted the influences of pressure, temperature, equivalence ratio on the destruction of fuel availability. Research investigations [36–45] in relation to exergy analysis of gaseous fuel combustion have addressed the major sources of irreversibility in multi component reactive flows for premixed and diffusion flame and their dependence on the operating conditions. In a recent review of thermodynamic irreversibility in combustion process, Som and Datta [35] identified the major contributors of irreversibility as heat conduction, chemical reaction and mass diffusion in order of merit in almost all combustion process. Relatively few works have been carried out on the thermodynamic aspect pertaining to micro combustor. Li et al. [46] 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 [47]. Jejurkar and Mishra [48] determined the entropy generation based on entropy transport equation from CFD (computational fluid dynamics) simulation of a reacting flow in a micro combustor. A relation between flame speed, heat recirculation and thermodynamic irreversibility at different operating conditions, namely, the heat loss, combustor geometry and thermal conductivity of combustor wall is essential for the design of an energy efficient micro combustor. This depends primarily on a physical understanding of the process of entropy generation from different sources, its spatial distribution, determined from fundamental entropy transport equation [50], in the process domain and the coupling between exergy transfer and its destruction due to thermodynamics irreversibility. The present article develops a comprehensive theoretical model with a detailed emphasis on these aspects in evaluating the irreversibility components from various sources and exergetic efficiency of a heat recirculating micro combustor. This aims to throw light on the design of an energy efficient process in a micro combustor.

2. Theoretical formulation

The physical model refers to a situation of premixed 'thin plane flame sheet' stabilized in an infinitely long narrow channel of height H formed by parallel plates of thickness t (Fig. 1). A stoichiometric mixture of gaseous methane and air has been considered as the reactants moving with a uniform velocity in a plug flow mode which refers to flame speed under the situation. The problem is considered to be steady, two dimensional and axisymmetric.