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Two-dimensional analytical model of flame characteristic in catalytic micro-combustors for a hydrogen–air mixture

S.A. Fanaee, J.A. Esfahani*

Center of Excellence on Modelling and Control Systems (CEMCS) & Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad 91775-1111, Iran

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ABSTRACT

The present paper aims to analytically investigate combustion phenomenon in micro-combustors by using a two-dimensional model. The main objective is to analyze the effects of main parameters such as reaction zone thickness, maximum temperature and quenching distance throughout the combustor under catalytic and non-catalytic conditions. In solution of energy and mass equations, the temperature and mass dependant reaction rates are considered with an iterative procedure. The reaction zone thickness is considered as a variable and is predicted by the solution results of the present study. In order to validate the present model, the normalized magnitude of flame temperature is compared with published data, which shows an acceptable agreement and confirms the accuracy of the predicted data. The results show that the effect of catalytic surface on expanding flammability limits in a lean mixture is larger than the rich one.

1. Introduction

Nowadays, declining in energy reserves is resulted in making a strong desire for lighter and longer devices with micro power generation. Therefore, the application of catalytic/non-catalytic micro-combustion in these devices appears as an important field. The investigation of micro-combustion powers, applications and their recent progresses are available in Ref. [1]. The paper states that micro-sized channel is termed as the characteristic length scale of confined space at the order of 100–1000 μm where the operating limitation is different from the conventional channel size. Also, the continuum approximation in both micro-scale and meso-scale devices is still valid since these dimensions are greater than the mean free path of molecules under typical conditions.

To investigate such problems, different models of heat transfer, heterogonous and homogenous combustion models have been put forward. Li et al. [2,3] developed a one-dimensional flame model to analyze the heat transport occurring in the cylindrical micro-combustors. In these works, the effects of various parameters such as channel size, fuel property, and unburned mixture temperature on heat loss for hydrogen–air and hydrocarbon–air mixtures were investigated. Fanaee and Esfahani [4] presented a semi-three-dimensional heat transfer model in the micro-channels. In this research, the governing equations were solved in two cases achieved from asymptotic and non-asymptotic approaches respectively, with considering the reaction zone thickness limits to zero and the narrow reaction zone thickness from order of micro-combustor height. The results show

* *Corresponding author*. Tel.: +98 915 134 4361; fax: +98 511 77 240 488.
E-mail address: Abolfazl@um.ac.ir (J.A. Esfahani).

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Nomenclature

A	frequency factor, $cm^3/(mol\ s)$
A_m	matching condition coefficients
A_n	boundary condition coefficients
C	catalytic conditions
$C_{1,2}$	constant coefficients, Equations (24) and (26)
C_P	constant pressure specific heat, J/(Kg K)
D	molecular diffusion coefficient, m^2/s
Da	Damkohler number
d	distance of parallel plates, m
d_q	quenching distance, m
e	Euler's number
E	activation energy, kJ/mol
k	thermal conductivity, w/(m K)
k_C	rate of catalytic reaction, cm/s
L	micro-combustor length, m
Le	Lewis number
M	molecular weight of samples
NC	non-catalytic conditions
Nu	Nusselt number
P	static pressure, atm
Pe	Peclet number
Pe_m	mass Peclet number
Pr	Prandtl number
Q	heat of combustion, J/m^3
Q^+	normalized heat of combustion, J/m^3
R	global gas constant, kJ/mol K
Re	Reynolds number
Sc	Schmidt number
S_T	normalized reaction rate of energy equation
S_Y	normalized reaction rate of mass equation
T	temperature, K
T_f	flame temperature, K
U	x-direction velocity, m/s
X	normalized axial coordinate
x	axial coordinate, m
Y	normalized mole fraction
y	mole fraction
Z	normalized perpendicular coordinate
z	perpendicular coordinate, m

Greek symbols

α	thermal diffusivity
β	Zeldovich number
β_m	total Eigen-value
γ_n	post-flame Eigen-value
δ	normalized reaction zone thickness
ε	reaction zone thickness
θ	normalized temperature
λ_n	preheat Eigen-value
ρ	density, Kg/m^3
ν	diffusion volumes of samples
Φ	equivalence ratio
ω_f	rate of combustion reaction, 1/s

Subscripts

i	inlet, samples
pre	preheat zone
post	post-flame zone
react	reaction zone
W	wall
Y	mole fraction

that the trends of main parameters are achieved similar in asymptotic and non-asymptotic approaches.

In the catalytic micro-channel, noble metals are held on ceramic supports coated on the micro-channel wall by using special deposition and drying methods, where the heterogeneous reactions occur on the catalyst [5]. Fanaee and Esfahani [6] presented a one-dimensional analytical model of heterogonous reaction on non-reactive flow in micro-channel. The sensitivity analysis shows that the sensitivity of hydraulic diameter is more than longitudinal coordinates because a large surface area to volume is available in micro-combustors. Appel et al. [7,8] investigated the numerical and experimental modeling of catalytic reactions used to stabilize the combustion reactions into micro-channels for H_2–air mixture over platinum. The understanding of the heterogeneous (catalytic) and the homogeneous (gas-phase) kinetics is crucial to the development of such systems. Qazizade et al. [9] numerically investigated the importance of gas-phase and surface reactions for H_2/air mixture at different inlet mass fluxes, equivalence ratios and channel heights in planar micro-channels. The results show that for lean limitations the gas-phase reactions become negligible compared to surface reactions. Furthermore, the results of this work are compared with the experimental data [7] across the micro-channel.

Chen et al. [10] numerically investigated an axisymmetric CFD model of a catalytic micro-tube to investigate the effects of catalytic wall on homogeneous combustion inside a micro-tube. The work shows the heterogeneous reaction and homogeneous combustion are governed at the upstream and downstream region, respectively. The region dominated by heterogeneous reactions expanded to downstream with increasing inlet velocity, and finally occupied the whole tube. In similar work, Wang et al. [11] investigated the comparison of reaction intensity between catalytic and non-catalytic combustors. In this paper, the catalytic combustor shows high stability, but weak reaction intensity. In addition, the experimental data [12] shows that the catalytic combustion can improve the homogenous combustion on micro-scale with novel schemes of catalytic micro-combustors. Benedetto et al. [13] investigated two-dimensional CFD simulations into the opportunity of setting up a micro-combustor. The numerical results show that this novel catalytic/non-catalytic scheme of micro-combustor allows stabilized combustion at high inlet gas velocities with complete conversions.

The investigation of flammability limits and quenching distance is very important in the micro-combustors problem considering existence of the high surface to volume ratio. Ju and Maruta [14] present the lean and rich standard flammability of a one-dimensional, infinite, planar, and un-stretched