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A numerical study on heat-recirculation assisted combustion for small scale jet diffusion flames at near-extinction condition

Jian Gao, Akter Hossain, Tsuneyoshi Matsuoka, Yuji Nakamura*

Department of Mechanical Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku, Toyohashi 441-8580, Japan

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ABSTRACT

In order to prove the existence of heat-recirculation (through burner wall) assisted flame stabilization mechanism for miniaturized jet diffusion flames, a series of two-dimensional axisymmetric numerical computations are performed for methane–air flames over a sub-millimeter (constant inner diameter of 0.8 mm) jet. A skeletal mechanism including 17 species and 58 steps is employed for the chemical kinetics and detailed transport properties are considered. Burner is considered as thermally conductive and chemically inert. Heat fluxes responsible for heat recirculation (feedback) (Q_{re}) and heat loss (Q_{loss}) through the burner surfaces are calculated respectively from the numerical results. An effective excess-enthalpy (H) is defined and used to measure the global thermal effect of the burner on the flame. A wide range of fuel jet velocities (V, from the minimum value to sustain a steady state flame to 3.2 m/s) for different burners with various thermal conductivities (k_b, from 1.0 W/m-K to 100 W/m-K, which covers most of the realistic burner materials) and wall thicknesses (c_b, from 0.2 mm to 0.8 mm) are considered in this work. The results show that, as V increases, the ratio of Q_{re} to Q_{loss} monotonically increases, resulting in a critical fuel jet velocity V_c, above which Q_{re} exceeds Q_{loss} and thus the heat recirculation effect could cancel out the heat loss effect by the presence of the burner. Further, it is suggested that the V_c can be reduced by reducing k_b and c_b, hence, heat-recirculation assisted combustion is found to be promoted at near extinction condition under such burner system. Flame temperatures are significantly elevated as k_b or c_b decreases at near extinction conditions, revealing that the extinction limit in fuel jet velocity can be extended under specific condition. Computations are then conducted for flames of hydrogen and dimethyl ether to examine the fuel dependence. It is indicated that the flame–burner thermal interaction is influenced by both physical properties of the fuel (Sc number) and chemical kinetics. For the fuels with $Sc > 1$, such as dimethyl ether ($Sc = 1.2$), flame is readily to be lifted, resulting in negligible flame–burner interaction ($H \approx 0$). For the fuels with $Sc < 1$, such as methane ($Sc = 0.7$) and hydrogen ($Sc = 0.2$), chemical kinetics that dominating the flame base structure becomes the key factor. Due to the flame–burner attachment, an extremely high H can be expected for a hydrogen jet diffusion flame to achieve excess-enthalpy combustion at certain condition. Overall, this study implies that, given the narrow operation flow rate range restrained by the quenching and the blow off limits in a premixed combustion system, heat recirculation assisted stable combustion could be possible in a relatively wider flow rate (power output) range by choosing a diffusion combustion mode.

1. Introduction

Recent increasing demand for portable power generators, micro-satellite thrusters, micro unmanned aircrafts and others have stimulated developments of combustion based micro- and mesoscale power generators, due to their relatively higher energy densities compared to batteries [1]. For guiding the design of combustors and burners for these devices, a large number of fundamental studies toward mall scale flames have been carried out in the past decades, which have been reviewed recently by Maruta [2] and Ju and Maruta [3].

For small scale combustors, heat loss effect becomes severe due to their significantly enlarged surface-to-volume ratios. At the same time, thermal coupling between combustor walls and the flame becomes stronger. Heat recirculation, namely, transferring certain amount of heat from post-flame to pre-flame, is considered as a promising approach to improve combustion performance at small scale, via extending the flammability limit [4] and increasing the burning rate [5,6]. By using a one-dimensional model including full chemistry for hydrogen combustion, Leach and Cadou [7]

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* Corresponding author.
E-mail address: yuji@me.tut.ac.jp (Y. Nakamura).

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Nomenclature

A_b	cross section area of burner wall, mm^2
c_b	burner wall thickness, mm
c_p	heat capacity, J/kg-K
C	constant, -
D	mass diffusion coefficient, m^2/s
D^T	thermal diffusion coefficient, m^2/s
g	gravitational acceleration, m/s^2
Gr	Grashof number, -
h	enthalpy, J/kg
H	effective excess enthalpy, J/kg
I	unit tensor, -
k	thermal conductivity, W/(m-K)
L_b	burner length, mm
M	mass flow rate of fuel flow, kg/s
Nu	Nusselt number, -
p	pressure, Pa
Pr	Prandtl number, -
q	local heat flux density at walls, W/m^2
Q	heat flux, W
r	radius, mm
R_b	thermal resistance of the burner wall, K/W
R_0	the universal gas constant, J/mole-K
Ra	Rayleigh number, -
Re	Reynolds number, -
Sc	Schmidt number, -
S	surface area, mm^2
t	time, s
T	temperature, K
v	velocity, m/s
V	fuel jet velocity, m/s
W	molecular weight, g/mol
Y	mass fraction, -

Greeks symbols

υ	kinetic viscosity, m^2/s
μ	dynamic viscosity, kg/m-s
α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
ε	emissivity, -
ω	production rate, kg/s

Subscripts

b	burner
c	critical
f	flame
g	gas phase
i	inner surface/inside burner
$loss$	heat loss
m	mean (average)
o	outer surface/outside burner
re	heat recirculation

proved that, as the size of a combustor reduces, heat recirculation plays an increasingly important role in determining its performance. Two-dimensional numerical simulations were performed by Norton and Vlachos to investigate the heat recirculation supported combustion of methane/air mixture [8] and propane/air mixture [9] in micro channels. One-step irreversible reactions were employed for chemical kinetics. It was concluded that wall conductivity and thickness are very important parameters because they determine the upstream heat transfer, which is necessary for ignition and combustion stability. Due to the blow-off limit at high flow velocities and the quenching limit at low flow velocities, there exists a narrow flow rate range that permits stable combustion. Veeraragavan and Cadou [10] claimed that the artificially assumed Nu number in the one-dimensional model might be misleading. Heat recirculation and heat losses to the environments occur together and hence should not be decoupled. They developed an analytical model by solving the two-dimensional partial differential equations involving heat transfer and species transport, indicating that the net heat recirculation (heat transfer from post-flame to pre-flame minus heat losses to the environment) is the key parameter to determine the flame speed in a micro-channel. Very recently, Gauthier et al. and Gauthier and Bergthorson [11,12] indicated that two-dimensional effects may play a significant role for micro- and meso-scale heat recirculating combustion, because the changes in flame shape result in an increase in burning surface area, which could further contribute in flame stability.

All of the above mentioned studies are limited to premixed combustion scenarios, for which unstable flame behaviors are readily to occur. The unstable flame behaviors are essentially periodic extinction/re-ignition events. Extinction occurs due to the heat loss to the environments, and then re-ignition of the fresh incoming mixture is triggered by the heated burner wall. The periodic extinction/re-ignition behaviors were experimentally captured by Richecoeur and Kyritsis [13] using rich methane/air mixtures (thus a diffusion flame was stabilized at the exit of the tube burner to sufficiently heat the burner), and by Maruta et al. [14] using an external heat source. Jackson et al. [15] could qualitatively reproduce these periodic behaviors by using a simplified two-dimensional model. Evans and Kyritsis [16] further examined effects of burner, concluding that only the burners with lower thermal conductivities (thus higher *Bi* numbers and lower *Fo* numbers) could sustain such periodic extinction/re-ignition behaviors.

Since stable flames are only available in a narrow flow rate range for a premixed combustion system, from a practical point of view, diffusion controlled non-premixed combustion might be a better choice in terms of a potentially wider range of power output. Small scale diffusion flames have also been extensively studied both experimentally and computationally. One of the earliest micro scale diffusion flame studies was conducted by Ban et al. [17] in 1994. Flame structures of three kinds of fuels (ethane, ethylene, and acetylene) were investigated using circular-port stainless-steel burners with inner diameters of 0.15, 0.25, and 0.40 mm. It was verified that the effect of buoyancy was almost negligible for these flames. In addition, their theoretical analysis indicated that including the axial diffusion effect, which is neglected in the Burke-Schumann model [18], is important for better predicting the flame shape. Matta et al. [19] examined the micro scale diffusion flames of propane with focus on the extinction and blow-off. They claimed that, at near extinction condition, the fuel burns in a flat premixed flame due to the mixing of fuel and air within the stand-off zone between flame and burner tip. The near-extinction flame structure was also investigated by Nakamura et al. [20,21]. The Damköhler number concept was used to explain the extinction of a micro-jet diffusion flame. Cheng et al. conducted a series of studies to investigate the characteristics of the micro-jet diffusion flames of hydrogen [22,23] and methane [24–26]. Discussions were made based on the comparison between the experimental results using a UV Raman/LIPF system and the numerical simulation results. Kuwana et al. [27] developed a theory to predict the extinction of a micro-jet diffusion flame. Such a theory was based on the extinction of a Burke-Schumann flame, and was found to be able to predict the extinction of methane and butane flames with reasonable accuracies. Recently, Kuwana et al. [28] developed a simple theoretical model to predict the interaction effect between two identical micro diffusion flames. The above mentioned small scale diffusion flames were stabilized in open environments.