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Studying the repetitive extinction-ignition dynamics for lean premixed hydrogen-air combustion in a heated microchannel

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A B S T R A C T

The mechanism of repetitive extinction-ignition dynamics for lean premixed hydrogen–air mixture is studied in a microchannel with prescribed wall temperature. In this dynamics, the reacting flow is affected by the wall temperature and leads to ignition near walls. The flame expands in both downstream and upstream directions until flame bifurcation occurs. Part of the flame which propagates towards inflow consumes all the unburned mixture along its way. As the flame reaches cold inflow mixture, it extinguishes due to the heat loss. Another part of flame consumes the unburned mixture in downstream until the flame is extinguished. Afterward, unburned mixture fills the tube again until it is reignited. The repetitive extinction-ignition dynamics can be classified in five phases, namely, initiation phase, ignition phase, propagation phase, weak reaction phase, and flowing phase. Three peaks were detected for hydrogen–air mixture combustion which all appears in propagation and weak reaction phases. In the remaining phases two peaks were present. Details of flow field indicate that bifurcation of flame is due to creation of recirculation zones formed close to the walls at the beginning of ignition phase. The recirculation zones grow and merge, until a boundary zone is created in flow field with zero velocity.

1. Introduction

Since hydrogen and most hydrocarbon fuels have much higher-energy densities compared with the most advanced li-ion batteries (20–50 times) [1], widespread application of power generating devices based on combustion in small scale is expected in near future [2]. Since the area-to-volume ratio in microscale devices is significantly large, it is necessary to use thermal management in order to attain stable combustion. Norton and Vlachos studied stability of stoichiometric methane–air [3] and propane–air [4] combustion in a microscale combustor using two-dimensional numerical simulation. They analyzed the effects of wall conductivity, external heat losses, wall thickness, and inlet velocity on combustion characteristics. They showed that each variable is bounded by a lower and upper limit with an extreme point located between them.

Zarvandi et al. [5] studied numerically the effect of added hydrogen to methane–air mixture as an additive to inlet mixture in a micro stepped tube. Their results showed that adding hydrogen can play an effective role to improve combustion instability. Also Baigmohammadi et al. [6] investigated the effect of wire insertion within a micro combustor on combustion characteristics.

Wan et al. [7] investigated numerically and experimentally the effect of triangular bluff body on flammability limits of hydrogen–air mixture flame. Their results showed that the blow-off limit is greatly extended as compared with that of the micro combustor without a bluff body. After that, Fan et al. studied numerically the effect of solid materials [8] and bluff body shape [9] on the blow-off limit in hydrogen–air combustion. Their results showed that the blow-off limit of the materials with small thermal conductivity is larger than the materials with higher thermal conductivity. Besides, the blow-off limits for the triangular (36 m/s) is smaller than semicircular bluff bodies (43 m/s). They found that the triangular bluff body has a smaller blow-off limit because of the stronger flame stretching as compared with the semicircular case.

Another important subject in small-scale combustion is strong thermal coupling between flame and wall, which is affected by the characteristics of combustion in micro- and meso-scale. Different dynamics of flame propagating in small scale have been reported by researchers in experimental, numerical and analytical works. The studied flame dynamics include mild or flameless combustion, FREI (flame with repetitive extinction and ignition), steady symmetric flame, steady asymmetric flame and tulip flame.

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Nomenclature

u	Velocity vector (m/s)
S	Stress tensor
I	Identity matrix
p_t	Thermodynamic pressure (Pa)
p_h	Hydrodynamic pressure (Pa)
$c_{p,i}$	Heat capacity (J/kg-K)
h_i	Enthalpy (J/kg)
T	Temperature (K)
T_{in}	inlet mixture temperature (K)
T_f	Adiabatic flame temperature (K)
T_w	Wall temperature
T_N	Dimensionless temperature
h	channel height (m)
h_{max}	The vertical distance between the flame tip and the lower wall of the channel normalized by the channel height (h)
Y_{H_2}	Hydrogen mass fraction
Y_{O_2}	Oxygen mass fraction
Y_{H_2O}	Water mass fraction
Y_{OH}	Hydroxide mass fraction
N_g	Species number
t	Time
u_x	Velocity vector along x coordinate (m/s)
$\overline{W}$	Mean molecular weight of the mixture
W_i	Molecular weight of ith species
R	Gas constant(J/kg-K)
R_u	Universal gas constant(J/kmol-K)
Y_i	Mass fraction of the ith specie
X_i	Mole fraction of specie i
D_{ij}	Binary diffusion coefficient of the ith species in jth species (m^2/s)
D_{im}	Average diffusivity of the ith specie (m^2/s)
k_B	Boltzmann constant, $1.381.10^{-23}$ (J/K)
V_i	Diffusion velocity of the ith specie (m/s)
V_c	Correction diffusion velocity (m/s)
V_i^*	Diffusion velocity of the ith specie (m/s) calculated by kinetic theory
U_{in}	Inlet velocity
Le	Lewis number
X_{H_2}	Hydrogen mole fraction
X_{O_2}	Oxygen mole fraction
X_{H_2O}	Water mole fraction
X_{OH}	Hydroxide mole fraction
Φ	Equivalence ratio

Greek symbols

ρ	Density (kg/m^3)
μ	Dynamic viscosity
λ	Mixture thermal conductivity
σ_i	Collision diameter (A)
ε_α	Lennard-Jones energy
$\dot{\omega}_i$	Rate of reaction of the ith specie ($kmol/m^3$-s)
Ω_D	Collision integral

Abbreviations

HRR	Heat Release Rate
FREI	Flame with Repetitive Extinction and Ignition
DNS	Direct Numerical Simulation
PLIF	Planar Laser-Induced Fluorescence

Subscripts

w	Wall
in	Inlet
i	ith species
ij	ith species in jth species
im	ith species in mixture

Maruta et al. have studied methane–air and propane–air combustion experimentally on straight [10] and U-shaped [11] micro tubes by imposing a temperature gradient on the exterior wall of the channel. They reported different combustion dynamics. Close to the lower flammability limit (at low inlet velocity), they observed a stable regime which they named as “weak flame.” In addition to weak flame, steady symmetric flame and repetitive extinction-ignition dynamics were reported close to the upper flammability limit and at intermediate velocity.

Steady axisymmetric and repetitive extinction-ignition dynamics have been also reported by Richecoeur and Kyritsis [12] working on curved tubes with variable internal diameters from 1 to 4 mm. Flame propagation in heated micro and mesoscale channels have been conducted by Pizza et al. for lean hydrogen–air mixture (equivalence ratio = 0.5). They used detailed chemistry and different mass diffusivity of species in their simulation. In a two-dimensional direct numerical simulation for micro planner channels, they observed different dynamics of flame, including repetitive extinction-ignition dynamics, steady symmetric flame, steady asymmetric flame and oscillating flame [13]. For mesoscale planner channels, mild combustion and open symmetric flame were also observed in addition to combustion dynamics were reported in microscale channels [14]. In three-dimensional simulation, Pizza et al. reported spinning flame [15]. Although they observed different dynamics, but there are a few detailed discussion on flame dynamics in the aforementioned studies.

Fan et al. developed a new experimental method using CH/OH chemiluminescence images [16] and phase-locked OH-PLIF imaging system [17] to observe FREI phenomenon for methane–air mixture in quartz channels. Their studies showed that thinner channels produce narrower regions of flammability limits, and higher wall temperatures result in wider regions. In their work the flame propagation was studied as a periodic process categorized into three stages, namely, ignition stage in which the flame ignites and expands in channel, propagation stage in which the flame propagates towards upstream and downstream direction until quenching occurs, and finally recharge stage including the incoming of fresh fuel/air mixture into channel.

The FREI behavior has also been reported in different analytical studies. Minaev et al. [18] investigated the behavior of premixed flame propagation in a microchannel with temperature gradient across channel walls. A one-dimensional nonlinear evolutionary equation including equations of thermal-diffusion model was used in their analytical work. Despite the simplifications, their model was able to capture FREI phenomenon and flame oscillation which was observed in experimental results. Jackson et al. [19] used a new mathematical method considering conservation of energy for gaseous phase, species and energy in axial direction and one-step chemical reaction. Their results indicated that FREI phenomenon may occur when Lewis number is greater than 1 in the presence of heat losses.

Kurdyumov et al. [20] examined the effect of channel height, inflow velocity and wall temperature on the dynamics and stability