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Effect of transport processes on ignition of stretched diffusion flames using laser spark

Yan Wei [a], Fidelio S. Segura [b], Weiwei Deng [c], Ruey-Hung Chen [d,*]

[a] Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[b] Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL 32816, USA
[c] Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[d] Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA

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ABSTRACT

Laser spark ignition of methane diffusion flames, in the stagnation region in counter-flow configuration, is studied with a range of transport properties achieved by using different levels of inert dilution with helium and argon as diluents in the fuel stream. The effects of transport properties on ignition strain rate and ignition delay time are investigated and possible effects of effective Lewis number (Le_e) are also discussed and compared with those for flame extinction. The following results are obtained:

(1) The role of Le_e on the critical global strain rate, beyond which ignition is not possible, is qualitatively similar to that on the extinction strain rate. That is, with the same level of dilution, the inert diluent with smaller Le_e (therefore relatively smaller heat loss rate) yields larger critical global strain rate.

(2) For successful ignition, the ignition delay time decreases with increasing level of helium dilution, while the opposite is true with argon dilution – the experimental results correlated with the calculated results of the diffusion times with these two inert diluents, suggesting that the successful ignition and the ignition delay time is limited by the thermal diffusion time across the flammable layer in the counter-flow region, rather than resulting from the Lewis number effect.

1. Introduction

Counter-flow diffusion flames share some common one-dimensional features with laminar flamelets and have been used to gain insight into combustion characteristics of turbulent non-premixed flames [1]. Topics of particular importance in laminar counter-flow flames, with and without inert gas diluents and/or with partial premixing, are related to extinction and ignition processes and have been experimentally, theoretically, and numerically studied [2–14]. Gaseous fuels investigated in these studies include hydrogen, hydrocarbons, and syngas. Some investigators analyzed the effects of inert diluents on the extinction of diffusion flames in terms of effective Lewis number or preferential diffusion effects [5,7,15,16]. Effective Lewis number has proven to be successful in explaining extinction phenomena when fuels were diluted with inert gases that possess vastly different diffusivities [17]. However, it is not known whether it can explain the ignition phenomena prior to successful ignition that leads to steady flames, where one does not expect the steep concentration gradients that exist in established flames.

Relatively few experimental studies have been performed on the forced ignition processes of laminar non-premixed combustion. Phuoc [17,18] studied the minimum ignition energy associated with laser spark ignition and concluded that the ignition energy obtained by the laser spark ignition does not differ greatly from that obtained by the electric spark ignition. Phuoc and Chen [19] also studied the effect of nitrogen dilution on the ignition stability and unburned hydrogen with the use of laser-induced spark. Other studies on successful ignition of counter-flow diffusion flames have been performed to study effects of spark position, spark duration, spark energy and strain rate which have also been numerically and theoretically investigated by Phuoc and coworkers [17,18,20,21]. These studies have focused on ignition probability and minimum ignition energy, and the effects of dilution, with the effects of diffusive and thermal transport properties largely left unaddressed. Furthermore, the ignition delay time has not been reported in the non-premixed counter-flow system. These unresolved issues are the focus of this study.

Many studies have focused on the effect of transport properties (preferential diffusion and Le_e) on extinction of counter-flow flames

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* Corresponding author.
E-mail address: chenrh@nmsu.edu (R.-H. Chen).

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Nomenclature

A_F	defined as $\nu Y_F/Y_O$
d_i	diameter of inner nozzle
d_o	diameter of outer nozzle
D	mass diffusivity
D_t	thermal diffusivity of the flammable mixture
Da_{ig}	Damkohler number based on $K_{g,ig}$
Da_{ex}	Damkohler number based on $K_{g,ex}$
K_g	global strain (or stretch) rate
$K_{g,ex}$	global strain (or stretch) rate at extinction
$K_{g,ig}$	limiting global strain (or stretch) rate beyond which ignition is not possible
L	separation of burners
Le_e	effective Lewis number (see Eq. (2))
L_F	fuel Lewis number
L_O	oxidizer Lewis number
ℓ	length of laser spark volume
S_L	laminar flame speed
t_k	time to flame kernel formation
T_{ad}	adiabatic flame temperature
T_f	flame temperature
V_F	velocity of the fuel stream
V_O	velocity of the oxidizer stream
Y	mass fraction
Y_F	mass fraction of fuel in the fuel stream
Y_O	mass fraction of oxidizer in the oxidizer stream
Y_{st}	stoichiometric mass fraction
δ	thickness of the flammable layer
ϕ_{rich}, ϕ_{lean}	equivalence ratio at rich and lean flammability limits
τ_d	diffusion time scale of the flammable layer
ν	stoichiometric oxidizer-to-fuel mass ratio
ρ_F	density in the fuel stream
ρ_O	density in the oxidizer stream

[6,7,9,10]. Diluent gases such as helium and argon have been used for systematic variation and control of these transport properties [9,10]. These two inert gases possess the advantages of identical molar specific heats to isolate either the effects of Le_e or D independent of the effect of heat capacity. By using the effective Lewis number ($Le_e \equiv D/D_t$), which is the weighted value of the fuel and oxidizer Lewis numbers [22], investigators were able to explained extinction phenomena [16]. Results from various studies indicate that $Le_e < 1$ leads to larger extinction strain rates. This can be explained as follows. For $Le_e < 1$, $D_t < D$ and the reactants (representing chemical enthalpy) diffuse into the combustion zone at a higher rate than the heat diffusion rate away from it, resulting in higher flame temperature as K_g is increased. At excessively high strain rates, the mass diffusion rate exceeds the reaction rate, leading to reactant leakage and eventually flame extinction. Therefore, for $Le_e < 1$, the flame temperature monotonically increases with increasing, until immediately prior to reaching $K_{g,ex}$. The opposite is true for $Le_e > 1$ – the flame temperature monotonically decreases with increasing K_g and at a sufficiently large strain rate, the flame temperature drops below the value for sustaining combustion. Therefore flames with $Le_e < 1$ is more resilient to flame stretch and extinguish at higher values of $K_{g,ex}$ than those with $Le_e > 1$. However its effects are not well known on ignition, such as the maximum strain rate for successful ignition and the ignition delay time.

Thus the purpose of this study is to investigate *whether or not* similar effects of Le_e on flame extinction exist on diffusion flame ignition and ignition delay time under hydrodynamic stretch. For effects of spark position, spark duration, spark energy, ignition probability, and minimum ignition energy level in counter-flow diffusion flames the reader is referred to published literature [17–21,23]. The process of ignition of combustion gases under sparks produced by a laser is described in detail and has been demonstrated to be a successful technique for the purpose of this study by Phuoc [17,19,21]. Helium and argon were chosen due to their vastly different mass diffusivities that enables large variations of the effective Lewis number by varying the level of dilution.

2. Experiment apparatus and procedure

The experimental apparatus is sketched in Fig. 1. It consists of two axisymmetric counter-flow nozzles, an Nd:YAG laser, three-axis motion controllers for positioning the laser spark with 1-μm precision, and transmitting lenses that focuses the lase pulse, and a high speed camera. Each side of the burner was composed of an inner main nozzle for the fuel/oxidizer flow and an outer concentric nozzle for the N_2 sheath flow to prevent the reactant streams and ignition process from external disturbances. The diameters of the inner and outer nozzles are 8.9 mm and13.56 mm, respectively, while the separation between the two opposing nozzles is L = 1 cm. Prior to entering the converging section of each of the two nozzles, the reactant flow was passed through a bed of brass beads forming sufficient flow resistance to ensure uniform flow.

The Nd:YAG laser (Quantel Brilliant; 1064 nm with a pulse duration of 3.5 ns) generated sparks for ignition. The energy per pulse was rated by the manufacturer to be 380 mJ. The transmitting optics consists of a 10x beam expander with an inlet diameter of 2 mm and was focused using a 100-mm focal length lens. The focused spark region, cylindrical in shape, was calculated to have a diameter of $\mathscr{d}$ = 2 μm and a length of ℓ = 1 mm using a method described in Phuoc [19]; the size of this region was confirmed using a microscope image taken with a high speed camera (described below). As shown in Fig. 1, the optical axis is at an angle of approximately 25° to the mid-plane between the two nozzles. The ANSYS FLUENT 15.0 code was used to calculate the location (i.e., the plane) where the stoichiometric condition (i.e., $Y = Y_{st}$) exists for positioning the laser spark. It also calculated the flammable layer thickness (δ); the flammable layer is defined as the region bounded by lean and rich flammability limits of methane-air mixtures (equal to, respectively, 5% and 15% fuel volume fraction, which translate to ϕ_{lean} = 0.5164 and ϕ_{rich} = 1.6182). The thickness of the flammable layer was also used in later analysis of the characteristic diffusion time of heat away from the energy deposition region; this diffusion time was to be compared with the heat generation and flow residence times. As will be shown in the Results and Discussion section, $\delta \approx 0.1$–0.6 mm.

For consistency, the laser spark was always focused on the intersection of the Y_{st} plane and the axis of symmetry of the burners. Because $\ell \cos 25^\circ = 0.9\ \text{mm} > \delta$, the flammable layer is entirely covered by the spark, so that the energy deposited per volume of the layer is constant except for shot-to-shot variations. Numerical/theoretical analyses in literature (see the review article [1] for example) suggest that the temperature profile in the counter-flow region achieves a nearly steady state 0.2 ms after laser spark energy deposition for methane-air counter-flow diffusion flame ignition. This result suggests that the effect of shock waves largely dissipates long before the flame kernel can be observed, as the shock wave would have exited the burner region in approximately 30 μs after the spark.