Combustion and Flame 162 (2015) 375–387

Contents lists available at ScienceDirect

Combustion and Flame

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

Scaling turbulent flame speeds of negative Markstein length fuel blends using leading points concepts

Prabhakar Venkateswaran [a,*], Andrew Marshall [b], Jerry Seitzman [c], Tim Lieuwen [b,c]

[a] *Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, United States*
[b] *School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States*
[c] *School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States*

ARTICLE INFO

Article history:
Received 1 October 2013
Received in revised form 25 February 2014
Accepted 11 July 2014
Available online 15 September 2014

Keywords:
Turbulent flame speed
Leading points
Negative Markstein length
Pressure
Stretch effects

ABSTRACT

This work describes analyses of turbulent flame speeds, S_T, of negative Markstein length fuel blends using leading point models. One implication of these models is that the maximum laminar burning velocity, $S_{L,\max}$, of highly stretched flames or "critically stretched flames", is the appropriate flame speed scale with which to parameterize the turbulent flame speed. More specifically, it leads to a scaling approach for the turbulent flame speed of the form $\frac{S_T}{S_{L,\max}} = f\left(\frac{\langle u'_{rms}\rangle_{LP}}{S_{L,\max}}, \frac{\tau_{S_{L,\max}}}{\tau_{flow}}\right)$, where $\tau_{S_{L,\max}}$ and τ_{flow} are the chemical time-scale associated with the leading point and a characteristic fluid mechanical time-scale, respectively. In this paper, we apply these scalings to data sets from the literature which explore pressure and fuel composition effects on S_T. Amongst these data sets are new measurements, acquired by our group, of $S_{T,GC}$ for H_2/CO mixtures at pressures up to 20 atm. It is shown that this approach can scale turbulent burning velocities from a range of different data sets, with significantly different fuel compositions, pressures, and stoichiometries. This result is particularly significant in understanding the strong pressure effects manifested in these data. Nonetheless, we also emphasize that time-scale, length scale, and Reynolds number effects on these correlations are difficult to differentiate as they exhibit similar pressure sensitivities, and further work is needed to conclusively understand the coupled (and very strong) effects of mixture stretch sensitivity and pressure on turbulent burning velocities.

1. Introduction

This paper describes investigations of coupled fuel and pressure effects on the turbulent consumption speeds, $S_{T,GC}$, of high hydrogen content fuel blends, with particular emphasis on H_2/CO fuel blends [1–3]. This work has been primarily motivated by the need to better understand preferential diffusion effects on turbulent flame propagation, a subject which has been well-documented in the literature [4–10]. For example, Wu et al. [4] demonstrated that two H_2/air mixtures, at $\phi = 0.80$ and 3.57, with the same unstretched laminar flame speed, $S_{L,0}$, and operated with the same turbulence intensity, u'_{rms}, can have substantially different turbulent flame speeds, S_T. This showed that classical correlations of the form $S_T = S_T(u'_{rms}, S_{L,0})$ [11] did not capture the sensitivities of the turbulent flame speed. Our own work has corroborated these findings for a broad range of H_2/CO mixtures for $u'_{rms}/S_{L,0}$ and pressures up to 45 and 10 atm respectively [1–3].

In addition, the influence of coupled pressure and fuel composition effects on S_T is also significant, and there is no clear consensus in the literature. For example, $S_{T,GC}$ measurements of lean CH_4/air flames for a pressure range of 1–30 atm were reported by Kobayashi et al. [12]. It was concluded that $S_{T,GC}/S_{L,0}$ increased with pressure due to $S_{L,0}$ decreasing but that $S_{T,GC}$ itself was independent of pressure. Kitagawa et al. [13] reported $S_{T,GC}$ measurements of H_2/air mixtures at pressures ranging from 1 to 5 atm and they found that the influence of pressure on $S_{T,GC}$ was a function of both equivalence ratio and turbulence intensity. Daniele et al. [14] reported that $S_{T,GC}/S_{L,0}$ increased with pressure for a fixed H_2/CO ratio and $u'_{rms}/S_{L,0}$ value. They also found that $S_{T,GC}$ increased slightly with pressure for a fixed H_2/CO ratio and equivalence ratio. Bradley et al. [15,16] reported turbulent flame speed data for ethanol/air and propane/air mixtures in a spherical bomb configuration, and concluded that the turbulent flame speed was augmented by pressure regardless of the mixture Markstein length. Liu et al. [17] reported turbulent flame speed measurements of a CH_4/air mixture and Chiu et al. [18] reported turbulent flame speed measurements of a H_2/CO/air mixture, at pressures up

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.combustflame.2014.07.028
0010-2180/

Nomenclature

$\overline{A}_{\langle c\rangle}$	mean flame area associated with given $\langle c\rangle$ contour
D	burner diameter
$\langle c\rangle$	average progress variable contour
δ_F	flame thickness
κ	stretch rate
κ_{ext}	extinction stretch rate
Ka_η	Karlovitz number based on the Kolmogorov time-scale
l_{int}	turbulent integral length scale
l_λ	Turbulent Taylor length scale
l_M	Markstein length
p	pressure
R_i	burner radius
Re_B	Bulk Reynolds number
Re_t	turbulent Reynolds number
R_i	outer radius of the LSB
S_L	stretched laminar flame speed
$S_{L,0}$	un-stretched laminar flame speed
$S_{L,\max}$	maximum stretched laminar flame speed
$S_{L,D,\max}$	maximum stretched displacement laminar flame speed
$S_{L,HR,\max}$	maximum stretched thermal consumption laminar flame speed
S_T	turbulent flame speed
$S_{T,GC}$	global turbulent consumption speed
$S_{T,LD}$	local turbulent displacement speed
T	temperature
U_0	mean axial velocity
$\dot{m}_R$	reactant mass flow rate
u'_{rms}	root mean square turbulence fluctuations
x	distance along flame normal
ρ_R	reactant density
ϕ	equivalence ratio
τ_B	bulk mechanical time-scale given by D/U_0
τ_{int}	integral time-scale given by l_{int}/u'_{rms}
τ_λ	Taylor time-scale given by l_λ/u'_{rms}
$\tau_{S_{L,\max}}$	chemical time-scale defined as $\delta_F\vert_{S_{L,\max}}/S_{L,\max}$

to 10 atm. Both studies conducted spherical-bomb experiments where the turbulent Reynolds number, Re_t, was held constant across the pressures by simultaneously varying the turbulence intensity, u'_{rms} and turbulent integral length scale, l_{int}. They reported that for both CH_4/air and H_2/CO/air mixtures, S_T decreased with increasing pressure at constant Re_t, while S_T increased with Re_t at a fixed pressure. In conclusion, it appears that the influence of pressure on the turbulent flame speed is not well understood, which is a key motivator for this work.

Returning to the fuel effects, the observed sensitivities to the fuel composition have been attributed to the non-unity Lewis number and preferential diffusion effects which arise due to the coupling between heat and reactant diffusion and the multi-dimensional and unsteady turbulent flame and flow field [19]. These effects are collectively referred to as "stretch effects", and result in significant variations in the burning rate along the flame front [19]. For example, the H_2/CO mixtures investigated in our prior studies are highly stretch sensitive because of the high mass diffusivity of H_2. Stretch effects have been incorporated into models for the turbulent flame speed through a "Lewis number" [20,21] or a mixture Markstein length [15,16,22] correction. However, these approaches have limitations. Attempting to capture just Lewis number effects neglects preferential diffusion effects which may have significance in multi-component fuels such as the H_2/CO mixtures considered in this work. On the other hand, the Markstein length, indicated in Fig. 1(b) and calculated using Eq. (1), describes the low stretch rate sensitivity of the mixture, and accounts for both Lewis number and preferential diffusion effects.

$$l_M = -\frac{\partial S_L}{\partial \kappa}\bigg|_{\kappa=0} \tag{1}$$

Data sets taken at a given pressure, e.g., Wu et al. [4], Kido et al. [23,24] or Venkateswaran et al. [1], demonstrate that, for negative Markstein length fuel/air mixtures, S_T increases as the absolute value of the Markstein length increases. However, a Markstein length scaling is alone insufficient to capture all turbulent burning velocity sensitivities, since increasing pressure decreases Markstein lengths by thinning the flame, as seen in Fig. 1(b). As described above, different measurements have shown that pressure both increases and has no effect on turbulent burning velocities [12,14]; a Markstein length scaling argument would predict that increasing pressure, and thereby decreasing Markstein lengths, as shown in the calculations in Fig. 1(b), should decrease turbulent burning velocities.

A promising approach to capture coupled fuel and pressure effects is based on leading points concepts [5,25,26]. Leading points are defined as the positively curved points on the turbulent flame front that propagate out furthest into the reactants. For negative Markstein length fuel blends, the local burning velocity is enhanced through stretch effects at these points [19], and it has been hypothesized that the dynamics of these leading points control the overall propagation rate [5,26]. The origins of leading points can be traced back to the Kolmogorov–Petrov–Piskunov (KPP) theorem, which has been used to derive an expression for S_T from the Reynolds averaged progress variable equation for a statistically planar turbulent premixed flame with a prescribed upstream turbulent flow. The final result shows that S_T can be related to the mean reaction rate at the leading edge of the flame brush, $\langle c\rangle = 0$ [27,28]. The importance of leading points follows naturally from the conclusions of the KPP analysis. Lipatnikov and Chomiak utilized the leading point ideas to develop a normalized leading point chemical time-scale that is used as an input into a model for S_T [5,29,30]. In their work, the ratio of the leading point time-scale and the un-stretched time-scale was equated to the ratio of the un-stretched laminar flame speed and the maximum stretched laminar flame speed, $S_{L,\max}$. This scaling was proposed based on the hypothesis that the leading points in $Le < 1$ mixtures would propagate at the maximum stretched flame speed, $S_{L,\max}$.

In our earlier work, we came to similar conclusions based upon a quasi-steady analysis of a flamelet propagating in a prescribed flow field [1] – specifically, that the flame propagated at a steady-state velocity equal to the burning velocity at the leading points in a spatially varying flow field. Furthermore, using the solution from the isothermal level-set equation, it was demonstrated for this model problem that the stable, steady-state burning velocity of the leading point is equal to the maximum stretched flame speed, $S_{L,\max}$, which is indicated in Fig. 1(b) [1].

Phenomenologically extending these model problems to a turbulent, reacting flow led to the following expression for the turbulent flame speed:

$$\frac{S_T}{S_{L,\max}} \leq 1 + \frac{\langle u'_{rms}\rangle_{LP}}{S_{L,\max}} \tag{2}$$

The inequality in Eq. (2) can be replaced by an equality when the turbulent fluctuations evolve slowly relative to the time taken for the leading point burning velocity to reach $S_{L,\max}$.