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Fuel effects on leading point curvature statistics of high hydrogen content fuels

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Abstract

Fuel composition has significant influences on the turbulent flame speed of mixtures with strong stretch sensitivity. These fuels effects are associated with reactant thermal-diffusive properties and stretch sensitivities, causing local variations in the burning rate along the flame front. This study is motivated by leading point descriptions of the turbulent flame speed, which argue that S_T is controlled by the flame characteristics at its positively curved leading edge. It has been argued that the leading edge of the flame approaches "critically stretched" values in thermo-diffusively unstable flames, implying that the appropriate laminar flame speed to parameterize the turbulent flame speed is the maximum flame speed across all potential values of flame stretch, $S_{L,max}$, as opposed to its unstretched value, $S_{L,0}$. This paper describes an experimental investigation of the characteristics of the flame leading point in high stretch sensitivity flames to assess this hypothesis more fully. Measurements of the flame curvature were obtained with a low swirl burner (LSB) for several H_2/CO mixtures at velocities from 30–50 m/s. These data show that the leading point conditioned curvature statistics are a strong function of the turbulence intensity of the flow. Counter to our expectations, however, the measurements show relatively weak influences of fuel composition on the leading point curvature of the turbulent flame front. As such, these results do not seem consistent with prior arguments that the increased turbulent flame speeds seen with increasing hydrogen content are the result of increasing flame curvature/stretch rates, and therefore $S_{L,max}$ values, at the flame leading points. Additional analysis is needed to understand the physical mechanisms through which the turbulent flame speed is altered by differential diffusion effects.
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Keywords: Stretch effects; Flame curvature; Leading points; High hydrogen content; Fuel effects

1. Introduction

The objective of this paper is to improve the understanding of turbulent flame propagation characteristics of high stretch sensitivity, premixed flames. Early models of the turbulent flame speed use the form:

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$$S_T = S_{L,0} f(u'/S_{L,0}) \quad (1)$$

where $S_{L,0}$ is the unstretched laminar flame speed and u' is the turbulence intensity [1,2]. However, studies have shown that S_T is also affected by turbulent length scales [3], bulk flow velocity [4], experimental configuration [5,6], and fuel composition [2,7–9]. Of particular interest to this paper is the effect of fuel composition, which has been well-documented in the literature [2]. For example, our group has reported measurements of H_2: CO blends showing factor of three variations in S_T across fuel blends with identical $S_{L,0}$ values, even at turbulence intensities $u'_{rms}/S_{L,0}$ up to 40. Similar observations were made by Karpov et al. [10], Wu et al. [11], Bradley et al. [12], Kido et al. [7,13], Brutscher et al. [14] and others, and summarized in the review of Lipatnikov and Chomiak [2].

The sensitivity of S_T to fuel composition is associated with the stretch sensitivity of the reactant mixture, which leads to variations in the local consumption speed along the turbulent flame front. This stretch sensitivity can arise from non-unity Lewis number and preferential diffusion effects [15]. In Particular, the high mass diffusivity of H_2 makes H_2-bearing mixtures highly stretch sensitive, such as shown in the illustrative calculations in Fig. 1. These calculations, which include detailed kinetics and transport mechanisms, incorporate both non-unity Lewis number and preferential diffusion effects. While various modeling approaches have been put forth for capturing these stretch sensitivities, leading points concepts appear to be a particularly natural approach for describing them. Leading points concepts were proposed by Zel′dovich [16] and expanded upon by a number of groups, as summarized by Lipatnikov and Chomiak [2]. Leading points are the positively curved (convex to the reactants) points on the flame front that propagate out farthest into the reactant mixture and can be shown to control the overall propagation velocity of the turbulent flame under certain conditions [3]. This can be shown, for example, by applying the Kolmogorov–Petrovskii–Piskunov (KPP) theorem [17] to the propagation of a one-dimensional turbulent premixed flame in frozen turbulence, where, under certain circumstances, S_T is controlled by the conditions at the leading edge of the flame brush, defined as the point where $\langle c \rangle \rightarrow 0$ [18,19].

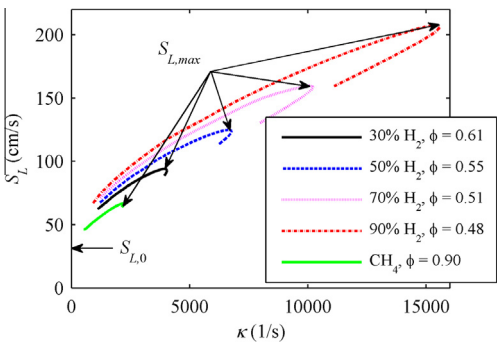

Fig. 1. Opposed flow geometry stretch sensitivity calculations of H_2:CO fuel blends and CH_4 [20].

Leading points ideas are particularly revealing for negative Markstein length mixtures, as calculations of laminar flame stretch sensitivities show that the positively curved leading point flame speed can substantially exceed $S_{L,0}$, as shown in Fig. 1 [15]. Assuming S_T is controlled by the leading point characteristics, the ensemble averaged laminar burning rate of this leading point turns out to be a very significant turbulent flame property. Directly following these ideas, Venkateswaran et al. [9,20] developed a scaling law for the turbulent flame speed of negative Markstein length flames, using the maximum stretched laminar flame speed, $S_{L,max}$, as the normalizing parameter, as opposed to the traditional approach of using the unstretched laminar flame speed, $S_{L,0}$. The form of this scaling law is given by:

$$\frac{S_T}{S_{L,\max}} \leq 1 + \frac{u'_{LP}}{S_{L,\max}} \quad (2)$$

where u'_{LP} is the turbulence intensity at the leading point of the flame. An example $S_{L,max}$ calculation for an opposed flow, strained flame configuration is shown in Fig. 1 The dynamical significance of $S_{L,max}$ in negative Markstein length mixtures arises from the fact that this velocity/strain rate at the leading point is a steady-state 'attractor' for constant density flames with positively curved wrinkles [20]. This idea that $S_{L,max}$, and not $S_{L,0}$, is the suitable velocity scale for correlating S_T was suggested by [3] and has found justification in data from Venkateswaran et al. [20], as shown in Fig. 2, which plots data obtained with a range of H_2:CO mixtures normalized by $S_{L,0}$ (Fig. 2a) and $S_{L,max}$ (Fig. 2b). Note the strong fuel effects manifested in the $S_{L,0}$ scaled data, but the good collapse of the data using the $S_{L,max}$ scaling.

However, questions remain concerning the application of leading points ideas to data. Of particular focus for this paper is the fact that the scaling in Fig. 2 is "global" in nature and work is needed to assess key assumptions of the leading point model concerning local attributes of the flame. For example, Fig. 1 clearly shows the monotonic increase in $S_{L,max}$ with increasing H_2 content. However, it also shows that the flame stretch rate at $S_{L,max}$ varies strongly with H_2 content, a prediction that can be evaluated from computations or measurements. If the physical arguments leading to this scaling approach are correct, then the flame stretch characteristics at its leading points should exhibit systematic differences that scale with S_T. Particularly, Fig. 1