

The Effect of Mixture Fraction on Edge Flame Propagation Speed

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1 Introduction

Time dependent analysis of the dynamics of flame extinction or re-ignition of a hole in a continuous, planar, nonpremixed flame provides important information for the understanding of the highly turbulent flame [1]. Edge flame, the transitional region from burning condition to non-burning condition, is used to illuminate many types of non-uniform flame phenomenon, e.g. local extinction and re-ignition in the highly turbulent flow fields in a reciprocating-piston internal combustion chamber, flames stabilized on a Bunsen burner, or flame spreading across solid fuel [2]. The key property used to describe the time dependent behavior is the edge flame propagation rate, U_{edge} , defined as the speed the flame tip moves relative to the unburned gases in the direction parallel to the flame sheet. According to theoretical studies on both premixed [3-5] and non-premixed [6-9] configurations, the edge flame may propagate with the non-burning region being overtaken by the burning region, forming an “ignition front” that has a positive propagation rate or retreat into the burned region, forming an “extinction front” that has a negative propagation rate. Many factors affect U_{edge} such as the global strain rate (σ), effective Lewis number (Le_{eff}) of the mixture, heat losses and for nonpremixed edge flames the stoichiometric mixture fraction (Z_{st}) defined as $1/(1+\nu X_f/X_o)$ where ν is the stoichiometric oxygen to fuel mass ratio and X_f and X_o represent the mass fraction of fuel and oxygen in the unburned mixture streams requires more elucidation.

While traditional nonpremixed combustion generally employs pure hydrocarbon fuel mixing and burning with highly diluted oxygen (i.e. air) resulting in a very low Z_{st} (typically 0.06), many new combustion technologies employing new fuels and modes of combustion (e.g. biofuels, oxyfuel combustion, massive Exhaust Gas Recirculation) resulting a much broader range of Z_{st} – as high as 0.8 for pure oxygen burning with highly diluted fuel. In the counterflow geometry, an increase in Z_{st} will move the flame location from the oxidizer side to the fuel side of the stagnation plane, which can result in a significant difference in temperature/composition/time history of the reactants. These effects can in turn result in very asymmetric flame properties with respect to $Z_{\text{st}} = 0.5$ (where the flame lies at the stagnation plane) [10, 11], which was attributed to a shift in the O_2 concentration profile as Z_{st} increases to coincide more closely with the location of peak temperature, which in turn increases radical production rates and leads to a more robust flame. Besides a large range of Z_{st} , new combustion technologies may also use fuels with very high diffusivity (e.g. low molecular weight

fuels such as hydrogen and methane) or very low diffusivity (e.g. heavy fuel oil, $C_{10} - C_{20}$) resulting in widely varying fuel Lewis numbers. The Lewis number effect may play a dramatic role on U_{edge} and extinction behavior by itself [10] or, as we will show, combined with the effect of varying Z_{st} .

Prior experimental work on nonpremixed edge flames [10] has focused on $Z_{\text{st}} = 0.5$ with one data set taken at $Z_{\text{st}} = 0.2$ and 0.8 and only for $\text{CH}_4/\text{O}_2/\text{N}_2$ mixtures for which $\text{Le}_{\text{fuel}} \approx \text{Le}_{\text{O}_2} \approx 1$. Moreover, no theoretical or computational study has examined the effect of Z_{st} on edge flame properties. Consequently, the objective of the present work is to study systematically the effects of Z_{st} on edge flame properties for varying Lewis numbers (by varying fuel and diluent type) and varying σ . Following prior work [10], we employ a counterflow slot-jet apparatus rather than a round-jet apparatus because the former provides extensional strain in the direction orthogonal to the plane of the slots but little strain or convection in the direction along the length of the slots. As a result, the convection velocity in the long dimension of the slot is very small and thus the propagation speed in the laboratory frame is nearly equal to the propagation speed relative to the cold unburned gas far ahead of the edge flame (or behind, in the case of retreating edge flames). This in turn simplifies the interpretation of the experimental data.

2 Experimental Apparatus

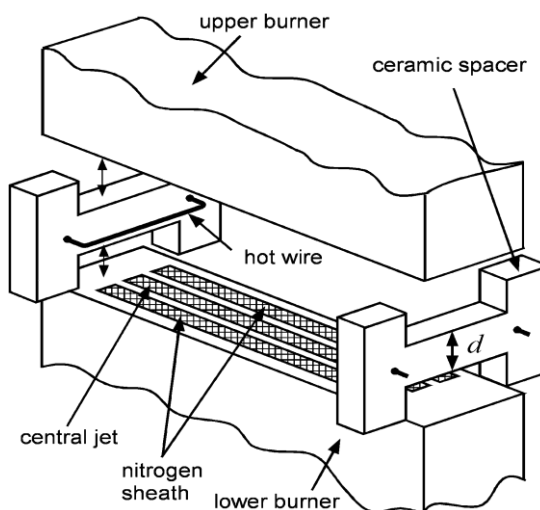


Figure 1. Schematic of the experimental apparatus [10].

The counterflow slot-jet burner is identical to the one used by a prior work of Cha and Ronney [10]. As discussed in [10], because of the finite length of the slot-jets, there is a slight extensional flow in the direction along the length of the jets which causes the edge speed to propagate against a slight opposing flow as it approaches the centerline of the jet, then propagate while “riding” this flow as it propagates away from the centerline. As a result, the value of U_{edge} measured directly at the jet centerline, where no biasing flow is expected, was taken as the most accurate value. Some may argue that global strain rate is less appropriate compared to local strain rate, keep in mind that one of the purposes of the present study is to construct correlations of strain effects for turbulent flames similar to the approach took by [12]. Please refer to [10] for detailed procedures of operating the experiments.

Table 1: Experimental conditions and corresponding flame properties

Fuel	Diluent	Fuel/O ₂ /Q (Molar Fraction)	Le _{fuel}	Le _{O₂}	T _{ad} (K)	S _L (cm/s)
CH ₄	N ₂	1/2/9.5	0.96	1.10	2030	22.2
CH ₄	CO ₂	1/2/7	0.73	0.83	1846	5.3
n-C ₄ H ₁₀	N ₂	1/6.5/30	2.15	1.04	2096	26.3
iso-C ₄ H ₁₀	N ₂	1/6.5/30	2.15	1.04	2096	20.6
iso-C ₄ H ₁₀	CO ₂	1/6.5/21.5	1.73	0.77	1930	5.1

Table 1 show the condition tested in this work. Values of laminar flame speed (S_L) were calculated using Cantera with GRI-Mech 3.0 and USC Mech II [13]. Adiabatic flame temperatures were calculated using GASEQ. For each fuel/O₂/diluent case, values of U_{edge} as a function of Z_{st} were measured for several fixed σ . A noteworthy feature of the presented work is that every point on the same plot possessed the same stoichiometric mixture composition, thus the same theoretical adiabatic flame temperature (T_{ad}) and same burning velocity (S_L) in a stoichiometric premixed flame, yet U_{edge} varies drastically depending on Z_{st} and σ .

3 Result and Discussion

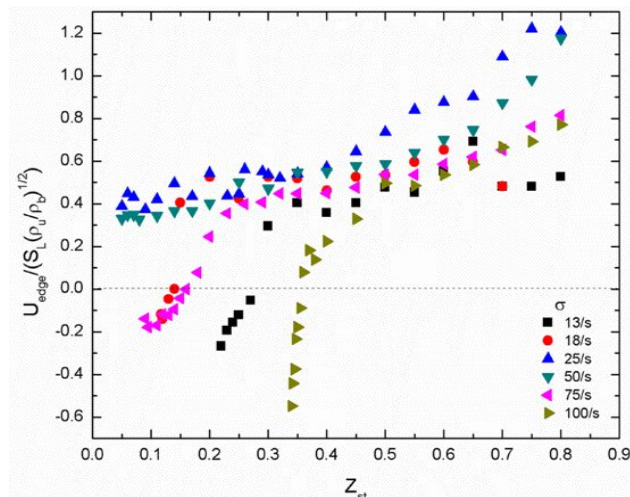


Figure 2. The case for CH₄:O₂:N₂=1:2:9.5 with U_{edge} varying with Z_{st} for different strain rate. Both fuel and oxidizer have near unity Lewis number.

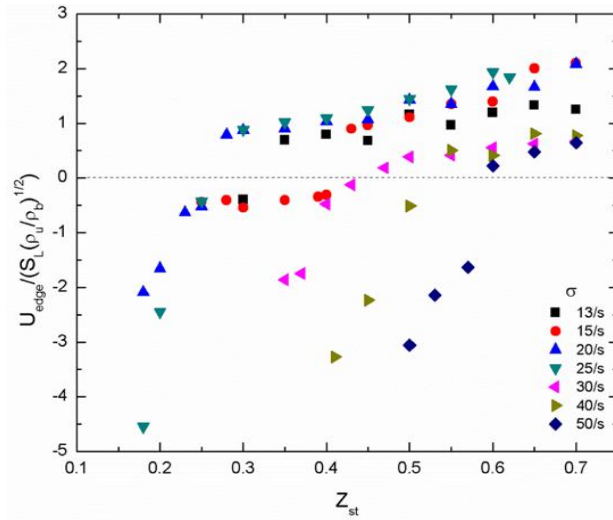


Figure 3. The case for $\text{CH}_4:\text{O}_2:\text{CO}_2=1:2:7$ with U_{edge} varying with Z_{st} for different strain rate. Both fuel and oxidizer have Lewis number smaller than unity.

As can be seen from figure 2, U_{edge} increases monotonically with increasing Z_{st} for moderate strain rate ($\sigma = 25/\text{s}$ and $50/\text{s}$). For both higher and lower strain rate conditions, this monotonic trend still exists. Chen and Axelbaum [11] attribute this behavior to a shift in the O_2 concentration profile as Z_{st} increases, the flame location moves toward the fuel side to coincide more closely with the location of peak temperature, which in turn increases radical production rates and leads to a more robust flame. Figure 3 showed that for less than unity Lewis number cases, the experimental results also exhibited the monotonic behavior. This indicates that the chemical effect is dominating for the entire Z_{st} range for Lewis number equal or smaller than unity.

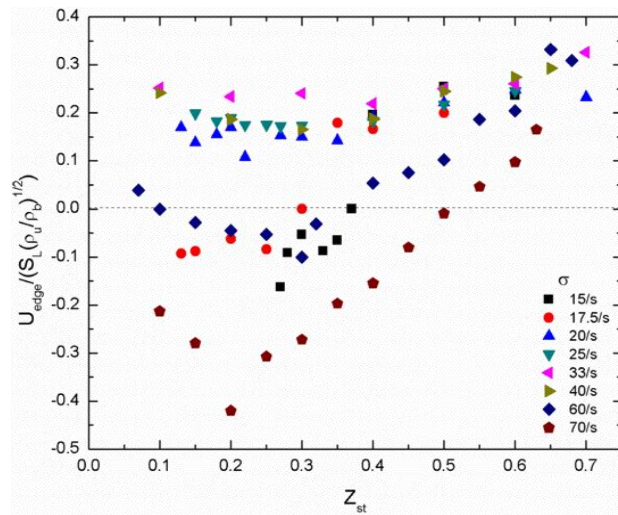


Figure 4. The case for $\text{iso-C}_4\text{H}_{10}:\text{O}_2:\text{N}_2=1:6.5:30$ with U_{edge} varying with Z_{st} for different strain rate. Both fuel and oxidizer have Lewis number greater than unity.

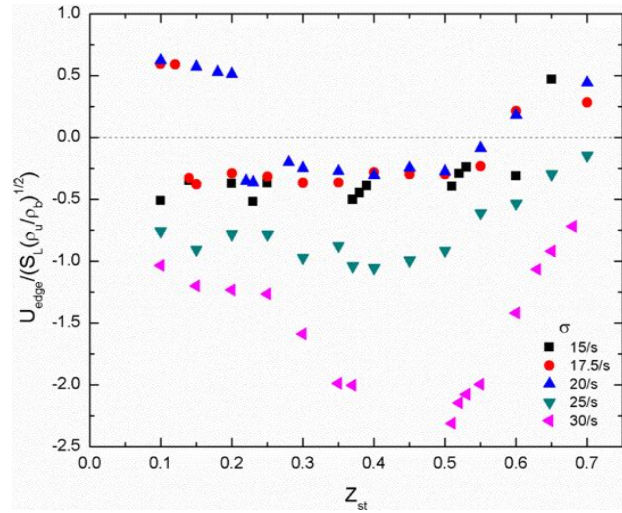


Figure 5. The case for iso-C₄H₁₀:O₂:CO₂=1:6.5:21.5 with U_{edge} varying with Z_{st} for different strain rate. This is the spanning Lewis number case, Le_{fuel} is greater than unity while Le_{O_2} is smaller than unity.

Figure 4 and figure 5 showed a different behavior at low Z_{st} region when compared with the Lewis number near or smaller than unity cases. The upswing of U_{edge} is observed for higher strain rate cases at Z_{st} smaller than approximately 0.3. The proposed reason for U_{edge} increasing as Z_{st} decreases from the minimum point is a shift in the fully consumed reactant from fuel to oxygen as Z_{st} decreases, leading to a smaller Le_{eff} and therefore stronger flame. Le_{eff} is defined as the Lewis number of the fully consumed reactant. According to Liñán [7], the determination of the more completely consumed reactant depends on a parameter $\alpha+2\beta$, where $\alpha = Y_{O_2,\infty}/vY_{F,\infty}$ is the ratio of oxidizer mass fraction in the oxidizer stream to fuel mass fraction in the fuel stream normalized by the stoichiometric oxidizer-to-fuel mass ratio (v) and β is the non-dimensional difference between temperatures of oxidizer and fuel streams. When $2\beta < 1$, the oxidizer/fuel is the more completely consumed component if $\alpha+2\beta$ is less/greater than unity. In the present work, $\beta = 0$, so the oxidizer/fuel is more completely consumed if α is less/greater than unity. From the definition of α and Z_{st} , when $\alpha < 1$ and $Z_{st} < 0.5$, the scarce reactant is O₂ resulting in $Le_{eff} \approx Le_{O_2}$. On the other hand, when $\alpha > 1$ and $Z_{st} > 0.5$, the scarce reactant is fuel resulting in $Le_{eff} \approx Le_{fuel}$. So for mixtures with $Le_{fuel} > Le_{O_2}$, there exists a transition to lower effective Lewis number as Z_{st} decreases. Therefore, U_{edge} is affected by varying Z_{st} and effective Lewis number. While at high Z_{st} ($Z_{st} > 0.3$) the Z_{st} effect dominates which resulting in the monotonically increase trend, at low Z_{st} the effective Lewis number takes over so the upwind trend is observed.

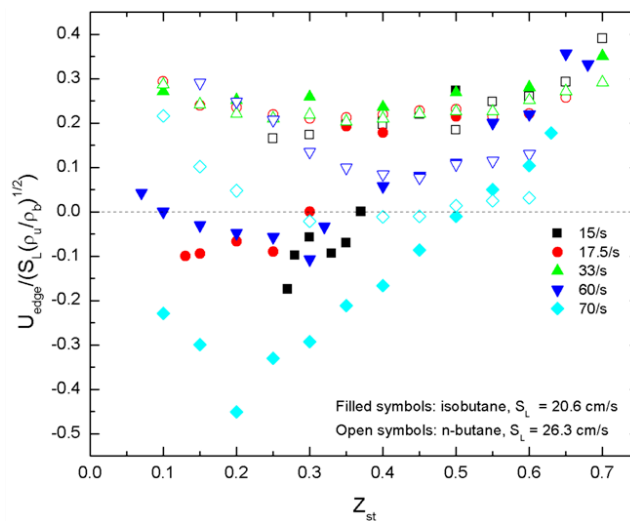


Figure 6. Iso-butane and n-butane comparison for the ratio of fuel:O₂:CO₂=1:6.5:21.5 with U_{edge} varying with Z_{st} for different strain rate.

Figure 6 is the comparison of iso-butane and n-butane. As can be seen from the plot, both fuels demonstrated the upswing trend at lower Z_{st} which is similar to the previously discussed cases due to Lewis number effect. Nevertheless, Lewis number effect seems to be much more dramatic for the iso-butane case. This is possibly due to the easier decomposition of n-butane to smaller intermediates which in terms lowers the effective Lewis number.

4 Conclusions

Some experimental studies of non-premixed edge flames were conducted for 4 cases, i.e. (1) Both fuel and oxidizer have near unity Lewis number. (2) Both fuel and oxidizer have Lewis number smaller than unity. (3) Both fuel and oxidizer have Lewis number greater than unity. (4) Le_{fuel} is greater than unity while Le_{O_2} is smaller than unity. In each case, U_{edge} was measured at constant fuel-oxygen-diluent mixture rate, varying Z_{st} for several strain rates.

The $U_{\text{edge}}-Z_{\text{st}}$ plots show the monotonic trends for case (1) and (2), and the upswing of U_{edge} is observed for higher strain rate cases at Z_{st} smaller than approximately 0.3. Based on the experimental results, varying Z_{st} has both chemical and Lewis number effects on non-premixed edge flame speeds. For $Le_{\text{fuel}} \approx Le_{\text{O}_2} \approx 1$, chemical effects dominate over the whole range of Z_{st} whereas for $Le_{\text{fuel}} > 1$ and $Le_{\text{O}_2} \approx 1$, Lewis number effects become important at low Z_{st} . Similar behavior observed for the two structural isomers of butane. More work needs to be done for this subject.

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