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Flame speed and tangential strain measurements in widely stratified partially premixed flames interacting with grid turbulence

Irfan A. Mulla, Satyanarayanan R. Chakravarthy *

Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600036, India

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ABSTRACT

Methane-air partially premixed flames subjected to grid-generated turbulence are stabilized in a two-slot burner with initial fuel concentration differences leading to stratification across the stoichiometric concentration. The fuel concentration gradient at the location corresponding to the flame base is measured using planar laser induced fluorescence (PLIF) of acetone in the non-reacting mixing field. Simultaneous PLIF of the OH radical and particle image velocimetry (PIV) measurements are performed to deduce the flow velocity and the flame front. These flames exhibit a convex premixed flame front and a trailing diffusion flame, with flow divergence upstream of the flame, as indicated by the instantaneous OH–PLIF, Mie scattering images, and PIV data. The mean streamwise velocity profile attains a global minimum just upstream of the flame front due to expansion of a gases caused by heat release. The flame speed measured just upstream of the flame leading edge is normalized with respect to the turbulent stoichiometric flame speed that takes into account variations in turbulent intensity and integral length scale. The turbulent edge flame speed exceeds the corresponding stoichiometric premixed flame speed and reaches a peak at a certain concentration gradient. The mean tangential strain at the flame leading edge locally peaks at the concentration gradient corresponding to the peak flame speed. The strain varies non-monotonically with the flame curvature unlike in a non-stratified curved premixed flame. The mechanism of peak flame speed is explained as the competition between availability of hot excess reactants from the premixed flame branches to the flame stretch induced due to flame curvature. The results suggest that the stabilization of lifted turbulent partially premixed flames occurs through an edge flame even at a relatively gentle concentration gradient. The strain is also evaluated along the flame front; it peaks at the flame leading edge and decreases gradually on either side of the leading edge. The present results also show qualitatively similar trends as those of laminar triple flames.

1. Introduction

Ever since the classification of combustion modes based on the degree of premixing of reactants, both premixed and non-premixed flames have been investigated for the flame structure and for the flame speed in the former case. Apart from the counter-flow burner, the non-premixed flames are also investigated in co-flow configuration. Since the pioneering work of Burke and Schumman on a co-flowing non-premixed flame, many researchers have studied jet diffusion flames. As part of these investigations, some of the research groups focused on the flame stabilization mechanism of lifted turbulent jet flames. A few theories have been proposed over the decades. Recently, Lyons [1] has reviewed these theories. The available results suggest that the flame stabilization occurs through the edge flames due to upstream partial premixing of reactants. Though the reactants are originally separated, they convect and diffuse over the lift-off distance of the flame from the burner. Thus, the original focus on stabilization of non-premixed jet flame is explained by the combustion in a partially premixed mode. Partially premixed flames (PPFs) also find a wide range of applications from domestic burners to gas turbines. Past investigations have reported that the pollutant concentrations reach a minimum at a certain degree of partially premixing of reactants in both laminar and turbulent flow fields [2,3].

Numerous researchers have investigated the flame stabilization mechanism of turbulent lifted jet diffusion flames. A few relevant theories are discussed here. Schefer et al. [4] show that the reactant mixture at the base of the flame lies within the flammability limits. They also evaluate the scalar dissipation rate, and find it not to exceed the extinction level. Their results support both concepts, namely, the premixed flame propagation and the large-scale

* Corresponding author. Fax: +91 44 22574002.
E-mail address: src@ae.iitm.ac.in (S.R. Chakravarthy).

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turbulence motion that transfers the radical from the product pool, which in turn ignites the upstream reactants. Stårner et al. [5] also confirm that the flame base lies within the flammability limits of the reactants. They also report the divergence of the mixture fraction field. There is evidence of possible triple flames, though no definitive flame structure is reported. Muñiz and Mungal [6] investigated lifted methane jet flames with the *Re* ranging from 3800 to 22,000. The measured flow velocity at the flame base is reported in terms of the planar laminar stoichiometric premixed flame speed S_L: it does not exceed $3S_L$, and the most probable value is found to be $1.5S_L$. They also report the flow divergence ahead of the flame, similar to the laminar triple flame. Based on these findings, the above investigators conclude that the leading edge exhibits characteristics of a triple flame. Hasselbrink and Mungal [7] extended the above investigation. The flow velocity relative to the flame velocity (relative flame propagation velocity) is measured. They attempt to evaluate the flame velocity in the laboratory frame of reference. They report that the variation in the relative flame velocity and flow velocity lies in the same range. Furthermore, the mean values are found to be nearly identical for the different flow velocities. The average flame velocity is non-zero, which they attribute to high uncertainties in the measurements.

Lyons and co-workers have carried out extensive investigations on lifted turbulent jet flames [8–11]. They measure average flow velocity at the leading edge as $3S_L$ [8]. Watson et al. [9] observed an edge flame structure at the base of the lifted jet flame. A weak CH-planar laser induced fluorescence (PLIF) signal resembling that of the fuel-lean branch of a triple flame is observed at the flame base, apart from the strong CH signal from the non-premixed branch. However, they do not observe a distinct fuel-rich branch, which the authors argue might be merged with the non-premixed branch. Moreover, the edge flame structure is not observed at all instances. They suggest that the flame may not have such a structure along all azimuthal locations, and only a portion of the stabilization ring may possess the edge flame structure. The planar nature of PLIF prohibits access to such out-of-plane information and makes this argument less definitive. The flame movement is classified as upstream propagating, downstream propagating and stationary flames, in the laboratory frame of reference [10]. A constant flow velocity of 1.14 ± 0.4 m/s at the flame base is reported for stationary flames, but the flow velocity with respect to the flame velocity for the non-stationary flames is not reported. Watson et al. [11] further assessed the flame stabilization theory based on extinction scalar dissipation rate. Their data shows that the scalar dissipation rate at the flame base, does not reach quenching levels as proposed by one of the theories. They conclude that the stabilization mechanism is governed by partial premixed flame propagation, rather than critical scalar dissipation rate. They also observe that the flame base lies in the flammable mixing layer, suggesting upstream partial premixing of reactants, similar to the observations of Stårner et al. [5]. Upatnieks et al. [12] adopted a cinema-PIV technique to obtain time resolved measurements of the flame velocity and the flow velocity. They deduce the flame propagation velocity as the difference between the flame and flow velocities. The reported propagation velocity shows a large variation. The instantaneous propagation velocity is high as $2S_L$. The average propagation velocity is found to be $0.7S_L$ and $1.2S_L$ for $Re = 4200$ and 8500 respectively. These values of propagation velocity are much lower than that reported by other researchers [6,8,10]. Upatnieks et al. [13] further assess various theories and find that large eddies do not change the flame propagation velocity. They report that the flame shifts its stabilization location in response to the change in the local velocity due to the eddy passage. The measured propagation velocities lie close to the laminar flame speed and are not correlated with turbulence intensity. The authors comment that these results are applicable only to jet flames below $Re = 8500$, and for other configurations, the role of turbulence could be dominant. Their results support the edge flame theory.

Joedicke et al. [14] imaged a multi-reaction zone in lifted turbulent jet flames by performing multi-species PLIF. At low *Re* (=3080 and 4730), they observed triple flame structure at the flame base along with the upstream flow divergence. On the other hand, at higher *Re* (=7100), the triple flame structure becomes broader and diffuse without any upstream flow divergence. They propose that the flame stabilizes by balancing the turbulent flame speed at triple point with the flow velocity.

The above investigations are focused on jet flames, which are basically non-premixed, but the turbulent mixing between the burner lip and the flame, sustains a partially premixed mixture at the flame base. Only a few investigations have been carried out on turbulent PPFs, perhaps due to the difficulty in stabilizing the flames. Mansour [15] developed a new burner that stabilizes such flames. The flame stabilization is achieved through a strong recirculation zone created by flow separation in a wide-angle cone.

Mansour [16] investigated three PPFs each at various jet velocities and equivalence ratios. All the three flames stabilize at a unique value of mixture fraction, suggesting the premixing of reactants. However, he has not reported the concentration gradient at the flame base. The same level of premixing can exist but with different concentration gradients. Mansour [17] further reports the instantaneous upstream flow field at $Re = 2446$ to be divergent, which is similar to that in a laminar triple flame. The results support the theory of turbulent flame stabilization through a triple flame structure. However, such flow divergence is not observed at higher $Re = 3634$ and 5036. This could be because the observations are on instantaneous flow fields, which can be misleading in a turbulent field due to the presence of fluctuating velocity that generates multiple local velocity minima and maxima. On the other hand, the mean flow field may indicate the actual velocity minima (if any) attributed to the flow divergence rather than turbulent fluctuations. Li et al. [18] carried out experimental and numerical studies on this conical burner. The highest scalar dissipation rate deduced from the simulation is still lower than the flamelet quenching limit. Hence, the triple flame model is suggested as appropriate.

The above investigations indicate that the theory of turbulent partially premixed flame structure has not fully evolved yet, although the most supported one is the triple flame theory. In our recent investigation on laminar partially premixed flames [19], a peak in the flame speed is observed at a certain critical fuel concentration gradient. We explain the mechanism of this observation as the heat contribution of the non-premixed branch to the flame speed of the premixed branches at the leading edge. The non-premixed branch exhibits a temperature overshoot due to the availability of hot excess reactants from the premixed branches. This, in turn, is dictated by the flame stretch of the premixed branches, caused by the imposed stratification. This work also reports the flame stretch along the flame branches.

The objective of the present work is to extend the above study to turbulent PPFs. Turbulence is generated by passing the flow through a perforated plate located near the burner lip. Flames with a wide range of stratification are stabilized in a rectangular two-slot burner. Stratification across the stoichiometric concentration is achieved with a range of initial concentration differences in the streams. Neither of the streams is within the premixed flammability limits, thus requiring turbulent partially premixed flame stabilization. The mixing layer is characterized through acetone PLIF. The velocity and scalar fields are deduced from simultaneous OH–PLIF/PIV experiments. The flame speed is normalized by the turbulent stoichiometric premixed flame speed corresponding to the prevailing turbulence levels, and compared across a degree of