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Edge flame structure in a turbulent lifted flame: A direct numerical simulation study

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ABSTRACT

This paper presents a statistical analysis of edge flames in a turbulent lifted flame using direct numerical simulation (DNS). To investigate the dynamics of edge flames, a theoretical framework describing the edge-flame propagation velocity as a function of propagation velocities of mixture-fraction and product-mass fraction iso-surfaces at the flame base is used. The correlations between these propagation velocities and several other variables are then studied, including iso-surface curvatures, iso-surface orientations, strain rates, scalar dissipation rate and gradients of product mass fraction. The contribution of these parameters to the overall behaviour of the edge flame is also investigated using conditional averaging on two-dimensional spatial locations at the flame base. The analysis reveals that the tangential and normal strain rates in addition to the curvatures and scalar dissipation rates have significant contributions to the overall behaviour of the edge flame. The elliptical motion of the flame base described in our earlier study [1] is extended to provide a clearer picture of how these various parameters affect the large fluctuations of edge-flame velocity observed at the flame base.

1. Introduction

Lifted flames are present in many energy producing systems such as industrial burners, gas turbines and diesel engines. They can occur when a high-velocity fuel jet is injected into a quiescent or a low velocity oxidising co-flow. If the jet velocity is high enough, the flame is not anchored at the nozzle lip but rather is stabilised some distance away from the nozzle. The location of the flame base has important implications for the design of the burners and the emissions they produce. As a result, a vast body of literature exists on understanding how lifted flames are stabilised [2–12]. Nevertheless, the stabilisation mechanism is still a poorly understood phenomenon. A number of theories such as the premixed flame theory [9], the edge-flame theory [13], the critical dissipation rate theory [14], and several theories involving a role played by large eddies [12,15] have been proposed. As discussed in several review articles [15–17], aspects of these theories, and combinations of different theories, have varying levels of support when assessed against experimental data, and a final consensus on details of the stabilisation mechanism has not yet emerged.

Among the theories that has the most support, however, according to Lyons' review [17], is the edge-flame theory. In this concept, originally proposed by Buckmaster [13], the leading edge of the flame is considered to be a partially premixed, self-propagating edge flame that is centred at the vicinity of the stoichiometric mixture fraction surface. Stabilisation is achieved as a result of the upstream self-propagation of the edge flame into flammable but as yet unburned mixtures, which balances the downstream flow. In the presence of low strain rates, the edge-flame structure has a tribrachial (or triple flame) structure consisting of two wings of premixed flames (one rich and one lean) and a tail of non-premixed (diffusion) flame. However, when the edge flame experiences high strain rates, one or both premixed branches collapse on the non-premixed tail creating a comet-shape structure.

There have been numerous studies of laminar edge flames, starting with the first experimental observation by Phillips [18], who showed that the edge flame is a self-propagating structure with a velocity balancing the oncoming flow. Kioni et al. [19] later observed the same structure in a similar experimental set-up. Kioni et al. [19] also used simulations to investigate the effects of strain rate on the structure of triple flames, showing that an increase in the strain rate resulted in the two premixed branches being merged on the diffusion tail. In another experimental study, Ko and Chung [20] measured the edge-flame propagation velocity

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in laminar non-premixed jet flames, reporting that it was much higher than the stoichiometric laminar burning velocity. It was also found that the propagation velocity was decreased when the fuel mass fraction gradient was increased. In an experimental study by Santoro et al. [21], the edge-flame structure was studied in a counter-flow mixing layer of methane and air. It was shown that flame extinction occurs when the edge flame experiences high strain rates, while a diffusion flame with no premixed wings was observed when the edge flame was subjected to sufficiently low strain rates. Away from these high and low strain limits, the flow and propagation velocities were balanced and a stable edge flame was observed.

Since the observation of the triple flame structure in experimental studies of laminar lifted flames, numerous analytical [13,22,23] and numerical [8,24–39] studies of this structure in different configurations were conducted. These studies are in general agreement about the influence of the strain rate on the edge-flame structure.

Analytical solutions can only be obtained under some restricted assumptions such as laminar flow, large activation energy and either neglecting heat release entirely or considering only weak heat release. For instance, Buckmaster and Weber [13] proposed a one-dimensional model for the edge-flame propagation in which the absolute speed can be negative, positive and zero. A negative absolute speed occurs when the strain rate is high leading to an extinction event whereas a positive absolute speed, i.e. ignition, coincides with low strain rate. When the flow velocity and edge propagation relative to the flow balance one another, the flame is stationary and the net speed is zero.

Ghosal and Vervisch [22] proposed an analytical expression for the edge-flame velocity in a symmetric laminar lifted flame assuming a large activation energy with a low, finite heat release rate. Their results showed that the edge-flame velocity departs from the laminar flame speed due to the effects of heat release and flame-front curvature. The importance of hydrodynamic effects (associated with the flame heat release rate) were also highlighted in several other analytical studies in the literature [8,22,40]. An interested reader is referred to an article by Buckmaster [23] provides a comprehensive review of analytical analyses of edge flames in different scenarios.

Detailed chemistry numerical simulations employing geometrically simple configurations, have also been used to study of laminar edge-flame characteristics [27,34,36]. The edge-flame structure in a scalar mixing layer between methanol and air was studied by Echekki and Chen [34]. Consistent with previous analytical and numerical studies [8,40], Echekki and Chen found that the edge-flame propagation velocity depends on hydrodynamic effects. In a separate study by Im and Chen [27], a hydrogen–air triple flame was disturbed by inducing a pair of counter-rotating vortices. Im and Chen [27] observed that the edge-propagation velocity was strongly correlated by the flame stretch and the flame-front curvature, rather than the scalar dissipation rate.

The local structure of turbulent edge flames and flow dynamics have been investigated using various laser-based measurements including particle image velocimetry (PIV), cinema particle imaging velocimetry (CPIV), laser-induced fluorescence (LIF), planar laser-induced fluorescence (PLIF), high-speed tomographic particle image velocimetry (TPIV), laser-induced predissociation fluorescence (LIPF), Rayleigh scattering and Raman–Rayleigh scattering [2–4,6,7,11,12,41–56]. Tribrachial structures have been observed in some of these measurements. For instance, Mansour [45] observed the rich wing and diffusion tail using LIPF measurements of OH radicals while Watson et al. [47] observed the rich and lean branches and the diffusion tail by adopting CH-PLIF measurements. The similarity of these visual observations of tribrachial structures to those observed in laminar triple flames suggests that edge flames, as self-propagating structures, play an important role in the stabilisation process [12,46,47,57].

Understanding the stabilisation process and dynamics of edge flames requires measurements of the flow velocity and the relative edge-flame propagation velocity. Significant fluctuations of these velocities and lifted height have been observed in various experimental studies of lifted turbulent flames [12,41,45,47]. Several experimental studies reported the instantaneous, two-dimensional flow velocity fields in the region of the flame base (without conditioning on instantaneous flame locations) [3,42,46,47,52,57,58]. It was observed that the streamlines of the flow diverged at the flame base due to the effects of heat release [3,12,45,46,52,57]. A consequence of this flow divergence is a decrease in the flow velocity in the region of the flame base. This was proposed to allow the propagation of the edge flames into these low-velocity regions. These observations are consistent with the earlier mentioned observations [18–21,59] and theoretical results [13,22,23] for laminar triple flames. Some studies also present two-dimensional measurements of the flow velocity conditioned on the instantaneous flame locations [3,46,57], and compared them with the laminar flame speeds. For instance, Muñiz and Mungal [3] observed that the fluid velocity at the flame base is less than three times the laminar flame speed, S_L, while Upatnieks et al. [46,57] reported the flow velocity to be similar to the laminar flame speed on average. Given that these measurements were conditional on the flame locations, and that the flow velocity and the edge-flame propagation velocity relative to flow should balance on-average, this suggests that the flames propagated at speeds in the order of S_L, thus providing support to the edge-flame theory of stabilisation.

Attempts to measure the relative edge-flame velocity were also made [41,43,60,61]. The two-dimensional absolute edge-flame velocity (flow plus relative edge-flame propagation) is accessible by comparing the flame-base location in two sequential measurements, and the relative edge-flame propagation velocity can then be obtained via a simultaneous measurement of flow velocity. Marking the flame location was critical to these experiments and some used the evaporation of liquid PIV seeding particles [6], while others used PLIF of a radical species, such as OH or CH [47,57,60,61]. These measurements of relative propagation speeds showed that although the relative speed was generally in the order S_L it was not a constant but fluctuated typically between about 0 and 3 S_L, with sometimes negative or large positive speeds being observed. However, because these measurements were entirely two-dimensional, it was unclear whether these fluctuations were the result of actual variations in the propagation speed or rather the result of out-of-plane motion. More recently, attempts were made to partially alleviate this problem using measurements of the out-of-plane component of flow velocity. Boxx et al. [41] recently used a combination of a two-camera, stereoscopic PIV and an OH-PLIF imaging system with overlapping fields of view to measure the flow velocity including the out-of-plane component. Flame islands were observed upstream of the flame base and the appearance of these islands was found to be closely coupled to out-of-plane flow motion of the edge flames. In later work by Gordon et al. [60], measurements of the absolute flame displacement in two dimensions and all three components of velocity were reported. Compared with the previous studies which did not condition velocities on small out-of-plane component, a smaller variance of the relative propagation speed was noted; however, fluctuations of the relative speed were still present - for example the mean speed was different for edge-flames moving downstream to those moving upstream at some of the experimental conditions. Gordon et al. [60] also noted that the appearance of flame islands appeared to be the main mechanism of upstream motion of the flame, thus demonstrating the importance of out-of-plane flame motion. Further support that the three-dimensional structure is important was