The effect of mixture fraction gradients in partially premixed combustion

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THE EFFECT OF MIXTURE FRACTION GRADIENTS IN PARTIALLY PREMIXED COMBUSTION

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Introduction

In many engineering applications, idealized models for premixed and non-premixed combustion do not accurately depict flame front behavior. For cases where fuel and oxidizer do not fully mix prior to ignition or where local extinctions allow unmixed reactants to premix, partial premixing occurs, which can alter system performance [1]. Significant reductions in fuel consumption and pollutant emissions have been achieved in direct injection engines and gas turbines as a result of implementing partially premixed combustion in such devices. Partial premixing is also central to understanding flame stabilization and defines the liftoff height and burnoff of lifted jets, often utilized in industrial burners. [2]

There are two distinct categories of partial premixing [3]. *Stratified premixed* flames occur in non-uniform reactant mixtures that are entirely fuel-rich or fuel-lean and in which stoichiometric mixtures do not occur. In such cases, local combustion zone structures are generally in the premixed regime where equivalence ratio variations affect local burning rates and cause excessive flame-front wrinkling. In contrast, *premixed/non-premixed* combustion occurs when fuel-rich and fuel-lean mixtures are coupled with stoichiometric mixtures to give flames with both premixed and non-premixed characteristics.

This paper focuses on the latter of the two categories and presents a concise review of advances in partially premixed flame research. Several approaches can describe combustion in non-homogeneous mixtures. The current review concentrates on flows in which the mixture fraction gradient runs transverse to the orientation of the laminar flame front. Following a discussion of experimental techniques in use and results of different research groups, the direction of the current study is described.

Transverse Mixture Fraction Gradients

Flames propagating perpendicularly to a mixture gradient consist of two leading premixed flames, one that is fuel-lean and the other fuel-rich, to which a diffusion flame tail is anchored. In the literature, these flames are generally referred to as “Edge flames” but can be further distinguished as either edge flames or triple flames based on the Damköhler number $Da = \left(\delta_m / \delta_L\right)^2$, where δ_m is the effective thickness of the mixing layer at the flame front and δ_L is the thickness of the preheat zone along the stoichiometric premixed flame. [4]

For $\left(\delta_m / \delta_L\right)^2 > 1$, or low strain rates, triple flames are observed and display three clearly defined branches in a tribrachial configuration. The premixed flames lead along the stoichiometric surface because of greater flame speed and tail off as the mixture strength weakens, giving them a curve-like shape. The excess fuel and oxidizer from the rich and lean branches feed the trailing diffusion flame that is stabilized at the triple point. Triple flames occur in ignition fronts such as at the base of lifted jet flames and have a positive laminar flame speed in that they propagate toward the unburned mixture. [5, 6]

At high strain rates, when $\left(\delta_m/\delta_L\right)^2 \approx 1$, the two premixed flames merge with the diffusion flame, resulting in a single flame with a leading edge, or edge flame [4]. This occurs in extinction/ignition fronts often found in diffusion flame sheets where local strain rates exceed critical values. Their propagation velocity is negative in that they recede away from the unburned mixture. [5, 6]

Triple Flames

Since Phillips' [7] first observations of triple flames in a horizontal methane/air mixing layer in 1965, reproduced in Fig. 1, triple flames have been investigated numerically, analytically, and experimentally under several different configurations such co-flow, counter-flow, and lifted jets. A brief review of the predominant works on the topic shows that several factors such as stain rate, Lewis number, and gravity have been evaluated. These are discussed briefly before considering the effect of the mixture fraction gradients on properties of triple flames in greater detail.

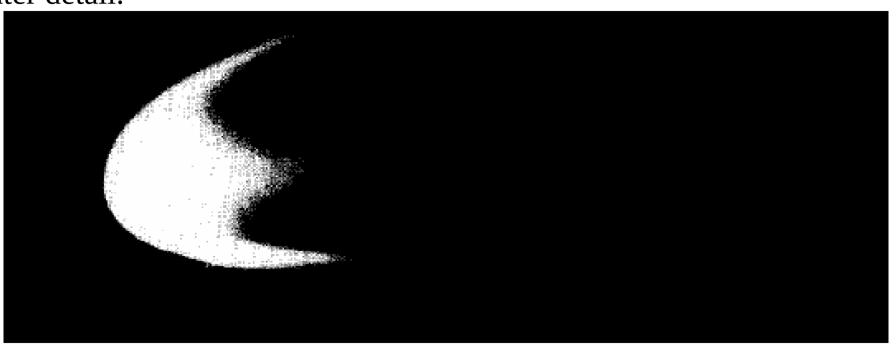

Figure 1. Triple flame observed in a horizontal methane/air mixing layer [7]

Fundamental examinations of triple flames have focused on their structure and propagation velocity, and more specifically on the region surrounding the triple point. Most notable are the theoretical works of Linan and Crespo [8] who derived the first theoretical model using large activation asymptotics and to which Dold [9] and Hartley and Dold [10] incorporated upstream heat conduction. Buckmaster and Matalon [11] studied the effect of non-unity Lewis numbers. Further analytical solutions were derived by Daou and Linan [12] for the effect of transverse enthalpy gradients and differential diffusion on triple flames. Daou *et al.* [13] investigated the effect of volumetric heat loss for a counter-flow flame [13, 14]

Numerical works by Ruetsch *et al.* [15] studied the effects of heat release, Kioni *et al.* [5] evaluated self induced strain, and Im and Chen [16, 17] considered flow strain. Gravity was investigated numerically by Azzoni *et al.* [18] and both numerically and experimentally by Lock *et al.* [19]. Plessing *et al.* [20] investigated the species distribution in the structure and propagation of triple flames numerically and experimentally. Multiple burners and flame configurations have been utilized to study triple flames including slot burners (e.g. Azzoni *et al.* [21]), flames in vortex rings (e.g. Choi *et al.* [22]), laminar non-premixed jets (e.g. Lee and Chung [23]), and counter-flow flames (e.g. Lockett *et al.* [24])., The stabilization mechanism of lifted jet flames has been extensively researched by many researchers and recently by Joedicke *et al.* [25] who investigated turbulent hydrocarbon lifted flames and observed a stabilization region with a triple flame structure.

The transverse mixture fraction gradient has a profound effect on the propagation of triple flames [5,7,10]. Phillips [7] first observed that for smaller transverse gradients, flame propagation velocity increased to above the adiabatic, stoichiometric flame speed. A larger radius of the flame tip was also documented under such conditions.

Dold [9] derived a simplified analytical model with low heat release for "slow varying" flames which neglected the effects of heat release and allowed for only a slight curvature in the flame front. He argued that lower flame speeds occurred at increased gradients, much like Phillips, but that the adiabatic laminar flame speed was the maximum propagation velocity of the flame which was achieved for a mixture fraction gradient of zero, i.e. a planar flame. Harvey and Dold [10] then considered greater mixture fraction gradients and observed large decreases in the flame speed so that the flames receded in the flow (so called "negative" flame speeds). Both studies concluded that properties in the stoichiometric region of the reaction zone, i.e. surrounding the triple point, strongly affect propagation speed.

In a two-part investigation of triple flames, Kioni *et al.* [5] presented preliminary observations for a co-flow burner with an adjustable linear concentration gradient and a theoretical model for a counter-flow configuration of varying strain rates. The experimental results showed an increase in the flame width, defined as the maximum distance between the premixed flames, with a decreasing mixture fraction gradient. They noted that this was consistent with Phillips' [7] observations of a smaller flame tip radius for larger gradients. Some observations, however, did not agree with other sources in that Kioni *et al.* found an increase in the flame speed for increasing mixture fractions.

Ruetsch *et al.* [15] addressed the effect of heat release and mixture fraction gradients on the propagation velocity of laminar triple flames in a direct numerical simulation (DNS). In contrast to Dold [9] and Harvey and Dold [10], the propagation velocity of a triple flame was found to be larger than that of a planar flame, even though local flame speeds along the premixed branches are slower than those at stoichiometric conditions. Ruetsch *et al.* [15] suggested that the heat release brings about a jump in the normal component of the velocity relative to the premixed branches as it passes through them. Because the tangential component of the velocity does not change, the flow is redirected toward the centerline, and induces a divergence of the flow field ahead of the flame front. This reduction in the horizontal component of the velocity is most pronounced at the triple point, where the local flame speed is highest, and allows the triple flame to propagate at a greater velocity than under stoichiometric conditions [15], as observed by Phillips [7].

The observations of Ruetsch *et al.* [15] on the effect of the mixture fraction gradient, or of the mixing thickness δ_m which is inversely proportional to the mixture fraction gradient, on the flame speed agree with those of Phillips [7], Dold [9], and Harvey and Dold [10] and disagree with Kioni *et al.* [5]. They argued that for a larger mixing thickness, a greater burning rate is sustained in the premixed branches, which further enhances flow acceleration across the flame front and results in an increased propagation velocity. They proposed a relation based on thermal expansion to determine the triple flame speed for small mixture fraction gradients [15].

Ko and Chung [26] experimentally measured flame displacement speeds of unsteady triple flames in a 2.08mm fuel nozzle. The results validated observations by Phillips [7] and conclusions by Ruetsch *et al.* [15] and showed propagation speeds greater than the stoichiometric laminar burning velocity that decrease with steeper mixture fraction gradients. A linear correlation between flame curvature and mass fraction gradient was derived, Eq. (1),

$$\frac{1}{r_{cur}^*} = \frac{\sqrt{2b}}{\sqrt{a}} \left. \frac{dY_F}{dx'} \right|_{st} \quad (1)$$

where r_{cur}^{*} is the radius of curvature of the flame front at the triple point, *a* and *b* are constants, and $\left.\frac{dY_F}{dx'}\right|_{st}$ is the fuel concentration gradient at the stoichiometric contour. [26]

In a recent study, Guo *et al.* [27] numerically investigated the local propagation velocity along the flame front of triple flames for three different mixture fraction gradients. Results showed a significantly lower heat release rate in the diffusion flame than in the premixed flames. Furthermore, the combustion intensity in the diffusion flame increased for a shorter mixing thickness, consistent with Dold [9] and Ruetsch *et al.* [15]. They also observed, as did Echekki and Chen [28], that all the primary fuel molecules in the rich premixed flame are converted to intermediate species such as H_2 and CO before they reach the diffusion flame and burn with the excess oxygen from the lean premixed flame. Finally, the authors claim that conduction heat transfer and radical exchange between the premixed and diffusion branches affect the local burning velocity, particularly in regions removed from the stoichiometric plane. Consequently, the correlation for burning speed versus stretch rate derived for homogeneous premixed flames cannot accurately depict the propagation velocity of triple flames. [29]

Experimental setup

Although several cited numerical investigations have helped identify mixture fraction gradient as a critical parameter affecting the premixed/non-premixed combustion process, to our knowledge, limited experimental data exist in which mixture fracture gradient has been an explicitly controlled parameter. The current research is designed to experimentally investigate premixed/non premixed combustion through the use of a slot burner that permits variation of the mixture gradient along the burner under conditions relevant to practical stratified combustion devices. Optical diagnostics are currently being setup to enable characterization of mixture fraction gradient, local air/fuel ratio, heat release and radical exchange taking part in the combustion process.

Premixed/non premixed burner

As shown in Fig. 2, the burner consists of a series of 65 x 15mm, rectangular tubular sections. Two reactant streams of different mixture strengths enter the 16 mm high lower section into separate triangular compartments divided by a sealed metal barrier. Each triangular section has been filled with porous metal foam to evenly distribute each separate inlet flow. The two different mixture streams are then allowed to mix laterally as they pass into in 6 equal, 10mm wide, 152.4mm long channels. The configuration of the inlet section is such that the flow in each channel will have a different mixture strength which is proportional to the relative flow amounts from each inlet stream entering that channel. The channels are filled with 3mm balls to promote lateral mixing of the two inlet streams. Finally, the flow is allowed to mix longitudinally as well in the exit section of the burner, which can be adjusted in height from 150mm to 350 mm to control the degree of longitudinal mixing. The exit section length is set to 225 mm for the current work. At the exit of the burner, a reactant flow with a smooth, longitudinally varying mixture gradient is produced.

In the present work, a gaseous isooctane/air mixture with desired equivalence ratio is obtained by injecting isooctane directly into an air flow heated to 80°C. Pressurized N_2 is used to push isooctane through a fuel flow meter and the injection rate can be adjusted to vary the equivalence ratio. In this study, an isooctane/air mixture with an equivalence ratio of 2, and heated pure air are the two inlet flows that enter the separate inlet compartments of the burner. This produces a mixture with smoothly varying equivalence ratio from approximately 0-2 at the burner exit. Reference experiments are also performed with a homogeneous premixed isooctane/air mixture with an equivalence ratio set to one. A 1.5 mm diameter rod placed perpendicularly to the slot burner can be used to stabilize the flame in a V configuration.

Optical diagnostics

Tracer based PLIF is used to track the fuel concentration and air/fuel ratio profile along the slot of the burner to characterize the mixture gradient which is the key parameter in our study. Tracer excitation is achieved with a high power, broadband KrF excimer laser at a wavelength of 248nm. A combination of cylindrical and spherical lenses forms a vertical laser sheet which is directed along the longitudinal axis of the burner. Although pure isooctane is not fluorescent at 248nm, several tracers are available which can be excited at 248 nm, including several aromatics and ketones as reported by Schulz and Sick [29] and Einecke *et al.* [30] respectively. For the current study, 3-pentanone is chosen since its fluorescence, centered at about 410 nm, is easily separated from the laser wavelength. Fluorescence is collected perpendicular to the laser sheet by a gated ICCD camera equipped with a 340-460 nm band pass filter and a UV Nikon lens. The fluorescence images can be calibrated at different laser fluences against a series of cold-flow reference images at known global equivalence ratios produced with high precision air and fuel flow meters. PLIF on 3-pentanone will also be used to visualize the fresh mixture without and with a flame present so to obtain additional information about the structure of the flame likely to reproduce a triple flame similar to that shown in Fig. 3.

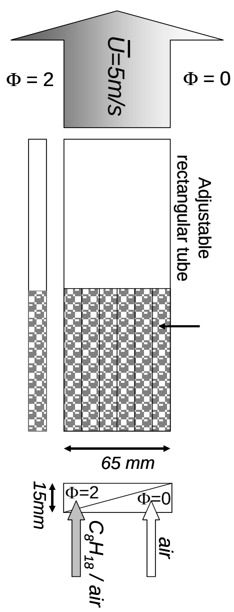

Figure 2. Stratified burner

Figure 3. Direct visualization of a stratified V flame stabilized in the gradient of a partially premixed isooctane-air mixture

Figure 2 is a direct visualization of the flame burning under stratified conditions. Combustion takes place behind the stabilizing rod and three luminous branches are observed. The triple V-flame exhibits blue light emission in the visible part of the spectrum. This light is mostly due to vibration of radicals such as OH*, CH*, CN*, C_2*, CO_2* taking part in the major exothermal chemical reactions. On the left side of the image, isooctane is in excess and the flame is apparently thicker, longer and brighter than the flame on the right side of the burner (where there is an excess of oxygen). Between the two branches of the partially premixed V-flame, a third branch is apparent just behind the rod. Additional light is emitted behind the third branch and the rich branch indicating the presence of radicals and intermediate species containing carbon that did not burn completely due to the lack of oxygen on this side of the flame. The blue light between the rich branch and the middle branch is continuous while the lean branch and the middle branch of the flame seem to be strongly distinct. In contrast, a reference homogeneous premixed V-flame only exhibits two symmetrical, thin branches.

In this work, the chemiluminescence spectrum of the flame along the direction of the mixture gradient will be analyzed at different heights in the flame. For this purpose a Chromex 500is imaging spectrograph is positioned normal to the mid-plane of the burner so that the collection slit is in a horizontal position. The burner can be moved vertically so we are able to get the spectral profiles of chemiluminescence at different heights in the flame. These results will provide insight into the combustion process occurring in the rich premixed flame branch (left), the lean premixed flame branch (right), or in the third branch present between the 2 premixed flames which exhibits a diffusion flame spectrum with soot formation. According to Higgins *et al.* [31, 32], Kojima *et al.* [33], and Hardalupas *et al.* [34], the OH*/CH* light ratio can also be related to the local equivalence ratio. In future experiments, we will attempt to correlate chemiluminescence imaging of OH/CH ratio with PLIF from 3-pentanone imaging.

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