Available online at www.sciencedirect.com

ScienceDirect

Progress in Energy and Combustion Science 33 (2007) 211–231

PROGRESS IN ENERGY AND COMBUSTION SCIENCE

www.elsevier.com/locate/pecs

# Toward an understanding of the stabilization mechanisms of lifted turbulent jet flames: Experiments

Kevin M. Lyons*

*Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695-7910, USA*

Received 5 April 2006; accepted 9 November 2006
Available online 20 December 2006

---

## Abstract

This review discusses recent progress in understanding turbulent, lifted hydrocarbon jet flames and the conditions under which they stabilize. The viewpoint is from that of the empiricist, focusing on experimental results and the physically based theories that have emerged from their interpretations, as well as from the theoretically founded notions that have been supported. Pertinent concepts from laminar lifted flame stabilization studies are introduced at the onset. Classification in broad categories of the types of turbulent lifted flame theories is then presented. Experiments are discussed which support the importance of a variety of effects, including partial premixing, edge-flames, local extinction, streamline divergence and large-scale structures. This discussion details which of the categories of theories are supported by particular experiments, comments on the experimental results themselves and their salient contributions. Overall conclusions on the state of the field are drawn and future directions for research are also discussed.

*Keywords:* Combustion; Jet flame; Turbulent combustion; Lifted flame; Flame stability; Partially premixed; Edge flame; Triple flame

---

## Contents

1. Introduction . . . 212
2. Laminar lifted flames . . . 213
3. Turbulent lifted flames . . . 216
    3.1. Categories of theories . . . 216
    3.2. Studies of turbulent lifted jet flames . . . 218
4. Final comments . . . 226
    4.1. Brief summary of advances in understanding lifted flame stabilization . . . 226
    4.2. Directions for future research . . . 226
    4.3. Concluding remarks . . . 227
Acknowledgements . . . 227
References . . . 228

---

*Tel.: +919 515 5293; fax: +919 515 7968.
*E-mail address:* Lyons@eos.ncsu.edu.

doi:10.1016/j.pecs.2006.11.001

## 1. Introduction

The study of jet flames is traditionally a central topic in combustion research, and the literature is replete with studies of flame structure, chemistry and dynamics. It is the lifted flame counterpart to the burner stabilized flame that is the present focus of this paper. When the burner stabilized jet flame is lifted from the burner by increasing the fuel or surrounding air co-flow velocity, the flame can stabilize without a physical element to use for stabilization, and a lifted jet flame is created. The flame can exist over a range of exit velocities until a critical velocity is reached and the flame blows out globally.

Lifted flames are found in practical applications like burners in commercial boilers, where the lifted jet flame is utilized to reduce damage to nozzle material by minimizing contact between the flame and the nozzle. Elevated flares also involve lifted flame phenomena. Combustion of stratified mixtures, such as those witnessed in turbines as well as diesel and direct fuel-injection gasoline engines and even mine fires, have elements of their reaction zone structures that prompt comparisons to the edge of the laboratory lifted flame.

Fundamentally, lifted flames are of interest since they are simple systems which exhibit important characteristics of finite-rate chemistry, turbulence-chemistry interaction, effects of heat release, local extinction of combustion as well as a host of other effects. Their simplicity lends them to joint modeling and experimental efforts in ongoing research to develop predictive codes in turbulent combustion.

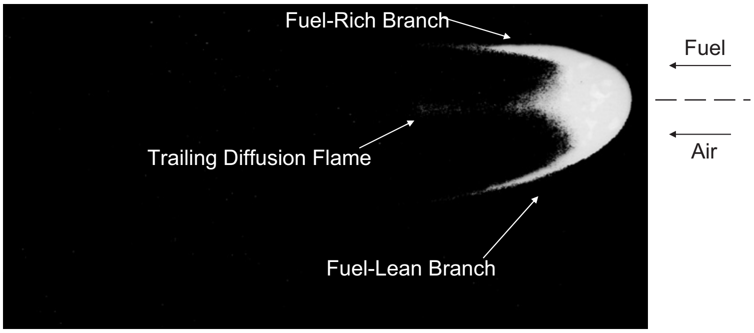
The stability of such reaction zones is of prime importance in the study of combustion, both from fundamental [1–3] as well as practical device point-of-view. The axisymmetric jet flame has served as a focal point of combustion researchers since it is a relatively simple system that lends itself to theoretical as well as experimental approaches, yet possesses elements present in more complicated devices (mixing considerations, strain, air-coflow). The lifted jet flame, in particular, has received a large amount of attention in the last 50 years. Perhaps it is the fascination that researchers have with flames that stabilize without the presence of flame holders (burner rims, stabilizers and the like) that has motivated the many diverse efforts attacking this problem. In the case of the lifted flame, the objective is to understand the conditions under which the lifted flame stabilizes and the associated causes. The current research approaches with the view that this understanding can come from knowledge of scalar and dynamic parameters in an appropriate framework that allows contributions from numerics, theory [4] and empiricism to be assembled into valid mechanistic theories.

The mechanisms that control jet flame liftoff, stabilization and blowout have been investigated for years by combustion scientists. The review by Pitts [5] in 1988 summarizes many of the standard theories concerning jet flame stability. These theories concern the roles of premixedness, scalar dissipation and large scale structures in controlling the conditions under which a lifted-jet flame stabilizes, extinguishes or blows-out. Since the review of Pitts, many experimental and theoretical studies have been completed that indicate the importance of triple (or tribrachial) flame and leading-edge, or simply "edge", flame concepts. A recent review by Buckmaster in 2002 details the mathematical foundations of edge-flames as well as select theoretical and experimental evidence supporting the edge-flame concept. Coats [6] discusses the theories of flame stability that are founded on the principal role of coherent, large scale structures in jet flame stabilization. Coats described, in detail, the work from Broadwell et al. [7] until recently, on entrainment and mixing in the flame brush of the lifted flame. The closing chapter in Peters' *Turbulent Combustion* discusses partially premixed combustion modeling with a focus on triple flames. Recent important DNS simulations of turbulent hydrogen lifted flames show great promise for illuminating the reaction zone structure at the leading edge [8,9]. Rendered are laminar leading edge flames, stabilized outside the turbulent jet in the form of triple flames, with velocities of the order of the laminar burning velocity. Also shown in these numerical studies of Mizobuchi are lean diffusion flame islands [10]. All of these reviews and studies discuss the lifted flame issue from different perspectives ranging from fundamental reaction zone structure considerations to empirical pictures of flame height oscillation. From yet another perspective, the discussion that follows reports on a diverse set of select experimental studies in lifted flames, especially focusing on recent imaging studies of turbulent flames performed since the review of Pitts. The issues raised by the experimental results will be related to theoretical counterparts. In this sense, the paper is intended as a contribution on the elements empiricism has added to the ongoing paradigm developments in partially premixed turbulent flames, akin to the paradigms already established for premixed and non-premixed turbulent combustion [11]. The details of the advanced imaging techniques utilized in the experiments described here are not included in this monograph. Readers who desire a review of the imaging diagnostic techniques utilized in many of these experimental studies would do well to read the reviews by Long [12], Seitzman and Hanson [13], and the books by Eckbreth [14] and Linne [15], as well as the original sources in this paper, many of which describe the experimental techniques in more detail.

## 2. Laminar lifted flames

A diffusion flame exists when fuel and oxidizer, initially separated, react at a flamefront, which can spread across an interface (as in flame spread over solid combustibles, liquid fuels or gaseous fuel/oxidized interfaces). Unlike fully premixed flames, which can propagate into regions of flammable composition, there is no flame speed associated with reaction zones based on fuel and oxidizer inter-diffusion since they possess no inherent mechanism of propagation. Depending upon the fuel properties, the flow characteristics, and the initial boundary conditions at the interface of a diffusion flame, partial premixing is thought to be responsible for flame spread along the interface, facilitating the propagation/stabilization of the “bulk” diffusion flame. While appearing quite different, diffusion flame stabilization in nonpremixed jets may have much in common with flame spread across liquid fuel pools and solid combustibles [16]. The role of partial premixing and edge-flames has been investigated and has often been utilized in explanations of the phenomena since it provides a mechanism for flame propagation along the interfaces in these various systems (various situations where flames propagate and spread along stratified regions whether in jets, wakes, pool fires or counterflow flames). Additionally, the issue of edge flame propagation is highly relevant when the dynamics of the locally extinguished regions of turbulent diffusion flames are considered (e.g., the “hole” torn in a flame sheet may be surrounded by an edge flame [17–21] or counterflow geometries devised to study such effects are examined [22].

The studies of Phillips [23], and Kioni et al. [24,25] investigate flame propagation in layered gaseous systems with various degrees of premixing and a variety of flammable zone thicknesses. All explicitly show triple-flame (or also called tribrachial-flame) structures: a lean premixed branch (LP), a rich premixed branch (RP), and a trailing diffusion flame (DF). For example, Fig. 1 shows a well-known image of a triple flame from Phillips [23], propagating in a layered gallery of fuel and oxidizer from left-to-right. Note that the diffusion flame is formed by the excess fuel and oxidizer left over from the premixed wings, as well as fuel and oxidizer diffusion from the individual streams. These types of studies were performed in both layered galleries (with a stationary layered fuel-on-air configuration and a propagating flame) and static flame rigs (with flow of a methane layer on top of an air layer and a stabilized, stationary triple flame structure). The flows appear quite laminar and the triple flame structures are observable by eye, exhibiting the tribrachial structure with the curved premixed “wings”. Theoretical and computational



*adapted from Phillips, 1965

Fig. 1. An image showing a triple-flame structure from an experiment by Phillips in 1965. Explicitly shown are the rich- and lean-premixed branches as well as the trailing diffusion flame. Fig. 5 from: Phillips [23].

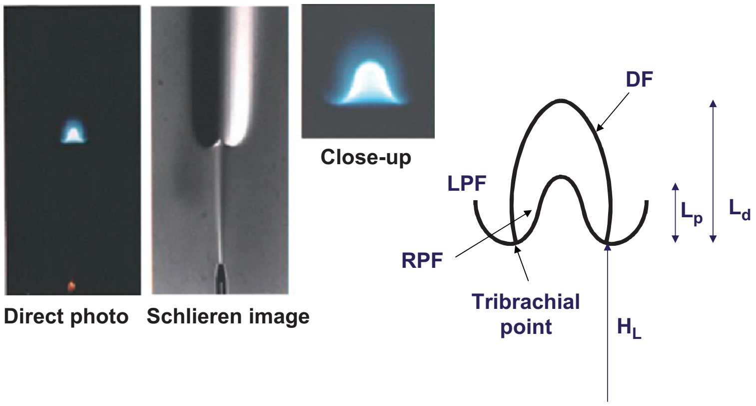


Fig. 2. Lifted flame data for a lifted 80% propane/20% laminar jet flame, demonstrating the tribrachial structure at the base of the lifted flame (diameter of nozzle = .195 mm, exit velocity = 12 m/s). The rich premixed flame (RPF), the lean premixed flame (LP) and the diffusion flame (DF) are labeled. Copyright 1997 from Combustion Science and Technology by Lee and Chung [39]. Reproduced by permission of Taylor and Francis Group, LLC., http://www.taylorandfrancis.com.

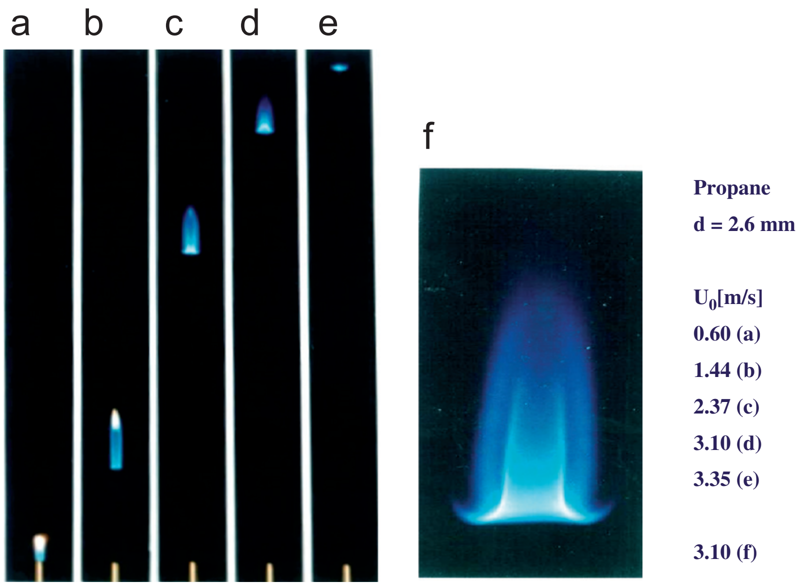


Fig. 3. Lifted flame imaged for a variety of flowrates for a propane jet flame. Shown are structures that generally correspond to the lean, rich and diffusion flame structures shown in Fig. 2. Adapted from Fig. 1 from Lee et al. [38] and used with permission from the Combustion Institute.

studies of triple flames in laminar flows have been performed, partially in attempts to explain the notion that Phillips' paper puts forward [26–30].

It is logical to comment on these studies of the lifted laminar jet flame [31] before discussing the current status of turbulent lifted flame research. The concept of the triple flame in stabilizing laminar lifted flames has been experimentally investigated and applied [24,25,32–40]. There is significant experimental evidence contained in these studies on the presence of triple flame structure with empirically visualized, explicitly reported lean, rich and diffusion branches at the leading edge reported, [41,42] akin to the Phillips data. In a related study, Azzoni et al. [43] examine triple flame structure and chemistry in a flame stabilized above a slot burner. This is done to examine the detailed structure of the three branches and their interactions in a steady triple flame system. Figs. 2 and 3 both display triple flame structures at the leading-edge of reaction zones in laminar jet flames from the group of S. H. Chung at Seoul National University. While not in a layered system as in Fig. 1, Fig. 2 shows a direct photo of the tribrachial point as well as premixed and diffusion flame branches. Fig. 3 also shows the tribrachial structure of a lifted propane flame, which lifts to blowoff corresponding to the loss in tribrachial structure. The evolution of the tribrachial structure to this reaction zone disk (Fig. 3(e)) before blowout is similar to the data shown by Savas and Gollahalli [44]. These studies establish the veracity of the triple flame concept in laminar jet flame stability theory.

Flame hysteresis in lifted jet flames is the phenomenon found when lift-off of the reaction zone is caused as a critical jet velocity is reached upon increasing the jet velocity, but it is found that the jet velocity must be reduced to below this critical liftoff velocity to attain reattachment. While this phenomenon impacts a small regime of the typical operating conditions of practical devices, research into its causes and explanations have produced insights into flame propagation/stabilization in general. This is particularly true regarding the ability of the reaction zone to propagate upstream toward the burner exit and the associated flow conditions. Gollahalli et al. [45], Savas and Gollahalli [44], Chung and Lee [33], Lee and Chung [39] and Terry and Lyons [46] all discuss flame and flow issues related to the hysteresis phenomena, mostly for laminar flames. Early work in lifted flames [47] implied that turbulent flow is necessary for a lifted jet flame to stabilize. Most lifted flames are turbulent, and the existence of a hysteresis condition for lifted flames (i.e., the jet velocity must be turned down below liftoff velocity toward a laminar regime to reattach) is somewhat consistent with this assertion. Later work by Savas and Gollahalli [44] and Lee and Chung [39] discuss further the criteria regarding conditions for a lifted flame to be stable. They examine laminar flames and find that stationary laminar propane flames do exist but, in experimental studies, stable laminar lifted flames are not witnessed with pure methane as the jet fuel. Their stability analysis implies that it is the Schmidt number (a measure of the viscosity to mass diffusion) of the fuel that dictates if a laminar lifted stationary flame can exist (it cannot for $0.5 > Sc > 1$; it can for $Sc > 1$), [not determined by whether the laminar or turbulent flow regime]. This is also discussed in Chung [34] and Law [1]. It is predicted from their stability analysis that the liftoff height (a) increases with jet velocity for $Sc > 1$ and (b) decreases with jet velocity for $.5 > Sc > 1$; (a) agrees with the experimental observation of stable stationary lifted laminar propane ($Sc = 1.3$) flames and (b) is supported in that a stable lifted laminar flame cannot be maintained. It is reasoned that (b) paints a scenario that is physically unrealistic—i.e., the flame moving farther downstream with decreasing jet velocity is not possible. An anchored *laminar* methane jet flame ($Sc = .7$), upon increasing the fuel velocity, blows out directly from the nozzle, never stabilizing as a lifted flame. In the laboratory, a lifted stable flame, similar to that shown in Fig. 1, cannot be achieved with pure methane (Fig. 1 is with propane). Chen et al. [48] examined inert-diluted hydrocarbon flames and also found the Schmidt number to be the controlling parameter for laminar jet flame stability. In summary, these various studies have all supported the significance of triple flame structures in laminar lifted flames that are unperturbed by turbulent structures.

Chen and Bilger [49], Ghosal and Vervisch [50] and Boulanger et al. [51] have examined similar problems in lifted laminar jet flames numerically and analytically. They highlight the importance of flow deflection from heat release [52] in allowing the flame to stabilize. Their numerical results show that the effect of heat release is to permit the flame to stabilize closer to the burner than that predicted without the heat release (Fig. 4). The effect is argued to be more pronounced as the jet Reynolds number is increased. Although their focus is not on turbulent lifted flames, it is also argued that the effect must be present in higher *Re* situations as edge-/tribrachial-flames transition to large partially premixed flames at larger axial locations. They suggest that “it would be necessary to include the effects of heat release in the axisymmetric flow description, upstream of the flame, to improve theoretical descriptions of liftoff height.” The issue of heat release contributing to streamline divergence at the turbulent lifted flame leading edge will be revisited later.

Determining the situations and the major parameters that determine whether intact triple flames, flame nubs, double flames or layered systems of flames exist is important, particularly as we try to extend these findings to turbulent flame cases. Wichman and Ramadan [31] and Wichman et al. [53] have pursued excellent analytical studies in this spirit; experiments along these lines are relatively few [41,42]. Buckmaster [54] surveys many of these studies in laminar lifted flames under the general heading of edge-flames and interested readers would

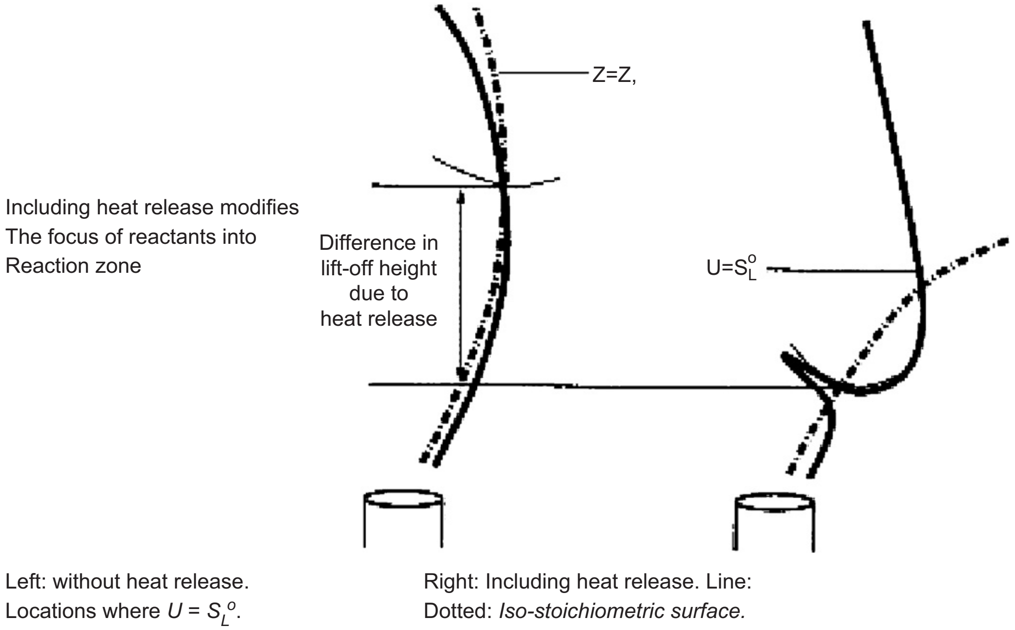


Fig. 4. Schematically shown is the effect for including heat release in numerical approaches. The effect of heat release is to permit the flame to stabilize closer to the nozzle exit (right) as opposed to models neglecting heat release (left). Reprinted by permission of Elsevier Science from Boulanger et al. [51] Copyright 2003 by The Combustion Institute.

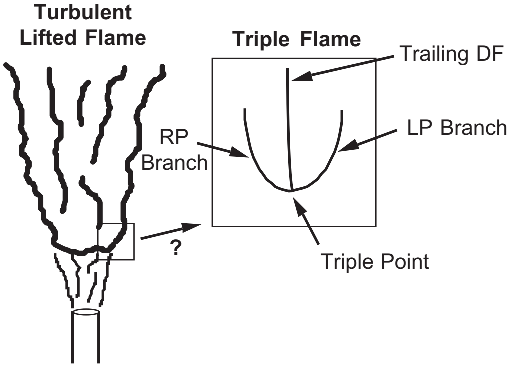


Fig. 5. Schematic representing a major question regarding the correspondence of the triple flame structures found in laminar lifted jet flames with the structures witnessed in turbulent jets.

be advised to consult his work and those which he references. Lockett et al. [55] have performed studies of reaction zones in laminar counterflow flames and construct stability maps for such flames. They have found triple flames existing at low stretch rates, merging into a double flame at higher stretch levels. This is a pioneering study that raises the question of whether intact triple flames can exist, generally, in highly turbulent flowfields, except in locally low strain regions.

With the studies described here, it is established that triple- and edge-flame paradigms have been established to describe the stabilization of laminar lifted flames. Elements of these findings for the laminar case will be utilized judiciously in our subsequent discussions, though the empirical findings from turbulent lifted flame studies have not been synthesized into as coherent and complete theories as those for the laminar issue. This paper continues to address our primary topic, recent empirical studies that have revealed information on the physics of lifted turbulent jet flame stabilization. Some of the obvious major questions, given the preceding discussions, are implied pictorially in Fig. 5: how can the elements established about triple flames in lifted laminar jet flames and laminar stratified systems be used to great effect in understanding turbulent lifted jet flames? Do experimentalists witness explicit, intact triple flames in *turbulent* flowfields? If not, what are the morphologies of these reaction zones? These and other questions are developed and discussed in the next section.

## 3. Turbulent lifted flames

### 3.1. Categories of theories

During the course of studying the lifted turbulent jet flame stability issue, different but sometimes overlapping theories of flame stabilization have been proposed, which can be loosely classified in the following five categories:

1. The Premixed Flame Theory [56,57]: It is argued that the lifted flame base is premixed [58] and burns at the local burning velocity, which permits flame stabilization (i.e., it is quasi-stationary in the laboratory frame).
2. The Critical Scalar Dissipation Concept [59]: This theory claims that it is the extinction of diffusion flamelets that controls flame stabilization. The lifted turbulent flame stabilizes where the relevant scalar dissipation rate falls below a critical value. Along the contour defined by the stoichiometric radius, the scalar dissipation rate increases with axial distance from the nozzle exit, but then falls off moving downstream.
3. The Turbulent Intensity Theory [60]: According to this theory, the enhanced turbulent burning velocity, instead of the laminar flame propagation speed, strongly impacts the propagation of the reaction zone, and is related to the turbulence intensity at the leading edge.
4. The Large Eddy Concept [7,61]: Conceptually, this argument illustrates the prime importance of large scale structures on flame stabilization. Some of the theories in this category assume that the flame leading-edge is attached to (or, in some way, connected with) large eddies, and is able to migrate to its upstream neighboring structure repeatedly to stabilize the reaction zone.
5. The Edge-Flame Concept [54,62]: This theory assumes that the flame leading edge is partially premixed, and thereby, can propagate upstream to counter the local flowfield, while also modifying it through heat release [63]. Edge-flames may have positive or negative propagation speeds and are thought to exist at flame-hole edges [64]. The edge-flame concept is rooted in the mathematics of idealized 2-D flame structures, which Buckmaster [54] extensively reviews. The edge-flame concept is also consistent with the triple, or tribrachial, flame structure uncovered experimentally [23] and analytically [65].

In his 1988 paper, regarding flame stabilization and blowout, Pitts offered that "no satisfactory models currently exist" and described the deficiencies in the theories. The criticism of Category (1) related to the lack of dependence on large scale structures and incorrect prediction of liftoff height on maximum laminar burning velocity. Category (2) has a lack of dependence on premixing. Also, in Category (4), the implications that there is a need to have hot products transported upstream in large scale structures near the jet edge is largely unsupported by experimental results. The author of this review does not intend to imply that particular flames or conditions pertain to one theory category or another; it will be discussed that most experiments will produce results that support, or are at least consistent with, more than one category.

In the premixed approach, Vanquickenborne and Van Tiggelen [56] proposed that the stabilization of lifted flames results from equilibrium between the premixed turbulent burning velocity and the average flow velocity entering the flame base. In this view, it is envisioned that the flame velocity counters the local flow velocity, thus permitting flame stabilization. This approach (Category 1), however, does not take into account the effect of large-scale structures in the jet [66].

Peters and Williams [59] argue (Category 2) that premixing has not occurred to any significant extent upstream of the flame's leading edge. Their alternative to the premixed argument is the concept of laminar flamelet extinction (i.e., the leading edge of the flame is akin to an ensemble of strained laminar flamelets, [67]). A main point of controversy in this theory centers on the role of scalar dissipation rates in causing diffusion flame extinction. One way of explaining the stabilization of turbulent lifted flames (for a range of $Re_\mathrm{d}$ up to blowout) is to argue that instead of positioning itself at a location where the velocities are balanced, the reaction zone moves downstream to a region of sufficiently low rate of scalar dissipation . At these downstream positions, it is argued that the rates of dissipation will not be high enough to extinguish the flame. Experiments in counterflow diffusion flames support the spirit of this argument—that is, if one accepts the leading edge structure to be that of a diffusion flame. Nevertheless, these counterflow studies arrive at critical values of the scalar dissipation rate, above which combustion ceases [68]). Arguments against this approach center on the fact that it virtually ignores partial premixing of the fuel and air upstream of the flame. Also, differentiating between mean values of scalar dissipation and shorter lived regions of high scalar dissipation is thought to be important.

Pitts discussed Category (3) to the extent that Kalghatgi [60] determined a relation for the liftoff height as a function of the inverse of the burning velocity squared. Category (5) was not discussed explicitly in the review though this topic has received substantial attention from the late 1980s to date. These categories are not necessarily independent, as illustrated by the example described by Eickhoff [69], who points out the similarities in the Kalghatgi Concept from Category (3) and the Edge Flame Concept in Category (5). Both notions can be cast in terms of the turbulent Damkohler number at the jet flame base [70].

### 3.2. Studies of turbulent lifted jet flames

A series of papers by Schefer et al. appeared in the 1990s on lifted turbulent jet flames [71,72]. Schefer et al. [73,74] describes a study of flame ignition, extinction and reignition by utilizing a dual pulse technique to obtain the temporal evolution of the reaction zone. This important paper describes the reaction zone being impacted by vortical structures from the methane jet, the existence of local extinction events in the reaction zone, and makes the case for lifted flame stabilization by turbulent premixed flame propagation. Their paper is consistent with the notions in Miake-Lye and Hammer [61] regarding the lifted flame propagation from stabilizing on one large-scale structure to another through low strain premixed regions, though some recent studies i.e., Upatnieks et al. [70] do not support this view, as will be seen later. Schefer et al. [73,74] additionally reports that the leading edge of a lifted methane flame resides in the region within the flammability limits. It also reports levels of scalar dissipation in the vicinity of the flame leading edge as being well below the critical value for extinction of comparable counterflow flames. The view furthered by this paper is an important one: “These observations are not meant to imply that flame stabilization is either controlled by interactions between large-scale turbulence and the flame, or by flame propagation at smaller scales. These two theories are not mutually exclusive. Rather, the view best supported by the data is that flame propagation is a consequence of large-scale motion, which established the local turbulence field through which the flame can propagate”. It is furthered that it is this propagation that permits the flame to move upstream, rather than facilitation by large-scale structures. These sequential planar image experiments raised some other questions when the leading-edge of the reaction zone was found to make rapid, discontinuous jumps upstream. Schefer [75,76] addresses this question by examining both planar CH-PLIF (planar laser-induced fluorescence) measurements as well as CH chemiluminescence. A major finding of this study is the considerable three dimensionality of the lifted flame for some conditions, particularly those stabilized close to the burner exit [75,76]. The asymmetry of the leading edge flame at $Re = 7000$ is reported, along with the observation that the leading edge of the reaction zone is found to be made up of multiple, small fragments of flames rather than a continuous reaction zone. These findings have implications for planar imaging related to the possibility that the true leading edge of the flame is located out-of-plane and the role of 3-D vortical structures in flame stabilization, work that has been further pursued [77]. Chen and Goss [78] have also examined OH structures over the regime from liftoff to blowout.

Studies on the velocity fields in lifted jet flames have appeared in the literature in recent years, largely due to developments in techniques such as particle image velocimetry (PIV). Advances in PIV are particularly beneficial for jet flame study since they provide a two-dimensional planar measurement of velocity, which can produce axial velocities conditioned on instantaneous reaction zone leading edge position. One interesting study by Muñiz and Mungal [79] involved the application of PIV to a lifted methane jet flame over the range of $Re$ from 3800 to 22,000. Supported by their results, they argue that the reaction zone seeks out relatively low velocity regions of the flowfield (lower than those implied by Schefer et al. [71]) and that the flame propagates to fulfill the criterion of flame propagation counterbalancing the incoming flow of reactants. Examples of the velocity fields produced in this study are shown in Fig. 6. Also shown in Fig. 6 is a contour showing the approximate location of the reaction zone; it is divided from the flow near the core of the jet by the solid line. This study also examined the reaction zone for evidence of triple-flame like behavior at the flame leading edge, prompted by the recently published works of Müller et al. [80] and Ruetsch et al. [28]. While explicit lean and rich reaction zone branches were not uncovered, arguments for the applicability of triple-flame-like behavior were made. The bright blue chemiluminescence witnessed at the leading edge is consistent with the reaction–rate profiles of triple

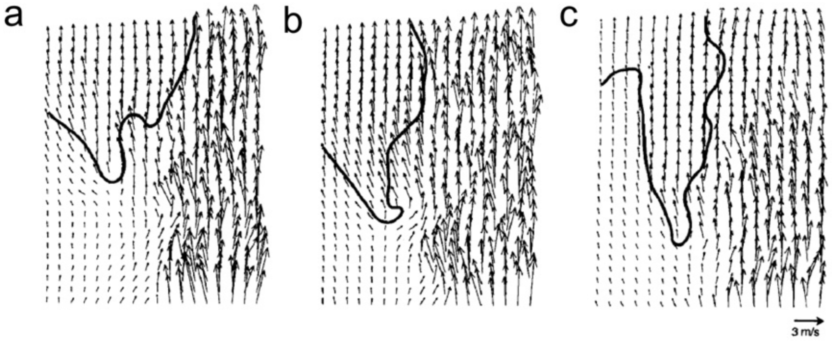


Fig. 6. Instantaneous velocity field shown at the leading edge of the reaction zone for a methane lifted jet flame with a Reynolds number = 3900. Reprinted by permission of Elsevier Science from Muñiz and Mungal [79] Copyright 1997 by The Combustion Institute.

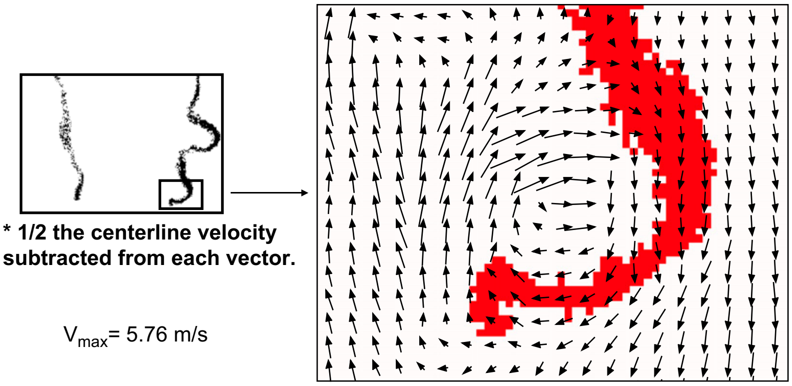


Fig. 7. An image of the simultaneous CH radical image at the leading edge of a lifted flame shown with an overlaying velocity field portraying the fluid motion around the leading edge. Reprinted by permission of Elsevier Science from Watson et al. [21] Copyright 1999 by The Combustion Institute.

flames. The divergence of the velocity field at the leading edge (the most probable velocity at the leading edge being about $1.5S_L$) and the inability of the lifted flame to stabilize in an air co-flow of more than $3S_L$ can also be argued to be consistent with triple flame-like-behavior. These studies of Muniz and Mungal (see Fig. 6) did not include scalars such as that obtained from CH- or OH-PLIF to mark the instantaneous reaction zone, though the "hot" region could be located from seeding density variation in the PIV particles. The study is important for the indirect evidence of triple flames at the leading edge of the reaction zone. This prompted a re-examination of the data of Schefer et al. [73] as well as future studies of reactive scalars for obtaining more definitive evidence of triple flame structures. Later studies by Watson et al. [20,21], shown in Figs. 7–9, emphasize the coupling of scalar measurements as well as scalars and velocity field measurements. Fig. 7 shows the interaction of the jet fluid with the leading edge of the reaction zone marked by the CH-fluorescence signature Watson et al. [81]. The correspondence between the measured CH radical profile and the OH radical profile is shown in Fig. 8, where the CH layer is found to lie on the fuel rich side of the reaction zone. This dual measurement approach is important since having both of the quantities allows for less ambiguous determination of local extinction (especially on the left of Fig. 8(a) and (c)) and the structure at the leading edge. Fig. 9 shows the dark hot zones for four instantaneous realizations of a lifted methane flame on the right with the corresponding CH zones on the left. In this case, obtaining the CH image allows the regions of intense reaction to be discerned from regions that are merely laden with hot products but devoid from reaction. Many of the studies discussed

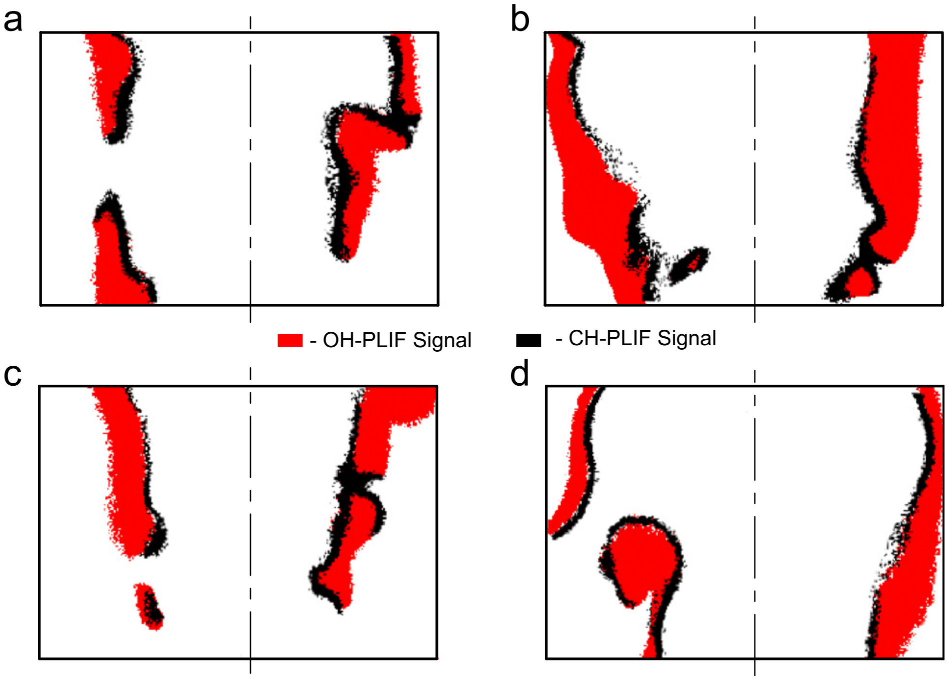


Fig. 8. An image showing the CH and OH radical fields showing the correspondence between the two flame markers. The CH marks the fuel rich side of the reaction zone while the OH marks the fuel lean side. Reprinted by permission of Elsevier Science from Watson et al. [21] Copyright 1999 by The Combustion Institute.

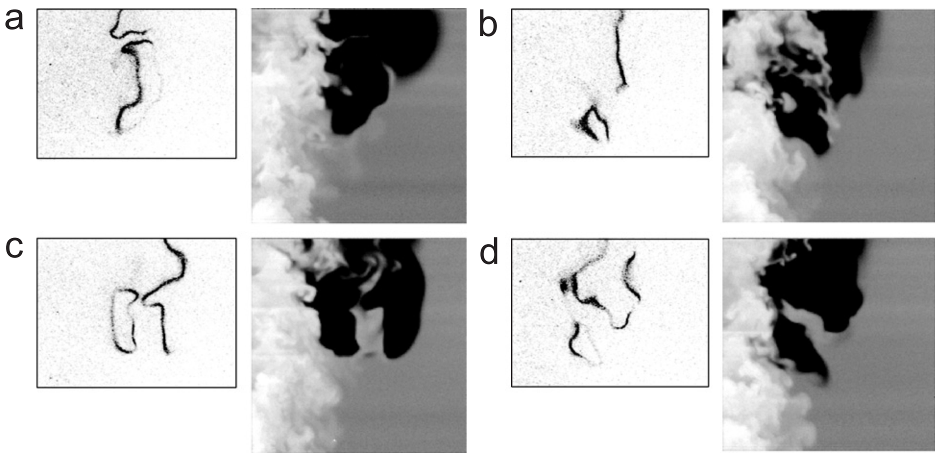


Fig. 9. Shown are four instantaneous visualizations of joint CH-PLIF and Rayleigh scattering in a turbulent lifted jet flame reaction zone at $Re = 8300$. The CH images show where reactions are occurring and the Rayleigh images show the hot zones. Reprinted by permission of Elsevier Science from Watson et al. [81] Copyright 2000 by The Combustion Institute.

subsequently apply simultaneous image measurements to mark the position of the instantaneous reaction zone and other quantities such as the relative temperature or flow dynamics.

Hasselbrink and Mungal [82] describe efforts to measure the fluid velocity in the laboratory flame, as well as the flame velocity in the same frame, to obtain the relative velocity of the flame to that of the incoming flowfield. The position of the reaction zone (at two times) is determined by shifts in the PIV particle seeding density and the fluid velocity by PIV. Some correlation between was found $V_{\text{fluid}}$ and

$V_{\text{flame}}$, however, the high uncertainty in $V_{\text{flame}}$ prohibits definitive conclusions. In addition, the simple analogy with triple flames may leave out important fluid dynamical effects like those described later, such as structures appearing in through-the-laser-sheet motion and helical structures. Watson et al. [83] report PIV data along with sequential CH-PLIF measurements to also assess flame velocities in the laboratory frame. By obtaining the flame position by CH location rather than seeding density shifts, the problems associated with uncertainties in the reaction zone position were reduced. A curious finding centers around the cases for which the stabilized lifted flame had a velocity in the laboratory frame near zero; for these cases, the axial flow velocity was found to be approximately $3S_L$ upstream of the CH leading edge over the range of $Re = 4500$–$8300$ (supporting Categories 1 and 5 theories). As with Hasselbrink and Mungal, elements of the triple flame analogies are supported by this data, but definitive conclusions are prohibited without more information on three dimensionality and true temporal evolution (see final comments).

Schefer and Goix [84] also examine the lifted flame to evaluate the veracity of the triple-flame argument for turbulent lifted jet flame stabilization. They find similar decelerations of the flow at the flame base, but also argue that this is to be expected from the expansion of stream tube dilation upstream and does not validate the triple flame argument. They also find distorted OH structures at the leading edge that bear similarity to those reported by Veynante et al. [85]. They reinforce the proposed requirement that the flame stabilizes in a premixed region (Categories 1 and 5) and the axial velocity must be low, near $S_L$, to provide a region for stabilization. They also call attention to the work of Domingo and Vervisch [86] in autoignition and discuss the suitability of these argument that ignition of incoming reactants is of prime importance. In these irregular, turbulent flowfields, the role of autoignition (locally) is still under investigation and notions of triple-layer or -deck structures, rather than the classic anchor-shaped triple-flame, have been forwarded. *Re*-ignition has also been investigated in a related study in turbulent diffusion flames by Kelman and Masri [87].

A study that results in a concept that combines many of the above categories is that of Kelman et al. [88], which builds on the notions developed by Schefer et al. [73,74] by constructing a drawing portraying their proposed entrainment/propagation/extinction at the flame leading-edge. Based on temporally resolved 2-D images of the mixture fraction, temperature and OH-PLIF obtained simultaneously, it is argued that the stabilization process of the lifted jet flame results from the scenario pictured in Fig. 10: the lifted jet flame is stabilized from a sequence of partially premixed upstream propagation (Case 1) which evolves into a diffusion flame structure (Case 2), is extinguished locally though a flame-vortex interaction from the jet structures (Case 3) and subsequently drops downstream fuel and air mix upstream to complete the cycle (Case 4), then repeating with Case 1, etc. Convincing experimental data is offered for each step of the process; however, no time sequences are available, leaving the theory unconfirmed. Constructing paradigms of the temporal behaviors of reaction zone from instantaneous image data is very difficult and this paper displays the impediments often encountered in interpreting 2-D image data. Is this sequence repeatable? Can the fraction of images found to be of a particular case (related to a "residence time") tell us about the importance of an individual mechanism? How do we differentiate transient behavior in the measurement plane from through-the-measurement-plane phenomena? Again, all are issues that can be addressed to varying degrees with the emerging experimental approaches mentioned at the end of this review.

Tacke et al. [89] performed a detailed study of hydrogen lifted flames utilizing Raman/Rayleigh/LIF. The stabilization zone was determined to be in lean mixtures (effects from differential diffusion of species and heat were ruled out as the cause), and the data were conditioned on the instantaneous stabilization point for each shot. They contend that the relative insensitivity of the stabilization point to the variation of stoichiometric mixture fraction for the fuels investigated supports theories based on large-scale turbulent structures. They also found oxygen concentrations below the ambient value in regions upstream from the lean stabilization point which supports, to a degree, the notion of upstream transport of products by large scale-structures to maintain stabilization (Category 4).

Watson et al. [90] examine the scalar dissipation field upstream from the leading edge flame to assess the suitability of notions based on Category 2 considerations. Alignment of the dissipation layers with the principal rates of strain is witnessed [91]. The values of $\chi$ measured at the flame base are below the critical values of $\chi$ resulting in extinction

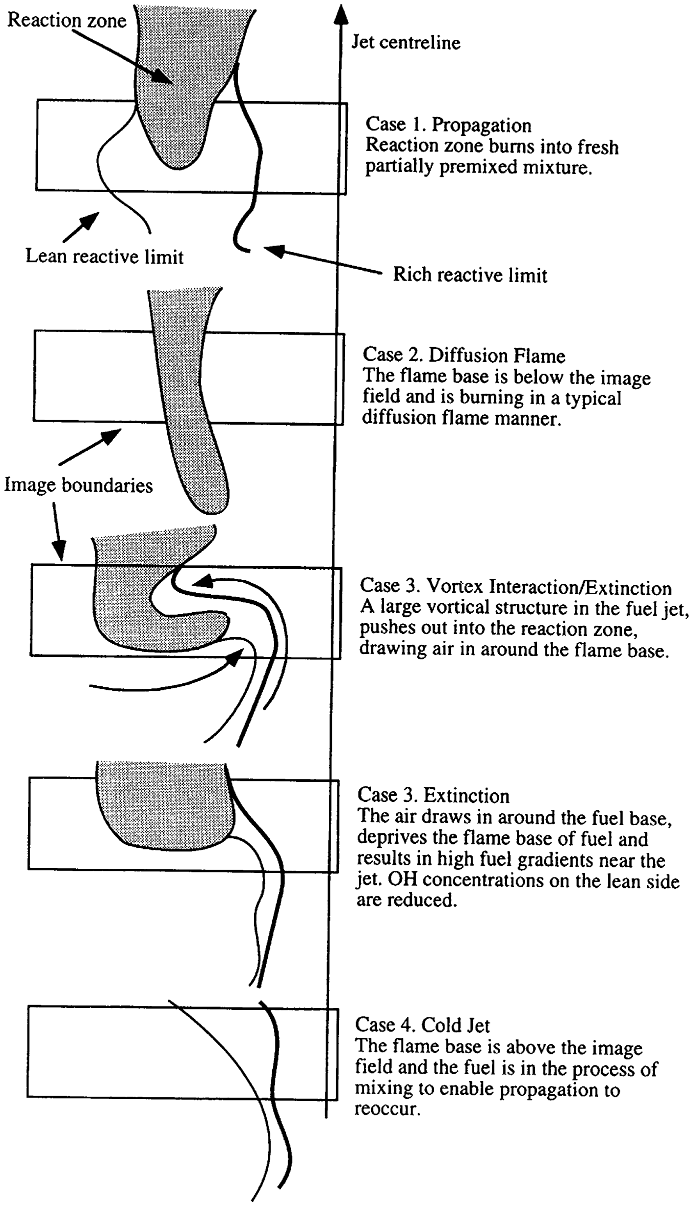
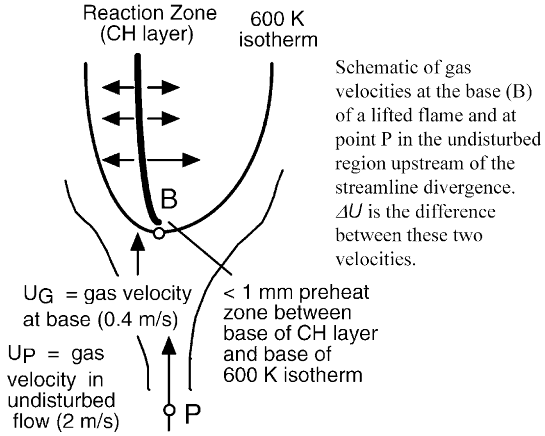


Fig. 10. An image of the proposed flame stabilization process. Copyright 1998 from Combustion Science and Technology by Kelman et al. [88]. Reproduced by Permission of Taylor and Francis Group, LLC., http://www.taylorandfrancis.com.

of counterflow flames ($\sim 10\,s^{-1}$ for methane). This is in qualitative agreement with the results of Schefer et al. [73,74] ($\chi < 8\,s^{-1}$) and Stårner et al. [92] ($\chi < 1\,s^{-1}$). However, this result is not consistent with the results of Everest et al. [93], who find values of the scalar dissipation rate high enough—by counterflow diffusion flame comparisons—to cause local extinction in a lifted propane jet. Their values of $\chi$ in the propane jet—up to $450\,s^{-1}$—are thought to be of a large enough value to even extinguish *premixed* counterflow flames [94]. The values reported in Everest et al. [93] are generally far in excess of those measured in the Watson et al. [90] study. This is one of the few recent studies, along with Feikema et al. [95] and Noda et al. [96], that still supports the principal importance of the critical scalar dissipation rate argument of Category 2. The role of mean scalar dissipation fields, and the persistence of high scalar dissipation layers for prolonged times, still needs more attention by the experimentalist.

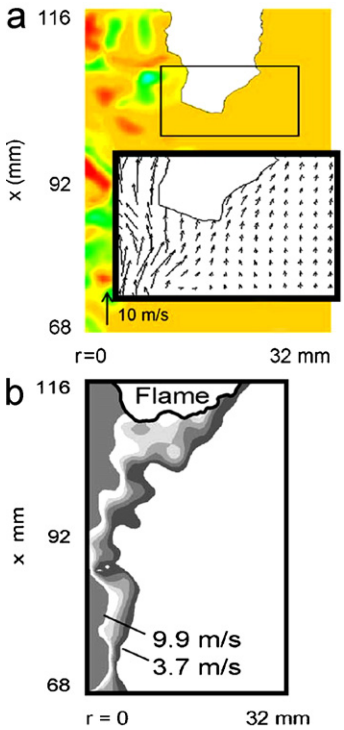
Cessou et al. [97] examine a variety of flow conditions for lifted methane jet flames. They show broadening of the OH regions as the flame conditions are varied closer to blowout. They also contend that the amplitude of liftoff height fluctuations is of the order of the local size of the large scale structures in the jet, deduced from PIV measurements as well as self-similarity laws for velocity [98]. They generally support the notions developed in Category 4 for flames near blowout, but do suggest that more measurements of fuel concentrations at the lean blowout condition may be needed to confirm more exactly the physics of the blowout condition. This is in keeping with the results of Han and Mungal [99], who discuss the sensitivity of the flame to dilution at blowout. Recent results by Kang and Kyritsis [100] on enhanced propagation velocities in lean regions of combustion in stratified layers accentuates the lean combustion issue and hold promise for this durability of this concept, especially serving as the final stabilization mechanism on the threshold of blowout [99]. These parameters controlling the blowout condition may yield information on the stabilization condition. A definite link between flame stabilization close to the jet exit [101–104] and blowout at large axial distance [105–109] is not to Han and Mungal's, or this reviewer's, understanding, in hand [110]. The correctness for of the Broadwell et al. [7] model in predicting blowout velocities has been established, but it possesses similar shortcomings to many other models in predicting liftoff height. Perhaps these notions of Broadwell, coupled with the new indications on lean premixed combustion, will allow for better determination of the conditions under which it is correct. This is likely to correspond to the situations where the lifted flame stabilizes with combustion largely across the complete jet width (where the homogenously mixed fluid is burning across the jet like that examined in [111]), as opposed to the situation where combustion is occurring outside the turbulent region, and flamelet-based theories may be more appropriate in those cases in the near field [80].

Upatnieks et al. [70,112] examined both (a) methane/nitrogen (77%/23% by volume) at $Re = 4300$ and (b) methane (100% methane) at $Re = 8500$ lifted turbulent jet flames. Related discussion is found in Eickhoff [69]. Their approach utilized a cinema PIV technique to examine the role of turbulence intensity ([60]; Category 3) and large-scale eddies (Category 4) on bulk flame propagation speed. The flame position was determined from the change in seeding density of the particulates utilized for the PIV measurement; the 600 K isotherm that outlined the bulk reaction zone was roughly identified. They found little correlation of either (a) the turbulence intensity, or (b) the passage of eddies, with flame propagation speed. Their results are results are in opposition of the notions in Kaplan et al. [113], who proposed the flame leading edge moves from vortex to vortex to stabilize. Upatnieks et al. offered that their results were consistent with the theory in Category 5, the edge flame concept. The "hot" zone (containing the region of high heat release surrounded by products) outlined by the 600 K isotherm is argued to exist in its own low axial velocity, low turbulence region that diverges streamlines at the leading edge (Figs. 11 and 12). As was seen in Fig. 4 from Boulanger et al., the streamline divergences change with jet $Re$ (liftoff height); specifically, the width increases with liftoff height. In concept, this permits the reaction zone to propagate at the laminar burning velocity locally, but be able to stabilize in a range of higher velocity streams due to the various degrees of streamline divergence the heat release in slowing the flow. Different reaction zone widths and morphologies impact the streamlines in a variety of ways. Since data on scalar fields (OH, CH, reaction rate) were not collected in this study, few meaningful conclusions can be drawn about the reaction



Schematic of gas velocities at the base (B) of a lifted flame and at point P in the undisturbed region upstream of the streamline divergence. $\Delta U$ is the difference between these two velocities.

Fig. 11. An edge-flame schematic that is proposed to explain the stabilization of lifted turbulent jet flames in jet flows up to $Re = 8500$. Reprinted by permission of Elsevier Science from Upatnieks et al. [70] Copyright 2004 by The Combustion Institute.



Divergence of velocity vectors (a) and streamlines (b) near the lifted edge flame. Re = 4300; solid line = 600K isotherm.

Fig. 12. Shown is experimental data of velocities fields diverging at the leading edge of the reaction zone. Reprinted by permission of Elsevier Science from Upatnieks et al. [70] Copyright 2004 by The Combustion Institute.

zone's detailed instantaneous structural characteristics (i.e., the intermittency of premixed branches witnesses in planar studies is not investigated) and their relation to the dynamics of flame liftoff height oscillation or reaction zone propagation. The authors [70] maintain that two propagation velocities of the edge flame are important. One is the actual burning velocity of the flame relative to the disturbed flow which is of the order of the laminar burning velocity. The second is the effective propagation velocity of the whole edge flame: it exceeds the laminar burning velocity by utilizing the streamline divergence. Maurey et al. [98] support this finding, maintaining that it is likely that the reaction zone propagates in excess of the laminar burning velocity through augmentation from heat release effects. It is thus implied that the role of turbulent fluctuations (Category 3) and large-scale structures (Category 4) are less relevant than edge flame concepts (Category 5) in explaining turbulent lifted flame stabilization, at least for low to moderate Reynolds number turbulent jets ($Re < 8500$).

The paper of Mansour [114] examines lifted partially premixed jet flames using OH-PLIF and PIV. The image data can be argued to support the triple-flame concept, since the velocity profile he reports (PIV) across the flame base (position ascertained with the OH measurement) resembles that of a laminar triple flame. Mansour [115] also reports on the mixture fraction at the stabilization point as being in a flammable region of the flowfield. The subsequent and related study by Joedicke et al. [116] argues that a definite triple flame structure exists at the leading edge of partially premixed methane jet flames in the *Re* range of 3000–8000. In Fig. 13, from Joedicke et al. [116], images of laser induced fluorescence (LIF) of $CH_2O$ and PAH as well as LIPF of OH are presented that show the scalar fields connecting at a point in a tribrachial flame shape. The point referred to as the tribrachial point is located in a fuel rich flammable region. Shown are images of the temperature field (a), and what are argued to be indicators of lean combustion (b), diffusive combustion (c) and rich premixed combustion (d). More investigations are necessary to determine the roles of the various branches presented. This is one of the few studies that reports experimental observation of all of the triple flame branches in a turbulent flowfield; the location of the tribrachial point in a flammable rich region is at odds with most other experimental studies of lifted turbulent flames. Also, most other lifted turbulent jet flame imaging studies typically do not report clear visualization of triple flame structures. Watson et al. [20,21] report intermittent lean premixed structures in turbulent lifted flames, however, results of this type are sparse and not definitive. Most imaging studies that report concrete images of tribrachial structures in jets do so solely in the laminar regime.

A more recent paper by Su et al. [117] offers a picture of the flame stabilization process utilizing elements of Categories (4) and (5). Their theory maintains that a lifted turbulent hydrocarbon flame base seeks out regions of low axial velocity that are impacted by the large-scale coherent structures in the mixing field. They examine lifted jet diffusion flames over the range of $Re = 4400$–10,700. As has been offered in the past [73,74,90], Su et al. contend that scalar dissipation rates are generally insufficient to cause flame stabilization primarily by the theory outlined in Category (2). The picture shown in Fig. 14 describes the flame base moving along the flammable region of the axisymmetric-mode

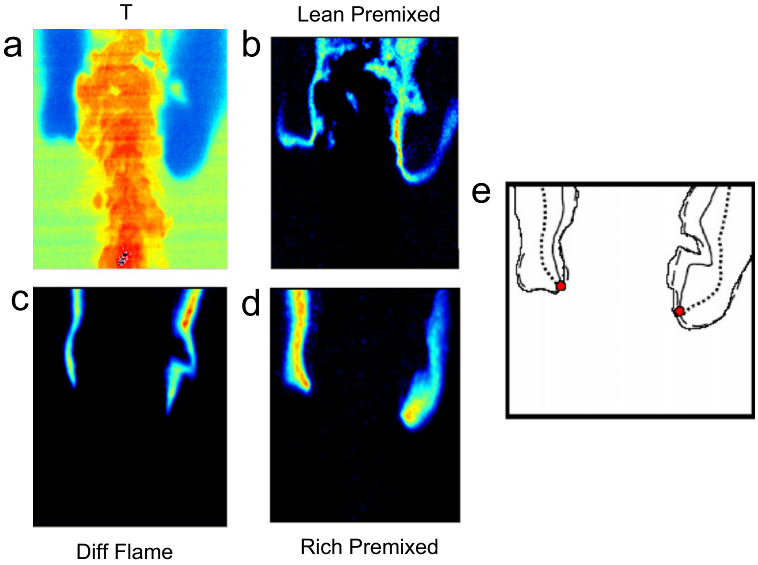


Fig. 13. Sample of (a) Rayleigh, (b) LIF of $CH_2O$, (c) LIPF of OH, and (d) LIF of PAH Images. The contours of flame boundary obtained from Rayleigh and reaction zones loci obtained from each LIF signals are shown in each image and then combined in (e) to argue. Reproduced from Fig. 3 in: Joedicke et al. [116] and used with permission.

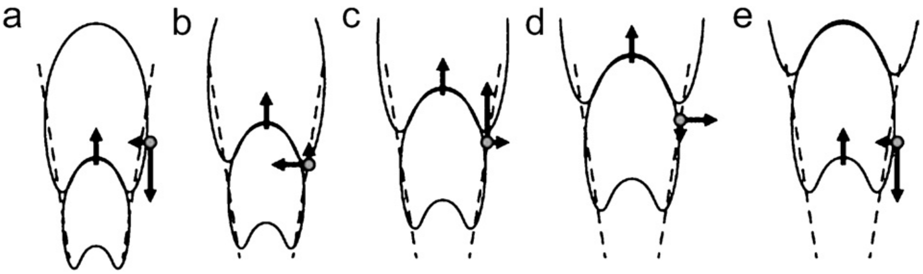


Fig. 14. A schematic from Su et al. [117] illustrating the proposed motion of the leading edge of the lifted flame reaction zone. Reprinted by permission of Elsevier Science from Su et al. Copyright 2006 by The Combustion Institute.

structure, though they argue that the picture could apply equally to the helical mode structure (see Demare and Baillot [77], Baillot and Demare [118], who have discussed the possible role of secondary instabilities, i.e. jet filaments and helical modes, in jet flame stabilization). The description essentially details the upstream motion of a flame edge initially at large radius with low axial flow speed proceeding upstream during the process; the flame is also moving radially inward along the flammable contour; moving upstream, the local axial velocity increases, eventually causing the flame to recede downstream; as the next fuel rich axisymmetric-mode structure overtakes the flame, the flame base moves downstream and radially outward, thus completing the cycle. However, as Upatnieks et al. [70] and Hammer and Roshko [119] found, there has been no definite correlation observed of the flame liftoff height oscillation with the passage of large scale structures. In addition, this theory predicts that flames stabilized at large radii would tend to propagate back upstream (down in the laboratory frame) and those stabilized at small radii generally be in the process of dropping downstream (up vertically). While no definitive set of measurements exists to test this scenario, the results of Watson et al. [83] do not observe this general trend regarding the radial position explicitly, but do agree that the scalar structures witnessed at the outer periphery of the jet merit focused consideration. This work of Su et al. [117] leaves us with the notion that the reaction zone does not actively affect the evolution of either the velocity field or scalar field upstream of the reaction zone, which can be challenged in the region immediately upstream of the instantaneous chemically reacting regions by other studies reviewed in this monograph. Also, the effect of intermittency [66] is not included. These results of Su, which focus on the dynamics of organized large-scale structures (whether axisymmetric or helical), coupled with partially premixed propagation, are in contrast with many of the other theories already presented in this review; most experimental studies do not support this focus on large-scale structures, but rather point toward the prominence of partial premixing and streamline divergence.

## 4. Final comments

This review surveys many experimental results of the past 15 years and describes the contributions of many of them. The triple flame picture of Phillips has been expanded upon greatly and laminar triple flame structures have been thoroughly investigated. Advancement in non-intrusive laser diagnostics have made planar measurement of velocity and scalar fields possible, and consequently, studies have appeared in turbulent lifted flames that reveal reaction zone structure and behavior. These results have contributed to the developments of theories regarding turbulent lifted flames both by showing what is present in leading flame edges, as well as what is absent. Notwithstanding the number of experimental studies in the past 15 years, a definitive picture of flame stabilization is not in hand, and there are inconsistencies. Most of the inconsistencies surround the following issues:

- What are the central and necessary roles of large-scale structures?
- How is upstream propagation (motion) accomplished? Ignition?
- What are the roles of local extinction in any phase of the process?
- How do turbulent velocity fluctuations impact flame stability, especially for intermediate *Re* Numbers?

In the subsequent sections, summary of the contributions to the advancement in understanding is given, followed by suggested further studies as well as concluding remarks.

### *4.1. Brief summary of advances in understanding lifted flame stabilization*

The recent work of Su et al. [117], Upatnieks et al. [70], Watson et al. [81,83,90] and Kelman et al. [88] all support the critical role of partially premixed flame propagation in turbulent lifted flame stabilization (Categories 1 and 5), although the role of large-scale structures (Category 4) differs in these various concepts. From a theoretical viewpoint, the approach to the problem by Peters [120] through the G equation, and its success in predicting flame liftoff heights using approximate turbulent burning velocities further supports the primary role of partial premixing. Little has been supported in this manuscript by scalar dissipation approaches (Category 2) and although, for example, Peters [120] explains that the notions of stabilization by flamelet extinction approaches has been superseded, work is still emerging that maintains its physical correctness [96] and hybrid approaches may still be viable [80,120]. Peters also goes on to explain that a variation of the approach of Muller et al., based entirely on partially premixed flame propagation, seems to yield very good prediction of liftoff heights and credits Vanquickenborne and Van Tiggelen, Eickhoff et al. and Kalghatgi with previous work on this concept. While the flamelet extinction approach has been largely abandoned as a dominant stabilization mechanism, studies like Kelman et al. [88] contend that extinction is important in certain phases of the lifted flame oscillation (Fig. 10), so that it is not clear that extinction should be completely overlooked in approaches accounting for transient stabilization behavior. Category 3, theories based on turbulent intensity, have been given less attention in explaining lifted jet flame stabilization, probably since its major regime of importance is at *Re* greater than those found in typical laboratory lifted flames. This is despite the interest in, and impact of, Kalgatghi's early work in this area.

### *4.2. Directions for future research*

As far as other future experiments, perhaps the reaction rate imaging approaches of Frank et al. [121], if high-quality data can be acquired in a single-shot fashion for the lifted flame situation, will yield more definitive results on the reaction zone structure. A diagnostic developed to produce experimental determination of the flame index of

Takeno at the flame leading edge [122] would also be most desirable. For a 2-D flame index, this requires measuring both fuel and oxidizer planar concentration fields with relatively high signal/noise (necessary for fuel and oxidizer spatial gradients), which is a challenging task. In addition, an approach to yield planar "movies" of scalars marking reaction zones (e.g., chemiluminescence [123], reaction-rate, CH, or even OH), simultaneous with cinema PIV results [70], would also clarify the veracity of some of the unconfirmed hypotheses discussed herein, particularly if a method to measure temperature in the plane can be added. Techniques for visualizing reaction zones in time such as those by Fajardo et al. [124] and Smith and Sick [125] may prove very useful.

Many theories support the flame stabilizing (and propagating upstream [117]) at large radii, presumably within flammability limits and arguably on the lean side of stoichiometric (see [88,89,126]). This significance of the premixed features has not been examined in enough detail in turbulent lifted flames. Just as it is discussed [16] that flame spread in general can be represented as lean-limit phenomena (flame spread over fuel pool), possibly lean regions in lifted jet flames may serve a similar role, especially with the recent results reported higher than previously presumed velocities witnesses in lean regions of combustion of stratified mixtures [100].

Perhaps "flip" experiments (where a lifted jet flame of air reacts in a co-flowing hydrocarbon environment) [109] will also be examined side by side with the hydrocarbon jet/coflowing air with the same types of diagnostics (CH, OH, reaction-rate, PIV) to better determine if the premixed branches (rich or lean) exits in all cases and are significant to the fundamental combustion theories of the problem, or possibly significant because of the low speed of the air, the large lean-premixed surface area in lifted fuel jet flame, or other related fluid mechanical causes.

Scalar dissipation rates fields, acquired in image fashion as functions of time are highly desirable to assess the impact on reaction zones of high, short lived regions of high dissipation as compared to relatively long lived regions of lower dissipation. Single shot laser imaging measurements are useful for statistical arguments, especially when acquired with other quantities such as mixture fraction, but they are not a substitute for data in time evolving format. Mixture fraction experimental data, hence scalar dissipation, in the form of "movies", is still largely unavailable.

### 4.3. Concluding remarks

The results to date seem generally point to theories based on partial premixing and edge-flames for foremost consideration. How heat release permits flames to stabilize in relative high-speed flows has also been established as being important. Explanations are at odds regarding the role of large-scale structures; while some studies see very little correlation of large scale structures with flame stabilization, others have built convincing fluid mechanical pictures of flame stabilization that involve necessary roles of large-scale structures. It seems possible that the way large-scale structures may impact the stabilization of lifted turbulent jets flames may be a result of their irrefutable presence in the typical regimes examined in the studies discussed, rather than a necessary condition. In this sense, a partially premixed type of edge-flame may be most central to successful emerging models, and the effect of large-scale structures to be present in the models may be viewed as an augmenting factor (for example, partly responsible why stable turbulent lifted methane flames can stabilize, but laminar lifted methane flames can not (and also due to the aforementioned fuel properties from Section 2)). It must be remembered that so many of these studies involve pure hydrocarbon fuels issuing into air (oxidizer environments) in configurations that possess very small stoichiometric mixture fractions, thereby lessening the interaction of the reaction zone with jet structures—than in a similar system with larger stoichiometric mixture fraction (like fuels with inert diluents). With increased turbulent structure/reaction zone interaction, the role of large-scale structures is likely to be more pronounced. How the relative importance of large-scale structures and partially premixed combustion changes with increasing Reynolds number and dilution is at present unconfirmed. Be that as it may, with the rate at which research has been reported in recent years, advances are certain to continue in the *interpretation* of reacting flow data [127–131].

## Acknowledgements

The writing of this paper has been supported in part by the US Army Research Office (Contract

W911NF0510045) and the US National Science Foundation (Grant CTS-99-09125).

## References

[1] Law CK. Combustion physics. Cambridge: Cambridge University Press; 2006.

[2] Liñán A, Williams FA. Fundamental aspects of combustion. New York: Oxford University Press; 1993.

[3] Williams FA. Combustion theory, 2nd ed. Menlo Park: Benjamin Cummings; 1985.

[4] Poinsot T, Veynante D. Theoretical and numerical combustion. Philadephia: R. T. Edward, Inc. Publishers; 2001.

[5] Pitts WM. Assessment of theories for the behavior and blowout of lifted turbulent jet diffusion flames. In: Twenty-second symposium (international) on combustion, The Combustion Institute, Pittsburgh, 1988. p. 809–16.

[6] Coats CM. Coherent structures in combustion. Progr Energy Combust Sci 1996;22:427–509.

[7] Broadwell JE, Dahm WJA, Mungal MG. Blowout of turbulent diffusion flames. In: Twentieth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1984. p. 303–10.

[8] Mizobuchi Y, Tachibana S, Shinjo J, Ogawa S, Takeno T. A numerical analysis on structure of turbulent hydrogen jet lifted flames. Proc Combust Inst 2002;29:2009–15.

[9] Mizobuchi Y, Shinjo J, Ogawa S, Takeno T. A numerical study of diffusion flame islands in a turbulent hydrogen jet lifted flames. Proc Combust Inst 2005;30:611–9.

[10] Lyons KM, Watson KA, Carter CD, Donbar JM. Upstream islands of flame in lifted-jet partially-premixed combustion. Combust Sci Tech, to be published.

[11] Bilger RW, Pope SB, Bray KNC, Driscoll JF. Paradigms in turbulent combustion research. In: Proceedings of the 30th symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2005. p. 21–42.

[12] Long MB. In: Taylor AMKP, editor. Instrumentation for flows with combustion. San Diego: Academic Press; 1993.

[13] Seitzman JM, Hanson RK. In: Taylor AMKP, editor. Instrumentation for flows with combustion. San Diego: Academic Press; 1993.

[14] Eckbreth A. Laser diagnostics for combustion temperature and species. (Cambridge, MA: Abacus Press, 1988) 2nd ed. (Gordon and Breach, 1996).

[15] Linne MA. Spectroscopic measurements. London: Academic Press/Elsevier Science Ltd.; 2002.

[16] Williams FA. Mechanisms of fire spread. In: Sixteenth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1977. p. 1281–94.

[17] Buckmaster J. Edge-flames and their stability. Combust Sci Technol 1996;115:41–68.

[18] Buckmaster J, Jackson TL. Holes in flames, flame isolas, and flame edges. Proc Combust Inst 2000;28:1957–64.

[19] Favier V, Vervisch L. Edge flames and partially premixed combustion in diffusion flame quenching. Combust Flame 2001;125:788–803.

[20] Watson KA, Lyons KM, Donbar JM, Carter CD. Observations on the leading edge in lifted flame stabilization. In: Watson KA, Lyons KM, Donbar JM, Carter CD, editors. Combust Flame 1999; 119:199–202.

[21] Watson KA, Lyons KM, Donbar JM, Carter CD. Scalar and velocity field measurements in a lifted $CH_4$-air diffusion flame. Combust Flame 1999;117:257–71.

[22] Amantini G, Frank JH, Gomez A. Experiments on standing and travelling edge flames around flame holes. Proc Combust Inst 2004;30.

[23] Phillips H. Flame in a buoyant methane layer. In: Tenth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1965. p. 1277–83.

[24] Kioni PN, Rogg B, Bray KNC, Liñán A. Flame spread in laminar mixing layers: the triple flame. Combust Flame 1993;98:276–90.

[25] Kioni PN, Bray KNC, Greenhalgh DA, Rogg B. Experimental and numerical studies of a triple flame. Combust Flame 1999;116:192–206.

[26] Dold JW. Flame propagation in a nonuniform mixture: The structure of anchored triple-flames. In: Kuhl AL, et al., editors. Eleventh international colloquium on dynamics of explosions and reactive systems. AIAA; 1988. p. 240–8.

[27] Plessing T, Terhoeven P, Peters N, Mansour MS. An experimental and numerical study of laminar triple flames. Combust Flame 1998;115:335–53.

[28] Ruetsch GR, Vervisch L, Liñán A. Effects of heat release on triple flames. Phys Fluids 1995;7:1447–54.

[29] Wichman IS. On diffusion flame attachment near cold surfaces. Combust Flame 1999;117:293–384.

[30] Wichman IS, Pavlova Z, Ramadan B, Qin G. Heat flux from a diffusion flame leading edge to and adjacent surface. Combust Flame 1999;118:651–68.

[31] Wichman IS, Ramadan B. Theory of attached and lifted diffusion flames. Phys Fluids 1998;10:3145–54.

[32] Cha MS, Chung SH. Characteristics of lifted flames in nonpremixed turbulent confined jets. In: Twenty-sixth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1996. p. 121–8.

[33] Chung SH, Lee BJ. On the characteristics of laminar lifted flames in a nonpremixed jet. Combust Flame 1991;86: 62–72.

[34] Chung SH. Stabilization, propagation and instability of tribrachial triple flames. In: Proceedings of the thirty-first symposium (international) on combustion, 2006.

[35] Kim NI, Seo JI, Oh KC, Shin HD. Lift-off characteristics of triple flame with concentration gradients. In: Thirtieth (international) on combustion. The Combustion Institute, Pittsburgh, 2005. p. 367–74.

[36] Ko YS, Chung SH. Propagation of unsteady tribrachial flames in laminar non-premixed jets. Combust Flame 1999;118:151–63.

[37] Ko YS, Chung SH, Kim GS, Kim SW. Stoichiometry at the leading edge of a tribrachial flame in laminar jets from Raman scattering technique. Combust Flame 2000;123: 430–3.

[38] Lee BJ, Kim JS, Chung SH. Effect of dilution on the liftoff of non-premixed jet flames. In: Twenty-fifth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1994. p. 1175–81.

[39] Lee BJ, Chung SH. Stabilization of lifted tribrachial flames in a laminar nonpremixed jet. Combust Flame 1997; 109:163–72.

[40] Won SH, Kim J, Hong KJ, Cha MS, Chung SH. Thirtieth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2005. p. 339–47.

[41] Qin X, Puri IK, Aggarwal SK. Characteristics of lifted triple flames stabilized in the near field of a partially premixed axisymmetric jet. Proc Combust Inst 2002;29(Part 2):1565–72.

[42] Qin X, Choi CW, Mukhopadhyay A, Puri IK, Aggarwal SK, Katta VR. Triple flame propagation and stabilization in a laminar axisymmetric jet. Combust Theory Model 2004;8:293–314.

[43] Azzoni R, Ratti S, Aggarwal SK, Puri IK. The structure of triple flames stabilized on a slot burner. Combust Flame 1999;119(1–2):23–40.

[44] Savas O, Gollahalli SR. Stability of lifted laminar round gas-jet flame. J Fluid Mechan 1986;165:297–318.

[45] Gollahalli SR, Savas O, Huang RF, Rodriguez Azara JL. Structure of attached and lifted gas jet flames in hysteresis region. In: Twenty-first symposium (international) on combustion, The Combustion Institute, Pittsburgh, 1986. p. 1463–1471.

[46] Terry SD, Lyons KM. Low reynolds number turbulent lifted flames in high co-flow. Combust Sci Technol 2005;177(11):2091–112.

[47] Scholefield DA, Garside JE. The structure and stability of diffusion flames. In: Third symposium (international) on combustion, 1949. p. 102–10.

[48] Chen RH, Kothawala A, Chaos M, Chew LP. Combust Flame 2005;141(4):469–72.

[49] Chen Y-C, Bilger RW. Stabilization mechanisms of lifted laminar flames in axisymmetric jet flows. Combust Flame 2000;122:377–99.

[50] Ghosal S, Vervisch L. Stability diagram for lift-off and blowout of a round jet laminar diffusion flame. Combust Flame 2001;124:646–55.

[51] Boulanger J, Vervisch L, Reveillon J, Ghosal S. Combust Flame 2003;134:355–68.

[52] Horlock JH. Actuator-disk theory. New York: McGraw-Hill; 1978.

[53] Wichman IS, Lakkaraju N, Ramadan B. The structure of quenched triple flames near cold walls in convective flows. Combust Sci Technol 1997;127:141–65.

[54] Buckmaster J. Edge-flames. Progr Energy Combust Sci 2002;28:435–75.

[55] Lockett RD, Boulanger B, Harding SC, Greenhalgh DA. The structure and stability of the laminar counter-flow partially premixed methane/air tripel flame. Combust Flame 1999;119:109–20.

[56] Vanquickenborne L, Van Tiggelen A. The stabilization mechanism of lifted diffusion flames. Combust Flame 1966;10:59–69.

[57] Wohl K, Kapp NM, Gazley G. The stability of open flames. In: Third symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1949. p. 3–21.

[58] Eickhoff H, Lenze B, Leuckel W. Experimental investigations on the stabilization mechanism of jet diffusion flames. In: Twentieth symposium (international) on combustion, The Combustion Institute, Pittsburgh, 1984. p. 311–318.

[59] Peters N, Williams FA. Liftoff Characteristics of turbulent jet diffusion flames. AIAA J 1983;21:423–9.

[60] Kalghatgi GT. Lift-off heights and visible lengths of vertical turbulent jet diffusion flames in still air. Combust Sci Technol 1984;41:17–29.

[61] Miake-Lye RC, Hammer JA. Lifted turbulent jet flames: a stability criterion based on the jet large-scale structure. In: Twenty-second symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1988. p. 817–824.

[62] Buckmaster JD, Weber RO. Edge flame holding. Proc Combust Inst 1996;26:1143–9.

[63] Favier V, Vervisch L. Investigating the Effects of Edge Flames in Liftoff in Non-Premixed Turbulent Combustion. In: Twenty-seventh symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1998. p. 1239–45.

[64] Lyons KM, Watson KA, Carter CD, Donbar JM. On flame holes and local extinction in lifted-jet diffusion flames. Combust Flame 2005;142:308–13.

[65] Buckmaster J, Matalon M. Anomalous Lewis number effects in tribrachial flames. Proc Combust Inst 1998;22:1527–35.

[66] Burgess CP, Lawn CJ. The premixture model of turbulent burning to describe lifted jet flames. Combust Flame 1999;119:95–108.

[67] Peters N. Local quenching due to flame stretch and non-premixed turbulent combustion. Combust Sci Technol 1983;30:1–17.

[68] Smooke MD. In: Lecture notes in physics, vol. 384. Berlin: Springer; 1991.

[69] Eickhoff H. Comment on "Liftoff on turbulent jet flames-assessment of edge flame and other concepts using cinema-PIV." In: Upatnieks A, Driscoll JF, Rasmussen CC, Ceccio SL, editors. Combust Flame 2005;142:324–5.

[70] Upatnieks A, Driscoll JF, Rasmussen CC, Ceccio SL. Liftoff on turbulent jet flames-assessment of edge flame and other concepts using cinema-PIV. Combust Flame 2004;138:259–72.

[71] Schefer RW, Namazian M, Kelly J. In: Twenty-second symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1988. p. 833.

[72] Schefer RW, Namazian M, Kelly J. CH, OH and $CH_4$ concentration measurements in a lifted turbulent-jet flame. In: Twenty-third symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1990. p. 669–76.

[73] Schefer RW, Namazian M, Filtopoulos EEJ, Kelly J. Temporal evolution of turbulence/chemistry interactions in lifted, turbulent-jet flames. In: Twenty-fifth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1994. p. 1223–31.

[74] Schefer RW, Namazian M, Kelly J. Stabilization of lifted turbulent-jet flames. Combust Flame 1994;99:75–86.

[75] Schefer RW. Three-dimensional structure of lifted, turbulent-jet flames. Combust Sci Technol 1997;125:371–94.

[76] Schefer RW. Flame sheet imaging using CH chemiluminescence. Combust Sci Technol 1997;126:255–70.

[77] Demare D, Baillot F. The role of secondary instabilities in the stabilization of a nonpremixed lifted jet flame. Phys Fluids 2001;13:2662–70.

[78] Chen TH, Goss LP. Statistical OH-zone structures of turbulent jet flames from liftoff to near-blowout. Combust Sci Technol 1991;79:311–24.

[79] Muñiz L, Mungal MG. Instantaneous flame-stabilization velocities in lifted-jet diffusion flames. Combust Flame 1997;111:16–31.

[80] Müller CM, Breitbach H, Peters N. Partially premixed turbulent flame propagation in jet flames. In: Twenty-fifth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1994. p. 1099–1106.

[81] Watson KA, Lyons KM, Donbar JM, Carter CD. Simultaneous Rayleigh Imaging and CH-PLIF measurements in lifted jet diffusion flames. Combust Flame 2000;123:252–65.

[82] Hasselbrink EF, Mungal MG. Measurement of the relative velocities of flame and fluid at the base of a lifted turbulent jet diffusion flame. Fall Meeting of the Western States Sectionof the Combustion Institute, Paper 97F-145, 1997.

[83] Watson KA, Lyons KM, Donbar JM, Carter CD. Simultaneous two-shot CH-PLIF and particle image velocimetry measurements in lifted $CH_4$-air diffusion flames. In: Twenty-ninth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2002.

[84] Schefer RW, Goix PJ. Mechanism of flame stabilization in turbulent, lifted-jet flames. Combust Flame 1998;112: 559–74.

[85] Veynante D, Vervisch L, Poinsot T, Liñán A, Ruetsch GR. Triple flame structure and diffusion flame stabilization. In: Proceedings of the Summer Program. Center for Turbulence Research, NASA Ames/Stanford University; 1994. p. 55–65.

[86] Domingo F, Vervisch L. Triple flames and partially premixed combustion in autoignition of non-premixed turbulent mixtures. In: Twenty-sixth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1996. p. 233–40.

[87] Kelman JB, Masri AR. Simultaneous Imaging of temperature and OH number density in turbulent diffusion flames. Combust Sci Technol 1997;122:1–32.

[88] Kelman JB, Eltobaji AJ, Masri AS. Laser imaging in the stabilisation region of turbulent lifted flames. Combust Sci Technol 1998;135:117–34.

[89] Tacke MM, Geyer D, Hassel EP, Janicka. A detailed investigation of the stabilization point of lifted turbulent diffusion flames. Proc Combust Inst 2000;27:1157–65.

[90] Watson KA, Lyons KM, Donbar JM, Carter CD. On scalar dissipation and partially premixed flame propagation. Combust Sci Technol 2003;175(4):649–64.

[91] Sreenivasan KR. On local isotropy of passive scalars in turbulent shear flows. Proc Roy Soc London Ser A 1991;434:165–82.

[92] Stårner SH, Bilger RW, Frank HH, Marran DF, Long MB. Mixture fraction imaging in a lifted methane jet flame. Combust Flame 1996;107:307–13.

[93] Everest DA, Feikema DA, Driscoll JF. Images of the strained flammable layer used to study the liftoff of turbulent jet flames. In: Twenty-sixth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1996. p. 129–36.

[94] Law CK. Dynamics of stretched flames. In: Twenty-second symposium (international) on combustion, The Combustion Institute, Pittsburgh, 1988. p. 1381–402.

[95] Feikema D, Everest DA, Driscoll JF. Images of the dissipation layers to quantify mixing within a turbulent jet. AIAA J 1996;34:2531–8.

[96] Noda S, Mori H, Hongo Y, Nishioka M. Nonpremixed flamelet statistics at flame base of lifted turbulent jet nonpremixed flames. JSME Int J 2005;46:75–82.

[97] Cessou A, Maurey C, Stepowski D. Parametric and statistical investigation of the behavior of a lifted flame over a turbulent free-jet structure. Combust Flame 2004;137:458–77.

[98] Maurey C, Cessou A, Lecodier B, Stepowski D. Statistical flow dynamics properties conditioned on the oscillating stabilization location of turbulent lifted flame. Proc Combust Inst 2000;28:545–51.

[99] Han D, Mungal MG. Observations on the transition from flame liftoff to flame blowout. In: Proceedings of the 28th symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2000. p. 537–43.

[100] Kang TY, Kyritsis DC. Methane flame propagation in compositionally stratified gases. Combust Sci Technol 2005;177:2191–210.

[101] Mongomery CJ, Kaplan CR, Oran ES. The effect of coflow velocity on a lifted methane-air jet diffusion flame. Proc Combust Inst 1998;27:1175–82.

[102] Takahashi F, Schmoll WJ. Lifting criteria of jet diffusion flames. In: Twenty-third symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1990. p. 677–83.

[103] Takahashi F, Schmoll WJ, Katta VR. Attachment mechanisms of diffusion flames. In: Twenty-seventh symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1998. p. 675–84.

[104] Takahashi F, Schmoll WJ, Trump DD, Goss LP. Vortex-flame interactions and extinction in turbulent jet diffusion flames. In: Twenty-sixth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1996. p. 145–52.

[105] Chao Y-C, Chang Y-L, Wu CY, Cheng TS. An experimental investigation of the blowout process of a jet flame. In: Twenty-eighth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2000. p. 335–342.

[106] Chao Y-C, Wu CY, Yuan T, Tseng CS. Stabilization process of a lifted flame tuned by acoustic excitation. Combust Sci Technol 2002;174:87–110.

[107] Chao Y-C, Wu CY, Lee K-Y, Li K-Y, Li YH, Chen R-H. Effects of dilution on blowout limits of turbulent jet flames. Combust Sci Technol 2004;176:1735–53.

[108] Dahm WJA, Dibble RW. Twenty-second symposium (international) on combustion, 1988. p. 801–8.

[109] Dahm WJA, Mayman AG. AIAA J 1990;28(7): 1157–62.

[110] Brown CD, Watson KA, Lyons KM. Studies on lifted jet flames in coflow: the stabilization mechanism in the near- and far-fields. Flow Turbul Combust 1999;62:249–73.

[111] Tieszen SR, Stamps DW, O'Hern TJ. A heuristic model of turbulent mixing applied to blowout of turbulent jet diffusion flames. Combust Flame 1996;106:442–66.

[112] Upatnieks A, Driscoll JF, Ceccio SL. Cinema PIV time histories of gas, flame, and propagation velocities at the base of lifted turbulent jet flames. Proc Combust Inst 2002;29:1897–903.

[113] Kaplan CR, Oran ES, Baek SW. In: Twenty-fifth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1994. p. 1183–91.

[114] Mansour MS. The flow field structure at the base of lifted turbulent partially premixed jet flames. Exp Thermal Fluid Sci 2004;24:771–9.

[115] Mansour MS. Stability characteristics of lifted turbulent partially premixed jet flames. Combust Flame 2003;133: 263–74.

[116] Joedicke A, Peters N, Mansour M. The stabilization mechanism and structure of turbulent hydrocarbon lifted flames. In: Proceedings of the 30th symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2005. p. 901–9.

[117] Su LK, Sun OS, Mungal MG. Experimental investigation of stabilization mechanisms in turbulent, lifted jet flames. Combust Flame 2006;144:494–512.

[118] Baillot F, Demare D. Physical mechanisms of a lifted nonpremixed flame stabilizaed in an acoustic field. Combust Sci Technol 2002;174:73–98.

[119] Hammer JA, Roshko A. Temporal behavior of lifted turbulent jet flames. Combust Sci Technol 2000;155: 75–103.

[120] Peters N. Turbulent combustion. Cambridge: Cambridge University Press; 2000.

[121] Frank JH, Kaiser SA, Long MB. Reaction-rate, mixture-fraction and temperature imaging in turbulent methane/air jet flames. In: Proceedings of the 29th symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2002. p. 2686–94.

[122] Domingo P, Vervisch L, Bray K. Partially premixed flamelets in les of nonpremixed turbulent combustion. Combust Theory Modelling 2002;6:529–51.

[123] Lyons KM, Watson KA. Visualizing diffusion flame formation in the wake of partially premixed combustion. J Energy Resour Technol Trans ASME 2001; 123:221–7.

[124] Fajardo CM, Smith JD, Sick V. Sustained simultaneous high-speed imaging of scalar and velocity fields using a single laser. Appl Phys B—Laser Optic 2006;85(1).

[125] Smith JD, Sick V. High-speed fuel tracer fluorescence and OH radical chemiluminescence imaging in a spark-ignition direct-injection engine. Appl Opt 2005;44(31):6682–91.

[126] Lyons KM, Watson KA. Partially premixed combustion in lifted turbulent jets. Combust Sci Technol 2000:97–105.

[127] Lee BJ, Cha MS, Chung SH. Characteristics of laminar lifted flames in a partially premixed jet. Combust Sci Technol 1997;127:55–70.

[128] Liepmann D, Gharib M. The role of streamwise vorticity in the near-field entrainment of round jets. J Fluid Mech 1992;245:643–68.

[129] Mansour MS, Peters N, Chen Y-C. Investigation of scalar mixing in thin reaction zones regime using a simultaneous CH-LIF/Rayleigh laser technique. In: Twenty-seventh symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1998. p. 767–73.

[130] Su LK, Han D, Mungal MG. Twenty-eighth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 2000. p. 327–34.

[131] Takahashi F, Katta VR. Unsteady extinction mechanisms of diffusion flames. In: Twenty-sixth symposium (international) on combustion. The Combustion Institute, Pittsburgh, 1996. p. 1151–60.