Experimental Investigation of the Dynamics and Blowoff Characteristics of Bluff-body Stabilized 2D, V-Shaped Turbulent Premixed Flames with Different Gaseous Hydrocarbon Fuels

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Experimental Investigation of the Dynamics and Blowoff Characteristics of Bluff-body Stabilized 2D, V-Shaped Turbulent Premixed Flames with Different Gaseous Hydrocarbon Fuels

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Experimental Investigation of the Dynamics and Blowoff Characteristics of Bluff-body Stabilized 2D, V-Shaped Turbulent Premixed Flames with Different Gaseous Hydrocarbon Fuels

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# Table of Contents

Acknowledgements........................................................................................................... iv  

Table of Contents................................................................................................................ vi  

List of Table........................................................................................................................... ix 

List of Figures.......................................................................................................................... x 

1. Introduction ......................................................................................................................... 1  
   Introduction.............................................................................................................................. 1  
   1.1 Turbulent Premixed Flame Studies ................................................................................. 3  
   1.2 Flame stabilization with bluff-body ............................................................................... 8  
   1.3 Summary ......................................................................................................................... 10  

2. Experimental Methodology................................................................................................. 12  
   2.1 Design of Burner ............................................................................................................. 12  
   2.2 Experimental Setup ....................................................................................................... 14  
   2.3 Diagnostic Techniques .................................................................................................... 16  
   2.3.1. High-Speed Chemiluminescence Imaging ............................................................... 16  
   2.3.2. Determination of blowoff equivalence ratio by CH* emission measurement ....... 16  
   2.3.3. Particle Image Velocimetry ...................................................................................... 18  
   2.3.4. Flow Field Characterization using Particle Image Velocimetry (PIV) ................. 19  

3. Study of Propane-Air Flame Behavior ................................................................................. 23
3.1 High-Speed Imaging of Propane-Air Flame chemiluminescence .................. 24
  3.1.1. Steady Burning Condition .................................................. 24
  3.1.2. Flame Evolution near Blowoff ........................................... 25
32 Flow field characterization of Propane-air flames .......................... 33

4. Study of Methane-Air Flame Behavior ................................................. 36
  4.1 High-Speed Imaging of Methane-Air Flame Chemiluminescence .......... 36
    4.1.1. Steady Burning Condition ............................................. 36
    4.1.2. Flame Evolution near blowoff ......................................... 38
42 Flow field characterization of Methane-air flames .......................... 44

5. Study of Ethylene-Air Flame Behavior ................................................. 47
  5.1 High-Speed Imaging of Ethylene-Air Flame Chemiluminescence .... 47
    5.1.1. Steady Burning Condition ............................................. 47
    5.1.2. Flame Evolution near Blowoff ......................................... 49
52 Flow field characterization of Ethylene-air flames .......................... 55

6. Asymmetric Index Calculation .......................................................... 59
  6.1 Concept of Asymmetric Index .................................................. 59
    6.1.2 Image Binarization and Flame Boundary Detection .................. 61
6.2 Asymmetric Index for Different Flames ........................................... 63
7 Effect of free stream flow turbulence on blowoff equivalence ratio for different fuel-air mixtures

7.1 Blowoff Equivalence Ratio Measurement at Different Levels of Turbulence

7.2 Effect of Ambient Temperature on Blow off Equivalence Ratio of Flames

8 Conclusions & Future Work

8.1 Summary

8.2 Scope for Future Work

References
List of Table

Table 1. Turbulence generating arrangements and air-fuel mixture flow rate corresponding to different turbulence intensities .................................................................15
List of Figures

Fig. 1.1. Schematic diagram of laminar premixed flame ................................................. 4

Fig. 1.2. Cartoon of flame /vortex interaction ................................................................. 6

Fig. 1.3. An arbitrary turbulent flow field................................................................. 8

Fig. 2.1. 2D CAD drawing of the burner and bluff-body ........................................... 13

Fig. 2.2. Schematic diagram of the experimental setup ................................................ 14

Fig. 2.3. Variation of PMT signal near blowoff ............................................................ 17

Fig. 2.4. Region of Interest of PIV measurement ......................................................... 18

Fig. 2.5. Schematics of the laser diagnostics setup ....................................................... 19

Fig. 2.6. Mean Velocity, Velocity fluctuation, and Turbulence Intensity for different turbulence intensities ................................................................. 20

Fig. 2.7. Representation of flow field at different locations of the burner exit (in the third dimension) ................................................................. 21

Fig. 2.8. Representation of the horizontal velocity component variation along the vertical direction for T.I. = (a) 4%, (b) 18% and (c) 34% cases (axial T.I. as reported before) ......................... 22
Fig. 3.1. Chemiluminescence Image of propane-air flames ($\phi = 0.85, U_m = 10 \text{ m/s}$).............25

Fig. 3.2. Cartoon representation of (a) Symmetric and (b) asymmetric flame edges..................26

Fig. 3.3. Symmetric and Asymmetric flame oscillations of propane-air flames ($U_m = 10 \text{ m/s}$)
approaching blowoff at (a) T.I. = 4%, ($\phi \sim 0.67$), (b) T.I. = 18%, ($\phi \sim 0.685$), (c) T.I. = 34%, ($\phi \sim 0.675$)..............................................................27

Fig. 3.4. Evolution of propane-air flame near blowoff ($\phi \sim 0.67, U_m = 10 \text{ m/s}, \text{T.I.} = 4%$)........29

Fig. 3.5. Side view of propane-air flame near blowoff ($\phi \sim 0.7$) .................................................30

Fig. 3.6. Evolution of propane-air flame near blowoff ($\phi \sim 0.685, U_m = 10 \text{ m/s}, \text{T.I.} = 18%$)....31

Fig. 3.7. Evolution of propane-air flame near blowoff ($\phi \sim 0.675, U_m = 10 \text{ m/s}, \text{T.I.} = 34%$)....32

Fig. 3.8. Velocity field of propane-air flame (a) $\phi = 0.85$, (b) $\phi = 0.72$, $U_m = 10 \text{ m/s}, \text{T.I.} = 4%$...34

Fig. 3.9. Vorticity field for propane-air flames at (a) $\phi = 0.85$, (b) $\phi = \phi_{bo} + 0.05$, $U_m = 10 \text{ m/s}$...35

Fig. 4.1. Chemiluminescence Image of methane-air flames ($\phi = 0.85, U_m = 10 \text{ m/s}$) .................37

Fig. 4.2. Symmetric and Asymmetric flame oscillations of methane-air flames ($U_m = 10 \text{ m/s}$)
approaching blowoff at (a) T.I. = 4%, ($\phi \sim 0.55$), (b) T.I. = 18%, ($\phi \sim 0.565$), (c) T.I. = 34%, ($\phi$
~0.55) .........................................................................................................................................39

Fig. 4.3. Evolution of methane-air flame near blowoff ($\phi \sim 0.55, U_m = 10 \text{ m/s}, \text{T.I.} = 4%$)........41

Fig. 4.4. Evolution of methane-air flame near blowoff ($\phi \sim 0.565, U_m = 10 \text{ m/s}, \text{T.I.} = 18%)$. ..42

Fig. 4.5. Evolution of methane-air flame near blowoff ($\phi \sim 0.55, U_m = 10 \text{ m/s}, \text{T.I.} = 34%)$......43

Fig. 4.6. Velocity field of methane-air flame (a) $\phi = 0.85$, (b) $\phi = 0.6$, $U_m = 10 \text{ m/s}, \text{T.I.} = 34%$).45

Fig. 4.7. Vorticity field for methane-air flames at (a) $\phi = 0.85$, (b) $\phi = \phi_{bo} + 0.05$, $U_m = 10 \text{ m/s}$....
..................................................................................................................................................46

xi
Fig. 5.1. Chemiluminescence Image of ethylene-air flames ($\phi = 0.85$, $U_m = 10$ m/s).........48

Fig. 5.2. Symmetric and Asymmetric flame oscillations of ethylene-air flames ($U_m = 10$ m/s) approaching blowoff at (a) T.I. = 4%, ($\phi \sim 0.56$), (b) T.I. = 18%, ($\phi \sim 0.575$), (c) T.I. = 34%, ($\phi \sim 0.565$)..........................................................50

Fig. 5.3. Evolution of ethylene-air flame near blowoff ($\phi \sim 0.56$, $U_m = 10$ m/s, T.I. = 4%) ......52
Fig. 5.4. Evolution of ethylene-air flame near blowoff ($\phi \sim 0.575$, $U_m = 10$ m/s, T.I. = 18%)....53
Fig. 5.5. Evolution of ethylene-air flame near blowoff ($\phi \sim 0.565$, $U_m = 10$ m/s, T.I. = 34%)....54
Fig. 5.6. Velocity field of ethylene-air flame (a) $\phi = 0.85$, (b) $\phi = 0.625$, $U_m = 10$ m/s, T.I. = 18%..........................................................56
Fig. 5.7. Vorticity field for ethylene-air flames at (a) $\phi = 0.85$, (b) $\phi = \phi_{bo} + 0.05$, $U_m = 10$ m/s, ..........................................................57

Fig. 6.1. Cartoon representation of chemiluminescence flame edge .........................60
Fig. 6.2. Binarization of flame chemiluminescence image ........................................62
Fig. 6.3. Flame Boundary overlaid onto flame chemiluminescence image ......................63
Fig. 6.4. Variation of the correlation coefficient ($r_{L,R}$) with equivalence ratio ($\phi$) for different flames at $U_m=10$ m/s. Measurements are shown for the peak flame response along vertical direction of the flame..........................................................65
Fig. 6.5. Variation of the correlation coefficient ($r_{L,R}$) with equivalence ratio ($\phi$) at (a) T.I. = 4%, (b) T.I. = 18%, and (c) T.I. = 34%, at $U_m=10$ m/s for different fuel-air mixtures .........................66
Fig. 7.1. Blowoff equivalence ratio of fuel-air mixtures at different Turbulence Intensities…68
Fig. 7.2. Arrangement of side windows at the burner exit ..............................................69
Fig. 7.3. Blowoff equivalence ratio of fuel-air mixtures at different Turbulence Intensities
Fig. 7.4. Variation of $\phi_{bo}$ with T.I. for conical and V-shaped propane-air flames ………..71

Fig. 7.5. Transition moment of propane-air flame at $\phi = 0.69$ from (a) T.I. = 4% to (b) T.I. = 34%……………………………………………………………………………………………………71

Fig. 7.6. Representation of flame holding in a disk and triangular bluff-body flame holder…72

Fig. 7.7. Variation of blowoff equivalence ratio with ambient temperature………………..74
CHAPTER ONE

1. Introduction

Introduction

‘Fire’ is unequivocally one of the greatest discoveries in human history. Anthropological evidences say that the early ancestors of ‘Homo sapiens’ had a lot of interest in this particular process of chemical reaction between aerial oxygen and fuel (essentially called fire) over thousands of years for cooking food, keeping predators away and most importantly to stay warm during the coldest periods of years. In present days, the above-mentioned chemical reaction process popularly known as ‘combustion’ finds most of its application in power generation and propulsion applications. Of different kinds of combustion processes, extensive amount of research related to turbulent premixed combustion has been conducted so far because of its widespread application in propulsion and energy devices such as spark ignition engines, aviation and land-based gas turbines etc. All these devices include a flame during the process of combustion and hence, the study of flames is one of the most important aspects of combustion research. Flames are primarily divided in two different categories, popularly known as ‘laminar’ and ‘turbulent’ flames. However, for the requirement of compact size and efficient mixing, most practical combustors include turbulent flames. For any combustor, mixing and flame stabilization is extremely important from the point of view of design. Commonly used flame stabilization methods involve bluff body stabilization, swirl stabilization or combination of both. Bluff body flame stabilization is found generally in afterburner applications such as in military aircrafts and in a few jet engines to provide an increased amount of thrust.
The early stages gas turbine development suffered from a serious problem of pollutant emission [1]. Even today, emission control especially, reduction of high thermal NO$_x$ generation is one of the most challenging aspects of combustion research. Considering today’s climatic condition and alarming increase of global warming, stricter regulations have been enforced on the acceptable levels of emission. Hence, to meet the new emission standard, engine manufacturers had to focus on innovating new combustion technologies to develop low emission gas turbines [2]. The Rich-Burn, Quick-Mix, Lean-Burn (RQL) combustor is one of such combustor technologies which came into market in 1980s [3]. Currently, Pratt and Whitney uses this technology for commercial development of their aero-engines. The other popular technology, which not only reduces the thermal NO$_x$ generation but also attains high combustion efficiency, is Lean Premixed (LP) combustion. It also helps in reducing the CO emissions from gas turbines significantly. However, the major problem associated with the development of this technology is combustion instability due to near lean-limit operation. Instabilities inside a lean premixed combustor can commonly lead to problems of flame stabilization and blowoff. Turbulence intensity inside a practical combustor is typically very high [4] and that influences those instabilities of combustor operation. Therefore, a proper and detailed understanding of lean premixed combustion is mandatory for the development of actual combustors and their healthy operations. In addition, there is an increasing demand of computational simulation of turbulent combustion to support the research as well as to address the practical design challenges of modern combustors [5-6].

The present thesis focuses on the experimental investigation of the effect of free stream turbulence
intensity (in the range of 4% to 34 %) on the dynamics and blowoff characteristics of two
dimensional, turbulent, lean premixed flames anchored by a triangular shaped flame holder placed
at the exit of a rectangular channel burner. Additionally, different gaseous fuels including methane,
ethylene and propane have been used to investigate the effect of fuel properties on the above-
mentioned phenomenon. The primary motivation of this research is to study the flame blowoff issue
by eliminating the three dimensional effects of flame-flow field interactions as found in the
previously reported studies of conical turbulent flames. This experimental study involves (1)
determination of flame blowoff equivalence ratios for different fuels and flow conditions, (2)
reactive and non-reactive time-resolved particle image velocimetry (PIV) experiments performed
in order to characterize the flow field and (3) flame structure of steady and near blowoff flames
using high-speed chemiluminescence imaging.

In the following sections, a review of experimental research on turbulent bluff-body stabilized
flames is provided followed by the various proposed mechanisms of flame blowoff based on the
literatures surveyed.

1.1 Turbulent Premixed Flames

A turbulent premixed flame is generally defined as a highly wrinkled thin flame sheet of
exothermic chemical reaction in a mixture of fuel and oxidizer that are mixed together
homogeneously at the molecular level before combustion [7, 8]. The flame is generally divided
into three different zones, (i) Preheat zone, (ii) Reaction zone and (iii) Post-flame zone. In the
preheat zone, fresh reactants are heated up and a little amount of heat is released. The reaction
zone consists of a thin, very fast-chemistry region where radical formation takes place, followed
by a wide, slow-chemical reaction zone [10]. The flame thickness is generally defined as the sum of the preheat zone thickness and reaction zone thickness. Formation of hot combustion products and NO\textsubscript{x} occur in the post-flame zone. For visual representation of those zones, a detailed structure of laminar premixed flame has been shown in Fig. 1.1.

![Schematic diagram of laminar premixed flame](image)

**Fig. 1.1. Schematic diagram of laminar premixed flame [9].**

In this context, Chaudhuri [8] mentioned a scaling analysis for different zones of premixed flames. It is important to note that the wrinkling in the reaction zone occurs due to the interaction of turbulent eddies with planar flame structure. Besides that, different instabilities such as, Landau-Darrieus instability, Rayleigh- Taylor instability and diffusion-thermal instabilities [11] also
contribute to a considerable extent in modifying the flame structure. Several questions regarding turbulent flames have been addressed so far. An important aspect of turbulent flame study is to detect the flame edge or flame front (for some cases) and the reaction zone thickness. Different experimental and computational methods were employed in past to determine the location of flames. In the past, Sweeney and Hochgreb [12] determined the flame front based on OH planar laser-induced fluorescence (PLIF) imaging technique. Hartung et al. [13] considered the OH-PLIF images together with Stereo particle image velocimetry (PIV) to locate the position of the flame front. The reaction zone thickness was defined to be the width of the overlap layer of OH and formaldehyde (CH$_2$O) by most of the previous studies [14-18]. However, in context of the present study, our motivation was to understand the behavior of flame structures and their time evolutions during blowoff for different levels of turbulence. Hence, the major findings and the results are based on high-speed imaging of flame chemiluminescence.

The effect of turbulence on premixed turbulent flames has been of interest for the past few decades. Both experimental and computational studies were conducted to investigate the flame-turbulence interactions. The fundamental concept behind that is when vortex structures interact with the flame, it modifies the flame front and induces some degree of wrinkling depending upon the strength of the vortices. From the practical point of view, vortex interaction largely dominates the rate of reaction and the combustion instability. However, in some cases, it also helps in flame stabilization by means of mixing enhancement. A detailed review of how vortex interaction plays vital role in modifying flame structures and related chemistry has been reported by Renard et al. [19]. To have a better understanding of this phenomenon, a schematic representation [19] of flame-vortex interaction is shown in Fig. 1.2. In this figure it is seen that the flame is anchored
by a bluff-body flame holder (as seen from the end view) and two vortex generating arrangement were placed on both sides of the flame. The effect of vortex interaction with flame is clearly observed from the figure by looking at the wrinkled left flame edge in comparison to the unwrinkled right edge.

For the purpose of experimental investigation, different flame geometries such as V-shaped flames, Bunsen flame, counterflow flames and propagating flame kernels have been considered previously [20].

However, most of the previous studies involving turbulent flames were limited to low or moderate levels of turbulence (~ 14%). A few experiments conducted before 2009 considered turbulent Reynolds Number of incoming flow up to 2000 [21, 22]. In this context, the turbulent

Fig. 1.2. Cartoon of flame/vortex interaction [19].
Reynolds Number is defined as \( (\text{Re}_t) = (u'l / \nu_0) \) where, \( u' \) is the turbulent velocity fluctuation magnitude, \( l \) is the turbulence integral length scale and \( \nu_0 \) is the kinematic viscosity of the unburnt reactant. However, recently premixed jet flames with very high free stream flow turbulence up to 46% and turbulent Reynolds Number up to 100,000 has been studied by Driscoll and his coworkers [23–25]. Their investigation shows that the preheat zone widens under the influence of high level of turbulence intensity. However, their experiments employed a large pilot flame enabling flame stabilization in extremely turbulent flows. These apart, significant contributions were made by Nair and Lieuwen [26, 27], Chaudhuri et al. [28, 29] to understand the lean blowoff mechanism in bluff-body stabilized turbulent premixed flames. Very recently, Chowdhury and Cetegen [30, 31] investigated the effect of free stream turbulence (in the range of 4% to 34%) on flame structure and lean blowoff characteristics of disk-shaped bluff-body stabilized turbulent premixed conical flames. Their work has shown that, the stability of flame degrades with increase of turbulence intensities. They also reported changes in the flame shape from conical to columnar as flame blowoff was approached. In some other studies, ‘V-shaped’ turbulent flames were investigated. Results from the experiments of Kheirkhah and Gülder [32, 33], Goix et al. [34] showed that a weakly wrinkled flame front is developed for low turbulence intensity (~ 4-6 %). However, strong wrinkling, mushroom shaped-structures, localized quenching and pockets of reactants have been reported [33] for higher turbulence intensities (~ 17 %).

In context of the present study, turbulent flow field is characterized by the classical Reynolds decomposition. The mathematical definition of turbulence intensity is obtained from the Reynolds Decomposition [35] of the instantaneous flow velocity is represented by:
\[ U(x, t) = U_m(x) + u'(x, t) \] (1.1)

Assuming the bulk flow is in x direction, \( u'(x, t) \) is defined as the velocity fluctuating component, \( U_m(x) \) is time averaged velocity component. A schematic representation of turbulent velocity profile with respect to time has been shown in Fig. 1.3. Turbulence intensity is defined as the ratio of fluctuating velocity component and the mean flow velocity, such that,

\[
\text{Turbulent Intensity (T.I.)} = \frac{U(x,t) - U_m(x)}{U_m(x)} \times 100 = \left( \frac{u'(x,t)}{U_m(x)} \times 100 \right) \%
\] (1.2)

![Turbulent Velocity Profile](image)

**Fig. 1.3.** An arbitrary turbulent flow field [36].

### 12 Flame stabilization using bluff-body

This section provides a brief summary of the flame stabilization mechanisms using bluff-body flame holders. Efficiency of real engineering devices in power generation and propulsion applications depends heavily upon the stability of flames and hence the study of flame stabilization is very important from practical point of view. The mechanism of bluff-body flame stabilization involves combination of fluid mechanics, aerodynamics of bluff-bodies and combustion chemistry.
along with reacting flow dynamics. The major application of such flame stabilization process is in industrial furnaces and aircraft afterburners. The non-reacting counterpart of such mechanism relies on the fundamental concept of creating a recirculation zone behind the bluff-body. Several experimental and computational researches have been carried out to understand the fluid mechanics of bluff bodies and their vortex shedding patterns at different regimes of Reynolds Numbers [37, 38]. In the context of flame holding, the strength of recirculation zone plays a vital role in anchoring the flame at the bluff-body. The low velocity recirculation zone created by the sudden flow divergence contains hot products of combustion and is bounded by shear layer where continuous ignition of fresh mixture takes place [39]. In pioneering works by Zukoski and Marble [40–41], Zukoski [42], Williams et al. [43], and Longwell [44] the effect of different bluff-body geometries on flame holding in a uniform mixture of premixed gases is reported. Other works by Plee and Mellor [45], Rao and Lefebvre [46], Rizk and Lefebvre [47] considered the issue of lean blowoff limits for different combustible mixtures, variable temperature and pressure and blockage ratio effects. Besides that, some other studies by Yamaguchi et al. [48], Pan et al. [49] reported the extinction behaviors of flames based upon flamelet theory. Shanbhogue et al., tried to establish a correlation between flame blowoff data reported in different studies by using different extinction parameters such as stretch rate and time scales [50].

Experimental studies were conducted by Kiel et al. [51] and other previously mentioned studies [26-31] in order to understand the modification in flame structure during lean flame blowoff. Notably the findings from those studies show that localized extinctions along the shear layer due to excessively high strain rates occurs as the flame front moves into the high vorticity region close to blowoff. Valuable observation of flame recession into recirculation zone was made before the event of global extinction. They found that the global blowoff is executed when the shear layer
becomes completely incapable of sustaining ignition. Ballal and Lefebvre [52] focused on
developing correlations for predicting the blowoff equivalence for lean, premixed flames by
considering the effect of free stream turbulence. Huelskamp et al. [53] at Air Force Research
Laboratory conducted several relevant experiments by using different gaseous fuels. Although
several experimental and computational efforts were taken, the understanding of blowoff in bluff-
body stabilized flames especially under high free stream flow turbulence is still limited and
requires further investigation.

13 Summary

Design and efficient operation of practical combustors rely primarily on flame stabilization.
Flame holding in any combustion device is the most critical challenge because of the existence
of high incoming flow velocity and turbulence intensities that may lead to flame instabilities
and blowoff. It is clear from previous studies that the free stream flow turbulence has definitive
effect on modifying the flame structure. Most of the studies reported so far are limited to low
turbulence intensity. Some previous works involving moderate or high free stream turbulence
were conducted in axisymmetric geometries and influenced by the three-dimensional effects.
In this study, it is desired to study the problem in a two dimensional flow configuration.
Therefore, the primary motivation of the current research is to investigate the mechanism of
blowoff in a two-dimensional flame at different levels of flow turbulence ranging from 4 to
34%. Experiments included particle image velocimetry (PIV) of non-reacting and reacting
flow fields, high-speed imaging of flame chemiluminescence and determination of flame
blowoff equivalence ratios in order to characterize the overall flame/flow field interactions. In
addition to the experiments, codes were developed for data analysis and image processing as will be presented in the following chapters.
CHAPTER TWO

2. Experimental Methodology

This chapter describes the design of the experimental burner, different experiments employed during this research and the schematics of the experimental setup in detail.

2.1 Design of the Burner

The primary motivation of the current research was to study two-dimensional premixed turbulent flames anchored by a triangular shaped bluff-body. For this purpose, a burner with rectangular exit dimensions of 35 x 42 mm was designed and manufactured in the workshop of Mechanical Engineering department at the University of Connecticut. A triangular shaped bluff-body flame holder with a width of 5mm and a length of 21mm was placed at the exit of the burner along its long dimension. Figure 2.1 represents a 2D CAD drawing of the experimental burner and the bluff-body. The top view of the test burner (Fig. 2.1a) shows the centrally located bluff-body having width of 5mm. As seen, the burner exit includes a corner radius of 5.08mm (0.2 inch) due to the tooling available for the purpose of manufacturing. The front and cross-sectional views of the burner is displayed in Fig. 2.1b. The topmost part of burner having a height of 38 mm is made out of 304 grade stainless steel. The middle part (25 mm) is of aluminum (6061 grade) and the convergent bottom section is a 3D printed plastic part. A contraction ratio of 5.7:1 (inlet: exit cross section) was used for the bottom part based upon two criteria: (a) allowing the fuel-air mixtures to flow through that section without wall separation, and (b) optimizing the overall height of the burner for the compactness of the design.

Figure 2.1(c) shows the cross sectional view of the stainless steel bluff-body flame holder. The
angle between two sides of the bluff-body is approximately 13.6 degree. This angle was selected by carrying out different experimental trials until the flame was perfectly anchored in the plane of bluff-body.

Fig. 2.1. 2D CAD drawing of (a-b) the burner and (c) bluff-body.

The aluminum section contains four jet holes (two on each side) of 3.175mm (1/8 inch) diameter in order to create high shear opposed coplanar fuel-air mixture jets to increase the turbulence intensity. The two jet holes on each side (of the aluminum section) are offset from opposing side jets in order to generate high turbulence. A fine mesh screen of 1mm opening was placed at the
interface of aluminum and stainless steel sections downstream of the jet location to break large scale eddies and generate more uniform turbulent velocity profiles at the burner exit.

2.2 Experimental Setup

Figure 2.2 shows the schematic layout of the experimental setup. A twin-screw air compressor (Gardner-Denver, Model ECHQHE) with a maximum mass flow rate capacity of 0.1 kg/s was used to supply the main airflow in the burner. The compressor discharge air was dried by a refrigeration dryer (Hankinson Model 80,200) at first and then metered by a bank of critical flow orifices. Instrument-grade propane (99.5% pure) and chemically pure grades of methane and ethylene (supplied by CT Airgas) were metered using a set of mass flow controllers (Porter Instruments, Model 202).

Fig. 2.2. Schematic diagram of the experimental setup.

Mass flow controllers were interfaced to a DAQ board (NI Model PCI-MIO-16E-1) and the data acquisition computer. Premixing of fuel with air was done at a straight pipe section downstream
of the air inlet tube containing a series of baffles and perforated plates. The fuel-air mixture first passed through a straight rectangular channel of cross section dimensions of 70 x 120 mm and then entered the rectangular burner. In some of the experiments, two detachable, protected aluminum coated 4-6λ mirrors (Edmund optics, 40-040) were placed at an angle of 45 degree to the centerline of the bluff body for capturing the side view of the flame chemiluminescence. Different levels of free stream turbulence intensities in the range of 4% to 34% were generated in the incoming fuel–air mixture by combination of perforated plate (P.P-1) and four side jets opposing each other. The jets used the exact same mixture to maintain the homogeneity of the final mixture at the exit of the burner. The fuel-air mixtures were drawn 150 mm downstream of the premixing section by means of oil-less vacuum pump having a maximum capacity of 110 LPM and delivered to the jets through an air flow meter (which was used to verify the flow rate of air-fuel mixtures). Different flow rates of mixtures were bypassed (mentioned in Table 1) through jets in order to produce different turbulence intensities.

**Table 1. Turbulence generating arrangements and air-fuel mixture flow rate corresponding to different turbulence intensities.**

<table>
<thead>
<tr>
<th>Turbulence Intensity (%)</th>
<th>Turbulence Generating Arrangements</th>
<th>Flow Rate (LPM) of Air-Fuel Mixtures Bypassed Through Four Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 ± 0.2 %</td>
<td>Perforated plate (P.P-1)</td>
<td>0</td>
</tr>
<tr>
<td>18 ± 0.5 %</td>
<td>Perforated plate (P.P-1) + four side jets</td>
<td>45 ± 2</td>
</tr>
<tr>
<td>34 ± 1 %</td>
<td>Perforated plate (P.P-1) + four side jets</td>
<td>85 ± 5</td>
</tr>
</tbody>
</table>
The uncertainties in flowrates and turbulence intensities (mentioned in the table) are determined purely based upon several experimental trials performed for each turbulence intensity.

### 2.3 Diagnostic Techniques

#### 2.3.1 High-Speed Chemiluminescence Imaging

High-speed chemiluminescence is very helpful in obtaining the time resolved information for turbulent reacting flows. During this research, flame dynamics was mainly studied by high–speed imaging of the broadband flame chemiluminescence recorded at 4000 frames per second without employing any spectral filtering to register good images at high speed for weakly radiating flames at lean equivalence ratios. This allowed good signal-to-noise ratio in the acquired recordings. A CCD camera (Photron Fastcam SA5) fitted with a 35 mm, f/1.4 Nikkor lens was used for this particular purpose. In a previous study of conical flame conducted in our laboratory by Chowdhury [58], there were no significant differences observed in the chemiluminescence signal when a CH* bandpass filter centered at 430nm +/-10nm was used for imaging. This suggests that the chemiluminescence acquired without spectral filter was mostly from CH*. The camera was focused in the mid plane normal to the long dimension of the burner outlet.

#### 2.3.2 Determination of blowoff equivalence ratio by CH* emission measurement

Condition for flame blowoff was approached by gradual reduction of the equivalence ratio (φ) by ramping down the fuel flow rate. A LabView software based interface was employed in order to control the fuel injection and ramp down process through fuel mass flow controller. Chemiluminescence signals from CH* emission were collected in photomultiplier-tube (PMT)
Ealing Electro Optics, Model S20 UV) configured with a narrow pass filter at $\lambda = 430 \pm 10$ nm in order to determine the blowoff equivalence ratio. A 20 mm field of view downstream of the bluff-body plane and a sampling frequency of 50 kHz were maintained for the PMT measurements. The fuel mass flow rate corresponding to an abrupt drop in PMT signal due to flame blowing off from the flame holder while ramping down fuel flow rate was recorded and used to calculate the blowoff equivalence ratio. The abrupt drop in PMT signal near the point of blowoff due to sudden decrease of CH* emission from the flame is shown in Fig. 2.3. In order to identify the flame blowoff point accurately, it is important to characterize the time response of the mass flow controller and the convective time delay of the flow from the flow controller to the burner exit. It was found that a fuel flow ramp down rate corresponding to equivalence ratio $d\phi/dt = 0.001/s$ produced consistent results. This value was established by experimenting with different fuel flow rate ramp down rates and also backed up by convective time delay calculations and mass flow controller response time specifications.

Fig. 2.3. Variation of PMT signal near blowoff [8].
2.3.3 Particle Image Velocimetry

To characterize the flow field Particle Image Velocimetry (PIV) measurements were performed at 10 Hz. A PIV system consisting of a dual-cavity 50 mJ/pulse Nd:YAG laser (New Wave Solo PIV III) along with a frame-straddling 1024 x 1280 CCD camera (Flow Master 3S) were employed for this purpose. Alumina particles of ~1µm diameter were used as flow seeding particles. The PIV camera was equipped with a Nikon 200-mm focal length lens fitted with a 532 +/- 1 nm bandpass filter (Andover 532FS02-50). The time between laser pulses was set based on the mean flow velocity, which ensured that the particles in the flow traveled roughly one-quarter width of the final interrogation window. The Mie scattering images were processed by using the LaVision DaVis 7.2 software package. Multi-pass cross correlation algorithm was used to start with an initial interrogation window size of 128 x 128 pixels and finally reducing to an interrogation window size of 16 x 16 pixels with 50% overlap. The final spacing between the velocity vectors was 0.296 mm. Different number of images such as 200, 400, 500 and 1000 were sampled to determine the flow field accurately. Number of images less than 500 produced improper velocity and turbulence profiles and images more than 500 in number did not exhibit any remarkable difference. Hence, a set of 500 images were sampled. A 35x15 mm region of interest (Fig. 2.4) was maintained in the mid-plane (of the 42mm dimension) of the burner exit.

![Fig. 2.4. Region of Interest of PIV measurement.](image)
The schematics of the laser diagnostics arrangement for PIV along with the high-speed camera setup is presented in Fig. 2.5. A pair of converging and diverging lenses was used for making the laser sheet at the above-mentioned region of interest.

![Schematics of the laser diagnostics setup](image)

**Fig. 2.5. Schematics of the laser diagnostics setup.**

### 2.3.4 Flow Field Characterization using Particle Image Velocimetry (PIV)

The burner exit flow field was first characterized by performing non-reacting PIV measurements. All the experiments were performed at an average exit velocity ($U_m$) of 10 m/s. This corresponds to a global flow Reynolds number of 6640, which is calculated based upon the width of the bluff-body at STP conditions. Turbulence generating method was varied for each turbulence level such that turbulence intensities of 4%, 18% and 34% were obtained.

Figure 2.6 represents the variation of average velocity ($U_m$), the root mean square RMS velocity fluctuation and turbulence intensity (T.I.) (in different color-coding) across the span (35mm) of the burner exit for all cases. The velocity $U_m$ is in the axial direction of the burner (vertically upward).
Fig. 2.6. Mean velocity, Velocity fluctuation and Turbulence intensity for (a) T.I. = 4%, (b) T.I. = 18% and (c) T.I. = 34%.

It is observed that the average velocity profile is reasonably uniform in the free stream for all cases, but dips down in the wake of the bluff-body as expected. The velocity approaches zero near the burner walls and at the edges of the bluff-body as expected. The RMS fluctuating velocity component is also found to be uniform across the burner exit. T.I. profile for the case
of 34% flow turbulence (Fig. 2.6c) becomes a bit noisy at the highest level of turbulence. Evidently, the turbulence intensity is apparently uniform throughout the span of the burner exit; however, it increases near the walls of the burner and the bluff-body edges due to abrupt fall in average velocity ($U_m$) at those locations, as seen in Fig. 2.6.

Additionally, the two dimensionality of the flow field was verified by from one particular case of T.I. = 4%. The flow field has been characterized at the burner mid plane ($z = 0$) and 15mm away from that mid plane on both side as represented in Fig. 2.7. It is observed that the flow profiles at different locations are very close to each other and hence, it can be concluded that the flow field is nearly two dimensional in nature.

![Fig. 2.7. Representation of flow field at different locations of the burner exit (in the third dimension).](image)

In addition to measurement of flow fields across the span of burner exit (35 mm) at a specific $y$ location (= 2mm) from the bluff-body plane, efforts are taken to calculate the variation of horizontal velocity component (in the outward direction from the centerline of the flame) along
the vertical direction (from the same PIV data). This specific information provides an approximate idea about the flame propagation in the outward (from centerline) direction. Figure 2.8 represents this particular velocity variation for the cases corresponding to T.I. = 4 (Fig. 2.8a), 18 (Fig. 2.8b) and 34% (Fig. 2.8c) in the axial direction. The magnitude of velocity fluctuation component ($v'$) along this direction (vertical) is found to be significantly lower and hence, it is not plotted simultaneously in order to maintain a proper and visually appealing axis spacing. It is observed that the overall magnitude of $V_m$ increases with increasing T.I. (in the axial direction).

Fig. 2.8. Representation of the horizontal velocity component variation along the vertical direction for T.I. = (a) 4%, (b) 18% and (c) 34% cases (axial T.I. as reported before).
CHAPTER THREE

3. Study of Propane-Air Flame Behavior

The flame dynamics was mainly studied by high-speed imaging of flame chemiluminescence recorded at 4000 frames per second without using any spectral filter. The motivation of this particular experiment was to understand the flame behavior in large scale and observe the flame evolution during blowoff. Hence, no spectral filtering was needed for this purpose. The camera was focused in the mid plane corresponding to the long dimension of the burner outlet. While the flame being nominally two-dimensional in nature, the left and right side views of the flame were also simultaneously recorded to observe the view in the third dimension to judge the two dimensionality as well as the deviations from it as flame approaches blowoff. This was made possible by installing two protected aluminum coated glass mirrors mounted at an angle of 45 degree to the centerline of the bluff body, which provided undistorted reflections of the flame side views. The later part of this chapter (3.1 & 3.2) will include the detailed discussion of flame behavior during steadily burning condition (equivalence ratio, \( \phi = 0.85 \)) and conditions near blowoff for propane-air mixtures at different levels of free stream flow turbulence at an averaged velocity \( (U_m) \) of 10 m/s. It is worth mentioning that the blowoff point is determined by collecting the CH* emission signal in the photomultiplier tube configured to view a 20 mm field downstream of the bluff-body plane. The blowoff point is captured by simultaneously performing the high-speed imaging and the CH* emission collection in the photomultiplier tube.
3.1 High-Speed Imaging of Propane-Air Flame Chemiluminescence

3.1.1 Steady Burning Condition

In this section, a brief discussion regarding the flame structure of robustly burning propane-air flames (\(\phi = 0.85\)) are presented with illustrative images.

Figure 3.1 represents the instantaneous flame chemiluminescence images for different turbulence intensities. The colorbar represents the intensity of light emitted from the flames. It is visible that two luminous reacting shear layers bound a ‘dome-shaped’ non-luminous recirculation zone (blue colored) from both sides of all the V-flames presented (highlighted in red rectangle). This is because the consumption and continuous ignition of incoming mixture occurs along the reactive shear layers and the recirculation zone is supplied with non-luminous hot products of combustion. It is evident that the included ‘V’ angle of flame continuously increases with flow turbulence intensity because of the gradually increasing turbulent flame speed. As the turbulence intensity increases, the flame looks more and more violent with increasing audible noise as perceived during the experiment. Hence, it is obvious that the free-steam flow turbulence intensity influences the modification of flame structure, as observed.

The reacting shear layers on both sides of the flames are approximately of similar brightness and as observed, the flames are quite symmetric about the centerline. Relatively continuous and unperturbed flame surfaces are also seen from the side views of the flames. However, more distorted flame surfaces are observed as the turbulence intensity is gradually increased.
3.1.2 Flame Evolution near Blowoff

Propane-air flames close to the blowoff condition were examined using chemiluminescence imaging. It was generally observed that the propane-air flame blows off at equivalence ratios of 0.67, 0.685 and 0.675 with an uncertainty of 0.005 corresponding to turbulence intensities of 4%, 18% and 34% respectively. The uncertainty was determined by experimental trials. These result are reported for an ambient temperature of 35°C. However, the
magnitude of the blowoff equivalence ratio was found to change with inlet air temperature as observed during experiments (Explained in Chapter 7). For imaging near flame blowoff, flame equivalence ratio ($\phi$) ratio is reduced gradually (from $\phi = 0.85$) by ramping down the fuel flowrate through the mass-flow controller, automated by computerized codes developed in ‘Labview’ platform. The final moments of flame blowoff were captured by using the ‘end trigger’ option in the high speed camera system corresponding to a sudden abrupt drop in the PMT signal amplitude.

As the flame equivalence ratio is ramped down, the flame structure gradually changes from symmetric to asymmetric structure. Figure 3.2 is a cartoon representation of symmetric and asymmetric flame structure. It is well understood from Fig. 3.2a that the flame edges in a symmetric flame structure are mirror image of each other, however, this is not true for an asymmetric flame structure where the edges are not mirror image of each other.

![Fig. 3.2. Cartoon representation of (a) Symmetric and (b) asymmetric flame edges.](image)

In Fig. 3.3 (a-c) symmetric and asymmetric flame undulations close to the blowoff point of a propane-air flame at different levels of flow turbulences are represented. Fig. 3.3a shows a symmetrical flame oscillations (varicose mode) up to 575ms prior to the blowoff event. The
symmetric (with respect to the centerline) appearance of the flame is reflected in the side views, which show propagation (upward) of flame rolls on both sides of the flame surface that are coincident with the vertical structures in the end view. At around 370ms before blowoff, flame structure is observed to be partially asymmetric (near the bluff-body plane). The degree of structural asymmetry increases in the next image at 170ms prior to blowoff. Hence, it is understood that the flame is undergoing a gradual transition from symmetric to asymmetric structure. Similar findings were also made in previous studies [26, 48 and 49].

**Fig. 3.3.** Symmetric and Asymmetric flame oscillations of propane-air flames ($U_m = 10$ m/s) approaching blowoff at (a) T.I. = 4%, ($\phi \sim 0.67$), (b) T.I. = 18%, ($\phi \sim 0.685$), (c) T.I. = 34%, ($\phi \sim 0.675$).

In Fig. 3.3b, it is observed that the flame possesses an asymmetric top and nearly symmetric bottom.
structure at 575ms before blowoff occurs. The divergence of top part of the flame is even more prominent at 370ms prior to blowoff. At 170ms prior to blowoff the flame structures is clearly observed to be asymmetric. From Fig 3.3c, it is evident that the flame possesses an asymmetric structure already at 575ms before blowoff. A ‘snake-like’ flame structure is also evident near the exit of the burner. As the flame equivalence ratio is further reduced, the existence of asymmetric flame structure becomes increasingly prominent at 370ms and 170ms before blowoff. Hence, it is observed that the surface of the flame becomes gradually more distorted with higher levels of flow turbulence signifying that the two dimensional nature of flame is decreased at high turbulence intensities.

Fig. 3.4 represents the final moments of propane-air flame at a turbulence intensity of 4% before undergoing a global blowoff event. As observed, the flame structure is predominantly asymmetric. However, flame chemiluminescence study is limited by the line-of-sight integration effect; an effort has been made to visualize the blowoff event based upon the criteria of very low or no chemiluminescence signal captured by the camera. Additionally, the dark patches (along the flame surface) observed in the side mirrors helped in supporting the proposition of blowoff being first initiated at the two edges of the flame holder in the third dimension. The general idea of flame blowoff is recognized as the mismatch between incoming mixture-flow velocity (which is greater) and the flame burning velocity. However, it is important to know the particular mechanism of blowoff for this particular experimental configuration. In the first image of Fig. 3.4 (24ms), very faint reacting shear layers with localized extinction (observed as non-luminous regions as seen in the mirrors) are observed on both sides of the flame, very close to the burner exit. However, strong chemiluminescence signal is seen in the upper part of the flame which confirms a reacting shear layers still exist downstream of that non-luminous part of the shear layer. In the next image (22ms),
almost no reacting shear layer is found up to a height of 25 mm downstream of the bluff-body (highlighted in yellow rectangle). Evidently, the weakly reacting shear layer close to the burner exit extinguished and the flame is lifted from the plane of bluff-body.

Fig. 3.4. Evolution of propane-air flame near blowoff (ϕ ~ 0.67, $U_m = 10$ m/s, T.I. = 4%)

The small flame ripples (at $y \sim 25$ mm) created in the image 24ms prior to blowoff has propagated to a downstream location of $y \sim 60$ mm in the next image and evolved into a relatively wider structure. A little trace of weak chemiluminescence signal at the region of $y \sim 25$ mm is seen 20ms before extinction and the overall flame is lifted off from the flame holder and gradually proceeds
towards global extinction state as seen in images 14 – 0ms before blowoff. Interestingly, a gradual thinning effect of flame surface is observed in the side views as the flame approaches blowoff. Hence, it can be concluded that the flame starts to extinguish from the both ends of the bluff-body (in the span wise direction) before it extinguishes in the central zone making a ‘U-shaped’ lifted flame base prior to global blowoff event. This particular observation of U-shaped flame base is supported by another flame imaging (Fig. 3.5) performed directly from one side of the propane-air flame near blowoff with similar inlet conditions. It is clearly seen that the flame has taken a U shape by lifting off from both ends of the bluff-body (± 21 mm) even at an equivalence ratio of 0.7.

![Fig. 3.5. Side view of propane-air flame near blowoff (ϕ ~ 0.7)](image)

As the bluff-body is in direct contact with the burner wall, the faster heat conduction through those walls might be a possible explanation for flame quenching on both ends of the bluff-body. Additionally, the cold air entrainment from both ends of the flame perpendicular to the bluff-body cross-section further enhances the cooling effect, which leads to localized extinction.
The final moments of flame blowoff for moderate and high T.I. (18% and 34%) has been furnished by a sequence of images in Fig. 3.6 and 3.7. A predominant sinuous mode of undulation is present in both cases. It is observed in Fig. 3.6 that the flame (at T.I. = 18%) has a relatively wider top part in relation to the bottom part. Distorted flame surface is observed in the side view for this flame (T.I. = 18%).

![Fig. 3.6. Evolution of propane-air flame near blowoff (\(\phi \sim 0.685\), \(U_m = 10\) m/s, T.I. = 18%).](image)

It is also observed that the flame base gradually changes to oval structure at first and finally to nearly circular structures close to blowoff. For the case of T.I. = 34% (Fig. 3.7) the observation of snake-like flame structure (near the bluff-body) become more prominent near blowoff. In addition, very frequent detachment of flame surfaces are also observed during extinction.
The region highlighted by yellow rectangles in images of 14ms and 13ms in Fig. 3.7 shows such detachment of small flame pockets from the main flame. The flame liftoff due to extinction of reacting shear layers is also noticed similar to that of T.I. = 4% case. It is worth noting that the pointed flame base gradually becomes more and more circular (end-view) as it lifts off from the bluff-body plane on its way to blowoff.
3.2 Flow field characterization of propane-air flames

The images of flame chemiluminescence presented in previous sections indicated wrinkled flame edges especially near blowoff due to significant flame vortices interaction. In fact, for high turbulence case the effect is even more pronounced as observed from the highly distorted flame boundary. From previous images (Fig. 3.3), an early initiation of asymmetric flame undulation mode was observed for T.I. = 34%. However, these observations needed further justification by actual investigation of the reacting flow field and the same was achieved by particle image velocimetry (PIV) measurement.

Reacting PIV was performed at $\phi = 0.85$ and an equivalence ratio of 0.05 above the blowoff equivalence ratio ($\phi = \phi_{bo} + 0.05$) at each turbulence level. Further reduction of equivalence ratio below $\phi_{bo} + 0.05$ was not possible due to high probability of premature flame blowoff due to PIV particle seeding. Figure 3.8 shows the representative velocity field for the two cases of T.I. = 4% using vector plot diagram. The region of interest for this particular measurement was 20x15 mm across the mid plane of the burner exit. Less than 5% vectors were found to be spurious. For detailed flow-field information, vorticity was calculated based on the obtained velocity field. Figure 3.9 represents the instantaneous vorticity field for different cases of propane-air flames.
Fig. 3.8. Velocity field of propane-air flame (a) \( \phi = 0.85 \), (b) \( \phi = 0.72 \), \( U_m = 10 \text{ m/s} \), T.I. = 4%.

As observed, the vorticity field is composed of granulated and concentrated vorticity patches. An approximate flame edge determined based on the basis of seeding density change between reactants and products from the Mie scattering images was overlaid onto the vorticity plot. It is seen from those plots (Fig. 3.9a) that the flame is symmetric at robustly burning conditions (\( \phi = 0.85 \)). However, near blowoff at \( \phi = \phi_{bo} + 0.05 \), concentrated vorticity patches interacting with the wrinkled flame surfaces are observed. In Fig. 3.9(b), the vorticity contour for T.I. = 4% represents a symmetrical flame structure at \( \phi \sim 0.72 \) supporting the previous observations in chemiluminescence images of the same flame, showing a varicose oscillation mode until 575ms prior to blowoff (\( \phi \sim 0.67 \)). For the case of T.I. = 18% a mixture of two oscillation modes are observed (symmetric and asymmetric), however, dominated mainly by asymmetric mode. Hence, it is well understood that the flame is undergoing a gradual transition from varicose to sinuous oscillation as it approaches blowoff. For the highest turbulence case of 34%, a predominant sinuous oscillation is clearly observed from the vorticity profile. Hence, an early initiation of asymmetric undulations observed in the high-speed imaging for this particular flame is confirmed.
The observation of different modes of flame oscillation will be later discussed by quantifying the degree of asymmetry in terms of ‘asymmetry index’.

Fig. 3.9. Vorticity field for propane-air flames at (a) $\phi = 0.85$, (b) $\phi = \phi_0 + 0.05$, $U_m = 10$ m/s.
CHAPTER FOUR

4. Study of Methane-Air Flame Behavior

This chapter concerns the study of premixed methane-air flame behavior in the same experimental setup. The flame was characterized by using the similar approach and measurements as performed in the investigation of propane-air flames presented in Chapter 3. The average exit-velocity of the mixture was maintained at 10 m/s for making comparison with other fuel-air mixtures.

4.1 High-Speed Imaging of Methane-Air Flame Chemiluminescence

4.1.1 Steady Burning Condition

The results of robustly burning methane-air flames ($\phi = 0.85$) at different levels of flow turbulence (4-34%) are furnished in this section. Representative chemiluminescence images acquired from high-speed camera (at 4000 frames per second) are also included for the purpose of explanation.

Instantaneous images of methane-air flame chemiluminescence at different turbulence intensities are shown in Fig. 4.1. As observed the luminosity of these flames are less than propane-air flames, presented previously (Fig. 3.1). The flame becomes wider with increasing turbulence levels and this is attributed to the increasing turbulent flame speed with higher turbulence intensities. A similar trend of increasing included ‘V’ angle with turbulence intensity was also observed in the case of propane-air flames. Hence, the freestream flow turbulence has definitive effect in modifying the methane-air flame structure. Based on observations of the two side views,
the flames are symmetric about the mid plane (perpendicular to the cross section) of the bluff-body. Reacting shear layers are clearly visible on both sides of the flame. The side views of the flame as obtained from the mirrors show a mostly continuous surface at this burning condition ($\phi = 0.85$). The reacting flow field analysis by using the results of PIV measurements for these flames are presented in Section 4.2 for further understanding of the flame dynamics.

Fig. 4.1. Chemiluminescence image of methane-air flames ($\phi = 0.85$, $U_m = 10$ m/s).
4.1.2 Evolution of Methane-air flame near Blowoff

Flame behavior near the condition of blowoff was also studied using chemiluminescence imaging technique. From the PMT measurements, it was found that the blowoff equivalence ratios for methane-air flames are 0.55, 0.565 and 0.55 (with an uncertainty of ± 0.005) corresponding to freestream turbulence intensities of 4%, 18% and 34% respectively. The flame equivalence ratio (ϕ) was reduced gradually (from ϕ = 0.85) by ramping down the fuel flowrate through the fuel mass-flow controller, automated by computerized codes developed in ‘Labview’ platform to approach the point of blowoff. The ‘end trigger’ option in the high-speed camera system was used to capture the final moments of flame blowoff corresponding to sudden abrupt drop in PMT signal amplitudes.

Figure 4.2 represents the symmetric and asymmetric oscillation modes for methane-air flames while approaching blowoff. Images at different freestream turbulence intensities of 4% (Fig. 4.2a), 18% (Fig. 4.2b) and 34% (Fig. 4.2c) are placed in three rows for comparison. From Fig. 4.2a, a symmetric flame structure (with respect to the centerline) is seen at 400ms before flame blowoff. Existence of upward propagating flame rolls along the surface of flame as observed in the side views (through mirrors) confirm the symmetrically rippled flame edges in the end view. However, those surface rolls are not very prominent in the side views due to reduced luminosity of methane-air flame close to blowoff. The flame structure at 270ms prior to blowoff shows a partially symmetric (near the burner exit) and asymmetric flame (the upper part of the flame) signifying a gradual transformation of the overall flame from varicose to sinuous mode of undulation. This is manifested in the last image (at 105ms) where the flame has clearly lost its symmetry. A gradual reduction of flame chemiluminescence signal is also observed in the end view as the flame approaches blowoff. Figure 4.2b shows that the flame at 18% turbulence
intensity has already undergone a partial transition to asymmetric oscillation mode (above y ~ 50mm).

Fig. 4.2. Symmetric and asymmetric flame oscillations of methane-air flames (U_m = 10 m/s) approaching blowoff at (a) T.I. = 4%, (φ ~ 0.55), (b) T.I. = 18%, (φ ~ 0.565), (c) T.I. = 34%, (φ ~ 0.55).

For the other two images at 270ms and 105ms before blowoff, a relatively brighter upper zone along with a low intensity flame zone near the burner exit is observed. Both of these flames exhibit asymmetric behavior. However, the top part of the flame at 270ms is very wide and possesses a ‘fountain-like’ structure. A purely asymmetric flame structure is seen at 400ms before blowoff for methane-air flame at T.I. 34% (Fig. 4.2c). As the flame equivalence ratio is further reduced down, the flame structure close to the burner exit becomes “sinuous” in appearance (images at 270ms
and 105ms).

It is also observed that the part of flame near the bluff-body plane gradually thins out as it approaches blowoff. A gradual change from wavelike flame surface to highly distorted surface is observed in the side views as the freestream turbulence level increases from 4 to 34%. Besides that, the existence of random dark islands are also recognized in the flame surface at T.I. 34%, similar to what was observed in propane-air flames at similar conditions (Fig. 3.2c).

Figure 4.3 represents the final few moments (40-0ms) of methane-air flame at a turbulence intensity of 4% before it blows off. For these cases, chemiluminescence signal is very weak as the flame is very close to blowoff and the asymmetry in flame structure is prominent. A very thin threadlike flame structure is observed up to a height of y ~ 30mm downstream of the bluff-body in images 40-16ms prior to blowoff. Hence, it is very difficult to differentiate between two reacting shear layers on both sides of the flame. The flame structure at 28ms and 24ms before blowoff looks apparently symmetric, however, from 20ms onward the flame continuously exhibits an asymmetric oscillation mode. The periodic dark patches observed in the side mirrors helps in understanding that the blowoff is first initiated at the two edges of the flame near the ends of bluff-body span. The image at 18ms prior to blowoff shows a temporary discontinuity in flame at y ~ 25mm (highlighted by yellow rectangle). This particular incident might be attributed to the dilution of the recirculation zone due to cold air entrainment from both ends of the flame. The corresponding side views also do not show any chemiluminescence signal, signifying a localized flame extinction has occurred in those regions. However, in the next image (16ms), it is seen that the shear layer reignited at that location and the flame is still weakly anchored at the bluff-body plane. At 14ms
before global blowoff the flame is found to be lifted off completely from the flame holder and gradually propagating upward due to the absence of any reacting shear layer upstream (up to $y \sim 30\text{mm}$). The end view of the flame base has a pointy shape and as the flame moves further upward, this pointy flame base gradually changes to a nearly flat structure (as seen in image 14-6ms before blowoff).

![Fig. 4.3. Evolution of methane-air flame near blowoff ($\phi \sim 0.55$, $U_m= 10 \text{ m/s}$, T.I. = 4%)](image)

A similar representation of blowoff moments for methane-air flames at T.I. 18% and 34% is given
in Figs. 4.4 and 4.5 respectively. The image at 40ms before global extinction for the case of T.I. = 18% shows almost no chemiluminescence signal near the bluff-body plane, whereas a relatively stronger signal demonstrating flame continuity all the way up to the flame holder was seen at the same condition (40ms before blowoff) for the case of T.I. = 4%. This signifies that the flame is already on the verge of lifting off or very weakly held at the bluff-body plane.

**Fig. 4.4. Evolution of methane-air flame near blowoff (ϕ ~ 0.565, U_m = 10 m/s, T.I. = 18%)**

The upper part of the flame is wider and brighter than the bottom part. At 31ms before blowoff, the flame shear layer close to burner exit is found to be broken into fragments of ignition and
extinction as indicated by the yellow rectangle. After a temporary re-ignition of the same shear layer, the flame finally lifts off from the flame holder around 22ms prior to extinction.

The near blowoff images for the case of T.I. = 34% (Fig 4.5) also show a prevalents asymmetric oscillation mode. The blowoff mechanism is not very different from the T.I. = 18% case, however the appearance of dark islands in the flame surface as observed in side views are more frequent.

Fig. 4.5. Evolution of methane-air flame near blowoff (ϕ ~ 0.55, U_m = 10 m/s, T.I. = 34%)
from the main flame (highlighted in image of 20ms before blowoff) which leads to localized flame extinctions. Such separations were also pronounced for the highly turbulent (34%) propane-air flames near blowoff (Fig 3.7). It is worth noting that the end view of the flame base gradually transforms to a nearly circular shape before final blowoff occurs (image at 6ms) unlike the other two cases (T.I. = 4% and 18%) where the base gradually flattens out.

4.2 Flow field characterization of methane-air flames

From chemiluminescence imaging of flames near blowoff, it is evident that there is a gradual change in flame oscillation mode from varicose to sinuous, as the fuel flow is ramped down with time. However, this incident can be investigated in detail by analyzing the corresponding flowfield. Hence, 2D reacting PIV measurements were performed and the vorticity information were deduced from the velocity field. 500 images were sampled in each case.

Reacting PIV experiments were performed at $\phi = 0.85$ and an equivalence ratio of 0.05 above the blowoff equivalence ratio ($\phi = \phi_{bo} + 0.05$) for each turbulence levels for methane-air flames. Reduction of equivalence ratio below $\phi_{bo} + 0.05$ was not possible because of intermittent flame blowoff during the PIV experiments. The region of interest for this particular measurement was 20x15 mm across the mid plane of the burner exit. Figure 4.6 demonstrates the reacting velocity field for the two cases of T.I. = 34% using vector plot diagram. Less than 5% vectors in the flow-field were found to be spurious. At $\phi = 0.6$, there exists an undulated recirculation zone, as observed.
For detailed flow-field information, 2D vorticity field was calculated from velocity data. Figure 4.7 represents the instantaneous vorticity field for different cases of methane-air flames. The vorticity contours shown for methane-air flames at ($\phi = 0.85$) manifests a symmetric flame structure as observed in chemiluminescence images also (Fig 4.6a). The vorticity contour for T.I. 4% (Fig 4.6b) represents a symmetrical flame structure at the condition ($\phi = 0.6$) which is consistent with our previous observation of varicose oscillation mode in chemiluminescence imaging of the same flame until 400ms prior to blowoff ($\phi \approx 0.55$). For the case of T.I. = 18%, a nearly dominant asymmetric mode is observed. However, a skewed (towards right) top symmetric flame structure above $y \sim 6$mm is also seen. Hence, the flame structure is undergoing a gradual transition from varicose to sinuous oscillation at this present instant.

A sinuous flame oscillation as found in the chemiluminescence imaging is obvious (Fig. 4.2c) from the vorticity map for the highest turbulence case of T.I. = 34%. Hence, an early initiation of asymmetric undulation observed in the high-speed chemiluminescence imaging (at 400ms) for this
Fig. 4.7. Vorticity field for methane-air flames at (a) $\phi = 0.85$, (b) $\phi = \phi_{bo} + 0.05$, $U_m = 10$ m/s.
CHAPTER FIVE

5. Study of Ethylene-Air Flame Behavior

In previous studies [50, 51] ethylene has been identified as an important component in the oxidation chemical mechanism of complex hydrocarbons. Hence, the study of ethylene-air flame behavior is interesting and pertinent in addition to those of propane and methane. In this chapter, the results of the study of ethylene-air flame are presented. High-speed imaging of flame chemiluminescence was performed (at 4000 frames per second) in addition to PIV measurements of the reacting flow field in order to investigate the flame behavior. These results are discussed in section 5.1 and 5.2.

5.1 High-Speed Imaging of Ethylene-Air Flame Chemiluminescence

5.1.1 Steady Burning Condition

In this section, the results obtained for steady ethylene-air flames (\(\phi = 0.85\)) at different levels of flow turbulence (4-34%) are discussed. Analysis of the flames are based upon the chemiluminescence images acquired from a high-speed camera.

Figure 5.1 represents the images of flame chemiluminescence with varying turbulence intensities (T.I.) from 4 to 34%. It is observed that the ethylene-air flames are very bright at the condition of \(\phi = 0.85\). A visual comparison can be drawn between these flames with propane-air flames (Fig. 3.1) and methane-air flames (Fig 4.1) at the same burning condition. Ethylene-air flame is shorter and wider (in V-angle) than the methane and propane flames.
In addition, this flame is extremely violent while burning (as observed during experiments). The flame structures are relatively symmetric about the mid plane (along y at x = 0) of the bluff-body. Presence of two reacting shear layers are observed on both sides of the flame. From the side views
(obtained from the mirrors), bright, continuous flame surfaces are identified. It is seen that the overall height of the flame reduces considerably with increasing T.I. from 4 to 34%. The flame also widens at higher T.I. as seen in figure 5.1. Hence, there is a strong influence of flow turbulence on the overall structure of the flame, as observed. A detailed analysis of these reacting flow fields are presented (Section 5.2) by performing PIV measurements.

5.1.2 Evolution of Ethylene-Air flame near Blowoff

Time evolution of ethylene-air flames near blowoff was recorded using high-speed chemiluminescence imaging. It was observed from the PMT measurements that ethylene-air flames blowoff at equivalence ratios of 0.56, 0.575 and 0.565 (with an uncertainty of ± 0.005) corresponding to free stream turbulence intensities of 4%, 18% and 34% respectively. The blowoff point was reached by reducing the fuel flow rate (from \( \phi = 0.85 \)) through the fuel mass-flow controller, automated by computerized codes developed in ‘Labview’ platform. The point of flame blowoff was determined based upon the sudden abrupt drop in PMT signal amplitude.

The symmetric and asymmetric oscillation modes for ethylene-air flames while approaching blowoff is shown in Fig. 5.2. Flame images at different turbulence levels of 4% (Fig. 5.2a), 18% (Fig. 5.2b) and 34% (Fig. 5.2c) are shown in three rows for the purpose of comparison. Figure 5.2a shows a symmetric flame structure (with respect to the centerline) up to 130ms before flame blowoff. Two bright reacting shear layers on both sides of the flame are observed. It is interesting to notice that a relatively low intensity zone is observed at the central part of the flame.
Fig. 5.2. Symmetric and Asymmetric flame oscillations of ethylene-air flames ($U_m = 10$ m/s) approaching blowoff at (a) T.I. = 4%, ($\phi \sim 0.56$), (b) T.I. = 18%, ($\phi \sim 0.575$), (c) T.I. = 34%, ($\phi \sim 0.565$).

The rippled flame edges as observed in the end view confirm the existence of symmetric flame
rolls in the side views (through mirrors). However, at 75ms prior to blowoff, an asymmetric flame oscillation (sinuous) mode is clearly visible. This signifies that the flame structure is gradually modified to an asymmetric structure as it approaches the point of blowoff. For the case of T.I. = 18% (Fig. 5.2b), an already existing sinuous mode of undulation manifests that the occurrence of asymmetric oscillation in this case is earlier than that of T.I. = 4%. At 75ms before blowoff, the flame adopts to a wider top structure along with an asymmetric narrow bottom structure. It is worth observing that there exists a central dark curvilinear zone (highlighted), however, it is difficult to comment about that zone without performing planer laser induced fluorescence measurements. For the T.I. = 34% case (Fig. 5.2c), the edges are seen to be clearly asymmetric at 130ms before blowoff. The side views show very highly undulated flame surfaces with the presence of dark patches, suggesting local flame extinction along the surface. With further reduction of flame equivalence ratio, the flame continues to exhibit sinuous undulations (at 75ms).

The blowoff moments of ethylene-air flames at a turbulence intensity of 4% is represented in Fig. 5.3. Asymmetry in the flame structure becomes more prominent with time as the blowoff is approached. Two weakly reacting shear layers on both sides of the flame near the exit of the burner are observed up to 34ms before blowoff occurs. However, from the next image (32ms) almost no chemiluminescence signal is seen up to y ~ 40mm downstream of the bluff-body. Hence, it is seen that the flame is already lifted from the bluff-body plane. The periodic dark patches as observed in the side mirrors signifies that the blowoff first initiates at the two edges of the ethylene-air flame in the third dimension. This particular observation is similar to that of propane and methane-air flames. From 20ms before blowoff, the flame is observed to become more divergent at its upper part. In addition, the flame apparently lost its V shape from 12ms onward. It is also seen that the
flame base gradually changes its pointed shape towards a nearly circular and finally a flat structure (image 10-4ms). Interestingly, the observation of ethylene-air flame extinction closely resembles the blowoff approach characteristics of propane-air flame (Fig. 3.3) where the flame was observed to be lifted off from the flame holder and eventually blown out. However, in case of methane-air flames an additional observation of periodic extinction and re-ignition of the reacting shear layer near the burner exit was noted (Fig. 4.3) close to the point of blowoff.

Fig. 5.3. Evolution of ethylene-air flame near blowoff ($\phi \sim 0.56$, $U_m = 10$ m/s, T.I. = 4%).

The blowoff moments for ethylene-air flames at T.I. 18% and 34% were also investigated to shed light into the corresponding flame blowoff sequences. In Fig. 5.4, the final moments of ethylene-air flame at T.I. = 18% are shown. Very weak or almost no chemiluminescence signal near the
bluff-body plane is observed at 40ms before global extinction. Hence, it is seen that the shear layer up to \( y \sim 50\text{mm} \) downstream of the plane of bluff-body is almost extinguished and the flame is lifted. The upper part of the flame (\( y \sim 100\text{mm} \)) in almost all the images are wider than the bottom part. Flame structure is evidently asymmetric.

![Evolution of ethylene-air flame near blowoff](image)

**Fig. 5.4.** Evolution of ethylene-air flame near blowoff \((\phi \sim 0.575, U_m= 10 \text{ m/s}, \text{T.I.} = 18\%)\).
Fig. 5.5. Evolution of ethylene-air flame near blowoff ($\phi \sim 0.565$, $U_m = 10$ m/s, T.I. = 34%).

Figure 5.5 is a representation of the final blowoff moments of ethylene-air flame at a T.I. of 34%.

It is very interesting to notice that the structure of this particular flame is divided into two parts (i) a wider upper zone and (above $y \sim 90$ mm) and (ii) thin tail-like flame zone (up to $y \sim 90$mm). Asymmetry is evidently present in the overall flame structure. At 42ms prior to blowoff the tail-like flame structure is found to be highly curved with a region of extinguished shear layer around $y \sim 25$mm (highlighted in yellow). In the next few images until 28ms before blowoff, it was seen
that the extinguished shear layer is reignited. However, there is another localized extinction of the shear layer, as observed around 28ms before the blowoff occurs (highlighted). After a temporary re-ignition of that shear layer, the flame is found to be lifted completely around 18ms before the occurrence of flame blowoff. From the side views, the existence of frequent dark islands indicating discontinuities in the surface proves that the extinction occurs in the flame surface on both sides of the flame first and eventually the entire flame undergoes a global extinction. The images in the final row shows that the flame is propagating upward during its blowoff transition. The included V-angle gradually increases with time and eventually, the flame base becomes flat before the final blowoff occurs.

5.2 Flow field characterization of ethylene-air flames

As the fuel flow is reduced, the flame gradually changes its structure from symmetric to an asymmetrical structure (Fig. 5.2). The analysis of corresponding reacting flow field aids in explaining the chemiluminescence observations. Hence, reacting PIV measurements were performed by sampling of 500 images for this specific purpose.

Reacting PIV performed at \( \phi = 0.85 \) and an equivalence ratio of 0.05 above the blowoff equivalence ratio \( (\phi = \phi_{bo} + 0.05) \) for each turbulence levels for ethylene-air flames. It was difficult to perform PIV at any equivalence ratio below \( \phi_{bo} + 0.05 \) because of the problem of premature flame blowoff in the seeded flow field. The region of interest for this particular measurement was 20x15 mm across the previously mentioned mid plane of the burner exit. Figure 5.6 demonstrates the reacting velocity field for the two cases of T.I = 18\% using vector plot diagram. Less than 5\% vectors in the flow-field were found to be spurious. At \( \phi = 0.85 \), it is observed that the velocity vectors from both sides of the bluff-body merge with each other at some location \( (y \sim 4\text{mm}) \) creating a nearly
triangular shaped recirculation zone behind the flame holder. However, at $\phi = 0.625$, the flow field behavior is close to non-reacting flow field and hence, it clearly demonstrates a typical wake zone behind the bluff-body. For further details, vorticity was calculated based upon the velocity field information obtained from PIV measurements.

Fig. 5.6. Velocity field of ethylene-air flame (a) $\phi = 0.85$, (b) $\phi = 0.625$, $U_m = 10$ m/s, T.I. = 18%.

Figure 5.7 represents the instantaneous vorticity field for different cases of ethylene-air flames. A mixture of granulated and concentrated vorticity patches are observed in the vorticity plots. An approximate flame edge based on the density change of seeding particles between reactants and products zone is overlaid onto the vorticity plot to observe the vortex shedding from corresponding edges of the flame.
It is evident that the ethylene-air flame is very wide in steady condition of $\phi = 0.85$. The symmetric flame structure observed at $\phi = 0.85$ confirms our similar symmetrical observation in flame chemiluminescence at the same condition. In Fig. 5.7b, the vorticity contour for T.I. = 4% represents a symmetrical flame structure at $\phi = 0.61$. For the case of T.I. = 18%, presence of two
oscillation modes is observed simultaneously. Apparently, the flame is undergoing a gradual transition from varicose to sinuous oscillation as it approaches blowoff. At T.I. = 34%, the sinuous oscillation mode is prominent. Evidently, the initiation of asymmetric undulation for this flame has occurred even before $\phi = \phi_{bo} + 0.05$. Hence, the observation of sinuous flame mode at 130ms before blowoff (Fig. 5.2c) is reasonable.
CHAPTER SIX

6.1 Asymmetric Index Calculation

6.1.1 Concept of Asymmetric Index

From the results of flame chemiluminescence as reported in Chapter 3-5 of this thesis, it was evident that the flame undergoes a gradual transformation from symmetric to asymmetric structure (with respect to the mid plane), as the blowoff point is approached. In the past, Chowdhury and Cetegen [31] observed intermittent shifts between varicose (symmetric) and sinuous (asymmetric) modes of flame oscillation for axisymmetric conical flames. Previously, Nair and Lieuwen [27], Chaudhuri et al. [28], Kiel et al. [51] have reported similar observations and for near blowoff flames and it was termed as the “second stage” which leads to flame blowoff [50]. Such reversal of the flame to a global asymmetric structure has been studied by Emerson et al. [56] and Mehta and Soteriou [57]. They concluded that the decrease in density ratio across the flame sheet and its effect on global stability is the primary reason for such reversal. Such reduction of density ratio lessens the dilatation effect on vorticity and the baroclinic vorticity generation which result in amplification of the importance of shear generated vorticity and the von Karman instability [58]. Hence, in addition to developing qualitative understanding of the symmetric vs. asymmetric flame structure, it is important to quantify it by defining the degree of correlation between the two edges of a flame.

In this chapter, an effort was made to calculate an index of asymmetry \((r_{L,R})\) of flames at each level of turbulence and track the variation of that index with flame equivalence ratio. The
following approach similar to that of Emerson *et al.* [56] was adopted for determining the asymmetry index. Flame dynamics was quantified using the transverse position of the left and right flame edges, $\zeta_L(y, t)$ and $\zeta_R(y, t)$, as a function of axial position and time as shown in Fig. 6.1. To characterize the degree of sinuous oscillation, a correlation was estimated between the wrinkling of the left and right flame edges, which is given by:

$$r_{L,R}(y) = \frac{\zeta_L(y, t) \zeta_R(y, t)}{\sqrt{(\zeta_L(y, t))^2 (\zeta_R(y, t))^2}} \quad (6.1)$$

An asymmetric and symmetric flame wrinkling is presented respectively by negative and positive correlation coefficients. The representation of nearly zero correlation coefficient signifies that the flame branches are disturbed by uncorrelated structures with a scale much smaller than their transverse separation distance [58].

![Fig. 6.1. Cartoon representation of chemiluminescence flame edge.](image)

It is understood that the determination of approximate flame edge based upon the chemiluminescence signal is important in order to determine the above-mentioned correlation in
equation 6.1. For this purpose, an image binarization process using an in-house Matlab code was employed as described in the next section.

6.1.2 Image Binarization and Flame Boundary Detection

Binarization is a process to convert an image to a binary image. A binary image is basically a digital image with only two possible values for each pixel of either 0 or 1. This is useful in order to determine an approximate flame edge from flame chemiluminescence image. A robust Matlab code developed at the Combustion and Fluid Dynamics Laboratory, University of Connecticut serves the purpose of converting the pixel chemiluminescence images into binary images. The code can store raw chemiluminescence images of 1024 x 1024 pixels dimension in three dimensional array format (image matrix of format M x N x P). The first two dimensions of the matrix represent the number of rows and columns involved in each image and the third dimension (P) represent the total number of images stacked into the matrix. A ‘jet’ color-bar highlighting the equivalent red, green and blue intensities for specific color is sometimes used to represent the raw gray-scale images in a visually appealing format. For the purpose of asymmetry index calculation a specific dimension of 365 x 235 pixels is iteratively chosen so that main region of interest of the flame (which includes two edges and the central part) remains centrally located and the remaining parts (not useful for this purpose) are removed to save memory space and computational time. A binarization function named ‘imageBinarization’ in the code was applied to binarize the above-mentioned region of interest from each image based upon user defined values of binarization cutoff, median filter kernel size and the standard deviation for Gaussian blurring. These values are determined on the basis of trial and error until an expected binarized image is received. The binarized images were then stored in a separate 3D array. Figure 6.2 represents the process of
The next part of the code is used to determine the approximate flame boundary based upon the binarized images. The flame boundary is determined by scanning through every row of each binarized image matrix and finding a sudden jump of intensity from zero (0) to one (1) in each row. Upon determination of the approximate flame edge, the same is overlaid onto the corresponding chemiluminescence image to verify the accuracy of the code in detecting the edge. This process was performed until the calculated edge closely fits to the boundary of the corresponding chemiluminescence image. This process of overlaying the flame edge is demonstrated in Fig. 6.3.

Fig 6.2. Binarization of flame chemiluminescence image.
6.2 Asymmetric Index for Different Flames

Figure 6.4 shows the values of asymmetric index ‘$r_{L,R}(y)$’ with respect to flame equivalence ratio for different fuel-air mixtures. Results have been furnished for the peak flame response. Figure 6.4a shows the similar variation of $r_{L,R}$ with respect to the flame equivalence ratio ($\phi$) for propane-air flames at different levels of flow turbulence. As the blowoff equivalence ratios of propane-air flames are higher than that of methane and ethylene-air flames the propane-air flames exhibit sinuous oscillation at relatively higher equivalence ratios (than other two fuel-air flames). In figure 6.4b, it is observed that the value of asymmetry index for methane-air flame at T.I. = 4% gradually decreases with decreasing equivalence ratio. For robustly burning case ($\phi = 0.85$), the asymmetric index has a value close to ‘+1’ signifying a strongly positive correlation between the edges of the
flame. This signifies that the flame possesses a symmetric structure at this burning condition and hence our previous observation of varicose flame oscillation mode from chemiluminescence (at $\phi = 0.85$) and PIV is confirmed. With decreasing flame equivalence ratio the magnitude of asymmetric index also decreases which indicates that the flame gradually loses its structural symmetry. The value of ‘$r_{L,R}$’ at $\phi = 0.6$ and 0.55 is observed as 0.4 and -0.6 respectively for the case of T.I. = 4%. Evidently, the sign of asymmetric index changes from positive to negative somewhere in between $\phi = 0.6$ and 0.55 for this particular case. This trend is expected as the flame approaches the point of blowoff. However, it is evident that the point of crossover for $r_{L,R}$ (positive to negative) gradually shifts to higher equivalence ratios as the T.I. increases from 4-34%. This signifies that the asymmetric modes of undulation for T.I. = 18% and 34% occurs earlier than T.I. = 4%. Hence, our previous observation of chemiluminescence imaging exhibiting earlier initiation of sinuous flame oscillation is supported by this finding (Fig. 3.3, 4.2 and 5.2). The $r_{L,R}$ variation with $\phi$ for ethylene-air flames are demonstrated in Fig. 6.4c. The pattern of variation is not much different from what is observed for propane and methane-air flames. However, the magnitudes of $r_{L,R}$ for these flames are higher than that other fuel-air flames, as observed. Hence, it suggests that the degree of structural symmetry for ethylene-air flames are higher than those of methane and propane-air flames at the similar equivalence ratios.

It is observed in general that the value of asymmetric index for T.I. = 34% is lower than that of the other two turbulence intensities. Similar observations were reported by Chowdhury [58] for the case of bluff-body stabilized conical flames. This incident might be attributed to decreasing temperature ratio across the flame sheet, as understood from previous studies [56, 57]. However, a detailed investigation is required in order to arrive at a more definite conclusion on this.
Fig. 6.4. Variation of the correlation coefficient ($r_{L,R}$) with equivalence ratio ($\phi$) for (a) propane-air, (b) methane-air and (c) ethylene-air flames at $U_m = 10$ m/s. Measurements are shown for the peak flame response along vertical direction of the flame.
Figure 6.5 represents the value of $r_{L,R}$ for different fuel-air flame at the same turbulence intensities. It is evident that the value of $r_{L,R}$ gradually decreases with increasing flow turbulence levels signifying an early initiation of sinuous flame undulation at higher turbulence levels.

![Figure 6.5](image)

**Fig. 6.5.** Variation of the correlation coefficient ($r_{L,R}$) with equivalence ratio ($\phi$) at (a) T.I. = 4%, (b) T.I. = 18%, and (c) T.I. = 34%, at $U_m = 10$ m/s for different fuel-air mixtures.
CHAPTER SEVEN

7. Effect of Free Steam Flow Turbulence on Blowoff Equivalence Ratio for different fuel-air mixtures

In this chapter, the influence of flow turbulence levels on the magnitude of blowoff equivalence ratio ($\phi_{bo}$) is discussed. Flame blowoff point is approached by gradually lowering the fuel flowrate until the flame was blown off from the flame holder as detected by a photomultiplier detector (described in Chapter 2).

In addition to the investigation of blowoff equivalence ratio variation with turbulence intensities for different fuels, effort was taken to record the variation of blowoff equivalence ratio change with mixture temperature (or air temperature). Besides that, the measurement of $\phi_{bo}$ was also carried out by confining the two ends of the V-flame with glass windows in order to observe the corresponding changes in blowoff equivalence ratios due to entrainment of ambient air at both ends of the flame holder. Each of these results will be discussed in the following.

7.1 Blowoff Equivalence Ratio Measurement at Different Levels of Turbulence

In this section results of blowoff equivalence ratio ($\phi_{bo}$) at different flow turbulence levels are presented for different fuel-air mixtures under investigation. Figure 7.1 demonstrates the above-mentioned variation of $\phi_{bo}$ for propane/ methane/ ethylene-air flames. The results are furnished for
an ambient temperature of 35°C. From the plot, it is observed that the blowoff equivalence ratio first increases up to certain level of free stream turbulence intensity and then it decreases for all fuel-air mixtures. For example, the value of $\phi_{bo}$ for propane-air mixture at T.I. = 18% is 0.685 however, it is 0.675 for the T.I. = 34%. Hence, it appears that the blowoff is extended at higher level of flow turbulence.

![Blowoff equivalence ratio at different T.I.](image)

**Fig. 7.1. Blowoff equivalence ratio of fuel-air mixtures at different Turbulence Intensities.**

In order to investigate this issue (extension of blowoff at higher T.I.) in further details, two glass windows confining the two ends of the flame were placed at the exit of the burner. Those windows helped in preventing the entrainment of cold air from two ends of the flame. Figure 7.2 represents the arrangement of glass windows at the burner exit. The dimension of each of those windows are 35 x 100 mm. Variation of blowoff equivalence ratio ($\phi_{bo}$) at different turbulence intensities are
shown in figure 7.3 when side plates were installed at the burner exit.

Figure 7.3 also manifests a similar trend of variation of blowoff equivalence ratio with turbulence intensity. However, the magnitude of $\phi_{bo}$ has decreased remarkably by putting those side plates. Hence, it is understood that the entrainment of cold air from both ends makes the flame even leaner which eventually leads to extinction at relatively higher equivalence ratio (Fig. 7.1). By putting
those end plates, cold air is prevented and hence, the flame blows off at a lower equivalence ratio.

![Blowoff equivalence ratio (Φ<sub>bo</sub>) at different T.I.](image)

**Fig. 7.3. Blowoff equivalence ratio of fuel-air mixtures at different Turbulence Intensities (with side plates installed).**

In previous study of conical flame by Chowdhury [58], it was observed that the blowoff equivalence ratio increases with increasing levels of flow turbulence in general for most of the flames. However, the present observation does not agree with the previously understood relation between Φ<sub>bo</sub> and turbulence intensity. Figure 7.4 shows the variation of Φ<sub>bo</sub> with T.I. for the case of conical propane-air flame and the present two-dimensional V-shaped flame (propane-air) at U<sub>m</sub> = 10 m/s, simultaneously. To understand why the blowoff equivalence ratio decreases at T.I. = 34%, the propane-air flame was left ignited (at T.I. = 4%) and at a condition near blowoff (Φ = 0.69) and quickly changed to the condition of T.I. = 34% to capture the moment of transition (from T.I. = 4 to 34%), which shown in Fig. 7.5.
The transition is found to be prominently visible if captured directly from one of the two sides of the flame. High-speed imaging (at 400 frames per second) of flame chemiluminescence was performed to capture the side view of the flame along the 42mm dimension of the bluff-body.

Fig. 7.5 Transition moment of propane-air flame at $\phi = 0.69$ from (a) T.I. = 4% to (b) T.I. = 34%.
It is observed that the propane-air flame (T.I. = 4%, fig 7.4a) at φ = 0.69 was lifted from the flame holder having a ‘U-shaped’ flame base. As soon as the T.I. was changed to 34% by turning on the side jets keeping all other conditions same, the flame structure is observed to change significantly. It is also important to notice that the flame base quickly adopts a shape of ‘W’ from ‘U-shape’ and also propagates upstream by approximately 5 mm towards the bluff-body plane. This signifies that the flame at T.I. = 34% is apparently more stable than the T.I. = 4% flame at that burning condition near blowoff. While the flame at T.I. = 4% is lifted and is on the verge of blowing off the same flame at T.I. = 34% is more stable and is located relatively nearer to bluff-body plane. This particular observation of relatively higher stability of the flame at T.I. = 34% provides the possible explanation the visible reduction of φbo at that level of turbulence for every fuel-air mixture (for the 2D V flame). In this context, a comparative study can be done between the disk shaped bluff-body and the present triangular cross-sectional bluff-body in order to understand the above-mentioned relative flame stability issue. Figure 7.6 is a cartoon representation of a disk-shaped and a triangular bluff-body flame holder.

![Diagram](image)

**Fig. 7.6.** Representation of flame holding in a disk and triangular bluff-body flame holder.
It can be observed that the surface of the disk-shaped flame holder where the flame is anchored is much smaller than that of the triangular cross-section flame holder. Apparently the two-dimensional V-shaped flame achieves higher stability due to the availability of a long span (42 mm) of the bluff-body. The flame starts to extinguish from the two extreme ends of the bluff-body as observed before (Fig. 3.4), however, the central part of the flame remains still attached to the bluff-body. Obviously, the conical flame does not have this kind of stability (at the central zone) due to the shape of the flame holder (disk). This is probably why the variation of $\phi_{bo}$ with T.I. shows a different trend for the triangular bluff-body (from a disk bluff-body) and the magnitude of $\phi_{bo}$ at higher T.I. (~ 34%) is lower for a triangular flame holder than a disk-shaped flame holder.

### 7.2 Effect of Ambient Temperature on Blow off Equivalence Ratio of Flames

During the span of experiment, blowoff equivalence ratio was measured at different days with varying ambient temperature. It is very interesting to observe that $\phi_{bo}$ changes remarkably with ambient temperature as shown in Fig. 7.5. For this particular study, propane-air mixture was considered. It is observed that the trend of variation of $\phi_{bo}$ remain same at every temperature. Evidently, the magnitude of $\phi_{bo}$ (at every T.I.) increases with decreasing ambient temperature. This is possibly because of the overall temperature of the fuel-air mixture decreases with decreasing ambient temperature leading to earlier quenching of the flame. It is also observed that the difference between the magnitude of $\phi_{bo}$ at T.I. = 4% and 18% decreases with decreasing ambient temperature. Hence, it is evident that there is an influence of ambient air temperature on the blowoff equivalence ratio at every levels of flow turbulence.
Fig. 7.7. Variation of blowoff equivalence ratio with ambient temperature.
CHAPTER EIGHT

8. Conclusions and Future Work

Flame stabilization is one of the most challenging task of designing any combustor. It is also well known that reliability and efficiency of operation for any combustion device depends heavily on establishing a stable flame. Besides that, stricter regulations have been enforced on the acceptable levels of emissions and hence, the focus of combustion research and development has shifted towards lean premixed combustion. However, the major problem associated with the development of such combustors is instability due to near lean-limit operation which leads to major problems of flame stabilization and blowoff. Many studies have been conducted in past few decades on flame blowoff. In previous studies, it was observed that the free stream turbulence intensity strongly modifies the structure of flame. It was also seen that the flow turbulence level influences the blowoff equivalence ratio significantly. However, most of the previous studies were limited to low (~ 4%) or moderate levels (~ 14%) of flow turbulence levels. Hence, the primary motivation of the present thesis is to study effect of free stream turbulence intensity on the dynamics and blowoff characteristics of a 2D bluff-body stabilized, V-shaped turbulent premixed flame. Studies were conducted for different levels of flow turbulence intensities in the range of 4 to 34% by using an effective turbulence generating arrangement developed during the span of this research. Characterization of the flow field was done by using reactive and non-reactive particle image velocimetry (PIV) technique. The structure of the steady flame and near blowoff flame was characterized using high-speed chemiluminescence imaging. Besides that, the blowoff equivalence ratio ($\phi_{bo}$) was measured at
different levels of turbulence using different fuel-air mixtures.

8.1 Summary

A rectangular exit burner with exit dimensions of 35 x 42 mm was designed for the purpose of this study. Flame was stabilized at the burner exit by means of a triangular shaped bluff body flame holder. Different levels of flow turbulence was generated by unique combinations of perforated plate and opposing side jets. To verify the turbulence level and velocity profile at the exit of the burner, non-reacting particle image velocimetry was performed. Different fuel-air mixtures such as methane, propane and ethylene-air were used during experiments.

Studies of different fuel-air flames by high-speed imaging of flame chemiluminescence at steady burning condition of equivalence ratio $\phi = 0.85$ show a symmetric flame structure in all the cases. As the flame equivalence ratio is reduced towards its blowoff value, the flame gradually loses its structural symmetry. This was evident for all fuel-air mixtures at different flow turbulence intensities. For the turbulence intensity (T.I.) of 18% and 34% the initiation of asymmetric flame oscillation mode (sinuous) occurred earlier than the case of T.I. = 4% for all fuel-air mixtures. Visually, methane-air flame is less luminous than propane and ethylene-air flames. The ethylene-air flame at $\phi = 0.85$ is short, wide and very bright. The luminosity of propane-flame was in between methane and ethylene flames at steady burning condition of $\phi = 0.85$. Symmetric upwards propagating flame rolls along the flame surface are observed in the side views of flames for different fuel-air flames at T.I. = 4% while the flame equivalence ratio is gradually reduced. However, distorted flame surfaces with intermittent dark patches were observed for T.I. = 18% and 34% signifying that the local extinction regions begin to appear along the flame surface first. The final moments of blowoff for propane-air flames at T.I. = 4%
showed extinction of the reacting shear layers very close to the bluff-body leading to lift off and global blowoff, eventually. However, methane-air flames at T.I. = 4% showed periodic extinction and re-ignition of shear layers before blowing off. Similar observations were found for ethylene-air flame at the similar flow conditions. Hence, the blowoff mechanism at T.I. = 4% is apparently governed by extinction of reacting shear layers, as observed. A snake-like undulating structures were observed in the final moments of blowoff for T.I. = 18% and 34% cases near the burner exit. However, the upper part of the flame for T.I. = 18% becomes very wide close to blowoff for almost all the flames. Vorticity information obtained from the reacting PIV measurements performed at the steady condition (ϕ = 0.85) confirms the structural symmetry for all flames. However, predominant sinuous undulation was confirmed from vorticity plots for T.I. = 18% and 34% for propane, methane and ethylene-air flames at an equivalence ratio φ = φ_{bo} + 0.05.

Calculation of asymmetry index based upon the flame edge obtained from the binarized image supports the previous observation of global flame structure observed from flame chemiluminescence. Variation of asymmetry index was shown with respect to equivalence ratio and turbulence level, with asymmetry being enhanced at leaner condition and increasing turbulence levels. It was observed that the degree of flame symmetry for ethylene-air flames are higher than those of methane and propane flames.

From the investigation of blowoff equivalence ratio for different turbulence intensities, it was observed that the magnitude of φ_{bo} first increases with T.I. and then decreases. Similar observation was made when the measurement of φ_{bo} was performed by partially confining both ends of the V flame with glass widows to prevent cold air entrainment. However, the magnitude of φ_{bo} decreased for the cases with end plates. Besides that, the measurement of φ_{bo} at different
ambient temperature manifested a gradual increase in the magnitude of $\phi_{bo}$ with decreasing ambient temperature.

### 8.2 Scope for Future Work

For verification and better understanding of the results presented in this thesis, a more detailed investigation of these flames will be needed.

- The important part of verification of the present results involves detection of flame edge. During this work, the flame behavior was studied by using the high-speed imaging of flame chemiluminescence which has a limitation of line-of-sight integration effect. An accurate detection of the flame front can be achieved by using OH- planar laser induced fluorescence (OH-PLIF) measurements which is currently planned.

- All the experiments performed here involved gaseous fuels such as methane, propane and ethylene. However, there is an increasing demand of conducting research with liquid fuels. An experimental setup has been developed in our laboratory, which can pre-vaporize liquid hydrocarbon fuels to create a premixed fuel-air mixture. In the future, the study of flame stabilization as well of blowoff experiments can be conducted using liquid fuels which strongly exhibits low temperature chemistry and can influence the flame structure.

- The shift of flame undulation modes from varicose to sinuous mode was observed near the condition of blowoff for every fuel-air mixtures. This was attributed to decreasing temperature ratio across the flame sheet in previous studies [56, 57]. Hence, a direct temperature measurement can be performed in future to investigate
this issue in more detail. Rayleigh scattering imaging used in our laboratory for a different experiment for temperature measurement can be used in this context.

- Besides the scope of fundamental study of flame blowoff, it would be interesting to develop laser based diagnostics for the detection of flame blowoff point and precursor events utilizing tunable diode laser absorption spectroscopy.
References:


81


[57] P.G. Mehta, M.C. Soteriou, Combustion heat release effects on the dynamics of bluff