Phase-resolved Characterization of Conical Turbulent Premixed Flames: An Investigation of Forced Blowoff Dynamics

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Master of Science Thesis

Phase-resolved Characterization of Conical Turbulent Premixed Flames: An Investigation of Forced Blowoff Dynamics

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To

My Mother
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Abstract

Flame dynamics of a bluff body stabilized turbulent premixed flame as it approaches lean blowoff is of interest for practical applications. It is also important to understand the flame behavior under harmonic flow perturbations as it may occur due to acoustically unstable operation of compact combustors. In this study, a harmonically excited conical flame was studied to determine its behavior under strong burning and near blowoff conditions. Chemiluminescence imaging was employed using a Photron high speed camera to characterize the phase resolved flame characteristics for a range of excitation frequencies from 50 to 400 Hz in confined and unconfined geometries. Phase-resolved measurements of stretch rate along the flame front can provide important insights for understanding of local flame behavior particularly near blowoff. Phase resolved particle image velocimetry (PIV) technique was utilized to map the different phases of the velocity field in harmonically modulated flow conditions. Processing of PIV data along the flame front identified from seed density change was employed to determine flame front location and utilize the PIV data to determine the stretch rate variations at different phases of flame oscillation. Oscillations of recirculation zone length were characterized at all external harmonic excitation frequencies accompanied by a cyclically varying strain rate along the flame front. At certain phases of the cycle, the strain rate reaches a maximum just before the phase when the recirculation zone length is a minimum. At this point, flame pinching and vortex breakdown phenomena were observed. This vortex breakdown phenomenon accompanies flame blowoff when the ratio of the minimum recirculation zone length to the convective length scale is in the range between 0.3 and 0.5.
Lean premixed flame blowoff experiments from two different experimental configurations were analyzed with the objective of determining the most appropriate time scale associated with lean premixed flame blowoff. Experimental results from combined particle image velocimetry and OH planar laser induced fluorescence reported earlier were analyzed to produce flame front conditioned strain rate probability density functions. The time scale associated with the inverse of the mean strain rate for each experimental condition is then compared with the three time scales from an opposed counter flow flame configuration using OPPDIF, a flame propagation time scale using PREMIX and an extinction time scale using a perfectly stirred reactor (PSR). In each case, the USC II chemical kinetic mechanism for C1-C4 hydrocarbons was used for detailed kinetics. It was found that the experimentally determined mean strain rate along the flame front just prior to blowoff correlates best with the extinction strain rate calculated for the same mixture using OPPDIF. The ratio of the extinction time scale from the OPPDIF to the experimental time scale obtained from the mean strain rate is found to be constant for all cases, namely unvitiated, axisymmetric, 0.15 vitiation and 0.25 vitiation respectively with a different constant value for each case irrespective of the global equivalence ratio. The other two time scales determined from PREMIX and PSR did not correlate with the experimental data as well. The good correspondence of experimental and computed results for extinction strain based time scales for the two different experimental configurations and for two different upstream vitiation levels and no vitiation suggests that premixed flame blowoff is due to attainment of a critical extinction strain rate in the mean and a larger fraction of the strain rate probability distribution exceeding this critical strain rate.
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Chapter 1
Introduction

1.1 Motivation and Overview

Limit behavior such as blowoff and flashback of turbulent lean premixed flames under oscillatory flow conditions is of interest for low emission combustion systems. Flame holding in high-speed flows of premixed combustion has been extensively studied over the past several decades. The abiding attention in this problem stems from its wide range of applications in aero propulsion and power generation industry as well as in many practical combustion devices. All these combustors rely on a flame holding device that anchors the flame in the combustor and enable its normal operation over a range of conditions without flame blowoff.

Flame stabilization in practical combustors often involves a competition between the rates of the chemical reactions and the rates of turbulent diffusion of species and energy. Widely used flame stabilization schemes that have been in such applications mainly involve bluff body or swirl stabilization, or a combination of both. Among these, the bluffbody flame stabilization scheme typically employed in gas turbine, turbojet and ramjet afterburners is of keen interest in the context of this study. The physics of anchoring a premixed flame behind a bluff body flame holder involves mixing of oncoming combustible reactants with the hot combustion products residing in the recirculation zone assisting as a continuous source of ignition for the fresh fuel-air mixture. The global flame holding characteristics of bluffbody stabilized flames have been explicated in a number of seminal works by Zukoski and Marble [1.1-1.2], Williams et al [1.3], Longwell [1.4] and Candel et al. [1.5-1.7]. Effect of different bluffbody geometries, fuel composition, pressure and temperature are thoroughly investigated by Rao and Lefebvre [1.8],
Plee and Mellor [1.9], and Rizk and Lefebvre [1.10] to establish lean blowoff limits of different systems. Some of these studies are devoted to explore fuel droplet vaporization and turbulent mixing which is often evident in commercial gas turbine combustors. Research, both experimental and computational, dedicated towards understanding the stabilization mechanism and the final blowoff event in bluff body stabilized flames has been conducted for the last six decades and significant progress has been reported in the archival literature spanning over 150 journal articles, which has been very well summarized in a recent review by Shanbhogue et al. [1.11-1.12]. However as reported in their paper, although much progress has been made, the problem of understanding the final blowoff mechanism continued to elude researchers over this time and has persisted to be a poorly understood problem in combustion science. In this thesis new perspectives are presented to explain the governing dynamics of blowoff for bluff body stabilized turbulent premixed flames.

Heuristically, simplified view of flame blowoff occurs when the chemical reaction time scale for ignition exceeds the characteristic flow time scale, expressed mathematically when Damköhler number as, $Da = \frac{\tau_{\text{fluid}}}{\tau_{\text{chem}}} < 1$. The residence time of oncoming combustible mixture in the recirculation zone has to be larger than the chemical reaction time scale to produce a stable flame. However, this simplified time averaged view of the flame stabilization does not account for the unsteady turbulent flame dynamics including unsteady vortex shedding and the increased unsteadiness exhibited near flame blowoff under upstream velocity oscillation. These unsteady effects are believed to play an important role on the onset of flame lifting off the flame holder leading to blowoff.

Bluff-body stabilized flame is a 'canonical' flame configuration of interest for studying flame characteristics relevant to practical combustion devices. Present study is focused to
establish a blowoff criteria for flame holding in uniform homogenized lean premixed gases under upstream velocity oscillation. Both active and passive combustion control strategies require a good knowledge of system dynamic response and near limit behavior. The drive towards reduced pollutant emissions has prompted the gas turbine industry to develop cleaner, more environmentally friendly power and propulsion systems, while simultaneously maintaining (or improving) efficiency, operability and performance.

The present study concerning various aspects of the dynamics of bluff body stabilized turbulent premixed flames have been reported in chapter 2. Phase resolved characterization of turbulent conical premixed flame and its dynamic behavior are investigated under external harmonic oscillation in a lab scale axisymmetric conical burner. A forced blowoff mechanism is proposed based on the flame extinction results under upstream velocity perturbation, which constitutes one of the most important finding of this thesis. To enhance our understanding towards blowoff, flame extinction time scale is calculated numerically for vitiated and unvitiated combustion. Computational results coupled with experimental data from a lab scale conical burner and a prototypical afterburner rig, are investigated to form a better understanding of forced blowoff mechanism.

A brief description of turbulent premixed flames, concept of aerodynamics stretch and strain rate in flames, bluffbody flame stabilization, lean blowoff mechanisms and limit behavior are presented in next few paragraphs.
\section*{1.2 Turbulent Premixed Flames}

A turbulent premixed flame is the thin region of exothermic chemical reaction in a homogenous mixture of fuel and oxidizer (along with other possible inerts like \( \text{N}_2 \) in case of air) with Reynolds number, \( Re > 3000 \) that are thoroughly mixed together prior to combustion \cite{1.13}. Some of experimental means of establishing turbulent flame are conical stationary flames on cylindrical nozzles, swirling flames, constant volume vessels, stagnation point flames etc. Detailed physical and chemical structures of laminar premixed flame are shown in Fig 1.1.

A typical turbulent premixed flame can be characterized by turbulent Reynolds number \cite{1.16} defined as,

\begin{equation}
Re_T = \frac{u' l}{v}
\end{equation}

where \( u' \) is fluctuating component of velocity, \( l \) is the turbulent integral length scale and \( v \) is the kinematic viscosity. Assuming equal diffusivities for all reactive scalars, a unity Schmidt number, \( Sc = \nu / D \) serves the scaling purpose. The flame thickness \( l_F \) can be defined:

\begin{equation}
l_F = \frac{D}{s_L}
\end{equation}

Where \( D \), diffusivity and \( s_L \) is the laminar burning velocity.

or, \( D = l_F s_L = \nu \quad (1.2a) \)

Using Equation (1.2a) and (1.1), \( Re_T \) can be written as,

\begin{equation}
Re_T = \frac{u' l}{l_F s_L}
\end{equation}

Turbulent Damkohler number can be expressed as,
where $\tau_F$ is characteristic fluid time scale, $\tau_c$ characteristic chemical time scale. This can be expressed,

$$Da = \frac{\tau_F}{\tau_c}$$  \hspace{1cm} (1.4)

Furthermore, using definitions of Kolmogorov time, length, and velocity scales, turbulent Karlovitz number can be written as the ratios of flame scales in terms of the Kolmogorov scales,

$$Ka = \frac{t^2}{\eta^2} = \frac{u_{\eta}^2}{s_L^2}$$ \hspace{1cm} (1.5)

Since the interaction between chemistry and turbulence occurs at the smallest scale only, the Damkohler number defined by (1.4) has no direct physical significance as far as the interaction between turbulence and chemistry is concerned. It can be shown, however, that the condition $Da = 1$ corresponds to the largest value of a mixing length scale that will be introduced below.

Using definitions of turbulent length, time and velocity scales the following relations between the ratios $u'/s_L$ and $l/l_F$ in terms of the non-dimensional numbers $Re$, $Ka$ and $Da$ can be expressed using equation (1.3) and (1.4) as,

$$\frac{u'}{s_L} = Re \left( \frac{l}{l_F} \right)^{-1}$$ \hspace{1cm} (1.6)

$$\frac{u'}{s_L} = \frac{1}{Da} \left( \frac{l}{l_F} \right)$$ \hspace{1cm} (1.7)

Using the relation, $Re = Da^2 Ka^2$ and (1.6, 1.7) it is obvious that,

$$\frac{u'}{s_L} = Ka^{2/3} \left( \frac{l}{l_F} \right)^{1/3}$$ \hspace{1cm} (1.8)
where $Ka$, turbulent Karlovitz number is the ratio between flame time, $t_f$ and Kolmogorov time scale, $t_\eta$. A regime diagram for premixed turbulent combustion is shown in Fig. 1.2.

Characteristics of turbulent premixed flame are well summarized in several literatures [1.17-1.20]. Based on imposed physical environment, boundary conditions and geometry constraints flame surface starts twisting and bending due to turbulent flow field. Local flow conditions such as localized turbulence propagation, vorticity and density gradient etc influence flame dynamics greatly. Huge difference in specific volume (six to eight times) between reactants and products generate an uneven pressure field which affects velocity field and circuitously the growth of flame surface. Flame becomes more unstable due to this irreversible feedback mechanism observed even in simplest case of laminar flame. Turbulence thus produces wrinkled flame surfaces where surface curvature, strain and stretch rate becomes imperative. These quantities along with few nondimensional parameters can be considered to characterize the flame discussed in next paragraph.

Depending on the $Re, Ka$ and $u'_0/L$ a region can be identified in turbulent regime diagram. Each region has their own characteristics. Flame vortex interaction plays an important role in flame stabilization for high $Re$ number flows. For wrinkled flamelets the flame is much thinner than the Kolmogorov length scale, retains the laminar flame structure of the flame within the turbulent flow field. So flamelet surface wrinkles slightly. In corrugated flamelet regime flame surface becomes highly convoluted due to strong flame vortex interactions. Increasing turbulence starts breaking down the reaction zone and may create holes in flamelet. Flame vortex interaction is shown in Fig. 1.3.
1.3 Bluffbody Flame Stabilization

Flow past a bluffbody with $Re > 100$ starts to separate downstream of the body due to adverse pressure gradient. In case of turbulent flow ($Re_T > 3000$, based on integral length scale) flow will generate wake region behind the bluffbody and dissipate energy in the form of vortices and eddies. It is well known that in non-reacting flows, the interaction of these vorticity regions creates large-scale, asymmetric vortices, termed Bernard-Von Karman (BVK) vortices, which shed from the base of the bluff body [1.21-1.22]. The bluff body generates a slowly moving recirculation zone of the combustion products, which serves as the hot stream to effect ignition and flame stabilization [1.23].

Analysis and results of the mixing-layer or shear layer ignition problem are commonly used to explain flame stabilization and blowoff in practical combustors like ramjets and afterburners. A schematic of high-speed, cold, combustible fluid flow over a bluffbody is shown in Fig. 1.4. A bluff body (wedge shaped bluff body is shown in Fig. 1.4) creates wake region behind it and helps in flame stabilization discussed in next paragraph.

Energy dissipation takes place in the bluff body generated wake region and fluid movement slows down compared to outer main stream velocity. It allows enough time for oncoming fuel-air mixture chemistry to occur continuously. Flame anchoring phenomena enhances with the shape and size of the wake region.

Thus the fundamental phenomenon of bluff-body stabilized flame attachment and blowoff is not mixing-layer ignition. The problem of interest here is actually the stabilization of an existing flame in the mixing layer, with stabilization being achieved by the dynamic balance between the local flow velocity and flame velocity at the leading edge of the flame as in Fig. 1.5.
1.4 Aerodynamic Flame Strain and Stretch Rate

The aerodynamic strain and stretch rates are important quantities in the understanding of flame phenomena such as extinction and the local unsteady structure of turbulent premixed flames. Stretch effects were first studied by Karlovitz (1963) to describe flame extinction, Lewis and Elbe (1961) to explain flame stabilization, Markstein (1964) to understand flame front instability.

Stretch rate at any point on this surface can be defined as the Lagrangian time derivative of the logarithm of the area $A$ of an infinitesimal differential element on the flame surface with the surface element boundary moving tangentially along the surface at the local tangential component of the fluid velocity [1.14]. This can be written as,

$$\kappa = \frac{1}{A} \frac{dA}{dt} \quad (1.9)$$

and could be expanded as,

$$\kappa = -\hat{\mathbf{n}} \hat{V} \left( \hat{\mathbf{v}}_{\text{surface}} \times \hat{\mathbf{n}} \right) + \left( \hat{\mathbf{v}}_{f} \cdot \hat{\mathbf{n}} \right) (\nabla \cdot \hat{\mathbf{n}}) \quad (1.10)$$

where $\hat{\mathbf{n}}$ is the surface normal vector and $\hat{\mathbf{v}}_{\text{surface}}$ is the flow velocity on flame surface, where the flame surface has a velocity $\hat{\mathbf{v}}_{f}$ and the flow has a velocity $\hat{\mathbf{V}}$. This could be shown to be the contribution of aerodynamic straining, flame curvature and flame motion respectively. For 2D flames in Cartesian coordinates the aerodynamic straining part can be shown to be,

$$\kappa_{s} = -\hat{n}_{x} \hat{n}_{y} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \left( 1 - \hat{n}_{x}^{2} \right) \frac{\partial u}{\partial x} + \left( 1 - \hat{n}_{y}^{2} \right) \frac{\partial v}{\partial y} \quad (1.11)$$
Flame stretch plays a key role expediting extinction characteristics for high Lewis number 
\((Le > 1)\) flames, \(Le = \frac{\text{Thermal Diffusivity}}{\text{Mass Diffusivity}}\) of deficient species which is 
fuel for lean propane-air combustion.

If the stretch rate is greater than some critical value, the flame will be extinguished 
because the flame temperature is too low or residence time is too short under such high stretch 
rates. This critical stretch rate is defined as the extinction strain rate.

For a turbulent flame, such as swirling flame, the stretch rate along the flame front is not 
a constant. At one specific point, if local stretch rate is higher than some critical stretch rate, 
local extinction occurs and a flame hole is generated [1.24].

1.5 Lean Blowoff Limit Behavior

Lean premixed (LP) combustion is currently the main method used in low NO\(_x\) emission 
land based gas turbines. Investigation of lean blowoff is very important from this point of view 
for normal operation of these combustors. Flame blowoff in practical combustor often involves a 
competition between the rates of the chemical reactions and the turbulent mixing. Based on this 
competition, currently there are two main approaches, perfectly stirred reactor (Damköhler 
number) and flame propagation models, used to model blowoff, see Fig. 1.2. Studies conducted 
by our group reveals different aspects of bluffbody stabilized flame behavior in previous studies 
in the literature [1.25-1.30].

According to perfectly stirred reactor (PSR) model for blowoff, flame stabilization occurs 
where turbulent and molecular mixing are quicker than chemical reactions, thus transport 
properties of the mixture are not limiting phenomena. So PSR model essentially assumes that
flame holding characteristics are mainly influenced if incoming reactants posses sufficient time for chemical reaction to occur. So Damköhler number based correlations are outcome of this model. When the residence time is too short relative to the chemical time, lean blowoff occurs.

Second approach uses flow speed and turbulent flame speed to explain flame blowoff limits introducing flamelet-like combustion properties, where the stabilization mechanism is related to front propagation, rather than reactor extinction. Whenever, turbulent burning velocity, $s_T$ exceeds local flow velocity, $u_{local}$ flame blowoff occurs. For correlation purposes, this approach establishes a dimensionless parameter, $s_T/u_{local}$ to explain blowoff. However, this brings additional complexity of calculating turbulent flame speed for widely varying mixture compositions.

Though the physics behind Damköhler number and flame propagation models are conspicuously different, a mathematical analogy can be drawn to interrelate them.

\[
Da = \frac{\tau_{flow}}{\tau_{chem}} = \frac{l_{char}/u_{local}}{l_{char}/s_T} \tag{1.12}
\]

where $l_{char}$ is the characteristic length scale, can be expressed as ratios between flow and chemical length scale. $l_{char}$, a characteristic length scale adds more difficulty to develop a general mechanism for blowoff as we first need to decide which length scale fits better describing blowoff event unambiguously. Especially our earlier studies have shown that lean blowoff is often not an abrupt process. Before blowoff, the flame tends to oscillate between extinction and reignition phases and finally extinguishes. This forces us to investigate an extinction timescale helpful in developing blowoff correlation.
1.6 References


Figures

(a)

(b)

**Fig. 1.1**: Schematic of (a) detailed structure of premixed flame including the reaction zone [1.14] (b) chemical structure of a premixed methane air flame [1.15]
Fig. 1.2: Regime diagram for premixed turbulent combustion [1.16]
Fig. 1.3: (a) Weak flame-vortex interaction ($u'_0 < s_L$) resulting in a wrinkled flamelet. (b) Strong flame-vortex interaction ($u'_0 > s_L$) resulting in a corrugated flamelet. (c) Strong flame vortex interaction with the smaller eddies penetrating into and broadening the preheat zone of the flame [1.16]
Fig. 1.4: Schematic showing flame stabilization by bluff body in high-speed flows [1.14].
Fig. 1.5: Schematic demonstrating that flame holding is a phenomenon of flame stabilization instead of ignition [1.14].
Chapter 2
Phase Resolved Characterization of Conical Premixed Flames Near and Far from Blowoff

2.1 Introduction

Flame stabilization and lean flame blow off phenomena in premixed combustion mode, has long been a subject of significant practical and technological interest for a wide variety of applications, such as gas turbine combustors, afterburners, ramjets, rockets and industrial furnaces. Commonly used two main flame stabilization schemes employed in premixed combustion systems include swirl and bluff-body stabilization. A number of seminal works by Zukoski and Marble have shown the global flame holding characteristics of a bluffbody stabilized turbulent premixed flame [2.1, 2.2]. Flame stabilization characteristics in spatially stratified fuel–air mixture configurations under external flow oscillations were recently studied by Chaudhuri and Cetegen [2.3] and a non-oscillatory configuration has been modeled in [2.4]. Flame blowoff occurs when the chemical induction time scale for ignition exceeds the characteristic flow time scale, expressed in terms of Damköhler number as $Da = \frac{\tau_{chem}}{\tau_{residence}} > 1$ [2.5]. But the scenario is not straight forward because of the closely-coupled nature of momentum transport in turbulent flow with chemical reaction [2.6]. Flame dynamics gets more complicated when external acoustic excitations are present.

To understand this fundamental, inherently complex phenomenon of acoustically excited premixed turbulent flame dynamics, phase resolved characterization technique has been applied in an axisymmetric disk shaped bluff body stabilized propane-air flame held at the exit of a
conical nozzle while a loudspeaker at the bottom of the nozzle induced axial harmonic oscillations. The velocity field was characterized at different phase angles within the imposed sinusoidal velocity oscillation cycle and characteristics of the recirculation zone length and strain rates along the flame front were determined from the velocity data.

2.2 Experimental Setup

The experimental setup is schematically shown in Fig. 2.1. The burner is made out of brass with a 3.2:1 nozzle diameter contraction with an exit diameter of 40 mm. A stainless steel rim of height 2.5 cm and of the same inner diameter is attached to the burner exit to prevent damage to the brass burner in the case of flame attachment to the burner rim. The fuel-air mixture was fed into the burner through eight equally spaced 0.95-cm-diameter radial ports on the side wall of the burner before the contraction section. A stainless steel circular rod sting with a diameter of 6.4 mm was centered at the burner exit and it was attached to the bottom of the burner. Upstream of the contraction, the burner contained a 2.5-cm-thick honeycomb flow straightener with a cell size of 4.0 mm and a stainless steel mesh screen above it to minimize the flow nonuniformities and to remove the possibility of flashback. Attached at the bottom of the burner was a loudspeaker cavity containing a 12.7 cm diameter subwoofer (Infinity Model 6012i) to modulate the flow. The loudspeaker cavity was designed to allow free movement of the speaker diaphragm while preventing leakage of the combustible mixture through the speaker. The loudspeaker response was calibrated in the frequency range of interest (50 Hz to 400 Hz) to maintain a constant flow velocity modulation amplitude with respect to the mean flow velocity \((u' / U_{mean} \approx 0.09)\) with ±5% error. The flow modulation amplitude was limited by the maximum level that can be attained by the loudspeaker system for the range of mean flow velocities.
studied. A calibrated hot film anemometer probe (TSI Model 1210-20) and IFA 100 signal processing system have been used to measure both $u'$ and $U_{mean}$. The probe was placed at an axial location 1 mm above the level of the disc shaped bluff body and was mounted on two micrometer stage for 2D radial traversing. The measurements at each location were taken over a period of 10 s to capture the turbulence characteristics. [2.7-2.9]

Air flow was supplied by a twin-screw air compressor (Gardner Denver, Model ECHQHE) with a maximum mass flow rate of 0.1 kg/s. The compressor air discharge was first dried by a refrigeration-type dryer (Hankinson Model 80200) and metered by a bank of critical flow orifices to obtain the desired air-mass flow rate or nozzle exit velocity. Instrument-grade propane with 99.5% purity from CT Airgas was metered using a set of mass flow controllers (Porter Instruments, Model 202). Mass flow controllers were interfaced to a DAQ board (NI Model PCI-MIO-16E-1) and the data acquisition computer. The whole experiment was controlled by LabView software interface.

2.2.1 High Speed Chemiluminescence Imaging

A high-speed monochromatic Photron (version 3.0) high speed imaging camera was used to capture flame luminosity at 1000-8000 fps depending on the flame excitation frequency employed. To better explore phase resolved characteristics more than 20 images were acquired per flow excitation cycle at different phases. Camera shutter opening was 1/frames per second.

2.2.2 PIV Measurement

LaVision PIV system was employed for phase resolved PIV measurements. This system includes a frame-straddling 1024x1280 CCD camera (Model Flow Master 3S) and DaVis 7.0.6
post processing software. The camera was coupled with a Nikon 50 mm lens and 532 nm optical bandpass filter to allow only Mie scattering from the approximately one micron alumina seed particles. An Andover bandpass filter (532FS02-50) with a bandwidth of ±1 was used to block the CH* emission. A New Wave (Solo PIV III) dual-cavity Nd:YAG laser (50 mJ/pulse) provided the two consecutive laser pulses for double image, double exposure PIV firing steadily at 10 Hz. The camera shutter opening was controlled by an external TTL trigger pulse coming from LabView generated signal. A delay generator was used to change the position of the pulse at different phase of the velocity excitation cycle.

2.3 Data Analysis Techniques

2.3.1 Conditioned Particle Image Velocimetry (CPIV)

Using Conditioned Particle Image Velocimetry (CPIV) technique, the flame front is identified from the sudden change in the particle number density in Mie scattering images caused by the steep temperature gradient in the reaction zone of flames. In a validation experiment the flame front position was deduced for comparison from planar laser induced fluorescence measurements of OH. Though CPIV is an approximate technique to locate the flame edge, it is found that CPIV yields nearly the same spatial position as the steepest slope in the OH distribution [2.10, 2.11]. Furthermore, this technique has previously proven to be an easy to adapt technique for determination of the simultaneous statistical quantities derived from the extracted flame front shape of reaction progress variable and flow fields, e.g., for the direct determination of turbulent fluxes, the flame surface density and the flame front curvature [2.12, 2.13]. Before going into details of CPIV, its significance and necessity are discussed in next few paragraphs.
Normally, the velocity of a flow field is measured by particle image velocimetry (PIV) for 2D or 3D region or point wise by laser Doppler velocimetry (LDV). Flame structure and subsequent important parameters like flame curvature, turbulent flux etc can be determined from the temperature field along with velocity measurements by planar laser Rayleigh scattering thermometry (PLRS) [2.14]. But this technique involves flames free from any external seeding particles, thus avert the possibility of using simultaneous application of PLRS with PIV or LDV. To surmount this problem a very narrowband molecular filter is used in order to suppress relatively stronger elastically scattered light from the seeding particles only allowing the transmission of spectrally broadened Rayleigh signal from very specific molecules present in flames. This optical diagnostics technique is known as filtered Rayleigh scattering (FRS) [2.15, 2.16]. Obtained FRS signal is then used to determine temperature distribution inside flame. Flame edge is calculated from the local density change due to steep temperature gradient along the flame front separating burnt and unburnt region. Nevertheless, simultaneous FRS and PIV require experimental intricacy and are associated with higher cost.

Hence, laser-induced fluorescence (LIF) signal from radicals which are generated in the flame front and partly persist in the product zone can be used to track the flame front. One commonly used and accepted flame marker is the hydroxyl radical (OH), which shows high concentration close to the main reaction zone, however with a known slight shift towards the product region. Besides OH, C₂, CH and CH₂O molecule can also be used for laser-induced fluorescence imaging to identify the reaction zone of hydrocarbon flames (e.g. [2.17-2.20]). All the optical diagnostics tools described before not only are costly and expensive [2.21], but also come with additional experimental complexity and require simultaneous implementation of
multiple techniques. This demands a relatively easy and quite inexpensive technique to calculate flame edge and related statistics within reasonable confidence level. Conditioned PIV or CPIV is an answer to this hunt.

A concept similar to CPIV is proposed by Armstrong and Bray in 1992 with the aim of measuring conditioned velocities simultaneously in reactant and product mixtures [2.22]. At that time, however, photographic PIV quality which did not allow a statistical evaluation with high enough confidence levels. In 1998 Stevens et al. [2.23] showed correlated vector-scalar measurements for a 1D flame with a similar technique. Since then a good number of journal articles have been published to establish and develop CPIV as an effective technique to define flame edge within a reasonable accuracy level. In present study, advantage of density reduction from unburned to burned region as a flame propagates through a mixture of fuel and air is employed to calculate flame edge. A thorough investigation of Mie scattering intensity over a region of interest, within the flame propagating media reveals a probability distribution function with two distinct peaks as shown in Fig. 2.2. Lower peak signifies the burned region, while the higher peak or the peak with high Mie scattering intensities corresponds to the unburned region. A value in between the high and low peaks may then be used as a level set value, which is one of the key parameter in CPIV technique is defined depending on the physics of the problem and boundary conditions. Any region in the normalized Mie scattering intensity plot with a value above the level set was designated as reactant, while any region below was designated as a product.

Even though seeding particles are moving during the time delay between two successive laser pulses in PIV, allowing us to do velocity calculation, it's reasonable to assume that the
flame front is frozen on both images, therefore the seeding particle displacement remains lower than the flame evolution. Many classical well known tools, such as erosion or dilatation filters, binarization, thresholding or equalization can be used for image processing. Here we will restrain our attention on the Gaussian filter and on active contour models that we have implemented especially to extract the flame front contour. A typical PIV result before and after image processing is shown as an example in Fig. 2.3.

In present studies of turbulent flows, due to high local velocity gradients [2.24] and nonuniformities of seed injection, seed distribution sometimes shows inconsistency and the product-reactant peaks in intensity PDF are close to one another. A crucial parameter for the CPIV technique is the adequate adjustment of the seeding particle density. In case of too high particle densities the accuracy of the velocity determination decreases combined with a non desirable falsification of the heat balance. For too low particle densities the noise in the images increases which prevents the precise positioning of the particle density gradient containing the flame front. The binary pseudo color Mie scattering image in Fig. 2.3a was composed of discrete values, either zero or one. This image was then filtered using Gaussian followed by a convolution filter, with a 9 x 9 kernel size and a standard deviation, $\sigma$, between 3 to 7. Mathematically a 2D Gaussian filter kernel may be expressed as,

$$G_{2D}(x, y, \sigma) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

(2.1)

The $\sigma$ is the standard deviation when we consider the Gaussian probability density function which determines the width of the Gaussian kernel or the adjacent inclusiveness of the convolution, and $\sigma^2$ is the variance. Finally, after careful use of Gaussian filter and active
contour method, flame edge is determined as the longest contour in the flow field as shown in Fig. 2.4.

2.3.2 Validation of CPIV algorithm using OH PLIF results

In present section, a brief discussion of CPIV validation steps have been added obtained by simultaneous particle imaging velocimetry (PIV) and OH planar laser-induced fluorescence (PLIF) imaging. PIV seeding density changes across the flame front allow one to 'approximate' the flame edge location is compared to relatively more accurate results from OH-PLIF technique. It has been observed that the identified flame front using conditioned PIV (CPIV) algorithm produces a good match with OH-PLIF results. Flame front identification as well as curvature statistics is presented side by side as extracted from both these techniques.

The PIV system was combined with the PLIF system for measurement of hydroxyl distributions within the flame as discussed in earlier studies in detail [2.8-2.9]. The PLIF system consisted of an Nd:YAG laser (Continuum, Model Surelite II) operating at 10 Hz and pumping a dye laser (Lumonics Model HD-500) containing Rhodamine 590 dye. The generated laser beam tuned to around 560 nm was then passed through a crystal in a frequency doubling conversion unit (Lumonics Model HyperTrax-1000) to create the UV beam needed for excitation of OH. Beam energy was about 3 mJ per pulse with a wavelength at 282.67 nm in air, centered on the Q_1(5) rovibrational transition in the A^2Σ⁺←X^2Π (1,0) band of OH. The Q_1(5) transition was selected based on its line strength and low Boltzmann fraction sensitivity between temperatures of 1000-2500 K. Once exiting the doubling crystal, the UV beam was passed through f = -250 mm and f = 500 mm cylindrical lenses to expand the beam and focus it into a sheet, through the desired region of interest above the burner. Power measurements were performed using a power
meter (Gentec Model EO ED-200UV). Timing of the pump laser was set such that the PLIF excitation pulse was temporally centered between the two PIV laser pulses. Results obtained for a flame $\phi = 0.9$ is shown in Fig. 2.5.

Determination of a correct flame edge is quite significant for the rest of this study as flame edge map is used to determine the normal direction for strain rate calculations. Fig. 2.5 shows flame edges extracted from simultaneous PIV and OH-PLIF. Fig. 2.5 (a) shows flame front from OH-PLIF data and Fig. 2.5 (b) is from CPIV technique on Mie scattering images. They agree with each other quite satisfactorily. The OH-PLIF images represent the location of hot products including the flame front and the recirculation zone, where CPIV identifies particle density change across flame front due to steep temperature gradient. For comparison purposes, single-shot image results are obtained from both these techniques and the characteristic curvature values along the flame front are determined and plotted in Fig. 2.6 as a function of the normalized arc-length parameter $S$, starting from the bottom of the region of interest (ROI), shown left of Fig. 2.6. The step-size for the cubic spline interpolation is limited by the cutoff window sizes in the PIV method used for this experiment is 2.5 mm.

In Fig. 2.7 a pdf diagram is shown curvature distributions from both these techniques. Here, the width as well as the center of the distributions shows almost similar behavior, whereas the distribution from CPIV is slightly wider than OH-PLIF, meaning that more strong curvatures (i.e., smaller radii) are present in the CPIV-images. This trend is obvious from Fig. 2.6 and may be attributed to the noisier images compared to the rather smooth OH-radical distribution.

Therefore, we can deduce that the shift introduced from OH-LIF and CPIV in different directions relative to the position of the true position does not significantly affect the analysis of geometrical structures.
2.3.3 Strain Rate Determination along Flame Edge

Assessment of curvature statistics for our premixed turbulent flame starts with a histogram based threshold setting with a preceding binning, followed by a binarization of the raw Mie scattering images. For the binarization into unburnt and burnt regions, here, a finer than needed grid-size is chosen to be applied for the evaluation of reaction progress variable fields. A filter length of 9x9 pixels is used for extracting of the flame contour which has proven to be reasonable as discussed in the next subsection where a comparison of CPIV results are compared with OH-PLIF results. Subsequently, the Cartesian coordinates of the region of interest which are located at the flame front are identified, a path-length parameter \( s \) is introduced and a parameterizing of the instantaneous flame front in form of two functions \( \{x(s), y(s)\} \) is performed. This enables the contour representation by a cubic spline interpolation. Finally, the signed curvature, \( \mathbb{R} \), is then calculated using following expression,

\[
\mathbb{R} = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{(\dot{x}^2 + \dot{y}^2)^{3/2}} = \frac{1}{r}
\]  

By convention the flame curvature \( \mathbb{R} \) and the curvature radius \( r \) are defined positive if the flame element is convex toward the reactants. An important curve fitting parameter is the appropriate choice of the interval length scale inside flow field. Oversampling of binary pixels or encountering too many interrogation windows may incur small-scale digitization noise, shifting the PDF towards extremely large curvatures, while relevant length scales of the flame front disturbances are neglected, if the sampling rate is too low or interrogation window size is too big. In present study the interval length is kept in the order of the laminar flame front thickness \( \delta_L \).
Velocity statistics including strain rate on the flame can then be computed from the PIV results. The two-dimensional stress tensor, $e_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$, can be written for an axisymmetric geometry in polar coordinates $(r, \theta, z)$ [2.26] as,

$$
\kappa = \begin{bmatrix}
\frac{\partial u_r}{\partial r} & \frac{1}{2} \left( \frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right) \\
\frac{1}{2} \left( \frac{\partial u_z}{\partial r} + \frac{\partial u_r}{\partial z} \right) & \frac{\partial u_z}{\partial z}
\end{bmatrix}
$$

(2.3)

Assuming no variation in the $\theta$ direction, thus ignoring $\kappa_{r\theta}$, $\kappa_{\theta z}$ and $\kappa_{\theta\theta}$ components of stress tensor matrix. This can be written as a symmetric two dimensional stress tensor containing the normal and shear strain rates that describe fluid element deformation. The final form of the strain rate can be obtained from,

$$
\kappa = -n_z n_r \left( \frac{\partial u_z}{\partial r} + \frac{\partial u_r}{\partial z} \right) + (1 - n_z^2) \frac{\partial u_z}{\partial z} + (1 - n_r^2) \frac{\partial u_r}{\partial r}
$$

(2.4)

Velocity gradients were calculated from the PIV vectors using a fourth order central difference scheme [2.27].

2.4 Results and Discussion

An analysis of the CH* emission signal near and far from flame blowoff is presented here. Experiments were performed at three different mean flow velocities of 5, 10 and 15 m/s. Corresponding to each mean flow velocity, the employed loudspeaker excitation frequencies were 50 Hz, 100 Hz, 300 Hz, 400 Hz in addition to the no excitation cases. For near blowoff cases air flow rate was kept constant in each experiment while the fuel flow rate was lowered gradually until the flame blowoff condition was reached.
There is a phase lag between the imposed speaker excitation signal and velocity excitation at the nozzle exit due to the convective delay. Comparing the cold flow PIV results with the speaker oscillation time series, it was found the velocity oscillation at the bluff body flame holder position was lagging by 15-20° of speaker excitation signal. In the results shown and discussed below, nine different equidistant phase angles of the velocity excitation cycle, labeled from 'a' to 'i' respectively, were selected for analysis as shown in Fig. 2.8.

2.4.1 Phase Resolved Flame Dynamics

Only cases presented here are for flow velocities of 5 m/s and 15 m/s for external excitation frequencies 0 Hz, 100 Hz, and 300 Hz for the unconfined and confined flow configurations. In blowoff sequences the cycle preceding the blowoff cycle has been shown followed by an image labeled as 'x' as the image at flame blowout. PIV results are shown later corresponding to a velocity oscillation cycle for the unconfined case and at different phase angles.

Fig. 2.9 shows the time sequence of flame luminosity without excitation and at 100 and 300 Hz excitation for unconfined configuration at 5 m/s mean flow velocity. Harmonic flow modulation results in vortical structures that are created near the flame holder and convect downstream. Successive flame structures appear to have a constant spacing at 100 Hz while merging of these structures occurs at 300 Hz. At 300 Hz flame structures are less well-defined. The flame blowoff sequence in the lower part of the figure indicates that blowoff occurs by progressive weakening of the flame near the base and eventual blowoff. At 100 Hz, the flame base gets extinguished and the flame blows off with the convection of the last flame structure. At 300 Hz, flame structures are less defined and flame blowoff occurs by progressive weakening.
of the flame base. Observations are similar for the higher velocity case of 15 m/s with the exception that the flames are more turbulent as expected in Fig. 2.10. In this case flame modulation at 100 Hz exhibits less symmetric flame structures and a more columnar flame near its base. Flame structures evolve to their largest lateral extent at distance of about seven to ten times flame holder diameters. At 300 Hz, the flame appears to be more fragmented and the vortical structures are disconnected indicating extinction of flames in between these structures. Flame blowoff sequence shown in Fig. 2.10 also suggests a progressive weakening of flame structures as blowoff is approached.

The flame images for the confined geometry are shown in Figs. 2.11 and 2.12 for the 5 and 15 m/s cases respectively. At 5 m/s, the flame envelope completely fills the quartz tube and modulations at 100 and 300 Hz create flame structures near the flame base and at the exit of the quartz tube. Close to blowoff, flow modulations result in disconnected flame structures near the base and gradual weakening of the flame emission precedes the final flame blowoff. At 15 m/s, flames do not fill the tube cross-section completely and are more slender. Because of the higher turbulence levels expected in these flames, flame structures are less symmetric with distinct breaks in the flame, particularly at 300 Hz. Blowoff sequence shows similar features of broken flame structures, extinct regions in between and gradual weakening of flames near the base before blowoff.

2.4.2 Flame Edge Identification

Flame edge is identified using CPIV algorithm and strain rate is determined along the flame edge using equations mentioned in 2.3.2. Identified flame edge is shown over a complete velocity oscillation cycle for $U = 5 \text{ m/s}, \phi = 0.9, f = 100 \text{ Hz}$ is shown in Fig 2.13. ROI (region
of interest) is restricted to 5-6 bluff body diameters downstream of the flame to keep uniformity in calculating strain rate pdfs presented subsequent paragraphs of this thesis. The flame loses its conical or 'V' shape as the cycle progresses. It becomes more columnar with a reduction in flame waist prominent in phase 'e'. At phase 'e', clear presence of outside vortex rings imposes strain on the flame, which gradually decreases at the end of the cycle. Phase 'a' and 'i' are identical, so does the flame behavior. For ease of understanding, a small schematic underneath each flame image indicates corresponding phase point on velocity oscillation cycle.

Fig 2.14 and 2.15 show the velocity field at different phases of the imposed flow oscillation for a mean flow velocity of 10 m/s at 100 and 300 Hz oscillation frequencies. Imposed on these velocity fields is the flame front as identified by the seed density change and the magnitude of the strain rate variation along the flame contour as color-coded levels. Strain rates were calculated from the velocity field given in previous section. Generated vorticity from the edge of the bluffbody as convected downstream is captured in velocity field data. These vortices play an important role on flame dynamics as average strain rate keeps changing at each phase, based on the location of vortex rings surrounding the flame.

From Figs. 2.14 and 2.15, strain rate changes are tracked along the flame contour. The flame contour is calculated using a conditioned particle image velocimetry (CPIV) algorithm. CPIV takes advantage of density reduction (>5) between cold reactants and hot products. Inert alumina particles (~ 1 micron) following the fluid motion encounter volumetric seed density change and thus Mie scattering from this particles change. From PIV Mie scattering image a sample region of interest is subdivided into many small regions over which Mie scattering intensity pdfs are calculated. These pdfs contain two distinct peaks as shown in Fig 2.2, the
smaller one indicates burned gas and the taller one represents the unburned air-fuel mixture. Their mean intensity is used as level intensity to extract flame contour. This is done over many small subsections. When successively decreasing the window size does not affect the extracted flame edge, the final flame edge contour is obtained. For all cases, a downstream region of 5 to 6 bluffbody diameters was considered to calculate flame strain. In both Figs. 2.14 and 2.15, the velocity oscillation in the form of advecting vortices is observed to decrease the flame width at some locations downstream and some phase angles. High magnitudes of strain are predominantly found in the close interaction regions of the flame front with vortices, particularly in the upstream regions (see for example, Fig. 2.14 e, f and g). At $f = 300$ Hz, the flame waist, or minimum flame width downstream, becomes smaller than that at $f = 100$ Hz; whereas the average flame widths are similar. At the same time, average strain along the flame front increases for $f = 300$ Hz compared to the case of $f = 100$ Hz. Outer shear layer pinching is more prominent at $f = 300$ Hz. As discussed later, this increased flame perturbation leads to a reduction in the blowoff equivalence ratio at $f = 300$ Hz; whereas at $f = 100$ Hz, the flame perturbation has no measurable effect on the blowoff equivalence ratio.

### 2.4.3 Strain Rate PDF

Figures 2.16 and 2.17 show the strain rate probability density functions (PDFs) as the flame undergoes an oscillation cycle for the same conditions as in Figs. 2.14 and 2.15. The most probable strain rate is lowest at phase “a” during the middle of the increasing portion of the velocity oscillation. The most probable strain rate on the flame front increases until it reaches a maximum at between phases “d” and “e” during the middle of the decreasing portion of the velocity oscillation and which then progressively decreases back to the beginning of the cycle.
This very repeatable behavior of strain rate PDFs are similar for all velocities and excitation frequencies although the distributions are wider for the higher frequency and velocity cases, particularly for those phases where maximum strain rates are observed. This broader distribution of strain rates is consistent with the larger perturbation of the flame front topology observed in Figs. 2.14 and 2.15 for higher oscillation frequencies.

In Fig. 2.14, the flame front during phase “a” – “b” is largely unperturbed below a height of 30 mm. As the velocity oscillation reaches a maximum during phase “c” – “d” the flame narrows. During the velocity decrease, the flame is modestly pinched and forms a waist that is apparent in phases “e” – “f” that then advects downstream. The waist is a minimum width near phase “g”. The perturbation of the flame surface by the vortex pinching is accompanied by an increase in the strain on the flame as apparent in Fig. 2.16. For the higher oscillation frequency (Fig. 2.15), the sequence of flame shape changes and strain increases are similar, but stronger pinching of the flame and a smaller waist is observed that correspond to a higher most probable strain in Fig. 2.16. With increased average velocity, as in Fig. 2.17, the same trends are observed but with a wider distribution of strain for both oscillation frequencies.

Idea behind exploring phase resolved flame dynamics requires instantaneous measurements and analysis of subsequent datasets. So the entire flame edge detection and strain rate PDF calculations are based on instantaneous images from chemiluminescence and particle image velocimetry. This raises a legitimate question on repeatability of measured strain rates over a particular velocity oscillation cycle. Strain rate pdf at phase 'e' plotted for different PIV images are shown in Fig. 2.18. This confirms adequate repeatability from experimental standpoint and ensures the consistency of average strain rates.
2.4.4 Oscillating Recirculation Zone

Oscillation of recirculation region has been studied by many researchers under a wide variety of experimental conditions due to acoustic perturbation, flow instability, variation in turbulence levels etc [2.28-2.30] and is itself a very fascinating research topic. In our studies, recirculation zone responds to the sinusoidal velocity excitation as it is clearly observed almost for all frequencies ranges from $f = 50$ Hz to 400 Hz. For the same level of turbulent intensity, higher the upstream velocity, fluctuation of recirculation zone length about the mean increases. At lower excitation frequency recirculation zone gets more time to respond, but with increasing frequency recirculation zone response reduces. In fact with frequency higher than $f = 400$ Hz, recirculation zone oscillation becomes so fast, that its length seems unaffected. Length of recirculation zone normalized by bluffbody diameter, $L_{RZ}/d$ is plotted over a full external oscillation cycle is shown in Fig 2.18. In the second half of the velocity oscillation cycle recirculation zone length becomes smaller than the mean RZ length, $L_{RZ|\text{mean}}$ and reaches minima at phase 'g'.

2.4.5 Flame Dynamics Near Blowoff

The chief purpose of the present study is to characterize near blowoff flame dynamics in order to better understand and predict unsteady processes associated with flame extinction and development of a subsequent blowoff mechanism under upstream velocity oscillation. An extensive amount of phase resolved particle image velocimetry measurements were conducted mainly at three different mean flow velocities, $U = 5, 10, 15$ m/s, with $u'/U \sim 0.08$ and over a range of sinusoidal excitation frequencies, $f = 0, 50, 100, 200, 300, 400$ Hz on an unconfined bluffbody stabilized propane-air premixed flame. First, blowoff points are determined for a fixed
mean velocity over different excitation frequencies. Then a common equivalence ratio is selected slightly higher than the highest blowoff equivalence ratio for that particular velocity. Thus, near blowoff equivalence ratios investigated in the present study for $U = 5, 10$ and $15 \, m/s$ are $\phi = 0.73, 0.8$ and $0.88$ respectively.

Figure 2.20 shows PIV seed effect on blowoff equivalence ratio. The near blowoff flame gets weaker and is highly susceptible to external disturbances, of possible concern is the the effect of seeded particles in the flame as they may change the flame blowoff limit. Fig. 2.20 confirms negligible effect of PIV seeds on the flame blowoff limit.

Figure 2.21 illustrates flame dynamics near blowoff. Flame front starts breaking down and flame curvature increases. At the lower flow velocity, $U = 5 \, m/s$ flame pinching is enhanced with increase in frequency up to $f = 300 \, Hz$. At higher frequency of $f = 400 \, Hz$ flame becomes quite unresponsive as the characteristic flame response time exceeds the time period of the external oscillation. For higher mean flow velocity, $U = 10$ and $15 \, m/s$, with increase in frequency shear layers roll up and pinch the flame making flame waist narrower, therefore helps in cold reactant entrainment. At higher equivalence ratio, away from blowoff, flame appears axisymmetric. As equivalence ratio reaches nearly blowoff limit, flame symmetry diminishes. This explains the fact that flame behavior becomes highly responsive to external perturbation and hence demands an explanation of the forced blowoff mechanism.

The vortex structures generated at the burner outlet is due to interaction between flame-quiescent ambient and is strongly dependent on mean velocity and excitation frequency. These vortical structures do not represent the preferred mode of the jet with a diameter of 40 mm (brass burner exit diameter). To reduce wall interference a bluffbody diameter 10 mm (1/4 times the diameter of exit nozzle) was selected. The disc shaped bluffbody is 4 mm higher than nozzle exit.
for ease of visualization. Vortex structures also depend on the diameter and shape of the bluff body.

Strain rate PDFs before flame blowoff are plotted in Fig. 2.22 and are compared with those away from blowoff for same flow conditions, $U = 10 \text{ m/s}, f = 300 \text{ Hz}$. The fact that average strain rate decreases as the flame approaches blowoff is evident from strain rate pdfs as they tend to shift to lower strain rate values as compared to the far-from-blowoff cases. Strain rate variation (difference between maximum and minimum strain rate) is higher for vigorously burning cases than those for the near blowoff cases. But surprisingly the phase where maximum strain occurs, remains unchanged for both the cases. For all cases this phase is in between two phases 'e' and 'f'.

A comparison of strain rate pdfs at phase 'e' and 'f' of a velocity oscillation cycle near and far from blowoff is presented in Fig. 2.23. In both cases probability of getting a high strain rate occurs at far from blowoff condition. As flames reaches near blowoff condition, strain rate decreases. This is further discussed in the context of the numerical results discussed in chapter 3.

Average extinction strain rate can be calculated as the mean of corresponding strain rate pdf, $\bar{\kappa} = \int_0^\infty \kappa P(\kappa) d\kappa$. As mean extinction strain rate reaches maximum at phase 'e', this is investigated over different flow conditions and equivalence ratio. Normalized strain rate can be expressed as Strouhal number, where $St = \frac{fL}{U}$ is the dimensionless Strouhal number, $f$ is the frequency of vortex shedding (in our case excitation frequency), $L$ is the characteristic length and $U$ is the velocity of the fluid. Extinction strain rate normalized by forcing frequency as shown in Fig 2.24 (top) produces a good fit. The equation of the curve can be represented by,
\[
\frac{\kappa}{f} = 1.052 \left( \frac{fL}{U} \right)^{-1.018}
\]  

(2.5)

It implies \( \kappa L/U \) is a constant. So extinction strain rate becomes independent of external forcing frequency near blowoff. Only dependence remains on mean flow velocity, \( U \) and characteristics length scale, \( L \) can easily be understood. Fig. 2.24 (bottom) shows a plot of \( \frac{\kappa L}{U} \) versus Strouhal number.

2.4.6 Forced Blowoff Mechanism

Figure 2.19 shows the streamwise length of the recirculation zone normalized by the bluff body diameter (10 mm) as a function of phase angle during the oscillation cycle for the mean velocities of 5 and 10 m/s. The recirculation zone length was determined from the phase resolved PIV data as the average axial location in the flow where the streamwise velocity changes from negative to positive. It is found that the recirculation zone length oscillates in phase with the imposed velocity oscillations and exhibits a maximum at the highest velocity and a minimum at the lowest velocity. The influence of this on flame blowoff under flow oscillations can be seen in Fig. 2.25 where normalized flame blowoff equivalence ratios, \( \psi(f) = \phi(f)/\phi_0 \) are plotted as a function of the ratio of minimum length of the recirculation zone (RZ) divided by the convective wavelength, \( \lambda = U/f \). Here \( \phi(f) \) is the blowoff equivalence ratio at a given flow oscillation frequency, \( f \), and \( \phi_0 \) is the unforced blowoff equivalence ratio. In both cases, the fuel fraction was decreased at constant average velocity and fixed oscillation amplitude and frequency until the flame was extinguished to determine the blowoff equivalence ratios. It is clear from Fig. 2.25 that the normalized equivalence ratio reaches a maximum between 0.3 < \( L_{RZ}^{\text{min}} / \lambda \) < 0.55.
For almost all cases, the minimum recirculation zone length occurs between phase angles of 270 and 315 degrees at phases between 'g' and 'h'. When the recirculation zone length is minimum, the cold reactants penetrate farther toward the centerline as is apparent in Fig. 2.14 and 2.15 where the minimum flame waist is observed around phase “g”. This pinching may lower the temperature of this zone leading to flame blowoff. Figure 2.26 shows one realization of Mie scattering for $U = 10 \text{ m/s}$ and $f = 300 \text{ Hz}$ during phase “f” near the minimum waist location. Enhanced penetration of seed into the recirculation zone is apparent as compared to other phases of the conditions with larger flame waists where little seed is observed directly in the recirculation zone. This potential cooling of the recirculation zone is consistent with our earlier finding reported elsewhere [2.8, 2.9].

After a careful study using time resolved chemiluminescence imaging and phase resolved PIV have been utilized to investigate the forced blowoff mechanism in bluff body stabilized turbulent premixed flames. The sequence of events has been summarized in the flow diagram shown in Fig. 2.27.

It was found that with reduction of equivalence ratio as blowoff was approached, the flame shape changes from a conical to a more columnar shape and the degree of interaction of the flame front with the shear layer consequently increases, with increased flame instability. Near blowoff, for initial phases (phase 'a' to 'd') of the oscillation cycle, vortices surrounding flame kernel interact with the flame to induce high local strain or hydrodynamic stretch rates that exceed the corresponding extinction stretch rates, resulting in local flame extinction along the shear layers. As the velocity oscillation cycle progresses (phase 'e' onward), it increases imposed strain rate on flame front followed by a reduction in recirculation zone size. Shear layers starts rolling up and makes the flame kernel weaker and narrower by pinching flame waist. Whenever
a flame hole is created due to shear layer extinction, fresh cold reactants entrain through the shear layers to react within the recirculation zone due to favorable residence time there. If recirculation zone contains enough heat to relight fresh reactants, flame may survive for several milliseconds (evident from high speed CH* imaging) and can reignite the shear layers such that the entire flame is reestablished temporarily. This extinction and reigation event can happen repeatedly before final blowoff which occurs when recirculation zone length drops below a certain critical range and flame strain exceeds the time scale duration it's acting on flame. Then the flame kernel fails to reignite the shear layers and flame blowoff occurs.

2.5 Conclusions

Physics behind blowoff mechanism of bluffbody stabilized premixed turbulent flame under flow field excitation still not fully understood and seeks further investigation. Detailed experimental studies are needed to unveil the details of the flame detachment from the flame anchoring point and eventual flame blowoff. Phase resolved characterization is the technique employed to study the flame response and behavior under imposed by external harmonic flow excitation. In this study flame chemiluminescence and particle image velocimetry have been employed to study this problem. Effects of flow modulation on flame topography at conditions near and far from blowoff have been presented in this thesis. Excitation at different frequencies result in some differences in flame structure and flame blowoff behavior as it was observed by our group previously. Lateral confinement of the flame also affects the flame behavior as shown in this study. Phase resolved particle imaging velocimetry was utilized to study the flow field of a bluff body stabilized conical flame undergoing forced periodic velocity oscillations. It was found that both the strain rates along the flame font and the recirculation zone length undergo
periodic oscillations. Maximum strain on the flame was found to occur between 270 and 315 degrees of the sinusoidal speaker excitation cycle corresponding to a minimum in the velocity oscillation. Flame front strain rates increase up to this phase consistent with enhanced perturbation of the flame front topology. This variation is similar for the different velocity and excitation frequency cases. The variation of the recirculation zone length is such that it becomes minimum at about the same phase angle where strain rates are maximum. This stage of the oscillation also results in convection of the cold reactant stream into the recirculation zone, as evidenced by higher density gases observed near the stagnation point, due to the presence of a strong vortex ring above the recirculation zone which leads to flame blowoff. As described in our group’s earlier work and refined in this study, the flame blowoff under oscillatory flow conditions is promoted when the ratio of the minimum recirculation zone length to the convective length scale is in the range between 0.3 and 0.5. Currently CH-PLIF diagnostic technique is being developed to determine the local effects on flame anchoring and flame-vortex interactions more clearly.

2.6 References


Fig. 2.1: Schematic of experimental setup for phase-resolved characterization of turbulent premixed conical propane-air flames.
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Fig. 2.3: PIV result before and after image processing on a flame of $\phi = 0.9, U = 5 \text{ m/s}, f = 100\text{Hz}$ (a) pseudo color Mie scattering image (b) after using Gaussian filter.
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Fig. 2.13: Flame front (shown by red lines) determination using CPIV algorithm over a complete velocity oscillation cycle for a flame of $\phi = 0.8, U = 5 \, m/s, f = 100 \, Hz$. Phase points are indicated underneath each flame image for ease in understanding.
Fig. 2.14: Velocity fields and strain rates determined along the flame front for $U = 10$ m/s, $f = 100$ Hz. Different phases correspond to those in Fig. 2.8.
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Fig. 2.18: Confirmation of strain rate reapeatability is shown for phase 'e' (critical phase as strain rate reaches maximum) for $\phi = 0.9, U = 5 \text{ m/s}, f = 100 \text{ Hz}$. 
Fig. 2.19: Oscillating recirculation zone (a) $U = 5 \text{ m/s} \ [\pm 1.8/-1.7 \text{ about mean}]$ (b) $U = 10 \text{ m/s} \ [\pm 2.5/-2 \text{ about mean}]$. 
Fig 2.20: PIV seed effect on blowoff equivalence ratio, $\phi_{\text{blowoff}}$. 
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**Fig. 2.21:** Near blowoff flame dynamics for different mean flow velocities and excitation frequencies. Flame edge shown by red line is determined using CPIV.
**Fig. 2.22**: Strain rate PDFs near and far from blowoff over a complete velocity oscillation cycle

$U = 10 \text{ m/s at } f = 300 \text{ Hz} \ (\text{left column, far from blowoff, most probable strain for phase 'a' } = 820 \text{ s}^{-1}, \text{ for phase 'e' } = 4280 \text{ s}^{-1}), \ (\text{right column, near blowoff most probable strain for phase 'a' } = 345 \text{ s}^{-1}, \text{ for phase 'e' } = 1120 \text{ s}^{-1})$. 
Fig. 2.23: Comparison of strain rate pdfs near and far from blowoff for $U = 10 \text{ m/s}$, $f = 300 \text{ Hz}$, at two different phases, phase 'e' (top) and 'f' (bottom).
Fig 2.24: Maximum strain rate per cycle normalized by forcing frequency, $f$ (top), strain rate normalized by $\frac{U}{L}$ (bottom) is plotted against Strouhal number, $\frac{fL}{U}$.

Fig 2.25: Ratio of blowoff equivalence ratio at a particular frequency of perturbation with that at no perturbation versus $L_{RZ}/\lambda$ for $U = 5$ and 10 m/s. Two separate measurements are done for each average velocity.
Fig. 2.26: Mie scattering image of shear layer pinching and vortex roll up at $U = 10 \text{ m/s}$, $f = 300 \text{ Hz}$, phase 'f'.
towards blowoff $\phi$ ↓ and $s_i$ ↓, vortex roll up due to forced oscillation becomes dominant

flame dynamics gets affected at the onset of strong shear layer pinching observable from CH$^*$ imaging

strain rate along flame front increases and reaches a maxima between phase 'e-f', evident from phase-resolved PIV

flame waist narrowed down, it affects RZ length and RZ reaches minimum at phase 'f/g'

cold reactant entrains into reduced length RZ and reduces its temperature

RZ temperature drops down below the ignition temperature of oncoming fresh mixture

RZ recovers from imposed strain rate and reignite the shear layer

RZ fails to relight fresh reactant, shear layers fails to reconnect

Fig 2.27: Flow diagram illustrating the hypothesis for lean forced blowoff mechanism.
Chapter 3
Scaling of Blowoff in Unvitiated and Vitiated Bluff Body Stabilized Premixed Flames

3.1 Introduction

Flame blowoff in high-speed combusting flows has been a topic of extensive research for over 60 years. One of the main issues addressed in the past research has been the correlation of flame blowoff as a function of flow parameters and flame holder characteristics. In bluff-body stabilized flame holding, early works have established flame holding criteria in terms of critical time scales or a Damköhler number as a ratio of chemical and flow time scales [3.1, 3.2]. Other work has related the flame holding to a critical heat exchange rate between reactants and products [3.3, 3.4]. Since then, many other studies have focused on establishing the flame blowoff parameters for uniform homogenized premixed gases including the effects of different bluff-body geometries on flame holding (see for example, works of Plee and Mellor [3.5]; Rao and Lefebvre [3.6]; and Rizk and Lefebvre [3.7]). These studies have considered the lean blowoff limits for different combustible mixtures, different bluff-body geometries as well as pressure and temperature effects. In some of these studies, effects of fuel droplet vaporization and turbulent mixing have been considered. In addition to these experimental efforts, a series of numerical models have been developed based on the competing time scales related to fluid mechanics in the vicinity of a recirculating flow, including the turbulent diffusion of mass and heat between the reactants and the products, compared to chemical reaction or ignition time scales. However, these global flame stability studies did not consider the detailed structure of the flame due to limited experimental diagnostics available then. With the availability of modern
non-intrusive laser diagnostic techniques detailed experimental characterization of bluff-body flames near extinction has been possible [3.8-3.15].

The motivation of this research work led to the following tasks. First, a comprehensive literature review is conducted to collect all relevant methods and analyses that had been conducted over last few decades on lean blowoff of bluff body stabilized flames. Then different numerical modules are used to evaluate blowoff time scales. They are compared with experimental results to find the best possible correlation and physical mechanism for lean premixed flame blowoff. Finally, these extinction time scales are analyzed to justify and investigate global trends and behaviors of lean flame blowoff.

3.2 Literature Review

Bluff body stabilization of flames is a commonly employed technique for numerous combustion applications, such as thrust augmenters, industrial furnaces and jet planes. Due to a lower stability limit on combustion process denoted by lean blowoff phenomena, these combustors are usually required to operate at lean conditions or equivalence ratio less than 0.75. Lean blowoff is a dynamically unstable phenomenon that directs a flame toward extinction or downstream convection from a stable burning state to enhanced instability. Existing theories envisage lean flame blowoff depending on some inflow parameters that were developed over specific geometry and boundary conditions. In the following paragraphs a comprehensive literature review is presented on flame blowoff mechanism.

There have been recent attempts to correlate the existing experimental flame blowoff data in the literature. Shanbhogue et al. [3.16] reviewed the existing bluff-body stabilized premixed
flame blowoff data and examined different ways of correlating them. Because of the differences
in the experimental configurations and conditions, as well as the lack of detailed upstream flow
characterization in some of the reviewed data sets, it was found to be difficult to obtain accurate
quantitative correlations for flame blowoff. For example, turbulence levels and fuel/oxidizer
mixing conditions upstream of the flame holder have not been typically available in past studies.
Nevertheless, they provided a good description of the flame dynamics behavior prior to blowoff
when flame holes in highly strained regions of the flame near the flame holder first appear. In
some studies, dynamic behaviors of flame luminosity [3.11], and of flame acoustic emission
[3.15] have been analyzed as precursors of flame blowoff.

In recent experimental studies, near blowoff behavior of bluff body stabilized premixed
flames was characterized in our laboratory by combined particle image velocimetry (PIV) and
OH planar laser induced fluorescence (PLIF) [3.12, 3.13] in two different experimental
configurations. Flame front conditioned strain rate data were extracted from these simultaneous
velocity and OH-PLIF measurements and spatio-temporal probability density functions of flame
front strain rates were calculated. Because of the local time-resolved nature of the diagnostics,
measurements of the strain field determine a local fluid time scale. It was the purpose of this
study to test the ability of correlating the experimental flame blowoff data from our group’s
previous studies with different computed time scales using detailed chemical kinetics. This test
is applied to data from two different geometry combustors, to measurements across a range of
lean upstream equivalence ratios, and to data encompassing both unvitiated and vitiated
incoming air streams. In the following we first briefly discuss the work done in past to correlate
lean blowoff phenomena with different non-dimensional numbers.
For a bluff body stabilized flame, Zukoski and Marble [3.17] proposed that, if flow time, \( L/U \) exceeds ignition time, \( t_{\text{ignition}} \) blowoff occurs. At the limiting case when these two timescales are equal is the blowoff criterion, can be expressed mathematically,

\[
Da = 1
\]  

(3.1)

where \( L \), characteristic length such as bluffbody diameter and \( U \), upstream flow velocity.

Longwell et al. [3.18] considered the recirculation zone behind the bluffbody acts like a perfectly stirred reactor (PSR). Using conservation laws for mass, momentum and energy they derived the same mathematical expression as the one derived by Zukoski and Marble [3.17]. Spalding et al. [3.19] modeled the recirculation zone as steady state heat transfer problem adding chemical reaction rate, \( \dot{\omega} \) as a source term. He found two non-dimensional parameters upon solving energy and species equations,

\[
\frac{UL}{a} \equiv \frac{UL \nu}{\nu a} = RePr = Pe \quad \text{and,} \quad \frac{Ap^{n-1}L^2}{a}
\]

(3.2)

where, \( Re \) is Reynolds number, \( Pr \) is Prandtl number, \( Pe \) is Peclet number, Peclet number is defined as the multiplication of Reynolds number and Prandtl Number, \( Pe = RePr \), \( A \) is Arrhenius pre-exponential factor, \( p \) is system pressure and \( L \) is characteristic length, \( \alpha \) is thermal diffusivity. Using these two parameter and laminar burning speed, \( s_L \sim \sqrt{\alpha \dot{\omega}} \) he reaches,

\[
\frac{u}{L} = \frac{1}{\alpha/s_L^2}
\]

(3.3)

where, a chemical time scale can be defined as, \( \alpha/s_L^2 \equiv \tau_{\text{chemical}} \). Then Spalding et al. predicted a blowoff criteria when, \( Da \sim 1 \).

Rizk and Lefebvre [3.20] reviewed the work of Longwell, Zukoski and Marble [3.17,3.18] and found all the models capitulated similar final conclusions, which is a Damkohler
number based correlation, irrespective of the influences of temperature, pressure, geometry and upstream flow condition. Compiling all these works Williams [3.21] proposed a blowoff correlation for bluffbody stabilized flame, and expanded the critical lean premixed blowoff equation as:

\[
\frac{u}{L} = \frac{2\rho s_L^2 c_p}{k} \text{or}, \quad \frac{1}{\frac{u}{L}} = 2 - \frac{s_L^2}{\frac{k}{ho c_p}} \text{or}, \quad \frac{u}{L} = 2 \frac{1}{\frac{s_L^2}{\alpha}} \text{or}, \quad Da = \frac{\tau_{flow}}{\tau_{chemical}} = \frac{L/U}{s_L^2/\alpha} = 2
\]  

(3.4)

where, \( c_p \) = constant pressure specific heat, \( \rho \) = mixture density, \( k \) = thermal conductivity.

Putnam and Jensen proposed a Peclet number based blowoff correlation [3.22]. For bluffbody stabilized flame Peclet number can be defined two different ways, depending on flow velocity, \( U \) and flame propagation velocity, \( s_L \),

\[
P e_I = \frac{UL}{\alpha} \quad \text{and} \quad P e_{II} = \frac{s_L L}{\alpha}
\]

(3.5)

Interpreting their experimental results Putnam and Jensen found, for lean blowoff, \( P e_I = C Pe_{II}^2 \)

which leads to \( C = f^n(Da) \). Essentially this is a Damkohler number correlation too.

All the studies described above didn't consider the effect of localized turbulent structures on flame blowoff. Radhakrishnan et al. [3.23] assumed existence of turbulent coherent structures that affect the lean blowoff significantly and came up with following correlation,

\[
\mathcal{C} = Da/Pr
\]

(3.6)

where \( \mathcal{C} \) is a constant whose value depends on the turbulent level and the geometry.

Loblich et al. [3.24] proposed his the lean blowoff correlations by combining the work of Zukoski and Marble [3.17] and Putnam and Jensen [3.22]. Loblich's formulation emphasizes Reynolds number dependency of lean blowoff and he showed blowoff model proposed by Zukoski and Marble [3.18] works well for \( Re < 10,000 \). Based on that Loblich derived a dimensionless stability number \( (N_x) \) defined as:

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Hoffman et al. [3.25] intimately investigated blowoff dynamics of swirling flows and found Peclet number correlation holds good to predict the blowoff limits in swirling premixed flames for a given geometry, upstream velocity and swirl number. But his work holds good mainly for swirl stabilized premixed combustion.

Lefebvre [3.26] found a non-dimensional parameter for lean premixed blowoff, using a large number of lean blowoff data set obtained from gas turbine and aircraft combustor,

\[ ND_{parameter}|_{blowoff} = \frac{m}{\nu \rho \omega \exp \left( \frac{T}{\lambda_{150}} \right)} \]  \hspace{1cm} (3.8)

where \( m, \nu, \rho \text{ and } T \) denote mass flow rate, recirculation zone volume, system pressure and average temperature of recirculation zone respectively. To reduce this parameter into familiar non-dimensional quantities, different terms in equation (3.8) can be scaled as,

\[ m = \rho U A \sim \rho U_0 L^2, \nu L^3 \text{ and } \exp \left( \frac{T}{\lambda_{150}} \right) \sim \omega \sim \frac{\dot{s}_L}{\alpha} \]  \hspace{1cm} (3.9)

Then,

\[ ND_{parameter}|_{blowoff} = \frac{\rho U_0 L^2}{\nu L^3 \rho \left( \frac{s_L}{\alpha} \right)} = \frac{\dot{s}_L}{\alpha} \]  \hspace{1cm} (3.10)

It is apparent that the indispensable part of this blowoff variable \( ND_{parameter} \) is still a Damköhler number.

Glassman [3.27] pointed out as majority of these theories involve relating the blowoff limits to a ratio of a residence time (or a flow time) and chemical reaction time, predicted lean blowoff mechanisms lead to essentially the same mathematical form of correlation, which is a
function of Damkohler number and Peclet number. He argued on the possibility of recirculation regions having distributed reactor-like properties besides having flamelet properties at most other points along the flame shear layer. This theory allows perfectly stirred reactors or PSR models in correlating lean premixed blowoff behavior.

Altogether a completely different physics governs PSR blowoff mechanism. PSR residence time is calculated as $\tau_{residence} = L/U$, where $L$ and $U$ are characteristic length and time scales respectively. Many studies had utilized flame holder or combustor geometry to define $L$. But in a perfectly stirred reactor, reactor volume plays significant role in the absence of any physical flame stabilizer. Most of the blowoff research work discussed above focused on correlating blowoff limits of a given fuel over varying geometry, pressure, or flow velocity.

### 3.3 Experimental Conditions

Experimental data utilized in this chapter were obtained from earlier studies reported in references [3.11-3.13]. Figure 3.1 shows example flame images from the two different experimental set-ups both using lean propane-air mixtures upstream of the bluff body. The flame image on the left is from an experimental rig with a rectangular test section with cross sectional dimensions of 7.62 cm wide and 3.81 cm high. An equilateral triangular bluff body of 9.5 mm dimension was placed in the mid span of the test section. In this set-up, experiments with both unvitiated and vitiated air streams were conducted with approach flow velocities of 15, 18.5, 20 m/s and 45, 55.5, 60 m/s for the unvitiated and vitiated cases, respectively. The composition and temperature of the vitiated streams are discussed in the next section. The image on the right is from an axisymmetric laboratory burner with a 10 mm bluff body centrally mounted on a stem.
The exit of the nozzle has a diameter of 4 cm and the flames are anchored on the bluff body in an unconfined atmosphere with the mixture flow velocities of 5, 10 and 15 m/s. In the axisymmetric burner only unvitiated room temperature mixtures were examined.

For both geometries, OH PLIF images were collected at a pump beam wavelength of \(~283\) nm using an Nd:YAG pumped dye laser in a region behind the bluff body. The OH fluorescence signal at \(~308\) nm represents the location of hot products including the flame front and the recirculation zone. These images were used to extract flame edge locations, as described in detail in [3.11-3.14, 3.28]. Extraction of a flame edge from a PLIF image involved background subtraction and correction for laser intensity distribution. Filtering of the image was performed by convoluting a two dimensional Gaussian filter kernel over the entire image to reduce noise [3.29]. After filtering, a set threshold of 50% of the maximum fluorescence intensity was used to binarize the image by redefining each pixel as either 1 (greater than the threshold indicating the presence of a flame or hot products) or 0 (less than the threshold) indicating no combustion or hot products. Edge locations were then defined as the locus of points with a change from 0 to 1 in the flame map. Velocity fields were simultaneously measured using a double pulse Nd:YAG laser and frame straddling camera. The OH-PLIF measurement occurred between the two laser pulses used for PIV. The PIV velocity fields were further processed by extracting velocities along the flame edges. These points were then used to determine the strain rate information along the flame front and also to evaluate extinction time scales based on the vorticity around the flame edge. Two-dimensional strain rate information was calculated using [3.30]

\[
\kappa = -n_x n_y \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \left( 1 - n_x^2 \right) \frac{\partial u}{\partial x} + \left( 1 - n_y^2 \right) \frac{\partial v}{\partial y} \quad (3.11)
\]
where \( u \) and \( v \) are the velocity components in the \( x \) and \( y \) directions, respectively, and \( n_x \) and \( n_y \) are the \( x \) and \( y \) components of the flame surface normal vector, \( n \). This strain is the hydrodynamic portion of the overall flame strain. In the present work, curvature effects on flame strain are not considered. Experimental strain rates were computed for two burner geometries, the axisymmetric conical burner and the 2D rectangular burner. In the experimental rectangular combustor, the bluffbody length in the cross-stream direction is eight times the width of the bluff body. Previous examination of the experimental measurements confirms that the flame is approximately two-dimensional in the mean. Detailed descriptions of both experimental configurations can be found in references [3.9-3.14] and the flame front conditioned velocities and strain rates are presented in [3.12-3.14, 3.28]. The inverse of these measured strain rates were used to characterize a local fluid time scale for the flame and are compared to chemical time scales computed from detailed kinetics simulations [3.31].

### 3.4 Computation of Extinction Time Scales

In this study, three different chemical time scales were computed separately using CHEMKIN Pro to compare with the experimental strain rate based time scales. The mixture conditions corresponded to those of the experiments and included premixed propane-air for unvitiated mixture and mixtures with two different vitiation levels. Vitiation in the rectangular burner rig was achieved by burning propane in air upstream of the bluff body test section. This preburner was globally lean with equivalence ratios of \( \phi_{vitiation} = 0.15 \) and 0.25. For unvitiated conditions, the preburner was not used. Just upstream of the bluff body test section, additional propane was injected into the vitiated (or unvitiated) mixture. Six different global equivalence ratios varying from \( \phi_{global} = 0.5 \) to \( \phi = 0.9 \) (lean mixtures) were studied. This global
equivalence ratio was computed from the total propane injected in both the test section and preburner (when vitiated) as, $\phi_{global} = \phi_{vitiation} + \phi_{test\ section}$. Initial mixture temperatures for vitiated cases were 718 K and 966 K for $\phi_{vitiation} = 0.15$ and 0.25, respectively, based on chemical equilibrium calculations. For the unvitiated case, the initial temperature was 298 K.

Chemical equilibrium was used to estimate the composition of the vitiated mixture prior to additional propane injection and this mixture was used in the chemical kinetic calculations. The calculated values of the adiabatic flame temperature from the equilibrium calculations were used as boundary conditions for OPPDIF, PREMIX and PSR calculations. Table 3.1 shows the computed premixed freely propagating adiabatic laminar burning velocity, $s_L$ and corresponding adiabatic flame temperature, $T_{ad}$ for each case examined.

**Table 3.1**: Laminar burning speed and adiabatic flame temperature for different mixture compositions from PREMIX calculations.

<table>
<thead>
<tr>
<th>$\phi_{global}$</th>
<th>Unvitiated</th>
<th>0.15 Vitiation</th>
<th>0.25 Vitiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{ad}$ (K)</td>
<td>$s_L$ (cm/s)</td>
<td>$T_{ad}$ (K)</td>
</tr>
<tr>
<td>0.5</td>
<td>1520.58</td>
<td>7.49</td>
<td>1536.59</td>
</tr>
<tr>
<td>0.6</td>
<td>1719.77</td>
<td>15.68</td>
<td>1735.67</td>
</tr>
<tr>
<td>0.65</td>
<td>1816.25</td>
<td>20.16</td>
<td>1830.16</td>
</tr>
<tr>
<td>0.7</td>
<td>1904.31</td>
<td>24.22</td>
<td>1919.73</td>
</tr>
<tr>
<td>0.8</td>
<td>2068.92</td>
<td>31.55</td>
<td>2085.71</td>
</tr>
<tr>
<td>0.9</td>
<td>2205.22</td>
<td>37.03</td>
<td>2208.63</td>
</tr>
</tbody>
</table>
For a given global equivalence ratio, the adiabatic flame temperatures are similar for varying levels of vitiation. This is expected since the adiabatic flame temperature is not strongly sensitive to whether the propane is burned in the preburner or in the test section. However, even with similar flame temperatures, the laminar burning speed shows a strong sensitivity to the level of upstream vitiation. For example, with a global equivalence ratio of 0.5, the laminar flame speed increases by a factor of ~9 from the unvitiated case (all fuel introduced in the test section) to that of $\phi_{\text{vitiation}} = 0.25$ (half of the fuel burned in the preburner and half in the test section). Laminar burning speeds are also plotted for unvitiated and the vitiated mixtures in Fig. 3.2. These results will be further discussed later in the context of flame stability.

Opposed flow premixed flame time scales were calculated using OPPDIF [3.32]. In each case, the composition of the vitiated gas mixture along with additional unreacted propane introduced in the test section were used boundary conditions on both sides of the opposed flow flame calculation. The solution consists of twin premixed flames propagating away from each other into the opposed streams. The inlet velocity was incrementally increased and the flame solution was obtained at each velocity. This increasing velocity causes an increase in aerodynamic strain on the flame and leads to merging of the twin premixed flames and eventual extinction as determined from the upper turning point of the maximum flame temperature versus strain. The inverse of this extinction strain rate is the extinction time scale expressed as, $\tau_{\text{OPPDIF}} = 1/\kappa_{\text{extinction}}$. $\kappa_{\text{extinction}}$ is accurately calculated from the turning point of the maximum flame temperature versus the strain rate. Several repeated calculations using OPPDIF were performed to capture the exact turning point for every case with reduced step changes in velocity to avoid ambiguity that may arise from Chemkin numerical solver settings. Results from OPPDIF were verified using the Extinction module where arc-length continuation
procedure was used. In these simulations, gas stream velocities have been increased keeping all other parameters (inlet temperature, pressure, mixture composition) the same. The maximum temperature versus strain rate is shown for different equivalence ratios in Fig. 3.2 (a). The local strain is computed from the slope of the axial velocity profile calculated at point 'p' shown in Fig. 3.2 (b), just before the axial velocity reaches its local minimum, in the pre-flame zone. To unambiguously report the extinction strain rate, the turning point of Fig. 3.2 (a) is calculated to make sure the extinction point is captured.

An alternate chemical time scale was calculated using the PREMIX [3.33] code of Chemkin as the ratio of flame thickness to the laminar burning velocity of the mixture, $\tau_{PREMIX} = \delta_f / s_L$. The flame thickness, $\delta_f$, was calculated as the full-width at half-maximum (FWHM) of the volumetric heat release rate. Inlet conditions for the vitiated cases were again computed using chemical equilibrium code. Species with mass fractions below $10^{-7}$ were neglected in specifying boundary conditions for each case.

Finally, an extinction time scale was calculated using the perfectly stirred reactor (PSR [3.34]) code from the upper branch turning point of the S curve. $\tau_{PSR}$ was obtained solving the energy equation for residence time ($\tau_{res}$) for a given temperature and mixture properties. As with the previous calculations, these mixture properties were set using the equilibrium composition of the vitiated gas stream with additional propane as added in the test section of the experiments. Starting from a relatively high inlet temperature, the temperature was incrementally reduced along the vigorously burning branch of the steady S curve to capture the minimum residence time before extinction. In the following section, these three time scales are compared with
experimental results to assess their ability to correlate flame blowoff data compared to the experimental fluid mechanical time scales determined by the local flame strain measurements.

**Table 3.2:** Calculated timescales from OPPDIF, PREMIX and PSR in milliseconds.

<table>
<thead>
<tr>
<th>$\phi_{global}$</th>
<th>Unvitiated</th>
<th>0.15 Vitiation</th>
<th>0.25 Vitiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPPDIF</td>
<td>PREMIX</td>
<td>PSR</td>
<td>OPPDIF</td>
</tr>
<tr>
<td>0.5</td>
<td>5.121</td>
<td>3.5514</td>
<td>4.167</td>
</tr>
<tr>
<td>0.6</td>
<td>2.0165</td>
<td>1.148</td>
<td>1.726</td>
</tr>
<tr>
<td>0.65</td>
<td>1.212</td>
<td>0.8333</td>
<td>1.0023</td>
</tr>
<tr>
<td>0.7</td>
<td>0.9192</td>
<td>0.6606</td>
<td>0.8023</td>
</tr>
<tr>
<td>0.8</td>
<td>0.7843</td>
<td>0.4596</td>
<td>0.5781</td>
</tr>
<tr>
<td>0.9</td>
<td>0.4325</td>
<td>0.3646</td>
<td>0.3984</td>
</tr>
</tbody>
</table>

### 3.5 Results and Discussions

In this study, three different chemical time scales were computed using CHEMKIN Pro to compare with the experimental strain rate based time scales. The mixture conditions corresponded to those of the experiments and included premixed propane-air for unvitiated mixture and mixtures with two different vitiation levels. Vitiation in the rectangular burner rig was achieved by burning propane in air upstream of the bluff body test section. This preburner was globally lean with equivalence ratios of $\phi_{vitiation} = 0.15$ and 0.25. For unvitiated conditions, the preburner was not used. Just upstream of the bluff body test section, additional propane was injected into the vitiated (or unvitiated) mixture. Six different global equivalence ratios varying from $\phi_{global} = 0.5$ to $\phi = 0.9$ (lean mixtures) were studied. This global
equivalence ratio was computed from the total propane injected in both the test section and preburner (when vitiated) as, $\phi_{global} = \phi_{vitiation} + \phi_{test\ section}$. Initial mixture temperatures for vitiated cases were 718 K and 966 K for $\phi_{vitiation} = 0.15$ and 0.25, respectively, based on chemical equilibrium calculations. For the unvitiated case, the initial temperature was 298 K.

Chemical equilibrium was used to estimate the composition of the vitiated mixture prior to additional propane injection and this mixture was used in the chemical kinetic calculations. The calculated value of the adiabatic flame temperature from the equilibrium calculations were used as boundary conditions for OPPDIF, PREMIX and PSR calculations.

3.5.1 Laminar Burning Velocity

The flame speed or laminar burning velocity is the measured rate of expansion or propagation of the flame front in a combustion reaction. This is a unique property of a particular mixture, that indicates its reactivity and exothermicity in a given diffusive medium. Besides, since laminar burning speed contains the physicochemical information of the mixture, many premixed flame phenomena, such as extinction, flash back, blowoff, and turbulent flame propagation, can be characterized using burning velocity being a reference parameter [3.34].

Laminar burning velocity is computed for two different vitiation levels, $\phi = 0.15$ and 0.25 respectively using PREMIX code and plotted as Fig. 3.3 for lean combustion. As anticipated for lean combustion burning velocity increases with increasing equivalence ratio. It turns out that the laminar burning velocity for propane-air mixture is almost 2-4 times higher for vitiated cases, compared to unvitiated cases. Enhancement in vitiation level raises this ratio.
3.5.2 Strain Rate PDF

In the experiments, spatial distributions of strain rates were computed along the flame front from each single shot simultaneous PIV-PLIF measurement. Fifty images of these single shot measurements were assembled to form spatio-temporal probability density functions (pdfs, \( P(\kappa) \)) of strain rate, \( \kappa \). Figure 3.4 shows these results for several different equivalence ratios from robustly burning flames (higher equivalence ratios) to near extinction flames (lower equivalence ratios).

For both geometries, the higher equivalence ratio flames far from blowoff show significant probabilities of very high strain rates and there is a shift towards lower strain rates as the equivalence ratio is reduced approaching blowoff. In each plot for Fig. 3.4, the flow rate is constant but the vitiated gas stream velocity is approximately three times the unvitiated gas stream velocity. Nevertheless, each case shows a similar change in the pdf as blowoff is approached. From each pdf, the mean strain along the flame sheet was computed. An experimental time scale for blowoff was then computed as the inverse of the average strain rate given by,

\[
\tau_{\text{Experiment}} = \frac{1}{\bar{\kappa}} = \frac{1}{\int_0^\infty \kappa P(\kappa) d\kappa} \quad (3.12)
\]

where \( \bar{\kappa} \) is the mean of the strain rate pdf.

3.5.3 Extinction Time Scale Ratios

Figure 3.5 shows the ratio of time scales obtained from each computation divided by the experimental time scale. It was found that the experimental data agree best with the computed time scale based on the counterflow extinction strain rate while the premix and perfectly stirred
reactor time scales show significant deviations from the experimental values as seen in Fig. 3.5. The OPPDIF time scale ratio is constant for all cases, namely unvitiated, axisymmetric, 0.15 vitiation and 0.25 vitiation respectively with a different constant value for each case irrespective of global equivalence ratio. This can be expressed as,

\[
\frac{\tau_{\text{OPPDIF}}}{\tau_{\text{experiment}}} = \mathcal{C}(\text{vitiation level})
\]

(3.13)

where \(\mathcal{C}\) is the scaling constant depends on vitiation level. Constant values are tabulated in the following Table 3.3. This shows a clear trend, with enhancement of vitiation level, scaling constant \(\mathcal{C}\) starts falling down.

**Table 3.3:** Value of extinction scaling constant, \(\mathcal{C}\) for different vitiation level, from OPPDIF calculations.

<table>
<thead>
<tr>
<th>Vitiation level</th>
<th>unvitiated</th>
<th>axisymmetric</th>
<th>0.15 vitiation</th>
<th>0.25 vitiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{C})</td>
<td>2.625</td>
<td>2.21</td>
<td>1.85</td>
<td>1.692</td>
</tr>
</tbody>
</table>

The time scales computed via the three different solvers represent different physical phenomena of flame propagation and extinction. The time scale from PREMIX represents the time for flame propagation over a distance of the flame thickness whereas the time scale from OPPDIF is more representative of the fluid strain measured via the OH-PLIF and PIV technique. It may not be surprising that the OPPDIF time scale would give better agreement to the measured strain. But the quantitative value of predicted strain does not scale correctly with varying levels of vitiation for PREMIX and PSR. However, a clear and consistent trend of these ratios over all conditions studied implies that the OPPDIF time scale correctly captures the variations in
kinetics that occur for unvitiated and vitiated conditions and the variations in flowfield that occur for the axisymmetric versus rectangular bluff body flows. Moreover, the consistancy of this ratio implies that the mean strain is sufficiently representative of the strain distribution as compared to say a maximum strain.

For PREMIX and PSR calculations, the time scale ratios are lower for the vitiated mixtures as compared to unvitiated mixtures and there is not a good collapse of the experimental data by these time scales. For vitiated cases, it is difficult to achieve extinction numerically because of high reactant inlet temperature and enhanced laminar burning speed as shown in Fig. 3.3. For identical global equivalence ratios, the vitiated flame can sustain larger strain compared to the unvitiated flame cases and hence flame stabilization can be achieved at higher velocities in vitiated flow. This finding is also supported from the strain rate pdfs in Fig 3.4, as overall strain rates are higher for the vitiated cases. Thus, the flame can sustain higher strain rates as compared to unvitiated combustion before extinction. The numerically computed $\kappa_{\text{extinction}}|_{\text{vitiated}} > \kappa_{\text{extinction}}|_{\text{unvitiated}}$, makes the vitiated time scale ratio curves fall below the unvitiated cases for $\phi = 0.5 \sim 0.9$. However, the experiments show that even with the significant change in laminar flame speeds resulting from vitiation (as listed in Table 1), the extinction strain rate is not sufficiently altered for a given vitiation level and this is correctly predicted by the OPPDIF extinction strain rate.

3.5.4 Characteristics of Strain Rate PDFs

Fig. 3.6 shows the probability density functions from Fig. 3.5 normalized with respect to the computed OPPDIF extinction strain rate for each respective case. Since the computed extinction strain rate is approximately a constant compared to the experimental mean strain rate
this is equivalent to normalizing by the mean. Thus, if the strain rate pdfs were self-similar in shape a collapse of the normalized pdfs would be observed. In these figures it is clearly seen that the shapes of the pdfs are not the same for the different conditions. Despite the difference in strain distribution, the mean still correlates well with the computed chemical time scales for extinction across the broad set of experiments. Previous work has suggested using the fraction of the pdf exceeding the extinction strain rate as a predictor for flame blowoff [3.16]. Here it can be clearly seen that the fraction of the pdf exceeding the extinction strain rate (or the mean strain rate since these are similar) is larger as the equivalence ratio decreases for all cases as shown in Fig. 3.7. For the unvitiated cases in the two dimensional and axisymmetric configurations, the fraction of the pdf exceeding the extinction strain rate varies from values around 0.1-0.2 at the highest equivalence ratios to values close to 0.5 at low equivalence ratios. The results are fairly similar for experiments from two distinct geometries. In comparison, the fraction of the pdf area exceeding the extinction strain rate is higher for the vitiated cases suggesting that vitiated flames can endure significantly higher strain rates relative to those computed before extinction actually occurs. Thus, for a particular level of vitiation, it would be possible to set a criterion using the fraction of the strain exceeding the extinction strain rate for predicting blowoff but this criterion would vary with upstream temperature or vitiation. The results here imply that the mean strain, at least for the conditions examined, would provide a more consistent correlation for blowoff prediction.

3.4 Conclusions and Recommendations

Correlation of flame blowoff data from earlier experimental studies conducted in our laboratory was sought by utilizing three different chemical time scales obtained from Chemkin
using a detailed propane kinetics mechanism. It’s clear that results indicate the time scale based on the extinction strain rate of a laminar counterflow flame correlates with the experimental results most closely, while time scales calculated based on a laminar premixed flame properties (thickness divided by the laminar burning velocity) and a perfectly stirred reactor do not correlate as well with the experiments. This points out that the initiation of flame blowoff is closely related to a critical extinction strain rate occurring in the vicinity of the flame holder. Our earlier studies reported in the references cited herein have also led to this conclusion and unveiled the flame dynamics preceding flame blowoff. The fraction of the area under the pdf exceeding the calculated strain rate from OPDIFF ranged from 0.1-0.2 at high equivalence ratios which monotonically increases to about 0.4 for lower equivalence ratios for the unvitiated experiments. This fraction is not constant across all experiments. Instead, the mean strain rate computed locally along the flame sheet agrees well with the computed extinction strain rates for all conditions. The fraction of the strain pdf that exceeds the extinction strain rate is significantly higher for the vitiated combustion cases indicating that vitiation allows higher relative tolerance of the flame to higher levels of straining. This also supports the observed fact of higher laminar burning velocity for vitiated cases compared to unvitiated mixture of similar $\phi_{global}$ equivalence ratio. Based on these results it is possible that a local extinction strain based flame blowoff criterion would be most suitable for correlating blowoff limits.
3.7 References


Figures

**Fig. 3.1**: Flame images from two dimensional combustor (left) and axisymmetric laboratory burner (right).
Fig. 3.2: (a) Maximum temperature versus extinction strain rate at 0.25 vitiation for different equivalence ratios. (b) Typical temperature and axial velocity profile for opposed flow simulation.
Fig. 3.3: Laminar burning speed, $s_L$ variation with vitiation levels.
Fig. 3.4: Strain rate probability density distributions from two dimensional and axisymmetric experimental set-ups.
**Fig. 3.5**: Time scale ratios for computed time scales from (a) perfectly stirred reactor, (b) laminar premixed flame and (c) opposed laminar premixed flame divided by the experimental time scale based on average strain rate.
Fig. 3.6: Renormalized probability density functions of flame front strain rates with respect to the extinction strain rate computed from OPPDIF.
Fig. 3.7: Fraction of area under PDF ($f_{PDF}$) exceeding extinction strain rate ($\kappa_{ext}$).
Chapter 4
Recommendations and Future Work

In the present study, a harmonically excited conical flame was studied to determine its behavior near and far from blowoff. After a careful investigation of flame dynamics under upstream velocity oscillation, a forced blowoff mechanism is proposed based on phase resolved particle image velocimetry (PIV) and high speed chemiluminescence results. Later in this study extinction time scale is calculated using different physical models to find out scaling for flame blowoff in vitiated and unvitiated air.

The phenomenological observation regarding the convection and recirculation zone lengths are a beginning, not an end. Strouhal number, $St = fL/U$ based correlation can well be formulated to predict blowoff behavior is a broader scope of study in near future. CH-PLIF measurement system will be introduced to this experimental setup shortly to determine flame edge intimately and unambiguously will help to clarify our proposed forced blowoff mechanism. Present study mostly restricted to unconfined flame configuration where flame can freely interact with ambient. In practice, most commercial furnaces, power generation engines and aircrafts combustion occurs inside a chamber or compartment. Effect of confinement could be significant depending on application. For a ducted flame, flame dynamics in the downstream of the duct depends heavily on upstream flow field history and affects blowoff dynamics accordingly. A thorough study of harmonically modulated flames in confined configuration will be an interesting topic for future research.
Computational timescale calculations are based on steady state physical model of opposed flow flame geometry, OPPDIF. In reality, flame extinction is a transient process where time scales become excessively significant with reduced length scales and increasing instability in the form of vortex shedding, flame pinching, flame front rupture, broken shear layer, flame holes etc near blowoff. Transient time scale and strain rate calculations can be performed using unsteady OPPDIF namely OPUS. This will give more insight to blowoff theory and can easily be correlated with Damkohler number, which sometime is difficult as in steady state time scale computation, local flow field and flow time scale remain unavailable.
Appendix A

Air Flow Calculations

Air mass flow equation and orifices diameter for the air-supply bench,

\[ \dot{m}_a = \left( a + b \cdot P_1 + \frac{c}{\sqrt{P}} \right) \frac{P_1}{\sqrt{T_1}} \text{ (lbm/s)} \]

where, a, b and c orifice constants supplied by manufacturer are tabulated below,

Table A.1: Orifice constant for the air-supply bench.

<table>
<thead>
<tr>
<th>Nozzle #</th>
<th>Orifice diameter (inch)</th>
<th>a x 10^3</th>
<th>b x 10^13</th>
<th>c x 10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.064</td>
<td>1.6998246</td>
<td>8.52067660</td>
<td>-6.80939</td>
</tr>
<tr>
<td>2</td>
<td>0.089</td>
<td>3.2872392</td>
<td>4.93720040</td>
<td>-11.1679</td>
</tr>
<tr>
<td>3</td>
<td>0.125</td>
<td>6.4848354</td>
<td>-9.05670540</td>
<td>-18.5893</td>
</tr>
<tr>
<td>4</td>
<td>0.177</td>
<td>13.0058200</td>
<td>0.309422998</td>
<td>-31.3267</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
<td>25.9727290</td>
<td>-0.57762318</td>
<td>-52.6139</td>
</tr>
</tbody>
</table>

\[ T_1 = \text{inlet temperaure (R)}, \ P_1 = \text{inlet static pressure (psia)}, \ \text{Porter Instrument mass flow controllers are calibrated for } \text{N}_2. \ \text{Conversion factor for } \text{C}_3\text{H}_8 \text{ measurement is 0.372. To reach a target equivalence ratio, } \phi_{\text{target}} \text{ required propane mass flow (SLPM) at room temperature is tabulated below,} \]

Table A.2: Mass flow controller calibration for propane measurement.

<table>
<thead>
<tr>
<th>Mean flow velocity</th>
<th>Mass flow reading (SLPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m/s</td>
<td>( \phi_{\text{target}}/0.026032 )</td>
</tr>
<tr>
<td>10 m/s</td>
<td>( \phi_{\text{target}}/0.012973 )</td>
</tr>
<tr>
<td>15 m/s</td>
<td>( \phi_{\text{target}}/0.008739 )</td>
</tr>
</tbody>
</table>
Appendix B

Hot Wire Anemometer Calibration

Voltage mapping for hot wire anemometer (HWA) with respect to imposed sinusoidal oscillation to maintain a consistent turbulence level of $u' / U \sim 0.08$ for different mean flow velocities are shown in the following table:

Table B.1: Voltage mapping for HWA

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Unconfined Configuration</th>
<th>Confined Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$U = 5 \text{ m/s}$</td>
<td>$U = 10 \text{ m/s}$</td>
</tr>
<tr>
<td>50</td>
<td>2.9</td>
<td>3.8</td>
</tr>
<tr>
<td>100</td>
<td>3.6</td>
<td>4.5</td>
</tr>
<tr>
<td>200</td>
<td>5.1</td>
<td>6</td>
</tr>
<tr>
<td>300</td>
<td>6.4</td>
<td>7.9</td>
</tr>
<tr>
<td>400</td>
<td>7.8</td>
<td>9</td>
</tr>
</tbody>
</table>

Fig. A.1: HWA calibration chart.