Flame-Turbulence Interaction for Deflagration to Detonation

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FLAME TURBULENCE INTERACTION FOR DEFLAGRATION-TO-DETONATION

by

JESSICA CHAMBERS

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the Department of Mechanical Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida.

Spring Term, 2016

Thesis Chair: Dr. Kareem Ahmed
ABSTRACT

Detonation is a high energetic mode of pressure gain combustion that exploits total pressure rise to augment high flow momentum and thermodynamic cycle efficiencies. Detonation is initiated through the Deflagration-to-Detonation Transition (DDT). This process occurs when a deflagrated flame is accelerated through turbulence induction, producing shock-flame interactions that generate violent explosions and a supersonic detonation wave. There is a broad desire to unravel the physical mechanisms of turbulence induced DDT. For the implementation of efficient detonation methods in propulsion and energy applications, it is crucial to understand optimum turbulence conditions for detonation initiation. The study examines the role of turbulence-flame interactions on flame acceleration using a fluidic jet to generate turbulence within the reactant flow field. The investigation aims to classify the turbulent flame dynamics and temporal evolution of the flame stages throughout the turbulent flame regimes. The flame-flow interactions are experimentally studied using a detonation facility and high-speed imaging techniques, including Particle Image Velocimetry (PIV) and Schlieren flow visualization. Flow field measurements enable local turbulence characterization and analysis of flame acceleration mechanisms that result from the jet’s high level of turbulent transport. The influence of initial flame turbulence on the turbulent interaction is revealed, resulting in higher turbulence generation and overall flame acceleration. Turbulent intensities are classified, revealing a dynamic fluctuation of flame structure between the thin reaction zone and the broken reaction regime throughout the interaction.
DEDICATION

This work is dedicated to all those who have helped me achieve success in my academic career and led me to where I am today. I would especially like to dedicate this to my mother and father for their devoted support, driving my personal development and will to excel academically.
ACKNOWLEDGEMENTS

I would like to acknowledge all those who have made this thesis possible. My deepest appreciation to my research advisor and Thesis Chair, Dr. Kareem Ahmed who has dedicated enormous amounts of time mentoring and preparing me for my future work in graduate school. My gratitude extends to my thesis committee members, Dr. Jayanta Kapat and Dr. Ali Gordon. I would also like to acknowledge all those who have provided guidance during my academic years, including Professor Chris O’Riordan-Adjah and Michael Aldarondo-Jeffries.
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CHAPTER ONE: INTRODUCTION

Detonation based engines have the potential to revolutionize existing combustion engine technology with the prospective of increased thermodynamic efficiencies, simplified manufacturability, and high specific impulse [1-3]. Detonation is a form of pressure gain combustion (PGC) which is total pressure rise in the system, fundamentally different from conventional constant pressure combustion processes used in propulsion and power generation engine [4]. With the augmented pressure and temperature rise of PGC, more energy is available and additional work can be extracted from the system. Although it is desirable to integrate detonation combustion into power generation and aviation propulsion applications [5], it has been a challenge because of its unstable and dynamic behavior. Detonation is an unsteady process profoundly affected by thermo-acoustic and hydrodynamic instabilities which renders it difficult to control and predict flame behavior[6, 7]. Not only is theoretical analysis a challenge[8], but acquiring experimental data to obtain flame flow field measurements requires powerful, high speed equipment and facility design improvements.

Detonation is achieved through the Deflagration-to-Detonation transition (DDT) process [9, 10]. DDT is applicable to multiple systems including Pulse Detonation Engines (PDEs), and Rotating Detonation Engines (RDEs). PDEs are semi-confined combustion chambers in tubular form that generate multiple detonation waves to produce a near constant thrust at the exit[11]. An RDE is in the form of an annular combustor ring that initiates a detonation wave propagating circumferentially, while being fueled by annular jets of premixed gas [12]. Although the geometry differs, the DDT mechanism is similar for both systems. The PDE configuration is less challenging to integrate advanced laser optical diagnostic techniques for flow field measurements, hence the
presented research is focused on DDT in semi-confined chambers. Focusing on semi-confined chambers, the DDT process begins with a source of energy igniting a fuel-air mixture at the closed end, initiating a deflagrated, subsonic flame that expands toward the open end. The flame advances downstream while experiencing intrinsic propagating flame instabilities and interacting with obstructions that perturb the flow. A growth of turbulence produces an expansion of the flame surface area and enhances transport of combustion products and unburned reactants, leading to increased burning rate and heat release [13]. This rapid flame expansion produces compression waves downstream that coalesce forming a shockwave. The turbulent flame accelerates and shock-flame interactions generate the conditions that promote DDT. The events occurring during shock-flame interactions are incredibly complex as they are affected by the initial state of the flame, turbulence generation and reflected shockwaves [14]. The propagating shock wave gathers sufficient energy to auto-ignite unburned reactants and localized ignition centers begin to form in the area between the combustion front and shock wave. Finally, one of these “hot spot” explosions initiates a detonation wave[15]. Zel’dovich explains this phenomenon as a gradient in chemical reactivity residing in the unreacted material that generates a supersonic spontaneous wave [16]. This mechanism is not the defining factor of DDT as there are occasions where the hot spots never developed into detonations, but instead result in decoupled shocks and flames. Further experimental research to understand the DDT process is required, as there is a large uncertainty in the local condition, location, and the time of detonation initiation [17].

High intensity turbulence generation is required to accelerate the flame and create the optimum conditions for DDT. Traditionally, solid obstacles have been used to effectively induce enough turbulence within the flow to produce rapid flame acceleration to detonation [18].
Obstacles generate hydrodynamic interfacial instabilities such as Kelvin Helmholtz, Rayleigh-Taylor, and Richtmyer-Meshkov that induce shear forces from fluids of different densities and flame-shock interactions, corrugating the flame surface. Flame acceleration to detonation in the presence of walls and obstacles has been extensively explored and is supported by observational evidence revealing the formation of hotspots from shock collisions [19-21]. There is a void, however, in the fundamental understanding of a flame transition to detonation solely induced by extreme turbulence. To further explore these mechanisms that drive DDT, the present study focuses on the use of a fluidic jet to generate intense turbulence within the flame by exposing it to direct high intensity turbulence. A fluidic jet has been shown to generate intense turbulence and induce DDT at shorter lengths compared to a solid obstacle [22]. This high velocity turbulent jet generates intense shear layer vortices that interact with the flame penetrating the reaction region and rapidly inducing high levels of turbulence. The flame’s interaction with direct turbulence creates large and small scale turbulent structures that enhance mixing and entrainment of reactants into the combustion products. Experimental analysis of these turbulence-flame interaction modes is required to provide insight on the underlying physics that drives flame acceleration to detonation.

The importance of understanding high-speed turbulent flame interactions is emphasized in recent investigations [23]. In particular, interest in this area has been driven by questions relating to a wide range of applications: from the optimization of detonation initiation for new propulsion and energy technology to astrophysical questions regarding the physics of a Type Ia supernova explosions. Numerous numerical investigations have been performed in the attempt to explain the unknown physical mechanisms that induce DDT as a result of high-speed turbulence-flame
interactions in varying conditions, such as in an unconfined environment. Key driving characteristics are examined and proposed by Poludnenko and Oran [23-25]. Poludnenko investigated the behavior of unconfined fast turbulent flames through numerical simulation and emphasizes self-acceleration through physical mechanisms that amplify turbulent intensities within the flame, such as the interplay between turbulence and intermittent flame collisions, formation of pressure waves due to unstable burning and the coupling pressure and density gradients that augments the turbulence inside the flame volume, also known as baroclinic torque [26]. While there are numerical simulations that investigate this process, experimental observations of fast propagating flames at high levels of turbulence are warranted to corroborate the findings and move closer to understanding unknown phenomenon. The present work is conducted to expand the experimental database of turbulence-flame interactions and aid in validating existing simulations and theories.

The present work investigates the interaction between a turbulent flame and fluidic jet to characterize turbulent flame dynamics and flame acceleration effects. The study provides experimental insight into the physical behavior and interaction mechanisms of high speed flames at high intensity turbulence regimes. Using Schlieren and high-speed PIV, the flame-flow interaction is captured and the flow field is analyzed. Using the Schlieren images to visualize the flame structures and overall behavior, the influence of initial flame turbulence level is identified by comparing the present case to a similar interaction of an initially laminar flame and fluidic jet. The turbulent flame experiences a higher flame acceleration and increased turbulent transport of reactants and combusted products. PIV provides velocity and vorticity fields that describe the flame evolution and enable an in-depth analysis of the local flame behavior. With local velocity
fluctuations and length scale values, flame turbulence levels are characterized throughout the flame evolution displaying a dynamic fluctuation between the thin reactions zones to broken reactions as it interacts with the jet turbulence. Peak turbulence levels approach the region on the diagram where detonation has been computationally modelled to occur, according to previous DDT simulations [24]. The data and analysis presented in the work will propel our understanding of turbulent flame acceleration and contribute key experimental data to identify mechanisms that can be used to further optimize the DDT process.
CHAPTER TWO: EXPERIMENTAL METHODS

Experimental Facility:

![Schematic of Experimental Facility](image)

**Figure 1: Schematic of Experimental Facility**

Experimental testing is conducted at the Propulsion and Energy Research Laboratory (PERL), an affiliate of the Center for Advanced Turbomachinery and Energy Research (CATER) at the University of Central Florida. A deflagration facility is designed and constructed from Plexiglas to obtain the flame-flow field data. The test facility is a square semi-confined channel 300mm in length and 45mm by 45mm cross section, representing H x W, displayed in Figure 1. To uniformly distribute the premixed reactant mixture throughout the chamber, eight 1/16 NPT holes are arranged around the perimeter of the cross section at the closed end for mixture injection. A spark plug placed at the center of the closed end is used to ignite the mixture.

The fluidic jet is composed of a 0.25mm traverse slot jet. The slot jet extends the width of the channel, positioned 3.1H downstream from the ignition point; this ensures the interaction occurs after the flame front is fully developed [27]. The fuel-air mixture enters a 30×23×45mm manifold through two 1/8 NPT inlets for uniform choked conditions. Incremental facility adjustments and testing are conducted to confirm jet uniformity. This enables the imaging to
capture nominally two-dimensional flame characteristics. The Schlieren imaging (larger, blue) and PIV (red) domain areas are highlighted by the dashed lines in Figure 1.

**Flow Measurements:**

The flow network for the fuel and air is shown in Figure 2. The mixtures for the main chamber and jet flow are individually premixed, originating from different sources. Methane gas and compressed air lines are used for the main flow reactant mixture. A pressure regulator is used to reduce any flow fluctuations and ensure the desired fuel-air ratio. The flow rate of 17 CFH for air is measured using a King Instrument Company 75301112C13 rotameter an accuracy of ± 4%. The fuel flow rate for the main flow is adjusted to 1.3 CFH using a Dwyer VFA-4 flowmeter, accurate ±3% of full scale flow. These flow rates are determined for a low main flow velocity to ensure minimum turbulence upon entering the chamber. Another compressed air line and a methane supplies the mixture for the jet flow. For a jet velocity, $u_j$, of 350 m/s, the air and fuel flow rates, $v_a$ and $v_f$ are set to 4.5 CFM and 38 CFH respectively, using King Instrument Company 75302113C07 and 75301112C13 rotameters. To enable continuous flow without altering the fuel-air ratio when the valves open and close, an exhaust line is included for the main jet flow.

The fuel flow rates quoted above represent the adjusted values to correct for methane measurements in an air flowmeter. To determine the correct flow rates, the density of the jet $\rho_j$,
momentum ratio MR, and the velocity of the jet $u_j$ are required. The desired air to fuel ratio AF, the density of methane, $\rho_f$, and air, $\rho_a$, are used to calculate the density of the jet mixture, seen in Equation 1. The velocity of the jet depends on the MR, which describes the penetration of the jet into the main flow as shown in Equation 2. With the slot dimensions and the conservation of mass equation, Equation 3 is used to calculate the jet flow rates. The tests for the present study are performed using the following flow parameters: MR = 0.55, and AF = 17.2.

$$\rho_j = \frac{AF \rho_a}{AF+1} + \frac{\rho_f}{AF+1} \tag{1}$$

$$MR = \frac{\rho_j u_j^2 DT}{\rho_o u_o^2 HW} \tag{2}$$

$$u_j = \frac{\rho_f v_f + \rho_a v_a}{\rho_j D} \tag{3}$$

System Control:

The system is precisely timed using a BNC Model 575 Pulse/Delay Generator to send TTL signals to the relays, spark plug, lasers, and cameras. The experimental operational procedure is composed of adjusting the main flow and jet flowmeters to their respective flowrates, and the chamber is filled for approximately 20 s. The pulse generator is triggered and begins by sending a signal to the relay that activates the main flow exhaust valve, Automatic Switch Co. 8262C22L. Simultaneously, the Omega SV126 solenoid valve for the jet is then activated to induce initial turbulence for 42 ms. After a settle time of 86 ms, a signal is sent to the ACCEL Super Coil 140001, powered by a Tektronix PWS4205 power supply, and triggers the Bosch 483 spark plug. The spark initiates the flame and a signal 4 ms later is sent to the jet valve, which triggers for 42 ms. This allows the flame to approach the jet location undisturbed so the flame-jet interaction can occur.
The chamber is slowly exhausted of the combustion products until the signal powering the main flow exhaust valve ends and the process can be initiated again.

**Schlieren Flow Visualization**

Schlieren imaging is an optical diagnostic system which is used to observe the fluid flow. In particular this setup enables the observation of flame structures and flame front velocity. Schlieren imaging is performed by using a series of mirrors and or lenses, a light source, a razor blade and a high speed camera. The Schlieren setup follows a z-setup formation. In a z-setup, there is a single diverging light source shining onto a parabolic mirror. The parabolic mirrors are first surface as normal mirrors are too damaged and will reflect on the data acquisition. An aperture is used to block out the non-focused light out. The aperture leaves a more concentrated and focused beam to continue on with the process. This light beam reflects off the first parabolic mirror, collimates, and travels through the experimental window until reaching the other mirror. When the collimated light beam passes through the experimental window, any slight changes in fluidic density causes the speed of light to slightly change, in turn resulting in a change of the index of refraction. The refracted light then travels to the second mirror and reflects into the high speed camera for recording. Before reaching the camera lens, the light beam focuses to a point, where a razor blade is positioned to block a portion of the incoming light. This results in a higher contrast for the observed Schlieren images which reveals the density gradient in the fluid. Shadows form in the resulting image that are indicative of the density gradients in the experimental flow.
Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a non-intrusive advanced optical diagnostic technique which enables detailed fluid flow measurements, in particular of the vector field that describes the fluid motion. The overall idea driving the method is introducing light reflecting particles into the flow, illuminating them with a laser sheet and tracking the particle movement to construct the instantaneous velocity vector field. Particles are seeded into the fluid flow to serve as tracking points, as their movement in the images is directly representative of the movement of the fluid at the location of each particle. A transparent test section is required to visualize the particle flow and allow access to laser light. With specialized optics, a laser light sheet is formed and focused through the test section. Pulsed lasers are typically used to illuminate the test section, and produce 0.1 - 0.3 joules per pulse at high frequencies. The laser light must be focused into a sheet in order to fully illuminate the particles and provide information for an entire 2-D region in the flow. This is achieved by using a series of cylindrical and spherical lenses. A high-speed camera observes their position, running at a very high shutter frequency to acquire many images in the short amount of time the experiment occurs. With the acquired images, the velocity of any particle can be calculated by dividing its position displacement by the known shutter speed.

The image analysis is an in depth procedure that can be performed in PIVlab on MATLAB software. This begins by breaking up the experimental images into sub regions called “interrogation regions”. Using a cross-correlation over each consecutive frame, a peak signal is produced that represents a common displacement of particles over the two frames. A velocity field is then created using the displacements throughout the entire image.
Optical Diagnostics Descriptions:

High speed optical diagnostic techniques such as Schlieren flow visualization and Particle Image Velocimetry (PIV) are implemented to characterize the flame-flow characteristics throughout the interaction. Schlieren reveals density gradients within the flow and provides insight into the flame front acceleration and overall turbulent structures generated by the interaction. A Photron Fastcam SA1.1 675K-M2 camera is used to record the Schlieren images at 10,000 fps. PIV enables instantaneous flow field measurements, such as velocity and vorticity vector fields, by tracking the position seeded particles throughout the flame flow interaction. 0.5 μm aluminum oxide particles are seeded within the main flow lines to be distributed throughout the PDE and illuminated by a Lee Laser LDP Dual Laser that pulses two 5 kHz lasers at 20mj. The Photron Fastcam SA1.1 675K-M2 with 1,024 x 1,024 pixel spatial resolution and 16-bit range with a 50 mm Nikon lens at f# of 1.2 records the seeded flame interaction at 10,000 fps. All images are recorded with Photron Fastcam Viewer computer software.

PIVlab 1.35 is used to process the images and determine the flow field measurements. The pre-processing includes contrast-limited adaptive histogram equalization (CLAHE) to filter image noise. A four pass processing method is used for the flow field data processing with a final pass of 16x16 pixels with 50% overlap. Precision error is calculated based on the camera and PIV settings. The important parameters are the image pulse separation $\Delta t = 0.019ms$ and magnification, $M = 0.06$ mm/pixel based on the known channel height in the images. The average precision error, Equation 4, for data extracted from the PIV images is at maximum 3.2px [28].

$$
e_{\text{PIV}} = \frac{5\cdot u'_{\text{rms}} \Delta t}{M} \quad (4)$$
CHAPTER THREE: RESULTS

Flame Characteristics

The primary motivation of the study is to identify key characteristics and acceleration effects produced by the interaction of a deflagrated turbulent flame with a turbulent jet. High-speed Schlieren flow visualization is used to highlight the overall structures and flame-flow characteristics produced by the interaction. The time evolution of the Schlieren images is displayed in Figure 3. Previous work studying a laminar flame interaction with the same fluidic jet is included in the images as a baseline for comparison [29]. The sequence of images progress from top to bottom displaying the flame propagation within the domain at different turbulence modes. Upon ignition, the flame expands towards the open end of the chamber and enters the visual domain.

The image sequence for the turbulent case initially displays the unsteady core products that is produced by the turbulent flow field of reactants in the chamber preceding ignition. As the flame initiates and expands, the turbulent fluctuations influence the flame topology by producing irregularities in the flame boundary. The flame experiences an upwards deflection due to the development of a high pressure region ahead of the jet injection location. Once the jet turbulence...
interacts with the bottom flame boundary, there is an exchange of energy between the highly energetic reactants generated by the jet and the propagating flame. The turbulence intensities propagate in the flame domain and two acceleration regimes develop, referring to the section of reactions at the flame front that separate at a higher acceleration than the bulk flame. The rapid propagation of turbulence from jet entrainment enhances transport of the unburned reactants into the products, exposing the flame to pockets of reactants and increasing flame burning rates.

The laminar flame displays different characteristics throughout the interaction. The flame initiates and develops a semi-parabolic shape that advances through the channel. After a similar upward deflection, the laminar flame interacts with the jet and the bottom flame boundary is prominently curved clockwise and entrained into the jet recirculation region. The interaction generates a significant amount of turbulence within the laminar flame, but exhibits different flame front dynamics. The laminar flame is more intensely affected by the recirculation region, which is notable in the last images of the Schlieren sequence. The jet penetrates the flame and entrains combusted products into the jet recirculation zone causing the flame front to marginally decelerate its forward expansion during the interaction. Once the turbulence levels propagate throughout the flame region, burning rates are increased and the flame front accelerates.
The influence of the initial flame turbulence level on flame propagation is detailed quantitatively with velocity and acceleration graphs that describe the Schlieren images. To acquire the velocity and acceleration information seen in Figure 4, the position of the flame front is tracked on the image according to pixels then converted using the known channel dimensions and time interval information from camera imaging settings. The flame propagation speed is normalized by the laminar flame speed, $s_L = 0.362 \text{ m/s}$ [30], and plotted against the axial displacement within the domain, with the jet injection location at $x = 0$.

The turbulent flame enters the domain at $79s_L$ and deflects vertically as it approaches the jet injection point where there is an initial acceleration. The first instance of interaction between the jet turbulence and the flame boundary displays the highest flame front acceleration of 33,800 m/s$^2$. After the interaction, the flame reaches speeds over $175s_L$ and is expected to continue accelerating downstream from the diagnostic domain. Comparatively, the laminar flame enters the domain at $53s_L$ and displays a small increase in acceleration as it deflects past the jet injection point. Once the jet turbulence penetrates the flame, it experiences a large deceleration from 12,900 m/s$^2$ to -20,900 m/s$^2$. Post interaction, the flame front reaches speeds of approximately $94s_L$ before

![Figure 4: Flame front velocity and acceleration data extracted from Schlieren images graphs](image-url)
exiting the domain. Comparing these behaviors illuminates the quantitative influence of the initial turbulence level on overall flame acceleration. With initially higher flame speed and a larger acceleration rate, the turbulent flame exhibits different turbulence transport properties that drive flame acceleration. The turbulent flame rapidly accelerates while the laminar flame experiences a large drop in velocity once the jet turbulence propagates throughout the flame. The high energy and momentum of the oncoming turbulent flame dynamically alter the jet penetration, allowing jet entrainment into the lower flame boundary without transporting a large portion of combustion products into the recirculation region. This phenomenon is evident as it suppresses flame front acceleration in the laminar flame.

**Figure 5:** Laminar and turbulent flame before and after interaction with fluidic jet to demonstrate instabilities
The PIV images in Figure 5 clearly demonstrate the alteration of the jet penetration in both the laminar and turbulent flames. Before and after the interaction, there is a dynamic change in the momentum ratio for both flame-flows, reflecting the acceleration characteristics displayed in the plots in Figure 4. The momentum ratio is held constant for both flames immediately before the flame approaches the jet location to ensure comparable experimental conditions. Once the flames pass over the jet injection and engage in turbulent transport of reactants and combusted products, the jet penetration changes. With a large deceleration of the laminar flame, the momentum ratio increases and the jet seems to straighten out vertically and penetrate the inner flame domain further. The turbulent flame interacts with the jet and accelerates rapidly, decreasing the momentum ratio and deflecting the jet penetration to a more horizontal profile. The observations of jet interaction modes provide insight into the turbulent flame dynamics of the interaction.

**Initial Conditions**

![Vorticity, velocity and vector plots of turbulent reactants before ignition](image)

**Figure 6: Vorticity, velocity and vector plots of turbulent reactants before ignition**

The turbulence intensity and conditions of the mixture prior to reaction are characterized. Flow field samples of the turbulence ahead of the flame are acquired with PIV. The turbulent flow-field is generated by operating the high pressure slot jet within the chamber. After a settling time
to allow for turbulence homogeneity, the initial deflagrated flame is ignited. The turbulence characteristics before ignition are detailed with instantaneous velocity, vorticity, and vector field plots shown in Figure 6. The horizontal velocity displayed in Figure 6a shows a range of +/- 11s_L with approximately zero mean velocity, derived from a sample sequence of instantaneous snapshots. The vertical velocity component is very similar and therefore is omitted. The small scale vorticity produced by the jet is presented in Figure 6b. Normalized by the laminar flame thickness l_f = 433 μm and s_L, the values range from +/- 3 l_f/s_L. The vorticity and vector field plots, 6b and 6c suggest a relatively uniform turbulence distribution within the chamber, with scattered counterclockwise and clockwise vorticity and distributed random vectors. This flow field information aids in correlating the turbulence of the unburned mixture to the flame mode produced, discussed later in the results.

Initial Turbulent Flame Characteristics

![Figure 7: Flame stretch values and flame boundary contours for turbulent flame before interaction, corresponding to frame 1-3](image)

The turbulent flame is initialized and the first stages of flame propagation are captured. The plots displayed in Figure 7 show the contour of the flame boundaries as they expands over a small time interval Δt, from the black outline to the red outline. The PIV images are imported into
computational software to manually outline the flame boundary based on a pixel intensity threshold that occurs between the interface of burned and unburned gas. The uncertainty of the flame outline based on the average amount of pixels that fluctuated from the flame boundary after a secondary assessment is +/- 0.48 mm, which is at most +/- 2% of the area values.

The expansion of the flame is visualized and quantified at the stage prior to direct interaction with the turbulent jet. The largest area change occurs at the front and lower boundary of the flame, in the direction of the overall flame propagation. As the flame advances, it interacts with the turbulent flow field downstream, increasing flame boundary turbulence and driving further expansion. The top boundary of the flame is not directly exposed to the flow fluctuations; therefore, it is not noticeably expanding. This characteristic highlights the influence of turbulence as well as the expansion towards the unconfined region or open end. The expansion is quantified using the flame stretch equation $k$, Equation 5 and plotted in Figure 10a. The quoted area values in the paper represent the two dimensional surface area of the flame front, shown by the flame contours in Figure 10b. $A_1$ represents the area of the flame first flame in frame 1 and $dA$ is the calculated change from the first to second frame, seen in the black and red outlines. The flame boundary becomes increasingly more turbulent as it advances which can be demonstrated in both the boundary outline plot and the increasing trend of flame stretch.

$$k = \frac{1}{A_1} \cdot \frac{dA}{dt} \ (5)$$

Turbulent flame speed, $s_T$, helps describe a flame’s local chemical reactions and the influence of the turbulent flow field. $s_T$ calculations are performed to characterize turbulent flame
dynamics before the flame-turbulence interaction using direct experimental measurements and a derived correlation. The $s_T$ measurements represent a global value for the flame based on a ratio of the surface areas of turbulent and laminar flames subject to the same jet flow conditions. This is calculated using the following Equation 6, originally derived by Damköhler from a mass conservation, [31]

$$s_{T1} = s_L \cdot \frac{A_T}{A_L}$$  \hspace{1cm} (6)$$

$A_T$ is the instantaneous surface area of the turbulent flame front while $A_L$ is the area of a laminar flame in the same experimental environment. The laminar flame is chosen based on how closely the flame datum matches, seen in Figure 8.

Figure 8: Flame boundary contour with corresponding PIV image to depict comparison to laminar flame (blue) for turbulent flame speed calculation
Table 1 includes the measured values of turbulent flame speed, velocity fluctuation and length scale ratio for the turbulent flame in Figure 8, as well as the secondary experimental case of the present work. The $s_T$ values in Table 1 are compared to a correlation using measured velocity fluctuations and length scales to directly calculate $s_T$ as well as other similar experimental values. 

$u'$ represents the velocity fluctuation of any point from the mean velocity $\overline{u}$, described in Equation 7. In this case, the highly turbulent propagating flame does not have one representative value to define $\overline{u}$ across the whole flame region. The mean convective velocity and fluctuating velocity are computed spatially in 4x4 grids throughout the flame region [32]. The root mean squared of the fluctuating velocity, $u'_{\text{rms}}$, is used in all further turbulence characterization computations, Equation 8.

$$u' = u - \overline{u} \quad (7)$$

$$u'_{\text{rms}} = \left[ \frac{1}{N-1} \sum_{i=0}^{N} (u')^2 \right]^{1/2} \quad (8)$$

<table>
<thead>
<tr>
<th>Frame</th>
<th>$s_{T1}$ (m/s)</th>
<th>$e$ (%)</th>
<th>$s_{T1}/s_L$</th>
<th>$u'_{\text{rms}}$ (m/s)</th>
<th>$u'_{\text{rms}}/s_L$</th>
<th>$L_1$</th>
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</tr>
</tbody>
</table>

Table 1: Flow field information extracted from the flame for frame 3 for both experimental cases of present work.
Comparatively, other turbulent flame speed values from various references are presented in Figure 9. Unfortunately, there are few references which provide these measured values for similar experimental conditions of the present work. The available correlation and data that details the relationship between $s_T/s_L$ and $u'/s_L$ for comparable conditions are displayed. The secondary case from the present experimental data is characterized and included in the plot to corroborate the measured values, but will not be considered throughout the rest of the paper. The graph in Figure 9 highlights the $s_T$ points from the present experiment and compares the values to the correlation for ($s_{T2}$) [33].

$$s_{T2} = s_L \left[ 1 + \left( -\frac{.39}{2} \frac{L}{l_f} + \left( \frac{.39}{2} \frac{L}{l_f} \right)^2 + .78 \text{Re}_T \right)^{1/2} \right] \quad (9)$$

Figure 9: $s_T$ values of flame for frame 3 to compare empirical correlation and previously acquired data.
This correlation, Equation 9, takes into account the velocity fluctuation and other parameters such as the length scale ratio and turbulent Reynolds number $Re_T$. The length scale ratio is defined by the integral length scale $L_{11}$, which describes the length scale of eddies present in the flow and is calculated by the integrating the spatial distance between correlating $u'_{\text{rms}}$ values. Equation 10. The turbulent Reynolds number, $Re_T$, shown in equation 11, is a non-dimensional parameter that relates the velocity and length scales. The uncertainty for the measured parameters $u'_{\text{rms}}$ and $L_{11}$ is computed to be 5.5% and 13% respectively. These values are attained by comparing the present instantaneous method with an ensemble averaged technique using 400 samples of a jet in crossflow by Ahmed et al.[34].

$$L_{11} = \int_{y_{\text{min}}}^{y_{\text{max}}} \frac{u'(x, y_o) \cdot u'(x, y)}{(u'(x, y_o))^2} dy$$

(10)

$$Re_T = \frac{u' L_{11}}{s_{L_{11}} l_f}$$

(11)

The derived correlation for $s_{T2}$ is shown on Figure 9, represented by 3 different length scale ratios $L_{11}/l_f=1, 10, 100$. Those lines support the notion that larger length scale ratios and turbulent Reynolds numbers result in higher turbulent flame speeds. The length scale ratio for the present work is computed locally within the flame domain throughout the interaction, but the average value as seen in Table 2, lies between 1 and 10. This provides a projected area where $s_{T1}$ should lie. The $s_{T1}$ values are very close to the line $L/l_f =1$, but are not entirely consistent with the correlation, as it predicts an $s_{T1}/s_{L}$ value closer to 8. The correlation for $s_{T2}$ has been supported by experimental data collected in Abdel-Gayed & Bradley [35], using many different sets of experiments to establish $s_T$ trends based on the turbulent Reynolds numbers $Re_T$. There is little to
no experimental data for the thin reaction zone at the present turbulence intensity level. One set is included on the plot as it has similar turbulence intensities to the present case, but differs in the flame turbulence regime. The experimental data set by Andrews et al. [36] represents flames with larger turbulent length scales $L$ and slightly lower levels of turbulence intensity $u'$ categorized in the corrugated flamelet regime. This and the derived correlation supports the notion that at different turbulent Reynolds numbers and length scales, the chemical reactions respond differently.

This discrepancy of turbulent flame speed can be attributed to the different conditions of the flames in the experiments, stationary stabilized flames as opposed to propagating flames. The correlation was also derived under the assumption of a steady stationary flame and does not consider the unsteadiness of the propagating flame as it is intensely affected by hydrodynamic instabilities. Even though it was derived for both flame turbulence regimes, the accuracy of the correlation has not been supported experimentally in the thin reaction zone.

There are also underlying assumptions that are made with the method of measuring $s_T$. It must be considered that presently we are using the total area to calculate a global $s_T$ value that may cause a dilution of certain flow field information. However, there are certain limitations of calculating turbulent flame speed locally and accurately for the current data set without further laser diagnostics that illuminate reaction areas. Therefore, the measured turbulent flame speed values provide an anchor point, based on the actual turbulent flame surface area that is experimentally visualized.
Reacting Flow field Analysis

The time evolution of flame propagation and jet interaction is visualized in Figure 10. The axial velocity plots highlight peak flame velocities and illuminate flame acceleration effects throughout the turbulent interaction. The upper boundary of the jet displays velocities of 100s_L-200s_L while the jet recirculation region reaches negative velocities of -100 s_L. The flame enters the frame at 135s_L, deflects vertically and upon initial interaction accelerates with peak velocities up to 285s_L that are spread throughout the center of the flame region. The interaction increases the flame front velocity up to 2.4 times; this is consistent with the Schlieren diagnostic results.

The oncoming flame’s outer boundary is bounded by counter clockwise (positive/blue) and clockwise (negative/red) vorticity, induced by Baroclinic torque. The interaction between the axial pressure gradients throughout the flame and the density gradients between the hot combusted products and cold reactants generate vorticities at the top and bottom boundaries (top experiences
counter clockwise while bottom experiences clockwise). The jet itself is extremely turbulent and is displayed in the vorticity plots as counterclockwise and clockwise eddies. This turbulence results from shear-layer vortices which are a property of a traverse jet in crossflow caused by the no-slip boundary. Beginning with Frame 4 in the sequence of vorticity plots, the counter-clockwise (blue) outer jet vorticity meets the clockwise (red) vorticity of the bottom flame and intensely disrupts the flame boundary. As the interaction occurs, the jet entrains reactants into the flame domain and produces a strong turbulent transport mechanism which generates high levels of vorticity within the center of the flame. These pockets of reactants enter the inner flame region and are quickly heated and rapidly combust to further expand the flame. The flame boundary becomes more intensely corrugated, producing large and small scale deformities such as the separated pockets and smaller flame wrinkles as shown in frame 5. Peak vorticities of approximately $\pm 30 \text{ l/s}$ develop at the interface and inner flame region as shown in frame 5 vorticity plot. The flame surface area is stretched, exposing more reactants to the hot products and generating local areas of rapid heat release within the inner flame; this mechanism works to amplify flame acceleration.

To further understand the underlying mechanisms which drive the interaction, a line integral convolution is performed as shown in Figure 11. The mean convective velocity is subtracted from the vector field to focus on the turbulence structures. This exercise highlights local turbulence levels and aids in visualization of the development of turbulent eddies throughout the

Figure 11: Line integral convolution of flame interaction frames 1,3,4,5,6

To further understand the underlying mechanisms which drive the interaction, a line integral convolution is performed as shown in Figure 11. The mean convective velocity is subtracted from the vector field to focus on the turbulence structures. This exercise highlights local turbulence levels and aids in visualization of the development of turbulent eddies throughout the
flame region. As the flame enters the domain it experiences mild wrinkling at the flame front boundary while the jet flow field is intensely convoluted and entirely composed of high fluctuating turbulent eddies. The outer boundary of the jet subsequently disrupts the lower boundary of the flame. This disturbs the continuous field of flame generated vorticity by rapidly spreading small scale turbulent vorticities of both signs throughout the flame front and the products region. The propagation of these turbulent intensities drives the flame acceleration by enhancing transport between reactants and products and increasing the flame’s reaction rate.

Figure 12: Turbulent flame characterization of interaction using the turbulent premixed combustion regime Borghi Diagram
The underlying turbulent mechanisms that drive flame acceleration are revealed through the characterization of flame turbulence levels throughout the evolution of the interaction. Premixed turbulent combustion can be classified into different turbulent flame modes in terms of velocity and length scale ratios on the Borghi/Peters flame regime diagram [37, 38]. The diagram categorizes flame turbulence levels according to the turbulence intensity $u'$ normalized by the laminar flame speed $s_L$ and the integral length scale $L_{11}$ normalized by laminar flame thickness $l_f$. The data points representing these parameters in Figure 12 are extracted from an outlined area of the lower flame boundary representing the region of turbulence induction. The quantitative characteristics of the regimes in the present work are visualized in the plot, in particular thin to broken reactions regime. Flames in the thin reaction zone form flamelets that are thickened by turbulence, where small eddies enter the preheat zone and disrupt the flame structure. A flame within the broken reaction regime contains small eddies that penetrate into the inner reaction layer to interrupt combustion reactions and cause local areas of flame quenching. DDT is also simulated to occur in the upper region of the broken reaction regime. By identifying key interaction modes of the flame’s progression through the turbulent flame regimes, further enhances the understanding of flame acceleration for DDT.

The initial turbulence within the channel before ignition provides information about the reacting flow field. The velocity fluctuation of this turbulence (Fig. 6) is estimated to be approximately $9s_L$ and if plotted on the turbulent flame regime diagram, lies on the Y axis just below $10^{1}$. This turbulence level of the reactant mixture corresponds to the thin reaction zone regime, which is where the initial flame is classified in. The flame at this regime is composed of
various turbulent flamelets, but not structurally broken. This supports a strong correlation between the regime of the reactant flow field and the initial flame structure.

Initializing in the thin reactions zone, the flame encounters disturbances in the channel and interacts with the jet, resulting in a progression throughout the flame regimes. At the initial stage of the jet turbulence interaction, the flame regime evolves further up into the thin reaction zone. It escalates to its peak in the broken reaction regime, where the $u'_{rms}$ reaches up to $80S_L$ and the $L_{11}$ ranges from $0.1 L_f$ to $20 L_f$. The jet intensely disrupts the turbulent flame boundary which causes this evolution into the next regime. The jet turbulence penetrates further into the inner flame region, transporting small scale intensities of reactants into the products. At this point there is a decay in the evolution of turbulence level back into the thin reaction regime for regions of the expanding flame. During the last stage of the interaction, the turbulence reduces with $u'_{rms}$ values as low as $10S_L$.

Turbulent kinetic energy fluctuates as various mechanisms become dominant within the flame as the stages of the interaction take place. The first instance where the jet disturbs the bottom flame boundary results in the peak turbulence intensity recorded for the interaction. This intensifies the turbulent kinetic energy of the flame interaction region and momentarily increases the velocity of the flame perturbations until the reactants penetrate the inner flame domain and cause rapid chemical reactions. The decay in turbulence once the flame-jet interaction escalates is induced by dilatation due to heat release and viscosity dependence on temperature [39]. The heat release and rapid gas expansion of the turbulent reactive gas tends to laminarize a turbulent flow to form larger orderly structures. The high temperature of the combusted gases reduces density and increases
local viscosity, in turn reducing the turbulent Reynolds number. The interaction of these variables consequently increases the viscous dissipation of turbulent kinetic energy, weakens eddy intensity and dampens small-scale perturbations within the flame.

**Local Flame Behavior**

![Probability distribution function graphs of vorticity, turbulent strain-rate and u’rms of frames 1,3,4,6 (Top to bottom)](image)

**Figure 13: Probability distribution function graphs of vorticity, turbulent strain-rate and u’rms of frames 1,3,4,6 (Top to bottom)**

Probability distribution functions are constructed for frames 1, 3, 4 and 6 (of Figure 10) to provide quantitative details describing local flame behavior as it approaches the jet turbulence and throughout the interaction. The information for the graphs in Fig.13 represent the same data points.
extracted from the bottom flame boundary for the turbulence characterization in Fig.12. Figure 13a displays the evolution of the vorticity values, $\omega$ normalized by ($l_f/s_L$). The bottom flame boundary enters with a strong negative vorticity bias, attributed to the baroclinic torque mechanism that produces an average clockwise vorticity of $-7 l_f/s_L$. The flame gradually accelerates and small scale turbulent eddies of the outer jet stream interact with the flame boundary. The vorticities grow larger in magnitude, show a more widespread distribution and represent more data points as the affected region grows larger. Once the flame boundary is completely disturbed, there is a more symmetrical distribution between clockwise and counter clockwise vorticities. By the last stage of the interaction in frame 6, the vorticity limits have extended to +/- 40 $l_f/s_L$.

The $u'_{\text{rms}}$ values normalized by $s_L$ are displayed in Figure 13b to highlight local turbulence levels. The flame enters the domain with local velocity fluctuation averaging to be approximately 9$s_L$. The data population moves towards larger values as the fluidic jet penetrates the flame region, inducing turbulence and increasing $u'_{\text{rms}}$. Frame 4 displays an increase in the maximum $u'_{\text{rms}}$ values above 80$s_L$, where the flame regime evolves into the broken reaction regime. This is the peak in turbulence intensity throughout the interaction. Frame 6 displays a further distribution into high $u'_{\text{rms}}$ values, but with a lower maximum value of approximately 67$s_L$. This supports the previously characterized decay in turbulence into the thin reaction zone regime.

Turbulent strain disregards convective velocity and provides information about the turbulence effects on flame structure. The turbulent strain-rate is represented by $u'_{\text{rms}}$ velocity gradients, computed over a horizontal displacement using Equation 12.
\[ S_{11}^{rms} = \frac{du'_{rms}}{dx} \quad (12) \]

The graphs in Figure 11c display turbulent strain normalized by \((l_f/S_L)\). The initial flame is shown to be nominally unstrained before the jet interaction in Frame 1. The flame is then deflected vertically and produces a slight negative strain-rate bias. As the jet interacts with the flame, the strain-rate distribution becomes more symmetrical. The interaction moves products and reactants rapidly over short distance which increases the magnitude of peak turbulent strain-rate values up to +/- 6 \(s_L/l_f\) as shown in Figure 13c. The peak value decreases in the last frame, similar to the \(u'_{rms}\) trend. There is also a slight bias toward the positive strain rate which can be attributed to the accelerating flame front with large \(u'_{rms}\) gradients.
CHAPTER FOUR: CONCLUSION

The interaction between a deflagrated turbulent flame and a fluidic jet is experimentally observed and analyzed. The objective of the study is to gain a better understanding of the turbulence induction and acceleration effects of initializing the oncoming flame within the turbulent flame regime. Turbulent flame and jet dynamics are characterized and analyzed. Velocity and vorticity fields constructed from PIV images reveal that a turbulent flame experiences high propagation of turbulence intensities resulting in increased flame acceleration. The turbulent flame effectively displays an increase in vorticity generation, velocity fluctuation and turbulent strain-rate throughout the interaction. To further identify the effects of an initially turbulent flame regime, the time evolution of interaction is characterized on a traditional turbulent flame regime diagram. The flame is initialized in the thin reaction zone and fluctuates in and out of the broken reaction regime due to the various mechanisms that dominate turbulent kinetic energy, such as gas expansion and temperature dependent. Local information is categorized to extend the experimental database of turbulent propagating flame interactions. The results provide an in depth analysis of a turbulent flame dynamics, advancing our understanding the various mechanisms of turbulence induction and flame acceleration for the initial stages of DDT. Future work will continue to analyze the influence of initializing at various turbulent flame regimes in the attempt to identify the driving physical mechanisms that enhance flame acceleration.
REFERENCES