Swirl Effects on Compactness of a Peripherally Piloted Reheat Combustor

A Dissertation
Presented to
The Academic Faculty

by

Alex Benjamin Miller

In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy in the
School of Mechanical Engineering

Georgia Institute of Technology

December 2020

Copyright © Alex Benjamin Miller 2020
Swirl Effects on Compactness of a Peripherally Piloted Reheat Combustor

Approved by:

Dr. Jerry Seitzman, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Ben T. Zinn
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Eugene Lubarsky
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Timothy Lieuwen
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Caroline Genzale
School of Mechanical Engineering
Georgia Institute of Technology

Date Approved: August 13, 2020
To D. Brent Hitchcock
(1986-2017)

“A friend loves at all times,
and a brother is born for adversity.”
Proverbs 17:17
Acknowledgements

First and foremost, this work belongs to God. The drive we possess to expend inordinate amounts of energy to incrementally increase our understanding of His creation is a testament to both His incredible power and magnificent artistry. Thank you, God, for sharing with us the beautiful mysteries of fire and fluid motion.

In addition to my own efforts, the completion of this work was enabled by a number of friends, colleagues, academic faculty, and classmates who provided significant support, advice, encouragement, and wisdom throughout this journey. I wish to sincerely express my gratitude by recognizing the contributions of these individuals.

My advisor, Dr. Jerry Seitzman, deserves my greatest thanks for his dedication to me and my work. He is not only a brilliant scientist and talented teacher, but also a high-quality human being. His genuine concern for his students and commitment to academic rigor are rightfully admired by all those who have had the pleasure to know him. It was a privilege to prepare this dissertation with his guidance, and sometimes it was even fun.

Next, I owe a great deal to Dr. Ben T. Zinn, who first took me on as his final PhD student. I am grateful for his many years of hard work in growing the (aptly named) Ben T. Zinn Combustion Laboratory into the prolific research organization it is today. During my nine full years in the Lab, I have grown substantially as a researcher, engineer, and person. I recall that Dr. Zinn once told me the only way he will ever leave the lab is in a coffin. He inspires me to become a lifelong student, and whenever I encounter a challenging problem, to “let it keep me up at night.”

From my first day at the Lab, I had the great privilege to work shoulder-to-shoulder with Dr. Eugene Lubarsky, who led the initial development of the test facility and test campaigns. Along with many valuable hands-on skills, he taught me the art of experimental work. No one else has pushed me so far outside of my comfort zone as Eugene, and that is what I needed. I will always remember how much he
believed in me and exhorted me to “keep pushing” when I (and everyone else) wanted to give up. I am delighted that he was the first to address me as “Dr. Miller” after my defense presentation.

I would also like to extend a special thanks to the two remaining members of my reading committee. Dr. Tim Lieuwen challenged me to dig deeply into the fundamentals of my research problem and set a high bar for attention to detail. Dr. Caroline Genzale, who taught my first combustion course, always encouraged me to write clearly and take the time to be thorough in my explanations. I am honored to have their approval for this thesis.

In addition to the committee, I must acknowledge other academic faculty who have played various major roles in my academic career at Georgia Tech. They include Dr. Jeff Jagoda, Dr. Wayne Whiteman, Dr. Alexander Alexeev, and Dr. Nazanin Bassiri-Gharb. It was a pleasure to work with them and I look forward to staying in touch.

One of the most valuable aspects of my experience at the Lab was the opportunity to work alongside many talented research engineers. I had the privilege of working closely with Oleksandr “Sasha” Bibik, who provided indispensable expertise in optical diagnostics. Sasha never ceases to amaze me with his creative solutions to implementation. Dmitriy Shcherbik developed instrumentation and controls for the test facility and was always eager to mentor me in data analysis techniques. His attention to detail and commitment to excellence are unmatched and his contributions to the project are invaluable. Svyatoslav “Slava” Yorish provided a great deal of mechanical design support and patiently taught me many of the machine shop skills that I used again and again throughout the project. Jeff Lovett was an instrumental resource and his many successful years of industry experience taught all of us important lessons along the way. I want to say thank you specifically to the research engineers Bobby Noble, David Wu, Chris Ballance, Ben Emerson, and Brad Ochs, who were
always willing to generously donate their time and expertise. Similarly, I want to thank Shane Getchell, Seth Hutchins, and Kristopher Manion for working tirelessly to maintain the Lab infrastructure, and without whose efforts my experiments would not have been possible. I am proud to call them all colleagues and friends.

Construction of the test facility would not have happened without the support of the machinists Scott Elliott, Scott Moseley, Red, and Jeff Wilkie. I sometimes spent weeks on end in their shops and thoroughly enjoyed learning their numerous machining tricks and techniques. My only regret is that I may never again hear their heavy sighs when I walk into the shop with impossible designs, negative budgets, and deadlines of “yesterday.” They were always willing to help, with the (often-misplaced) hope that I would not return the next day with a melted part.

The life of the Combustion Lab is, of course, the many graduate students who reside within its walls. Despite our diverse backgrounds, different experience levels, demanding coursework, and massive research project responsibilities, we have become a family. First, I would like to recognize Alex Klusmeyer, who recommended me to the Combustion Lab when I was an undergraduate student. He introduced me to the fascinating line of work that has defined my career so far, and was my first mentor and friend in the Lab. He along with Aimee Williams and Tan Zu Puayen, the other Zinn PhD students, showed me the ropes of graduate school. I also want to acknowledge Nishant Jain, Ianko Chterev, Sampath Adusumilli, Tim Cook, Travis Smith, Nick Rock, Vedanth Nair, Debolina Dasgupta, Henderson Johnson, Dan Fries, Chris Douglas, Hanna Ek, and Nathan Prestridge, who made the Lab feel like home. Even with the trying pursuit of a PhD, I will always look back on the time I spent with these fellow students as some of the best years of my life.
# Contents

Acknowledgements iv  
List of Figures ix  
Nomenclature xv  
Summary xviii  

1 Introduction 1  
1.1 Motivation ........................................ 1  
1.2 High-g Combustion ................................ 2  
1.3 Swirl Augmentor .................................... 3  
1.4 Confined Swirling Flows ............................ 5  
1.5 Thesis Objectives and Outline ...................... 8  

2 Swirl Combustion Background 11  
2.1 Swirl-Stabilized Combustion ...................... 11  
2.1.1 Vortex Breakdown ............................... 12  
2.1.2 Precessing Vortex Core ......................... 15  
2.1.3 Shear Instabilities ............................. 16  
2.1.4 Boundary Layer Separation ...................... 16  
2.2 Flame Speed Enhancement .......................... 18  

3 Approach 20  
3.1 Experimental Facility Concept ........................ 20  
3.2 Peripherally Piloted Swirl Combustor Facility .......... 21  
3.2.1 Core Fuel Injection ............................ 22  
3.2.2 Swirl Generator ................................ 23  
3.2.3 Pilot Combustor ................................ 24  
3.2.4 Center Body .................................... 26  
3.3 Optical Diagnostics .................................. 28  
3.3.1 Low-Speed Chemiluminescence Imaging .......... 28  
3.3.2 High-Speed Chemiluminescence Imaging .......... 29  
3.3.3 High-Speed OH-Planar Laser Induced Fluorescence . 30  
3.3.4 Stereoscopic Particle Image Velocimetry .......... 31  
3.3.5 Planar Particle Image Velocimetry ............... 33  
3.4 Data Processing Techniques ........................ 34  
3.4.1 Flame Length ................................ 34  
3.4.2 Outer Flame Angle ............................. 35  
3.5 Stereo-PIV Calculations ............................ 38  
3.6 Planar-PIV Calculations ............................ 43  
3.7 Density Calculations ................................ 43  
3.8 Swirling Strength .................................. 44  
3.9 Vortex Tracking ................................... 45
4 Swirl Effects on Heat Release Distribution
   4.1 Flame Length Parametric Study .................................. 47
   4.2 Outer Flame Angle Study ......................................... 54
   4.3 High-Speed Planar Imaging ....................................... 60
   4.4 Inner Flame Characterization ................................. 65
      4.4.1 Inner Flame Initiation .................................. 70
      4.4.2 Inner Flame Structure .................................. 74

5 Effects of Swirl and Heat Release on Flow Field .......... 75
   5.1 Non-Reacting Mean Velocity Field ............................. 76
   5.2 Reverse Flow Statistics ...................................... 80
   5.3 Flow Separation .............................................. 83
   5.4 Helical Vortices .............................................. 86
   5.5 Heat Release Effects .......................................... 90

6 Comparison of Scalar Field and Flow Field .......... 96
   6.1 Inner Flame ................................................... 96
   6.2 Outer Flame .................................................. 103
   6.3 Flame Compactness .......................................... 108

7 Conclusions and Recommendations .................. 110
   7.1 Major Findings and Contributions ............................. 111
      7.1.1 Inner Flame ........................................... 111
      7.1.2 Outer Flame .......................................... 114
   7.2 Recommendations for Future Work ........................... 115

References ................................................................. 117
## List of Figures

1. Results from propane-air combustion centrifuge experiments indicating enhancement of observed flame speed by centrifugal forces, from [1].
2. Schematic of a compact peripherally piloted swirl augmentor from [2].
3. Drawing of small-scale swirl augmentor rig from [3].
4. A typical gas turbine burner from [4].
5. Prominent flow features in a typical gas turbine main combustor from [5]; labels have been altered to be consistent with terminology in this document.
6. Sketch of the helical structure formed by the precessing vortex core from Chanaud [6].
7. Schematic representation of the test rig and instrumentation.
8. Core fuel injectors.
9. Interchangeable vane sections.
10. Swirl vanes (30°) installed, showing tight fit around center body.
11. Design of the pilot combustor.
13. Circumferential v-gutter flameholder with teeth.
14. Scaled drawing of center body trailing edge geometry. Linear dimensions are in millimeters.
15. Schematic and field of view of the chemiluminescence imaging system.
16. Schematic of the high-speed chemiluminescence imaging system.
17. Schematic of the high-speed OH-PLIF imaging system.
18. Schematic of the stereo PIV setup.
19. Schematic of the planar PIV system.
20. Cumulative CH* intensity as function of distance downstream of pilot exit ($z = 0$).
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Dependence of total CH* chemiluminescence intensity (normalized by exposure time) on core fuel mass flow rate for all vane angles.</td>
</tr>
<tr>
<td>22</td>
<td>(left) Inverse Abel transform of CH* chemiluminescence image depicting the region, shown as a white rectangle, selected for calculation of the outer flame angle ( \theta_f ) (right) Maximum CH* intensity points and best fit line calculated by flame angle algorithm.</td>
</tr>
<tr>
<td>23</td>
<td>In-plane mean velocity field obtained using PIV with 45° vanes and ( \Phi_{core} = 1.0 ).</td>
</tr>
<tr>
<td>24</td>
<td>Mean radial velocity profiles at two axial locations obtained from PIV measurements using 45° vanes with ( \Phi_{core} = 1.0 ).</td>
</tr>
<tr>
<td>25</td>
<td>Mean of particle scattering images used for image correction.</td>
</tr>
<tr>
<td>27</td>
<td>Comparison of axial velocity fields with and without raw particle scattering image correction.</td>
</tr>
<tr>
<td>28</td>
<td>Summary of operating conditions for flame length and flame angle parametric studies.</td>
</tr>
<tr>
<td>29</td>
<td>Dependence of flame length on pilot characteristics for 30° vanes.</td>
</tr>
<tr>
<td>30</td>
<td>Dependence of flame length on ( M ) for 30° vanes.</td>
</tr>
<tr>
<td>31</td>
<td>Dependence of flame length on ( \Phi_{core} ) for all vane angles.</td>
</tr>
<tr>
<td>32</td>
<td>Theoretical unstretched laminar flame speeds (from CHEMKIN) as a function of core equivalence ratio for the measured combustor inlet conditions.</td>
</tr>
<tr>
<td>33</td>
<td>Dependence of flame length on swirl angle for ( \Phi_{core} = 0.55 - 1.0 ). The 30° data points were interpolated using the second order polynomial fit shown in Figure 31.</td>
</tr>
<tr>
<td>34</td>
<td>Dependence of outer flame angle on inlet ( M ).</td>
</tr>
<tr>
<td>35</td>
<td>Dependence of outer flame angle on ( \Phi_{pilot} ) and ( f_{pilot} ).</td>
</tr>
<tr>
<td>36</td>
<td>Dependence of outer flame angle on ( \bar{u}<em>{core} - \bar{u}</em>{pilot} ) and ( \rho_u/\rho_{pilot} ).</td>
</tr>
</tbody>
</table>
37 Dependence of outer flame angle on $\Phi_{\text{core}}$ and $\rho_u/\rho_b$ for all vane angles
38 Dependence of outer flame angle on swirl angle
39 Time sequence of OH-PLIF images with 30° vanes and $\Phi_{\text{core}} = 0.85$
40 Time sequence of OH-PLIF images with 30° vanes and $\Phi_{\text{core}} = 0.70$
41 OH-PLIF probability fields with 30° vanes and different core equivalence ratios.
42 Time-averaged CH* chemiluminescence images of the flame for three different swirl angles
43 Inverse Abel transform of time-averaged CH* chemiluminescence images with 30° vanes
44 Time-averaged CH* chemiluminescence images with 45° vanes
45 Inverse Abel transform of time-averaged CH* chemiluminescence images with 45° vanes
46 Colormapped CH* chemiluminescence image sequence (only includes every 5th frame) showing typical core flame ignition event
47 Colormapped flame luminescence image sequence (only includes every 15th frame) showing inner flame propagating upstream to stable location just after autoignition
48 Colormapped flame luminescence image showing helical flame structure (white dashed line)
49 Operating conditions at which SPIV was acquired
50 Radial profiles of mean axial velocity under non-reacting conditions (nominally $T_{in} = 1123$ K, $\Phi_{\text{pilot}} = 1$, $\Phi_{\text{core}} = 0$) for all three vane angles
51 Radial profiles of mean radial velocity under non-reacting conditions (nominally $T_{in} = 1123$ K, $\Phi_{\text{pilot}} = 1$, $\Phi_{\text{core}} = 0$) for all three vane angles
Radial profiles of mean azimuthal velocity under non-reacting conditions (nominally $T_{in} = 1123$ K, $\Phi_{pilot} = 1$, $\Phi_{core} = 0$) for all three vane angles.

Randomly selected instantaneous velocity field sequence from the $30^\circ$ non-reacting case with $v_z = 0$ contour shown in white. Spatial coordinates are normalized by test section diameter ($D$).

Reverse flow probability fields for $30^\circ$ and $45^\circ$ vanes with $\Phi_{core} = 0$.

Selected instantaneous velocity fields with $30^\circ$ vanes. White curve is the $v_z = 0$ contour.

Selected instantaneous velocity fields with $30^\circ$ vanes. White curve is the $v_z = 0$ contour.

Typical time series of in-plane velocity field for the $30^\circ$ non-reacting case. The white contour represents $v_z = 0$. Spatial coordinates are normalized by test section diameter ($D$).

Typical time evolution of swirling strength field and in-plane velocity field for the $30^\circ$ non-reacting case. Spatial coordinates are normalized by test section diameter ($D$).

Mean swirling strength field for the $30^\circ$ non-reacting case.

In-plane mean velocity field obtained using SPIV with $0^\circ$ vanes; non-reacting case is shown on the left, reacting case is shown on the right.

In-plane mean velocity field obtained using SPIV with $30^\circ$ vanes; non-reacting case is shown on the left, reacting case is shown on the right.

In-plane mean velocity field obtained using SPIV with $45^\circ$ vanes; non-reacting case is shown on the left, reacting case is shown on the right.

Reverse flow probability map from PIV with $30^\circ$ vanes and $\Phi_{core} = 0$ (left), $\Phi_{core} = 1$ (right).
Reverse flow probability map from PIV with 45° vanes and $\Phi_{core} = 0$ (left), $\Phi_{core} = 1$ (right) ........................................ 93

Swirling strength=0.6 s$^{-1}$ isocontours for non-reacting and reacting flows with 30° vanes. ........................................ 94

Time series of swirling strength field and in-plane velocity field for the 30° reacting case showing symmetric vortices. Spatial coordinates are normalized by test section diameter ($D$). ............................. 95

Time series of swirling strength field and in-plane velocity field for the 30° reacting case showing asymmetric vortices. Spatial coordinates are normalized by test section diameter ($D$). ............................. 95

Inverse Abel transform of time-averaged CH* chemiluminescence images with overlay of 10% isocontour (white curve) of reverse flow probability at stoichiometric conditions ........................................ 97

OH-edge probability for $\Phi_{core} = 0.85$ with overlay of 10% reverse flow probability contour (solid white) and swirling strength=0.6 s$^{-1}$ contour (dashed white) for 30° reacting case. Higher reverse flow probabilities and swirling strengths occur in the narrow region between the white contours. Although the colormap is saturated, the peak OH-edge probabilities away from the laser sheet edge are ∼5%. ........................................ 99

Isocontours of 2% OH-edge probability vs. core equivalence ratio . . 100

Inverse Abel transform of time-averaged CH* chemiluminescence images with overlay of 10% isocontour (white curve) of reverse flow probability with 45° vanes ........................................ 101

2% isocontours of OH-edge probability with pilot on ($\Phi_{pilot} = 1.0$) and pilot off ........................................ 102

Randomly selected instantaneous OH-edges for a short flame ($\Phi_{core} = 0.54$) and a long flame ($\Phi_{core} = 0.85$) ........................................ 104
74 OH-edge probability fields with 30° vanes and different core equivalence ratios. ........................................ 105
75 Radial profiles of axial velocity for 30° vanes at $z/D = 0.4$ under non-reacting and reacting conditions .......................... 107
Nomenclature

Abbreviations

CFD  Computational fluid dynamics
IRZ  Inner recirculation zone
ORZ  Outer recirculation zone
PIV  Particle image velocimetry
PLIF Planar laser-induced fluorescence
PVC  Precessing vortex core
SPIV Stereoscopic particle image velocimetry
VBD  Vortex breakdown

Symbols

$\bar{u}_{\text{core}}$  Mean streamwise velocity in the core
$\bar{u}_{\text{core}}$  Mean streamwise velocity in the pilot
$\dot{m}_{\text{air,core}}$  Mass flow rate of air through the core
$\dot{m}_{\text{air,pilot}}$  Mass flow rate of air through the pilot
$\dot{m}_{f,\text{core}}$  Mass flow rate of fuel through the core
$\lambda$  Eigenvalue
$\lambda_{ci}$  Swirling strength
$\omega$  Vorticity
$\Phi$  Equivalence ratio
\( \Phi_{\text{core}} \)  Core equivalence ratio

\( \Phi_{\text{pilot}} \)  Pilot equivalence ratio

\( \rho \)  Density

\( \rho_b \)  Density of (burned) products

\( \rho_{\text{pilot}} \)  Pilot density

\( \rho_u \)  Density of unburned reactants

\( \theta \)  Azimuthal coordinate

\( \theta_f \)  Outer flame angle

\( D \)  Test section diameter

\( f_{\text{pilot}} \)  Pilot mass fraction

\( g \)  Earth’s gravitational acceleration

\( G_z \)  Axial flux of axial momentum

\( G_\theta \)  Axial flux of angular momentum

\( h \)  Planck constant

\( L_f \)  Flame length

\( M \)  Mach number

\( m \)  Azimuthal wavenumber

\( p \)  Pressure

\( R \)  Characteristic radius

\( r \)  Radial coordinate
\( Re \)  Reynolds number
\( S \)  Swirl number
\( S_L \)  Laminar flame speed
\( S_{L0} \)  Unstretched laminar flame speed
\( S_{cr} \)  Critical swirl number
\( t \)  Time
\( T_{in} \)  Inlet temperature
\( u \)  Velocity in the \( x \)-direction/streamwise direction
\( v \)  Velocity in the \( y \)-direction/transverse direction
\( v_r \)  Radial velocity
\( v_z \)  Axial velocity
\( v_\theta \)  Azimuthal velocity
\( x \)  Horizontal planar coordinate
\( y \)  Vertical planar coordinate
\( z \)  Axial coordinate
Summary

In aircraft turbine engines, it is desirable to minimize size and maximize efficiency. One of the largest components found in high-performance aircraft turbine engines is the thrust augmentor. Historically, thrust augmentors employ bluff body flameholders. One advanced design concept instead uses a peripheral pilot to stabilize a flame around the outside of a swirling flow. Removal of the bluff body reduces pressure losses and initial experiments suggest that the swirling flow creates a shorter flame, allowing for a more compact device. Previous work has focused on 1-D centrifuge experiments and development of practical devices, but little detailed work has been done to elucidate the fundamental mechanisms controlling flame stabilization in this architecture.

This thesis shows how swirl affects flame length in this concept and tests current hypotheses that describe the fundamental mechanisms behind this effect. It includes development of a test facility and an experimental investigation in a well-characterized swirl combustor with outer-diameter flame stabilization and realistic augmentor inlet conditions. Premixed flame configuration and dynamics are captured by advanced instrumentation, high-speed OH-PLIF, and CH* chemiluminescence imaging. High-speed stereoscopic PIV is used to characterize the unique flow field near the trailing edge of a tapered center body in a confined swirling flow both with and without combustion. Simultaneous analysis of the scalar field and flow field reveal the physics that control flame compactness in this type of combustor.

Initial parametric studies of flame length identified the core equivalence ratio and swirl level as the parameters that control flame length. Pilot characteristics were determined to be inconsequential when the pilot is burning. The flame length was significantly reduced by swirl, but exhibits a non-monotonic relationship to core equivalence ratio when swirl is present. This behavior was not predicted and was found to depend on two important features: the outer flame, stabilized by the pilot,
and the inner flame, anchored on the conical trailing edge of the center body.

When swirl is present, reverse flow provided by helical vortices allows the inner flame to propagate upstream and stabilize on the center body. Correlation of the flow field measurements to planar imaging statistics revealed that the flame is anchored where the flow separates on the conical center body trailing edge. The flame length is reduced as higher swirl levels strengthen the adverse pressure gradient and move the flow separation, together with the inner flame, upstream. This effect does not depend on the core equivalence ratio as long as the inner flame is present. The helical vortices were quantified for the lower swirl level, showing that they originate from where the flow separates on the center body and exist in the same location regardless of whether or not the core flame is present. The inner flame is then shown to be confined to the helical vortex region.

Detailed instantaneous images revealed large-scale distortions in the outer flame front only at the leanest core equivalence ratios. The outer flame propagates across the core flow significantly faster at these conditions, contributing to a shorter flame. Several hypotheses are examined that could explain the outer flame behavior, including a Rayleigh-Taylor mechanism, a baroclinic push mechanism, a shear-driven mechanism, and vitiation effects.

The scalar and velocity field measurements obtained in this investigation form a large experimental database in a well-documented, well-characterized test facility. This is essential for validation of CFD models and serves as a foundation for future experimental research that aims to further explore the flame stabilization and flow physics in this configuration.
1 Introduction

1.1 Motivation

Since its advent in the early 1900s, the development of the modern gas turbine engine has been led by its application to aircraft propulsion. Its robustness and inherently high thrust-to-weight ratio have allowed it to be used across the spectrum of aircraft from small recreational transportation to advanced combat vehicles. Gas turbine combustors in particular have been the subject of extensive research due to their influence on a number of key engine performance metrics including thrust specific fuel consumption, longevity, operational range, weight, and environmental impact to name a few.

In order to meet a wide range of performance demands, some aircraft gas turbine engines have special combustors designed to provide temporary thrust gains. This is accomplished by introducing and burning additional fuel in the high-temperature vitiated (reduced oxygen content) flow downstream of the main combustor and turbine. Advanced reheat combustion concepts could be located either between the turbine exit and the nozzle or implemented between the stages of a turbine [7, 8, 9]. Because of the demand for more compact and efficient engines, a key component of these advanced concepts is the development of new flameholding schemes that aim to reduce the size and stagnation pressure losses associated with reheat devices [10, 11, 12, 3].

Some of these combustor concepts are based on the 1-D combustion centrifuge experiments of Lewis [13, 1, 2]. He showed that turbulent flame speeds can be dramatically enhanced by a centrifugal force field when the density gradient produced by the flame is misaligned with the centrifugal force vector. His experiments have also been modeled and expanded upon by Briones et al. [14] and Katta et al. [15]. These findings set in motion the development of new “high-g” combustion devices for applications where combustor compactness is important.
One concept in particular uses a peripheral pilot combustor to initiate and sustain combustion around the outer diameter of a swirling mixture of fuel and air, which is the topic of the present study. This flame then propagates radially inward through the unburned mixture. Previous researchers hypothesized that adding swirl to a flow where a flame lies between an inner high-density layer of unburned reactants and the outer low-density layer of products would enhance the turbulent flame speed in a similar fashion to the 1-D combustion centrifuge experiments of Lewis due to the Rayleigh-Taylor instability. Following this logic, higher density ratios would be expected to lead to higher turbulent flame speeds. Since this work, additional mechanisms that could affect flame speeds in this configuration have also been proposed; these are discussed in Chapter 2.

The peripherally piloted swirl combustor configuration aims to take advantage of these centrifugally enhanced flame speeds to improve combustor compactness with a lower stagnation pressure penalty than more intrusive flameholding approaches. While it has successfully been demonstrated in one application [16], there is little experimental data available for developing design tools and elucidating the physical mechanisms that may govern its performance and provide insight to combustor designers.

1.2 High-g Combustion

The effect of centrifugal forces on flame propagation was studied experimentally by Lewis in a constant-volume premixed combustion centrifuge. He observed that flame speeds increased with the square root of centrifugal acceleration within a range of accelerations, which were large compared to gravity. Some results of this study are shown in Figure 1. Lewis hypothesized that buoyant forces controlled the spreading of the flame when the terminal velocity of the flame “bubble” exceeded the turbulent flame propagation rate [1]. The study culminated in the development of an analytical
model that uses bubble mechanics to predict flame propagation rates in a centrifuge [2]. Numerical simulations of Lewis’s combustion centrifuge experiments were later performed by Briones et al. [14] and Katta et al. [15], although only the former modeled a closed system. Both of these numerical studies showed good agreement with Lewis’s experimental results.

Figure 1: Results from propane-air combustion centrifuge experiments indicating enhancement of observed flame speed by centrifugal forces, from [1]

Unlike the constant volume experiment of Lewis, practical approaches that are adaptable to gas turbines should be flowing systems which operate at nearly-constant pressure. In these implementations [10, 11, 12, 3], the centrifugal force is produced by a swirling flow. Little detailed work has been done to determine whether this “high-g” effect can be harnessed to significantly enhance flame propagation in swirling flows.

1.3 Swirl Augmentor

Of the high-g combustion devices that have been developed, the peripherally piloted swirl augmentor concept is perhaps the most direct practical application of centrifugal enhancement of flame propagation in a swirling flow. Figure 2 shows a
schematic of this concept. A centrifugal force field is generated by using vanes upstream of the combustion chamber to impart swirl to the flow. A center body is incorporated as the intended application is found downstream of a turbine and the flow field would be influenced by the wake of the shaft. An annular pilot combustor around the outer diameter of the swirling flow provides a continuous ignition source to initiate and sustain combustion of the incoming fuel and air mixture, similar to the function of the recirculation zone in a traditional bluff-body-stabilized augmentor or swirl-stabilized primary combustor. While non-swirled augmentors have traditionally used pilot combustors, which are often near the flow centerline [17, 18], a key feature of the swirl augmentor is that the peripheral pilot ensures that the flame is always anchored around the outer diameter of the swirling flow. The combination of the centrifugal force field and the arrangement of low-density combustion products and intermediate species near the outer diameter and high-density reactants in the center was expected to create a scenario analogous to Lewis’s combustion centrifuge.

Both experimental and analytical efforts studied the peripherally piloted swirl augmentor. Experimental results from a small-scale test rig, shown in Figure 3, suggest that the peripherally piloted swirl combustor configuration allows for reduction of combustor length without compromising combustion efficiency or operational
Figure 3: Drawing of small-scale swirl augmentor rig from [3]

range [3, 19]. An analytical model was developed alongside the combustion centrifuge model that aimed to predict the flame front location in this type of combustor [2]. The model assumed that a flame bubble, initiated by the pilot, was driven radially inward by buoyant forces until it reached the combustor centerline. Experimental characterization of the flame, however, was limited to temperature probe traversing in the chamber and gas sampling at the exhaust plane using test sections of different lengths. Flow field characterization consisted only of air angle measurements under non-reacting conditions. As a result of these limited diagnostic capabilities, it remains unclear whether or not the observed performance was truly due to enhancement of flame propagation by centrifugal forces. Additionally, lack of flame configuration and reacting flow field measurements leaves the flame stabilization physics in this type of combustor largely unknown.

1.4 Confined Swirling Flows

Fundamental studies of swirling flows have been covered extensively in the literature and the important flow features unique to swirling flows are, in general, well-known. Much of the early work on confined swirling flows was limited to laminar pipe
flows due to the historical limitations of experimental diagnostic tools and numerical modeling. A comprehensive review of this work was composed by Lucca-Negro and O’Doherty [20]. Practical applications of swirling flows, however, almost invariably fall into the turbulent regime. Among the first to study turbulent swirling pipe flows in detail were Kitoh [21] and Sarpkaya [22]. They both showed that swirling flows may exhibit distinct and highly complex features, such as conical forms of vortex breakdown, not observed in laminar flows [22]. This work will thus be limited to discussion of turbulent swirling flows.

Besides the swirl augmentor work, most previous research on confined swirling flows can be placed into one of two categories: swirling flows with a center body issuing into a large outward area expansion or swirling pipe flows with no center body. The former describes a typical configuration used in a modern gas turbine main combustor such as the one shown in Figure 4. To give a few representative examples of studies employing premixed, swirl combustors with center-bodies, a combustor with a bluff center body and an area expansion ratio of 22.2 was examined in [23, 24, 25], while Steinberg et al. studied a device with a tapered center body and an area expansion ratio of 12 [26].

Hallett and Toews [27] showed that when the area expansion is sufficiently large, the flow in the near field of the nozzle is not a strong function of the area expansion ratio. An augmentor, due to its location downstream of the turbine, is typically limited to a very modest area expansion. Thus, the occurrence and behavior of important flow features such as the onset of vortex breakdown may be quite different when compared to typical engine main combustor geometries.

Studies have also been conducted on swirling flows with no area expansion. For example, Nishibori et al. [28] and Facciolo et al. [29] studied swirling flows with no expansion in axially rotating pipes. In this scenario, swirl is imposed at the boundary and thus does not decay along the length of the pipe. These studies therefore do not
include the effects of swirl decay on axial and radial pressure gradients, which could affect vortex breakdown onset and mode selection [30]. Genc et al. [31, 32] studied flows in which the swirl is generated upstream of a stationary pipe. Moreover, none of these studies of swirling pipe flows include the effects of a center body on the flow field.

The flow downstream of a stationary swirl generator with a center body will have a different velocity profile from that of a rotating pipe or a tangential entry swirler. Specifically, there could be a local axial velocity minimum in the wake of a center body. Without a center body, the velocity profile in a pipe flow could have an axial velocity maximum along the centerline. Several studies have shown that the radial and axial velocity profiles, which depend on center body geometry, has a significant influence on the development of swirling flow fields [33, 34, 35].

The influence of center body geometry has also been studied in annular jets without swirl by Ko and Chan [36, 37, 38]. By measuring the flow field with a bluff center body, a conical center body, and an ellipsoidal center body, they found that features in the mean flow are strongly influenced by the geometry of the center body trailing
edge. The bluff center body allowed for the formation of an inner recirculation zone in the mean flow while the two aerodynamic center body shapes did not.

In all, there has been very little characterization of swirling flow fields with a center body and no outer expansion. One exception is Lei et al., who studied the effects of swirl in a turbofan exhaust system with lobed mixers [39]. There is strong evidence in the literature that the effects of swirl, center body geometry, and area expansion are all significant for the combustor configuration of the current study. Thus, the flow features that could promote flame stabilization cannot be predicted a priori.

1.5 Thesis Objectives and Outline

The overall goal of this thesis is to show how swirl affects flame compactness in a peripherally piloted swirl combustor and understand the physical mechanisms behind these effects. The work focuses on the following specific objectives which aim to provide data and understanding of physical processes critical to the development of a more efficient and compact combustor.

1. The first objective is to conduct a detailed parametric study to identify which parameters control the flame length in the peripherally piloted swirl combustor. Parameters are selected that would be expected to influence flame stabilization and propagation, and are varied over a range relevant to practical devices.

2. The second objective is to generate temporally and spatially resolved scalar and velocity data that varies the parameters identified in the first objective. This data set is obtained in a well-controlled and well-documented facility and can be used for further understanding of the important physical processes and for future CFD validation studies of this unique flow field.

3. The third objective is to understand the effect of swirl level on flame stabilization
downstream of the center body, which could significantly reduce flame length.

4. The fourth objective is to investigate the role of the outer flame in determining combustor compactness. This objective focuses on investigating flame speed enhancement in the outer flame and testing hypotheses that could explain the underlying physical mechanisms behind the observed outer flame behavior.

Chapter 2 provides technical background that is important for understanding the experimental results and analysis. This includes selected details from the topics of swirl-stabilized combustion, instabilities in turbulent swirling flows, boundary layer separation, and turbulent flame speed enhancement mechanisms.

Chapter 3 describes the experimental and numerical approach, and analysis techniques used for this thesis. First, the design of the test facility and its instrumentation is described along with the details of the chemiluminescence imaging systems and the stereo-PIV system. Next, the methodology behind the flame speed and equilibrium calculations is explained. Finally, the algorithms used to analyze the experimental data are presented.

The flame length and flame angle parametric studies are presented in Chapter 4. Specifically, the dependence of flame length on swirl level, pilot mass fraction, pilot equivalence ratio, Mach number, and core equivalence ratio are determined. High-speed imaging of the flame is then examined to reveal the inner flame ignition mechanism and dynamics.

The results of the stereo-PIV experiments are shown in Chapter 5. The mean velocity field near the center body trailing edge is first characterized under non-reacting conditions both without swirl and at multiple swirl levels. Statistics of the velocity field and are used to identify and quantify the flow structures that control inner flame stabilization. The effects of heat release on the flow field are also characterized in this chapter.
Chapter 6 combines the analysis of the scalar field and flow field to explain the physics controlling flame compactness.

The key contributions of the thesis are then summarized in Chapter 7. Practical implications of the results are presented along with recommendations for future work.
2 Swirl Combustion Background

The primary function of most practical combustors is to mix fuel with air and burn the mixture with high combustion efficiency in a restricted volume. Gas turbine combustors accomplish this by creating recirculation zones or regions of low velocity. The relatively high residence times and mixing rates in these zones allow the fuel and oxidizer to mix at a molecular level and react, releasing heat quickly enough to continuously ignite the unburned mixture flowing into the combustor over a wide range of operating conditions. These flow patterns are normally achieved by some combination of: a sudden area expansion, a bluff body, a strongly swirling jet, and/or transverse jets [40]. Understanding and predicting the highly complex fluid mechanics that promote flame stabilization is therefore a significant prerequisite to combustor design. Additionally, there are several mechanisms known to enhance or suppress flame propagation in swirling flows, which could have significant implications for combustor compactness. This chapter provides technical background on these flow features and their interactions with combustion relevant to this work.

2.1 Swirl-Stabilized Combustion

Flame stabilization in main-stage gas turbine combustors is accomplished by a strongly swirling turbulent jet issuing into a sudden area expansion. Such a flow field is shown in Figure 5, which highlights the key time-averaged flow features that influence flame stabilization. These include both an inner recirculation zone (IRZ) and outer recirculation zone (ORZ). The IRZ is associated with vortex breakdown (VBD) and a center body wake; the ORZ is a secondary flow induced by the sudden area expansion. These recirculation zones provide multiple low and reversed velocity regions where a flame can stabilize. As such, a single combustor configuration can support a variety of flame topologies, which occur at different operating conditions. Shear layers
are found between the high-velocity annular flow not entrained into the recirculation zones and the recirculation zones themselves, and are appropriately known as the inner shear layer (ISL) and outer shear layer (OSL). Flow instabilities often found in the shear layers can influence burning rates. Swirl-stabilized combustors also contain organized time-dependent flow structures such as a precessing vortex core (PVC) that spins around the IRZ. This section provides background on vortex breakdown, the precessing vortex core, hydrodynamic instabilities relevant to swirling flows, and the interaction of these phenomena with flames.

2.1.1 Vortex Breakdown

Vortex breakdown (VBD) is perhaps the most significant feature of strongly swirling flows. It can be described as an abrupt and severe change in the vortex structure when certain conditions are achieved. This phenomenon has been the subject of extensive research due to its occurrence in many flows of practical importance. One of the earliest examples of this comes from the flow over a delta wing at high angles of attack in which unfavorable aerodynamic characteristics may arise from VBD.
This motivated some of the first theoretical studies by Squire [41] and Benjamin [42] which led to the understanding of VBD as essentially a critical phenomenon, occurring when part of the flow becomes subcritical to downstream disturbances. This was later supported experimentally by Sarpkaya [43]. In contrast to delta wings, VBD has long been used as the primary mechanism of flame stabilization in gas turbine combustors. Accordingly, extensive analytical, numerical, and experimental studies have sought develop a general theory of VBD and at present have only partially succeeded. This is because the onset, topology, and dynamics of VBD depend on swirl generator type, hardware geometry, swirl number, Reynolds number, outlet conditions, and many other parameters [20, 44]. These results have been summarized in reviews by Hall [45], Leibovich [46, 47], Lucca-Negro and O’Doherty [20], Escudier [48], Althaus et al. [49], and Syred [50] among others.

The criteria for VBD onset are often described in terms of the swirl number $S$, which is the primary similarity parameter used to characterize swirling flows. The swirl number is generally defined as the ratio of axial flux of angular momentum $G_{\theta}$ to the product of axial flux of axial momentum $G_z$ and a characteristic radius $R$. Its most general form was proposed by Beér and Chigier [51] and is given by equation 1, although the pressure integral term in the denominator is often neglected [52]. It is used to represent the relative significance of rotational motion compared to axial motion in the flow. Large values of $S$ represent strong swirl while small values represent weak swirl. Note that the swirl number can be difficult to measure experimentally and can also be defined using the geometry of the swirl generator [53].

$$S_0 = \frac{G_{\theta}}{RG_z} = \frac{\int_0^R \rho v_{\theta} r v_z 2\pi r dr}{R \int_0^R \rho v_z v_z 2\pi r dr + R \int_0^R \rho 2\pi r dr}$$  \hspace{1cm} (1)

The swirl number above which VBD occurs is known as the critical swirl number $S_{cr}$. For swirling jets and confined swirling flows with a large expansion, $S_{cr}$ is approximately equal to 0.6; however, the onset of VBD is not purely a function of the
swirl number. A physical examination of VBD recognizes that it is strongly coupled to the pressure distribution in the flow. The axial decay of velocities in a confined swirling flow or jet, which is also a function of area expansion, generates an adverse axial pressure gradient. When the adverse axial pressure gradient is large enough to overcome the axial momentum of the flow, a stagnation point appears followed by a region of reverse flow. This creates what is often referred to as the VBD “bubble.”

For flows with small area expansions, $S_{cr}$ increases as the area expansion ratio decreases, indicating that a primary effect of high confinement is the suppression of VBD [27], though VBD can still occur in flows with no expansion [54, 55]. On the other hand, increasing the rate of area expansion (and thus the adverse axial pressure gradient) has a similar effect to increasing the swirl level. A higher divergence angle encourages VBD and moves the its location upstream as long as the boundary layer does not separate [30]. Thus, a swirl combustor typically uses a large, sudden area expansion to stabilize the location of the vortex breakdown just downstream of the swirl nozzle.

Much of the early work focused on understanding the modes and flow regimes associated with vortex breakdown in laminar flows. The review paper by O’Doherty and Lucca-Negro [20] in particular summarizes much of the experimental, numerical, and theoretical work on vortex breakdown in mostly laminar flows; however, most practical devices, such as industrial burners and gas turbines, have highly turbulent base flows (high $Re$). Sarpkaya [22] was one of the first to study VBD in a turbulent flow. He showed that VBD can manifest with fundamentally different topologies when the base flow is turbulent. At high Reynolds numbers ($Re \sim O(10^5)$), an axisymmetric VBD bubble begins to merge with its wake to form a conical turbulent VBD structure. In Sarpkaya’s study, the conical VBD mode reached its final form at around $Re = 200,000$.

Finally, it has been shown that vortex breakdown in a reacting flow such as a gas
turbine combustor has a similar form to an isothermal flow. In a confined swirling flow, a fluid element experiences primarily axial acceleration as it enters the flame. Weber and Dugué pointed out that this reduces the effective local swirl number by increasing the axial momentum without a corresponding increase in angular momentum. A reduction in the effective swirl number therefore results in a smaller and weaker inner recirculation zone (IRZ) [56].

2.1.2 Precessing Vortex Core

While the most basic form of VBD consists of a toroidal axisymmetric recirculation bubble with a stagnation point on the flow centerline, more complex phenomena can occur when the stagnation point moves off the axis and precesses around the flow centerline. This is known as the precessing vortex core (PVC) and commonly accompanies VBD in strongly swirling flows. The PVC interacts with the VBD bubble to create a spiral or helical vortex, which is depicted in Figure 6.

![Figure 6: Sketch of the helical structure formed by the precessing vortex core from Chanaud [6]](image)

As with VBD, the criteria for onset and characteristics of the PVC are complex
and depend on an array of variables including but not limited to density stratification (modified by flame configuration), reverse flow, and outlet geometry [23, 24, 25]. It has been shown that the influence of combustion could be to strengthen the PVC or to prevent its formation in the same combustor depending on operating conditions [26].

2.1.3 Shear Instabilities

A similar but distinct flow instability arises in the shear layers, which are associated with the Kelvin-Helmholtz instability. Because swirling flows have both axial and tangential shear, the Kelvin-Helmholtz instability in a swirling shear layer results in vortex shedding that forms a helical structure. Helical vortices can therefore be found in the ISL and OSL, and can coexist and interact with the PVC.

Helical vortices are typically classified by their azimuthal wavenumber $m$. The absolute value of the azimuthal wavenumber describes the number of helices and the direction of winding relative to the swirl direction of the base flow. For example, the $m = 0$ mode is axisymmetric and $|m| = 1$ describes a single helix. The sign of the azimuthal wavenumber describes the direction of winding relative to the swirl direction of the base flow. A wavenumber of $m = −2$ represents a double-helix that winds in the opposite direction to the base-flow swirl. Note that a helical vortex that winds opposite to the swirl direction rotates in the same direction.

In turbulent swirling flows, the $m = −1$ helical mode is most commonly observed at moderate swirl numbers. At higher swirl levels both the $m = −1$ and, though less commonly, $m = −2$ modes have been observed [57, 58, 59].

2.1.4 Boundary Layer Separation

It has already been stated that a flame can easily stabilize in a region of reversed flow. Thus it is important to consider another common source of reverse flow. In a
viscous fluid flow over a solid boundary, there exists a thin layer of fluid next to the boundary that is dominated by viscous effects. This is known as the boundary layer. The fluid velocity is zero relative to the boundary at the surface and the velocity gradient normal to the surface is large within the boundary layer.

In the case of a negative streamwise (favorable) pressure gradient, the boundary layer will remain attached to the surface. When there exists a positive streamwise (adverse) pressure gradient, the boundary layer slows down, thickens, and eventually may stagnate. At the stagnation point, the velocity gradient normal to the surface becomes zero, resulting in zero shear stress at the boundary. Beyond the stagnation point, reverse flow occurs and the flow is said to have separated [60].

Adverse axial pressure gradients in swirling flows make them susceptible to boundary layer separation. In some scenarios, such as a sudden outward expansion in a swirl combustor, the boundary layer predictably separates at the sudden expansion due to the very strong adverse pressure gradient. In a more gradual expansion such as a conical diffuser or a tapered center body, the situation is more complex. The adverse pressure gradient, and thus the tendency for the boundary layer to separate, depends on both the level of swirl and the rate of area expansion. For example, it is well-known that swirling flows may be used to improve performance of conical diffusers by suppressing flow separation along the outer walls [61, 62]. Annular flows over a center body can separate near the center body trailing edge, and the position of the flow separation will depend on the strength of the adverse pressure gradient [63, 64]. Importantly, the separated center body wake in a swirling flow could merge with the VBD bubble at sufficiently high swirl levels which substantially alters the flow dynamics of swirling flow structures [65].
2.2 Flame Speed Enhancement

Swirling flows are also susceptible to instabilities and vorticity dynamics related to centrifugal and inertial effects that could affect turbulent flame speeds. The Rayleigh criterion gives a condition for centrifugal instability with respect to axisymmetric disturbances; specifically, instability occurs when the square of the circulation does not decrease with radius \([66]\). This condition is expressed in equation 2 in terms of the azimuthal velocity \(v_\theta\). Note that the flow could still be unstable to non-axisymmetric disturbances even when this criterion is not met.

\[
\frac{\partial}{\partial r} (r^2 v_\theta^2) < 0 \quad (2)
\]

When combustion occurs in a swirling flow, instabilities arising from density gradients interacting with body forces could also become important. Adding swirl to a flow creates a radial pressure distribution in which pressure increases with distance from the swirl axis to primarily balance the centrifugal force, as represented by Equation 3. Higher azimuthal velocities create stronger radial pressure gradients, strengthening the effective body force (analogous to a gravitational acceleration) on the fluid.

\[
\frac{\partial p}{\partial r} \approx \frac{\rho v_\theta^2}{r} \quad (3)
\]

A Rayleigh-Taylor unstable configuration occurs when the fluid is subjected to an acceleration that acts in an opposing direction to the density gradient \([67, 68]\). It has been shown that the density gradient created by a flame in a centrifugal force field can trigger this instability \([13, 14]\). For flames in vitiated systems with high reactant temperatures, the density ratio across the flame can be significantly lower, and this can cause dramatically different interactions between the flame and flow instabilities \([69]\). It has also been shown that even when conditions are favorable for the Rayleigh-Taylor instability, hydrodynamics are not necessarily Rayleigh-Taylor-
dominated [70]. These flow instability mechanisms are important because they can amplify or suppress fluctuations in the velocity field that wrinkle or corrugate the flame, acting to increase or decrease turbulent flame speeds.

A third mechanism that is distinct from the Rayleigh-Taylor instability, but occurs in a similar scenario, is known as baroclinic push [71, 72]. Vorticity production at the flame front through baroclinic torque could occur when the density gradient across the flame is misaligned with the pressure gradient. This is illustrated mathematically in Equation 4. Velocities induced by this vorticity could have an effect on the turbulent flame speed similar to the aforementioned instability mechanisms [73]. These effects of flame coupling with the flow field are expected to be most significant for the case of strong vortices ($\nu_\theta/S_L \sim O(1)$) that are normally incident to the flame front [74].

$$\frac{d\omega}{dt} = \frac{\nabla \rho \times \nabla p}{\rho^2}$$  

(4)
3 Approach

This chapter describes the experimental facility and diagnostic techniques used for this work. The first section details the design of the apparatus and instrumentation. The second section describes implementation of the diagnostic techniques used for flame and flow measurements. The third section describes the raw data processing methodology.

3.1 Experimental Facility Concept

The experimental approach requires a unique test facility capable of producing flow conditions relevant to a reheat combustor, providing independent control of important operating parameters, and supporting the wide range of instrumentation and diagnostics needed for the study. Importantly, these requirements must be applied in the context of the swirl augmentor configuration, which was described in Section 1.3.

For this study, the flow was designed to represent conditions after the flow has expanded through the turbine in a modern gas turbine engine, as described in the literature by Lovett et al. [17]. Specifically, the pressure is nominally atmospheric, oxygen content is reduced to 15%, temperature is 850°C, and maximum velocities are nearly 150 m/s.

The instrumentation must be able to measure and record inlet conditions with good temporal resolution. This includes the temperature, pressure, and mass flow rate through each air and fuel flow path, and oxygen content of the vitiated flow.

Based on previous work described in Sections 1.2 and 1.3, the factors expected to have the greatest influence on combustor compactness in the swirl augmentor include laminar flame speed, density ratio between pilot and core flows, velocities in the combustor, and swirl level. Practically, the laminar flame speed can be varied by adjusting the equivalence ratio in the core with independent air and fuel throt-
ting. The density ratio between the pilot and core flows can be adjusted similarly by changing the equivalence ratio of the pilot combustor, which controls the flame temperature in the outer pilot flow. Velocities in the combustor will depend on the total air and fuel flow rates as well as the level of vitiation. Finally, the swirl level in the test section can be controlled by the choice of swirl vane angle.

In order to investigate the controlling physical mechanisms in the combustor, it is necessary to implement diagnostics that characterize both the heat release field and flow field. Standard optical diagnostic techniques were chosen for their ability to measure these variables with high spatial and temporal resolution, and without influencing the physical processes in the combustor. Some of these techniques require multiple cameras and lasers, so the test section must provide optical access to the flame from multiple angles. The following sections provide additional details describing how these design requirements were achieved.

3.2 Peripherally Piloted Swirl Combustor Facility

Figure 7 is a schematic representation of the test rig and instrumentation used for this study. Preheated air is supplied from the lab facilities to both the preburner and pilot combustor, which are separately throttled. This air temperature is nominally set to 350°C for stable and reliable operation of the preburner and pilot combustor. Preheated air is mixed with natural gas using a commercial swirl injection nozzle and burned in the preburner at a lean equivalence ratio. Dilution air is supplied toward the downstream end of the preburner to achieve the representative inlet conditions outlined in the previous section (850°C, 15% O₂, 150 m/s).

The gas leaving the preburner passes through a perforated plate to create a straight and uniform flow. The flow is choked at the preburner exit to prevent thermoacoustic coupling between the preburner and augmentor. Temperature and pressure measurements are taken as the flow passes through the annulus around the center body.
High-speed pressure transducers are installed in the core and pilot to monitor thermoacoustic instabilities. Natural gas is injected into the core flow upstream of the swirl vanes to create a uniformly premixed flow. The swirling mixture of fuel and air then mixes with the pilot flow at the entrance to the test section at atmospheric pressure. The test section is comprised of a 260-mm diameter, 760-mm long quartz tube which allows 360° optical access to the full length of the flame under most conditions. More detailed descriptions of the fuel injectors, swirl vanes, and pilot combustor are provided in the following sections.

3.2.1 Core Fuel Injection

Natural gas is mixed with the vitiated core flow upstream of the swirl vanes to provide a homogeneous mixture to the test section. The core fuel injection system consists of two concentric fuel injector rings with 112 and 115 orifice pairs oriented...
30° relative to the flow direction on the inner and outer rings, respectively. Figure 8a shows a close-up view of the core fuel injection orifices with the swirl vanes in the foreground. The fuel rings are each supplied by an outer manifold, shown in Figure 8b, with two inlets and three outlets. The fuel supply to the core fuel manifolds is controlled by a single TESCOM electropneumatic pressure regulator, independent of the pre-burner and pilot fuel flow rates.

(a) Fuel injection orifices  (b) Fuel injection rings and manifolds

Figure 8: Core fuel injectors

3.2.2 Swirl Generator

The level of swirl in the rig is adjusted by installing one of the three vane sections shown in Figure 9. The stationary curved axial swirl vanes have a profile designed to minimize flow separation. The vanes were manufactured from Haynes 188 alloy and designed to withstand the high inlet temperatures and aerodynamic load in the core flow. A wire EDM machine was used to cut out the vane profile with high precision and a smooth surface finish. The vanes protrude through the outer wall of the core and are welded from the outside so that the material added during welding does not disrupt the velocity profile. A custom jig was used for assembly and welding of the swirl vane sections to ensure a close fit around the center body; the result is shown in Figure 10.
3.2.3 Pilot Combustor

Figure 11 shows a section view of the test rig in the region of the pilot combustor.
The annular pilot is situated around the outer diameter of the core flow. It supplies a flow of hot combustion products, indicated by the red arrows, to the outer diameter of the premixed core flow, indicated by the yellow arrows, at the entrance to the test section. The purpose of the pilot is to initiate and stabilize the core flame. The outer wall of the pilot combustor is cooled by a water jacket; the inner wall is not cooled. The cross-sectional area of the pilot decreases in the streamwise direction to enhance the favorable pressure gradient and reduce the boundary layer thickness before the pilot flow meets the core flow.

The inlet air to the pilot combustor is unvitiated (21% $O_2$) and preheated to 350°C. It is supplied to the pilot through an insulated manifold with three inlets and six outlets. The air passes through four layers of 35% perforated plates, which promote flow uniformity, as it is turned 90° from the inlet toward the leading edge of the flameholder. The first layer of perforated plate is normal to the inlet flow, the second layer is at 45° to the first, and the third and fourth layers are normal to the primary flow direction in the test rig. The air flow rate through the pilot is variable but is nominally set to 10% of the total flow. A parameter called the pilot mass fraction or pilot fraction ($f_{\text{pilot}}$) is used to describe the air flow rate through the pilot relative to the total air flow rate. It is defined as the ratio of the mass flow rate of air flowing through the pilot to the total mass flow rate of air through the test rig, as shown in Equation 5, and is reported as a percentage.

$$f_{\text{pilot}}(\%) \equiv \frac{\dot{m}_{\text{air,pilot}}}{\dot{m}_{\text{air,total}}} \times 100 \quad (5)$$

Pressurized natural gas is supplied to the pilot by a ring located at the leading edge of the flameholder. The fuel ring has 49 orifice pairs similar to the core fuel rings, however they are oriented ±30° relative to the upstream direction for higher mixing rates. The pilot fuel injection orifices are shown in Figure 12a; Figure 12b shows water flowing through the pilot fuel jets to assess fueling uniformity during routine
maintenance of the rig. The fuel ring is supplied by a fuel manifold with two inlets and four outlets. The fuel flow rate is measured by a calibrated orifice plate and controlled independently by a TESCOM electropneumatic pressure regulator. For most of the test configurations studied, the pilot combustor operates at a stoichiometric global equivalence ratio.

![Figure 12: Pilot fuel injector ring](image)

(a) Pilot fuel injection orifices, which are aimed upstream  
(b) Water test of pilot fuel injector

Figure 12: Pilot fuel injector ring

The pilot flame is stabilized by a single circumferential v-gutter flameholder that has triangular “teeth” designed to promote strong mixing and complete combustion before the pilot and core streams mix. The pilot flameholder is shown in Figure 13.

### 3.2.4 Center Body

The flow through the annular core is routed around the water-cooled center body. The surface temperature of the center body reaches a maximum of around 500 K. The center body is cylindrical and has a constant outer diameter of 102 mm through most of the core section. The conical center body trailing edge dimensions are shown in Figure 14. The base of the conical trailing edge is located 18 mm upstream of the
entrance test section, where the pilot flow meets the core flow. The right circular cone with a blunt tip has a radius of 51 mm and an opening angle of 50°. This means that the flow expands inwardly around the cone at an angle of 25°, as indicated in the figure.

Figure 14: Scaled drawing of center body trailing edge geometry. Linear dimensions are in millimeters.
3.3 Optical Diagnostics

3.3.1 Low-Speed Chemiluminescence Imaging

CH* chemiluminescence provides an overall measure of flame behavior, as it is generally a good measure of local heat release rate [75]. The chemiluminescence imaging system consists of three synchronized CCD cameras, each with a spatial resolution of 1600x1200 pixels and 32 bits per pixel. A schematic of the system is shown in Figure 15. The cameras capture wavelength-filtered time-averaged images of the flame through the quartz wall of the test section. The first monochromatic camera (FOculus FO531B) is equipped with a 511±8 nm band-pass filter, corresponding to the chemiluminescence band of the C₂* radical. The second monochromatic camera (FOculus FO531B) is equipped with a 425±5 nm band-pass filter, corresponding to the chemiluminescence band of the CH* radical. The third is a three-channel color camera (FOculus FO531C) which captures two pedestal bands used for subtraction of background emission from CO₂ and soot. The green and blue channels of the camera are used to collect light for the C₂* and CH* pedestal bands, respectively.

Figure 15: Schematic and field of view of the chemiluminescence imaging system
3.3.2 High-Speed Chemiluminescence Imaging

Images of the flame were captured at a rate of 10,000 frames per second to show time-resolved flame dynamics and ignition events. A schematic of this high-speed imaging system is shown in Figure 16; it consists of a Photron FASTCAM SA5 CMOS camera coupled to a Lambert HiCATT high-speed intensifier with a Nikon 50-mm f/5.6 lens. The intensifier had a gate time of 10 µs. The camera has a post-triggering capability that allowed for recording high-speed videos of fast ignition events. The images were acquired without a spectral filter, so the light collected by the imaging system includes contributions primarily from CH*, C₂*, and CO₂* chemiluminescence. The field of view covers the full width of the test section. It begins at the upstream end of the test section and extends downstream to z = 375 mm. This field of view was selected to show the structure and dynamics of the inner flame in the near field of the center body.

![Figure 16: Schematic of the high-speed chemiluminescence imaging system](image)
3.3.3 High-Speed OH-Planar Laser Induced Fluorescence

High-speed OH-Planar Laser Induced Fluorescence (OH-PLIF) was used to capture detailed instantaneous images of the flame and hot products. A schematic of the OH-PLIF system is shown in Figure 17. A pumped Sirah Credo tunable dye laser was located outside the test cell wall because of spatial constraints in the test cell. The dye laser was tuned to a wavelength of 282 nm to excite the OH molecules. A set of four mirrors (the first mirror on the diagram represents the net effect of the first two mirrors) was used to turn the laser beam upward, through the test cell wall, through the set of two sheet-forming lenses, and into the test rig.

![Schematic of the high-speed OH-PLIF imaging system](image)

The gradually expanding laser sheet passed through a central diameter of the test rig and had a height of 110 mm in the test section. The laser sheet on the right side of
the rig was partially blocked by the center body, as shown in the diagram. The field of view of the camera, indicated on the schematic by a violet circle, is primarily on the left side of the combustor. The field of view was chosen to show where the inner and outer flames interact with the $30^\circ$ vanes, based on analysis of initial time-averaged CH* chemiluminescence imaging.

The OH fluorescence signal was spectrally isolated using a 308-nm band-pass filter and captured by a NAC GX-3 high-speed camera coupled to a Lambert HiCATT high-speed image intensifier. The frame rate of the camera was set to 2,000 fps. Each movie contains 880 frames and has a duration of 0.44 s.

### 3.3.4 Stereoscopic Particle Image Velocimetry

Measurements of the flow field were obtained using a high-speed stereoscopic particle image velocimetry (SPIV) system. Figure 18 shows a schematic of the SPIV system. Two Photron FASTCAM SA-Z high-speed CMOS cameras were positioned with one directly above the other; the upper camera was angled $25^\circ$ downward and the lower was angled $25^\circ$ upward. Each camera had a 50-mm lens mounted on a Scheimpflug adapter to bring the entire measurement plane into focus. Background radiation from the flame and glowing of the quartz tube was reduced by adding 532-nm band-pass filters in front of each camera lens. A Continuum MESA PIV-532-80-L dual-pulse PIV laser was used to illuminate 0.5μm TiO$_2$ seeding particles in a plane of the flow. This system allows for three-component velocity measurements in a 260-mm by 260-mm plane, which spans the entire diameter of the test section. The location of the SPIV measurement plane is indicated by the green line beginning at the tip of the center body in Figure 18. The laser sheet was oriented at $90^\circ$ relative to the plane of the two cameras.

The laser was placed outside of the test cell due to spatial constraints in the lab; this required additional mirrors and placed several constraints on the optics. Four
Figure 18: Schematic of the stereo PIV setup

532-nm lenses were used to turn the laser beam. Note that the first two lenses in the beam path are represented in the figure by a single lens. The beam was first turned 90° upward and then turned horizontally to pass through the hole in the test cell wall. The sheet-forming optics consisted of a telescope with a focal length of 2000 mm, a 75-mm cylindrical lens, and a 50-mm cylindrical lens.

This combination produced a 1.5-mm thick vertical laser sheet with a height of 260 mm in the test section. The separation time between the laser pulses was 10 µs. For the reacting flow case with 45° vanes, the theoretical maximum velocities normal to the laser sheet are around 100 m/s, meaning that some particles following the flow will move 1 mm normal to the laser sheet between laser pulses. It is common practice to select a sheet thickness and separation time such that seeding particles move a distance of around half of the laser sheet thickness between laser pulses so that a sufficient number of particles remain in the laser sheet during the first and second laser pulses. Due to a combination of limited availability of optics and spatial...
constraints in the test cell, the laser sheet thickness could not further be increased. Furthermore, the minimum time between frames was a limitation of the cameras that prevented a laser pulse separation time lower than 10 μs.

The cameras were set to 10,000 frames per second, yielding velocity field measurements at a sampling rate of 5,000 measurements per second. A total of 2,728 consecutive velocity field measurements (5,456 images) were obtained at this frame rate for each set of operating conditions, producing movies that were approximately 0.55 seconds in length.

### 3.3.5 Planar Particle Image Velocimetry

Some measurements of the flow field were also obtained using high-speed planar PIV. A schematic of the planar PIV imaging system is shown in Figure 19. There are three major differences between the planar PIV system and the SPIV system described in 3.3.4. First, the planar PIV system is so-named because it produces only two-component velocity vectors \((v_r, v_z)\) parallel to the measurement plane. Second, the images were captured using a NAC GX-3 camera set to 2,000 fps, which gives a 1,000-Hz PIV measurement rate. The field of view for the planar PIV data was further upstream. Lastly, the laser sheet extends from the upstream end of the test section at \(z = 0\) mm to just beyond the tip of the center body at \(z = 120\) mm. The width of the camera field of view, as shown in Figure 19, is equal to the radius of the test section and shows the region of the combustor between the combustor centerline and the quartz tube on the left side of the combustor.

A total of 672 consecutive velocity field measurements (1,344 images) were obtained at this frame rate for each set of operating conditions, producing movies that were 0.672 seconds in length. The laser pulses were separated by 10.5 μs. The flow was seeded with 2-μm particles. The scale of the images was 8.14 px/mm. This means that a particle moving at an axial velocity of \(v_z = 60\) m/s would move approximately
3.4 Data Processing Techniques

3.4.1 Flame Length

The flame length $L_f$ in this combustor is defined as the axial distance along the combustor, measured from the pilot exit plane ($z = 0$), at which heat-release completes. It is approximated in this study from the time-averaged CH$^*$ chemiluminescence images. Each CH$^*$ chemiluminescence image is first normalized by its respective core fuel mass flow rate $\dot{m}_{f,\text{core}}$ and exposure time. The cumulative sum of the image is calculated and the end of the flame is taken as the location at which the cumulative sum reaches 95% of the maximum value as shown in Figure 20.
The flame length measurement methodology is based on the assumption that combustion was complete within the test section for all cases. To support this assumption, Figure 21 shows the relationship between $\dot{m}_{f,\text{core}}$ and the total CH* chemiluminescence emission rate for all swirl levels. The CH* chemiluminescence emission rate is shown to be approximately proportional to the flow rate of the fuel burning in the core for the entire range of core fuel flow rates and swirl levels tested, which is the expected result for complete combustion of a lean hydrocarbon fuel.

### 3.4.2 Outer Flame Angle

The outer flame angle $\theta_f$ was also determined from the time-averaged CH* chemiluminescence images. The term *outer flame angle* here refers to the angle at which the flame propagates just after being initiated by the pilot combustor. It is measured relative to the streamwise direction of the flow and is defined as positive when the flame tilts radially inward toward the combustor centerline. Thus, for a given flow...
Figure 21: Dependence of total CH* chemiluminescence intensity (normalized by exposure time) on core fuel mass flow rate for all vane angles.

The angle is defined such that more positive values of $\theta_f$ represent a flame propagating more rapidly inward toward the combustor centerline. Figure 22 shows an example of a calculated positive flame angle.

To approximate the average outer flame angle, the time-averaged CH* chemiluminescence images are first smoothed in MATLAB using a 2-D Gaussian filter with a standard deviation of 0.5. This smoothing is an important pre-processing step for the inverse Abel transform because the algorithm involves spatial derivatives approximated (using central differencing) from the discrete projected emission function; a noisy function will cause large positive and negative values of derivatives, amplifying the noise in the final calculation.

Next, the smoothed images are processed using an inverse Abel transform algorithm, which calculates the radial intensity distribution from the projected signal acquired by the camera. Next, a rectangular region of the images indicated by the white box in Fig. 22 is extracted for analysis. This section of the image was chosen...
Figure 22: (left) Inverse Abel transform of CH* chemiluminescence image depicting the region, shown as a white rectangle, selected for calculation of the outer flame angle $\theta_f$ (right) Maximum CH* intensity points and best fit line calculated by flame angle algorithm to be representative of the initial angle of the flame brush after it is initiated by the pilot and propagates radially inward through the swirling mixture of fuel and air flowing through the core. The region extends from $z=25$ mm to $z=134$ mm. The inverse Abel transformed intensity distributions are then smoothed along the horizontal direction using a 5th order polynomial fit in MATLAB. The time-averaged radial position of the turbulent flame front is assumed to correspond to the location of maximum CH* chemiluminescence intensity in the inverse Abel transformed images. The radial positions of the maximum intensity pixels are used because the angle of the flame relative to the axial direction is small. Finally, the flame angle is calculated from a linear least squares regression of the maximum intensity pixel locations in this region. The dashed line representing the flame angle is the best-fit line drawn through the maximum-intensity pixels. The calculated flame angle results are presented in Section 4.2.
Recognizing that the inverse Abel transform uses only one side of the images, it should be noted that all flame angles are based off of the left side of the chemiluminescence images. This side was chosen because of soot on right side of the quartz tube in a few of the images that corrupts the inverse Abel transform in the outer flame angle region. To be sure that this choice does not affect the results or their interpretation, angles were calculated for both sides of every image. It was found that, while the values of the measured angles change slightly, all qualitative trends remain the same.

3.5 Stereo-PIV Calculations

The SPIV data was processed using the DaVis software. Multi-pass processing with decreasing interrogation window size was used to improve the resolution of the vector field. The first two passes used a 128x128-pixel interrogation window with 50% overlap and 48x48 was used for the third and fourth pass with 75% overlap. Processing using these parameters produced a 81x76 vector field for each image pair, with each velocity vector representing a physical area of 3.2 mm x 3.2 mm.

Figure 23 shows an example of the in-plane velocity field measured in the test section, averaged over the entire particle-scattering movie. The core equivalence ratio was approximately stoichiometric and the vane angle was 45°. This result represents the worst-case scenario for SPIV in the sense that it was obtained at the condition expected to have the highest out-of-plane velocities, highest total velocities, and largest seeding density gradients due to combustion. As expected, the highest axial velocities measured with PIV near the upstream end of the field of view are comparable to the theoretical mean velocity in the annulus calculated using the test rig geometry and the flow rates measured by the instrumentation upstream of the test section.

Figure 24 shows three-component radial velocity profiles at two different axial locations extracted from the velocity field shown in Figure 23. The mean axial and azimuthal velocity profiles show reasonable flow symmetry in the test section, espe-
Figure 23: In-plane mean velocity field obtained using PIV with 45° vanes and $\Phi_{core} = 1.0$

...cially in the further downstream location away from the center body. The azimuthal velocities are comparable in magnitude to the axial velocities as would be expected for a geometric swirl angle of 45°. The radial velocity magnitudes are much lower than the axial and azimuthal components. The average radial flow is outward (positive) closer to the center body, but exhibits a non-symmetric inward motion at the more downstream location. Given the low radial velocities in this region, however, this behavior may be attributable to systematic errors in the measurement. Nevertheless, these PIV results are considered reliable and demonstrate the validity of the measurement approach.

Certain artifacts in the PIV raw images caused bias in the processed velocity fields in some cases, primarily on the right side of the field of view. These artifacts are due to laser sheet reflections and nonuniformities in the quartz tube. Laser sheet
Figure 24: Mean radial velocity profiles at two axial locations obtained from PIV measurements using 45° vanes with $\Phi_{\text{core}} = 1.0$

reflections in the quartz tube could not be avoided due to the cylindrical geometry of the tube. Other stationary artifacts in the images are horizontal bands of low laser sheet intensity bands in the laser sheet. These bands were produced by horizontal striations in the quartz tube surface that act as lenses. Because of the divergence angle of the laser sheet, the bands become larger as the laser sheet propagates from the left to the right side of the images. When performing the SPIV calculations, these large, sharp variations in intensity result in strong cross-correlation peaks that appear almost stationary in time. As a result, the SPIV algorithm calculates artificially small velocity vectors on the right side of the field of view where the intensity bands are most significant.

Several pre-processing filtering techniques were tested to remove time-invariant features from the particle scattering images and improve the quality of the data. The technique that was found to be most effective was dividing each raw particle scattering image by a “background” image. Four background images were calculated for each image set. The artifacts look different from the perspectives of the two different cameras, so different background images were needed for each camera. Additionally,
the PIV laser actually contains two separate lasers that have slightly different beam intensity distributions. As such, two background images were used for each camera, one for each laser. The background images were calculated by averaging all of the images in one data set, from the same camera and the same laser. An example of a calculated background image is shown in Figure 25. Next, the each individual image was divided by its corresponding background image. Finally, the images were re-normalized to preserve the dynamic range before being converted back to a 16-bit integer format for SPIV processing. Examples of an uncorrected and a corrected particle scattering image are shown in Figure 27.

Careful attention was paid to make sure the observed asymmetry in the velocity fields was artificial. The symmetry of the flow field in the combustor was first confirmed using a high-quality quartz tube; this data is shown in Figures 23 and 24. Other data sets were taken with lower-quality quartz tubes, and only these data sets contained significantly lower velocities on the right side of the vector fields. Further, the correction applied to the entire raw particle scattering images only had a significant effect on the processed velocities near the right side of the images, except where
the laser sheet reflections appear on the left side of the images. Because the correction method was aimed at removing only stationary features present in all particle scattering images, it was concluded that the asymmetry was due to artificial bias.

Figure 27: Comparison of axial velocity fields with and without raw particle scattering image correction

An example of a velocity field processed using uncorrected images is shown next
to a velocity field processed using corrected images in Figure 27. Even after applying the correction, some bias remained. This is because the spatio-temporal variation in seeding density, which causes variation in particle scattering intensity within and between frames, prevents complete removal of the stationary artifacts. Knowing this, the statistics of the velocity field presented in this thesis are based on the left side and center of the images, which remains largely uncorrupted. Some flow features, such as vortices, could still be identified throughout most of the images and a larger portion of the measurement window is shown in these cases.

3.6 Planar-PIV Calculations

The planar PIV particle scattering data was processed using the DaVis software. Multi-pass processing with decreasing interrogation window size was used to improve the resolution of the vector field. The first two passes used a 128x128-pixel interrogation window with 50% overlap and 48x48 was used for the third and fourth pass with 75% overlap. Processing using these parameters produced a 81x76 vector field for each image pair, with each velocity vector representing a physical area of 1.5 mm x 1.5 mm.

3.7 Density Calculations

In this experiment, there are three regions of the flow that have different densities: the pre-flame or “unburned” core flow, the post-flame or “burned” core flow, and the (burned) pilot flow. The chemical equilibrium solver Gaseq is used to calculate these densities based on measured inlet conditions, and these calculations are used to tabulate density ratios and, along with measured mass flow rates and combustor geometry, the mean velocities in the pilot and core streams at the entrance to the test section.

The input parameters for the pilot density \( \rho_{\text{pilot}} \) calculation are the measured
inlet flow temperature and the measured fuel and air mass flow rates. It was assumed that the pressure was atmospheric, combustion was complete, the flow was adiabatic and uniform, the air composition was 79% \( \text{N}_2 \) and 21% \( \text{O}_2 \), and the fuel composition was pure \( \text{CH}_4 \). In reality, the outer wall of the pilot is water-cooled and the inner wall allows heat transfer to the core flow, so the actual pilot exit density is slightly lower than the calculated value.

For the unburned core density \( (\rho_u) \) calculation, the flow was also assumed to be uniform and at atmospheric pressure. Unlike for the pilot flow, the core flow was only assumed to be adiabatic downstream of the thermocouple in the instrumentation section. This thermocouple is located just upstream of the core fuel injectors, as described in Section 3.2. The core flow is expected to have more significant heat loss to the water-cooled walls than the pilot because of the higher post-combustion residence times in the core. As such, the core temperature is taken to be the measured temperature in the instrumentation section instead of the adiabatic flame temperature based on measured fuel and air flow rates.

Finally, the burned core density calculation \( (\rho_b) \) is simply an adiabatic flame temperature calculation using the previously calculated unburned core flow temperature and composition as an input, with appropriate amounts of \( \text{CH}_4 \) added to match the core equivalence ratio.

### 3.8 Swirling Strength

Many methods have been proposed for vortex identification in a two-dimensional velocity field, which is complicated by the lack of a rigorous definition of a vortex [76]. Methods based on the calculation of the swirling strength \( \lambda_{ci} \) have become popular in part because of its unambiguous physical interpretation. The swirling strength is a measure of the rate of swirling inside a vortex core. The quantity \( 2\pi/\lambda_{ci} \) is equal to time period required for a particle on a streamline to complete one revolution. The
swirling strength criterion was chosen for vortex identification in the present work because of its ability to distinguish vortices from boundary layers and shear layers in the flow [77, 78]. Mathematically, the swirling strength is defined as the imaginary part of the complex eigenvalues of the velocity gradient tensor [79].

The two-dimensional velocity gradient tensor is given by:

\[ \nabla \vec{u} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix} \quad (6) \]

The characteristic equation of the two-dimensional velocity gradient tensor is given by:

\[ \lambda^2 + P\lambda + R = 0 \quad (7) \]

\[ P = -\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \quad \text{and} \quad R = \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} \quad (8) \]

The swirling strength criterion \( \lambda_{ci} \), which is only nonzero when the streamlines are spiraling or closed, is then given by:

\[ \lambda_{ci} = \begin{cases} \frac{1}{2} \sqrt{- (P^2 - 4R)} & \text{if } P^2 - 4R < 0 \\ 0 & \text{otherwise} \end{cases} \quad (9) \]

The swirling strength calculations were performed in MATLAB using central differencing approximations for gradients at interior points and single-sided differencing at the boundaries.

### 3.9 Vortex Tracking

Timescales associated with helical vortices are determined using the swirling strength fields calculated as described in Section 3.8. A rectangular region span-
ning x=-32 mm to 3 mm and y=140 mm to 162 mm was defined for vortex detection. This region begins 63 mm downstream of the center body tip and is offset from the centerline to capture the vortices passing through the plane on the left side. This side was chosen because of the data distortion on the right side of the images, described in Section 3.3.4.

A threshold for the total swirling strength in the region was used to determine whether or not a vortex was in the rectangular detection window for each frame. This produces a binary time history of vortex detection. The midpoint of each distinct high section of the signal is calculated and the elapsed time between midpoints is stored in an array. Outliers, defined as values more than three scaled median absolute deviations from the array median, are removed. The period of the vortices is then the mean value of the elapsed times after the outliers have been removed.
4 Swirl Effects on Heat Release Distribution

This chapter presents results and analysis from experiments designed to characterize the heat release distribution in the test facility. The first objective was to show whether or not the flame length may be significantly reduced by introducing swirl to the flow, and whether the flame length may be further reduced by increasing the swirl level. Time-averaged axial heat release distributions were captured using CH* chemiluminescence imaging and the flame length was quantified using the algorithm described in Section 3.4.1. The flame length was determined for a range of operating conditions including without swirl and at two different swirl levels. The second objective was to test whether or not swirl reduces the flame length by enhancing turbulent flame propagation rates around the outer diameter of the combustor. Time-averaged CH* chemiluminescence was used again to quantify the influence of combustor inlet flow conditions on outer flame angle, which is expected to be a function of the local turbulent flame speed. The outer flame angle was calculated from the chemiluminescence data using the algorithm described in 3.4.2.

4.1 Flame Length Parametric Study

To uncover the physics that control flame compactness in this combustor, a parametric study was first conducted to reveal how the flame compactness changes with operating conditions. The flame in this experimental setup is initiated at the location where the pilot flow meets the core flow. In this fixed-diameter test section, a more compact flame will have a shorter flame length as defined in section 3.4.1. Thus, flame compactness translates to flame length here.

Filtered time-averaged CH* chemiluminescence imaging was used to characterize the spatial distribution of heat release rate in the combustion chamber. These images of the flame were captured at a range of pilot equivalence ratios, pilot mass
fractions, inlet Mach numbers, core equivalence ratios, and vane angles. Ten images were captured for each condition. The error bars in the following plots represent 95% confidence intervals calculated using the percentile method.

Figure 29 shows the flame lengths calculated as a function of pilot characteristics, namely the pilot equivalence ratio and pilot mass fraction. The flame length remained relatively constant over the range of pilot equivalence ratios and pilot fractions tested, with the exception of when the pilot fuel was closed ($\Phi_{\text{pilot}} = 0$). In this case, when the pilot is not burning, the flame is not anchored as far upstream and thus the flame is longer. The chemiluminescence images do still show a flame burning when the pilot is not fueled, which suggests another stabilization mechanism. This will be addressed in Section 4.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Case</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{\text{core}}$</td>
<td>1.0</td>
<td>0.55-1.1</td>
</tr>
<tr>
<td>$\Phi_{\text{pilot}}$</td>
<td>1.0</td>
<td>0.0-1.4</td>
</tr>
<tr>
<td>$f_{\text{pilot}}$</td>
<td>10%</td>
<td>7%–13%</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.15</td>
<td>0.15-0.24</td>
</tr>
<tr>
<td>$T_{\text{in}}$</td>
<td>1123 K</td>
<td></td>
</tr>
<tr>
<td>vane angle</td>
<td>30°</td>
<td>0°, 30°, 45°</td>
</tr>
</tbody>
</table>
Figure 30 shows the influence of Mach number on flame length. Higher Mach numbers were achieved simply by increasing the mean axial velocity. Inlet air flow rates were increased and all of the fuel flow rates were increased proportionally in order to keep the inlet temperature and composition constant. Unsurprisingly, the flame length increased linearly with velocity. This is the expected result based on the principle of kinematic balance, since factors affecting the (laminar) flame speed were unchanged.

![Figure 30: Dependence of flame length on $M$ for 30° vanes](image)
The measured influence of $\Phi_{\text{core}}$ on flame length is shown in Figure 31. Measurements were taken at core equivalence ratios ranging from $\Phi_{\text{core}} \approx 0.55 \rightarrow 1.0$ with all other operating conditions held constant. Note that a second-order polynomial curve fit was used to approximate the trends because of the significant variation in the core equivalence ratios at which these data points were obtained. When no swirl is present, the flame length increases as the core equivalence ratio approaches stoichiometric, throughout the entire range of equivalence ratios measured. For the both of the swirled cases, however, the trend is not monotonic. As the equivalence ratio increases from 0.55 toward 1.0, the flame length first increases, peaks, and then decreases. The 45° flame length peaks at a leaner condition than for 30° swirl.

To understand why the flame length might increase as the core equivalence ratio approaches stoichiometric, first consider a simple laminar premixed conical flame, such as a Bunsen flame. In this case, the flame length will depend on where the flame is anchored, the laminar flame speed, and the flow velocity of the unburned reactants.
Suppose that the burner is altered such that the flame is anchored at a larger radius, thereby increasing the area of the base of the conical flame. Holding the flow velocity and laminar flame speed constant, increasing the diameter of the base of the conical flame means that more mass will be consumed by the flame. Because of kinematic balance requirements, the flame will propagate radially inward at the same angle, and the resulting cone will close out further downstream. Now, keeping the flame anchored at the same radius, either an increase in the flow velocity or a decrease in the laminar flame speed will decrease the included angle of the conical flame, making it longer. Taking another view of this scenario, recognize that if more mass passes through the flame per unit time, the flame area must increase and/or the rate at which the reactants are consumed must increase.

Returning to the experiment in question, there are two key differences from the simple conical flame example above. The first difference is that the flame is turbulent, meaning the flame speed depends not only on the reactant temperature and composition, but also on the properties of the turbulent flow. Increasing the level of turbulence in the flow will increase the turbulent flame speed unless local extinction occurs. Otherwise, the turbulent flame speed generally increases when the laminar flame speed increases.

The second difference is that, unlike a Bunsen flame, the experimental combustor is confined by a cylindrical wall around the outer diameter of the pilot flow. When the dependence of flame length on core equivalence ratio, shown in Figure 31, was measured, the reactant temperature and mass flow rate were held constant. This means that the inlet Reynolds number was held approximately constant, with negligible variations in viscosity due to small changes in reactant mixture composition. As such, changes in turbulent flame speed with equivalence ratio are primarily due to changes in the laminar flame speed of the mixture. The pilot conditions were also held constant, so the flame was always anchored in the same location: where the pilot
flow first mixes with the core flow.

Increasing the core equivalence ratio toward stoichiometric increases the unstretched laminar flame speed, \( S_0^L \), which would be expected to increase the turbulent flame speed. These unstretched laminar flame speeds were calculated using CHEMKIN for the inlet conditions in this combustor and are shown in Figure 32. Considering only the laminar flame speed effect could incorrectly lead to the expectation that the flame would shorten. This expectation relies on the assumption that the flame speed changes independently of the reactant flow velocities. This assumption may not be valid when the flow is highly confined. Increasing the core equivalence ratio toward stoichiometric also leads to higher post-flame temperatures. In a Bunsen flame, the flow streamlines diverge radially to compensate for this. In this experimental combustor, the flow may not expand radially outward due to the confining wall. The flow acceleration across the flame must then be primarily in the axial direction. This large axial acceleration of the post-flame gas, which is maximized at a near-stoichiometric equivalence ratio, will also increase the velocity of the pre-flame gas. This axial acceleration of the pre-flame gas leads to a longer flame.

This effect is not unprecedented in the literature. Mallens et al. observed increase in flame length in confined laminar premixed flames with confinement, and attributed this effect to lack of radial expansion of the burned gases [80]. In fact, it was also observed by Clements that the combustion efficiency, measured at a fixed downstream position, in a swirl augmentor test rig decreased as the equivalence ratio increased [19]. This decrease in measured combustion efficiency at a specific location is consistent with an increasing flame length, as observed in this study. The physics behind the influence of core equivalence ratio on flame length when swirl is present, however, are more involved and not immediately apparent from the data in this section. As such, this topic will be revisited in Chapter 5.

The final parameter that was varied in the flame length parametric study was
Figure 32: Theoretical unstretched laminar flame speeds (from CHEMKIN) as a function of core equivalence ratio for the measured combustor inlet conditions.

The swirl vane angle. The vane angle was varied by installing each of the three interchangeable sets of fixed vanes, as described in section 3.2.2. Chemiluminescence image sets were captured at four different core equivalence ratios with each of the three vane sets. The influence of vane angle on flame length for different core equivalence ratios is shown in Figure 33. The flame length decreases linearly as the swirl level is increased. This is a key result that serves to validate the swirl augmentor concept, and is consistent with what previous researchers predicted.

Figure 33 also highlights that there is a significant equivalence ratio effect. The leanest core equivalence ratio ($\Phi_{\text{core}} = 0.55$) always produces the shortest flame. The stoichiometric equivalence ratio, on the other hand, produces the longest flame when there is no swirl, and the second shortest flame when the vane angle is 45°. When the core equivalence ratio is 0.70, the flame length changes by only a small amount when the vane angle is increased from 30° to 45°.

These initial results indicate that the presence of swirl produces a more compact...
Figure 33: Dependence of flame length on swirl angle for $\Phi_{\text{core}} = 0.55 - 1.0$. The $30^\circ$ data points were interpolated using the second order polynomial fit shown in Figure 31.

flame and serve as validation of the peripherally piloted swirl combustor concept. Importantly, the results of the parametric flame length study suggest that the most important parameters to investigate moving forward are the swirl vane angle and the core equivalence ratio.

4.2 Outer Flame Angle Study

It was hypothesized by previous researchers that adding swirl to a flow where a flame lies between an inner high-density layer of unburned reactants and the outer low-density layer of products would enhance the turbulent flame speed through a centrifugal instability mechanism. Higher density ratios are generally expected to lead to higher turbulent flame speeds. Recall from Section 1.3 that in the swirl augmentor, this was expected to drive the flame front, after being initiated by the pilot, more rapidly toward the combustor centerline [19]. To investigate this, an algorithm was
developed to determine the angle at which the flame spreads radially inward using the time-averaged chemiluminescence images. This algorithm is described in section 3.4.2. The outer flame angles were calculated from the same data presented in the flame length parametric study, as summarized in Figure 28. This section presents results and analysis from the outer flame angle parametric study.

Figure 34: Dependence of outer flame angle on inlet $M$

Figure 34 shows the influence of Mach number on the outer flame angle. Unlike the flame length dependence (Figure 30), the outer flame angle does not vary monotonically with Mach number. The variation in flame angle across the range of Mach numbers tested, however, is relatively small.

The left plot in Figure 35 shows the dependence of the outer flame angle on the pilot equivalence ratio. This parameter was varied by changing the pilot fuel flow rate while holding the air mass flow rate through the pilot constant. The outer flame angle exhibits a minimum of 5.6 degrees for a stoichiometric pilot, a drop of nearly $2^\circ$ from the maximum values measured. The size of the flame angle confidence interval is also minimized at the stoichiometric condition, suggesting a more stable outer flame. This could be due to the minimized sensitivity of flow parameters to small equivalence
ratio variations at the stoichiometric condition.

The right plot in Figure 35 shows the dependence of the outer flame angle on the pilot mass fraction. This parameter was varied by adjusting only the total mass flow rate through the pilot, keeping the pilot equivalence ratio set to stoichiometric. The mass flow rate through the core was held constant, which means there was some variation in the total mass flow rate through the combustor as the pilot mass fraction was varied. This changes the shear rate while keeping the density ratio \( \rho_u/\rho_{\text{pilot}} \) constant. Because the pilot flow always has a lower mean velocity than the core flow at all conditions presented in this study, higher pilot fractions translate to lower shear rates.

The plot shows that the flame angle increases linearly with pilot fraction. In other words, the flame tilts outward (lower angle) as the shear rate increases (lower pilot fraction). Higher shear rates would typically lead to higher turbulence and thus higher turbulent flame speeds. In this case, higher shear rates do not tilt the flame further inward because the flame position is a function of both flame speed and flow velocity. The velocities in the entire shear layer between the pilot and core are decreasing as the shear rate increases, and this appears to be the dominant effect, driving the flame...
radially outward.

Because changing the pilot equivalence ratio and pilot fraction affect other physical parameters that could control the outer flame position, such as the shear rate and the density ratio, it is difficult to draw further conclusions from the plots in Figure 35 alone. The same data will now be presented as a function of two other parameters, namely the difference between the pilot stream and core stream mean velocities ($\bar{u}_{\text{core}} - \bar{u}_{\text{pilot}}$), and the density ratio between the unburned reactants and the pilot stream ($\rho_u/\rho_{\text{pilot}}$). The densities used in the following analysis were calculated based on measured parameters as described in Section 3.7.

The left plot in Figure 36 shows how the outer flame angle changes with the bulk velocity difference between the pilot and core streams. This plot includes the data both from when the pilot equivalence ratio was varied and when the pilot fraction was varied, as previously presented in Figure 35. For lower velocity differences, the outer flame angle did not vary significantly. When the velocity difference is high, there is no clear correlation, which suggests that this is not the parameter that controls the outer flame angle on its own.

![Figure 36: Dependence of outer flame angle on $\bar{u}_{\text{core}} - \bar{u}_{\text{pilot}}$ and $\rho_u/\rho_{\text{pilot}}$.](image)

The dependence of the outer flame angle on the density ratio between the pilot
stream and the unburned reactants $\rho_u/\rho_{pilot}$ is shown in the right plot of Figure 36. Unlike the pilot equivalence ratio relationship from Figure 35, there is no clear correlation between the flame angle and the density ratio between the pilot and the reactants $\rho_u/\rho_{pilot}$. This does not mean that density ratios do not influence the outer flame angle. The pilot stream and the unburned reactants come into contact when the core flow first meets the pilot flow, but there is a fluid layer containing mostly products from the core flame in between the unburned reactants and the pilot stream that increases in size in the axial direction. After the core flame has been ignited by mixing with the pilot flow, the density ratio $\rho_u/\rho_b$ between the unburned and burned core flow would be expected to have a greater influence on turbulent flame speeds, according to the centrifugal instability theory and other buoyancy-related mechanisms.

To investigate the influence of this density ratio $\rho_u/\rho_b$, measurements were obtained with different core equivalence ratios. This was done by adjusting the core fuel mass flow rate while holding the pilot at stoichiometric, and the mass flow rate of vitiated air through the core and all other conditions constant. The experiments were repeated for all three vane angles.

Figure 37: Dependence of outer flame angle on $\Phi_{core}$ and $\rho_u/\rho_b$ for all vane angles
The left plot of Figure 37 shows the dependence of the outer flame angle on the core equivalence ratio for each of the three vane angles. While it is apparent in Figure 37 that most significant influence on the flame angle is actually the swirl level, that will be discussed in the following paragraphs. Both swirl levels and the non-swirled case show a variation in flame angle across the range of core equivalence ratios tested. The angles initially increase, reach a local maximum, and then decrease as the core equivalence ratio approaches stoichiometric.

As before, these flame angles are also shown in the right plot of Figure 37 as a function of the density ratio across the flame $\rho_u/\rho_b$ because this density ratio does not change linearly with core equivalence ratio. This plot also shows that there is a nonmonotonic correlation between the outer flame angle and the density ratio across the flame when swirl is present. Near-stoichiometric equivalence ratios produce the highest density ratios across the flame. At the same time, the thermal flow expansion effect on the velocity field discussed in Section 4.1 is also maximized near stoichiometric, when the heat release rate is the highest. While higher flame speeds could act to drive the flame inward, the influence of thermal expansion of the burned gas on the velocity field could produce a competing effect, acting to drive the flame outward near stoichiometric.

Figure 38 shows the calculated flame angles as a function of $\Phi_{\text{core}}$ and the vane angle. The flame angle, like the flame length, shows a strong dependence on the vane angle. When swirl is added to the flow ($30^\circ$ vanes), the flame angle decreases slightly for all equivalence ratios tested. When the swirl level is further increased, the flame angle not only decreases by a much greater amount, but it actually becomes negative, tilting away from the combustor centerline. Early research suggested that $\theta_f$ would increase when the swirl vane angle is increased, resulting in a shorter flame. The results from this work show that although the flame length does decrease with larger vane angles as predicted, $\theta_f$ actually decreases, i.e., the flame initially tilts away from
the centerline as swirl is increased.

The negative correlation between vane angle and the initial outer flame angle does not rule out enhanced turbulent flame speeds in the outer flame region, which could become significant farther downstream than the flame angle measurements presented here. The following sections examine the outer flame dynamics and other aspects of the flame configuration that could influence flame compactness.

### 4.3 High-Speed Planar Imaging

Although analysis of the time-averaged CH* imaging shows some features of the flame and allows for a large field of view, it does not directly show dynamics. It is also integrated over the line of sight, rendering it unable to show the topology of the flame in a radial-axial plane. OH-PLIF imaging was employed at some operating conditions to provide detailed information about the flame front position and its dynamics. All of the OH-PLIF data was captured using 30° vanes. The OH-PLIF imaging system used for this part of the study is described in Section 3.3.3.

Figure 39 shows a sequence of OH-PLIF images with $\Phi_{core} = 0.85$. The bright
regions of high OH-fluorescence signal represent regions of hot products. The dark regions are cooler, unburned reactants. Although sufficiently high strain rates technically could cause local extinction and produce hot products not bounded by a flame, it is unlikely that reactants at a highly-flammable equivalence ratio of $\Phi_{\text{core}} = 0.85$ and a temperature of $T_{\text{in}} = 1123$ K would be extinguished. Thus, it will also be assumed that boundary between the bright regions and the dark regions is a flame front.

Figure 39: Time sequence of OH-PLIF images with 30° vanes and $\Phi_{\text{core}} = 0.85$

There are two large regions of high OH-fluorescence in each image in the sequence. These correspond to a distinct inner flame and outer flame. The outer flame is stabilized by the pilot and the inner flame is stabilized near the center body trailing edge. The outer flame front is highly wrinkled, tilts inward at a shallow angle, and appears broken at times, especially in the second image in the sequence. The sharp gradients on either side of the inner flame show that both sides of the inner flame are visible, at least in the upstream portion of the measurement window. In contrast to the outer flame, the inner flame appears less wrinkled and is not broken. Its position also remains more constant. At this condition, the inner and outer flames remain separated throughout the measurement window.

Figure 40 shows a second sequence of OH-PLIF images, where the core equivalence ratio was lowered from $\Phi_{\text{core}} = 0.85$ to 0.70, but all the other operating conditions are the same as those of Figure 39. In the first image of this sequence, there are also distinct inner and outer flame regions in the upstream portion of the image. At first, the outer flame tilts inward at a shallow angle. Farther downstream, around $z = 120$ mm, the
outer flame turns sharply inward. The outer flame angle calculations presented in Section 4.2 were based on the region extending from \( z = 25 \text{ mm} \) to \( z = 134 \text{ mm} \), so this inward turning of the outer flame occurs at the downstream end of that region. While it is not clear because of the lower laser sheet intensity near the top of the image, it appears that the inner and outer flames connect at around \( z = 160 \text{ mm} \), downstream of where the initial outer flame angle measurements were based.

![Figure 40: Time sequence of OH-PLIF images with 30° vanes and \( \Phi_{\text{core}} = 0.70 \)](image)

In the following images of the sequence, however a drastic change occurs. Between the first and second image, a time period of 0.5 ms, a portion of the flame front between the inner and outer flame regions (in the neighborhood of \( x = -50 \text{ mm} \)) appears to have moved upstream from \( z = 120 \text{ mm} \) to at least 60 mm. This corresponds to a velocity of 120 m/s in the lab reference frame, and much higher in the reference frame of the mean flow. This is strong evidence that a pocket of hot products has convected into the laser sheet from the out-of-plane motion in the swirling flow. Still, it shows that flame can sometimes exist all the way across the core annulus upstream of the center body tip. Furthermore, the existence of a flame at this location where mean velocities are expected to be nearly 100 m/s, much faster than turbulent flame speeds, is an indication of instantaneously low axial velocities or reverse flow. This could be caused by a large-scale flow structure such as a precessing vortex core; this is investigated further in Chapter 5.

These two image sequences were presented primarily to illustrate the types of flame behavior captured by the OH-PLIF data. Although there are considerable differences
between the image sequences shown for the two different core equivalence ratios, it is important to examine whether these observations are actually representative of the flame behavior for each operating condition.

To calculate OH-PLIF statistics, the images were first binarized. This is because they are not being used to quantify gas properties, but rather are intended to show contrast between zones of hot combustion products and unburned reactants. Each individual image was binarized using the `imgaussfilt` (2-D Gaussian smoothing with default standard deviation of 0.5) function in MATLAB followed by the `imbinarize` function, which employs Otsu’s thresholding method [81].

Movies, each containing 880 binarized OH-PLIF images, were averaged for different operating conditions to obtain OH-PLIF probability fields. This statistic represents the probability that hot products containing OH exist at each location. Figure 41 shows the OH-PLIF probability fields with 30° vanes for four core equivalence ratios in the range \( \Phi_{\text{core}} = 0.54-1.1 \), roughly corresponding to the conditions examined in the parametric study using time-averaged chemiluminescence imaging. All four plots cases exhibit two distinct regions of relatively high OH-PLIF probability corresponding to the outer flame and the inner flame. Thus, the basic flame configuration is the same for all four equivalence ratios.

These OH-PLIF probability fields reveal several interesting characteristics of the inner and outer flames. First, the variation of the flame front position is a strong function of core equivalence ratio. The \( \Phi_{\text{core}} = 0.54 \) and 0.70 cases shown in Figures 41a and 41b have significant variation in flame front position, as evidenced by the relatively shallow gradients in probability, when compared to the other cases. In these leaner cases, the outer flame often moves far inward. In contrast, for the \( \Phi_{\text{core}} = 0.85 \) and 1.1 cases, Figures 41c and 41d indicate that the inner and outer flames almost never move close enough to each other to interact within the measurement plane.

It was previously shown (Figure 37) that the initial outer flame has a mean angle
for $\Phi_{\text{core}} = 0.75$ of 5.5° with a 95% confidence interval of $(2.3^\circ,8.2^\circ)$, while for $\Phi_{\text{core}} = 0.88$, it was 5.4° with a confidence interval of $(3.3^\circ,7.2^\circ)$. The mean flame angle therefore changed little with core equivalence ratio, though there was a small increase in the angle variability for the lower equivalence ratio. The instantaneous OH-PLIF data for a similar pair of conditions, however, reveal a significant difference. This points to important flame dynamics that were not revealed in the analysis of the time-averaged chemiluminescence images.

Figure 41: OH-PLIF probability fields with 30° vanes and different core equivalence ratios.
More importantly, this result shows that the outer flame is highly unsteady for the leaner cases. For 30° swirl (Figure 31), the time-averaged flame length was shorter for the leaner cases and longest for \( \Phi_{core} \) near 0.9. This relationship was not fully explained by the initial outer flame angle results, but it is consistent with the observations from the OH-PLIF data that the outer flame often moves sharply inward, even interacting with the inner flame at leaner equivalence ratios. The question of why the flame again becomes shorter for higher \( \Phi_{core} \), however, still remains.

A second observation from the OH-PLIF probability fields relates to the inner flame. The most consistent OH fluorescence from the inner flame region occurs for the \( \Phi_{core} = 0.85 \) case. There is a large region that begins near the tip of the center body where OH was almost always detected, and this region tapers off quickly. This corresponds to the longest flame. The leaner cases and the rich case have much lower OH-PLIF probabilities in this region, suggesting that the inner flame is less robust. The rich \( \Phi_{core} = 1.1 \) case has the weakest inner flame, but also has an outer flame that does not move inward as often as the leaner cases.

A third observation from the OH-PLIF probability fields is that, while the steadiness of the inner flame is a strong function of core equivalence ratio, the stabilization location is not. It remains anchored near the tip of the center body for \( \Phi_{core} = 0.54 - 1.1 \), and does not move around much in the vicinity of the center body. Other parameters besides the core equivalence ratio could influence inner flame location and this is examined next.

### 4.4 Inner Flame Characterization

As detailed in Section 4.1, the flame length should depend on 1) the locations at which the flame is anchored and 2) how rapidly the flame can propagate across the combustion chamber. Flame imaging presented in Section 4.3 for 30° swirl revealed the flame is not only anchored around the outer diameter of the core flow but also
near the center body trailing edge. The characteristics of this inner flame, such as when it is present and where it is anchored, would be expected to strongly influence the overall flame length. Thus, a significant portion of the remaining work is devoted to understanding the inner flame.

Figure 42: Time-averaged CH* chemiluminescence images of the flame for three different swirl angles

Figure 42 contains time-averaged CH* chemiluminescence images captured using three different vane angles. These images show that heat release near the inner region of the core flow occurs only when swirl is present. This flame configuration is commonly observed in swirl combustors [82]. Heat release was not observed in this combustor near the center body trailing edge in the absence of swirl. This inner flame spreads radially outward and merges with the outer flame that is stabilized by the pilot. The downstream location where the inner and outer flame meet is the end of the flame, corresponding to the flame length described in Section 4.1.

The chemiluminescence signal captured by the images in Figure 42 is inherently integrated across the line of sight. Interpretation of such images must be performed with caution when the flame is axisymmetric, as in this case. The light in the hori-
Horizontal center of the image is integrated across the entire diameter of the combustor while elsewhere the light is integrated across chords, which decrease in length as the radius increases. Applying the inverse Abel transform to the images corrects for this effect. The inverse Abel transform calculates the radial emission function from its projection, i.e., the raw chemiluminescence images, assuming that the projection is from an axisymmetric distribution.

Figure 43: Inverse Abel transform of time-averaged CH* chemiluminescence images with 30° vanes

Figure 43 shows the inverse Abel transform of the CH* images for different core equivalence ratios with 30° vanes. These images of the radial CH* intensity distribution show a region of significant heat release that begins near the trailing edge of the center body when swirl is present. Planar imaging results from Section 4.3 confirmed that this is true for at least $\Phi_{core} = 0.54 - 1.1$, even though the images at higher equivalence ratios in Figure 43 are not as clear. It is possible that the inner flame is more unsteady (primarily radial motion) at the higher equivalence ratios, which effectively “smears” the images due to the timescales of these flame motions being much smaller than the image exposure times. The reduced OH probabilities
seen in Figure 41 for this core equivalence ratio suggest the inner flame could also be intermittent, which would make it less visible in the time-averaged CH* results.

Figure 44: Time-averaged CH* chemiluminescence images with 45° vanes

Figure 44 shows CH* chemiluminescence images of the flame with the 45° vanes for a similar range of core equivalence ratios, while Figure 45 shows the corresponding inverse Abel transforms. Similar to the 30° results, there is high chemiluminescence signal in the shear layer between the pilot and core flows and another distinct region of chemiluminescence signal closer to the combustor centerline. In this higher-swirl case, however, the inner heat release region appears at a radial position farther from the centerline and is anchored further upstream. For the leaner equivalence ratios, the flame even appears to be anchored upstream of the quartz test section where the chemiluminescence cannot be detected by the camera. As in the 30° case, the mean local chemiluminescence intensities in the inner flame region are lower for the near-stoichiometric condition. Again, this does not necessarily mean that the local heat release rate is lower near stoichiometric. The lower intensity could be due to the
flame moving around more or becoming intermittent at those conditions.

As shown previously (Figure 33), the flame length is a strong function of swirl; the flame length decreases as the swirl level increases (for a fixed core equivalence ratio). As these images now reveal, this decrease in flame length is also correlated to the inner flame anchoring location moving upstream and radially outward while the outer flame remains anchored in the same location. Moving the inner flame stabilization location upstream while keeping the mass consumption speed constant would tend to cause the flame to close out sooner. Thus, in order to better understand the physics controlling flame compactness, it is important to understand the physics governing the inner flame stabilization location.

Two further questions regarding the inner flame require investigation. First, it is not immediately apparent how the inner flame is initiated. The inner flame could autoignite. If this happened, inner flame initiation could be very sensitive to inlet temperature. The inner flame could also be lit by a pocket of hot products that
advects radially inward from the outer flame. Another possibility is that the outer flame could propagate backward near the centerline and stabilize near the center body. Second, it is unclear exactly what physical mechanism stabilizes the inner flame and why this mechanism only exists in a swirling flow. This question is partially addressed by examining the heat release field in this chapter, but is continued with a detailed examination of the velocity field in Chapter 5.

4.4.1 Inner Flame Initiation

One possible mode of inner flame initiation is autoignition. To investigate whether the inner flame could autoignite under standard conditions, the inlet conditions were set to the standard values given in Figure 28, except the core and pilot fuel remained closed. Thus, there was initially no flame in the combustor. Beginning with the standard core inlet temperature of $T_{in} = 1123$ K, fuel was supplied to the core stream and the core equivalence ratio was slowly increased to stoichiometric. No ignition occurred. The fuel valve was closed and the core inlet temperature was then increased by 10 K. Fuel was again supplied to the core stream and the core equivalence ratio gradually increased to stoichiometric. This procedure was repeated, increasing the core inlet temperature by 10 K each time, until autoignition occurred. The first autoignition event occurred when the core inlet temperature reached $T_{in} = 1163$ K. The temperature was then reduced by 10 K and fuel was supplied again to check for hysteresis; no autoignition occurred in the test section. This result shows that the center flame may not autoignite under normal operating conditions, though a relatively small increase in core inlet temperature (40 K) produces conditions under which autoignition reliably occurs.

The inner flame was then investigated using high-speed CH* chemiluminescence imaging of core ignition events under standard operating conditions. The high-speed CH* chemiluminescence system used for this is described in section 3.3.2. To capture
a movie of an ignition event, the pre-burner and pilot were ignited and the standard inlet conditions shown in Figure 28 were set, with the exception of the core fuel. Four 10 000-fps movies, each containing 3970 frames, were captured as the core fuel valve was suddenly opened. The core fuel supply pressure was regulated such that a core equivalence ratio of \( \Phi_{\text{core}} \approx 0.8 \) would be maintained under steady operation.

![Figure 46: Colormapped CH* chemiluminescence image sequence (only includes every 5th frame) showing typical core flame ignition event](image)

Figure 46 shows a typical sequence of images that begins when the core flame is ignited. The chemiluminescence signal first increases near the edges of the image and then increases near the center. This indicates that the outer flame ignites from the pilot before the inner flame begins burning. Large scale fluid motion in the combustor could transport the outer flame near enough to the centerline to ignite the inner flame, but it is somewhat unclear from these images for a couple of reasons. First, the overall image intensity was found to oscillate at around 530 Hz so it is difficult to discern between when higher signal is due to higher chemiluminescence and when higher
signal is a result of the overall image intensity oscillating. Second, the inherent line-of-sight nature of this imaging technique results in light being collected from both the inner and outer flames at the same pixel locations, making it difficult to see exactly where the inner flame is initiated.

The inner flame initiation mechanism was then investigated using a different approach. During the previously described autoignition experiments, it was found that the core inlet temperature to $T_{in} = 1163$ K was found to produce reliable autoignition as soon as the core fuel valve was opened. This allows the high-speed chemiluminescence system to view only the inner flame, uncontaminated by light from the flame around the outer diameter of the combustor.

The core inlet temperature was set to $T_{in} = 1163$ K and fuel was supplied to the core by suddenly opening the core fuel valve. The camera was manually post-triggered to capture the autoignition event. Four 10 000-fps movies, each containing 3970 frames, were captured that show autoignition of the inner flame and its transition into a stable configuration.
Figure 47 shows a colormapped sequence of images from one of the inner flame autoignition movies. The sequence begins just after the autoignited flame enters the field of view of the camera. The flame propagates upstream, in the negative $z$-direction, from out of the camera’s field of view until it reaches the trailing edge of the center body. This process is typical of the other movies that were captured.

While these images do not directly show what happens during a “normal” ignition event, they do provide some insight into the inner flame initiation mechanism. Once the flammable mixture has been ignited far downstream, it can easily propagate back upstream to its stable location near the center body trailing edge. Even without autoignition, the downstream portion of the flame stabilized by the pilot can propagate back to form the previously described stable inner/outer flame configuration.
4.4.2 Inner Flame Structure

The high-speed footage of the inner flame autoignition events was also used to reveal characteristics of the inner flame structure. Coherent flame motions were observed in the video. Figure 48 shows what appears to be a double helix inner flame anchored near the tip of the conical center body trailing edge, rotating about the combustor’s $z$-axis. This is likely the result of the flame being trapped in a double helical vortex breakdown ($|m| = 2$ mode).

Figure 48: Colormapped flame luminescence image showing helical flame structure (white dashed line)

A helical vortex breakdown could serve as the primary stabilizing mechanism for the inner flame. The reverse flow created by the helical vortices would allow a flame downstream to propagate back to the anchoring location near the center body tip even when the mean velocities in the combustor are very high. Vortices increase residence times in the inner flame region, allowing the hot combustion products to mix with and ignite the unburned reactants.
5 Effects of Swirl and Heat Release on Flow Field

This chapter focuses on understanding the flow field with the primary goal being to determine the physics controlling flame stabilization. Further analysis of the flow field is included to improve understanding of the flow patterns in a swirl combustor with high confinement and a tapered center body because, as described in Chapter 2, this class of flows has not yet been well-characterized in the literature.

SPIV measurements were obtained at six conditions, as shown in Figure 49. Measurements were taken under both reacting (stoichiometric) and non-reacting conditions for each of the three vane angles while holding all other conditions nominally constant. The pilot characteristics, inlet temperature, and Mach number were set to match the base case used in Chapter 4. The velocity fields were measured just downstream of the center body trailing edge, in the region of the combustor indicated in Figure 18. This region, which measures approximately 250 mm x 250 mm and cover almost the full diameter (D) of the test section, was selected for study because it was expected to contain the flow features that control inner flame stabilization. Three-component velocity field measurements were obtained at a rate of 5,000 measurements per second for a period of ~0.55 seconds (2,728 consecutive measurements). The statistics presented in this section are based on 2,728 samples unless stated otherwise.

<table>
<thead>
<tr>
<th>Vanes</th>
<th>(\Phi_{\text{core}})</th>
<th>(\Phi_{\text{pilot}})</th>
<th>(J_{\text{pilot}}) (%)</th>
<th>(T_{\text{in}}) (°C)</th>
<th>(Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0</td>
<td>1</td>
<td>10</td>
<td>864</td>
<td>0.15</td>
</tr>
<tr>
<td>0°</td>
<td>0.96</td>
<td>0.9</td>
<td>10</td>
<td>859</td>
<td>0.15</td>
</tr>
<tr>
<td>30°</td>
<td>0</td>
<td>0.9</td>
<td>10</td>
<td>851</td>
<td>0.15</td>
</tr>
<tr>
<td>30°</td>
<td>0.93</td>
<td>0.9</td>
<td>10</td>
<td>848</td>
<td>0.15</td>
</tr>
<tr>
<td>45°</td>
<td>0</td>
<td>0.9</td>
<td>10</td>
<td>796</td>
<td>0.15</td>
</tr>
<tr>
<td>45°</td>
<td>1</td>
<td>0.9</td>
<td>10</td>
<td>764</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 49: Operating conditions at which SPIV was acquired

First, non-reacting flow field measurements and analysis are presented for 0°, 30°,
and 45° vanes to show the effects of swirl on flow characteristics. Next, reacting flow fields for all three vane angles are compared to the non-reacting flow fields with otherwise matched inlet conditions to show the effects of combustion.

5.1 Non-Reacting Mean Velocity Field

Figure 50 shows the radial profiles of mean axial velocity for all three vane angles under non-reacting conditions. These velocity profiles were extracted from nine equally spaced axial positions that span the axial extent of the measurement plane. The mean velocity measurements show that this flow field does not contain all of the typical features of a swirl combustor, which were described in Chapter 2. One key difference is that there is no outer recirculation region because there is no outer expansion or backward facing step. Instead, the pilot combustor is an annular co-flow with a lower velocity than the core flow (for all the conditions tested), resulting in a shear layer around the outer diameter of the core flow. By the time the flow has reached the measurement window, the pilot flow has already begun to mix with the core flow. For all three of these cases, this outer shear layer spreads and the velocity deficit decays in the streamwise direction. The shear in the outer flow decays more quickly as the level of swirl increases. By the downstream end of the measurement window, the velocity profile actually reaches a maximum near the outer wall in the 45° case.

A strong inner recirculation zone downstream of the center body is generally a design requirement for swirl combustors because it serves as the primary means of flame stabilization. No reverse flow was observed in the mean flow measurements for the 0° case. With the 30° swirler, a very small reverse flow region along the combustor centerline exists, with reverse mean flow found only near the most upstream edge of the measurement region ($z/D = 0.34$). Furthermore, the maximum width of the reverse flow region in the mean field was $0.3D$ and occurred at the bottom of the
Figure 50: Radial profiles of mean axial velocity under non-reacting conditions (nominally \( T_{in} = 1123 \) K, \( \Phi_{pilot} = 1, \Phi_{core} = 0 \)) for all three vane angles measurement window. For the 45° case, the reverse flow region is annular, with no reverse flow at the centerline and the maximum mean negative velocity occurring around \( r/D = 0.1 \). Moreover, reverse mean flow extends farther downstream (to \( z/D = 0.7 \)) and its maximum radial extent is wider (0.9\( D \)). The reverse flow under the conditions tested is enabled by swirl and the prominence of the reverse flow region increases as the swirl strength increases.

The measurement window does not show the upstream extent of the mean reverse flow regions for the 30° and 45° cases. In a typical swirl combustor, the inner recirculation zone begins downstream of the nozzle exit. This is because the sudden outer expansion occurs at the nozzle exit and the center body is contained within the
nozzle. In contrast, reverse flow in this combustor was observed at the most upstream axial location in the SPIV measurement window. Thus, these velocity profiles serve as evidence that the recirculation zones begin upstream of the center body trailing edge in this combustor. Limited planar PIV measurements were taken upstream of the center body trailing edge to more clearly show the upstream extent of the reverse flow regions. Discussion of this issue is continued in Section 5.3.

Figure 51: Radial profiles of mean radial velocity under non-reacting conditions (nominally $T_{in} = 1123\,\text{K}$, $\Phi_{pilot} = 1$, $\Phi_{core} = 0$) for all three vane angles

Figure 51b shows radial profiles of radial velocity for the non-reacting case for each vane angle. The general lack of radial motion overall is expected due to the very low area expansion ratio in this combustor. There is essentially no mean radial motion when swirl is not present. For the 30° case, there is some flow radially outward
near the centerline that decays in the axial direction. In the $45^\circ$ case, there is radially outward motion near the outer diameter of the combustor near the center body trailing edge, and then the flow moves radially inward further downstream.

Figure 52: Radial profiles of mean azimuthal velocity under non-reacting conditions (nominally $T_{in} = 1123$ K, $\Phi_{pilot} = 1$, $\Phi_{core} = 0$) for all three vane angles

Figure 52b shows the radial profiles of the azimuthal velocity for the non-reacting cases for all three vane angles. The non-swirled case has near-zero azimuthal velocities at all locations, but is shown for completeness. As expected, the $30^\circ$ and $45^\circ$ cases have profiles with similar shapes, but the $45^\circ$ case has stronger swirl. Near the centerline of the flow, the azimuthal velocity profiles are characteristic of a forced vortex, decreasing linearly toward $r = 0$. Just outside of the forced vortex core, the azimuthal velocities reach a peak and decrease gradually toward the outer diameter
of the flow. The swirl decays axially. All of this is typical of a confined swirling flow.

5.2 Reverse Flow Statistics

As described previously in Chapter 2, swirl combustors typically contain a large central region of flow recirculation in which hot products of combustion convect upstream, serving as a continuous ignition source for the inflowing unburned reactants. This is illustrated in Figure 5. Although the flow field in the present study does not always contain a prominent region of mean reverse flow downstream of the center body, stable flameholding was still observed along the centerline for all of the swirled cases. This was first shown in the time-averaged chemiluminescence images and again in the high-speed images in Section 4.4. Recognizing that the amount of reverse flow in the mean velocity field often underestimates the true impact of flow reversal on the flow field, it is important to analyze reverse flow in the instantaneous velocity field. Characterization of flow reversal both provides greater understanding of the dynamics of swirling flows with a center body and no outer expansion and begins to reveal the physics governing inner flame initiation and stabilization mechanism.

Figure 53 shows a randomly selected sequence of velocity field measurements from the 30° non-reacting case. Large unsteady regions of reverse flow near the combustor centerline were often observed that stretch far beyond the downstream extent of the mean reverse flow zone described in Section 5.1. These regions of reverse flow are shown in Figure 53, bounded by the white $v_z = 0$ contour. Because these large regions of strong reverse flow are not apparent in the mean velocity fields, it is helpful to look at the reverse flow probability field. The reverse flow probability calculation begins with binarization of the $v_z$ field. Locations at which the flow is reversed, defined simply by the condition $v_z < 0$, were assigned a value of 1 and all other locations were assigned a value of 0. The mean of these binary arrays is referred to here as the reverse flow probability field.
In the absence of swirl, no instances of reverse flow were observed in the measurement window. The reverse flow probability field for the 0° vanes is therefore not shown; it is simply zero everywhere. This result shows that the adverse axial pressure gradient induced by the inward area expansion at the entrance to the test section is too small to cause flow separation for the conditions tested. The flow reversal observed with the 30° and 45° vanes is therefore due to an adverse axial pressure gradient that has been strengthened by swirl. Swirl-induced flow reversal, known as vortex breakdown, is a commonly observed phenomenon and is not necessarily surprising. The conditions under which vortex breakdown occurs, however, are unpredictable at present. As described in Chapter 2, the onset of vortex breakdown has been shown to be highly dependent on the geometry, swirl number, and Reynolds number, among other flow variables. Vortex breakdown is also known to manifest itself in many different modes and may couple with other hydrodynamic instabilities. It is therefore of interest to document and describe in detail the mode of vortex breakdown observed.
in this combustor.

The reverse flow probability fields for the two sets of swirl vanes are shown in Figure 54. Although the mean velocity field in the 30° case exhibited reverse flow only very near the centerline and in just the most upstream location, the reverse flow probability field reveals that flow reversal often occurs (e.g., >10% of the time) near the centerline within a broader region that extends the full axial length of the measurement window. In the 45° case, for which the mean field exhibited reverse flow extending a bit farther downstream and in an annular region, the reverse flow probability field reveals a broad region (roughly 0.4D wide) that often exhibits flow reversal. As in the 30° results, this region is radially centered at the middle of the combustor and extends the full length of the measurement window, but now the peak probabilities occur well off-center.

So, the extent of the region in which reverse flow may occur is significantly larger in both cases than what is suggested by the mean velocity fields. Also, the probability of reverse flow is much greater and radially much broader for the higher swirl level. Furthermore, high swirl moves the most probable region of reverse flow outward.

Figure 54: Reverse flow probability fields for 30° and 45° vanes with $\Phi_{\text{core}} = 0$
5.3 Flow Separation

Limited planar (2-component) PIV data was collected during test rig validation experiments that shows the velocity field upstream of the center body trailing edge with the 30° vanes installed. Thus, this data can reveal where the flow separates on the center body. The data was obtained with only the pilot burning, and thus the core flow temperature was colder than in the measurements presented above (only 623 K). The mass flow rate was nominally the same as for the remainder of the PIV data presented in this work. So while the velocities are lower in this data set compared to the vitiated results, the only difference in Reynolds number between the sets is due to the difference in dynamic viscosity. Thus the Reynolds number for the unvitiated flow is 33% higher than for the vitiated case, while the axial velocities are roughly 45% lower.

Figure 55 shows two instantaneous images from the planar PIV data set. The $v_z = 0$ contour is shown in white such that the flow inside the contour is in the $-z$ direction. Identifying the most upstream point of the reverse flow region for the full data set revealed that it never appeared further upstream than $z/D = 0.23$. If flow reversal is identified as being indicative of flow separation on the center body, then the two images shown Figure 55 are representative of the flow field when the separation point is furthest upstream in the planar PIV measurement window. In Figure 55a, the flow velocity drops rapidly just upstream of the separation point, while in Figure 55b, the deceleration is more gradual.

Figure 56 shows four instances where reverse flow appears in the PIV plane downstream of $z/D = 0.23$. In Figures 56a and 56b, the flow appears to separate further downstream, near the tip of the conical center body. Unlike in Figure 55, these reverse flow regions rapidly spread outward. In Figure 56a, the boundary of reverse flow is surrounded by a large velocity deficit region, i.e., the deceleration is gradual, while in Figure 56b the velocity gradient is high, i.e., the flow outside of the reverse
flow boundary has a large axial component that is comparable to flow in the rest of the measurement window. In Figure 56c, the reverse flow region is small and occurs downstream of the centerbody, while in Figure 56d there is no reverse flow region within the PIV measurement plane.

If this flow were 2-D (axisymmetric), these instantaneous velocity measurements would mean that the flow separation point moves significantly in the radial and axial direction, and that sometimes the flow does not separate at all. Due to the 3-D nature of this swirling flow, however, this is likely not the case. Precessing vortices are commonly observed in strongly swirling flows such as this one, and thus a more likely explanation is that a region of reverse flow is revolving around the center body, and periodically passing through the PIV measurement window. If this is true, it appears that the revolving flow structure is centered on the measurement plane in Figure 55, is slightly offset from the plane in Figures 56a and 56b, is just glancing the measurement plane in Figure 56c, and does not pass through the plane anywhere in Figure 56d.

Also note that the most upstream separation location from Figure 55 occurs at a
radial position of $x/D = -0.04$. This is quite close to the radial location where the reverse flow probability field drops to zero for the $30^\circ$ case with the lower Reynolds number (Figure 54). Thus, it is reasonable to conclude that the reverse flow regions observed in the downstream measurement plane are convectively connected to the flow separation features. Returning to the discussion of flow recirculation with $45^\circ$ vanes in Section 5.2 (Figure 64), it is even more likely that the reverse flow regions at the higher swirl level are connected to flow separation. Furthermore, the location of
the high reverse flow probabilities implies that the flow separation point on the center body has moved upstream and outward due to a larger adverse pressure gradient at the higher swirl level.

5.4 Helical Vortices

The behavior of the flow separation phenomenon described in Section 5.3 is consistent with a precessing vortex core or helical vortices that have merged with the separated centerbody wake, a phenomenon known to occur in swirling flows. This section presents analysis of the SPIV measurements that aims to further classify this structure. Note that the methods use to identify vortices in this section produce noisy, incoherent results for the 45° case, so the discussion will be primarily restricted to the 30° data. Figure 57 shows a sequence of non-reacting velocity field measurements with 30° vanes. The zones of reverse flow \( v_z < 0 \) are enclosed by the white contour. These velocity fields appear to show vortices passing through the measurement plane on both sides of the center body tip at a radius of around 20 mm and convecting downstream.

![Figure 57: Typical time series of in-plane velocity field for the 30° non-reacting case. The white contour represents \( v_z = 0 \). Spatial coordinates are normalized by test section diameter \((D)\).](image)

It is difficult to unambiguously identify and track these vortices using the raw velocity vector field alone. Calculation of the 2D swirling strength field, detailed in
Section 3.8, is a common method used to visualize and identify vortices from velocity field data. Mathematically, the swirling strength $\lambda_{ci}$ is defined as the magnitude of the imaginary part of the complex eigenvalues of the velocity gradient tensor. Physically, the quantity $2\pi/\lambda_{ci}$ represents the period of rotation inside a vortex [76]. The top row of Figure 58 shows the swirling strength fields calculated from the same velocity field sequence shown in Figure 57. The bottom row of Figure 58 shows a second typical sequence of swirling strength fields from the same data set.

The regions of high swirling strength represent vortices passing through the measurement plane. The in-plane velocity vectors used to calculate the swirling strength are overlaid to show how the swirling strength compares to the velocity field. Although the vortices represented by this data are likely helical and inclined, and therefore not normal to the measurement plane, comparison of the swirling strength and velocity fields shows that the swirling strength still provides a good indication of where the vortices intersect the plane.

Figure 58 reveals pairs of vortices, radially separated, that appear to convect downstream. The swirling strength does not show the direction of rotation, but the velocity vectors reveal that the vortex pairs are counter-rotating. The vortices on the left side always rotate clockwise and the vortices on the right side always rotate counter-clockwise, which is consistent with the shear in the mean flow. This leads to the large reverse flow regions observed near the centerline.

These single-plane, radial-axial measurements can be used to determine whether or not the azimuthal wavenumber of a helical vortex mode is even (i.e. $|m| = 0, 2, 4...$) based on the symmetry of the vortices across the centerline. The counter-rotating vortex pairs in Figure 58 are approximately aligned in the horizontal (or radial) direction. This is characteristic of an even helical vortex breakdown mode; an odd helical mode would have a staggered or “zig-zag” pattern. These measurements alone cannot be used to differentiate between, for example, the $|m| = 2$ and $|m| = 4$ modes.
Figure 58: Typical time evolution of swirling strength field and in-plane velocity field for the 30° non-reacting case. Spatial coordinates are normalized by test section diameter ($D$).

The instantaneous images of the 2D swirling strength reveal a wide variation in the spacing of the vortices in the radial-axial plane. To gain a better understanding of where these vortices are most likely to pass through the plane, it is helpful to look at the time-average of the swirling strength field; this is shown in Figure 59 for the 30° case. Although the locations where vortices pass through the measurement plane are highly unsteady, the mean swirling strength field clearly shows the vortex trajectories as distinct regions with high mean swirling strength relative to other locations in the measurement plane. In the plane, the vortices, on average, move downstream and radially outward from the center body tip at a constant angle before dissipating as they approach the downstream end of the measurement window.

This knowledge of the mean vortex locations may be combined with convective timescales of the vortices to obtain approximate rotational speeds for the apparent helical structure. From observing time sequences of the swirling strength fields,
such as those shown in Figure 58, it is apparent that the displacement of the vortices through the measurement plane is time-resolved. Knowing this, approximate timescales of vortex pairs moving through the plane were determined using the algorithm described in Section 3.9. For the 30° case, the mean period of a vortex passing through an interrogation window is around 1.15 ms. For a helical vortex with an azimuthal wavenumber $|m| = 2$, this represents the half period of the overall structure’s rotation, meaning the base of each strand of the helix would complete one full rotation every 2.30 ms. At the axial location of the interrogation window at which these timescales were determined, the mean radius at which the vortices appeared is around 24 mm. This corresponds to an azimuthal velocity of 64 m/s for the overall structure. For comparison, the maximum time-averaged azimuthal velocity from the SPIV measurements in this region is 58 m/s. Thus, the mean azimuthal velocity is comparable to the approximate rotational velocity of a helical vortex if we assume it has a wavenumber $|m| = 2$.  

Figure 59: Mean swirling strength field for the 30° non-reacting case.
5.5 Heat Release Effects

Up to this point, only velocity results for the non-reacting cases have been presented. This section examines the effects of heat release on the flow field. Apart from the core equivalence ratio, which is nearly stoichiometric for the data presented in this section, the operating conditions are nominally the same as shown for the corresponding non-reacting flow fields (see Figure 49).

Figures 60 and 61 show both the non-reacting and reacting velocity fields with 0° vanes and 30° vanes, respectively. When no swirl is present, the velocity fields with and without heat release are qualitatively the same. The reacting case, as expected, has higher downstream velocities due to flow acceleration from heat release.

Figure 60: In-plane mean velocity field obtained using SPIV with 0° vanes; non-reacting case is shown on the left, reacting case is shown on the right.

When swirl is added to the flow by increasing the vane angle to 30° (Figure 61), heat release produces similar changes. However, since swirl creates a shorter flame, the effects of flow acceleration due to heat release are more readily apparent within the SPIV measurement window. For example, the velocities near the outer diameter of the combustor are much higher for the reacting case. Also, the non-reacting case
has a narrow wake downstream of the center body that spreads slowly and persists downstream of the field of view. The reacting case on the right shows a wake with the same initial width that does not persist as far downstream as in the non-reacting case. This is also a result of flow acceleration from heat release on the centerline, which was observed in the CH* chemiluminescence images captured at the same operating conditions and shown in Section 4.4. Because there was no inner flame without swirl, the centerline flow acceleration is much more significant in the swirled case.

Figure 62 shows the mean velocity fields with 45° vanes, otherwise at the same nominal inlet conditions as Figures 60 and 61. A much broader wake region downstream of the center body is observed in both non-reacting and reacting cases. The initial width of the wake in both cases is comparable to the center body diameter (around 0.4D), suggesting that the flow now separates near the base of the center body’s conical trailing edge. As seen with lower swirl, the flow near the outer diameter has much higher axial velocities when the flame is present. Axial flow acceleration from heat release near the centerline is also significant. As in the 30° case, the reacting mean wake narrows downstream of the annular reverse flow region. However
unlike the lower swirl result, the mean wake attains a near-constant width and persists beyond the measurement window.

Figure 62: In-plane mean velocity field obtained using SPIV with 45° vanes; non-reacting case is shown on the left, reacting case is shown on the right.

To further examine the effects of heat release downstream of the center body, it is helpful to return once again to the reverse flow probability fields. Figures 63 and 64 show the non-reacting and reacting reverse flow probability fields for the 30° and 45° cases. With the 30° vanes, the effect of heat release is simply to reduce the length of the region in which reverse flow is likely to occur, consistent with what was shown in the mean velocity fields.

With the vane angle increased to 45°, there are two regions of reverse flow in the measurement plane with approximately equal offsets from the centerline. This is true for both the reacting and non-reacting cases, but, as with the 30° case, the reverse flow region is significantly shorter. Interestingly, reverse flow may still occur throughout the axial extent of the measurement window at this swirl level even though the primary recirculation zone closes out much sooner. The offset-peak structure of the recirculation region could be due to helical vortices that occur at a larger radius at the higher swirl level. In the reacting flow, these vortices could dissipate or merge.
Figure 63: Reverse flow probability map from PIV with 30° vanes and $\Phi_{core} = 0$ (left), $\Phi_{core} = 1$ (right)

Figure 64: Reverse flow probability map from PIV with 45° vanes and $\Phi_{core} = 0$ (left), $\Phi_{core} = 1$ (right)

into a simpler structure or a more slender helix.

To examine the effects of heat release on helical vortices, the mean swirling strength fields which show the location of the vortices are first considered. Figure 65 shows the 0.6 s$^{-1}$ isocontours of swirling strength for the non-reacting and reacting case, which approximately bound the distinct regions of high swirling strength. Re-
markably, the swirling strength field contours appear completely unaffected by heat release. On average, the helical vortices remain in the same location both with and without heat release.

Figure 65: Swirling strength=0.6 s\(^{-1}\) isocontours for non-reacting and reacting flows with 30° vanes.

Figure 67 shows a sequence of swirling strength fields, like those shown before in Section 5.4, for the 30° reacting flow case. Like in the non-reacting case, symmetric vortex pairs are seen moving through the measurement window. Figure 66 shows a second sequence from the same data set. In contrast to the swirling strength fields shown in Figure 66, these vortices are asymmetric. For the 30° reacting case, both even and odd helical modes were observed within the same 0.55-second SPIV recording.

The period of vortices passing through the measurement window was calculated for this case as described in 3.9. The period was found to be 1.09 ms. Even though the reacting flow sometimes has a mode with a lower azimuthal wavenumber, the timescale is nearly the same as for the non-reacting case (1.15 ms). Thus, the primary effect of heat release on the helical vortices for the 30° case is to allow the \(|m| = 1\)
Figure 66: Time series of swirling strength field and in-plane velocity field for the 30° reacting case showing symmetric vortices. Spatial coordinates are normalized by test section diameter ($D$).

Figure 67: Time series of swirling strength field and in-plane velocity field for the 30° reacting case showing asymmetric vortices. Spatial coordinates are normalized by test section diameter ($D$).

helical mode to appear.

In all, the heat release does not produce drastic changes in the time-averaged flow field under these conditions. The most significant effects are flow acceleration near the inner and outer flame regions and the mode selection of the helical vortices, however evidence will be shown in Chapter 6 that it may also affect growth of instabilities in the outer flame region.
6 Comparison of Scalar Field and Flow Field

The previous two chapters separately characterized the flame behavior and the flow field. In this chapter, these results are synthesized and compared to further elucidate the physics governing flame compactness in the combustor. Additional analysis is presented that correlates the flame behavior to features of the flow field. The inner flame anchoring mechanism is revealed along with the parameters that control its location. With the flow field characterized, new insight into interactions between the flame and unsteady flow field is provided to help elucidate the physical mechanisms that improve flame compactness.

6.1 Inner Flame

In Chapter 5, the reverse flow probability fields were presented for each swirl level (Figure 63). With 30° vanes, there is a region of high reverse flow probability along the centerline of the combustor. It was also shown that the flow separates near the tip of the center body at a radius approximately equal to the radius of the reverse flow region. With 45° vanes, the reverse flow region is much broader, suggesting that the flow separates near the base of the center body cone.

Figure 68 shows the inverse Abel transform of the time-averaged CH* chemiluminescence images for the swirled cases at near-stoichiometric conditions; superimposed on the flame images are the 10% isocontours of reverse flow probability, which is taken as an approximation of the recirculation zone boundary. For both swirl levels, the high chemiluminescence signal from the inner flame lies just outside the recirculation zone, i.e., at a slightly larger radius away from the centerline. For the 30° case, the chemiluminescence from the inner flame converges toward the center body tip near the boundary of the recirculation zone. For the 45° case, the situation is less clear because the chemiluminescence signal is low near the center body at the
Figure 68: Inverse Abel transform of time-averaged CH* chemiluminescence images with overlay of 10\% isocontour (white curve) of reverse flow probability at stoichiometric conditions near-stoichiometric condition; this is explained in the following paragraphs.

First, statistics from the OH-PLIF data can be used to show more precisely where the inner flame is anchored on the center body. The binarized images presented in Chapter 4 were further reduced using the \textit{bwboundaries} function in MATLAB to locate the edges of regions with high OH fluorescence signal. The edges of the hot product regions are assumed to coincide with the instantaneous locations of the (thin) flame front, though the edges found by the algorithm will also show the boundaries of the laser sheet. The edges of the high-OH regions were found for each individual image in a movie and edge probability fields were calculated. The value of the OH-PLIF edge probability at each location should represent the probability that a flame front can be found at that location.

Figure 69 shows an OH-edge probability field for $\Phi_{\text{core}} = 0.85$, the nearest equiv-
The high OH-edge probability corresponding to the inner flame meets the center body just upstream of the tip (around $z/D = 0.27$); note the OH-PLIF laser sheet extends further upstream than this. Thus we can conclude that this $z/D$ position corresponds to the flame’s anchor location (on average). The same 10% reverse flow probability isocontour presented earlier is overlaid on the OH-edge probability. This comparison reveals that the flame is anchored at the recirculation zone boundary, where the flow likely separates on the center body. The non-reacting PIV results presented in Chapter 5 suggested the separation point occurred at $z/D = 0.23$, further supporting the conclusion that the inner flame is anchored at the separation point on
Figure 69: OH-edge probability for $\Phi_{\text{core}} = 0.85$ with overlay of 10% reverse flow probability contour (solid white) and swirling strength=0.6 s$^{-1}$ contour (dashed white) for 30° reacting case. Higher reverse flow probabilities and swirling strengths occur in the narrow region between the white contours. Although the colormap is saturated, the peak OH-edge probabilities away from the laser sheet edge are $\sim$5%.

Since the high velocities outside the separation region are well in excess of likely flame speeds, the flame cannot stabilize there. Furthermore the high core velocities allow the flame to propagate radially outward only a small distance. Accordingly, the OH-edge probability shows that the flame front just outward from the anchoring point with a relatively shallow angle to the axial direction. The initial angle is slightly greater due to the initial growth of the separation bubble previously seen in Figure 56. Figure 69 also shows the swirling strength=0.6 s$^{-1}$ isocontour, which approximately bounds the region where helical vortices were observed (see Figure 59). This further shows that the inner flame primarily resides in the region where helical vortices are found.

It was observed that the chemiluminescence images captured at different core equivalence ratios for 30° vanes (Figure 43) appear to show the inner flame in the
same position, though it is not clear for the near-stoichiometric cases. As shown in Figure 69, the region of relatively high OH-edge probability is approximately bounded by the 2% isocontour for the inner flame; choosing a different contour shows a much different plot for the outer flame, but does not change the conclusions of the following discussion for the inner flame. Thus, the 2% isocontours of edge probability can be compared to determine how the mean inner flame front position varies with core equivalence ratio more precisely. This comparison is shown in Figure 70. For the range of equivalence ratios shown, the inner flame anchoring location does not seem to move at all. This is consistent with the observation from Chapter 5 that the flow’s recirculation zone boundaries were the same for no heat release (non-reacting) and for the maximum possible (local) heat release (a stoichiometric core equivalence ratio).

![Figure 70: Isocontours of 2% OH-edge probability vs. core equivalence ratio](image)

Although no planar measurements of the flow field or OH scalar field were obtained upstream of the center body tip for the 45° vanes, it is still possible to infer where the flame is stabilized. It was established in Chapter 5 that the broad recirculation zone boundary for this case likely marks where the flow separates on the center body, and that, as with the 30° case, this does not depend on whether or not the core
flow is burning. The near-stoichiometric chemiluminescence images do not clearly show where the inner flame is anchored, but the leaner conditions do. Figure 71 shows the recirculation zone boundary from the reacting SPIV data overlaid on the inverse Abel transform of the CH* images for leaner conditions. For all the core equivalence ratios, the inner flame edge corresponds well to the (fixed) recirculation boundary. This suggests that for the 45° swirl, the mean inner flame anchoring position is independent of $\Phi_{\text{core}}$ (over this range), just as in the 30° swirl case, and that the inner flame is again anchored where the flow separates. When the vane angle is increased from 30° to 45°, the flow separates farther upstream on the center body. Because the trailing edge is conical, the separation also moves radially outward. This allows the inner flame to anchor farther upstream and radially outward.

![Figure 71: Inverse Abel transform of time-averaged CH* chemiluminescence images with overlay of 10% isocontour (white curve) of reverse flow probability with 45° vanes](image)

To this point, it has only been demonstrated that higher swirl can move the separation point, and therefore the inner flame anchoring location upstream. The data used for this analysis had the pilot burning; changing core equivalence ratio therefore influenced the heat release rate in both the inner and outer flame. It happens
that the inner flame anchoring location does not only depend on the swirl level.

Figure 72 shows 2% isocontours of OH-edge probability for \( \Phi_{\text{core}} \approx 0.7 \) with \( \Phi_{\text{pilot}} = 1.0 \) and with \( \Phi_{\text{pilot}} = 0 \). The air flow rate was held constant between the two cases, with \( f_{\text{pilot}} = 10\% \). The flame with \( \Phi_{\text{pilot}} = 0 \) was achieved by supplying fuel to the core with the pilot burning and then turning the pilot fuel off. When the pilot fuel is turned off, the outer flame blows off leaving only an inner flame. The solid contour in the plot, which represents the stoichiometric pilot case, outlines an inner and outer flame. The dashed contour for \( \Phi_{\text{pilot}} = 0 \) shows only an inner flame, which now meets the center body significantly farther upstream. Although the inner flame anchoring location is not a strong function of core equivalence ratio when the outer flame is present, it exists significantly upstream and radially outward without the outer flame.

![Figure 72: 2% isocontours of OH-edge probability with pilot on (\( \Phi_{\text{pilot}} = 1.0 \)) and pilot off](image)

Because this flow is confined and the outer flame lies near the outer wall of the combustor, the hot products from the flame around the outer diameter cannot expand radially outward. The heat release from the outer flame increases the momentum of
the core flow, which tends to suppress flow separation on the center body. At the same time, hot products in the recirculation zone from the inner flame can only expand radially outward. The center flame strengthens the adverse axial pressure gradient, which tends to encourage flow separation. When both flames are present, these competing effects roughly balance each other. When neither flame is present, as shown in the velocity fields in Chapter 5, the flow still likely separates near the same location. When only the inner flame is present, however, the expansion from heat release pushes the separation point, and thus the inner flame anchoring location, upstream. This finding reveals interaction between the inner and outer flames via the flow field that has not been taken into account up to this point.

6.2 Outer Flame

It was shown previously that the outer flame region is highly unsteady at the leaner conditions. Regions of hot products often move radially inward at a high angle relative to the $z$-direction (Figure 41). Analysis of the OH edges gives a clearer picture of the flame front motion. Figure 73 shows randomly selected examples of instantaneous OH edges. Each plot contains sets of OH edges from seven OH-PLIF images, with each image represented by a different color.

Figure 73a shows the OH edges for $\Phi_{\text{core}} = 0.54$. In the flame length parametric study, this corresponds to the shortest flame observed for 30° vanes. The OH edges corresponding to the flame front contain many small wrinkles and vary dramatically between realizations. They also exhibit large-scale curvature, sometimes remaining nearly parallel to the flow before turning severely toward the center. The cyan OH edge in particular actually forms a narrow peninsula resembling a slice of a mushroom vortex aimed upstream in the region between the mean inner and outer flame locations.

Figure 73b shows the OH edges for $\Phi_{\text{core}} = 0.85$, corresponding to the longest
flame. The OH edges in this case also contain many small wrinkles. In contrast to the leaner case, however, the OH edges are confined to a much smaller region and exhibit smaller variations in position. The outer OH edge specifically, with the exception of one realization, remains at a shallow angle relative to the $z$-axis. Inner and outer flame regions are thus easily distinguishable. Furthermore, the size and motions of the large-scale structures in the outer flame are significantly reduced compared to the lean condition.

![Figure 73: Randomly selected instantaneous OH-edges for a short flame ($\Phi_{core} = 0.54$) and a long flame ($\Phi_{core} = 0.85$)](image)

These observations of the instantaneous OH edges reveal the specific underlying flame dynamics that determine the edge probability fields, which are now shown in Figure 74 for $\Phi_{core} = 0.54 - 1.1$. The large spread of the OH edge probability in Figure 74a is consistent with the uncertainty of location and large-scale structures observed instantaneously at $\Phi_{core} = 0.54$. Similarly, the organized structure and clearly-defined flame regions of Figure 74c is consistent with the small variability in OH edge position and the lack of large-scale structures observed from the instantaneous data. Note that the $\Phi_{core} = 0.70$ probability field appears strikingly similar to the $\Phi_{core} = 0.54$ probability field while the $\Phi_{core} = 0.85$ and $\Phi_{core} = 1.1$ cases also resemble one
As described in Chapter 2, several mechanisms could cause large-scale flow structures to distort the outer flame. As previous researchers hypothesized, the configuration of low-density products around the outer diameter of swirling high-density reactants is a configuration that could be subject to Rayleigh-Taylor instability. This could cause velocity fluctuations in the outer flame region, but it does not explain why the instabilities would be most significant at the leanest equivalence ratios. The
density ratio across the flame should increase monotonically as the equivalence ratio increases from lean to stoichiometric. A higher reactant/product density ratio would be expected to enhance disturbance growth rates; however, the opposite trend is observed.

On the other hand, the instabilities could possibly be dominated by a shear (Kelvin-Helmholtz) mechanism. Because the velocities in the pilot stream are always lower than the velocities in the adjacent core stream, acceleration in the outer flow by the flame would tend to weaken the shear layer. The leanest equivalence ratios are less exothermic and therefore induce the least amount of flow acceleration. Lean equivalence ratios could then be considered most susceptible to a shear-driven instability.

Figure 75 shows a comparison of the reacting and non-reacting profiles at \( z/D = 0.4 \), near where the large-scale structures become significant in the outer flame. The mean velocities in the outer flame region at this axial location are not significantly affected by heat release. While the flame front fluctuations were not observed at the stoichiometric condition (shown in the figure), but rather at lean conditions, the flow acceleration from heat release would be expected to be most significant at stoichiometric. As the velocity profile comparison shows, this is not the case; the radial gradients in axial velocity are nearly identical in the outer flame region (approximately \( r/D = 0.3 \)). This suggests that the lower equivalence ratios would not be more susceptible to a shear-driven instability, and further lessens the likelihood that these are Kelvin-Helmholtz instabilities.

It was shown in the combustion centrifuge literature that the influence of centrifugal forces is non-monotonic and may also have an equivalence ratio or laminar flame speed dependency. The upper limit on centripetal accelerations that could enhance flame propagation was attributed to local extinction by excessive flame stretch when the instabilities become too strong. No evidence of local outer flame extinction was
Figure 75: Radial profiles of axial velocity for 30° vanes at $z/D = 0.4$ under non-reacting and reacting conditions

found in the OH-PLIF images, so this is not a likely explanation of reduced flame speeds. The equivalence ratio dependency was thought to occur when the laminar flame speeds are unusually high, such as in a system with high preheat temperatures. Centrifugal forces no longer dominated when laminar flame speeds were sufficiently high (in excess of around 2 m/s). Given that the theoretical laminar flame speeds in this combustor range from around 2-3.5 m/s depending on the equivalence ratio, this is a plausible explanation of the equivalence ratio dependence of the outer flame behavior.

Finally, besides disturbance growth rates, the effect of induced flow fields from flame-generated vorticity should be considered. Vortices normal to the flame front could induce a velocity toward the reactants through the baroclinic mechanism, accelerating the flame front into the reactants. This coupling of the flame front with the flow field becomes most significant for vortices that are strong relative to the laminar flame speed. The decrease in the flame speed as the equivalence ratio is lowered could therefore increase coupling between the flame front and flow field; the resulting
induced velocities then lead to the observed large-scale distortions in the outer flame front, increasing the turbulent flame speed.

6.3 Flame Compactness

Recall from Figure 31 (Chapter 4) that the shortest flames were observed at the leanest equivalence ratios. When swirl is present, the flame length first increases with equivalence ratio before decreasing again. The separate discussions of the inner and outer flame will now be put together to help understand how swirl affects flame compactness.

First, it was revealed that swirl creates helical vortices that allow a flame to propagate upstream toward the center body trailing edge. Swirl also strengthens the adverse axial pressure gradient, which causes the flow to separate on the center body. This creates a recirculation zone where the inner flame can stabilize. The inner flame stabilization reduces the radial distance across which the flame must propagate in order to consume all of the incoming reactants, resulting in a dramatically shorter flame. Furthermore, increasing the level of swirl further strengthens the adverse axial pressure gradient, moving the separation location upstream. This in turn moves the inner flame even further upstream and outward, which explains why the flame becomes even shorter when the swirl angle is increased from 30° to 45°.

The influence of core equivalence ratio on flame length is mostly explained by the outer flame. At low equivalence ratios, the outer flame front is significantly distorted by large-scale structures. These structures cause the flame front to protrude significantly inward toward the combustor centerline and even upstream. The increased area of the flame front causes an increase in the mass consumption turbulent flame speeds, allowing the flame to consume the reactants in a shorter axial distance and thereby contributing to the compactness of the flame. These structures vanish within the measurement window as the equivalence ratio is increased, resulting in an
increased flame length.

Once the large distortions in the outer flame have decreased enough, it is possible that relative importance of the inner flame becomes more significant. At higher equivalence ratios, and thus higher laminar flame speeds, the inner flame could cause the flame shortening observed. Since the non-swirling flow has no inner flame, it continues to increase in length at higher core equivalence ratios. The reason for this phenomenon, however, remains unclear.
7 Conclusions and Recommendations

This chapter reviews the key contributions of this thesis. Practical implications of the findings are included for the benefit of engineers and designers of advanced high-performance combustion devices. Finally, future work recommendations are provided to researchers who wish to continue fundamental investigation of these topics.

Development of more compact and efficient combustion devices, especially for aircraft turbine engines, requires improved fundamental understanding of combustion and fluid-mechanical physics that could be harnessed to improve combustor performance and reliability. Previous fundamental experimental and numerical studies on enhancement of turbulent flame speeds by centrifugal forces suggested this effect could be realized in a swirling flow to dramatically improve combustor compactness.

The swirl augmentor is combustor configuration that was designed to use this principle. It incorporates a pilot combustor around the outer diameter of a swirling flow with a center body. An experimental peripherally piloted swirl combustion facility was developed and characterized to study the underlying physics of swirl effects on combustor compactness. First, a study was conducted using time-averaged imaging of flame chemiluminescence to identify which operating parameters control flame length. Using this knowledge, advanced high-speed diagnostics (CH* chemiluminescence imaging, OH planar laser-induced fluorescence, and particle image velocimetry) were employed to reveal the influence of swirl and core equivalence ratio on flame configuration and flame front dynamics. Detailed measurements of the flow field were obtained to identify and quantify flow features such as separation and hydrodynamic instabilities in the flame region. Flow field results were then correlated to the scalar field to elucidate the physical mechanisms that control flame stabilization and combustor compactness.
7.1 Major Findings and Contributions

This experimental investigation began with a parametric study of operating conditions that, based on prior knowledge, could affect combustor compactness. The sensitivity of flame length and initial outer flame angle to pilot equivalence ratio, pilot mass fraction, inlet Mach number, core equivalence ratio, and swirl level (0°, 30°, and 45°) was determined. Core equivalence ratio and swirl level were identified as the controlling parameters. Pilot characteristics were determined to be relatively inconsequential over the range tested, indicating that the pilot simply anchors the outer flame. This result is significant for the design of a practical swirl augmentor because it suggests the pilot could have a relatively simple design with minimal contribution to cold pressure losses, unlike the design used for this experimental study.

CH* chemiluminescence imaging of the flame definitively showed that flame length is significantly reduced by swirl. It also revealed that, for a given swirl level, the flame length varies with core equivalence ratio. The shortest flames occurred at the leanest conditions, which was not expected given that they have the lowest laminar flame speeds. The flame length decreased again at near-stoichiometric equivalence ratios. This behavior was found to depend on two important features: the outer flame, stabilized by the pilot, and the inner flame, anchored on the conical trailing edge of the center body. The remainder of this section summarizes the role of the inner and outer flame in controlling combustor compactness and why they are affected by swirl and core equivalence ratio.

7.1.1 Inner Flame

In a combustor with fixed geometry, the flame compactness is determined by the stabilization locations and a combination of the flame speed and flow velocities at the flame front. Chemiluminescence images used to measure the flame length also allowed for an initial characterization of the flame configuration in this experimental
combustor. Analysis of the chemiluminescence images revealed that the flame was stabilized where the pilot stream first meets the core stream and also near the trailing edge of the center body. While this result may not be surprising, previous studies that predicted the physics controlling flame compactness in the swirl augmentor configuration did not account for flame stabilization on the center body in addition to the outer pilot-stabilized flame. It turns out, however, that the inner flame plays an important and nuanced role in determining the flame length. As such, high-speed OH-PLIF imaging of the flame was used in conjunction with high-speed SPIV to quantify the flow features that control inner flame stabilization and how they are affected by swirl.

The inner flame was found for both 30° and 45° swirl for the entire range of core equivalence ratios tested, but never appeared in the non-swirled cases. At the lower swirl level, the inner flame was stabilized near the tip of the conical center body trailing edge, but when the vane angle was increased, the flame moved significantly further upstream, near the base of the cone (which also coincides with where the outer flame is anchored).

Analysis of the velocity data in the inner flame region showed that the flow separates on the center body when swirl is present and that the separation location is primarily a function of swirl. The effect of swirl is thus to strengthen the adverse axial pressure gradient, which encourages flow separation. Higher swirl levels move the separation location upstream, which also depends on the specific geometry of the center body trailing edge. Comparing the velocity field to the flame front location then revealed that the inner flame is stabilized on the center body where the flow separates. One effect of swirl on combustor compactness is thus to promote flow separation on the center body, determining how far upstream the inner flame is anchored. This also implies that some minimum swirl threshold is required for flow separation to occur; below this threshold, the flame could not anchor on the center body and a
significant combustion efficiency penalty could be incurred.

It is also important to understand how the inner flame is initiated. High-speed chemiluminescence imaging of inner flame ignition events revealed that an inner flame can propagate back along the combustor centerline, and that it appears to take on a double-helical structure. Analysis of the instantaneous swirling strength field in this region showed strong evidence of helical vortices originating from the separated flow. The vortices extend downstream, far past the separation point, and create a region of reverse flow that allows the flame to propagate upstream and stabilize on the center body; however, at marginally higher temperatures, or with a configuration that produces longer residence times, the inner flame could easily autoignite.

A review of the literature emphasized the uniqueness of this flow field together with sparse experimental data that could be used to predict helical vortices at high \(Re\). As such, the helical vortices in this combustor were quantified and it is argued that they have azimuthal wavenumbers of \(|m| = 1\) and \(|m| = 2\). While the \(|m| = 1\) mode has been commonly observed, this is one of the first studies to provide experimental evidence of the \(|m| = 2\) mode in a high-\(Re\) flow. Furthermore, it is shown that the helical vortices, like the flow separation, have nearly identical spatial characteristics both with and without heat release.

Anticipating inner flame stabilization is critical for hardware designers in part because high heat loading on the end cap of a turboshift, especially in the high-temperature flow downstream of a turbine, will require some additional cooling scheme. Furthermore, this air cooling could suppress the flow separation that allows for inner flame stabilization. Even if the flow separates, operation of the combustor at conditions that do not produce helical vortices or autoignition could prevent inner flame initiation. This would fundamentally alter the flame configuration and significantly increase the flame length.
7.1.2 Outer Flame

Previous research predicted enhanced turbulent flame speeds in the outer flame due primarily to a Rayleigh-Taylor instability mechanism. The peripheral pilot anchors a flame around the outer diameter of the core flow, resulting in a layer of low-density combustion products situated outside the higher-density reactants. When swirl is imparted to the flow, the positive radial pressure gradient and negative radial density gradient is unstable. Rapid growth of flow disturbances would wrinkle and distort the outer flame front, increasing the turbulent flame speed. This is the fundamental mechanism that was expected to govern compactness in the swirl augmentor.

Using high-speed OH-PLIF, this study provided the first detailed images of the instantaneous outer flame front in this type of combustor. The images indeed revealed large distortions in the outer flame front, but only at the leaner core equivalence ratios corresponding to the shortest flames. It is argued that this behavior is unlikely to be dominated by shear-driven instabilities, but could be explained by a Rayleigh-Taylor or baroclinic push mechanism and vitiation effects. Nevertheless, it was shown that shorter flames occur when the instantaneous area of the outer flame front is increased by these large-scale motions, allowing it to consume reactants at a higher rate.

Thus, the effect of swirl on combustor compactness is the stabilization of the inner flame in addition to enhancement of turbulent flame speeds in the outer flame.

Many experiments were performed in this well-characterized, well-documented test facility for the purposes of this investigation. This produced a large experimental database of detailed flame measurements that capture the influence of various operating parameters relevant to practical devices. It also includes high-resolution measurements of the flow field that were not available in the literature prior to this study. This is extremely valuable to the scientific community for further analysis of the physics important to novel compact combustion systems and validation of advanced CFD models.
7.2 Recommendations for Future Work

It was shown that flame stabilization on the center body is one of the most essential features for achieving a compact flame. The level of swirl required for inner flame stabilization was not determined in this study due to the limited number of discrete swirl levels that could be produced in the test facility. The literature also provides little guidance for prediction and control of flow separation on a tapered center body in a swirling flow with no outer expansion. It is therefore recommended that a variable-angle swirl generator be designed and implemented in this combustor to allow for precise quantification of flow separation as a function of swirl. Stereo-PIV measurements of the velocity field upstream of the center body tip will show the onset of flow separation. This is a necessary step for development and validation of a predictive model of inner flame stabilization in this combustor configuration. Predictive capabilities would also be valuable for designers of practical devices with similar flow fields where center body flow separation is undesirable.

A related fundamental topic of interest to the scientific community is the helical vortices that allow the inner flame to stabilize. This combustor has a wide operational range and also provides the somewhat unique opportunity to observe the $|m| = 2$ helical instability mode in a high-$Re$ flow. With a variable swirler, additional high-speed SPIV measurements could be obtained to help understand when this mode appears and how it is affected by heat release. The SPIV setup in this study, however, resulted in laser reflections on the quartz tube which prevented helical vortex quantification at the higher swirl level. It is recommended to apply a heat-resistant coating to the inside of the quartz tube that will absorb rather than reflect the laser light.

The specific instability mechanism that enhances flame speeds in the outer flame was not conclusively determined. This knowledge gap should be closed in order to optimize the many high-g combustion devices currently being developed. Stability analysis of the various mechanisms proposed in Chapter 6 should be compared to the
experimental results to conclusively show the underlying physics of large-scale outer flame distortion. It would also be useful to acquire simultaneous high-speed OH- or CH-PLIF and SPIV measurements in the outer flame region. Knowledge of the instantaneous velocities at the flame front would allow for validation of disturbance growth models as well as quantification of local turbulent flame speeds.

Acoustic pressure sensor data that was continuously recorded during these experiments revealed strong coherent pressure oscillations under some operating conditions. While these operating conditions were successfully avoided to limit the scope of this work, an investigation of thermoacoustic instabilities in this architecture is unavoidable. Large pressure oscillations can impose significant operability limits related to flame blow-off, dramatically reduce longevity, and cause catastrophic engine failure. Predicting how heat release could couple with acoustic modes of the combustor will enable designers to incorporate features that can passively or actively prevent this. Additionally, targeted investigations of thermoacoustics often have the secondary benefit of improving the understanding of flame stabilization physics. Pursuit of this goal would begin with mapping the operating conditions that produce thermoacoustic instabilities and then acquiring planar measurements of the flame and flow field at some of those conditions with high temporal resolution. With the knowledge from this study that the inner flame is closely coupled to flow separation, this region of the combustor should be given special attention. Pressure oscillations could potentially modulate the flow separation and feed back through inner flame heat release.

Accurate CFD models can be used to quickly develop practical devices and gain a deeper understanding of physical mechanisms in a combustor. The large experimental database provided in this work enables the development and validation of such models. A CFD effort in parallel with further experimental studies and instability analysis is anticipated to be highly productive toward attaining a complete picture of the governing physics.
References


