Concentration And Velocity Fields Throughout The Flow Field Of Swirling Flows In Gas Turbine Mixers

2004

Louis James Turek
University of Central Florida

Find similar works at: http://stars.library.ucf.edu/etd

University of Central Florida Libraries http://library.ucf.edu

Part of the Engineering Commons

STARS Citation

http://stars.library.ucf.edu/etd/153

This Doctoral Dissertation (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
CONCENTRATION AND VELOCITY FIELDS
THROUGHOUT THE FLOW FIELD OF SWIRLING FLOWS
IN GAS TURBINE MIXERS

by

LOUIS JAMES TUREK
B.S. University of Central Florida, 2000
M.S. University of Central Florida, 2001

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Mechanical, Materials, and Aerospace Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Summer Term
2004

Major Professor: Ruey-Hung Chen
ABSTRACT

Air velocity and fuel concentration data have been collected throughout the flow fields of two gas turbine mixers in an effort to better understand the mixing of fuel and air in gas turbine mixers. The two gas turbine mixers consisted of an annular flow profile and incorporated swirl vanes to produce a swirling flow to promote fuel/air mixing. The fuel was injected into the bulk flow from the pressure side of the swirl vanes. The first mixer had a swirl angle of 45°, while the second had a swirl angle of 55°.

In order to examine the effect of the swirl angle on the mixing of fuel and air as the flow progressed through gas turbine mixers, axial and tangential air velocity data was taken using a laser Doppler velocimeter (LDV). Also, fuel concentration data was taken separately using a hydrocarbon concentration probe with methane diluted with air as the fuel. The data were taken at varying axial and varying angular locations in an effort to capture the spatial development of the fuel and velocity profiles. The spectra of the data were analyzed as well in an effort to understand the turbulence of the flow.

It was found that the 55° swirler exhibited smaller variations in both velocity and fuel concentration values and that the fuel reached a uniform concentration at axial locations further upstream in the 55° degree mixer than in the 45° mixer. The RMS values of the velocity, which were influenced by the swirl vanes, were higher in the 55° mixer and likely contributed to the better mixing performance of the 55° mixer. The fuel concentration spectrum data showed that the spectra of the two mixers were similar, and that the fluctuations in fuel concentration due to flow emanating from the swirl vanes were seen throughout the length of the two mixers.
ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge the technical assistance of Dr. Marcos Chaos, Mr. Anupam Kothawala, and Mr. Chris Douglass in the setup of equipment and hardware in the work discussed herein. The advice and support of the committee members, particularly the committee chair Dr. Ruey-Hung Chen, is also greatly appreciated. The author is also thankful for the donation by Siemens-Westinghouse Power Corporation of the hardware examined in this work. Also, appreciation for the love and support of my parents, Anna and Lou Turek, is beyond what can be expressed in mere words.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................... v
LIST OF TABLES........................................................................................................... xvi
LIST OF SYMBOLS ....................................................................................................... xvii
INTRODUCTION ............................................................................................................. 18
  Background ............................................................................................................... 19
  Previous Work ......................................................................................................... 23
EXPERIMENTAL METHODS AND SETUP................................................................. 38
  Laser Doppler Velocimeter ................................................................................... 43
  Hydrocarbon Concentration Probe ...................................................................... 57
RESULTS ......................................................................................................................... 67
  Velocity Data ........................................................................................................ 69
    Axial Velocity vs. θ .......................................................................................... 74
    Axial RMS Velocity vs. θ .............................................................................. 84
    Tangential Velocity vs. θ .............................................................................. 94
    Tangential RMS Velocity vs. θ ................................................................. 103
    Axial Velocity vs. x/Dh ............................................................................ 112
    Axial RMS Velocity vs. x/Dh .................................................................. 118
    Tangential Velocity vs. x/Dh ................................................................ 125
    Tangential RMS Velocity vs. x/Dh ........................................................... 131
  Fuel Concentration Data ..................................................................................... 138
    Fuel Concentration vs. θ ........................................................................... 139
    RMS Fuel Concentration vs. θ ................................................................. 149
    Fuel Concentration vs. x/Dh .................................................................... 159
    RMS Fuel Concentration vs. x/Dh .......................................................... 166
  Unmixedness ....................................................................................................... 173
    Unmixedness at θ = 0 degrees .................................................................... 173
    Sector Averaged Unmixedness .................................................................. 176
  Spectrum Analysis .............................................................................................. 179
    Axial Velocity Spectrum ........................................................................... 180
    Tangential Velocity Spectrum ................................................................ 193
    Fuel Concentration Spectrum .................................................................... 206
CONCLUSIONS ............................................................................................................. 245
LIST OF REFERENCES ................................................................................................ 248
APPENDIX..................................................................................................................... 250
LIST OF FIGURES

Figure 1. Diagram of swirl vane geometric parameters................................. 40
Figure 2. Test rig with swirler mounted into acrylic tube............................... 42
Figure 3. Test hardware with lasers passing through antireflective glass........ 44
Figure 4. Diagram of LDV and test rig............................................................ 45
Figure 5. Module 3 mounted in test rig........................................................... 46
Figure 6. Module 4, with optically clear aft shroud, mounted in test rig........... 47
Figure 7. Drawing of laser crossing with dimensions diagramed.................... 48
Figure 8. Typical Doppler burst during velocity data collection.................... 50
Figure 9. Histogram showing data points clustered around the mean velocity value (33.39 m/s).................................................................. 51
Figure 10. Diagram of data acquisition equipment connections....................... 52
Figure 11. Diagram of swirler nozzle with titanium dioxide supply system...... 53
Figure 12. Diagram of concentration probe hardware................................... 59
Figure 13. Diagram of fuel flow system with test hardware............................ 60
Figure 14. FFT plots at with frequency of (a) 50 Hz and (b) 550 Hz.............. 63
Figure 15. FFT plot a frequency too high (600 Hz) to be resolved by concentration probe. ................................................................. 64
Figure 16. Data collection locations for Module 3 (a) and Module 4 (b).......... 68
Figure 17. Mean axial velocity at x/Dh= 0.87 for Module 4............................. 70
Figure 18. Mean tangential velocity at x/Dh= 0.87 for Module 4.................... 71
Figure 19. Mean axial velocity at x/Dh= 2.60 for Module 4............................. 72
Figure 20. Mean tangential velocity at x/Dh= 2.60 for Module 4.................... 72
Figure 21. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 0.89 for Module 3................................................................. 75
Figure 22. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 0.87 for Module 4................................................................. 75
Figure 23. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 1.11 for Module 3................................................................. 76
Figure 24. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 1.06 for Module 4................................................................. 76
Figure 25. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 1.32 for Module 3................................................................. 77
Figure 26. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 1.25 for Module 4................................................................. 78
Figure 27. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 1.74 for Module 3................................................................. 78
Figure 28. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 1.63 for Module 4................................................................. 79
Figure 29. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 2.17 for Module 3................................................................. 79
Figure 30. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 2.02 for Module 4................................................................. 80
Figure 31. Radial profiles of normalized mean axial velocity vs. \( \theta \), \( x/D_h = 2.60 \) for Module 3.................................80
Figure 32. Radial profiles of normalized mean axial velocity vs. \( \theta \), \( x/D_h = 2.21 \) for Module 4.................................81
Figure 33. Radial profiles of normalized mean axial velocity vs. \( \theta \), \( x/D_h = 3.02 \) for Module 3.................................81
Figure 34. Radial profiles of normalized mean axial velocity vs. \( \theta \), \( x/D_h = 2.60 \) for Module 4.................................82
Figure 35. Radial profiles of sector averaged normalized mean axial velocity for Module 3.................................82
Figure 36. Radial profiles of sector averaged normalized mean axial velocity for Module 4.................................83
Figure 37. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 0.89 \) for Module 3.................................85
Figure 38. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 0.87 \) for Module 4.................................85
Figure 39. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 1.11 \) for Module 3.................................86
Figure 40. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 1.06 \) for Module 4.................................86
Figure 41. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 1.32 \) for Module 3.................................87
Figure 42. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 1.25 \) for Module 4.................................87
Figure 43. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 1.74 \) for Module 3.................................88
Figure 44. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 1.63 \) for Module 4.................................88
Figure 45. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 2.17 \) for Module 3.................................89
Figure 46. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 2.02 \) for Module 4.................................89
Figure 47. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 2.60 \) for Module 3.................................90
Figure 48. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 2.21 \) for Module 4.................................90
Figure 49. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 3.02 \) for Module 3.................................91
Figure 50. Radial profiles of normalized axial RMS velocity vs. \( \theta \), \( x/D_h = 2.60 \) for Module 4.................................91
Figure 51. Radial profiles of sector averaged normalized axial RMS velocity for Module 3.................................92
Figure 52. Radial profiles of sector averaged normalized axial RMS velocity for Module 4.................................92
Figure 53. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 0.89$ for Module 3.

Figure 54. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 0.87$ for Module 4.

Figure 55. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.11$ for Module 3.

Figure 56. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.06$ for Module 4.

Figure 57. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.32$ for Module 3.

Figure 58. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.25$ for Module 4.

Figure 59. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.74$ for Module 3.

Figure 60. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.63$ for Module 4.

Figure 61. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 2.17$ for Module 3.

Figure 62. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 2.02$ for Module 4.

Figure 63. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 2.60$ for Module 3.

Figure 64. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 2.21$ for Module 4.

Figure 65. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 3.02$ for Module 3.

Figure 66. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 2.60$ for Module 4.

Figure 67. Radial profiles of sector averaged normalized mean tangential velocity for Module 3.

Figure 68. Radial profiles of sector averaged normalized mean tangential velocity for Module 4.

Figure 69. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 0.89$ for Module 3.

Figure 70. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 0.87$ for Module 4.

Figure 71. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.11$ for Module 3.

Figure 72. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.06$ for Module 4.

Figure 73. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.32$ for Module 3.

Figure 74. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.25$ for Module 4.
Figure 75. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.74$ for Module 3.  

Figure 76. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.63$ for Module 4.  

Figure 77. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 2.17$ for Module 3.  

Figure 78. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 2.02$ for Module 4.  

Figure 79. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 2.60$ for Module 3.  

Figure 80. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 2.21$ for Module 4.  

Figure 81. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 3.02$ for Module 3.  

Figure 82. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 2.60$ for Module 4.  

Figure 83. Radial profiles of sector averaged normalized tangential RMS velocity for Module 3.  

Figure 84. Radial profiles of sector averaged normalized tangential RMS velocity for Module 4.  

Figure 85. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 0$ deg for Module 3.  

Figure 86. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 0$ deg for Module 4.  

Figure 87. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 6$ deg for Module 3.  

Figure 88. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 6$ deg for Module 4.  

Figure 89. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 12$ deg for Module 3.  

Figure 90. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 12$ deg for Module 4.  

Figure 91. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 18$ deg for Module 3.  

Figure 92. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 18$ deg for Module 4.  

Figure 93. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 24$ deg for Module 3.  

Figure 94. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 24$ deg for Module 4.  

Figure 95. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 30$ deg for Module 3.  

Figure 96. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta= 30$ deg for Module 4.
Figure 97. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 0 deg for Module 3 ................................................................. 119
Figure 98. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 0 deg for Module 4 ................................................................. 119
Figure 99. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 6 deg for Module 3 ................................................................. 120
Figure 100. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 6 deg for Module 4 ................................................................. 120
Figure 101. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 12 deg for Module 3 ................................................................. 121
Figure 102. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 12 deg for Module 4 ................................................................. 121
Figure 103. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 18 deg for Module 3 ................................................................. 122
Figure 104. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 18 deg for Module 4 ................................................................. 122
Figure 105. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 24 deg for Module 3 ................................................................. 123
Figure 106. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 24 deg for Module 4 ................................................................. 123
Figure 107. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 30 deg for Module 3 ................................................................. 124
Figure 108. Radial profiles of normalized axial RMS velocity vs. x/Dₜₜ, θ = 30 deg for Module 4 ................................................................. 124
Figure 109. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 0 deg for Module 3 ................................................................. 125
Figure 110. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 0 deg for Module 4 ................................................................. 125
Figure 111. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 6 deg for Module 3 ................................................................. 126
Figure 112. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 6 deg for Module 4 ................................................................. 126
Figure 113. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 12 deg for Module 3 ................................................................. 127
Figure 114. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 12 deg for Module 4 ................................................................. 128
Figure 115. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 18 deg for Module 3 ................................................................. 128
Figure 116. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 18 deg for Module 4 ................................................................. 128
Figure 117. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 24 deg for Module 3 ................................................................. 129
Figure 118. Radial profiles of normalized mean tangential velocity vs. x/Dₜₜ, θ = 24 deg for Module 4 ................................................................. 130
Figure 119. Radial profiles of normalized mean tangential velocity vs. \( x/D_h \), \( \theta = 30 \) deg for Module 3. ................................................................. 130
Figure 120. Radial profiles of normalized mean tangential velocity vs. \( x/D_h \), \( \theta = 30 \) deg for Module 4. ................................................................. 131
Figure 121. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 0 \) deg for Module 3. ................................................................................. 132
Figure 122. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 0 \) deg for Module 4. ................................................................................. 132
Figure 123. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 6 \) deg for Module 3. .................................................................................. 133
Figure 124. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 6 \) deg for Module 4. .................................................................................. 133
Figure 125. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 12 \) deg for Module 3. ................................................................. 134
Figure 126. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 12 \) deg for Module 4. ................................................................. 134
Figure 127. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 18 \) deg for Module 3. ................................................................................. 135
Figure 128. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 18 \) deg for Module 4. ................................................................................. 135
Figure 129. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 24 \) deg for Module 3. ................................................................................. 136
Figure 130. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 24 \) deg for Module 4. ................................................................................. 136
Figure 131. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 30 \) deg for Module 3. ................................................................................. 137
Figure 132. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 30 \) deg for Module 4. ................................................................................. 137
Figure 133. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 0.89 \) for Module 3. ................................................................................. 141
Figure 134. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 0.87 \) for Module 4. ................................................................................. 141
Figure 135. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 1.11 \) for Module 3. ................................................................................. 142
Figure 136. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 1.06 \) for Module 4. ................................................................................. 142
Figure 137. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 1.32 \) for Module 3. ................................................................................. 143
Figure 138. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 1.32 \) for Module 4. ................................................................................. 143
Figure 139. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 1.74 \) for Module 3. ................................................................................. 144
Figure 140. Radial profiles of normalized mean CH\(_4\) concentration vs. \( \theta \), \( x/D_h = 1.63 \) for Module 4. ................................................................................. 144
Figure 141. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.17$ for Module 3. ................................................................................................................ 145
Figure 142. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.02$ for Module 4. ................................................................................................................ 145
Figure 143. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.60$ for Module 3. ................................................................................................................ 146
Figure 144. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.21$ for Module 4. ................................................................................................................ 146
Figure 145. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=3.02$ for Module 3. ................................................................................................................ 147
Figure 146. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.60$ for Module 4. ................................................................................................................ 147
Figure 147. Radial profiles of sector averaged normalized mean CH$_4$ concentration for Module 3. ................................................................................................................ 148
Figure 148. Radial profiles of sector averaged normalized mean CH$_4$ concentration for Module 4. ................................................................................................................ 148
Figure 149. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=0.89$ for Module 3. ................................................................................................................ 150
Figure 150. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=0.87$ for Module 4. ................................................................................................................ 150
Figure 151. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=1.11$ for Module 3. ................................................................................................................ 151
Figure 152. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=1.06$ for Module 4. ................................................................................................................ 151
Figure 153. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=1.32$ for Module 3. ................................................................................................................ 152
Figure 154. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=1.25$ for Module 4. ................................................................................................................ 152
Figure 155. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=1.74$ for Module 3. ................................................................................................................ 153
Figure 156. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=1.63$ for Module 4. ................................................................................................................ 153
Figure 157. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=2.17$ for Module 3. ................................................................................................................ 154
Figure 158. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=2.02$ for Module 4. ................................................................................................................ 154
Figure 159. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=2.60$ for Module 3. ................................................................................................................ 155
Figure 160. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=2.21$ for Module 4. ................................................................................................................ 155
Figure 161. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=3.02$ for Module 3. ................................................................................................................ 156
Figure 162. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h=2.60$ for Module 4. ................................................................................................................ 156
Figure 163. Radial profiles of sector averaged normalized RMS CH$_4$ concentration for Module 3. ................................................................. 157
Figure 164. Radial profiles of sector averaged normalized RMS CH$_4$ concentration for Module 4. ................................................................. 157
Figure 165. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 0 deg. for Module 3. ................................................................. 160
Figure 166. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 0 deg. for Module 4. ................................................................. 160
Figure 167. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 6 deg. for Module 3. ................................................................. 161
Figure 168. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 6 deg. for Module 4. ................................................................. 161
Figure 169. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 12 deg. for Module 3. ................................................................. 162
Figure 170. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 12 deg. for Module 4. ................................................................. 162
Figure 171. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 18 deg. for Module 3. ................................................................. 163
Figure 172. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 18 deg. for Module 4. ................................................................. 163
Figure 173. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 24 deg. for Module 3. ................................................................. 164
Figure 174. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 24 deg. for Module 4. ................................................................. 164
Figure 175. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 30 deg. for Module 3. ................................................................. 165
Figure 176. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_h$, $\theta$ = 30 deg. for Module 4. ................................................................. 165
Figure 177. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 0 deg. for Module 3. ................................................................. 167
Figure 178. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 0 deg. for Module 4. ................................................................. 168
Figure 179. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 6 deg. for Module 3. ................................................................. 168
Figure 180. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 6 deg. for Module 4. ................................................................. 168
Figure 181. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 12 deg. for Module 3. ................................................................. 169
Figure 182. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 12 deg. for Module 4. ................................................................. 170
Figure 183. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 18 deg. for Module 3. ................................................................. 170
Figure 184. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 18 deg. for Module 4. ................................................................. 171
Figure 185. Radial profiles of normalized RMS CH₄ concentration vs. x/D₇, θ = 24 deg. for Module 3. .......................................................................................................... 171
Figure 186. Radial profiles of normalized RMS CH₄ concentration vs. x/D₇, θ = 24 deg. for Module 4. .......................................................................................................... 172
Figure 187. Radial profiles of normalized RMS CH₄ concentration vs. x/D₇, θ = 30 deg. for Module 3. .......................................................................................................... 172
Figure 188. Radial profiles of normalized RMS CH₄ concentration vs. x/D₇, θ = 30 deg. for Module 4. .......................................................................................................... 173
Figure 189. Unmixedness at θ= 0 deg., x/D₇= 0.89 for Module 3 and x/D₇= 0.87 for Module 4. ................................................................................................................ 174
Figure 190. Unmixedness at θ= 0 deg., x/D₇= 1.74 for Module 3 and x/D₇= 1.63 for Module 4. ................................................................................................................ 175
Figure 191. Unmixedness at θ= 0 deg., x/D₇= 2.60 for Module 3 and x/D₇= 2.60 for Module 4. ................................................................................................................ 176
Figure 192. Sector averaged unmixedness at x/D₇= 0.89 for Module 3 and x/D₇= 0.87 for Module 4. ................................................................................................................ 177
Figure 193. Sector averaged unmixedness at x/D₇= 1.74 for Module 3 and x/D₇= 1.63 for Module 4. ................................................................................................................ 178
Figure 194. Sector averaged unmixedness at x/D₇= 2.60 for Module 3 and x/D₇= 2.60 for Module 4. ................................................................................................................ 178
Figure 195. Axial velocity spectrum vs. x/Dₗ for Module 3, θ = 0 deg........................... 181
Figure 196. Axial velocity spectrum vs. x/Dₗ for Module 4, θ = 0 deg........................... 182
Figure 197. Axial velocity spectrum vs. x/Dₗ for Module 3, θ = 6 deg.......................... 183
Figure 198. Axial velocity spectrum vs. x/Dₗ for Module 4, θ = 6 deg.......................... 184
Figure 199. Axial velocity spectrum vs. x/Dₗ for Module 3, θ = 12 deg........................ 185
Figure 200. Axial velocity spectrum vs. x/Dₗ for Module 4, θ = 12 deg........................ 186
Figure 201. Axial velocity spectrum vs. x/Dₗ for Module 3, θ = 18 deg........................ 187
Figure 202. Axial velocity spectrum vs. x/Dₗ for Module 4, θ = 18 deg........................ 188
Figure 203. Axial velocity spectrum vs. x/Dₗ for Module 3, θ = 24 deg........................ 189
Figure 204. Axial velocity spectrum vs. x/Dₗ for Module 4, θ = 24 deg........................ 190
Figure 205. Axial velocity spectrum vs. x/Dₗ for Module 3, θ = 30 deg........................ 191
Figure 206. Axial velocity spectrum vs. x/Dₗ for Module 4, θ = 30 deg........................ 192
Figure 207. Tangential velocity spectrum vs. x/Dₗ for Module 3, θ = 0 deg.................... 193
Figure 208. Tangential velocity spectrum vs. x/Dₗ for Module 4, θ = 0 deg.................... 194
Figure 209. Tangential velocity spectrum vs. x/Dₗ for Module 3, θ = 6 deg.................... 195
Figure 210. Tangential velocity spectrum vs. x/Dₗ for Module 4, θ = 6 deg.................... 196
Figure 211. Tangential velocity spectrum vs. x/Dₗ for Module 3, θ = 12 deg................... 197
Figure 212. Tangential velocity spectrum vs. x/Dₗ for Module 4, θ = 12 deg................... 198
Figure 213. Tangential velocity spectrum vs. x/Dₗ for Module 3, θ = 18 deg................... 199
Figure 214. Tangential velocity spectrum vs. x/Dₗ for Module 4, θ = 18 deg................... 200
Figure 215. Tangential velocity spectrum vs. x/Dₗ for Module 3, θ = 24 deg................... 201
Figure 216. Tangential velocity spectrum vs. x/Dₗ for Module 4, θ = 24 deg................... 202
Figure 217. Tangential velocity spectrum vs. x/Dₗ for Module 3, θ = 30 deg................... 203
Figure 218. Tangential velocity spectrum vs. x/Dₗ for Module 4, θ = 30 deg................... 204
Figure 219. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 0$ deg., $r/R = 0.085$.

Figure 220. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 0$ deg., $r/R = 0.085$.

Figure 221. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 0$ deg., $r/R = 0.51$.

Figure 222. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 0$ deg., $r/R = 0.51$.

Figure 223. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 0$ deg., $r/R = 0.96$.

Figure 224. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 0$ deg., $r/R = 0.96$.

Figure 225. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 6$ deg., $r/R = 0.085$.

Figure 226. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 6$ deg., $r/R = 0.085$.

Figure 227. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 6$ deg., $r/R = 0.51$.

Figure 228. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 6$ deg., $r/R = 0.51$.

Figure 229. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 6$ deg., $r/R = 0.96$.

Figure 230. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 6$ deg., $r/R = 0.96$.

Figure 231. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.085$.

Figure 232. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.085$.

Figure 233. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.51$.

Figure 234. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.51$.

Figure 235. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.96$.

Figure 236. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.96$.

Figure 237. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 18$ deg., $r/R = 0.085$.

Figure 238. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 18$ deg., $r/R = 0.085$.

Figure 239. CH$_4$ concentration spectrum for Module 3 vs. $x/D_h$ at $\theta = 18$ deg., $r/R = 0.51$.

Figure 240. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 18$ deg., $r/R = 0.51$. 
Figure 241. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 18 deg., r/R= 0.96.
................................................................................................................................. 229
Figure 242. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 18 deg., r/R= 0.96.
................................................................................................................................. 230
Figure 243. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 24 deg., r/R= 0.085 ........................................................................................................................ 231
Figure 244. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 24 deg., r/R= 0.085 ........................................................................................................................ 232
Figure 245. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 24 deg., r/R= 0.51.
................................................................................................................................. 233
Figure 246. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 24 deg., r/R= 0.51.
................................................................................................................................. 234
Figure 247. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 24 deg., r/R= 0.96.
................................................................................................................................. 235
Figure 248. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 24 deg., r/R= 0.96.
................................................................................................................................. 236
Figure 249. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 30 deg., r/R= 0.085 ........................................................................................................................ 237
Figure 250. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 30 deg., r/R= 0.085 ........................................................................................................................ 238
Figure 251. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 30 deg., r/R= 0.51.
................................................................................................................................. 239
Figure 252. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 30 deg., r/R= 0.51.
................................................................................................................................. 240
Figure 253. CH4 concentration spectrum for Module 3 vs. x/Dh at θ= 30 deg., r/R= 0.96.
................................................................................................................................. 241
Figure 254. CH4 concentration spectrum for Module 4 vs. x/Dh at θ= 30 deg., r/R= 0.96.
................................................................................................................................. 242
Figure 255. Mean axial velocity at x/Dh= 0.87 for Module 4 with ± 4.9% error bar. .... 253
Figure 256. Mean tangential velocity at x/Dh= 0.87 for Module 4 with ± 4.9% error bar.
................................................................................................................................. 253
Figure 257. Mean axial velocity at x/Dh= 2.60 for Module 4 with ± 4.9% error bar. ... 254
Figure 258. Mean tangential velocity at x/Dh= 2.60 for Module 4 with ± 4.9% error bar.
................................................................................................................................. 254
LIST OF TABLES

Table 1. Geometric parameters of swirler nozzles........................................................... 39
Table 2. Geometric parameters of swirl vanes.................................................................. 40
Table 3. LDV parameters (see Figure 7). ........................................................................ 47
Table 4. Axial locations for data collection..................................................................... 68
LIST OF SYMBOLS

a mean particle diameter, \( \mu \text{m} \)
C methane concentration measured by concentration probe
\( C_f \) methane concentration in methane/air mixture at fuel injection holes
\( c_v \) length of swirl vane along chord line, mm
\( d_f \) fringe spacing, \( \mu \text{m} \)
\( d_m \) probe volume diameter, mm
\( l_m \) probe volume length, mm
\( D_a \) diameter of receiving optics lens
\( D_{e2} \) diameter of laser beams, mm
G particle scattering parameter
\( f \) focal length of LDV optics, mm
\( f_k \) frequency of Kolmogorov eddy fluctuation, Hz
\( f_m \) frequency of integral scale eddy fluctuation, Hz
\( h_v \) height of swirl vane from leading edge to trailing edge, mm
\( L \) length of absorption path in concentration probe, mm
\( l_{camber} \) length of swirl vane along camber line, mm
\( P_L \) power in each laser beam of LDV, watts
\( P_o \) reference pressure for concentration measurements, atm
\( P_{total} \) total pressure of sample for concentration measurements, atm
\( R \) universal gas constant, \( \text{(atm cm}^3\text{/mol K)} \)
\( r_a \) focal length of receiving optics lens, mm
SNR signal to noise ratio, dimensionless
T temperature, K
\( t_{max} \) maximum thickness of swirl vane, mm
\( U_n \) Uncertainty of methane concentration measurements, percent
\( V \) velocity, m/s
\( V_{bulk} \) bulk velocity, m/s
\( V_i \) visibility of particles
\( \chi \) molar concentration
\( \Delta f \) bandwidth of signal, MHz
\( \varepsilon \) decadic molar extinction coefficient
\( \phi \) equivalence ratio, dimensionless
\( \kappa \) half angle between laser beams, degrees
\( \eta_k \) size of Kolmogorov eddies, mm
\( \eta_{q} \) quantum efficiency of photodetector, dimensionless
\( \lambda \) wavelength of laser light, nm
\( \theta \) angle of module orientation, degrees
\( \tau_{IR} \) infrared transmittance of the sample
INTRODUCTION

In the combustion processes of gas turbines, extensive research has been done in an effort to minimize certain chemical species in the exhaust gases. These chemical species are sources of pollution in the atmosphere, and thus are an undesirable result of the combustion process.

Two chemical species that have been the focus of a great deal of effort are nitric oxide (NO) and nitrogen dioxide (NO₂), collectively referred to as NOₓ. The importance of minimizing NOₓ production is discussed by Seinfeld [1], and stems largely from the effect that NOₓ has on ozone molecules in the atmosphere. Seinfeld [1] discussed the destruction of ozone by NOₓ, which is the most important destruction process for ozone molecules, and is given by Equations (1) and (2) below:

\[
O + NO₂ \rightleftharpoons NO + O₂
\]  
\[
NO + O₃ \rightleftharpoons NO₂ + O₂
\]

The monatomic oxygen present in (1) results from the dissociation of an ozone molecule due to interaction with ultraviolet radiation, as ozone absorbs radiation strongly in the ultraviolet range of wavelengths (240 to 320 nm). This monatomic oxygen would then recombine with diatomic oxygen to form additional ozone by:

\[
O + O₂ + M \rightleftharpoons O₃ + M
\]

where M is any third body in the chemical interaction. However, as can be seen from Equation (1), the presence of NO₂ converts the monatomic oxygen to diatomic oxygen and thus reduces the generation of ozone by Equation (3). In addition, the presence of NO converts ozone to diatomic oxygen by Equation (2). Thus, by Equations (1) and (2),
NO\textsubscript{x} reduces the amount of ozone in the atmosphere and in so doing reduces the benefits of ultraviolet light absorption by ozone molecules. Seinfeld [1] discusses how NO\textsubscript{x} is principally generated by combustion processes (such as those in gas turbines), and hence it is important to understand the fundamental aspects of NO\textsubscript{x} formation in gas turbine combustion processes and what means may be used to minimize NO\textsubscript{x} formation.

**Background**

The formation of NO\textsubscript{x} in combustion reactions has been studied extensively, particularly with applications towards flames used in gas turbines. There are two mechanisms which lead to the formation of nitric oxide, the first of which is the thermal mechanism. The thermal mechanism of NO formation was first proposed by Zeldovich, and consists of the following reactions:

\[
\begin{align*}
O+N_2 & \rightleftharpoons NO+N \\
N+O_2 & \rightleftharpoons NO+O
\end{align*}
\]

With the formation of NO, NO\textsubscript{2} may be formed by the following reaction:

\[
\begin{align*}
NO+HO_2 & \rightleftharpoons NO_2+OH \quad \text{(formation)} \\
\end{align*}
\]

Hori et al. [2] studied the process of NO conversion to NO\textsubscript{2} by Equation (6) in detail. They examined the formation of NO\textsubscript{2} from NO by mixing hot combustion gases with cool air with low levels of various hydrocarbon fuels. The combustion gases were at approximately 1400 K while the cool air was at ambient conditions. Their results showed that even small quantities of fuel in the exhaust gases can lead to a large portion of the
NO\textsubscript{x} being NO\textsubscript{2} by Equation (6). For C\textsubscript{3}H\textsubscript{8} at 40 ppm in the cool air being added to the exhaust gases, the percentage of NO\textsubscript{2} in the NO\textsubscript{x} increased from 24 percent to 90 percent. For methane, they examined equivalence ratios ranging from 0.76 to 1.2, with the maximum levels of NO\textsubscript{2} and NO\textsubscript{x} occurring at \(\phi \approx 1.0\). The amount of fuel that was required to be added in order to bring the percentage of NO\textsubscript{2} to nearly 100 percent of the NO\textsubscript{x} varied with equivalence ratio, with the maximum being at \(\phi \approx 1.0\). In all cases, an increase of fuel in the cool air lead to a large increase in the NO\textsubscript{2} found in the NO\textsubscript{x}. It should be noted that the levels of NO\textsubscript{x} did not vary with the amount of fuel added.

Chemical kinetic calculations done by Hori et al. [2] showed that reaction (6) was the primary mechanism for the conversion of NO into NO\textsubscript{2}, and that this reaction was promoted strongly by the use of fuels that readily decompose to form species which can lead to formation of HO\textsubscript{2}. Their chemical kinetic calculations showed that, for a temperature of 1000 K and an initial concentration of 10 ppm of NO, hydrocarbon fuels such as C\textsubscript{3}H\textsubscript{8}, C\textsubscript{2}H\textsubscript{4}, and C\textsubscript{2}H\textsubscript{6} would promote the formation of HO\textsubscript{2} and thus NO\textsubscript{2} in the exhaust gases the most. CH\textsubscript{4} did not promote the formation of NO\textsubscript{2} as significantly. One important result of their work was to determine that the conversion of NO to NO\textsubscript{2} was heavily dependent on the temperature of the reaction, and that the temperature at which NO\textsubscript{2} formed most quickly varied with each hydrocarbon fuel. In their experiment, though the exhaust gases were at approximately 1400 K, NO conversion to NO\textsubscript{2} was found to occur at temperatures as low as 650 K with hydrocarbons present.

The activation energy of Equation (4) is 315 kJ/mole, which is considerably greater than the activation energy of many combustion reactions involving hydrocarbon fuels (approximately 160 kJ/mole) [3,4]. The activation energy of Equation (5) is
considerably less, equal to 26 kJ/mole [4]. This difference of activation energies means that the reaction rate of Equation (4) is much slower than that of combustion reactions. Reactions (4) and (5) are governed by an equation of the following form:

\[ k \approx \exp \left( -\frac{E_a}{RT} \right) \quad (8) \]

Where \( k \) is the reaction rate constant, \( E_a \) is the activation energy of the reaction, \( R \) is the gas constant, and \( T \) is the temperature. This mechanism is strongly dependent on the flame temperature, as can be seen by the temperature quantity in the exponent, and hence is referred to as the thermal mechanism. Glassman [4] discussed the fact that, due to the activation energy of reaction (4) being much higher than that of combustion reactions, the formation of NO by the thermal mechanism is heavily dependent on temperature. As previously mentioned, the formation of NO leads to the formation of NO\(_2\) by Equation (3). The fact that NO\(_x\) formation is related to flame temperature suggests that in lean flames (which are commonly used in modern gas turbines), the areas of greatest NO\(_x\) formation will be the regions that have equivalence ratios larger than the average equivalence ratio for the entire flame. These regions, which are still fuel lean, will have a larger temperature due to the larger equivalence ratio, which in turn will lead to greater NO\(_x\) formation.

The second method of NO\(_x\) formation is the prompt NO\(_x\) mechanism. This mechanism was proposed by Fenimore [5] and consists of the following process:

\[ \text{CH} + \text{N}_2 \rightleftharpoons \text{HCN} + \text{N} \quad (9) \]

\[ \text{C}_2 + \text{N}_2 \rightleftharpoons 2\text{CN} \quad (10) \]

The N atoms formed in (9) could then form NO from reaction (5), and NO\(_2\) could form from reaction (6). Measurements have been carried out on flat flame burners, and have
been observed most commonly in fuel rich hydrocarbon flames. Results have shown that the concentration of prompt NOx in methane flames can increase from nearly zero ppm in fuel lean flames ($\phi \approx 0.7$) to approximately 40 ppm in fuel rich flames ($\phi \approx 1.3$). Data collected has shown that the activation energy required for the prompt NOx mechanism to be on the order of 50 to 60 kJ/mole. This lower activation energy leads to the prompt NOx mechanism having a much faster reaction rate (hence it is called prompt NOx) than the thermal mechanism [4]. Fenimore speculated that reactions (9) and (10) could occur in flames which posses hydrocarbon fuels, as can be seen by the CH term in Equation (9). The fact that the concentration of hydrocarbon fuels contributes to this reaction suggests that the prompt NOx mechanism will indeed be more prevalent in fuel rich flames [5]. For fuel rich flames, the equivalence ratio is greater than one, and thus the temperature will be lower than if the fuel and air were mixed in stoichiometric proportions. This lower flame temperature means that formation of NOx by the thermal mechanism can be expected to be negligible compared to the NOx formed by the prompt mechanism. However, since gas turbine flames are usually fuel lean, the prompt mechanism is not likely to be significant compared to the thermal mechanism. As discussed in Glassman [4], the thermal mechanism can be controlled through reduction of flame temperature and residence time. Reducing regions that have equivalence ratios larger than the average value is a means of eliminating hot spots, thus reducing NOx formation in gas turbine combustors. In addition, a velocity field which limits the residence time of the reacting species in the reaction zone will also promote lower concentrations of NOx.

Regions that would lead to high NOx formation due to larger equivalence ratios can be reduced through complete mixing of the fuel and air, and the velocity of the flow
field has important implications to the mixing of the reacting species. The free shear between regions with different mean velocities can create large values of RMS velocity, which will promote mixing of the fuel and air. In addition to influencing the RMS velocity, the mean velocity of the flow field determines the residence time of the reacting species, which is an important consideration since various components of the thermal and prompt mechanisms have different reaction rates. Thus, both the velocity and concentration fields of a flow are important with regards to the formation of NO\textsubscript{x}.

**Previous Work**

A significant amount of work has been done by a number of researchers into the formation of NO\textsubscript{x} under various conditions, and how NO\textsubscript{x} formation might be reduced. Steele *et al.* [6] studied the effect of various parameters (flame temperature, pressure, residence time, inlet temperature) on the formation of NO\textsubscript{x} under lean premixed combustion conditions. This work was done in two different atmospheric jet-stirred reactors with air as the oxidizer burning with various fuels in an effort to examine the fundamental aspects of NO\textsubscript{x} formation and the effects of various parameters such as temperature, pressure, and fuel species. For both reactors, the air and fuel were premixed in lean proportions prior to entering the reaction zone so that no mixing took place in the reaction zone. One of the reactors had a single center premixed fuel/air jet, while the second had eight diverging premixed fuel/air jets. The reason for the two configurations was to study the effects of inlet configuration on NO\textsubscript{x} formation. Due to the fact that the mixture was fuel lean, there was excess oxygen present in the exhaust gases. However, the molar concentration of oxygen will vary from one set of results to the next. Hence,
the results were corrected to a 15% O$_2$ dry basis. The results being on a dry basis simply means that the water formed by the combustion reaction was removed, as described in Turns [3]. Correcting to a 15% O$_2$ basis means that the mole fraction of the NO$_x$ in the exhaust gases was adjusted to correspond to what it would be if the molar concentration of oxygen in the exhaust gases were 15%. Correcting the results to 15% O$_2$ allows for easy comparison between the results of different experiments, which may have different mixtures and dilutions. The equation for normalizing the NO$_x$ concentration to a 15% O$_2$ basis is given by Equation (11):

$$\chi_{15\%} = \frac{\chi \cdot N_{\text{mix}}}{N_{\text{mix, 15\%}}}$$  \hspace{1cm} (11)

where $\chi$ is the mole fraction of NO$_x$ measured in the exhaust gases, $N_{\text{mix}}$ is the total number of moles of all chemical species in the measured sample, $N_{\text{mix, 15\%}}$ is the total number of moles of all chemical species at 15% O$_2$, and $\chi_{15\%}$ is the calculated mole fraction of the NO$_x$ at 15% O$_2$. The data collected from the two reactors in the work of Steele et al. [6] was for a mean equivalence ratio ranging from 0.56 to 0.71. Their results showed that there was no change in the ppm of NO$_x$ between the two inlet arrangements. However, other parameters studied did have an effect on NO$_x$ formation, such as the flame temperature, which depends on the equivalence ratio $\phi$.

When Steele et al. [6] examined the effects of temperature on NO$_x$ formation, the residence time of the reacting species kept at 3.5 ms under lean premixed conditions. They examined NO$_x$ levels generated using methane, propane, ethylene, and hydrogen/carbon monoxide as the fuel. Their results were taken over a temperature range
from approximately 1500 K to 1800 K. The levels of NO\textsubscript{x} formed at 1500 K were approximately 1.5 ppm for all four fuels. As the temperature increased to 1800 K, the NO\textsubscript{x} levels generated by the methane flame increased to 4 ppm while the NO\textsubscript{x} levels from the propane flame increased to 7 ppm. The NO\textsubscript{x} levels from the hydrogen/carbon monoxide and ethylene flames were approximately 5 and 6 ppm, respectively. The work of Steele \textit{et al.} [6] showed that the difference in NO\textsubscript{x} levels between the various fuels increased with increasing flame temperature, particularly above 1700 K. From the raw data given in the appendix of their paper, NO\textsubscript{x} concentrations can be seen to increase in an exponential manner with temperature, which is consistent with the dependence of the thermal mechanism on temperature. However, the effects of unmixedness between the fuel and air were not analyzed in this experiment. As previously discussed, the mixing of fuel and air can have a significant impact on NO\textsubscript{x} formation. Since the flames investigated by Steele \textit{et al.} were fuel lean, the prompt mechanism is not expected to have been significant in the NO\textsubscript{x} generated.

Barnes and Mellor [7] used a numerical technique called a characteristic time model (CTM) to compute the sensitivity of NO\textsubscript{x} emissions to fuel/air unmixedness in the reaction zone. They used an unmixedness parameter that is calculated by dividing the standard deviation of the equivalence ratio by the time averaged equivalence ratio as given by Equation (12):

\[
s = \frac{\sigma_\phi}{\phi_{ave}} \tag{12}
\]

where \(s\) is the unmixedness parameter, \(\sigma_\phi\) is the standard deviation of the equivalence ratio, and \(\phi_{ave}\) is the mean equivalence ratio. The type of flame that was modeled was a lean premixed flame emanating from a combustor which had swirl vanes upstream of the
flame zone and a pilot nozzle along its centerline. As a result of the swirl vanes, there was a recirculation zone present in the flow. The model that was developed assumed that the main fuel/air mixture burned at an equivalence ratio less than one, and that this region of lean combustion surrounded the recirculation zone. Inside the recirculation zone, the fuel coming from the pilot nozzle burned with air near an equivalence ratio of one. One of the most important conclusions from this work is that turbulent eddies with equivalence ratios greater than the time averaged value contribute the most towards high concentrations of NO\textsubscript{x}. With a time averaged value of $\phi = 0.6$, their numerical results predicted that approximately seventy percent of the NO\textsubscript{x} formation will be from eddies with $\phi > 0.6$. In this work, NO\textsubscript{x} formation was quantified by the use of an emission index (grams of NO\textsubscript{x} formed per kilogram of fuel burned). Their results also showed that for an unmixedness parameter of $s = 0.15$, NO\textsubscript{x} production is 15% greater than for the same fuel flow rate under conditions in which the fuel and air are perfectly mixed. These numerical results further validate the importance of the thermal theory in that the greatest NO\textsubscript{x} formation is seen to come from relatively fuel rich eddies.

Barnes and Mellor [8] compared the predictions of their CTM to experimental data in an effort to quantify the effects of unmixedness in operational gas turbines and estimate the unmixedness of the fuel and air in the reaction zone, where unmixedness for their research was defined by Equation (12). The data were collected from the exhaust gases at the exhaust plane of a lean premixed gas turbine combustor under fired conditions, and consisted of the NO\textsubscript{x} and CO emissions. CO emissions were measured so that the effect of unmixedness on them as well as on NO\textsubscript{x} emissions could be analyzed as CO is also a pollutant of concern. The exhaust gases were sampled simultaneously over
the entire exhaust plane and analyzed. The NOx data gathered represented the area average value of NOx for the exhaust plane. Because of this area averaging of the exhaust gases, it was not possible to examine the fluctuations of NOx concentration at different points across the exhaust plane, or to examine the temporal variations of NOx at any point in the exhaust plane. The equivalence ratio was varied from 0.5 to 0.8. They compared their test data to the CTM for various values of unmixedness in the reaction zone. They plotted their test data along with CTM data, and found that the test data plot collapsed onto the CTM data plot for an unmixedness value of \( s = 0.35 \) very well.

However, because they were unable to gather fuel concentration data from the reaction zone, they cannot confirm this result. The fact that the measurements were taken from the exhaust gases also may lead to inaccuracy since the levels of NOx and CO in the exhaust gases may be different than those in the reaction zone due to changing chemical equilibrium and the oxidation of CO. As previously mentioned, it was desired to determine the effects of unmixedness on CO as well as NOx.

Fric [9] also took measurements of the unmixedness of a fuel/air mixture and correlated its effect on NOx emissions, although the unmixedness parameter used by Fric was different than that used by Barnes and Mellor [7,8]. The unmixedness parameter used by Fric was calculated as follows:

\[
U = \frac{c'^2}{(c_{\text{ave}} (1-c_{\text{ave}}))}
\]  

(13)

where \( U \) is the unmixedness parameter, \( c'^2 \) is the variance of the fuel concentration fluctuations and \( c_{\text{ave}} \) is the time averaged fuel concentration. A coflow jet arrangement was used to study four different cases, varying from purely premixed to purely unmixed flow, with a mean equivalence ratio of 0.5 in all cases and at atmospheric pressure. It
was shown that for levels of unmixedness on the order of 10%, NO\textsubscript{x} production was approximately double that of the case in which there is no unmixedness. One aspect of fuel/air mixing that was not addressed by Fric [9] was mixing in regions other than the reaction zone, and the potential importance of this mixing is a significant motivation for the work proposed here.

Mongia et al. [10] used an unmixedness parameter defined as in Equation 10 in the same way as Fric [9] to quantify the effect of unmixedness at different equivalence ratios and different pressures in a lean premixed burner in which methane mixed with air. Their results qualitatively confirmed the results of Fric [9] with regards to NO\textsubscript{x} production versus unmixedness values, and also showed that for low levels of unmixedness ($U \approx 0.0002$), the production of NO\textsubscript{x} is independent of pressure. However, they found that for higher levels of unmixedness, NO\textsubscript{x} production increases with pressure. Their data showed that for typical gas turbine conditions ($T= 1800$ K, $\phi = 0.5$), the NO\textsubscript{x} produced at 20 atm is approximately three times larger than for 1 atm with an unmixedness value of $U = 0.001$ at both 1 atm and 20 atm. This experiment did not incorporate the swirled flow that many modern gas turbines do and the examination of the development of the mixing profile of a swirling flow is important to understanding the formation of NO\textsubscript{x} in gas turbines.

Frey et al. [11] experimentally investigated the effect of the length of the premixed and turbulence on the mixing of fuel into air in a gas turbine premixer. The premixer they examined had a length of 8.89 cm and had 16 spray bars located downstream of the swirl vanes, which had a swirl angle of 48°. The spray bars consisted of cylindrical bars with multiple holes in them through which the fuel flowed into the
swirling air. The fuel was simulated using 1 μm size aluminum oxide particles. The concentration of the simulated fuel was measured using a Mie scattering imaging technique, which used a pulsed laser to illuminate the seeder particles in the air in the premixer. Based on the intensity of the scattered light, the concentration of the particles can be calculated. This allows for examination of the concentration of fuel across an entire plane of the airflow. Frey et al. [11] used this Mie scattering imaging technique to examine the concentration field at the exit of the premixer. The turbulence, which was measured by hot wire anemometry, was created by the use of an inlet grid. Their experimental setup used two different inlet grids, which generated turbulence levels of 2.5% and 8%, with the baseline case being no grid and therefore laminar flow at the entrance plane of the premixer.

It was found that the increased turbulence from these grids reduced the unmixedness of the flow, but not significantly. For their baseline case (no inlet grids), the value of the unmixedness parameter (defined the same as Barnes and Mellor [7]) was \( s = 0.29 \). With the inlet grids in place, this improved only to 0.27 for the 2.5% turbulence level and to 0.23 for the 8% turbulence level. They speculated that the turbulence due to the wakes of the swirl vanes and the spray bars were sufficiently strong such that the turbulence due to the inlet grids was not significant to the mixing of the fuel and air. However, as the free stream turbulence did have an effect on the unmixedness of the flow (and therefore would have an effect on the NO\(_x\) formed from combustion of such a flow), analysis of the turbulence of a flow field could yield insight into the mixing process of fuel and air in a gas turbine mixer. Frey et al. [11] did not present any power spectrum data of the turbulence they measured, and analyzing the power spectrum of the
The turbulence of a mixing flow will help to illustrate the contribution of free stream turbulence to the mixing of fuel and air.

More significant reduction in unmixedness observed by Frey et al. [11] was due to increased premixer length. The two different extensions of 2.5 cm and 5 cm increased the length of the mixing channel by 57% and 116%, respectively. The 2.5 cm extension reduced the unmixedness from $s = 0.29$ to 0.23, and the 5 cm extension reduced the unmixedness to 0.19. The increased residence time of the fuel and air in the premixer obviously will promote further mixing, and the work done by Frey et al. [11] highlights the importance of this parameter. Their work, however, did not examine the velocity field of the test hardware. The velocity field has great importance to the mixing of the fuel and air, and this was discussed in their conclusions. Due to the fact that they used a Mie-scattering imaging technique to measure the concentration of the simulated fuel, they were only able to analyze the concentration profile at the exit of the premixer, and were not able to analyze the development of the mixing profile throughout the length of the premixer. Analysis of the development of the mixture profile along with the velocity profile could yield a greater understanding of the dependence of fuel concentration on various parameters.

Stufflebeam et al. [12] used an acetone fluorescence method to examine the fuel air ratio across the flow fields of premixed nozzles. The concentration of the acetone could be calculated by measuring the intensity of the scattered light, which is similar to the work done by Frey et al. [11]. The acetone was injected both through a pilot nozzle located along the centerline of the flow (this gave an annular cross section to the flow), and through two main lines which supply fuel to the airflow parallel to the direction of
the airflow, and without the use of swirl vanes. The air was seeded with 2% acetone by weight, and the fuel/air momentum flux ratio at the location of fuel (air seeded with acetone) was kept identical to that in an operational gas turbine. For this work, unmixedness was defined as the standard deviation of the fuel/air ratio divided by the average fuel to air ratio, which is the definition given by Equation (12). They showed that, among other parameters the fuel/air ratio was strongly dependent on the geometry of the nozzle. It was illustrated that by varying parameters such as the number of holes through which the fuel is injected and the momentum ratio of the fuel to the air, significant reductions in unmixedness can be realized. Their results showed that by injecting fuel at the upstream end of the pilot nozzle, the fuel/air ratio was largest near the inner wall of the annular geometry. Conversely, injecting the fuel near the downstream end of the pilot nozzle resulted in the fuel/air ratio being largest near the outer wall. These results were taken at the exit of the nozzles. The effect of fuel injection geometry on the development of the concentration profile was not examined.

Acetone laser induced fluorescence (LIF) was also used by Thomsen et al. [13] to determine the effect of the orientation angle of the fuel jet to the flow on mixing between the fuel and air in a lean premixed gas turbine premixer that incorporated swirl vanes. The LIF images taken showed the mixing of the fuel and air along the premixer length, which was 3.5 cm. The fuel was injected through 16 fuel delivery tubes that were located in between the swirl vanes. The swirl vanes themselves were located at the entrance of the swirler. The angle of the fuel jet to the flow was varied from −60° to 60° in increments of 20°. In this experiment, a negative angle means that the fuel is injected against the flow of the air. Analysis of their results showed that an angle of -20° yielded
the most uniform fuel/air mixture (i.e., the smallest levels of unmixedness). Their results also showed that for the case of a 0° fuel injection angle, the mixing of fuel and air was nearly complete prior to the flow entering the reaction zone. This work highlights the importance of fuel injection angle to mixing of fuel and air, and the LIF images taken illustrate the importance of premixer length in swirled flows.

Work has also been done to numerically analyze the mixing of fuel and air in turbulent non-premixed flows. Komori et al. [14] used an unmixedness parameter similar to that used by Barnes and Mellor [6], which they refer to as a segregation parameter. It is defined by Equation (14):

\[ \alpha = \frac{\overline{c_A c_B}}{\overline{c_A}} \times \frac{\overline{c_B}}{\overline{c_B}} \]  

(14)

where \( \overline{c_A} \) is the mean concentration of species A, \( \overline{c_B} \) is the mean concentration of species B, and \( \overline{c_A c_B} \) is the cross correlations between the fluctuation of the concentration of species A and B, and \( \alpha \) is the segregation parameter. Their findings showed that increasing shearing in the flow (such as the free shear caused by a recirculation zone) can significantly improve mixing as evidenced by smaller values of the segregation parameter. Improved mixing will improve combustion by reducing fuel unmixedness and therefore NOx production by the thermal mechanism.

Mori et al. [15] showed that for the lean premixed gas turbine combustor that they examined, a second order Reynolds Stress Model was successful in modeling the concentration of methane across the profile of the flow field. The hardware that they attempted to model was a lean premixed gas turbine combustor incorporating an axial swirler and a pilot nozzle along the centerline of the combustor. The air entered the
combustor at one atmosphere and at ambient temperature by two different paths. Some of the air was injected into the flow along the axis of the combustor by the pilot nozzle (there were swirl vanes inside the pilot nozzle to swirl the air passing through it), while premixed gas pipes located upstream of the swirl vanes injected the fuel/air mixture into the main airflow. The air passing through the gas pipes and swirl vanes enters the combustor at a diagonal angle to the centerline of the combustor. Instead of fuel being used to seed the airflow for concentration measurements, small oil particles were used and their concentration measured by a planar Mie scattering technique, as was done by Frey et al. [11]. The results presented by Mori et al. [15], which consisted of simulated fuel concentration data taken at the exit of the combustor, showed that the second order Reynolds Stress Model correctly predicted the radial profile of mass fraction of fuel to within five to ten percent except at the outer ten percent of the radius. As with other concentration work done, such as by Stufflebeam [12] and Thomsen [13], the data was gathered only at the exit of the test hardware. No data was gathered throughout the mixing region of the hardware, and knowledge of the mixing behavior in this region could lead to insights into the design of better gas turbine mixers.

Some work has been done with regards to the velocity field of a reacting flow by Puri et al. [16]. They used a laser Doppler velocimeter to analyze the axial and tangential velocity components from a lean premixed combustor for an industrial gas turbine. The purpose of this work was to confirm their numerical modeling of the flow field, in which they modeled the velocity fields and the mixing of fuel and air as the flow progressed through a gas turbine combustor. The lean premixed combustor that they examined incorporated a radial swirler upstream of a converging-diverging nozzle section. The
reaction zone was located in the diverging section of the nozzle. The combustor examined could be configured with several different fuel hole patterns and swirler configurations, and atmospheric tests were performed with a concentration probe to determine which arrangement yielded the most complete mixing of fuel and air. The results of combustion tests showed that the configuration that gave the most uniform fuel concentration at the exit of the combustor also had the lowest concentration of NO$_x$, with a NO$_x$ concentration of 4 to 6 ppm at $\phi = 0.68$. Under operational conditions, the amount of NO$_x$ generated was shown to vary between the different configurations (and therefore the different concentration profiles). With less uniform mixing, the levels of NO$_x$ generated were approximately 10% higher. However, the amount of NO$_x$ formed was shown to depend more strongly on the flame temperature. For all configurations, the NO$_x$ concentration was approximately 6 ppm at 1435 K, while at 1655 K the NO$_x$ concentration was approximately 40 ppm. The combustion temperature was varied by changing the temperature of the air entering the combustion section. These results show the importance of both flame temperature and fuel/air mixing in NO$_x$ formation.

Due to the swirling nature of the flow and the flow expansion in the combustor examined by Puri et al. [16], there was a recirculation zone present in the flow field. While the width and length of the recirculation zone was described and its importance to the stability of the flame in their radial swirler was discussed, no detailed information was given as to how the velocity field corresponded to or affected the concentration field of the flow. Numerical modeling had shown that the wakes of the fuel injection tubes resulted in rapid mixing of the fuel and air, but the effect these wakes was not discussed extensively. Axial velocity profiles at various locations throughout the combustor were
given, but none for the tangential velocity component. In addition, no RMS velocity data was given for either the axial or tangential velocity components. Since the flow in gas turbine combustors is a highly turbulent region due to the free shear between velocity layers, the RMS velocity will play an important part in the mixing between fuel and air.

The importance of the RMS velocities to mixing in the free shear layers due to the presence of a recirculation zone was shown by Ahmed et al. [17]. They used a two component (axial and tangential velocity component) argon-ion LDV to measure airflow emanating from an axial dump combustor which had 20 swirl vanes at an angle of 45° and a fuel injector along its centerline. The airflow was seeded with titanium dioxide particles so that the mean velocities as well as the turbulence intensity could be measured. They found that large velocity gradients and turbulence levels are important to the improvement of the mixing of the species, particularly at axial locations much less than one combustor radius downstream. Due to the fact that the flow emanating from the combustor expanded, there was a significant radial component near the exit of the combustor. It was found that the high turbulence of the flow, combined with the impinging of the airflow on the wall of the flow channel, lead to the radial component diminishing at locations less than one combustor radius downstream of the combustor exit. After the dissipation of the radial velocity component, the flow was two-dimensional in nature. Ahmed et al. [17] concluded that confined swirling flows were highly dissipative, particularly in the region near the swirl vanes and that rapid mixing of the flow would be an important consequence of this dissipative behavior.

Much of the work done in regions near swirl vanes or turbine blades has focused on heat transfer phenomenon rather than fuel/air mixing. Camci and Arts [18] studied the
effect of incidence on the flow around a set of swirl vanes, in addition to studying the
effect of mass ejection from the blades on the secondary flow around the vanes. The
focus of this work, and many other papers like it, was to examine the effect of various
parameters on the heat transfer behavior of the vanes. The mass ejection from the vanes
that was studied was for the purposes of film cooling, rather than for providing fuel for a
combustion reaction. In particular, the changing location of the stagnation point of the
flow on the swirl vanes was analyzed. The motivation for studying the effect of
incidence on the flow behavior was the changing incidence of vanes in operational
turbines due to the wakes of vanes at upstream locations. It was found that the ejection of
mass from the vane affected the flow transition and separation within distances of 20% of
the chord length downstream of the mass ejection location. The effect of mass ejection
from vanes is an important consideration in any work which involves mass ejection from
vanes. While the work done by Camci and Arts [18] illustrated the impact of mass
ejection from the vanes on flow turbulence, their work focused on heat transfer and the
flow behavior downstream of the swirl vanes was not analyzed.

Friedrichs et al. [19] also showed that the mass ejection from the vane can
significantly alter the boundary layer flow. This work also focused largely on heat
transfer effects, and the mass being ejected was ejected at an angle of 30° to the surface
of the blade. They found that the mass ejection can significantly affect the losses of the
flow through the vanes. Depending on the inlet Mach number, the flow losses due to
mass ejection varied from 6% to 8% of the total losses. The separation behavior of the
flow was also influenced. Mass ejection upstream of the point of flow separation was
shown to delay the separation, while mass ejection downstream of the separation point
did not alter the flow behavior significantly. Thus, from the work of Friedrichs et al. [19] and Camci and Arts [18], it can be seen that mass ejection from the vanes can significantly affect the flow around the vanes. Hence, mass ejection for the purposes of injecting fuel into the air flow through a gas turbine mixer could also be expected to influence the flow around the swirl vanes, and hence the mixing of the fuel and air.

Such mass ejection would have an impact on the turbulence of flow around such vanes, and since this is the case the spectrum of the turbulence will be important to any effort to understand the behavior of flow emanating from swirl vanes. The importance of the spectrum of turbulence is discussed by Tennekes and Lumley [20]. They discussed how energy is typically imparted to turbulence by large scale structures, such as swirl vanes. However, the dissipation of this energy typically occurs at relatively small scales.

From the above literature discussed, it is clear that the mixing of fuel and air has a significant effect on the emissions from lean swirled flames emanating from gas turbine mixers. Thus, it is desirable to better understand the mixing process in swirling flow through a gas turbine mixer. In order to do this, the development of the velocity and fuel concentration profiles in two gas turbine mixers was analyzed. The two gas turbine mixers had different swirl angles, and the primary purpose of this work was to develop a greater understanding of the effect of swirl vane angle on the velocity field, the mixing of fuel and air, and their implications towards NOx formation.
EXPERIMENTAL METHODS AND SETUP

It has clearly been shown, by Fric [9] and also Barnes and Mellor [7,8] and others, that both the spatial and temporal unmixedness between the fuel and air has strong implications towards NO\textsubscript{x} emissions from lean premixed flames. It has also been shown that the velocity field (both the mean and RMS velocities) has significant effect on the mixing of fuel and air, and that the length of the mixing channel and hardware geometry also can affect the development of the concentration profile. This makes it important to know the concentration and velocity fields of a fuel/air flow in order to better understand the mixing of the fuel and air.

Therefore, a concentration probe was used to examine the mixing of methane into air from two different lean premixed gas turbine mixers in conjunction with the use of a Laser Doppler Velocimeter (LDV) to measure the velocity field (note that the LDV and concentration probe were not used simultaneously). From the concentration probe, both the time averaged and temporal variation in concentration (for the purposes of an FFT analysis) was measured. From the LDV, axial and tangential velocity as well as axial and tangential RMS velocity data was measured. The only significant geometric difference between the gas turbine mixers was the angle of the swirl vanes (45° versus 55°). The swirler nozzle with a 45° angle will be referred to as Module 3, and the swirler nozzle with a 55° angle will be referred to as Module 4, following their nomenclature from Siemens-Westinghouse Power Corporation, which is the designer of the two swirler nozzles examined. The use of these two modules allowed for an examination of the effect of the swirl angle on both the velocity field and concentration field. Table 1 below
shows the relevant geometric parameters of the two gas turbine mixers examined in this work

Table 1. Geometric parameters of swirler nozzles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module 3</th>
<th>Module 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius</td>
<td>47 mm</td>
<td>49.5 mm</td>
</tr>
<tr>
<td>Inner radius</td>
<td>23.5 mm</td>
<td>23.5 mm</td>
</tr>
<tr>
<td>Swirl Angle</td>
<td>45°</td>
<td>55°</td>
</tr>
<tr>
<td>Fuel Injection Profile</td>
<td>Flat</td>
<td>Flat</td>
</tr>
</tbody>
</table>

The concentration and velocity measurements were taken downstream of the swirl vanes throughout the region in which the concentration and velocity profiles of the flow field are changing. The configuration of the test hardware, as well as its relevant dimensions, can be seen in Figure 2 below. The region in which both velocity and concentration measurements will is referred to as the aft shroud. The aft shroud of Module 3 has a hydraulic diameter of 47 mm, and the range over which measurements were taken was 0.89 to 3.02 hydraulic diameters downstream of the trailing edge of the swirl vanes. For the aft shroud of Module 4, the hydraulic diameter is 52 mm and the range over which measurements were taken was 0.87 to 2.60 hydraulic diameters downstream of the trailing edge of the swirl vanes. The distance between the trailing edge of the swirl vanes and the data collection locations will be labeled as x/Dh.
A diagram of a swirl vane and its associated geometric parameters can be seen in Figure 1. The geometric parameters described in Figure 1 are the chord length of the swirl vane \( (c_v) \), the height from the leading edge to the trailing edge \( (h_v) \), the maximum thickness \( (t_{\text{max}}) \), and the length along the camber line of the swirl vane \( (l_{\text{camber}}) \). The value of each of these parameters is listed in Table 2 for both Module 3 and 4.

![Diagram of swirl vane geometric parameters.](image)

**Figure 1. Diagram of swirl vane geometric parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module 3</th>
<th>Module 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_v )</td>
<td>25.4 mm</td>
<td>22.2 mm</td>
</tr>
<tr>
<td>( h_v )</td>
<td>15.9 mm</td>
<td>20.6 mm</td>
</tr>
<tr>
<td>( t_{\text{max}} )</td>
<td>6.4 mm</td>
<td>6.4 mm</td>
</tr>
<tr>
<td>( l_{\text{camber}} )</td>
<td>28.6 mm</td>
<td>28.6 mm</td>
</tr>
</tbody>
</table>

It was intended that \( x/D_t = 2.40 \) would be one of the data collection locations for Module 4, however there was a change in outer diameter in the acrylic aft shroud of
Module 4 at this location. This change in outer diameter resulted in the LDV not being able to receive Doppler signals due to the changing optical properties that accompanied the change in outer diameter at \(x/D_h=2.40\). In order to be able to examine the development of the flow field, it was decided to collect data at \(x/D_h=2.21\) and \(x/D_h=2.60\) in Module 4. These locations differed by only 10 mm from the two most downstream data locations in Module 3, and are the reason that the range of hydraulic diameters over which data was collected differs for Modules 3 and 4.

At the far end of the acrylic tube shown in Figure 2 is a fan motor which draws the airflow through the test rig. The bolt on feed flange shown in Figure 2 is the path through which methane was supplied to the test hardware for concentration measurements. Since it was desired to keep methane concentrations very low to prevent a risk of combustion, the methane was diluted with air, and the momentum flux ratio between the air flowing through the swirler and the air/methane mixture being injected was set to match operational conditions. The methane/air mixture is injected into the airflow through holes in the lower (pressure) side of the swirl vanes.

As previously mentioned, the LDV and the concentration probe were used separately to collect data in this work, and therefore the discussion of their use will be done separately as well.
Figure 2. Test rig with swirler mounted into acrylic tube.
Laser Doppler Velocimeter

In order to allow the lasers of the LDV to pass through the wall of the aft shroud into the airflow, a groove was machined into the aft shroud and a piece of glass inserted into the groove. The glass was covered with an antireflective coating, the purpose of which is to prevent laser light reflections off of the glass from interfering with reception of Doppler signals by the receiving optics. A diagram of the lasers from the LDV entering the aft shroud through the antireflective glass is shown in Figure 3, and Figure 4 shows a diagram of the LDV in relation to the test rig. A picture of the Module 3 mounted into the test rig is shown in Figure 5. The machining of a groove was not necessary for the case of Module 4, as the aft shroud that was designed for it was made of acrylic, and therefore was optically accessible by the LDV.

The LDV was configured to collect Doppler signals in backscatter mode. This was done because the presence of the swirler hub along the centerline of the hardware prevented light signals from being seen by the receiving optics had they been placed on the opposite side of the aft shroud. As can be seen in Figure 4, the receiving optics are mounted onto the LDV and receive Doppler signals generated in the probe volume of the LDV. The directions that the Doppler signals travel in is opposite to the direction that the lasers travel in, hence the term “backscatter”.
Figure 3. Test hardware with lasers passing through antireflective glass.
Figure 4. Diagram of LDV and test rig.
In Figure 5 (a photograph of Module 3), it can be seen that arcs were machined into the leading edge flange of the aft shroud. The purpose for doing this was to allow for the aft shroud to be rotated around its axis and secured at a given angle. This allowed for examination of the axial and tangential profiles at various angles of rotation. By rotating the hardware in the $\theta$ direction, the wakes of the swirl vanes can be analyzed at different angular locations. Each arc machined into the aft shroud encompasses an angle of $45^\circ$. The mounting plate to which the test hardware is bolted has also has $45^\circ$ arcs machined into it. Thus, the test hardware can be rotated to the desired angle and the aft shroud rotated in the opposite direction so as to always keep the antireflective glass window facing the LDV. This was only a problem with Module 3, as it was not completely optically clear, whereas the aft shroud of Module 4 was. A picture of Module 4 mounted in the test rig can be seen below in Figure 6. Data was taken for both modules at the same $\theta$ angles.
In using the concentration probe and the LDV, it is important to consider the spatial and temporal resolution of the data of these two systems. The LDV uses a 100 mm beam spacer with a 250 mm focal length. This gives the following dimensions for the probe volume, shown below in Table 3:

Table 3. LDV parameters (see Figure 7).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_m$</td>
<td>0.655 mm</td>
</tr>
<tr>
<td>$d_m$</td>
<td>0.131 mm</td>
</tr>
<tr>
<td>$d_f$</td>
<td>1.38µm</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>514.5 nm</td>
</tr>
</tbody>
</table>
and \( d_f \) is calculated by:

\[
d_f = \frac{\lambda}{2 \cdot \sin \kappa}
\]  

where \( l_m \) is the length of the probe volume, \( d_m \) is the diameter of the probe volume, \( d_f \) is the fringe spacing, \( \lambda \) is the wavelength of the laser light, and \( \kappa \) is the half angle between the lasers. Once the frequency of a given Doppler burst is known, the velocity of particle which scattered the laser light can be calculated by:

\[
V = F \cdot d_f
\]

where \( F \) is the frequency of the Doppler burst and \( V \) is the velocity of the particle.

A drawing of the laser crossing (the shaded region) is shown below in Figure 7. The LDV has, in previous work, been shown to be capable of collecting data at frequencies more than sufficient for this work. It was desired to collect data at 300 to 500 Hz, and the LDV can easily handle this data rate, provided that the flow is sufficiently seeded so as to generate enough Doppler signals.

![Figure 7. Drawing of laser crossing with dimensions diagramed.](image-url)
Towards the inner annular region (close to the swirler hub) and the outer annular region (close to the wall of the aft shroud) the data is collected at 0.5 mm increments, in an attempt to examine in detail the flow behavior in these regions. For middle area of the annular region between the swirler hub and the aft shroud, the data is taken at 2 mm increments. Since the annular gap for Module 3 is 23.5 mm and 26 mm for Module 4, the probe dimensions above (\(d_m = 0.655 \text{ mm}, l_m = 0.131 \text{ mm}\)) are two orders of magnitude smaller than the annular gap distances, and thus gave sufficient spatial resolution for the work done here. The LDV (schematically shown in Figure 4) is mounted on a three-axis traversing table that allows it to be moved in all three spatial directions. The traversing table is moved by the use of stepper motors, and a digital display of the location of the table in the X, Y, and Z axes ensures that the LDV is precisely positioned.

The implementation of the LDV began with a 30 minute warm up period for the laser. During this warm up period, the electronic equipment which aided in velocity data collection were activated and checked to ensure that they were set properly. This consisted mostly of checking the filter through which the LDV signals passed, and to checking the LabView software used to collect the data.

The purpose of adjusting the data filter was to minimize the presence of noise in the data. In order to do this, the low frequency and the high frequency limit were set, usually to around 1 MHz and 50 MHz, respectively. The reason for this range was that any Doppler signals lower than 1 MHz or higher than 50 MHz would correspond to velocities either lower than 1.3 m/s or greater than 70 m/s. Given that all velocity values observed were in the range of 20 to 30 m/s, signals with a frequency lower than 1 MHz or greater than 50 MHz were obviously noise and thus could be discarded. The use of an
oscilloscope allowed for visual inspection of the signals being received by the LDV, and thus it could be determined if a signal was a Doppler burst due to titanium dioxide particles passing through the laser crossing or simply noise. An example of a Doppler burst resulting from a titanium dioxide particle passing through the laser crossing is shown in Figure 8. A real time histogram display on a data acquisition computer also allowed for visual inspection of the data trend, and when noise was present in the system, it manifested on the histogram as a time varying fluctuation in the shape and size of the histogram. In Figure 9 a typical velocity histogram can be seen. The histogram in Figure 9 is from the tangential velocity data collection of Module 4 and has a mean value of 33.39 m/s. Thus, the oscilloscope, data filter, and the real time histogram helped ensure the accuracy of the data collected. A diagram illustrating the arrangement of the data acquisition hardware can be seen below in Figure 10.

![Figure 8. Typical Doppler burst during velocity data collection.](image-url)
Figure 9. Histogram showing data points clustered around the mean velocity value (33.39 m/s).
Figure 10. Diagram of data acquisition equipment connections.
The LDV data was collected and stored for analysis by LabView software installed on a separate data acquisition computer, connected to the data filter. The LabView software simultaneously recorded the frequency of the Doppler burst (which by Equation (16) yields the velocity of the particles scattering the laser light and thus the velocity of the airflow) and the time between the Doppler bursts. The time between signals was needed so that the power spectra of the velocity data could be analyzed.

The seeding of the airflow entering the module was done by utilizing pressurized air supplied to a manifold containing titanium dioxide powder, as shown in Figure 11.

![Diagram of swirler nozzle with titanium dioxide supply system.](image)

Figure 11. Diagram of swirler nozzle with titanium dioxide supply system.

Also connected to the manifold were several plastic tubes that carried the titanium dioxide powder from the manifold to the inlet of the swirler nozzle. The air coming from the compressor was at 3 to 4 psig. This pressure proved to be sufficient to carry the titanium dioxide powder from the manifold to the swirler nozzle but was not so large as to potentially disturb the inlet velocity profile of the swirler nozzle. The ends of the
plastic tubes were held several inches away from the inlet of the swirler nozzle which was also a precaution against the flow of air and titanium dioxide coming from them disturbing the inlet profile. Another precaution taken with regards to the seeding of the airflow was to cover the fuel injection holes on the pressure side of the swirl vanes with thin transparent tape. This was done to prevent the entrapment of titanium dioxide particles in these holes and thus clogging them. The tape used was chosen because it was thin enough (several thousandths of an inch thick) to minimize any disturbances to the airflow and durable enough not to easily lose adhesion to the swirl vanes. The minimization of disturbance of the flow by the tape was verified through preliminary velocity data taken with the LDV. Several configurations of sealing the fuel injection holes were implemented, including various types of tape (with varying thickness) and varying areas of coverage over the surface of the swirl vanes. It was found that when approximately 40% or more of the swirl vanes were covered by tape, there was a noticeable change in the shape of the velocity profiles. However, with less than 40% of the surface area of the swirl vanes covered, there was no effect on the shape of the velocity profiles. During velocity data collection, only 16% of the surface area of the vanes was covered (just enough to cover the fuel injection holes) and thus the effect of the tape on the flow field was minimized. This tape was removed before collecting concentration data.

Velocity data was collected with the LDV in a systematic way. Data was collected at 7 axial locations along the length of the aft shroud. Each axial location was measured from the upstream end of the aft shroud. This flange was chosen to consistently be the datum for all data collected because it is a convenient location to
measure from. The axial locations at which velocity data was taken from Module 3 were 1, 2, 3, 5, 7, 9, and 11 cm downstream of this flange. In the upstream end of the aft shroud, it was expected that the effect of the wakes from the swirl vanes would affect the airflow, while at the downstream end the wakes would have dissipated. This is why data was collected every 1 cm at the upstream end, and every 2 cm further downstream of the 3 cm location. For Module 4, data was taken from the axial locations of 1, 2, 3, 5, 7, 8, and 10 cm downstream of the flange, due to a change in outer diameter at the 9 cm location, as previously discussed. When fuel concentration data was collected using the concentration probe, data was collected at the same locations for both modules as described for the velocity data.

As previously discussed, data was collected every 0.5 mm along the radius near the inner and outer walls of the annular gap between the swirler hub and the aft shroud so as to allow examination of the behavior of the flow near each wall. In the middle of the annular gap between the two walls, data was collected every 2 mm. Once data had been collected across the entire radius at a particular axial location, the LDV was moved to the next axial location by means of the three axis traversing table it was mounted on. It was only possible to collect axial or tangential data alone. Thus, data collection was done in a one-dimensional manner at all 7 axial locations of interest for one velocity component (axial or tangential) and then the process of data collection was then repeated at all 7 axial locations for the other velocity component.

Once all the axial and tangential velocity data for a particular angular orientation of the module was complete, the next step of data collection was to rotate the module to the next angular orientation and repeat the process of data collection for both the axial
and tangential velocity components. A total of 6 angular locations with 6° separation between them were chosen for data collection. This was because the swirler nozzles had 10 swirl vanes, and therefore each vane would affect a 36° sector of the flow. Analyzing 6 angular locations in this manner yielded an accurate picture of how the wakes of the swirl vanes influence the flow field. For this work, 0° was defined as being the angular orientation in which the leading edges of one set of swirl vanes were horizontal.

Of primary concern with regards to the uncertainty of the LDV data is the signal to noise ratio of the system. The signal to noise ratio (SNR) is given by Equation (17) as:

\[
\text{SNR} = 4 \cdot 10^{11} \frac{\eta q P_L}{\Delta f} \left( \frac{D_a}{r_a} \cdot \frac{D_{e2}}{f} \right)^2 \cdot a^2 \cdot G \cdot V_i^2
\]

where \( \eta_q \) is the quantum efficiency of the photodetector (0.22, dimensionless), \( P_L \) is the power in each laser beam (0.6 Watts), \( \Delta f \) if the bandwidth of the signal (49 MHz), \( D_a \) is the diameter of the receiving optics (50 mm), \( D_{e2} \) is the diameter of the laser beams (1.7 mm), \( r_a \) is the focal length of the receiving optics (250 mm), \( f \) is the focal length of the lens which focuses the laser beams (250 mm), \( a \) is the mean titanium dioxide particle diameter (0.65 \( \mu \)m), \( G \) is a scattering parameter (0.12, dimensionless), and \( V_i \) is the visibility of the particles (0.63, dimensionless). The definition of \( V_i \) is the ability of the receiving optics based on the diameter of the particles that scatter the laser light, and is given by TSI Corporation (the manufacturer of the LDV). Using Equation (17), the SNR for the LDV used in this work is calculated to be 40.1:1. The data signals being more than an order of magnitude greater than the noise in the system is consistent with the good quality Doppler signals and histograms that were observed during data collection.
It should be noted that this represents the SNR under the best operational conditions of the LDV, which for this work was when the probe volume of the lasers was in the middle of the annular gap of the two modules. In this region, the visibility of the particles \( (V_i) \) was at its largest. In the inner and outer annular regions, the visibility of the particles was lower due to laser light reflections from the surfaces of the modules. As Equation (17) is dependent on the square of \( V_i \), it is not surprising that the data rate in the inner and outer annular regions was much lower than in the middle of the annular gap. The reason that the data rate was lower in the inner and outer regions was that careful control of the data filter and focusing of the receiving optics of the laser were necessary to maintain the quality of the Doppler signals and histograms. This helped to reject and suppress noise in the system, although due to the way in which the data acquisition system was set up, it is not possible to know the precise data rejection rate. The data in the inner and outer annular regions was simply collected at a lower rate, and fewer total points were taken. As the quality of the Doppler signals and the histograms in these regions was maintained, and the trends in the data taken in these regions were consistent, it is felt that noise in the LDV system did not significantly affect the data statistics. The uncertainty analysis for the LDV data, shown in detail in the appendix of this document, gives an uncertainty of 4.9% for the velocity data.

**Hydrocarbon Concentration Probe**

The concentration probe operates by detecting the absorption of laser light by hydrocarbon fuels. The concentration probe to be used in this work uses a HeNe laser. The molar concentration \( \chi \) of the hydrocarbon fuel can be calculated from:
\[ \chi = -\log \left( \frac{\tau_{IR} RT}{\varepsilon P_{total} L} \right) \]  

(18)

where \( R \) is the universal gas constant, \( T \) is the absolute temperature, \( P_{total} \) is the total pressure of the sample, \( L \) is the absorption path length of the concentration probe, \( \tau_{IR} \) is the infrared transmittance of the sample, and \( \varepsilon \) is the decadic molar extinction coefficient. The decadic molar extinction coefficient was shown by Yoshiyama, et. al. [22] to be:

\[ \varepsilon = 1.1 \times 10^5 \left( \frac{P_{total}}{P_o} \right)^{-0.302} \text{ cm}^2 \text{ mol}^{-1} \]

where \( P_o \) is a reference pressure (1 atm, for this study). A diagram of the concentration probe system taken from Girard et. al. [21] is shown below in Figure 12 (which is essentially the same as the one used in this study), and a diagram of the fuel flow system is shown in Figure 13. The diagram in Figure 12 shows the length of the sampling probe (20.5 cm for the work done by Girard et al., 26 cm for this study), which is an important aspect of the maximum frequency of concentration fluctuation that the probe can resolve. Also, the length of the absorption cell is shown (12.7 mm for the work done by Girard et al., 50 mm for this study). The probe was mounted on the same three-axis traversing table as the LDV, allowing the tip of the sampling probe to be precisely positioned.

The vacuum pump (shown in Figure 12) that drew the sampled air through the concentration probe was a rotary vane vacuum pump. The suction pressure of the pump was adjusted by means of a pressure control valve and was maintained at 4.0 psi. Preliminary tests of the stability of the baseline voltage of the concentration probe with and without the pump in operation showed no affect on the readings of the probe.
All measurements taken in this proposed work were done at one atmosphere and in a cold flow regime. Methane diluted with air was the mixture used for the concentration work. The average concentration of methane in the flow through the two modules was 5000 ppm, which was a safety precaution since this concentration of methane is too low to present a risk of combustion.
Figure 13. Diagram of fuel flow system with test hardware.
In addition to spatial resolution, it is important to consider the temporal resolution of the concentration probe. Specifically, the maximum frequency which can be resolved must be considered. In order to determine this, the residence times of the gas in the absorption cell and sampling probe are important. The reason for this is that the larger these residence times, the smaller is the maximum resolvable frequency of the probe. For the purpose of minimizing these residence times, a vacuum pump is used to draw the sample gas through the system as fast as possible. Isentropic flow of an ideal gas gives the maximum possible speed of the gas through the sampling probe as being sonic. From John [23] the pressure of the sample should be no more than 0.53 times the static pressure of the flow through the aft shroud in order to achieve sonic flow through the sampling probe. If the pressure of the sample were greater than this value, the flow through the sampling probe would not be sonic. During data collection, the pressure of the sample was kept less than this value.

The time that the sample gases spend in the concentration probe is calculated to be 2.09 msec. Using this value, and applying the Nyquist criterion [24], the maximum resolvable frequency of the concentration probe is 240 Hz. The maximum resolvable frequency of the concentration probe was tested, and in the configuration in which the probe was tested the maximum resolvable frequency was calculated to be 602 Hz. When the maximum resolvable frequency was tested, the length of the absorption cell was 12.5 mm, as opposed to 50 mm during the actual collection of concentration data. The reason for using the 50 mm absorption cell length during data collection was that it allowed for the measurement of lower methane concentrations than did the 12.5 mm cell length.
To test the maximum resolvable frequency of the probe, a methane/air mixture (ten percent methane by molar concentration) was supplied to the concentration probe at various frequencies of fluctuation. The frequency of the methane/air mixture was controlled through the use of an optical chopper, which is simply a bladed disk rotating at a known frequency. The chopper was placed in between the methane/air supply line and the concentration probe so that the blades would interrupt the flow of the methane/air mixture. The frequency of the blade rotation was varied from 50 Hz to 600 Hz. The probe successfully captured the frequency of the fluctuations up to 600 Hz, as shown by Figure 14 and Figure 15 below. By inspection of Figure 14, the peaks on the FFT plots are seen to occur at nearly the precise frequency as the optical chopper was rotated at. The FFT plot in Figure 15 shows that, while there is a slight peak at 600 Hz, the magnitude of this peak is approximately one order of magnitude below the peaks in Figure 14. In addition, there are several other peaks in Figure 15, such as at 635 Hz and 573 Hz. However, these peaks are also nearly an order of magnitude below those in Figure 14. The plots in Figure 14 and Figure 15 clearly show the ability of the concentration probe to resolve the frequency of fluctuations in methane concentration up to a frequency of 550 Hz. As previously discussed, this configuration, which gave a maximum resolvable frequency of 550 Hz, was unsuitable for the concentration work done here since the minimum measurable concentration was too high.
Figure 14. FFT plots at with frequency of (a) 50 Hz and (b) 550 Hz.
The hydrocarbon concentration probe was mounted onto the same three axis traversing table which supported the LDV so that the concentration probe could be positioned just as accurately as the LDV could be. In order that the sampling probe (see Figure 12) could be inserted into the flow of the two modules and thus be able to sample the free stream flow, small holes were drilled into the wall of the aft shrouds of both Modules 3 and 4. These holes were placed at the same axial locations at which velocity data had been collected. Thus, velocity and fuel concentration data could be compared since they were taken at the same physical locations.

The procedure for collecting concentration data was similar to that for the velocity data. The probe was moved to the desired axial location, and the tip of the sampling probe was inserted through the hole drilled into the wall of the aft shroud. The vacuum pump (as shown in Figure 12) was activated so as to draw air through the probe, and data

Figure 15. FFT plot a frequency too high (600 Hz) to be resolved by concentration probe.
was taken at each location along the annular section. Data was taken at 2000 Hz, since this would allow frequencies up to 1000 Hz to be seen by the Nyquist criterion, which is above the maximum resolvable frequency of the probe of approximately 600 Hz. At each point, 4096 data points were taken for the computation of the average concentration and also for the analysis of the spectrum of the concentration. Prior to taking data with methane flowing through the test hardware, 4096 data points were taken with no methane in the system for the purpose of measuring the baseline voltage of the concentration probe. The voltage was generated by the laser light impacting the IR detector. The purpose for measuring the voltage of the probe before and during the presence of methane is to gain an accurate measure of the transmittance of the sampled air. By Equation (18), the transmittance of the sampled air is then used to calculate the molar concentration of methane. Measuring the baseline voltage at each individual location just prior to when methane is injected ensures that errors due to minor fluctuations in laser intensity over time are minimized. Also, as depicted in Figure 13, the probe records the pressure and temperature (since these values are required by Equation (18) to compute the molar concentration of methane) at 2000 Hz just as it records the voltage of the IR detector at 2000 Hz. Before and after taking data at a given axial location, the laser light was blocked so that the voltage of the IR detector alone could be recorded. This value, referred to as the dark voltage since it is the voltage when no laser light is impacting the IR detector, was measured to improve the accuracy of the concentration data. When computing the transmittance of the sampled air, the dark voltage was subtracted from the voltage of both the data taken with and without methane flowing through the system. Thus, the error due to the voltage of the IR detector itself could be reduced. The dark
voltage tended to fluctuate slightly with time, and thus the dark voltage was measured before and after taking data at an axial location and the average value was used in computing the transmittance of the sampled air.

The methane diluted with air mixture (the air compressor was the source of the dilution air) was supplied through the bolt on feed flange, as previously discussed and as shown in Figure 2. The two valves shown in Figure 13 allowed for rapid initiation and ceasing of the flow of both methane and dilution air. The flow gauge and pressure gauges ensured that the dilution air and methane were flowing at the proper rates, and were checked constantly. As with the collection of velocity data, once data had been collected at all the axial locations, the test hardware was rotated to the next angular orientation of interest.

As with the LDV, the uncertainty of the hydrocarbon concentration probe was important. One very important measure taken to minimize the uncertainty of the concentration data was constant monitoring of the pressure regulators and gauges of the dilution air and methane shown in Figure 13. In particular, the flow meter that regulated the flow of methane into the system was checked before every instance in which data was taken to ensure that the flow rate of methane was kept constant. The readability of this flow meter was such that the flow of methane could be kept within 3% of the desired value. The details of the uncertainty analysis for the concentration probe are discussed in the appendix, and result in a total uncertainty of 6.3%.
RESULTS

As previously discussed, the axial locations at which data was collected have been normalized by the hydraulic diameter of the two gas turbine mixers. For both the velocity and fuel concentration data, the data are presented based on the number of hydraulic diameters downstream of the trailing edge of the swirl vanes at which the data was taken. In addition, the radial location the data was taken at has been normalized by the annular gap distance. The ratio of the radial location data was taken at to the annular gap distance will be labeled r/R. In all cases, r/R= 0 is the inner radius of the annular gap, and r/R= 1.0 is the outer radius. During the data collection process, the axial distance was measured from the upstream end of the aft shroud (see Figure 2) since measurement from this location was simple and straightforward. Due to the fact that Module 3 had a slightly different hydraulic diameter than Module 4, the axial locations for the two modules have slightly different x/Dh ratios. The x/Dh ratios for the axial locations at which data was collected are shown below in Table 4. The axial locations of data collection are shown for both modules in Figure 16, and are numbered corresponding to their location number in Table 4.

The axial and tangential velocity data for both Modules 3 and 4 were normalized by the respective bulk velocities of the modules. The bulk velocity of each module was calculated by dividing the mass flow rate of air by the air density and the cross sectional area of the module. The mass flow rate of air through Module 3 and 4 was 0.13 kg/s and 0.115 kg/s, respectively, and were calculated by integration of the axial velocity profiles. Numerical integration of the axial velocity profiles for both modules yielded mass flow
rate values that were consistent with one another within 5%. These mass flow rates gave bulk velocity values of 21.2 m/s for Module 3 and 16.1 m/s for Module 4.

Table 4. Axial locations for data collection.

<table>
<thead>
<tr>
<th>Location</th>
<th>Axial location</th>
<th>Module 3 x/Dh</th>
<th>Module 4 x/Dh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 cm</td>
<td>0.89</td>
<td>0.87</td>
</tr>
<tr>
<td>2</td>
<td>2 cm</td>
<td>1.11</td>
<td>1.06</td>
</tr>
<tr>
<td>3</td>
<td>3 cm</td>
<td>1.32</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>5 cm</td>
<td>1.74</td>
<td>1.63</td>
</tr>
<tr>
<td>5</td>
<td>7 cm</td>
<td>2.17</td>
<td>2.02</td>
</tr>
<tr>
<td>6</td>
<td>8 cm</td>
<td>—</td>
<td>2.21</td>
</tr>
<tr>
<td>7</td>
<td>9 cm</td>
<td>2.60</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>10 cm</td>
<td>—</td>
<td>2.60</td>
</tr>
<tr>
<td>9</td>
<td>11 cm</td>
<td>3.02</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 16. Data collection locations for Module 3 (a) and Module 4 (b).
For the fuel concentration data, the concentration was by the methane concentration in the methane/air mixture coming from the fuel injection holes located on the pressure side of the swirl vanes. This will illustrate the degree of dilution the fuel has undergone as it mixes with the free stream flow. The methane concentration of the sampled air will be labeled as $C$, and the concentration of methane in the methane/air mixture at the injection hole will be labeled as $C_f$.

First, the average and RMS values for the velocity and fuel concentration will be presented and discussed, and then the spectrum analysis will be examined. The RMS and spectrum data have important implications as they can give insight into the turbulence of the flow, which has a strong effect on the mixing of the fuel and air.

**Velocity Data**

The collection of data at six different angles allowed for the examination of the change in the velocity and concentration profiles across a section of the flow. By examining the various angular plots at different axial locations, the development of the velocity and fuel concentration profiles can be seen. Figure 17 below shows the normalized axial velocity profiles at the six different $\theta$ angles for $x/D_h= 0.87$ for Module 4. By inspection, it can be seen that the axial velocity profiles in Figure 17 fluctuate between values of $V/V_{bulk}$ of 1.1 and 1.25 over the range of $0.35 < r/R < 0.65$, and the radial location of the maximum and minimum values of $V/V_{bulk}$ differ from one angular location to another. However, this same effect of $\theta$ on the velocity profiles is not as prominent in Figure 18, which is of tangential velocity profiles also at $x/D_h= 0.87$. The data in both Figure 17 and Figure 18 was collected at $x/D_h= 0.87$ for Module 4, which
was the most upstream location (and therefore the closest to the swirl vanes) at which data was collected. Thus, it can be expected that the swirl vanes will influence the angular sections of the flow. The lack of dependence on angular orientation can be seen in Figure 18 by the fact that the various plots of tangential velocity for all values of θ investigated nearly collapse onto one another, whereas the axial velocity plots in Figure 17 do not. The data points in Figure 18 vary by less than 2% from one another, illustrating the similarity between the profiles at the six angular locations.

Figure 17. Mean axial velocity at x/Dₕ= 0.87 for Module 4.
As the flow progresses through the length of the swirler nozzle, the dependence of the axial velocity profiles on the angular orientation is diminished. Figure 19 shows that the axial velocity plots at x/D_h = 2.60 (the furthest downstream point at which data was taken for Module 4). In Figure 19 the profiles are relatively constant at V/V_{bulk} = 1.25 over the range 0.35 < r/R < 0.65. As previously discussed, the profiles in Figure 17 fluctuate between values of V/V_{bulk} of 1.1 and 1.25 over the range 0.35 < r/R < 0.65. The fact that the profiles in Figure 19 do not fluctuate in this manner illustrates the diminished effect of θ on the axial velocity profiles. Since the tangential velocity profiles were largely unaffected at the upstream end of the flow, it is not surprising that the downstream end of the flow shows the same lack of dependence on θ as well, as seen in Figure 20 by the fact that the profiles are again within 2% of each other.

Figure 18. Mean tangential velocity at x/D_h = 0.87 for Module 4.
Figure 19. Mean axial velocity at $x/D_h=2.60$ for Module 4.

Figure 20. Mean tangential velocity at $x/D_h=2.60$ for Module 4.
Examination of these axial and tangential velocity profiles not only shows how the axial velocity profiles depend on $\theta$, but shows the growth of the boundary layer as well. In Figure 19, the axial velocity profiles near the inner radius region are seen to be increasing with increasing $r/R$ until approximately $r/R = 0.35$. In Figure 17, the axial profiles exhibit the same behavior but stop increasing with increasing $r/R$ at approximately $r/R = 0.2$. The same trend is present in the tangential velocity. In Figure 18, the maximum tangential velocity occurs at approximately $r/R = 0.2$. In Figure 20, the maximum tangential velocity occurs at approximately $r/R = 0.35$. It should also be noted that the tangential velocity can be seen to be decaying as the flow progresses. In Figure 18, the maximum normalized tangential velocity is 2.37. In Figure 20, the maximum normalized tangential velocity is 2.08. This is a decrease of 12%, and the normalized tangential velocity can be seen to be decreasing across the annular gap. For the middle and outer regions of the flow (approximately $r/R = 0.5$ and 0.75, respectively), the normalized tangential velocity decreases by 6% and 4%, respectively.

In order to allow for easier examination of the radial profiles of the normalized velocity profiles along the length of the two swirler nozzles, three dimensional plots will be used to plot the various angular data at each axial location. First, the radial profiles of the normalized velocity data will be plotted at each axial location with different angular profile shown on the same graph to give a sense of how the data are changing with $\theta$. In these figures, each profile represents data taken at a particular angular location, and the legends on the right side of these graphs correspondingly show the color of each angular data set and the name of the profile indicates at what angle the data was taken at. In addition, the sector averaged velocity profiles of the data at the six angular locations will
be graphed so that the overall nature of the flow across the 36° sector can be examined. The sector averaged profiles were computed by averaging the data points of the six angular plots at each axial location. Then, the following section, the data will be plotted at each angular location, with data from different axial locations shown on the same graph. For these figures, each profile will be for a particular x/Dh ratio, and the legends on the right side of these graphs will show the color of each axial data set and the name of the profile indicates at what x/Dh ratio the data was taken at. Graphing the data in this manner will give two ways to yield an understanding of how the flow is developing both in the angular and axial directions.

Axial Velocity vs. θ

The three dimensional graphs in the figures below show the change in axial velocity profiles for Modules 3 and 4 at the upstream end of the flow, where the effects of the swirl vanes will be the strongest. Figure 21 and Figure 22 show the axial velocity data for Module 3 and Module 4 at the most upstream locations. Inspection of these figures shows that there is less variation in the velocity profile as θ changes for Module 4 than for Module 3. For 0.2 < r/R < 0.8 in Figure 21, the values of normalized axial velocity fluctuate between 1.16 and 1.34 for Module 3. However, in Figure 22, the normalized axial velocity fluctuates between 1.1 and 1.26 over the same radial region for Module 4.
Figure 21. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=0.89$ for Module 3.

Figure 22. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=0.87$ for Module 4.
Figure 23. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h = 1.11$ for Module 3.

Figure 24. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h = 1.06$ for Module 4.

In Figure 23 and Figure 24 the profiles vary less in the radial direction than those in Figure 21 and Figure 22. In Figure 23 the profiles vary between 1.18 and 1.3 and in
Figure 24 between 1.27 over 0.2 < r/R < 0.8. This trend of diminishing variation continues as the flow progresses through both modules. Examination of the normalized axial velocity profiles for both modules showed that there was little observable dependence of the flow on θ after x/Dh = 1.25 for Module 3 and x/Dh = 1.32 for Module 4. These data are shown in Figure 25 and Figure 26 below. Figure 27 through Figure 34 show the axial data at successively farther downstream points for Modules 3 and 4. Inspection of Figure 27 through Figure 34 reveals that the range of variation in the radial profiles continue to diminish.

![Figure 25](image)

Figure 25. Radial profiles of normalized mean axial velocity vs. θ, x/Dh = 1.32 for Module 3.
Figure 26. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=1.25$ for Module 4.

Figure 27. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=1.74$ for Module 3.
Figure 28. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=1.63$ for Module 4.

Figure 29. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=2.17$ for Module 3.
Figure 30. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=2.02$ for Module 4.

Figure 31. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=2.60$ for Module 3.
Figure 32. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=2.21$ for Module 4.

Figure 33. Radial profiles of normalized mean axial velocity vs. $\theta$, $x/D_h=3.02$ for Module 3.
Figure 34. Radial profiles of normalized mean axial velocity vs. θ, x/Dh= 2.60 for Module 4.

Figure 35. Radial profiles of sector averaged normalized mean axial velocity for Module 3.
The data in Figure 35 and Figure 36 above are the sector averaged values of the axial data taken at each location. Examining the sector averaged plots, it is immediately apparent that averaging the angular profiles results in the curves being smoother than the angular plots themselves, even at the most upstream locations. In Figure 35 the radial profiles vary between 1.13 and 1.27 over the range $0.2 < r/R < 0.8$ at $x/D_h = 0.89$, which is smaller than the fluctuations between 1.16 and 1.34 in the same radial region and in Figure 21. The radial profiles in Figure 36 for Module 4 vary between 1.12 and 1.2 over $0.2 < r/R < 0.8$ for $x/D_h = 0.87$ while the radial profiles in Figure 22 vary between 1.1 and 1.26. Also, inspection of Figure 36 reveals that Module 4 has a strong trend of boundary layer growth near the inner annular region (small values of $r/R$). This can be seen by the low $V/V_{bulk}$ values. The value of the $V/V_{bulk}$ profile for $x/D_h = 0.87$ in Figure 36 reaches a value greater than 1.0 at $r/R = 0.12$, while the radial profile for $x/D_h = 2.60$ reaches a value greater than 1.0 at $r/R = 0.22$. The fact that the normalized velocity ratio is reaching the
bulk velocity value at a greater distance from the inner wall is a clear illustration of boundary layer growth. For Module 3, the radial profile for $x/D_h = 0.89$ becomes greater than 1.0 at $r/R = 0.11$, while the profile for $x/D_h = 3.02$ becomes greater than 1.0 at $r/R = 0.12$. The significance of greater boundary layer growth in Module 4 is that the turbulence which promotes the growth of the boundary layer may also promote the mixing of fuel and air.

Another trend which is visible in Figure 21 and Figure 22 is the effect of $\theta$ on the flow. This can be seen by the fact that the radial location of the peaks in the $V/V_{bulk}$ profiles varies from one angular profile to another. As the flow progresses through the modules, the difference between the various angular profiles is seen to diminish with increasing $x/D_h$ (Figure 23 through Figure 34).

**Axial RMS Velocity vs. $\theta$**

In addition to examining the trends in the average axial velocity values, it is important to examine the trends in the axial and tangential RMS velocity data. Figure 37 through Figure 50 below show the axial RMS velocity as $\theta$ changes at each axial location for Modules 3 and 4. As with the mean axial velocity values, the strongest fluctuations are seen at the most upstream locations for both modules.
Figure 37. Radial profiles of normalized axial RMS velocity vs. θ, x/Dₘ = 0.89 for Module 3.

Figure 38. Radial profiles of normalized axial RMS velocity vs. θ, x/Dₘ = 0.87 for Module 4.
Figure 39. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 1.11$ for Module 3.

Figure 40. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 1.06$ for Module 4.
Figure 41. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 1.32$ for Module 3.

Figure 42. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 1.25$ for Module 4.
Figure 43. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 1.74$ for Module 3.

Figure 44. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 1.63$ for Module 4.
Figure 45. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 2.17$ for Module 3.

Figure 46. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 2.02$ for Module 4.
Figure 47. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 2.60$ for Module 3.

Figure 48. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h = 2.21$ for Module 4.
Figure 49. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h=3.02$ for Module 3.

Figure 50. Radial profiles of normalized axial RMS velocity vs. $\theta$, $x/D_h=2.60$ for Module 4.
As with the mean axial velocity values, the sector average plots tend to have less variation than the angular plots used to compute them. The sector averaged plots of
Module 4 show an increase in axial RMS values near the inner annular region (small values of r/R), while the sector averaged plots of Module 3 do not show this trend. This is to be expected since Figure 37 through Figure 50 consistently showed a higher axial RMS velocity in the inner annular region for Module 4 than for Module 3. The mean axial velocity plots in Figure 36 showed that there was a growth of the boundary layer in this same region for Module 4. Figure 35 did not show the same observable trend for Module 3, and indeed Figure 51 correspondingly does not show a large increase in axial RMS velocity for small values of r/R. Examination of Figure 51 and Figure 52 also shows that the normalized axial RMS velocity is higher for Module 4 than for Module 3. The average value of the radial profile for x/Dh= 0.87 in Figure 52 is 0.124, while the average value for x/Dh= 0.89 in Figure 51 is 0.11. This trend is apparent at all axial locations. For x/Dh= 2.02 in Figure 52, the average normalized axial RMS velocity is 0.136, while for x/Dh= 2.17 in Module 3 in Figure 51 the average value is 0.114. The reason that the average normalized axial RMS velocity values have increased for the modules is the increased RMS velocity due to boundary layer growth. The higher normalized axial RMS velocity of Module 4 is significant since a higher level of RMS velocity will further promote the mixing of fuel and air, and this difference in flow behavior and mixing between the two modules is an important consequence of the different swirl angles.

The normalized axial RMS velocity values in the region r/R= 0.5 at x/Dh= 2.02 for Module 4 and x/Dh= 2.17 for Module 3 are within approximately 5% of the values at the most upstream locations for both modules for r/R= 0.5. Inspection of both the sector averaged plots and the individual angular plots for both Modules 3 and 4 shows that the
normalized axial RMS values tend to have larger values at the most downstream location than further upstream locations. In Figure 52, the average normalized axial RMS velocity increases by 44% from the most upstream to the most downstream axial location, while in Figure 51 the increase is 52% from the most upstream to the most downstream axial location. This increase in RMS velocity is seen across the annular gap near the exit of both modules, and thus is likely due to flow behavior near the exit of the modules.

Tangential Velocity vs. $\theta$

The tangential velocity for both modules consistently showed a peak near the inner annular region and a linear decay with increasing $r/R$. Since Module 4 had a higher swirl angle ($55^\circ$ versus $45^\circ$ for Module 3), Module 4 had a higher peak tangential velocity than Module 3. In Figure 53, the maximum tangential velocity is approximately 33 m/s, while in Figure 54 the maximum tangential velocity is approximately 38 m/s.

Figure 53. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h = 0.89$ for Module 3.
Figure 54. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=0.87$ for Module 4.

Figure 55. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=1.11$ for Module 3.
Figure 56. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h = 1.06$ for Module 4.

Figure 57. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h = 1.32$ for Module 3.
Figure 58. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.25$ for Module 4.

Figure 59. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 1.74$ for Module 3.
Figure 60. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=1.63$ for Module 4.

Figure 61. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=2.17$ for Module 3.
Figure 62. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=2.02$ for Module 4.

Figure 63. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=2.60$ for Module 3.
Figure 64. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=2.21$ for Module 4.

Figure 65. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h=3.02$ for Module 3.
Figure 66. Radial profiles of normalized mean tangential velocity vs. $\theta$, $x/D_h= 2.60$ for Module 4.

Figure 67. Radial profiles of sector averaged normalized mean tangential velocity for Module 3.
The individual angular plots in Figure 53 through Figure 66 show the growth of a boundary layer in Module 4 that is not seen in the Module 3 data. This boundary layer growth is reflected in the normalized tangential velocity plots, just as is was in the normalized axial velocity plots. Figure 68 shows that, with increasing x/D_h, the inner annular region exhibits smaller V/V_{bulk} values. For example, at r/R= 0.2, the normalized tangential velocity is 18% lower at x/D_h= 2.60 than at x/D_h= 0.87 (decreasing from V/V_{bulk}= 2.327 to 1.906). For Module 3, at r/R= 0.2 (see Figure 67), there was only a 4% decrease from V/V_{bulk}= 1.491 at x/D_h= 0.89 to V/V_{bulk}= 1.429 at x/D_h= 3.02. This trend of stronger boundary layer growth is consistent with the data in Figure 51 and Figure 52, and again is significant since the increased turbulence in Module 4 may promote the mixing of fuel and air and is an important result of the difference in swirl angle between the two modules. The cause of the greater boundary layer growth in Module 4 is likely
due to the behavior of the flow emanating from the swirl vanes. Thus, the difference in swirl vane angle has an impact on the flow through the modules.

It is also notable that the peak tangential velocity for each module decayed with increasing $x/D_h$. From the most upstream to the most downstream location, the peak normalized tangential velocity for Module 3 decreased by 9% from 1.56 to 1.42, while the peak normalized tangential velocity for Module 4 decreased by 12% from 2.37 to 2.08, as can be seen in Figure 67 and Figure 68.

Tangential RMS Velocity vs. $\theta$

The tangential RMS velocity data, unlike the mean tangential data, did show a dependence on $\theta$, and this dependence diminished with increasing $x/D_h$. For example, in Figure 69, the peak value of each plot is approximately $V_{RMS}/V_{bulk} = 0.11$, but the radial location at which the peak occurs varies from $r/R = 0.26$ to 0.75.

![Figure 69. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h = 0.89$ for Module 3.](image)
Figure 70. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h = 0.87$ for Module 4.

Figure 71. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h = 1.11$ for Module 3.
Figure 72. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.06$ for Module 4.

Figure 73. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.32$ for Module 3.
Figure 74. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h=1.25$ for Module 4.

Figure 75. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h=1.74$ for Module 3.
Figure 76. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 1.63$ for Module 4.

Figure 77. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h= 2.17$ for Module 3.
Figure 78. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h=2.02$ for Module 4.

Figure 79. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h=2.60$ for Module 3.
Figure 80. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h = 2.21$ for Module 4.

Figure 81. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h = 3.02$ for Module 3.
Figure 82. Radial profiles of normalized tangential RMS velocity vs. $\theta$, $x/D_h=2.60$ for Module 4.

Figure 83. Radial profiles of sector averaged normalized tangential RMS velocity for Module 3.
Examination of the normalized tangential RMS velocity profiles of Figure 69 through Figure 82 and the sector average profiles of Figure 83 and Figure 84 reveals that they indicate increased RMS velocity due to the growth of a boundary layer at the inner annular region of Module 4, but not in Module 3. For example, the value of the plots in the inner annular region in Figure 69 are approximately $V_{\text{RMS}}/V_{\text{bulk}} = 0.12$ for Module 3 while in Figure 70 they are approximately $V_{\text{RMS}}/V_{\text{bulk}} = 0.15$ for Module 4. In Figure 81, the value of the $V_{\text{RMS}}/V_{\text{bulk}}$ have increased to 0.20 for Module 3, but the values of $V_{\text{RMS}}/V_{\text{bulk}}$ for the plots in Figure 82 for Module 4 have increased to approximately 0.38.

This is consistent with the trends observed in the normalized axial RMS velocity profiles in Figure 37 through Figure 52. Comparing Figure 51 to Figure 83 shows that both the normalized axial and tangential RMS velocity plots for Module 3 show the same trend of increasing across the annular gap at the most downstream location, most likely
due to flow conditions near the exit of the module. This trend is shown to also occur in Module 4 by Figure 52 and Figure 84. Thus, the normalized axial and normalized tangential RMS velocity profiles for the two modules show the same trends.

Axial Velocity vs. x/Dh

The figures in this section show axial velocity plots for Modules 3 and 4 at a constant $\theta$ value with changing $x/D_h$. Figure 85 through Figure 96 consistently show the trends that were observed in Figure 21 through Figure 36 of smaller variations in the normalized axial velocity plots of Module 4 versus those of Module 3.

![Figure 85. Radial profiles of normalized mean axial velocity vs. x/Dh, $\theta=0$ deg for Module 3.](image-url)
Figure 86. Radial profiles of normalized mean axial velocity vs. x/Dh, θ = 0 deg for Module 4.

Figure 87. Radial profiles of normalized mean axial velocity vs. x/Dh, θ = 6 deg for Module 3.
Figure 88. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta = 6$ deg for Module 4.

Figure 89. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta = 12$ deg for Module 3.
Figure 90. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta = 12$ deg for Module 4.

Figure 91. Radial profiles of normalized mean axial velocity vs. $x/D_h$, $\theta = 18$ deg for Module 3.
Figure 92. Radial profiles of normalized mean axial velocity vs. \(x/D_h\), \(\theta=18\) deg for Module 4.

Figure 93. Radial profiles of normalized mean axial velocity vs. \(x/D_h\), \(\theta=24\) deg for Module 3.
Figure 94. Radial profiles of normalized mean axial velocity vs. \(x/D_h\), \(\theta = 24\) deg for Module 4.

Figure 95. Radial profiles of normalized mean axial velocity vs. \(x/D_h\), \(\theta = 30\) deg for Module 3.
Figure 96. Radial profiles of normalized mean axial velocity vs. x/D_h, θ= 30 deg for Module 4.

Figure 85 through Figure 96 illustrate the growth of the boundary layer in Module 4 in the inner annular region, as well as the diminishing variations with increasing x/D_h. For example, in Figure 85 the normalized axial velocity values in the inner annular region of Module 3 decrease from V/V_{bulk} = 1.231 to 0.98. In Figure 86 the normalized axial velocity values in the inner annular region of Module 4 decrease from V/V_{bulk} = 1.048 to 0.705. This decrease of 33% for Module 4 versus the 20% for Module 3 illustrates the stronger boundary layer growth present in Module 4.

Axial RMS Velocity vs. x/D_h

Figure 97 through Figure 108 show axial RMS velocity plots for Modules 3 and 4 at a constant θ value with changing x/D_h. As with Figure 37 through Figure 52, the larger V_{RMS}/V_{bulk} values in the inner annular region of Module 4 versus those at the inner
annular region of Module 3 are apparent. As previously discussed, the higher $V_{RMS}/V_{bulk}$
values of Module 4 are significant in that the RMS velocity will further promote the
mixing of the fuel and air as the flow progresses through the modules.

Figure 97. Radial profiles of normalized axial RMS velocity vs. $x/D_h$, $\theta=0$ deg for
Module 3.

Figure 98. Radial profiles of normalized axial RMS velocity vs. $x/D_h$, $\theta=0$ deg for
Module 4.
Figure 99. Radial profiles of normalized axial RMS velocity vs. $x/D_h$, $\theta = 6$ deg for Module 3.

Figure 100. Radial profiles of normalized axial RMS velocity vs. $x/D_h$, $\theta = 6$ deg for Module 4.
Figure 101. Radial profiles of normalized axial RMS velocity vs. $x/D_h$, $\theta = 12$ deg for Module 3.

Figure 102. Radial profiles of normalized axial RMS velocity vs. $x/D_h$, $\theta = 12$ deg for Module 4.
Figure 103. Radial profiles of normalized axial RMS velocity vs. x/Dh, θ = 18 deg for Module 3.

Figure 104. Radial profiles of normalized axial RMS velocity vs. x/Dh, θ = 18 deg for Module 4.
Figure 105. Radial profiles of normalized axial RMS velocity vs. x/Dh, θ = 24 deg for Module 3.

Figure 106. Radial profiles of normalized axial RMS velocity vs. x/Dh, θ = 24 deg for Module 4.
Figure 107. Radial profiles of normalized axial RMS velocity vs. x/Dh, θ = 30 deg for Module 3.

Figure 108. Radial profiles of normalized axial RMS velocity vs. x/Dh, θ = 30 deg for Module 4.
Tangential Velocity vs. x/Dh

Figure 109 through Figure 120 show tangential velocity plots for Modules 3 and 4 at a constant $\theta$ value with changing $x/D_h$. The trend of boundary layer growth is easily visible in the figures for Module 4 (Figure 110, for example), while in Figure 109 does not show such a boundary layer growth. The remaining figures (Figure 111 through Figure 120) also show this trend prominently.

Figure 109. Radial profiles of normalized mean tangential velocity vs. $x/D_h$, $\theta=0$ deg for Module 3.
Figure 110. Radial profiles of normalized mean tangential velocity vs. x/D_h, θ = 0 deg for Module 4.

Figure 111. Radial profiles of normalized mean tangential velocity vs. x/D_h, θ = 6 deg for Module 3.
Figure 112. Radial profiles of normalized mean tangential velocity vs. x/D_h, \( \theta = 6 \) deg for Module 4.

Figure 113. Radial profiles of normalized mean tangential velocity vs. x/D_h, \( \theta = 12 \) deg for Module 3.
Figure 114. Radial profiles of normalized mean tangential velocity vs. x/Dh, θ = 12 deg for Module 4.

Figure 115. Radial profiles of normalized mean tangential velocity vs. x/Dh, θ = 18 deg for Module 3.
Figure 116. Radial profiles of normalized mean tangential velocity vs. x/D_h, θ = 18 deg for Module 4.

Figure 117. Radial profiles of normalized mean tangential velocity vs. x/D_h, θ = 24 deg for Module 3.
Figure 118. Radial profiles of normalized mean tangential velocity vs. $x/D_h$, $\theta = 24$ deg for Module 4.

Figure 119. Radial profiles of normalized mean tangential velocity vs. $x/D_h$, $\theta = 30$ deg for Module 3.
Figure 120. Radial profiles of normalized mean tangential velocity vs. x/D_{h}, \theta = 30\,\text{deg} for Module 4.

Tangential RMS Velocity vs. x/D_{h}

Figure 121 through Figure 132 show tangential RMS velocity plots for Modules 3 and 4 at a constant \theta value with changing x/D_{h}. Figure 121 and Figure 122 show difference between Modules 3 and 4 in terms of larger \( V_{\text{RMS}}/V_{\text{bulk}} \) values at the inner annular region for Module 4, due to the more substantial boundary layer growth in Module 4. The consistently larger \( V_{\text{RMS}}/V_{\text{bulk}} \) values of Module 4 in Figure 121 through Figure 132 as compared to Module 3 will be beneficial to the mixing of fuel and air in Module 4.
Figure 121. Radial profiles of normalized tangential RMS velocity vs. $x/D_h$, $\theta = 0$ deg for Module 3.

Figure 122. Radial profiles of normalized tangential RMS velocity vs. $x/D_h$, $\theta = 0$ deg for Module 4.
Figure 123. Radial profiles of normalized tangential RMS velocity vs. x/Dh, θ = 6 deg for Module 3.

Figure 124. Radial profiles of normalized tangential RMS velocity vs. x/Dh, θ = 6 deg for Module 4.
Figure 125. Radial profiles of normalized tangential RMS velocity vs. x/Dₜₜ, θ= 12 deg for Module 3.

Figure 126. Radial profiles of normalized tangential RMS velocity vs. x/Dₜₜ, θ= 12 deg for Module 4.
Figure 127. Radial profiles of normalized tangential RMS velocity vs. x/D_h, θ = 18 deg for Module 3.

Figure 128. Radial profiles of normalized tangential RMS velocity vs. x/D_h, θ = 18 deg for Module 4.
Figure 129. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 24 \) deg for Module 3.

Figure 130. Radial profiles of normalized tangential RMS velocity vs. \( x/D_h \), \( \theta = 24 \) deg for Module 4.
Figure 131. Radial profiles of normalized tangential RMS velocity vs. $x/D_h$, $\theta = 30$ deg for Module 3.

Figure 132. Radial profiles of normalized tangential RMS velocity vs. $x/D_h$, $\theta = 30$ deg for Module 4.
Figure 109 through Figure 120 and also Figure 121 through Figure 132 show the trend of the smoothing of the plots as x/D_h increases. In addition, the plots for Module 4 clearly show the boundary layer growth for every value of θ, while the plots for Module 3 do not show such growth. As previously discussed, the cause of the difference in boundary layer growth, as well as the difference in average RMS velocity values between the two modules, is likely due to the turbulence of the flow emanating from the swirl vanes. From the data, it may be concluded that the turbulence from the swirl vanes in Module 4 is larger in the region near the swirl vanes, thus resulting in the trends observed in the data.

**Fuel Concentration Data**

For the fuel concentration data, as previously discussed, the concentration measured by the probe (labeled as C) was normalized by the methane concentration in the methane/air mixture coming from the fuel injection holes (labeled as C_f) located on the pressure side of the swirl vanes. Normalization of the methane concentration values in this way will illustrate the degree of dilution the fuel has undergone as it mixes with the free stream flow. For example, a value of C/C_f = 0.10 means that the fuel has been diluted to one tenth of its concentration at fuel injection holes.

Just as with the normalized velocity data, three-dimensional plots will be used to graph the normalized fuel concentration data. First, the radial profiles of the normalized methane concentration will be plotted at each axial location with different angular profile shown on the same graph to give a sense of how the data are changing with θ. In these graphs, each profile represents data taken at a particular angular location, and the legends...
on the right side of these graphs correspondingly show the color of each angular data set and the name of the profile indicates at what angle the data was taken at. Then, in a separate section, the data will be plotted at each angular location, with data from different axial locations shown on the same graph. For these graphs, each profile will be for a particular \( \frac{x}{D_h} \) ratio, and the legends on the right side of these graphs will show the color of each axial data set and the name of the profile indicates at what \( \frac{x}{D_h} \) ratio the data was taken at. As with the normalized velocity data, graphing the data in this manner will give two ways to yield an understanding of how the flow is developing both in the angular and axial directions.

Fuel Concentration vs. \( \theta \)

The graphs of this section show the methane concentration profiles for various angular locations at a constant value of \( \frac{x}{D_h} \). For both modules, the methane was injected at such a rate that when the methane concentration was perfectly uniform, \( \frac{C}{C_f} \approx 0.05 \). Just as with the velocity plots, each profile represents data taken at a particular angular location, and the legends on the right side of these graphs correspondingly show the color of each angular data set and the name of the profile indicates at what angle the data was taken at. For the sector averaged profiles, the name of the individual profile gives the \( \frac{x}{D_h} \) value at which the data was taken.

Comparison of Figure 133 with Figure 134 (both of which are from the most upstream location of each module) shows that the mean methane concentration in Module 4 (at \( \frac{x}{D_h} = 0.87 \)) does not vary across the annular area as much as it does in Module 3 (at \( \frac{x}{D_h} = 0.89 \)). The \( \frac{C}{C_f} \) values in Figure 133 vary between 0.008 and 0.12, while the \( \frac{C}{C_f} \)
values in Figure 134 vary between 0.02 and 0.09. This behavior of smaller $C/C_f$
variations in Module 4 than in Module 3 is significant since the variations in normalized
axial velocity were smaller in Module 4 than in Module 3 (see Figure 21 and Figure 22,
which are at the same $x/D_h$ ratios as Figure 133 and Figure 134). This trend of smaller
variations in the normalized concentration data of Module 4 continues in the remaining
figures of this section (Figure 135 through Figure 148). Also in Figure 135 through
Figure 148, it can be seen that the magnitude of the variations in the normalized
concentration profiles diminishes for both modules with increasing $x/D_h$.

The residence time of the flow for each module was defined as the time it takes
for the flow to go from the most upstream data collection location to the most
downstream location. In other words, simply the distance between the most upstream
and down stream locations divided by the bulk velocity. For Module 3, the two extreme
locations were $x/D_h= 0.89$ and 3.02 with a bulk velocity of 21.2 m/s, while for Module 4
they were $x/D_h= 0.87$ and 2.60 with a bulk velocity of 16.1 m/s. The residence time of
the flow in each module is 4.8 milliseconds for Module 3 and 5.5 milliseconds for
Module 4.
Figure 133. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h= 0.89$ for Module 3.

Figure 134. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h= 0.87$ for Module 4.
Figure 135. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, x/D$_h$= 1.11 for Module 3.

Figure 136. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, x/D$_h$= 1.06 for Module 4.
Figure 137. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h$ = 1.32 for Module 3.

Figure 138. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h$ = 1.25 for Module 4.
Figure 139. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h= 1.74$ for Module 3.

Figure 140. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h= 1.63$ for Module 4.
Figure 141. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, x/D$_h$ = 2.17 for Module 3.

Figure 142. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, x/D$_h$ = 2.02 for Module 4.
Figure 143. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.60$ for Module 3.

Figure 144. Radial profiles of normalized mean CH$_4$ concentration vs. $\theta$, $x/D_h=2.21$ for Module 4.
Figure 145. Radial profiles of normalized mean CH₄ concentration vs. θ, x/Dₕ = 3.02 for Module 3.

Figure 146. Radial profiles of normalized mean CH₄ concentration vs. θ, x/Dₕ = 2.60 for Module 4.
Figure 147. Radial profiles of sector averaged normalized mean CH$_4$ concentration for Module 3.

Figure 148. Radial profiles of sector averaged normalized mean CH$_4$ concentration for Module 4.

The plots of mean methane concentration clearly show the mixing of the fuel and air as the flow progresses. Both the individual angular plots and the sector averaged plots
show that the variations in the profiles are diminished for both modules as \( x/D_h \) increases, and the profiles become more uniform in methane concentration at the downstream locations. The figures also show that the methane concentration profiles vary less at each axial location for Module 4 than for Module 3. For example, in Figure 147 the \( C/C_f \) vary between 0.039 and 0.09 at the most upstream location and 0.048 and 0.06 at the most downstream location. The values in Figure 148 vary between 0.044 and 0.06 at the most upstream location and 0.048 and 0.05 at the most downstream location. The smaller variations in methane concentration observed in Module 4 show that the flow in Module 4 (55° swirl vane angle) results in more complete mixing of the fuel and air than the flow in Module 3 (45° swirl vane angle) does. Also, the fact that these variations are smaller in Module 4 than in Module 3 even at the most upstream axial location shows that the flow in the region near the swirl vanes is important in the mixing of the fuel and air.

RMS Fuel Concentration vs. \( \theta \)

As with the axial and tangential velocities, it is important to examine not only the mean methane concentration profiles but the RMS concentration as well. The importance of the RMS concentration is that, like the RMS velocities, it can give insight into the turbulence affecting the flow field. Also, by Equations (12) and (13), it is indicative of the unmixedness of the flow as well.
Figure 149. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h= 0.89$ for Module 3.

Figure 150. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h= 0.87$ for Module 4.
Figure 151. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h= 1.11$ for Module 3.

Figure 152. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h= 1.06$ for Module 4.
Figure 153. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h = 1.32$ for Module 3.

Figure 154. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h = 1.25$ for Module 4.
Figure 155. Radial profiles of normalized RMS CH₄ concentration vs. $\theta$, $x/D_h=1.74$ for Module 3.

Figure 156. Radial profiles of normalized RMS CH₄ concentration vs. $\theta$, $x/D_h=1.63$ for Module 4.
Figure 157. Radial profiles of normalized RMS CH₄ concentration vs. $\theta$, $x/D_h= 2.17$ for Module 3.

Figure 158. Radial profiles of normalized RMS CH₄ concentration vs. $\theta$, $x/D_h= 2.02$ for Module 4.
Figure 159. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h = 2.60$ for Module 3.

Figure 160. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, $x/D_h = 2.21$ for Module 4.
Figure 161. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, x/D$_h$ = 3.02 for Module 3.

Figure 162. Radial profiles of normalized RMS CH$_4$ concentration vs. $\theta$, x/D$_h$ = 2.60 for Module 4.
Figure 163. Radial profiles of sector averaged normalized RMS CH$_4$ concentration for Module 3.

Figure 164. Radial profiles of sector averaged normalized RMS CH$_4$ concentration for Module 4.
Examination of Figure 149 through Figure 164 shows that the normalized RMS methane concentration profiles follow the same trend as the normalized mean concentration profiles. In particular, the normalized RMS methane concentration profiles for Module 4 are seen to have less variation across the annular gap than those of Module 3. For example, in Figure 149 there are variations from 0.011 to 0.026 present across the annular gap for Module 3. However, in Figure 150 there are variations in the normalized RMS concentration from 0.011 to 0.018 for r/R > 0.7, but for smaller values of r/R the normalized RMS concentration is relatively constant at approximately 0.01. In addition, the normalized RMS methane concentration for Module 3 in Figure 149 often reaches a peak value of 0.025 to 0.03, whereas the peak normalized RMS methane concentration for Module 4 in Figure 150 is approximately 0.02. Inspection of Figure 149 and Figure 150 reveals that the greatest variations occur at large values of r/R for both modules. At small values of r/R for Module 3 the variations reach a peak of 0.022, while the profiles for Module 4 are nearly constant at a value of 0.01. Thus, it can be seen that both modules exhibit the same trend of larger variations in the $C_{RMS}/C_f$ profiles at large r/R values, and that these variations are smaller for Module 4 than for Module 3. The smaller variations in Module 4 are indicative of better mixing performance in the flow field of Module 4. Also, the radial location of the peaks in the various angular profiles in Figure 149 and Figure 150 vary from one profile to another. This shows that there is a variation in the flow with $\theta$, as was seen in the mean and RMS axial velocity profiles (Figure 21 and Figure 22 and Figure 37 and Figure 38, for example) and mean concentration profiles (Figure 133 and Figure 134, for example).
The subsequent plots (Figure 151 to Figure 162) show that the variations in the normalized RMS profiles for Module 4 diminish at axial locations further upstream than in Module 3, suggesting better mixing performance in Module 4 than in Module 3. At $x/D_h= 1.63$ (Figure 156), the normalized RMS concentration for Module 4 varies between 0.044 and 0.63. At $x/D_h= 1.74$ for Module 3 (Figure 155), variations in the normalized RMS profiles are from 0.038 to 0.012. By examination of Figure 139 and Figure 140, which show the normalized mean methane concentration for the same locations as Figure 155 and Figure 156 show normalized RMS concentration, it can be seen that the mean methane concentration profiles have also largely ceased to vary for Module 4, while the profiles of Module 3 are still seen to have variations. The profiles of Module 4 in Figure 140 are nearly all at the average value of $C/C_f$ of 0.05, while the profiles of Module 3 in Figure 139 are still reaching values as high as 0.1 or 0.13 at some angular locations.

Fuel Concentration vs. $x/D_h$

Just as the axial and tangential velocity profiles were examined both for how they changed both in the angular and the axial directions, so too the mean and RMS normalized methane concentration plots will be examined. This will be done, as before, in an effort to gain a greater understanding of how the flow and the methane concentration develop. The legend on the right hand side of each figure shows the color of the data taken at each respective axial location, and the name of each profile gives the $x/D_h$ value at which the data was taken.
Figure 165. Radial profiles of normalized mean CH₄ concentration vs. x/Dₜ, θ = 0 deg. for Module 3.

Figure 166. Radial profiles of normalized mean CH₄ concentration vs. x/Dₜ, θ = 0 deg. for Module 4.
Figure 167. Radial profiles of normalized mean CH₄ concentration vs. x/Dₙ, θ = 6 deg. for Module 3.

Figure 168. Radial profiles of normalized mean CH₄ concentration vs. x/Dₙ, θ = 6 deg. for Module 4.
Figure 169. Radial profiles of normalized mean CH₄ concentration vs. x/Dₕ, θ= 12 deg. for Module 3.

Figure 170. Radial profiles of normalized mean CH₄ concentration vs. x/Dₕ, θ= 12 deg. for Module 4.
Figure 171. Radial profiles of normalized mean CH$_4$ concentration vs. $x/D_h$, $\theta$ = 18 deg. for Module 3.

Figure 172. Radial profiles of normalized mean CH$_4$ concentration vs. $x/D_h$, $\theta$ = 18 deg. for Module 4.
Figure 173. Radial profiles of normalized mean CH₄ concentration vs. x/Dₜ, θ= 24 deg. for Module 3.

Figure 174. Radial profiles of normalized mean CH₄ concentration vs. x/Dₜ, θ= 24 deg. for Module 4.
Figure 175. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_{h}$, $\theta$ = 30 deg. for Module 3.

Figure 176. Radial profiles of normalized mean CH$_4$ concentration vs. x/D$_{h}$, $\theta$ = 30 deg. for Module 4.
As was seen in Figure 133 through Figure 164, the normalized methane concentration varied less in Module 4 than in Module 3. In Figure 165, the normalized concentration in Module 3 varies between 0.025 and 0.11 at the most upstream location and 0.047 and 0.064 at the most downstream location. In Figure 166 the normalized concentration in Module 4 varies between 0.044 and 0.077 at the most upstream location and 0.046 and 0.05 at the most downstream location. Figure 165 and Figure 166 are for $\theta = 0$ degrees, but the same trend is present in the figures for the other angle values (Figure 167 through Figure 176). Thus, the smaller variations in the profiles for Module 4 again show that the mixing performance of Module 4 is superior to that of Module 3 as Module 4 yields more spatially uniform concentration profiles. In addition, Figure 165 through Figure 176 show that even for the most upstream axial location, the variations in the mean concentration value are smaller for Module 4 than for Module 3. This again illustrates that the flow near the swirl vanes is important in the mixing of the fuel and air.

Figure 165 through Figure 176 show the importance of mixing length as well. In Figure 170, for example, the peak value in the methane concentration for Module 4 diminishes from approximately double the mean value at $x/D_h= 0.87$ to only 20% above the mean value at $x/D_h= 1.63$. The distance between these two axial locations is only 30% of the total distance between the trailing edge of the swirl vanes and the exit plane for Module 4.

RMS Fuel Concentration vs. $x/D_h$

Figure 177 through Figure 188 show the RMS methane concentration profiles at each $x/D_h$ location for a constant value of $\theta$. Just as was seen in Figure 149 through
Figure 164, Figure 177 through Figure 188 show that the RMS methane concentration exhibits less variation at each x/Dh location for Module 4 than for Module 3. In Figure 182, for example, the variations in the normalized RMS concentration for Module 4 are 30% smaller than for those of Module 3 in Figure 183 (with a peak of $C_{RMS}/C_f = 0.027$ for Module 3 versus a peak of $C_{RMS}/C_f = 0.018$ for Module 4).

![Figure 177. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta = 0$ deg. for Module 3.](image_url)
Figure 178. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜ, θ = 0 deg. for Module 4.

Figure 179. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜ, θ = 6 deg. for Module 3.
Figure 180. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 6 deg. for Module 4.

Figure 181. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, $\theta$ = 12 deg. for Module 3.
Figure 182. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜ, θ = 12 deg. for Module 4.

Figure 183. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜ, θ = 18 deg. for Module 3.
Figure 184. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜₕ, θ= 18 deg. for Module 4.

Figure 185. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜₕ, θ= 24 deg. for Module 3.
Figure 186. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜh, θ= 24 deg. for Module 4.

Figure 187. Radial profiles of normalized RMS CH₄ concentration vs. x/Dₜh, θ= 30 deg. for Module 3.
Figure 188. Radial profiles of normalized RMS CH$_4$ concentration vs. x/D$_h$, θ = 30 deg. for Module 4.

Unmixedness

The methane concentration data was used to calculate the unmixedness of the flow through the two modules by Equation (12) in an effort to further analyze their mixing performance. The resulting unmixedness values are shown graphically in Figure 189 through Figure 194.

Unmixedness at θ = 0 degrees

Figure 189 through Figure 191 show the unmixedness of modules 3 and 4 at three different axial locations. In Figure 189, the unmixedness is shown at the most upstream axial location for both modules. The profiles show that the unmixedness of the flow in the two modules both vary across the annular gap, and that the range of the unmixedness values for the two modules are similar, and both exhibit their greatest variation in the
outer annular region. The values for Module 3 in Figure 189 range from 0.215 to 0.442, while the values for Module 4 range from 0.225 to 0.447.

Figure 189. Unmixedness at $\theta = 0$ deg., $x/D_h = 0.89$ for Module 3 and $x/D_h = 0.87$ for Module 4.

Figure 190 shows the unmixedness at radial locations approximately half way along the length of the respective modules, and it is obvious that the variations along the annular gap are much smaller for Module 4 than for Module 3. In particular, the unmixedness for Module 3 still varies considerably in the outer annular region (between 0.26 and 0.377) while the data for Module 4 varies between 0.214 and 0.243 across the entire annular gap. It can also be seen in Figure 190 that the unmixedness values for Module 4 are equal to or smaller than the unmixedness values for Module 3. This smaller variation in unmixedness and smaller average unmixedness is an important difference between the two modules.
Figure 190. Unmixedness at $\theta = 0$ deg., $x/D_h = 1.74$ for Module 3 and $x/D_h = 1.63$ for Module 4.

Figure 191 shows unmixedness data from the two modules at near the end of the length of each module, and it can be seen that the variations across the annular gap are smaller for both modules. In addition, the trend of smaller unmixedness values in Module 4 versus Module 3 has continued. Figure 191 is also significant since the range of unmixedness values for both modules is comparable to the values found in other unmixedness research. The data of Frey et al. [11] (which was at the exit of several configurations of a gas turbine mixer) varied from 0.23 to 0.29, depending on the configuration of the premixer they examined, and the data in Figure 191 varies from 0.232 to 0.260 for Module 3 and from 0.214 to 0.232 for Module 4.
Figure 191. Unmixedness at \( \theta = 0 \) deg., \( x/D_h = 2.60 \) for Module 3 and \( x/D_h = 2.60 \) for Module 4.

Sector Averaged Unmixedness

Figure 192 through Figure 194 shows the sector averaged unmixedness in Modules 3 and 4. Just as was seen in Figure 189, Figure 192 shows that the greatest variations in the profiles for both modules occur in the outer annular region. Also, Figure 192 shows that most of the sector averaged unmixedness values at the most upstream location for Module 4 are smaller than those for Module 3. This is noticeably different than the profiles in Figure 189, where the unmixedness values for Modules 3 and 4 were very similar across the annular gap.
Figure 192. Sector averaged unmixedness at \(x/D_h = 0.89\) for Module 3 and \(x/D_h = 0.87\) for Module 4.

In Figure 193 and Figure 194, the trend of diminishing variation in the unmixedness profiles can be seen, as can the fact that the unmixedness values for Module 4 are smaller than those of Module 3. In Figure 193, the unmixedness values range between 0.230 and 0.339 for Module 3 and 0.215 and 0.260 for Module 4. It should be noted that the majority of values for Module 4 in Figure 193 are smaller than 0.250. In Figure 194 the unmixedness values range between 0.230 and 0.255 for Module 3 and 0.219 and 0.237 for Module 4. Thus, the sector averaged unmixedness profiles clearly show that the unmixedness is lower in Module 4 as compared to Module 3. Also, as was the case in Figure 191, the unmixedness values for Modules 3 and 4 in Figure 194 are consistent with the unmixedness values observed by Frey et al. [11].
Figure 193. Sector averaged unmixedness at $x/D_h=1.74$ for Module 3 and $x/D_h=1.63$ for Module 4.

Figure 194. Sector averaged unmixedness at $x/D_h=2.60$ for Module 3 and $x/D_h=2.60$ for Module 4.
Spectrum Analysis

In addition to analyzing the mean and RMS velocity and methane profiles for each module, the spectrum of the data was analyzed as well. Since methane concentration data was collected at 2000 Hz, and 4096 data points were taken at every location, it was possible to analyze the spectrum of the methane concentration at every location. However, this is not possible with the axial and tangential velocity data. Axial and tangential velocity data collection rates of several hundred Hz were achieved in the middle of the annular region for both modules. In the inner and outer annular regions though, the maximum data rate was lower and it was not possible to collect sufficient data points for a spectrum analysis.

Thus, the spectrum of the axial and tangential velocity are presented for both modules at the middle point of the annular region, which corresponds to a value of $r/R = 0.51$. The figures for the velocity spectrum are presented with spectrum data from all seven axial locations at a constant $\theta$ angle on the same plot. This is done so as to allow for examination of any changes in the spectrum as the flow progresses through each module. For the concentration data, the spectrum are again presented with data from all seven axial locations at a constant $\theta$ angle on the same plot. However, the concentration spectrum data is presented for the inner most annular point at which data was taken ($r/R = 0.085$), the middle annular point ($r/R = 0.51$, the same as for velocity data), and the outer most annular point ($r/R = 0.96$).

For both the velocity and methane concentration spectrum data, the graphs have been scaled to the number of decades on the horizontal and vertical axes so that the slope of the plots may be visually inspected. Also, on each graph a line with a slope of $-5/3$
has been placed so that the slope of the plots may be compared to this value. As discussed by Tennekes and Lumley [20], the power spectral density of turbulent flows will typically decay with a slope of –5/3, which is indicative of homogeneous turbulence that is receiving energy at large scales and dissipating energy at small scales.

Axial Velocity Spectrum

Figure 195 through Figure 206 show the spectra of the axial velocity data from the radial location \( r/R = 0.51 \). Visual inspection of the tangential plots reveals that the spectrum plots for the Module 3 axial velocity data are similar to those of Module 4, and have a slope which is smaller in magnitude than –5/3.
Figure 195. Axial velocity spectrum vs. $x/D_h$ for Module 3, $\theta = 0$ deg.
Figure 196. Axial velocity spectrum vs. x/Dh for Module 4, θ = 0 deg.
Figure 197. Axial velocity spectrum vs. x/Dₜ for Module 3, θ = 6 deg.
Figure 198. Axial velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 6$ deg.
Figure 199. Axial velocity spectrum vs. $x/D_h$ for Module 3, $\theta = 12$ deg.
Figure 200. Axial velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 12$ deg.
Figure 201. Axial velocity spectrum vs. $x/D_h$ for Module 3, $\theta = 18$ deg.
Figure 202. Axial velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 18$ deg.
Figure 203. Axial velocity spectrum vs. $x/D_h$ for Module 3, $\theta = 24$ deg.
Figure 204. Axial velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 24$ deg.
Figure 205. Axial velocity spectrum vs. $x/D_h$ for Module 3, $\theta = 30$ deg.
Figure 206. Axial velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 30$ deg.
Figure 207 through Figure 218 show the spectra of the tangential velocity data from the radial location $r/R = 0.51$. Visual inspection of the tangential plots reveals that, like the axial velocity spectrum plots, the spectrum for the Module 3 tangential velocity data are similar to those of Module 4, and have a slope that is smaller in magnitude than $-5/3$.

Figure 207. Tangential velocity spectrum vs. $x/D_h$ for Module 3, $\theta = 0$ deg.
Figure 208. Tangential velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 0$ deg.
Figure 209. Tangential velocity spectrum vs. $x/D_h$ for Module 3, $\theta=6\text{ deg.}$
Figure 210. Tangential velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 6$ deg.
Figure 211. Tangential velocity spectrum vs. x/Dh for Module 3, θ = 12 deg.
Figure 212. Tangential velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 12$ deg.
Figure 213. Tangential velocity spectrum vs. x/D_h for Module 3, θ= 18 deg.
Figure 214. Tangential velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 18$ deg.
Figure 215. Tangential velocity spectrum vs. $x/D_h$ for Module 3, $\theta=24$ deg.
Figure 216. Tangential velocity spectrum vs. $x/D_h$ for Module 4, $\theta = 24$ deg.
Figure 217. Tangential velocity spectrum vs. $x/D_h$ for Module 3, $\theta=30$ deg.
Figure 218. Tangential velocity spectrum vs. x/D_h for Module 4, θ = 30 deg.

As previously discussed, it is obvious from the spectrum figures of both axial and tangential velocity for both modules that the plots have a slope considerably smaller in magnitude to the line of slope \(-5/3\). However, the plots do show a negative slope as would be expected for turbulent flow. The reason for this difference is likely to be largely due to the fact that the data rate for the LDV was typically in the range of 300 Hz,
which is far less than the fluctuations of the smallest turbulent eddies. The size and frequency of the smallest turbulent eddies (those at the Kolmogorov microscale) are calculated from Tennekes and Lumley [20] by Equations (19) and (20) below:

\[
\eta_k = \left( \frac{\nu R}{V_{\text{bulk}}} \right)^{0.25} \quad f_k = \left( \frac{V_{\text{bulk}}}{\nu R^2} \right)^{0.25}
\]

where \(\eta_k\) and \(f_k\) are the length scale and frequency (respectively) of the Kolmogorov eddies, and \(\nu\) is the kinematic viscosity of the air. \(\eta_k\) and \(f_k\) are calculated to be .01 mm and 131800 Hz, respectively. Since the maximum achievable sampling rate of the LDV was several orders of magnitude lower than the fluctuations of these eddies, it is not unexpected that the spectrum data of the velocity do not fully capture the effect of turbulence in the velocity field.

In addition to the smallest turbulent eddies, the LDV may have had difficulty capturing the largest eddies as well. The frequency of the fluctuation of the largest eddies in the flow (those at the integral scale) can be estimated by Equation (21):

\[
f_m = \frac{V_{\text{bulk}}}{R}
\]

where \(V_{\text{bulk}}\) is the bulk velocity, \(R\) is the distance of the annular gap, and \(f_m\) is the frequency of the fluctuations of the eddies at the integral scale. The value of \(f_m\) was approximately 1000 Hz for both modules and therefore not captured by the several hundred Hz sampling rate of the LDV. Since the \(-5/3\) slope decay occurs over the range between the integral and Kolmogorov scales, it is not unexpected that the spectrum plots of the velocity data do not decay at \(-5/3\), since the sampling rate of the LDV was insufficient to capture this behavior.
Even though the LDV sampling rate was too low to capture the \(-5/3\) slope decay of the flow, the velocity spectrum plots of the two modules are similar to one another, and the spectrum plots of the axial velocity are similar to those of the tangential velocity.

Fuel Concentration Spectrum

Figure 219 through Figure 254 show the spectrum data of the methane concentration data in both Modules 3 and 4. As previously discussed, the spectrum for the methane concentration data are presented with data from all seven axial locations at a constant $\theta$ angle on the same plot. Also, the methane concentration spectrum data is presented for the inner most annular point at which data was taken ($r/R = 0.085$), the middle annular point ($r/R = 0.51$), and the outer most annular point ($r/R = 0.96$) for both modules. The analysis of the spectrum of the methane concentration data at the inner and outer annular regions was possible since, unlike the LDV, the concentration probe did not suffer from a reduced data rate in these regions.
Figure 219. CH$_4$ concentration spectrum for Module 3 vs. x/D$_h$ at $\theta = 0$ deg., r/R = 0.085.
Figure 220. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta= 0$ deg., $r/R= 0.085$. 
Figure 221. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 0 deg., r/R = 0.51.
Figure 222. CH₄ concentration spectrum for Module 4 vs. x/Dₙ at θ = 0 deg., r/R = 0.51.
Figure 223. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 0 deg., r/R = 0.96.
Figure 224. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 0 deg., r/R = 0.96.
Figure 225. CH$_4$ concentration spectrum for Module 3 vs. x/D$_h$ at $\theta=6$ deg., r/R= 0.085.
Figure 226. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 6 deg., r/R = 0.085.
Figure 227. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 6 deg., r/R = 0.51.
Figure 228. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 6 deg., r/R = 0.51.
Figure 229. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 6 deg., r/R = 0.96.
Figure 230. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 6 deg., r/R = 0.96.
Figure 231. CH$_4$ concentration spectrum for Module 3 vs. x/D$_h$ at $\theta=12$ deg., r/R= 0.085.
Figure 232. CH$_4$ concentration spectrum for Module 4 vs. x/D$_h$ at $\theta=12$ deg., r/R=0.085.
Figure 233. CH$_4$ concentration spectrum for Module 3 vs. x/D$_h$ at $\theta$ = 12 deg., r/R = 0.51.
Figure 234. CH$_4$ concentration spectrum for Module 4 vs. $x/D_h$ at $\theta = 12$ deg., $r/R = 0.51$. 
Figure 235. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 12 deg., r/R = 0.96.
Figure 236. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 12 deg., r/R = 0.96.
Figure 237. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ= 18 deg., r/R= 0.085.
Figure 238. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 18 deg., r/R = 0.085.
Figure 239. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 18 deg., r/R = 0.51.
Figure 240. CH$_4$ concentration spectrum for Module 4 vs. x/D$_h$ at $\theta = 18$ deg., r/R = 0.51.
Figure 241. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 18 deg., r/R = 0.96.
Figure 242. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 18 deg., r/R = 0.96.
Figure 243. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 24 deg., r/R = 0.085.
Figure 244. CH$_4$ concentration spectrum for Module 4 vs. x/D$_h$ at $\theta$ = 24 deg., r/R = 0.085.
Figure 245. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ= 24 deg., r/R= 0.51.
Figure 246. CH$_4$ concentration spectrum for Module 4 vs. x/D$_h$ at $\theta = 24$ deg., r/R = 0.51.
Figure 247. CH₄ concentration spectrum for Module 3 vs. x/Dₜ at θ = 24 deg., r/R = 0.96.
Figure 248. CH$_4$ concentration spectrum for Module 4 vs. x/D$_h$ at $\theta =$ 24 deg., r/R = 0.96.
Figure 249. CH₄ concentration spectrum for Module 3 vs. x/Dₙ at θ = 30 deg., r/R = 0.085.
Figure 250. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 30 deg., r/R = 0.085.
Figure 251. CH$_4$ concentration spectrum for Module 3 vs. x/D$_h$ at $\theta$ = 30 deg., r/R = 0.51.
Figure 252. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 30 deg., r/R = 0.51.
Figure 253. CH$_4$ concentration spectrum for Module 3 vs. x/D$_h$ at $\theta = 30$ deg., r/R = 0.96.
Figure 254. CH₄ concentration spectrum for Module 4 vs. x/Dₜ at θ = 30 deg., r/R = 0.96.
Examination of the spectrum plots of the methane concentration for the two modules shows that they follow the trend of the line with a slope of \(-5/3\) much more closely than the axial and tangential velocity spectrum plots. Tennekes and Lumley [20] discussed how the typical trend for turbulent flow is for turbulence to receive energy at large scales and dissipate that energy at small scales, and to be homogeneous in nature. The fact that the spectrum plots for both modules closely follow this line shows that this trend is being followed by the flow in both Modules 3 and 4. In the case of this work, the swirl vanes are an obvious source of large scale turbulence. Also, as with the velocity spectrum plots, the methane concentration spectrum data for Module 3 and Module 4 are similar to one another.

Although the sampling rate of the concentration probe was nearly two orders of magnitude less than the frequency of fluctuation of the eddies at the Kolmogorov length scale, it was much greater than the sampling rate of the LDV. Thus, it can be expected that the concentration data will more effectively capture the behavior of the turbulence in the flow field. When examining the spectrum figures for the concentration data is it important to remember that the concentration probe can only resolve frequencies in concentration fluctuation up to approximately 240 Hz. Thus, any preferred frequencies that appear in the spectrum plots above 240 Hz may be ignored as noise. This happened quite rarely in the spectrum plots.

One preferred frequency that did appear quite often in the spectrum plots was 142 Hz. This frequency appeared for both Modules 3 and 4 intermittently throughout the flow field. For example, the 142 Hz frequency appears at nearly all of the axial locations in Figure 251, but at only two of the axial locations in Figure 247 (both figures are from
Module 3). The reason for this intermittent appearance of the 142 Hz peak is the different θ values of the various data. When the spectral data was being post processed (one radial location at a time), this peak at 142 Hz was often observed begin to emerge in the data at a particular radial location, reach a maximum as the radial location changed, and then diminish at a further radial location. This behavior suggests that the 142 Hz peak is the result of concentration fluctuations due to flow emanating from the swirl vanes, which would be periodically present in the flow. It should be noted that this peak was observed throughout the length of the two modules, whereas the variations in mean axial and tangential velocity and mean concentration were observed to diminish by the time the flow reached the end of the modules.

The intensity of this preferred frequency was seen to decrease slightly along the length of the modules. For example, in Figure 234 the 142 Hz frequency has a power spectral density of 0.0033 at x/D_n = 0.87, while at x/D_n = 2.21 and 2.60 its power spectral density is approximately three times lower. Also, in Figure 254 the power spectral density of the 142 Hz peak is 0.004 at x/D_n = 1.06 and is 0.003 at x/D_n = 2.60, which is a decrease of only 25%. In examining the spectrum data for both modules, it was found that the power spectral density of the 142 Hz peak was typically on the same order of magnitude at the most downstream location as at the most upstream location. For both modules, the maximum power spectral density value (observed at the most upstream axial locations) of the 142 Hz peak was typically 0.004 to 0.0015. Thus, it can be seen that the flow throughout the modules is affected by this fluctuation in methane concentration, and that the relative strength of this fluctuation was similar in the modules.
CONCLUSIONS

The velocity and fuel concentration fields of two different swirler modules have been extensively examined. Of primary concern is the effect that the different characteristics of the two modules will have on the mixing of fuel and air as the flow progresses through them.

Both the velocity and concentration data are very consistent in showing that the variations of the velocity and concentration profiles are smaller in magnitude across the annular cross section in Module 4 than in Module 3. In addition, these variations are seen to diminish at axial locations further upstream in Module 4 than in Module 3. This behavior of smaller variations and more rapid mixing of fuel and air shown by Module 4 would have the favorable effect of reducing the levels of unmixedness in the flow in Module 4 more so than in Module 3, and indeed the unmixedness profiles show that the unmixedness of Module 4 is lower than that of Module 3. This is indicative of better mixing performance by Module 4 versus Module 3.

The superior mixing performance of Module 4 is a very significant finding since it has been shown by Fric [9] and Mongia et al. [10] as well as other researchers that NOX formed by the thermal mechanism can be reduced as the levels of unmixedness in the fuel/air mixture are reduced. One important aspect of the mixing of fuel and air in the flow is the RMS velocity of the flow, and the data showed that the axial and tangential RMS velocity values were larger for Module 4 than for Module 3. Thus, the higher RMS velocity values of Module 4 are likely a contributing factor of the velocity field to the better mixing performance of Module 4.
The spectrum data from the two modules (both velocity and concentration spectrum data) are similar to one another, and the concentration spectra for both modules exhibit a preferred frequency at approximately 142 Hz, and this frequency appears intermittently throughout the flow of both modules. Although the power spectral density of the 142 Hz frequency does decrease as the flow progresses through the modules, it is still on the same order of magnitude at the most downstream location as at the most upstream location. The fact that the 142 Hz peak is present throughout the entire length of the modules shows that the effect of the swirl vanes on the flow is persistent and still affecting the fuel concentration even at the most downstream location. The mean concentration values have become uniform across the annular cross section of the modules, but the effect of the swirl vanes is still present.

The velocity spectrum of the two modules are similar to one another, but do not follow the trend of having a \(-5/3\) slope decay due to the fact that the sampling rate of the LDV was smaller than the frequency of the fluctuations of the eddies at the macroscale. The concentration spectrum data for both modules, however, do closely follow the \(-5/3\) slope trend. The fact that this trend is followed suggests that large scale structures contribute most of the turbulent energy in the flow, and that the turbulent energy is then dissipated at small scales.

Since the swirl vanes are large scale structures which influence the flow field, the turbulence generated by the swirl vanes is likely to be an important contributor to the mixing of fuel and air in the flow through the modules. This conclusion is supported by the work of Frey et al. [11], who found that the mixing of fuel and air in the flow field of a gas turbine mixer was strongly affected by the large scale turbulence of the swirl vanes.
The work of Ahmed et al. [17] and Puri et al. [16] also showed that the flow emanating from swirl vanes can be highly dissipative, which would promote the rapid mixing of fuel and air. The fact that the fluctuations across the annular region in the axial velocity profiles and the mean methane concentration profiles were smaller for Module 4 even at the most upstream location compared to Module 3 also supports the conclusion that the region near the swirl vanes has an impact on the flow.

Frey et al. [11] also concluded that the length of the gas turbine mixer is an important factor in the unmixedness of the flow at the exit of the hardware, and in the mean concentration plots in this work it can be seen that the effect of the length of the premixer is significant. Significant decreases in the magnitude of the fluctuations in the mean concentration were observed to occur over distances comprising only 30% of the length of the premixer.

In summary, the data from two gas turbine mixers has been shown to support the fact that the mixing of the fuel and air is significantly affected by the large scale turbulence caused by the swirl vanes, and the spectrum data has shown that the effect of the swirl vanes is present throughout the length of the modules. From the data in this work, it can be seen that the flow conditions generated by the 55° swirl angle of Module 4 will yield more favorable mixing of the fuel and air (lower levels of unmixedness) in the flow.
LIST OF REFERENCES

The uncertainty of the velocity measurements was governed by several factors, the first of which was the readability of a manometer connected to an orifice plate, used to measure the flow through the test rig. The orifice plate was mounted downstream of the acrylic tube (see Figure 2), and a manometer was connected to pressure taps mounted upstream and downstream of the orifice plate. A changing manometer reading would be indicative of a change in the flow rate through the test rig (and therefore affect the velocity measurements), and so it was routinely checked to be sure that its value had not changed. The readability of the manometer was 2.8%. A second factor which influenced the flow rate through the test rig is the rotational speed of the fan itself. The rotational speed of the fan was determined by the power delivered to it by the wall mounted electric circuit. Although the amount of power delivered did not vary significantly, it was inevitably influenced by other electrical loads in the building where this research was conducted. Hence, the rotational speed of the fan could have changed slightly, and therefore this must be taken into account in the uncertainty analysis of the velocity measurements. Based on measurements using a digital voltmeter of various 3-phase circuits and their voltage fluctuations, a typical value for the variation in voltage for such circuits is 2.3%.

The above variations in manometer reading and voltage supplied to the fan motor gives a specific uncertainty to the velocity measurements. Based on the calculation of total uncertainty by combining elemental errors as discussed in Figliola and Beasley [24], and given by Equation (22), the uncertainty for the velocity measurements is 4.9%.

\[
Un = \sqrt{\left(e_{\text{manometer}}\right)^2 + \left(e_{\text{voltage}}\right)^2}
\]  

(22)
where $U_n$ is the total uncertainty for the velocity measurements, $e_{\text{manometer}}$ is the uncertainty due to the manometer (2.8%), and $e_{\text{voltage}}$ is the uncertainty due to the manometer (4.0%). It should be noted that these variations in readings represent the worst observed scenario. The manometer reading, for example, rarely fluctuated as much as 2.8%, and hence it is likely that the uncertainty of the velocity measurements was often less than 4.9%. However, even with an uncertainty of 4.9%, useful conclusions can be drawn from the trends in the normalized axial and tangential velocity data.

This uncertainty has been shown to scale in the figures below, which are the same as Figure 17 through Figure 20. The uncertainty is depicted as the length of the horizontal bar in the upper right hand corner of each figure. As can be seen, the data points in the normalized tangential velocity profiles in particular lie within the range of uncertainty of each other, which supports the conclusion that the tangential velocity is unaffected by $\theta$. In the normalized axial velocity plots, many of the variations of the profiles are outside the range of experimental error, which shows that there is indeed an effect of $\theta$ on the normalized axial velocity profiles. In Figure 255, this can especially be seen in the middle annular region. In Figure 257, the profiles are much closer to the range of error of one another, which shows that the variation between the data points of the profiles in Figure 257 are not likely due to a strong effect of $\theta$ on the flow.
Figure 255. Mean axial velocity at $x/D_h=0.87$ for Module 4 with ± 4.9% error bar.

Figure 256. Mean tangential velocity at $x/D_h=0.87$ for Module 4 with ± 4.9% error bar.
For the concentration probe, as previously discussed, 4096 points were taken with only air flowing through the system prior to taking data with methane in the system at each individual location. This was done so that the effect on the data of time varying fluctuations in the baseline voltage of the probe would be minimized. Implementing this
practice resulted in the baseline voltage of the concentration probe changing by approximately 0.8% at most from one location to the next. The significance of these fluctuations in the baseline voltage of the concentration probe is that if the baseline voltage changes between the time that the baseline data is recorded (with no methane in the system) and the time that data is collected with methane in the flow, the computed concentration of methane will be less accurate. The baseline voltage changing by 0.8% represents the worst case scenario, as the fluctuations in the baseline voltage were frequently smaller than 0.8%. A baseline voltage fluctuation of .8% would affect the computed methane concentration by 5.5%.

Again, from Figliola and Beasley [24], the uncertainty of the concentration probe will be given by Equation (22), modified to take into account the uncertainties of the concentration data collection system.

\[
Un = \sqrt{(e_{\text{flowmeter}})^2 + (e_{\text{baseline}})^2 + (e_{\text{dark}})^2} \tag{22}
\]

where \( Un \) is the total uncertainty of the methane concentration measurement, \( e_{\text{flowmeter}} \) is the uncertainty due to the flow meter error (3%), \( e_{\text{baseline}} \) is the uncertainty due to the baseline voltage error (5.5%), and \( e_{\text{dark}} \) is the uncertainty due to the dark current error (.004%). Thus, the uncertainty of the concentration probe is given as 6.3% by Equation (19) for the worst case scenario described above.