Cross Fire Simulation Rig

Sponsor: GE Energy

Principle Investigators:
Ben Zinn, Eugene Lubarsky

Participants:
Dimitri Scherbik, Sasha Bibik, Rajeev Atluri, Zachary Cantrell, Emmanuel Oyewole

3/1/2013

Ben T. Zinn Combustion Laboratory, Georgia Institute of Technology, 635 Strong St, Atlanta GA 30318
# TABLE OF CONTENTS

Introduction ........................................................................................................................................... 2
Crossfire Rig Design Overview ............................................................................................................. 2
Experiment Design ............................................................................................................................... 3
Preliminary Testing ............................................................................................................................... 4
Results .................................................................................................................................................. 4
Appendix A: CROSSFIRE RIG DEVELOPMENT PRESENTATION .................................................... 6
Appendix B: FLOW RATE TEST SETUP AND RESULTS ............................................................... 20
Appendix C: SAMPLE TEST RESULTS ............................................................................................. 22
Appendix D: BINARY DATA ................................................................................................................. 26
INTRODUCTION

The primary purpose of the project was to investigate the threshold for flame propagation between two combustors of crossfire rig designed to simulate conditions in a GE gas turbine engine. Figure 1 shows the critical dimensions of the crossfire rig. The rig combustors are connected by a crossfire tube of length, $L$ that allows the flame to propagate from one can to the other. The investigation consisted of five independent variables:

![Crossfire Rig Critical Dimensions](image)

1) $L$ = the length of the cross-fire tube (in)
2) $d_{cf}$ = the diameter of the cross-fire tube (in)
3) $x$ = the distance from the edge of the nozzle to the center of the crossfire tube (in)
4) $m_{air}$ = the mass flow rate of air (lbs/s)
5) $\phi$ = the equivalence ratio (phi)

Each variable except, $L$, was manipulated with all others held constant to determine its effect on the flame propagation. The report includes an overview of the crossfire rig design, a description of the experimental design, preliminary test results, sample data analysis and an appendix containing the crossfire rig images and test results.

CROSSFIRE RIG DESIGN OVERVIEW

Figure 2 shows an overhead view of the crossfire rig. The gray painted portion of the rig consists of the combustion cans and detachable “tube” sections. The “tube” sections are 2, 3, and 4 inches long, and 7 inches in diameter. These sections were repositioned to obtain different values of $x$ (the distance from the edge of the nozzle to the center of the crossfire tube). The crossfire tube was attached to the 4” long tube sections such that its centerline was 2 inches from the edge of the tube section (See Appendix A, Figure 14 for details). The 2” and 3” section served as spacers to increase the value of $x$ from 2 to 4 and 7 inches (see Appendix A, Figure 8 & 9 for detail drawings).
Also shown in Figure 2 are the flow-boxes, which supply the nozzles with a steady, uniform flow of cool air (See Appendix A, Figure 7&12 for detail drawings). General Electric provided the nozzles contained in the flow-boxes. The blue hoses originate from an air plenum that evenly distributes the air to each hose. There are total of five hose connections on each flow box.

To test the different values of crossfire tube diameter ($d_{xf}$): 0.75, 1.25 and 1.75 inches, crossfire inserts with corresponding diameters were installed on the rig (See Appendix A figure 7, 25 & 26 for details). A 5-inch detachable mid-section was also designed to adjust the length of the crossfire tube (L) from 10 to 5 inches (See Appendix A, figure 8 for details).

See Appendix A for detailed drawings of all crossfire rig components.

**EXPERIMENT DESIGN**

All data points tested were provided by the sponsor, GE. Each configuration of rig was tested at three different airflow rates: 0.4, 0.8 and 1.2 lb/s. A total of 72 data points were tested. Figure 3 shows a schematic of the piping and instrumentation of the rig. Photomultipliers (PMT) installed above the viewports were used to detect flame inside each can. Pressure transducers, $P_{c1}$ & $P_{c2}$, were attached upstream of the flow to measure the pressure in the two cans while thermocouples, $T_{c1}$ & $T_{c2}$, were installed in the exhaust nozzles to measure the exist temperatures. All the sensors attached to the rig were connected to a data acquisition system that monitored and recorded the flow rate, pressure, and temperature of the incoming air.

**Figure 3: Piping and Instrumentation Schematic of Crossfire Rig**
A video camera was mounted above the rig to capture videos of each test run.

**PRELIMINARY TESTING**

Prior to data acquisition, a shakedown test was conducted to ensure the fuel passage was designed according to General Electric specifications. The inner and outer fuel channels on the nozzle were adjusted to have a 35/65 split by adding restrictors with the appropriate inner diameter. Table 1 shows the results of the flow rate test. See Appendix B for flow rate test details and results.

**Table 1: Flow Rate Test Results**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Restrictor LD. (in)</th>
<th>Pressure (psia)</th>
<th>Temperature (°C)</th>
<th>Q (ACFM)</th>
<th>Flow (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 1</td>
<td>Test 2</td>
</tr>
<tr>
<td>Fuel Passage 1</td>
<td>0.2044</td>
<td>46.66</td>
<td>46.84</td>
<td>21.43</td>
<td>22.49</td>
</tr>
<tr>
<td>(Outer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Passage 2</td>
<td>0.150</td>
<td>33.74</td>
<td>45.96</td>
<td>21.53</td>
<td>22.45</td>
</tr>
<tr>
<td>(Inner)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Two tests with each restrictor
*Each test was approximately 60 seconds
*The recorded values are the averaged values over the number of data points
*Flow % Passage 1, 2 = \[(Q_{Passage 1} + Q_{Passage 2})/2\]* 100
*Refer to ‘Flowrate_Test_062612.xls’ for raw data

**RESULTS**

Figure 4 and 5 are time histories of the pressure, temperature, and photomultipliers. Such time histories and live video were made for each test point. After each test, the video was reviewed along with the time histories for each test point in order to verify initial observations. If visual evidence was not definitive, these histories were used for deeper analysis. Time histories for all test points have been submitted to General Electric.

**Figure 4: Pressure and Temperature Time History**

![Figure 4: Pressure and Temperature Time History](image-url)
In accordance with the sponsor’s request the test data was provided in binary format shown in Table 2. The primary can, referred to as Can 2, was equipped with the igniter. “2, 1” indicates that cross-fire occurred, and Can 2 ignited before Can 1 while “N” indicates that crossfire did not occur.

There were several cases of combustion instabilities such as rumble. There were other instances where cross-fire occurred, but the pressure spike in the secondary combustor (Can 1) blew out the flame in the primary combustor (Can 2) and extinguished the flames in both cans. In some tests, the same scenario occurred, but the secondary can remained ignited while the flame in the primary can was extinguished. All the binary data can be found in Appendix D, along with notes on unusual cases.

**Figure 5: Photo Multiplier Time History**

![Photo Multiplier Time History](image)

**Table 2: Sample Binary Data**

<table>
<thead>
<tr>
<th>Date</th>
<th>Test #</th>
<th>Configuration</th>
<th>Flow Condition</th>
<th>Ignition</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/13/12</td>
<td>2</td>
<td>1.25</td>
<td>10</td>
<td>0.62</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>0.70</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>0.85</td>
<td>1.02</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>0.95</td>
<td>0.96</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>1.05</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>1.15</td>
<td>1.02</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>1.20</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td>1.25</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>0.60</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>0.40</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>0.60</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Development of the Cross-Fire Ignition Optimization Rig

Presented on June 20th, 2012

Co-Principle Investigators:
Ben Zinn, Eugene Lubarsky

Participants:
Dmitri Scherbik, Sasha Bibik, Rajeev Atluri, Jeff Marks, Emmanuel Oyewole, Matt Harner, Zach Cantrell, Ryan Burns, Domingo Uceda

Figure 6

Goal

To understand the threshold for a flame to propagate from one can to an adjacent can

Figure 7
**Cross-fire Simulation Rig - Overview**

**Single Can Conditions**
- \( \text{Air Flow} = 0.2, 0.4, 0.6 \text{ lb/s} \)
- Ambient Temp, Pressure
  - \( \Phi = 1 \)
  - \( PR_{can} = 1.01 \& 1.04 \)

**Geometric Ranges**
- \( d_x = 0.75-2.25'' \)
- \( x = 2-7'' \)
- \( L = 10'' \)

Phase 2 of testing would vary "L" parameter as well as an additional cross-talk area between cans near exit.

**Setup:** Single nozzle, swirling and non-swirling flow

**Variable Parameters:** cross-fire tube offset (x), cross-fire tube diameter (\( d_{ax} \)), can back pressure (\( A_{can} \)), can air flow

**Output:** Binary data collection (Cross-fire/No Cross-fire) with an understanding of the threshold in a non-dimensionalized space (\( x/d_{ax}, L/d_{ax} \))

---

**Figure 8**

**Cross-fire Simulation Rig – Test Matrix**

<table>
<thead>
<tr>
<th>Test Point</th>
<th>( d_{xf} )</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1.75</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>2.25</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>0.75</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>1.25</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>1.75</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>2.25</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>0.75</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>1.25</td>
<td>7</td>
</tr>
<tr>
<td>11</td>
<td>1.75</td>
<td>7</td>
</tr>
<tr>
<td>12</td>
<td>2.25</td>
<td>7</td>
</tr>
</tbody>
</table>

Air Flow Range: 0.2, 0.4, 0.6 lb/s

Ambient Temp, Pressure
- \( \Phi = 1 \)
- Pressure Ratio: 1.01 & 1.04
- \( L = 10'' \)

Total # of Test Points = 72
Variable Diameter Cross-Fire Inserts

*Inserts are only required for dxf = .75", 1.25", and 1.75"
**Shown configuration is L = 5". Air flow nipples will not interfere with each other due to 30° rotated offset between the flow boxes

Figure 7

5" Cross-fire Tube Section

*L = 10" when this 5" tube is connected to the 4" can section
*A 10" tube can be connected instead of the 5" tube for L = 15" for later stages of testing

Figure 8
Figure 12

Flow Box Assembly with Nozzle

Figure 13

4" Can Section with Viewport

- Satisfies $x = 2''$ requirement
- dxf = 2.25" is built-in
- Provides connections for cross-fire tube
- 1.5” view port to check for flame propagation
- PMT also installed on view port
- L=5" for later stages of testing are satisfied when connected to a mirrored section on the other combustor, without any additional tubing
**2" and 3" Can Sections**

**2" Can Section**

**3" Can Section**

Can be moved around to satisfy cross-fire tube position requirements \((x = 2", 4", 7")\)

---

**10" Can Section**

- Mainly to satisfy 19” requirement

---

**Figure 14**

**Figure 15**
Cone Section for Pressure Drop

Figure 16

Flow Box

Figure 17
**Cartridge Assembly**

- GE provided cartridge slides in and connects to cartridge flange.
- Gas fuel connection has also been added.

**Can Holder**

- Nozzle fits flush with the top of the can.
- 3 fittings for igniter and sensors are available at 120° intervals at the angle shown in the schematic.
Spacer Flange

Figure 20

Cartridge Flange

Figure 21
Flowbox Flange

Figure 24

Can Holder Flange 1

Figure 25
Figure 26

Cross-Fire Inserts

Dxf = 0.75", L=10"

Dxf = 1.25", L=10"

Dxf = 1.75", L=10"

Figure 30

Cross-Fire Inserts

I.D.=0.75", L=10”

Insert

I.D.=1.75", L=10”

Insert
Igniter Details

Optional H₂ Supply (plugged)

3/8” Stainless Steel Tube

Ceramic O.D. 1/4” I.D. 1/8”

1/8” Stainless Steel Electrode

Firing Igniter

Figure 31
Preliminary Flow Check Test Setup

Restrictor
Shop Air
K-type Thermocouple
Turbine Flow Meter
Type: FTB-934
Pressure Transducer
Type: PX303-300G5V
Valve

Figure 28

Flow Check Test Data

<table>
<thead>
<tr>
<th>Channel</th>
<th>Restrictor I.D. (inch)</th>
<th>Pressure (psia)</th>
<th>Temperature (°C)</th>
<th>Q (ACFM)</th>
<th>Flow (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 1</td>
<td>Test 2</td>
</tr>
<tr>
<td>Fuel Passage 1</td>
<td>0.2044</td>
<td>46.66</td>
<td>46.84</td>
<td>21.43</td>
<td>22.49</td>
</tr>
<tr>
<td>(Outer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Passage 2</td>
<td>0.150</td>
<td>33.74</td>
<td>45.96</td>
<td>21.53</td>
<td>22.45</td>
</tr>
<tr>
<td>(Inner)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Two tests with each restrictor
*Each test was approximately 60 seconds
*The recorded values are the averaged values over the number of data points
*Flow % Passage 1, 2 = \(((Q_{Passage 1}, 2)/(Q_{Passage 1} + Q_{Passage 2})) \times 100
*Refer to ‘Flowrate_Test_062612.xls’ for raw data

Figure 29
APPENDIX C: SAMPLE TEST RESULTS

Figure 36

Figure 37
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
<th>Column 6</th>
<th>Column 7</th>
<th>Column 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data 1</td>
<td>Data 2</td>
<td>Data 3</td>
<td>Data 4</td>
<td>Data 5</td>
<td>Data 6</td>
<td>Data 7</td>
<td>Data 8</td>
</tr>
<tr>
<td>Data 9</td>
<td>Data 10</td>
<td>Data 11</td>
<td>Data 12</td>
<td>Data 13</td>
<td>Data 14</td>
<td>Data 15</td>
<td>Data 16</td>
</tr>
</tbody>
</table>

**APPENDIX D: BINARY DATA**