Understanding Transient Combustion Phenomena in Low-NO$_x$ Gas Turbines
Program Monitor: Mark Freeman

PI: Jacqueline O’Connor, Ph.D.
Co-PI: Dom Santavicca, Ph.D.
RE: Stephen Peluso, Ph.D.
Graduate students: Dan Doleiden, Wyatt Culler, Adam Howie, John Strollo
Undergraduates: Olivia Sekulich

Industry Partner: GE Global Research
Keith McManus, Tony Dean, Fei Han

Mechanical and Nuclear Engineering
Pennsylvania State University
sites.psu.edu/rfdl/
Overview of presentation

— Project motivation and approach
— Review of previous results
— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics
— Conclusions and next steps
Overview of presentation

— Project motivation and approach
— Review of previous results
— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics
— Conclusions and next steps
Objective of the program is to understand, quantify, and predict combustion instability during transient operation.

— Two major deliverables for the program:

1. Fundamental understanding of flow and flame behavior during combustion transients and mechanisms for transition to instability

2. Development of a stability prediction or quantification framework
The transients will be quantified using three different metrics: \textit{amplitude}, \textit{timescale}, and \textit{direction}.
Varying the transient timescales allows for different processes to equilibrate during the transient, changing the path.
Project Management Plan – progress to date

- **Task 1** – Project management and planning
- **Task 2** – Modification of current experimental facility with monitoring diagnostics and new hardware for transient control
- **Task 3** – Map combustor timescales at target operating points
- **Task 4** – Design of transient experiments
- **Task 5** – Fuel split transients (multi-nozzle combustor)
- **Task 6** – Equivalence ratio transients (single- and multi-nozzle)
- **Task 7** – Fuel composition transients (single- and multi-nozzle)
- **Task 8** – Data analysis and determination of prediction/quantification framework
Three types of transients are being considered in both multi-nozzle and single-nozzle combustors

- Fuel-staging transients
  - Multi-nozzle only

- Equivalence ratio transients
  - Multi- and single-nozzle

- Fuel composition transients
  - Multi- and single-nozzle
Experimental facilities include both a single-nozzle and multi-nozzle combustor, fuel splitting on multi-nozzle only.
Hardware modification focused on a valve with linear actuation to control fuel flow transients for fuel-splitting studies.
Single-nozzle combustor is created by plugging four nozzles and using a smaller quartz liner with the same dump ratio.
Overview of presentation

— Project motivation and approach

— Review of previous results

— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics

— Conclusions and next steps
Major Result #1: Fuel staging works both in axisymmetric and non-axisymmetric configurations.
Major Result #2: While instability decay is smooth, instability onset takes longer and is intermittent – direction matters!

Major Result #3: Time-scale of a transient matters in the multi-nozzle combustor, and heat transfer likely plays a role.
Major Result #4: Most significant difference between the single- and multi-nozzle instability is transient timescales

Major findings and remaining questions

1. Fuel staging works both in axisymmetric and non-axisymmetric configurations
   — *What is driving the differences between staging efficacy?*

2. While instability decay is smooth, instability onset takes longer and is intermittent – direction matters!
   — *How do we quantify the intermittency we see during onset?*

3. Time-scale of a transient matters in the multi-nozzle combustor, and heat transfer likely plays a role
   — *What are the flame dynamics occurring during the transition?*

4. Most significant difference between the single- and multi-nozzle instability is transient timescales
   — *How much of a role does flame/flow interaction play on the transient physics?*
Overview of presentation

— Project motivation and approach
— Review of previous results
— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics
— Conclusions and next steps
Short- and long-duration transient behavior was different – long-duration timescales did not scale with the actuation time.

**Short Timescales**

- 1 ms: 17, 18
- 16 ms: 12, 9
- 58 ms: 13, 12

**Long Timescales**

- \( T_{\text{Transient}} = 4000 \text{ ms} \): 8, 11
- \( T_{\text{Transient}} = 10000 \text{ ms} \): 13, 19

**Staging \( \Phi \)**

- PSI vs. Time (s)
The long-duration tests were done slowly enough; system responded quasi-steadily, allowing heat transfer to “keep up”
This steady-state behavior allowed us to see the instability evolve in real time and identify the stability bifurcation point.
Overview of presentation

— Project motivation and approach
— Review of previous results
— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics
— Conclusions and next steps
Quantifying the thermoacoustic damping of the combustor is a way to understand the efficacy of fuel staging.

**Thermoacoustic system model**

\[ \sum_{n=1}^{N} [\ddot{\eta}_n + 2\alpha_n \dot{\eta}_n + \omega_n^2 \eta_n = \dot{q}_n] \]

**Heat release rate model**

\[ \dot{q}_n' = 2\beta_n \dot{\eta}_n - \kappa \eta^2 \dot{\eta}_n \]

**Van der Pol oscillator**

\[ \ddot{\eta}_n + 2 \left( \alpha_n - \beta_n + \kappa \eta_n^2 \right) \dot{\eta}_n + \omega_n^2 \eta_n = \zeta(t) \]

**Autocorrelation function**

\[ k_{\eta_n \eta_n}(\tau) = \exp(-\nu_n \tau) \cos(\omega_n \tau) \]
Damping is a more reliable metric for quantifying suppression because of variations in the bifurcation equivalence ratio.

### Center Nozzle

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Bifurcation Equivalence Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>0.79</td>
</tr>
<tr>
<td>Nozzle 1</td>
<td>0.85</td>
</tr>
<tr>
<td>Nozzle 2</td>
<td>0.83</td>
</tr>
<tr>
<td>Nozzle 3</td>
<td>0.80</td>
</tr>
<tr>
<td>Nozzle 4</td>
<td>0.78</td>
</tr>
</tbody>
</table>

### Nozzle 1

### Nozzle 2
Overview of presentation

— Project motivation and approach
— Review of previous results
— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics
— Conclusions and next steps
Local flame dynamics were measured with a high-speed OH-PLIF system at a rate of 10 kHz, imaging two of five flames.
OH-PLIF provides localized flame oscillation information, which we link back to the heat release rate oscillations.
The first goal of this analysis was to test the hypothesis about phase cancellation as the suppression mechanism with staging.

Unstable:

\[ \phi_{\text{outer}} = 0.70, \phi_{\text{middle}} = 0.70 \quad \phi_{\text{overall}} = 0.70 \]

Stable:

\[ \phi_{\text{outer}} = 0.70, \phi_{\text{middle}} = 0.86 \quad \phi_{\text{overall}} = 0.73 \]

We considered three cases: unstable, center-nozzle staged, and right-nozzle staged, two nozzles with different efficacy.
The unstable case displayed significant flame oscillations, where the adjacent branches oscillated in-phase.
Center nozzle staging showed almost no oscillations, while Nozzle 1 staging still had some coherent oscillations.
We quantify the flame branch oscillations using the lateral movement of the flame and the phase between the branches.
Overview of presentation

— Project motivation and approach

— Review of previous results

— Year 3 major results:
  — Stability bifurcation during long-duration transients
  — Damping quantification
  — Local flame dynamics

— Conclusions and next steps
Wrap-up and Questions

— **Key findings to date**
  — Implemented a number of new quantification metrics for stability in multi-nozzle combustors
  — Quantified the impact of transient timescales on combustor behavior for multi- and single-nozzle combustors
  — Began investigating local flame oscillations as a way to understand the effects of staging and flame dynamics in multi-nozzle systems

— **Next steps**
  — Understand the role of intermittency in the dynamics of transient systems – need to quantify it as well
  — Sensitivity of flame behavior to fuel composition with blends of natural gas + hydrogen
Acknowledgements

— **Penn State:** Dom Santavicca, Bryan Quay, Janith Samarasinghe, Wyatt Culler, Dan Doleiden, Adam Howie, John Strollo, Xiaoling Chen, Jackson Lee, Steve Peluso, Ankit Tyagi, Olivia Sekulich

— **GE Global Research:** Keith McManus, Tony Dean, Janith Samarasinghe, Fei Han

— **DOE/NETL:** Mark Freeman

— College of Engineering Instrumentation Grant Program, Mechanical and Nuclear Engineering at Penn State
Questions?

Understanding Transient Combustion Phenomena in Low-NOₓ Gas Turbines

Project DE-FE0025495, Oct. 2015 – Sept. 2018

Program Monitor: Mark Freeman
PI: Jacqueline O’Connor, Ph.D.
Co-PI: Dom Santavicca, Ph.D.
RE: Stephen Peluso, Ph.D.
Graduate students: Wyatt Culler, Dan Doleiden, Adam Howie, John Strollo
Undergraduates: Olivia Sekulich
Industry Partner: GE Global Research
Keith McManus, Tony Dean, Fei Han

Mechanical and Nuclear Engineering
Pennsylvania State University
sites.psu.edu/rfdl/
Backup slides
The convective time depends on the amount of additional fuel added.

<table>
<thead>
<tr>
<th>Center Staging</th>
<th>Calculated Convective Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>75 ms</td>
</tr>
<tr>
<td>0.80</td>
<td>37 ms</td>
</tr>
<tr>
<td>0.85</td>
<td>25 ms</td>
</tr>
</tbody>
</table>
A general logistic regression is used to obtain the time constants.

Used to model the growth (or decay) of systems that have a lower and upper asymptote
Growth is initially exponential before leveling off
Logistic fits are symmetric, but can be made general to change where the maximum growth rate is
Using a more general logistic regression:

\[ P'(t) = \frac{A - B}{1 + b e^{k(t-t_0)}} + B \]

A: Instability Amplitude
B: Stable Amplitude
k: Logistic Rate (negative is growth, positive is decay)
\( t_0 \): Time offset
b: Pre-exponential factor, typically taken as 1
A general logistic regression is used to obtain the time constants.

Original Equation: \( P'(t) = \frac{A-B}{1 + e^{k(t-t_0)}} + B \)

Fractional Amplitude Characteristic Time:
\[
\frac{A-B}{R} = \frac{A-B}{(1 + e^{k(t-t_0)}) + B}
\]

\( R \) is the amplitude fraction

Solving for \((t - t_0)\)
\[
(t - t_0) = \ln \left( \left( R + \frac{B}{A-B} - 1 \right) \right) \left( \frac{1}{k} \right)
\]

The absolute value of this should be proportional to a time constant
This will not be dependent on valve actuation time

Half-Maximum Time for \( b=1 \) (neglecting zero offset \( B \))
Given by \( t_0 \):
\[
P(t_0) = \frac{A-B}{1 + e^{k(t_0-t_0)}} = \frac{(A-B)}{2}
\]

Will depend on valve actuation time
Both staging strategies, i.e. increasing overall equivalence ratio and keeping overall equivalence ratio constant resulted in successfully suppressing instabilities.
Differences in staging efficacy near the bifurcation point typically relate back to the level of intermittency.

- Sharp transition to coherent phase relationship
- In-phase relationship between heat release rate oscillations and pressure
- Continued, but somewhat intermittent, growth in instability amplitude after coherence switch
Images of forced flames can be decomposed into mean, RMS and phase components to understand instability mechanisms.

\[
\text{Filtered Image} = \text{Mean Image} + \sqrt{2} \times \text{RMS Image} \times \cos(2\pi ft + \text{Phase Image})
\]

Mean, RMS, and phase images are analyzed at different test conditions to determine the effects of fuel staging on time-averaged and phase-averaged flame structure.
Flame structure does not change significantly with additional staging, though center flame has higher heat release.

\[ \phi_{\text{global}} = 0.65 \ (p_{\text{rms}} = 0.024 \text{ psi}) \]
Stable – not staged

\[ \phi_{\text{global}} = 0.70 \ (p_{\text{rms}} = 0.21 \text{ psi}) \]
Unstable – not staged

\[ \phi_{\text{global}} = 0.71 \ (p_{\text{rms}} = 0.20 \text{ psi}) \]
Marginally stable – staged

\[ \phi_{\text{global}} = 0.73 \ (p_{\text{rms}} = 0.027 \text{ psi}) \]
Stable – staged
Line-of-sight chemiluminescence images are acquired at 5° increments around the combustor to create tomographic images.

180° circular track

High-speed camera-intensifier setup

Multi-Nozzle Combustor

Optical Table
Different flame structures are observed between stable unstaged and stable staged cases through tomographic imaging.

![Flame structure images](image-url)

- **No fuel staging**
  - Global $\phi = 0.65$
  - 10 mm, 25 mm, 50 mm, 90 mm images show distinct flame structures.

- **Fuel staging**
  - Global $\phi = 0.7$
  - Similarly, images at 10 mm, 25 mm, 50 mm, 90 mm illustrate unique patterns.
Heat release rate RMS levels are suppressed with staging, though signature is visible even at highest staging amount.

- \( \phi_{\text{global}} = 0.65 \) (\( p_{\text{rms}} = 0.024 \) psi)
  - Stable – not staged

- \( \phi_{\text{global}} = 0.70 \) (\( p_{\text{rms}} = 0.21 \) psi)
  - Unstable – not staged

- \( \phi_{\text{global}} = 0.71 \) (\( p_{\text{rms}} = 0.20 \) psi)
  - Marginally stable – staged

- \( \phi_{\text{global}} = 0.73 \) (\( p_{\text{rms}} = 0.027 \) psi)
  - Stable – staged
Phase of oscillations seems to indicate phase shift in oscillations during staging, possible suppression mechanism.

\[ \phi_{\text{global}} = 0.65 \ (p_{\text{rms}} = 0.024 \text{ psi}) \]

\[ \phi_{\text{global}} = 0.70 \ (p_{\text{rms}} = 0.21 \text{ psi}) \]

\[ \phi_{\text{global}} = 0.71 \ (p_{\text{rms}} = 0.20 \text{ psi}) \]

\[ \phi_{\text{global}} = 0.73 \ (p_{\text{rms}} = 0.027 \text{ psi}) \]
Task 4: Test matrix for initial transient testing considers step-change transients to determine natural time-scales of system.
Impulse transients are executed using a fast-acting proportional control valve.

Feedback Voltage
Scaled Valve Pressure Difference
Control Signal

Scaled Response

Time (s)

0 seconds  2 seconds  4 seconds  6 seconds

High-speed CH* recording start

\( \Phi_{\text{center}} = 0.7 \)

High-speed CH* recording end

\( \Phi_{\text{center}} > 0.7 \)
Both the fluctuation in CH* (blue) and pressure (red) track each other through the transient event.
The growth/decay time of the instability reflects a natural time-scale of the system, and is dependent on staging level.

Center-nozzle: $\phi = 0.8$

Unstable $\rightarrow$ Stable

Stable $\rightarrow$ Unstable

Center-nozzle: $\phi = 0.85$
The growth/decay time of the instability reflects a natural time-scale of the system, and is dependent on staging level.

Unstable $\rightarrow$ Stable

Stable $\rightarrow$ Unstable
Box-and-whisker plots provide a useful way to visualize ensemble data.
Box-and-whisker plots provide a useful way to visualize ensemble data.
The pressures before and after the transient mirror the steady-state test results, showing high repeatability.
The characteristic decay time depends on staging amplitude, but the characteristic rise time does not appear to
The functional form of the growth and decay profiles can help illuminate some of the physics involved in the processes

**Model 1: Damped linear oscillator decaying at a single frequency**

\[ P'(t) = Ae^{-\lambda t} + AB \left( 1 - e^{-\lambda t} \right) \sin(\omega t + \Phi) \]

**Model 2: General Logistic Growth/Decay**

\[ P'(t) = \frac{A - B}{1 + e^{k(t-t_0)}} + B \]

\[ P'(t) = AB e^{-\lambda t} + B \left( 1 - e^{-\lambda t} \right) \sin(\omega t + \Phi) \]
A tomographic reconstruction technique is used to obtain the 3-D chemiluminescence distribution.

(a) Each line-of-sight image is divided into pixel wide horizontal bins

(b) The horizontal bins from each image acquired around the combustor are combined into an array

(c) This array is input into a filtered backprojection algorithm which reconstructs a 2-D cross section of the flame

(d) The cross sections at every axial location are stacked to obtain a 3-D matrix of the flame’s chemiluminescence distribution
Horizontal 2-D slices of the 3-D image illustrate the flame structure at different points downstream of the dump plane.
Time-averaged FSD images

\[ \phi = 0.65, \text{ all nozzles fueled equally} \]

\[ \phi = 0.70, \text{ all nozzles fueled equally} \]

Staged - \( \phi_{\text{outer}} = 0.67, \phi_{\text{middle}} = 0.82 \)

Staged - \( \phi_{\text{outer}} = 0.70, \phi_{\text{middle}} = 0.85 \)
Engine load is typically varied by either varying fuel staging or the equivalence ratio of certain fuel nozzles.

Source: Davis and Black, “Dry Low NO\textsubscript{x} Combustion Systems for GE Heavy-Duty Gas Turbines”
Stability limits of certain operating points are already known, current work focuses on mapping instability with fuel splits.

<table>
<thead>
<tr>
<th>U (m/s)</th>
<th>15.5</th>
<th>18.1</th>
<th>20.7</th>
<th>23.3</th>
<th>25.8</th>
<th>28.4</th>
<th>31.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>0.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Measurements include:**
- Flow rates
- Dynamic pressure
- Surface temperatures
- Global heat release
- High-speed flame imaging

**Goals of Q1/Q2 testing:**

- Quantify steady-state flame behavior and stability
- Develop methodologies for ensuring repeatability
U = 22.5 m/s, $T_{\text{in}} = 200^\circ\text{C}$, fully premixed, unforced

$\varphi = 0.65$

$\varphi = 0.60$

$\varphi = 0.55$

$\varphi = 0.50$

$\varphi = 0.45$
Instabilities may arise as a result of changes in flame shape and flame anchoring that occur with variation in equivalence ratio.
To further investigate the structure of the multi-nozzle flame, 3-D image sets were obtained at $\phi = 0.60$ and $\phi = 0.48$. 
Data from unforced and forced flames are available in a range of operating conditions.

<table>
<thead>
<tr>
<th>Inlet temperature</th>
<th>U (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td>$\phi$</td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>Stable</td>
</tr>
<tr>
<td>0.45</td>
<td>Stable</td>
</tr>
<tr>
<td>0.50</td>
<td>Unstable</td>
</tr>
<tr>
<td>0.55</td>
<td>Poor Stabilization</td>
</tr>
<tr>
<td>0.60</td>
<td>Poor Stabilization</td>
</tr>
<tr>
<td>0.65</td>
<td>Poor Stabilization</td>
</tr>
<tr>
<td>0.70</td>
<td>Cannot Achieve Condition</td>
</tr>
</tbody>
</table>

Inlet temperature = 100°C

Inlet temperature = 150°C

Inlet temperature = 200°C

Inlet temperature = 250°C
An inlet temperature of 200°C and an inlet velocity of 25 m/s was chosen for the steady-state tests.

<table>
<thead>
<tr>
<th>Inlet temperature = 200°C</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
<td>17.5</td>
<td>20</td>
<td>22.5</td>
<td>25</td>
<td>27.5</td>
<td>30</td>
</tr>
<tr>
<td>0.40</td>
<td>Green</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Black</td>
<td>Black</td>
<td>Black</td>
</tr>
<tr>
<td>0.45</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>0.50</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>0.55</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>0.60</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
</tr>
<tr>
<td>0.65</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
</tr>
<tr>
<td>0.70</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Red</td>
<td>Red</td>
</tr>
</tbody>
</table>

Based on the stability maps of fully premixed operation, this condition was chosen as it enables both transition in flame structure and transition to instability by varying fuel flow rate.
<table>
<thead>
<tr>
<th>φ</th>
<th>$T_{in} = 100\degree C$</th>
<th>$T_{in} = 200\degree C$</th>
<th>$T_{in} = 275\degree C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>25 m/s 30 m/s 35 m/s</td>
<td>LBO LBO LBO</td>
<td>LBO LBO LBO</td>
</tr>
<tr>
<td>0.525</td>
<td>LBO LBO</td>
<td>57 Hz 72 Hz 81 Hz</td>
<td>97 Hz 106 Hz</td>
</tr>
<tr>
<td>0.55</td>
<td>LBO 68 Hz 84 Hz</td>
<td>78 Hz 86 Hz 111 Hz</td>
<td>105 Hz 116 Hz</td>
</tr>
<tr>
<td>0.60</td>
<td>71 Hz 96 Hz 117 Hz</td>
<td>94 Hz 110 Hz 124 Hz</td>
<td>111 Hz 125 Hz</td>
</tr>
<tr>
<td>0.65</td>
<td>89 Hz 114 Hz 124 Hz</td>
<td>101 Hz 115 Hz 125 Hz</td>
<td>117 Hz 127 Hz</td>
</tr>
<tr>
<td>0.70</td>
<td>104 Hz 117 Hz 129 Hz</td>
<td>112 Hz 118 Hz 128 Hz</td>
<td>129 Hz 145 Hz</td>
</tr>
</tbody>
</table>

- **stable**
- **unstable**
- **estimate lean blow-off**
### Stability map for GE-15 single-nozzle experiment (FPM)

<table>
<thead>
<tr>
<th></th>
<th>Tin=100 C</th>
<th>Tin=150 C</th>
<th>Tin=200 C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 m/s</td>
<td>25 m/s</td>
<td>30 m/s</td>
</tr>
<tr>
<td></td>
<td>20 m/s</td>
<td>25 m/s</td>
<td>30 m/s</td>
</tr>
<tr>
<td>Φ</td>
<td>0.50</td>
<td>LBO</td>
<td>LBO</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>LBO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- **Green**: stable
- **Red**: unstable
- **Blue**: estimate lean blow-off
Fuel injection strategy for staging

Two options for adding additional fuel to middle nozzle:

1. Inject fuel at swirler → technically premixed
2. Inject fuel at air manifold with a choke → fully premixed

Poravee showed using acetone PLIF, that the fuel and air are well mixed at the nozzle exit of the GE-15 nozzle.

The main difference between these then becomes the type of governing mechanisms during the unstable flame case.
Fuel injection strategy for staging

We currently don’t have a flowmeter that can accurately measure as low of a flow rate as we are planning to run.

Backup option is to use a rotameter.

Solenoid → Flow meter → Middle Nozzle → To Experiment

72