Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

Project DE-FE0025495, Oct. 2015 – Sept. 2018 (now Sept. 2019 with NCE)
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PennState

Overview of presentation

- Project motivation and approach
- Review of previous results
- Year 4 major results:
  - Intermittency quantification
  - Hydrogen effects
- Conclusions and implications

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Objective of the program is to *understand, quantify,* and *predict* combustion instability during ***transient operation***

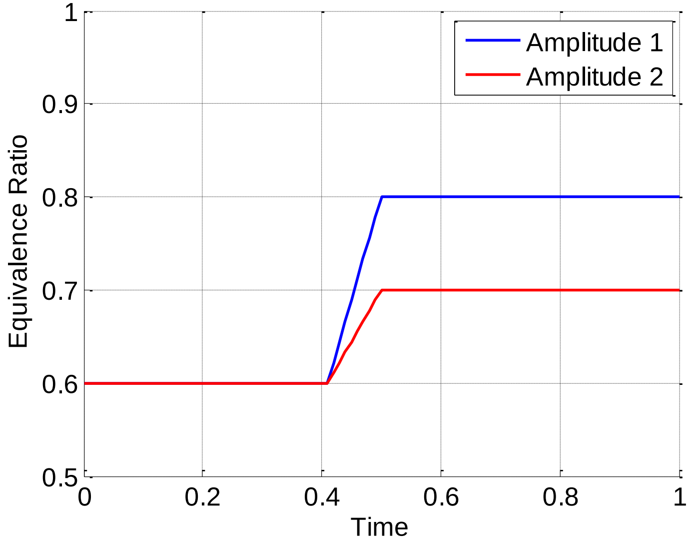
— Two major deliverables for the program:

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

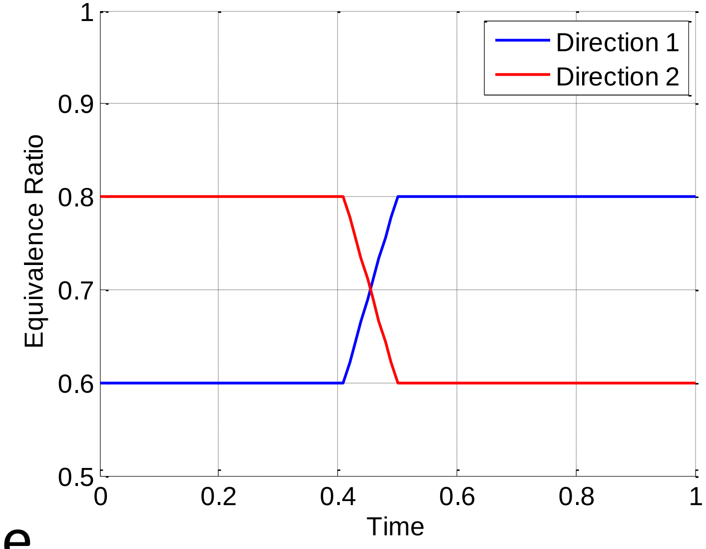
2. Development of a stability prediction or quantification framework

The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

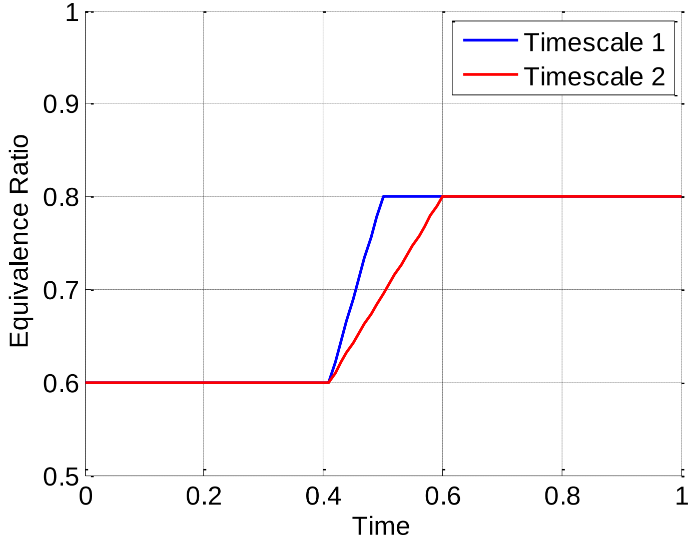
Amplitude



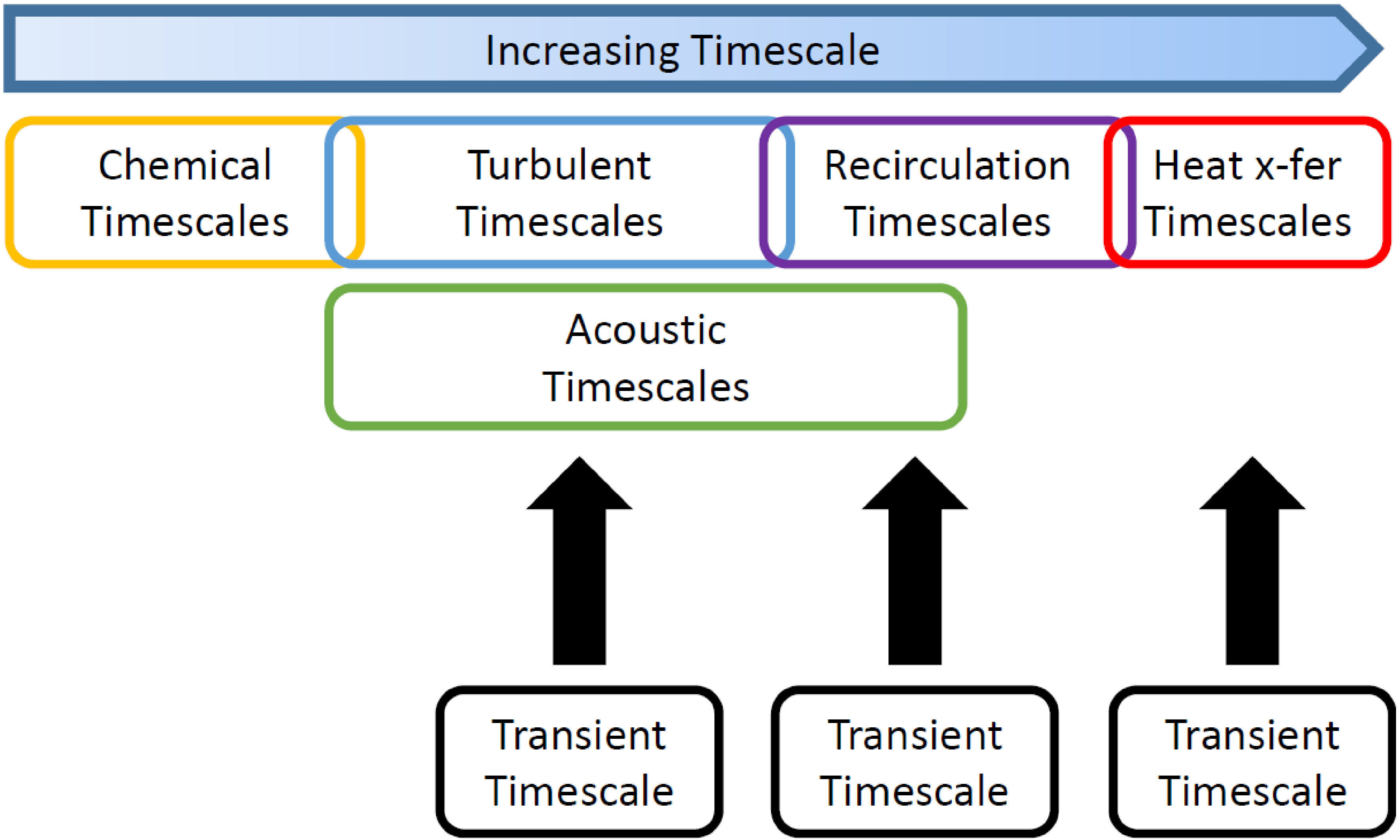
Direction



Timescale



Varying the transient timescales allows for different processes to equilibrate during the transient, changing the path

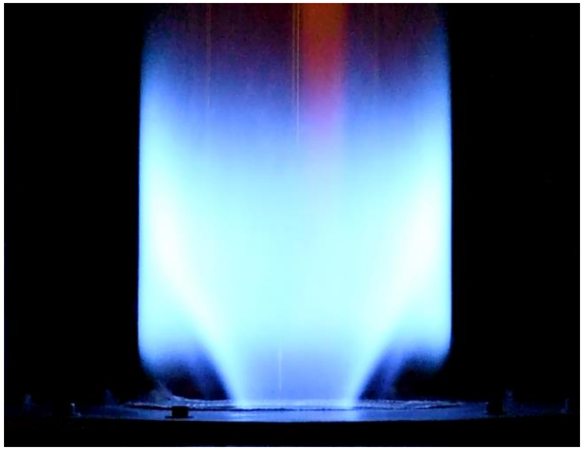


Project Management Plan – progress to date

- **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

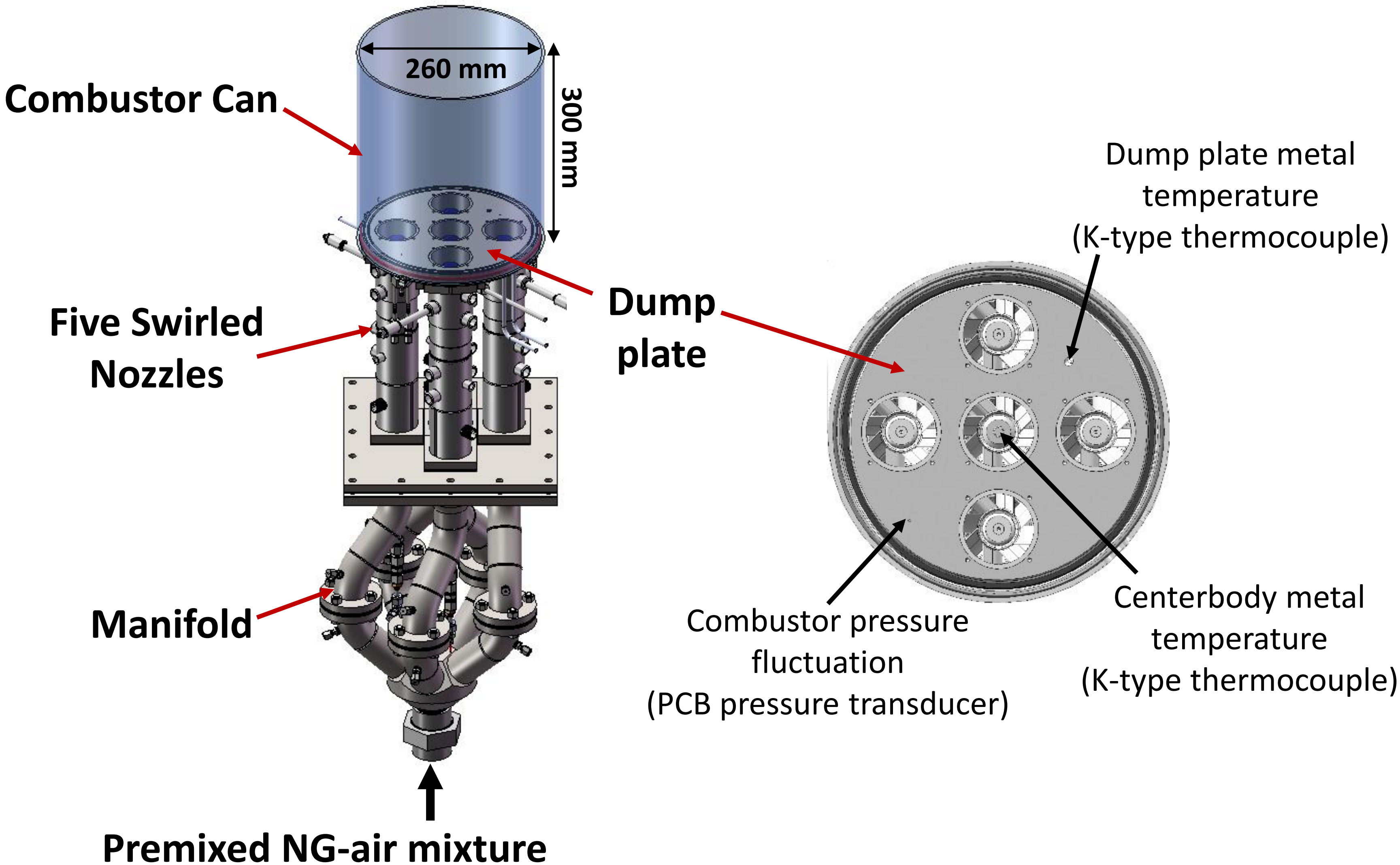
- Fuel-staging transients
  - Multi-nozzle only



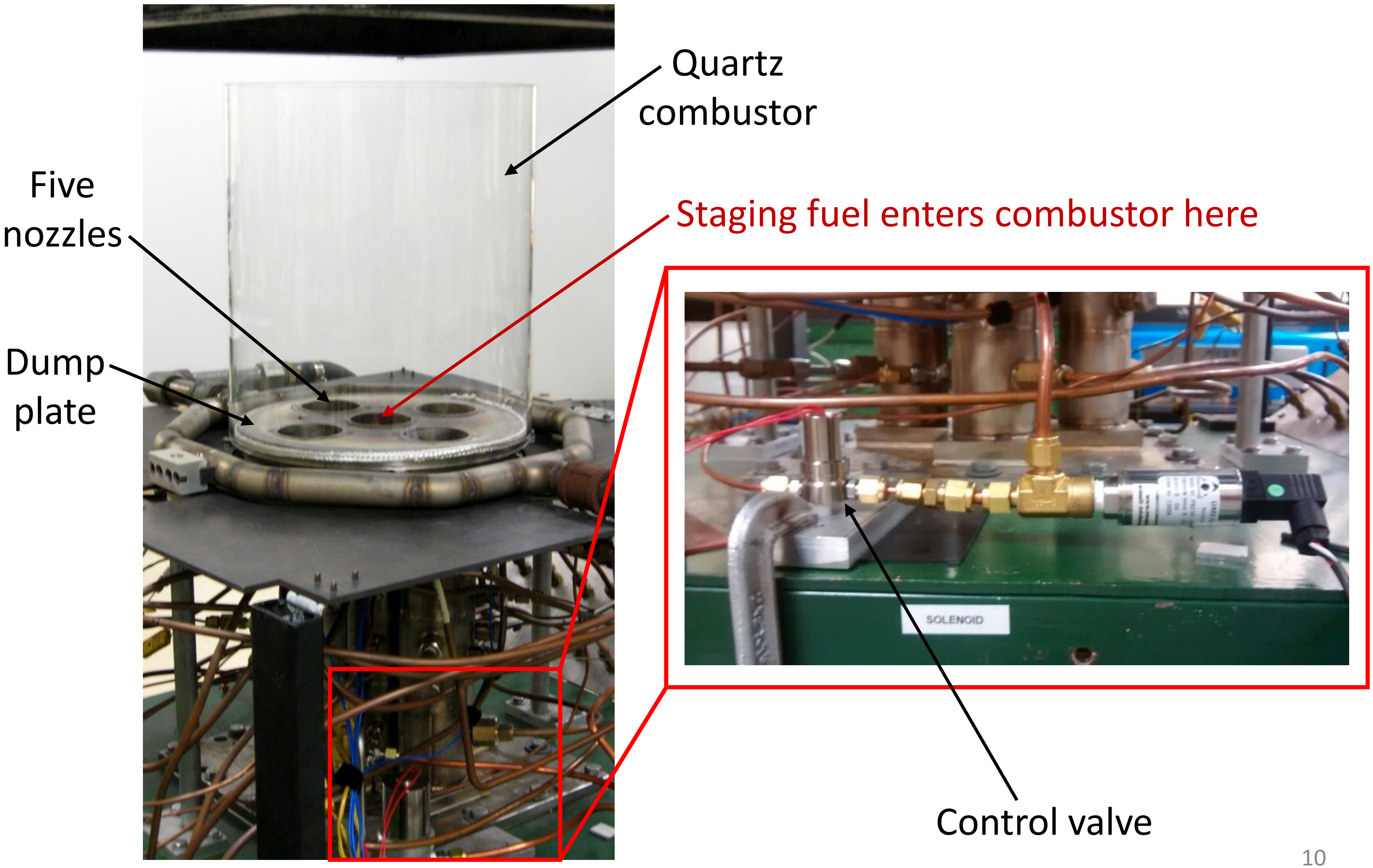
- Equivalence ratio transients
  - Multi- and single-nozzle

- Fuel composition transients
  - Multi- and single-nozzle

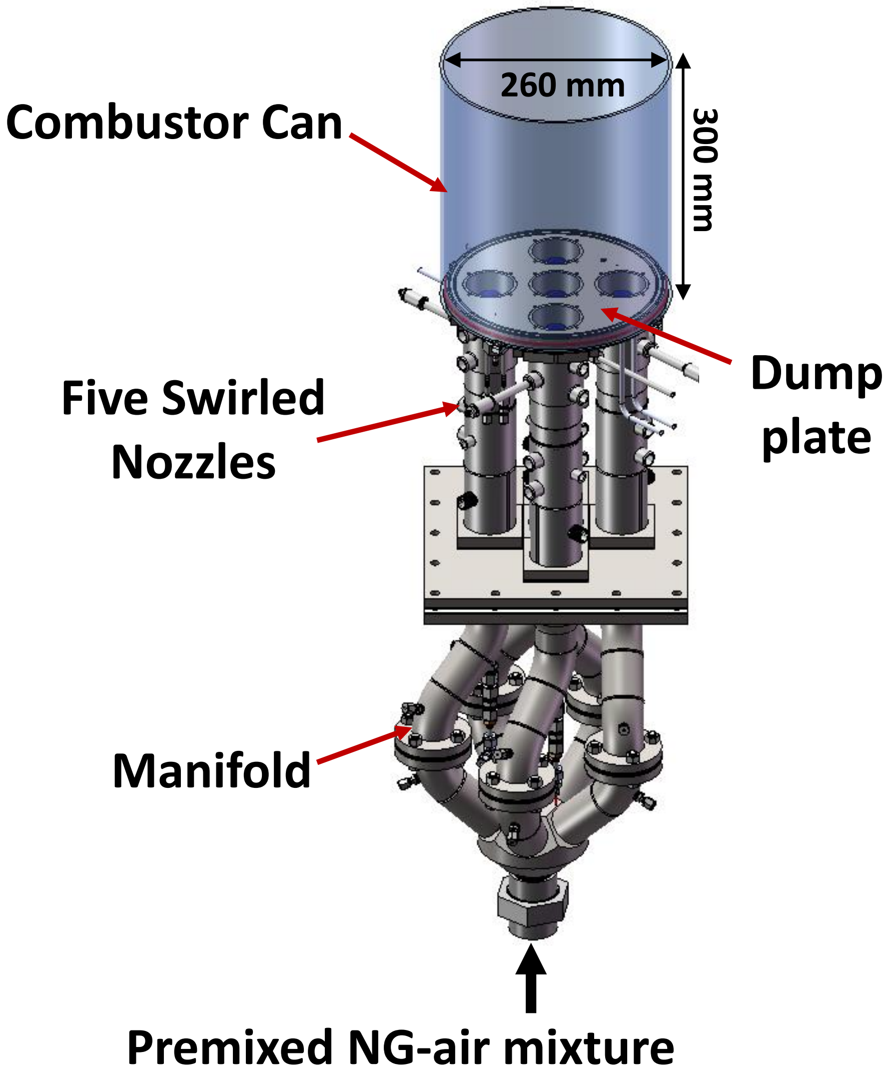
Experimental facilities include both a single-nozzle and multi-nozzle combustor, fuel splitting on multi-nozzle only

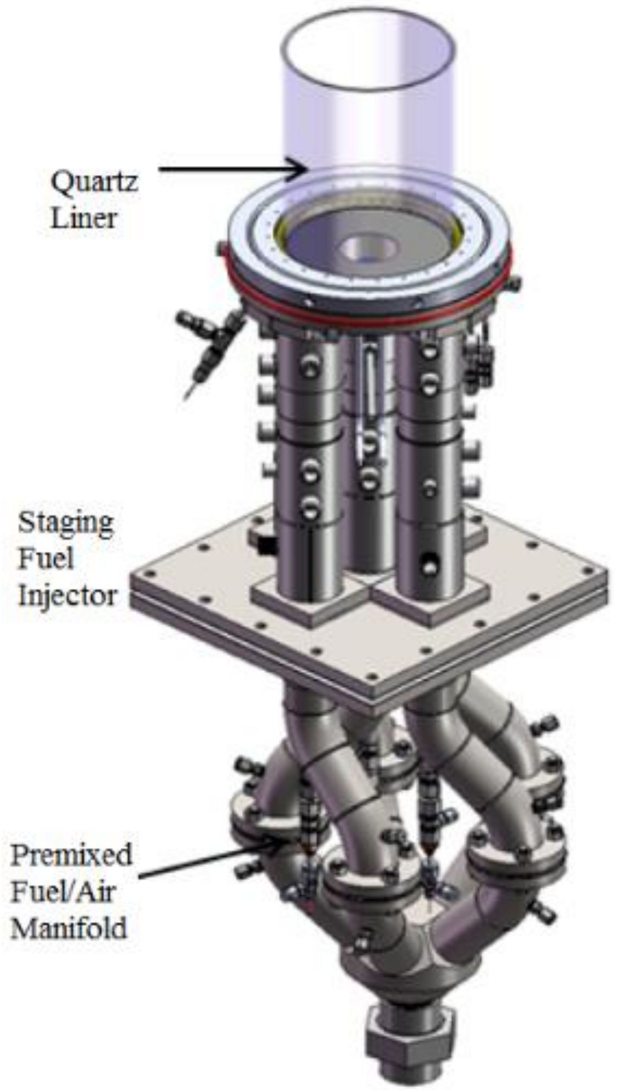


Hardware modification focused on a valve with linear actuation to control fuel flow transients for fuel-splitting studies



Single-nozzle combustor is created by plugging four nozzles and using a smaller quartz liner with the same dump ratio





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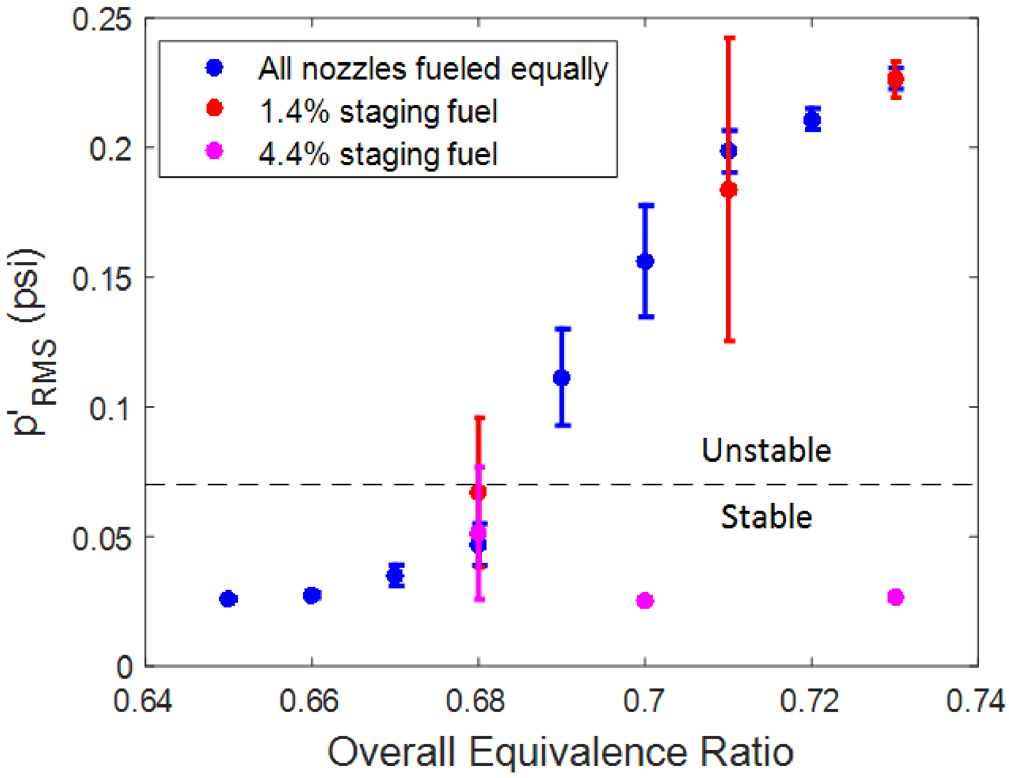
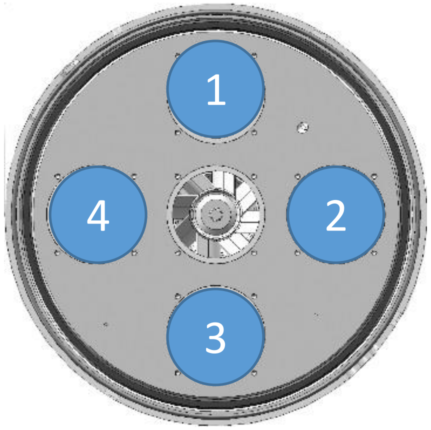
Major Result #1: Fuel staging works both in axisymmetric and non-axisymmetric configurations

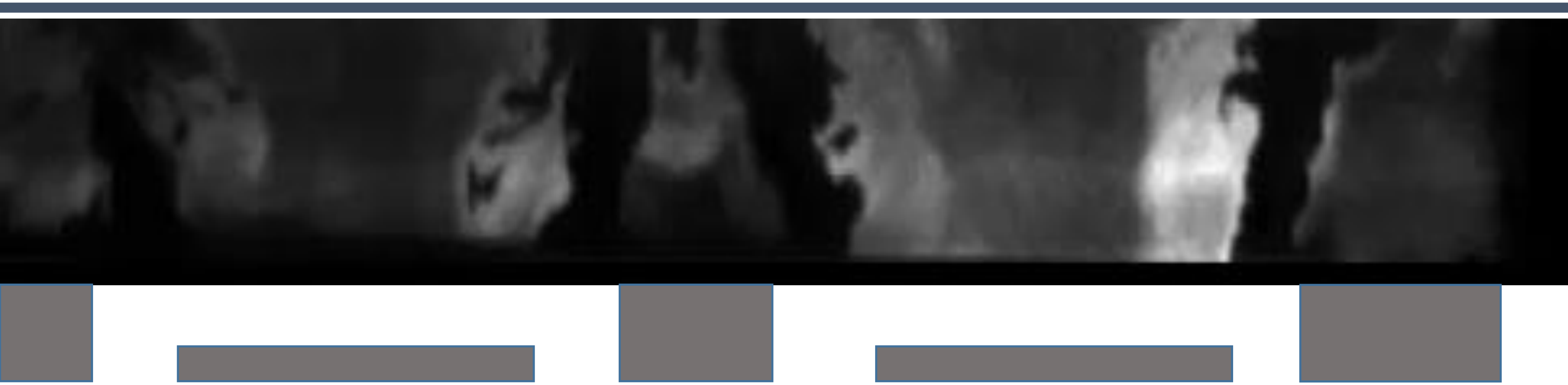


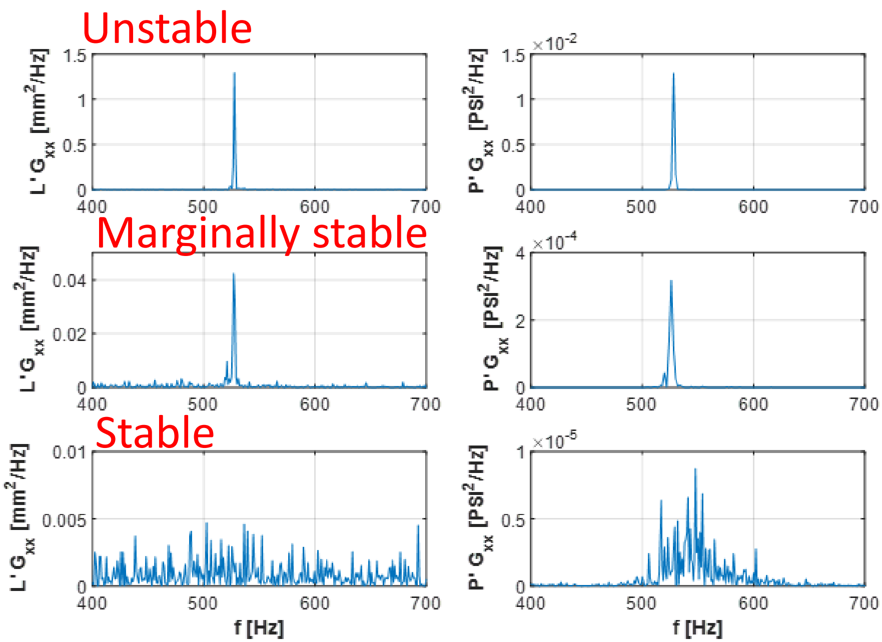


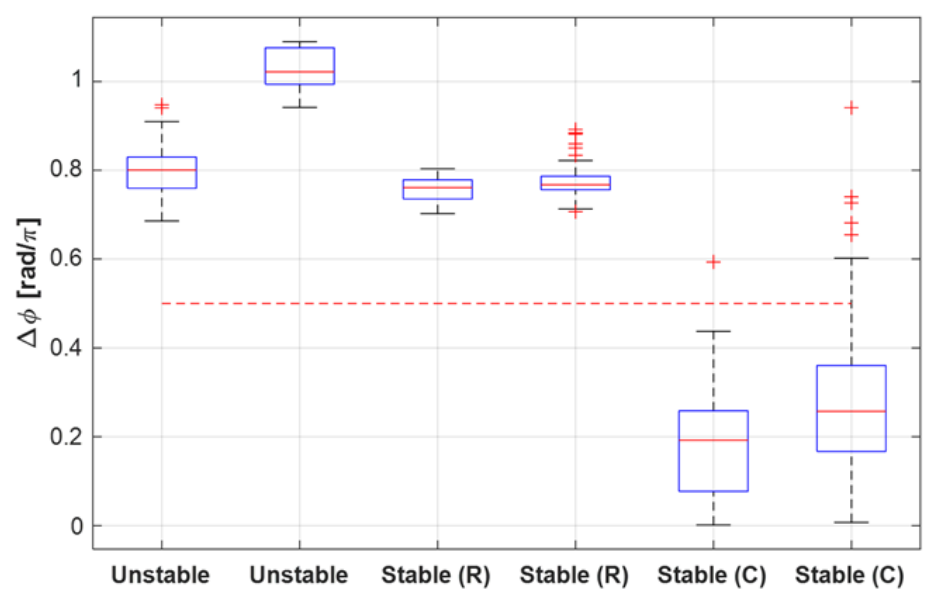
Nozzle	Bifurcation Equivalence Ratio
Center	0.79
Nozzle 1	0.85
Nozzle 2	0.83
Nozzle 3	0.80
Nozzle 4	0.78

Culler, W., Chen, X., Peluso, S., Santavicca, D., Noble, D., O'Connor, J., (2018) "Comparison of Center Nozzle Staging to Outer Nozzle Staging in a Multi-Flame Combustor," ASME Turbo Expo

Major Result #2: Analysis of local flame dynamics shows that change in flame shape, dephasing drive stability suppression



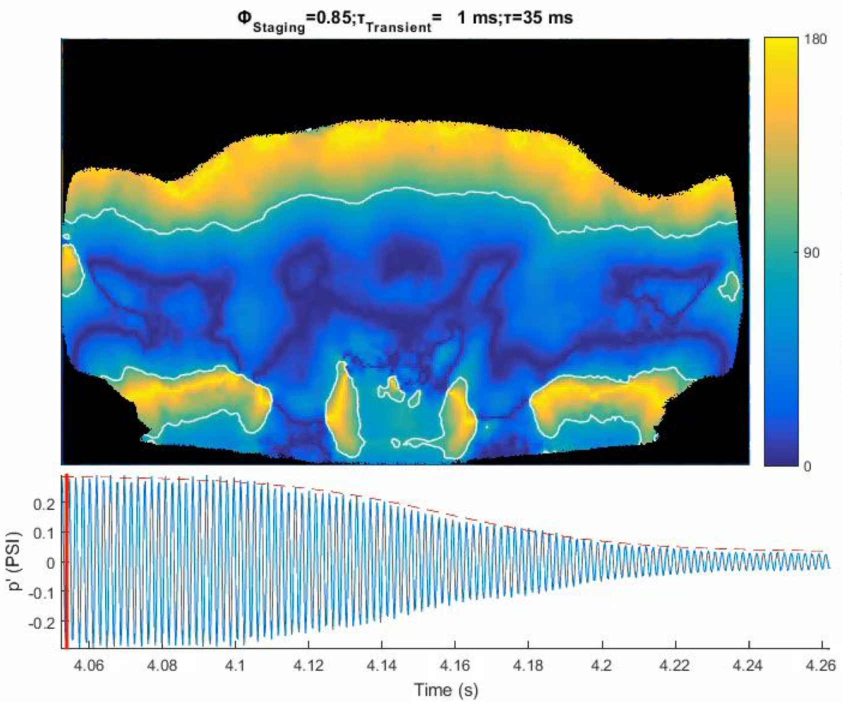




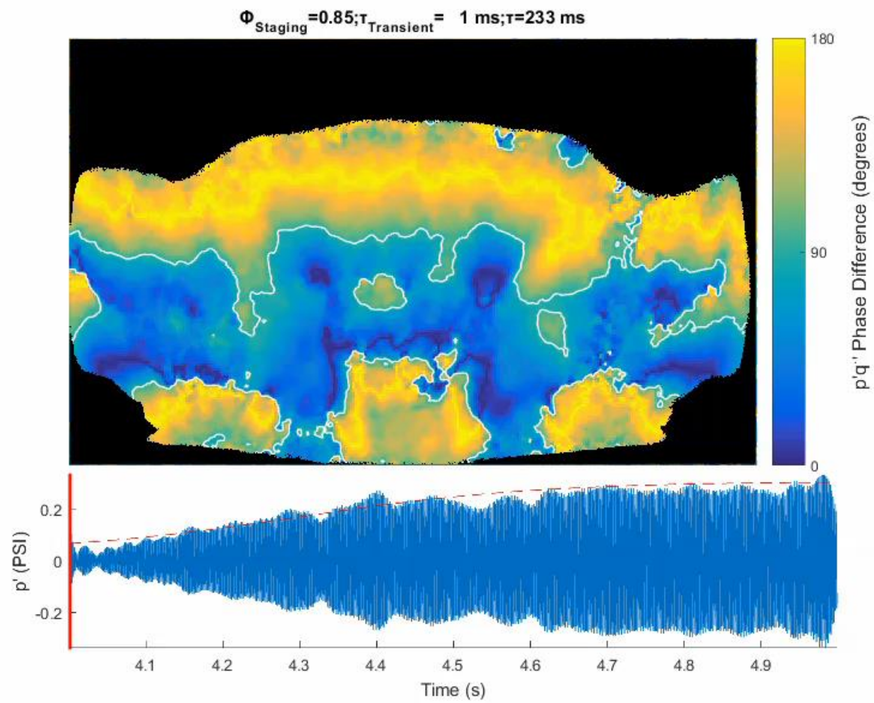
Doleiden, D., Culler, W., Tyagi, A. Peluso, S. O'Connor, J., (2019) "Flame edge dynamics and interaction in a multi-nozzle can combustor with fuel staging" ASME Turbo Expo

Major Result #3: While instability decay is smooth, instability onset takes longer and is intermittent – direction matters!

<u>Instability Decay</u>



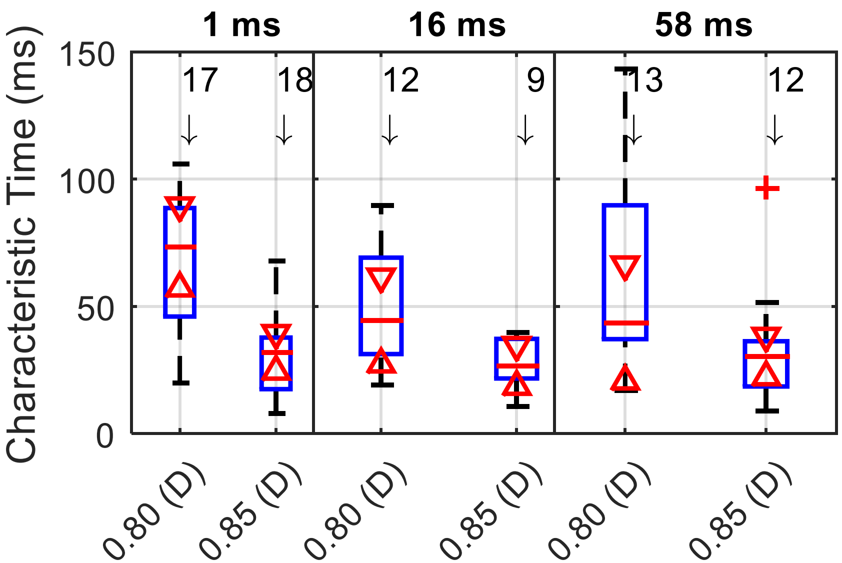
<u>Instability Onset</u>

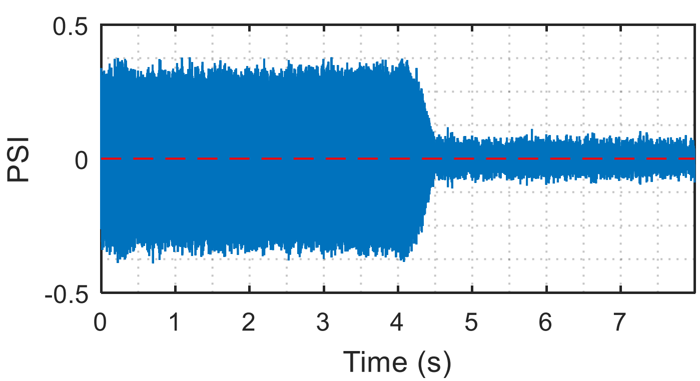


Culler, W., Chen, X., Samarasinghe, J., Peluso, S., Santavicca, D., O'Connor, J., (2018) "The effect of variable fuel staging transients on self-excited instabilities in a multiple-nozzle combustor," Combustion and Flame, vol. 194, pg. 472-484

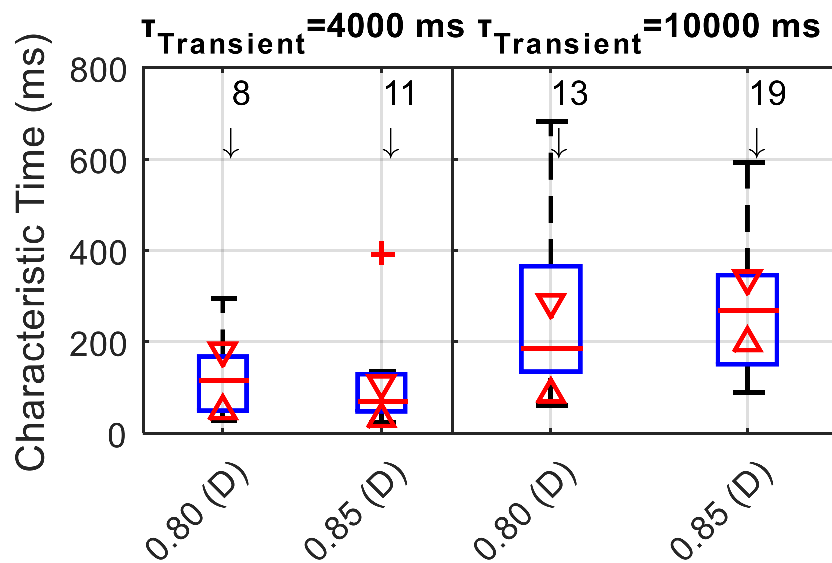
Major Result #4: Time-scale of a transient matters in the multi-nozzle combustor, and heat transfer likely plays a role

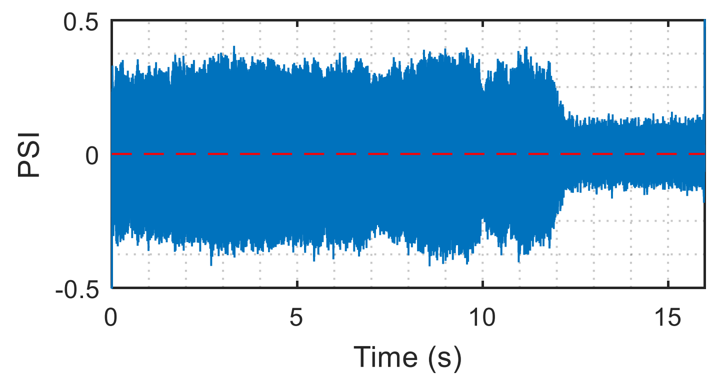
Short Timescales





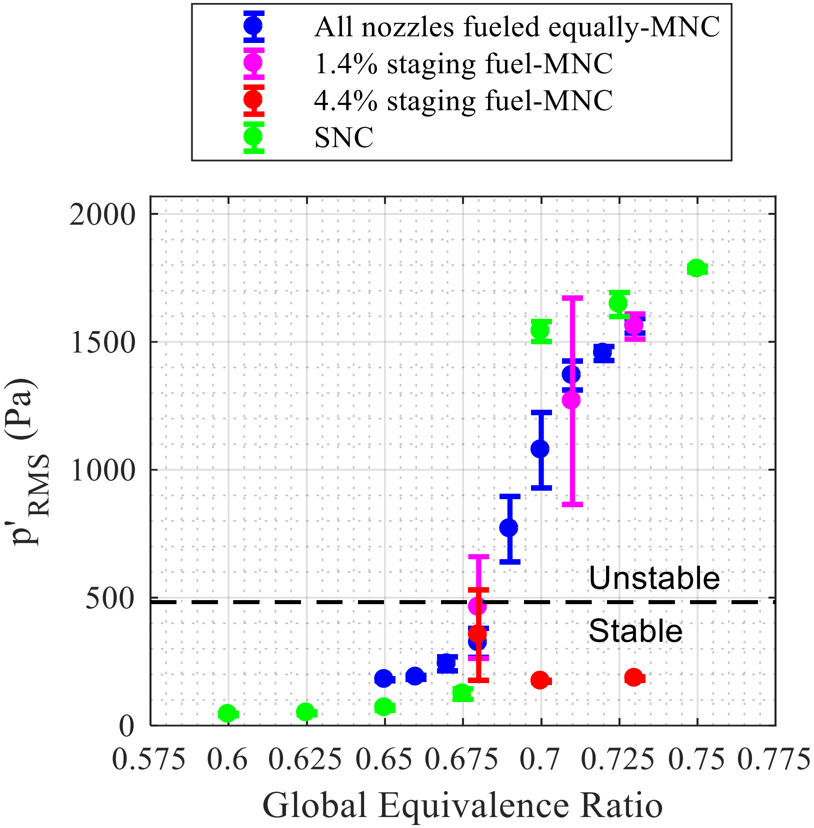
Long Timescales



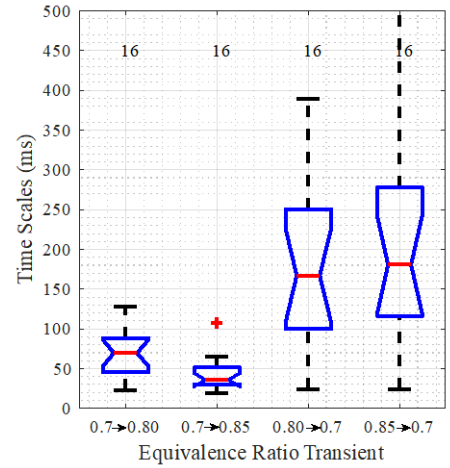


Culler, W., Chen, X., Samarasinghe, J., Peluso, S., Santavicca, D., O'Connor, J., (2018) "The effect of variable fuel staging transients on self-excited instabilities in a multiple-nozzle combustor," Combustion and Flame, vol. 194, pg. 472-484

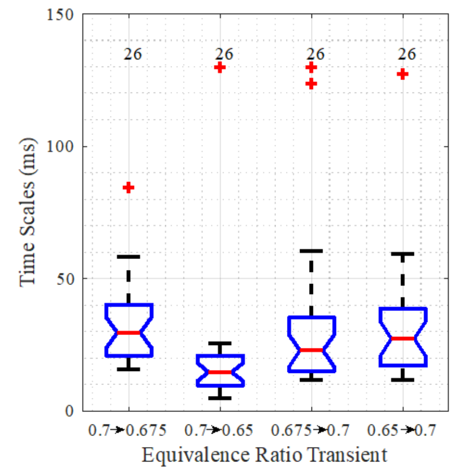
Major Result #5: Most significant difference between the single- and multi-nozzle instability is transient timescales



Multi-Nozzle Transients



Single-Nozzle Transients



Chen, X., Culler, W., Peluso, S., Santavicca, D., O'Connor, J., (2018) "Comparison of equivalence ratio transients on combustion instability in single-nozzle and multi-nozzle combustors," ASME Turbo Expo

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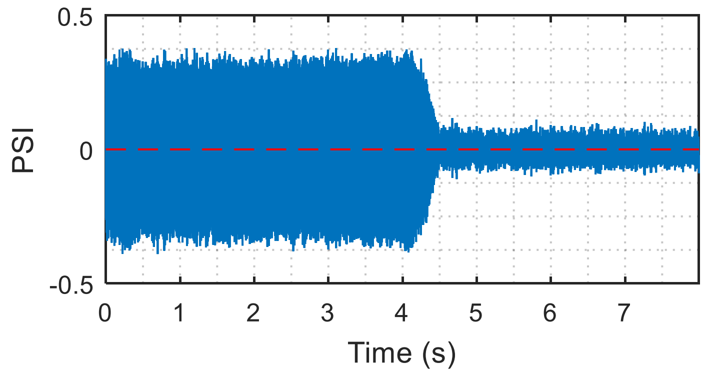
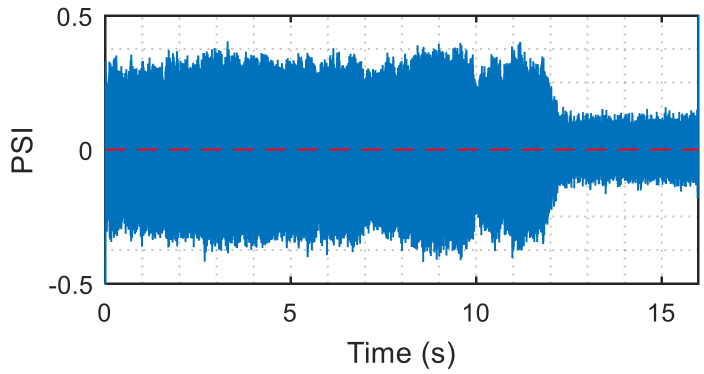
Analysis of the multi-nozzle cases showed that many conditions displayed intermittency in the instability amplitude

Low Intermittency

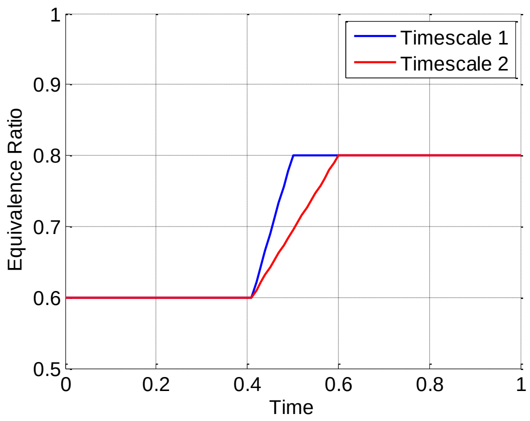


High Intermittency

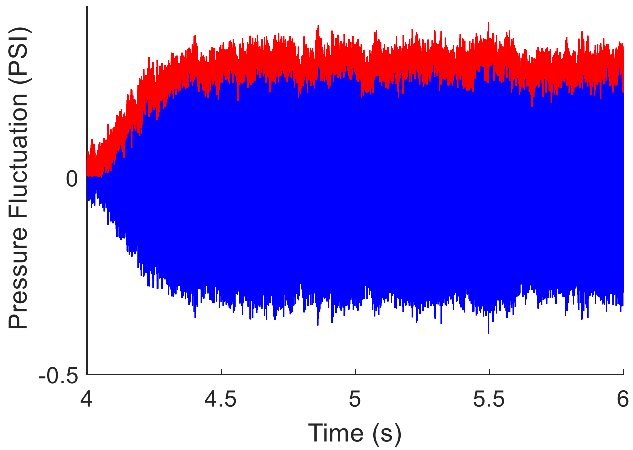


With three years of data, we were able to correlate key parameters to understand the source of the intermittency

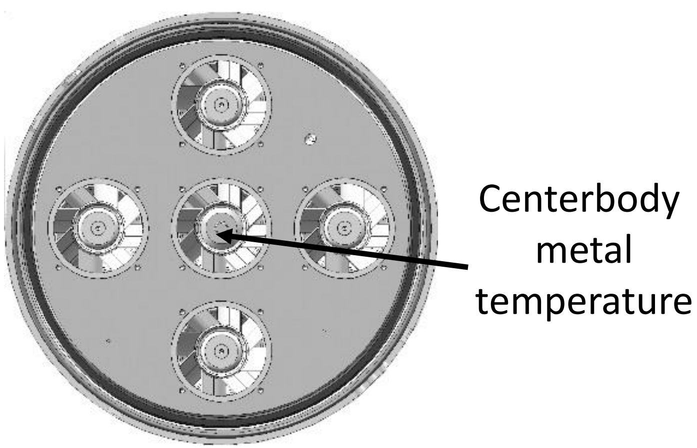
Transient Characteristics



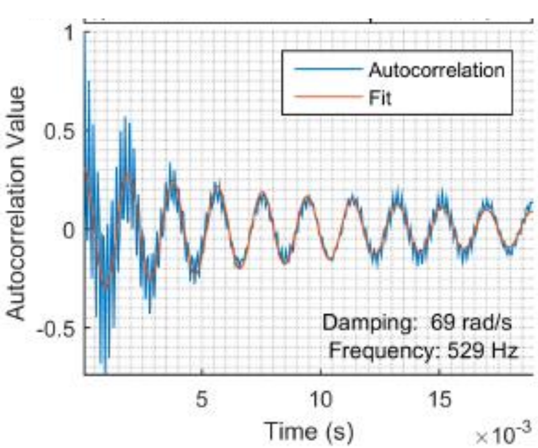
Instability Amplitude



Centerbody Temperature



Damping Rate



Quantifying the thermoacoustic damping and driving of the combustor indicates strength of instability

Thermoacoustic system model

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

Heat release rate model

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

Van der Pol oscillator

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

Acoustic damping + Flame driving = Thermoacoustic Damping/driving

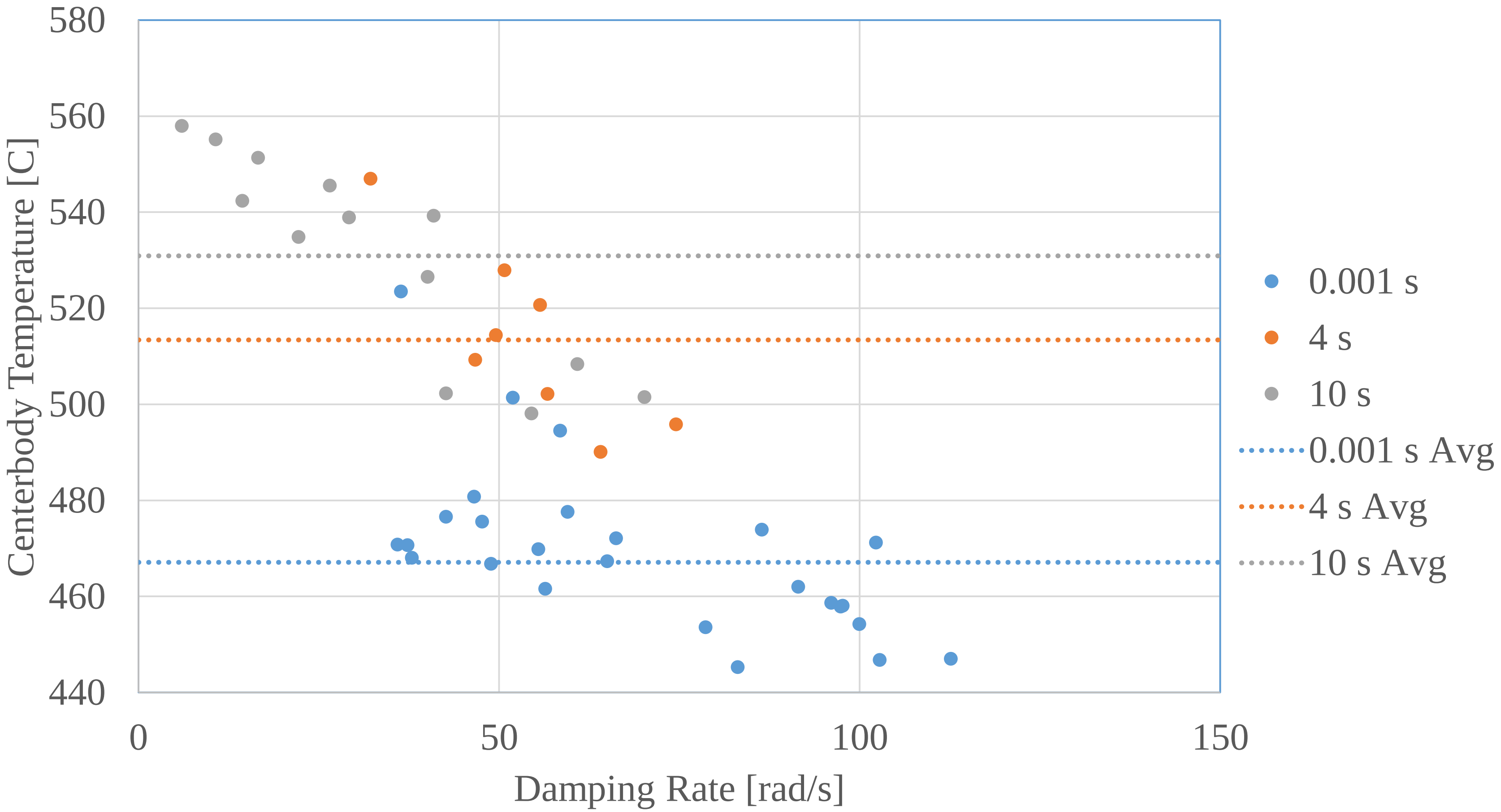
For stable conditions

$$k_{\eta_n\eta_n}(\tau) = \exp(-\nu_n\tau)\cos(\omega_n\tau)$$

For unstable conditions

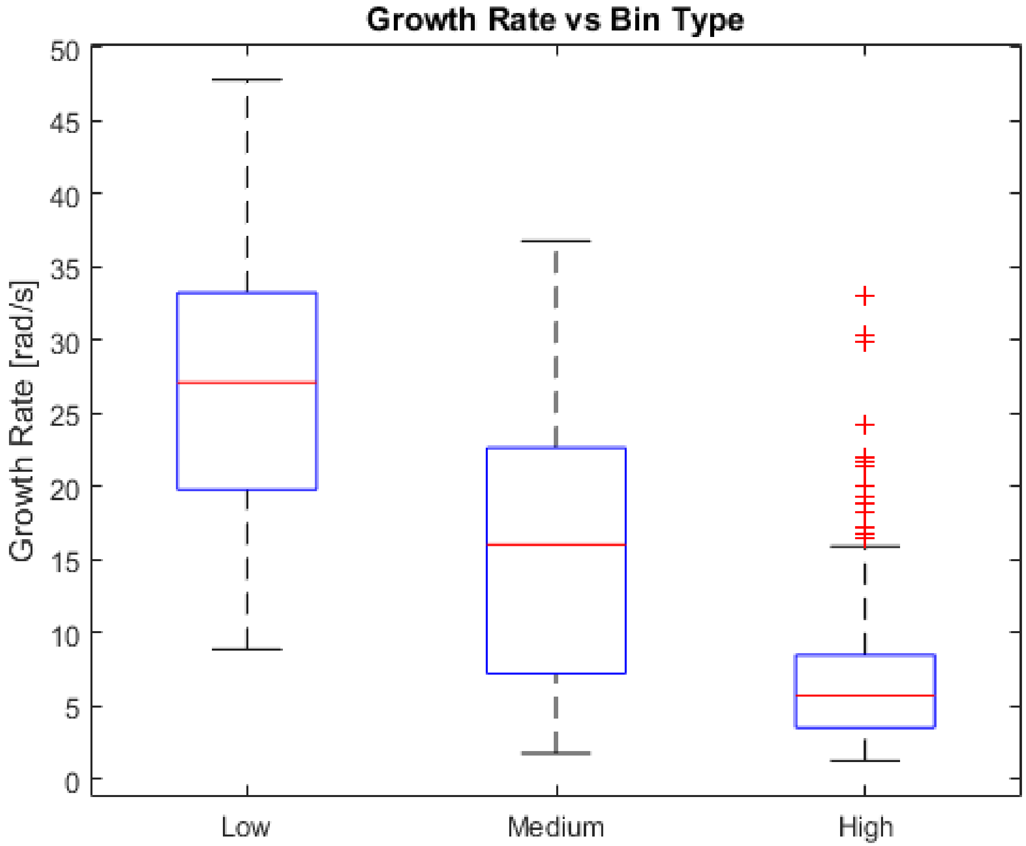
$$k_{A'A'} = \exp(2\nu_n\tau)$$

Thermoacoustic damping is highly correlated to centerbody temperature, with long timescale cases having less damping



$$k_{\eta_n \eta_n}(\tau) = \exp(-\nu_n \tau) \cos(\omega_n \tau)$$

Intermittency is higher in cases with lower thermoacoustic driving, likely a result of the combustor thermal condition



$$k_{\mathcal{A}'\mathcal{A}'} = \exp(2\nu_n \tau)$$

Westfall, S., Sekulich, O., Culler, W., Peluso, S., O'Connor, J., (2020) "Quantification of intermittency in combustion instability amplitude in a multi-nozzle can combustor" ASME Turbo Expo

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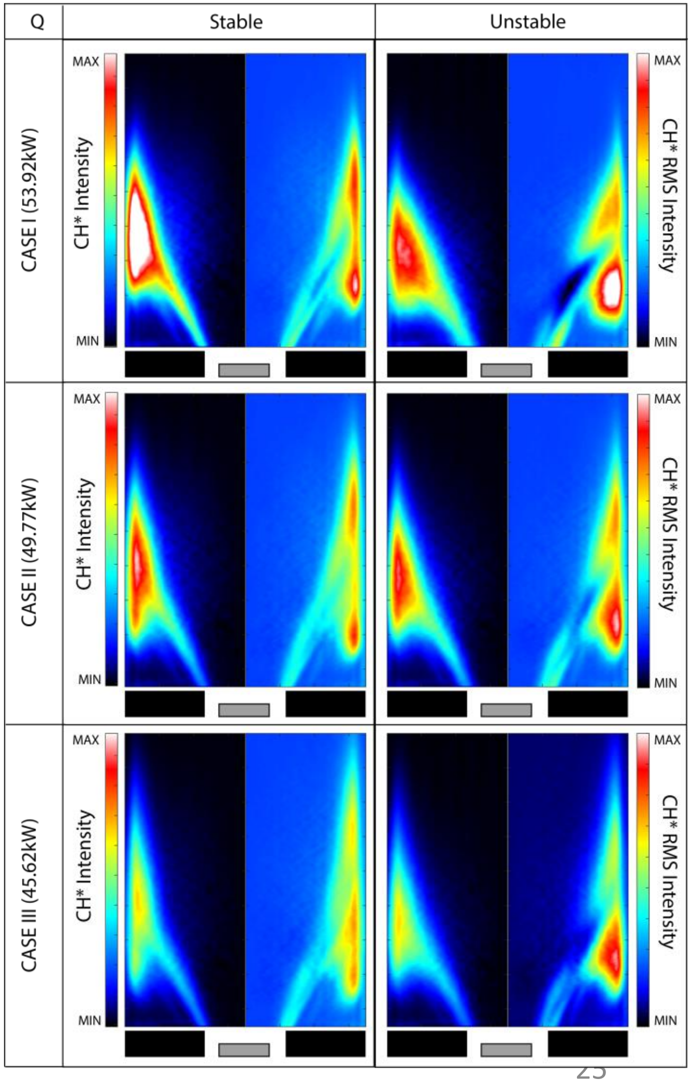
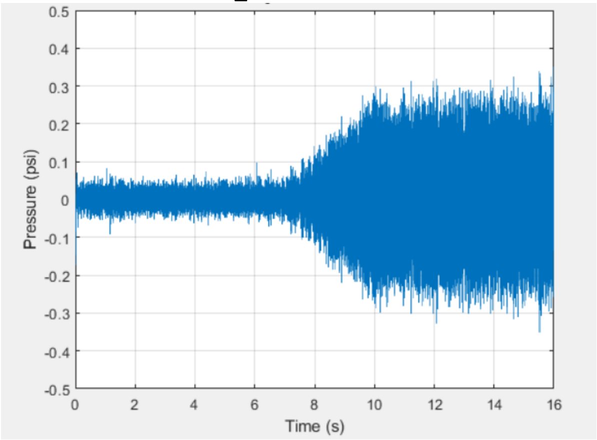
Single-nozzle studies were done first to baseline performance and system stability was dependent on heat rate, %vol H_2

T_{in}=200°C	$xNG:xH_2$				
$\dot{Q}$ (kW)	**1.0:0.0**	**0.9:0.1**	**0.8:0.2**	**0.7:0.3**	**0.6:0.4**
41.47		0.0039psi 435.61Hz	0.0050psi 445.99Hz	0.0122psi 450.79Hz	0.1620psi 460.21Hz
45.62	0.0052psi 509.15Hz	0.0078psi 428.86Hz	**0.0501psi 443.95Hz**	**0.1741psi 463.30Hz**	0.1328psi 488.64Hz
49.77	0.0066psi 456.25Hz	**0.0333psi 441.70Hz**	**0.1474psi 466.51Hz**	0.1065psi 484.14Hz	0.1665psi 510.28Hz
53.92	0.0209psi 471.38Hz	**0.0412psi 459.25Hz**	**0.2205psi 525.50Hz**	0.1798psi 538.30Hz	0.0912psi 540.55Hz
58.06	0.2709psi 522.35Hz	0.2565psi 537.46Hz	0.2230psi 548.55Hz	0.1930psi 564.68Hz	0.1503psi 578.07Hz
62.21	0.2750psi 541.80Hz	0.2387psi 557.06Hz	0.2290psi 568.94Hz	0.2109psi 578.69Hz	

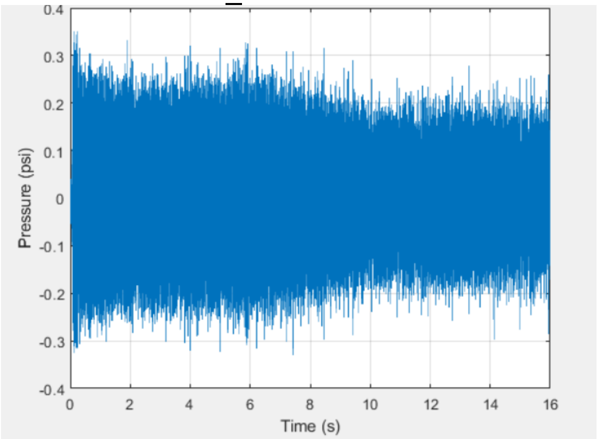


Transient behavior is most sensitive to direction and amplitude; like NG results, timescale is not a factor

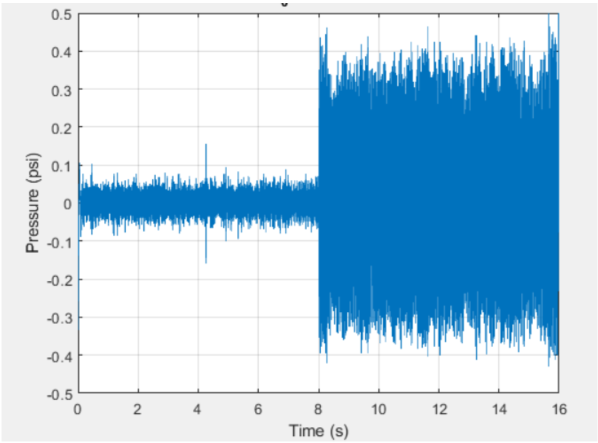
Φ=0.55 H_2%=20→30 t=4s



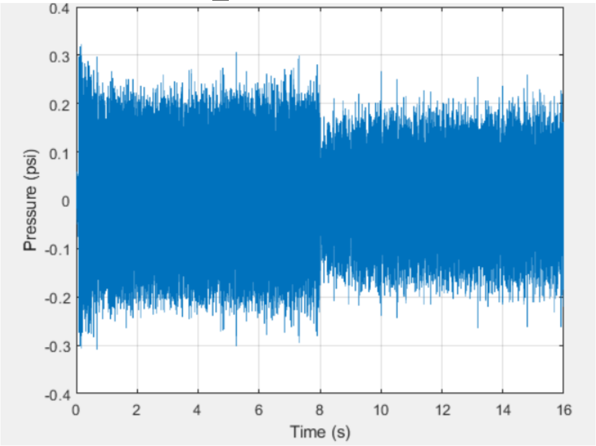
Φ=0.55 H_2%=30→20 t=4s



Φ= 0.55 H_2%=20→30 t=1ms



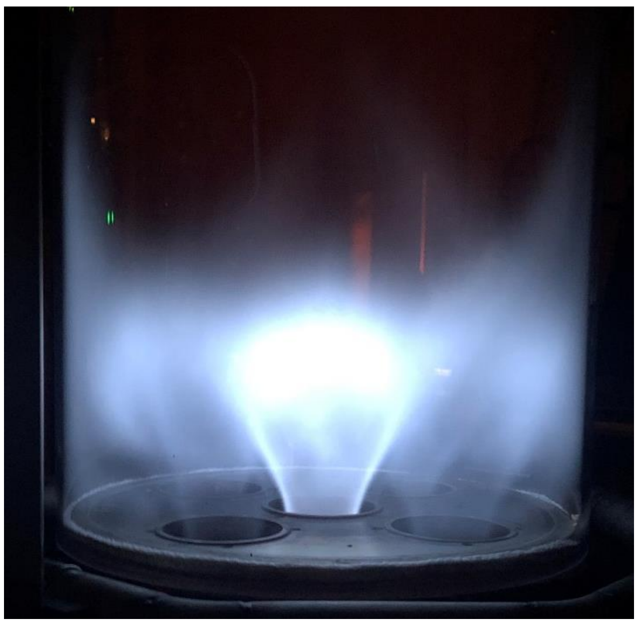
Φ=0.55 H_2%=30→20 t=1ms



Strollo, J., Peluso, S., O'Connor, J., (2020) "Effect of hydrogen on steady-state and transient combustion instability characteristics" ASME Turbo Expo

Multi-nozzle stability has been mapped and transient tests are on-going to understand the role of flame interaction

T_{in}=200ºC p' rms [psi] peak freq [Hz] Outer Nozzle Heat Rate [kW] Outer Nozzle Equivalence Ratio (NG Only)	Center Nozzle FPM Natural Gas / TPM H2 Split (% - Mole Basis)				
Center Nozzle Heat Rate	100/0	90/10	80/20	70/30	60/40
(41.47 kW)	0.0025 1305.7 41.47kW 0.5	0.0035 249.9 40.13kW 0.48	0.0024 491.4 38.57kW 0.46	xxx	xxx
(45.62 kW)	0.0025 522.7 45.62kW 0.55	0.0027 524.7 44.14kW 0.53	0.0032 509.9 42.42kW 0.51	0.0040 505.4 40.40kW 0.49	0.0021 1930.3 37.99kW 0.46
(49.77 kW)	0.0035 578.0 49.77kW 0.60	0.0025 1926.8 48.16kW 0.58	0.0027 522.9 46.28kW 0.56	0.0030 536.8 44.08kW 0.53	0.0032 493.2 41.44kW 0.50
(53.92 kW)	0.0245 498.0 53.92kW 0.65	0.0046 500.6 52.17kW 0.63	0.0085 482.6 50.14kW 0.60	0.0151 486.5 47.75kW 0.58	0.0052 493.2 44.90kW 0.54
(58.06 kW)	0.2138 534.9 58.06kW 0.70	0.2138 526.2 56.18kW 0.68	0.0322 500.6 54.00kW 0.65	0.0636 498.3 51.42kW 0.62	0.0087 509.6 48.35kW 0.58
(62.21 kW)	0.2332 536.6 62.21kW 0.75	0.2299 537.3 60.20kW 0.72	0.0778 519.2 57.85kW 0.70	0.0862 512.2 55.10kW 0.66	xxx



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Key findings from this program will have implications for combustion instability research going forward

- Transient behavior is fundamentally different than steady-state behavior – amplitude, direction, and timescale matter
  - *Implication: Both steady and transient studies are needed*

- The impact of timescale on the final state after a transient event is mostly driven by its comparison to heat transfer timescales, likely due to its role in determining thermoacoustic damping
  - *Implication: Conjugate analysis of combustion systems is useful*

- Multi-nozzle systems display different behaviors than single-nozzle, particularly with respect to instability intermittency
  - *Implication: Need more understanding of what drives differences*

- System behavior with H_2 is not fundamentally different
  - *Implication: Stability map changes, needs to be characterized*

The work in this project has been widely disseminated to the academic and industrial communities – Published papers:

1. Doleiden, D., Culler, W., Tyagi, A., Peluso, S., O'Connor, J., (2019) "Flame edge dynamics and interaction in a multi-nozzle can combustor with fuel staging," *Journal of Engineering for Gas Turbines and Power*, 141(10), p. 101009.
2. Doleiden, D., Culler, W., Tyagi, A., Peluso, S., O'Connor, J., (2019) "Flame edge dynamics and interaction in a multi-nozzle can combustor with fuel staging," *ASME Turbo Expo*, Phoenix, AZ.
3. Culler, W., Chen, X., Samarasinghe, J., Peluso, S., Santavicca, D., O'Connor, J., (2018) "The effect of variable fuel staging transients on self-excited instabilities in a multiple-nozzle combustor," *Combustion and Flame*, 194, p. 472-484.
4. Culler, W., Chen, X., Peluso, S., Santavicca, D., O'Connor, J., Noble, D., (2018) "Comparison of center nozzle staging to outer nozzle staging in a multi-flame combustor," *ASME Turbo Expo*, Oslo, Norway.
5. Chen, X., Culler, W., Peluso, S., Santavicca, D., O'Connor, J., (2018) "Comparison of equivalence ratio transients on combustion instability in single-nozzle and multi-nozzle combustors," *ASME Turbo Expo*, Oslo, Norway.
6. Chen, X., Culler, W., Peluso, S., Santavicca, D., O'Connor, J., (2018) "Effects of equivalence ratio transient duration on self-excited combustion instability time scales in a single-nozzle combustor," *Spring Technical Meeting of the Eastern States Section of the Combustion Institute*, State College, PA.
7. Sekulich, O., Culler, W., O'Connor, J., (2018) "The effect of non-axisymmetric fuel staging on flame structure in a multiple-nozzle model gas turbine combustor," *Spring Technical Meeting of the Eastern States Section of the Combustion Institute*, State College, PA.
8. Samarasinghe, J., Culler, W., Quay, B., Santavicca, D. A., O'Connor, J. (2017) "The effect of fuel staging on the structure and instability characteristics of swirl-stabilized flames in a lean premixed multi-nozzle can combustor." *Journal of Engineering for Gas Turbines and Power*, 139(12), 121504.
9. Culler, W., Samarasinghe, J., Quay, B., Santavicca, D. A., O'Connor, J. (2017) "The effect of transient fuel staging on self-excited instabilities in a multi-nozzle model gas turbine combustor," *ASME Turbo Expo*, Charlotte, NC.

Forthcoming papers for ASME Turbo Expo 2020

1. Westfall, S., Sekulich, O., Culler, W., Peluso, S., O'Connor, J., (2020) "Quantification of intermittency in combustion instability amplitude in a multi-nozzle can combustor" ASME Turbo Expo

2. Strollo, J., Peluso, S., O'Connor, J., (2020) "Effect of hydrogen on steady-state and transient combustion instability characteristics" ASME Turbo Expo

3. Howie, A., Doleiden, D., Peluso, S., O'Connor, J., (2020) "The effect of the degree of premixedness on self-excited instability," ASME Turbo Expo

Acknowledgements

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

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

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Questions?

Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

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