Investigation of Flame Structure for Hydrogen Gas Turbine Combustion

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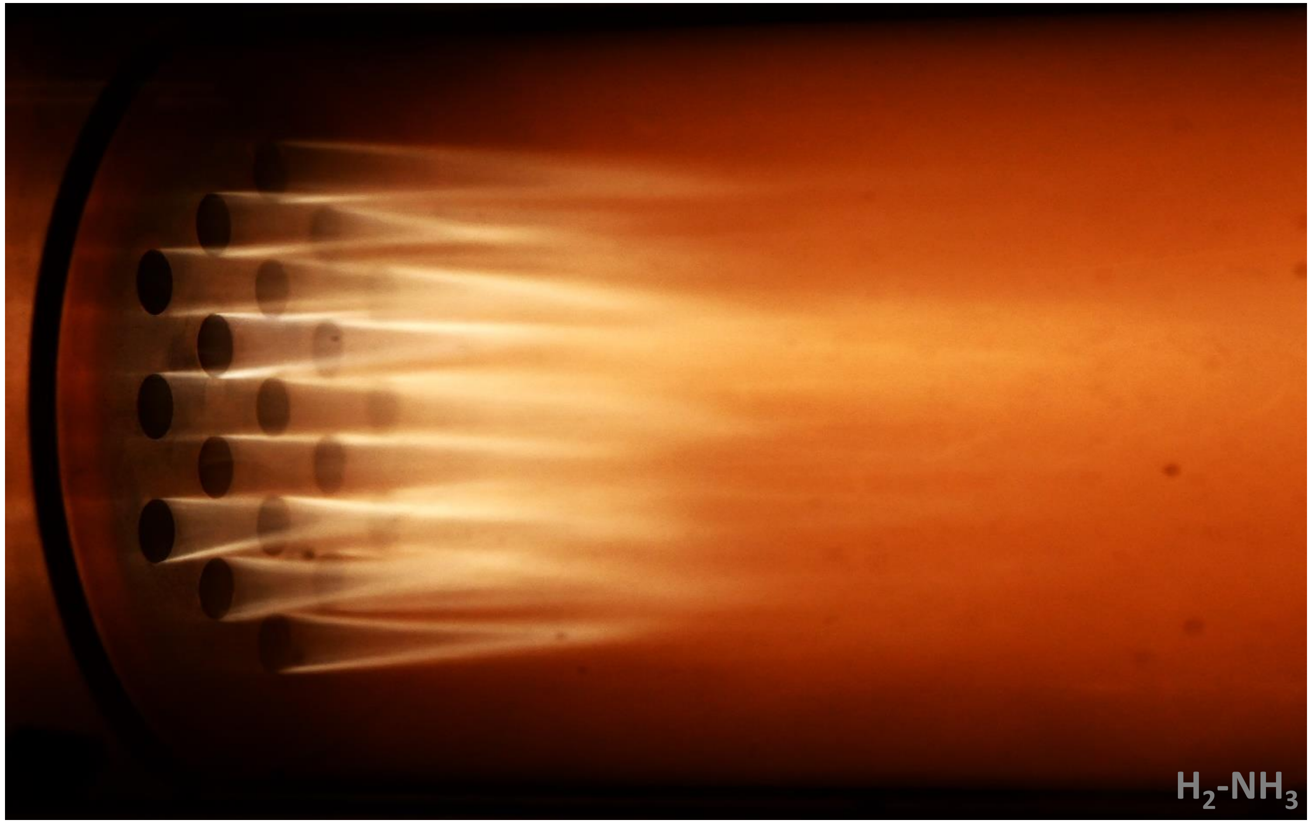


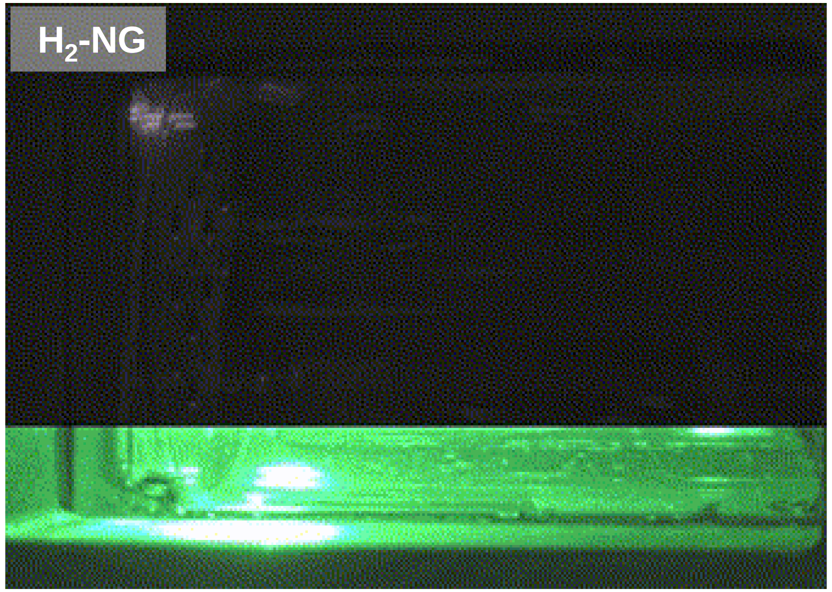
Investigation of Flame Structure for H_2 Gas Turbine Combustion

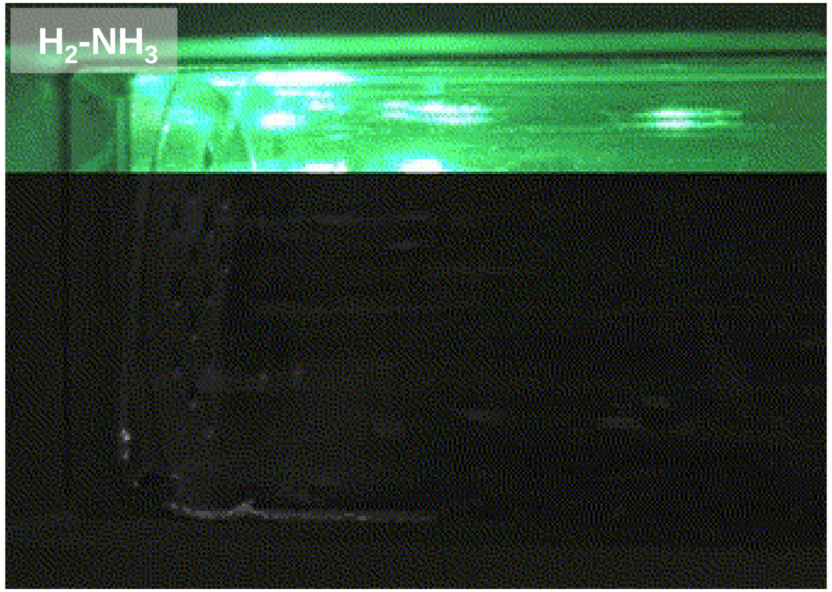
Advance hydrogen combustion technology from the current technology concept and/or application formulated stage (TRL 2) to a component and/or system validation in laboratory environment (TRL 4)

- Explore flame structure and dynamics with hydrogen, ammonia, and mixtures of these fuels with natural gas
- High-pressure optically accessible combustor designed to operate engine relevant conditions (P_3: 40 bar, T_3: 1080 K)
  - Unsteady configuration for studies of self-excited combustion instabilities
  - Steady-state configuration for emissions, LBO, flashback.
- Research focus on premixed multi-stage, multi-tube, micromix (M^3) injectors
- Application of advanced diagnostic methods to study flame structure and dynamics
  - High-speed particle imaging velocimetry (PIV), coherent anti-Stokes Raman scattering (CARS) for T, species, and planar laser-induced fluorescence (PLIF) imaging for OH, NO, and NH concentrations
  - Extractive gas sample based emissions characterization

Summary

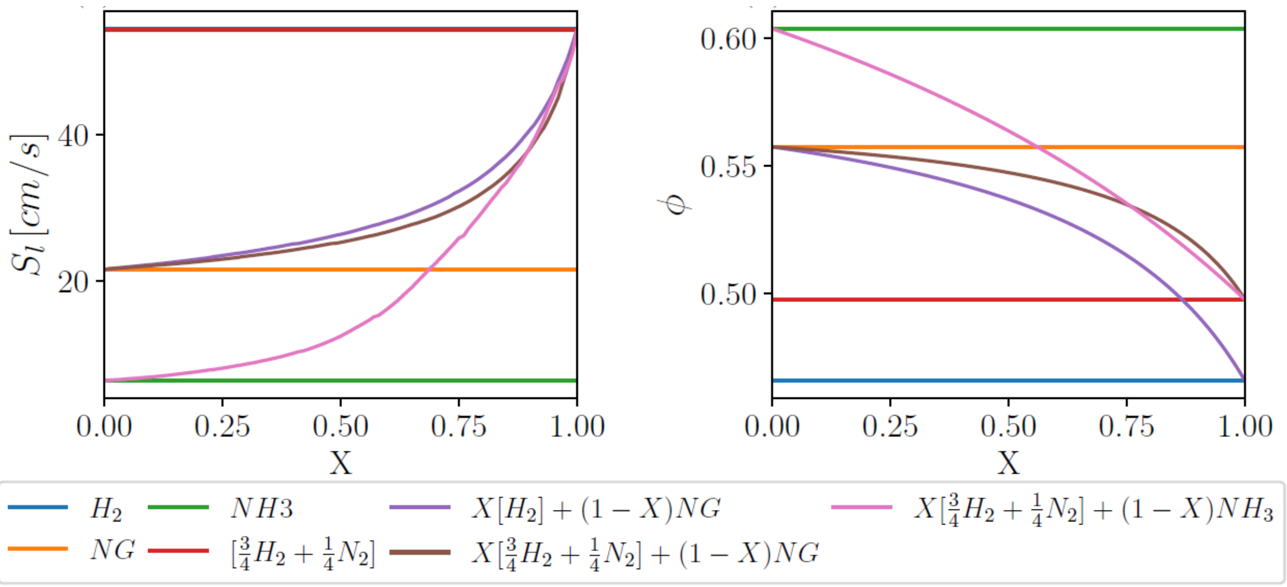
- Completed development of a modular multi-stage, multi-tube, micromix (M^3) injector
- Developed high-pressure gaseous and liquid ammonia delivery system to the experiment
  - Verified operation over range of operating pressures and flowrates
  - Robust operation with liquid and vapor-phase injection
- Characterized influence of fuel composition on self-excited combustion instabilities with ammonia, hydrogen, and natural gas fuels
  - Experiments in high-pressure optically accessible combustor at 10-12 bar and inlet air temperature of 750 K





Design Envelope

- Investigation of H_2 and NH_3 (H_2 carrier), and mixtures of these fuels with natural gas
- Hydrogen assumed to be derived from NH_3 decomposition
- NH_3 decomposition efficiency (η) swept from 0.4 to 0.9
  - Combustor length sized for ~14.5 ms residence time to allow retrofit to current combustors
- Fuel fraction (χ) swept from 0.5 to 0.9
- Equivalence ratio determined at a fixed flame temperature of 1980 K (DOE target for 65% combined cycle efficiency gas turbines)



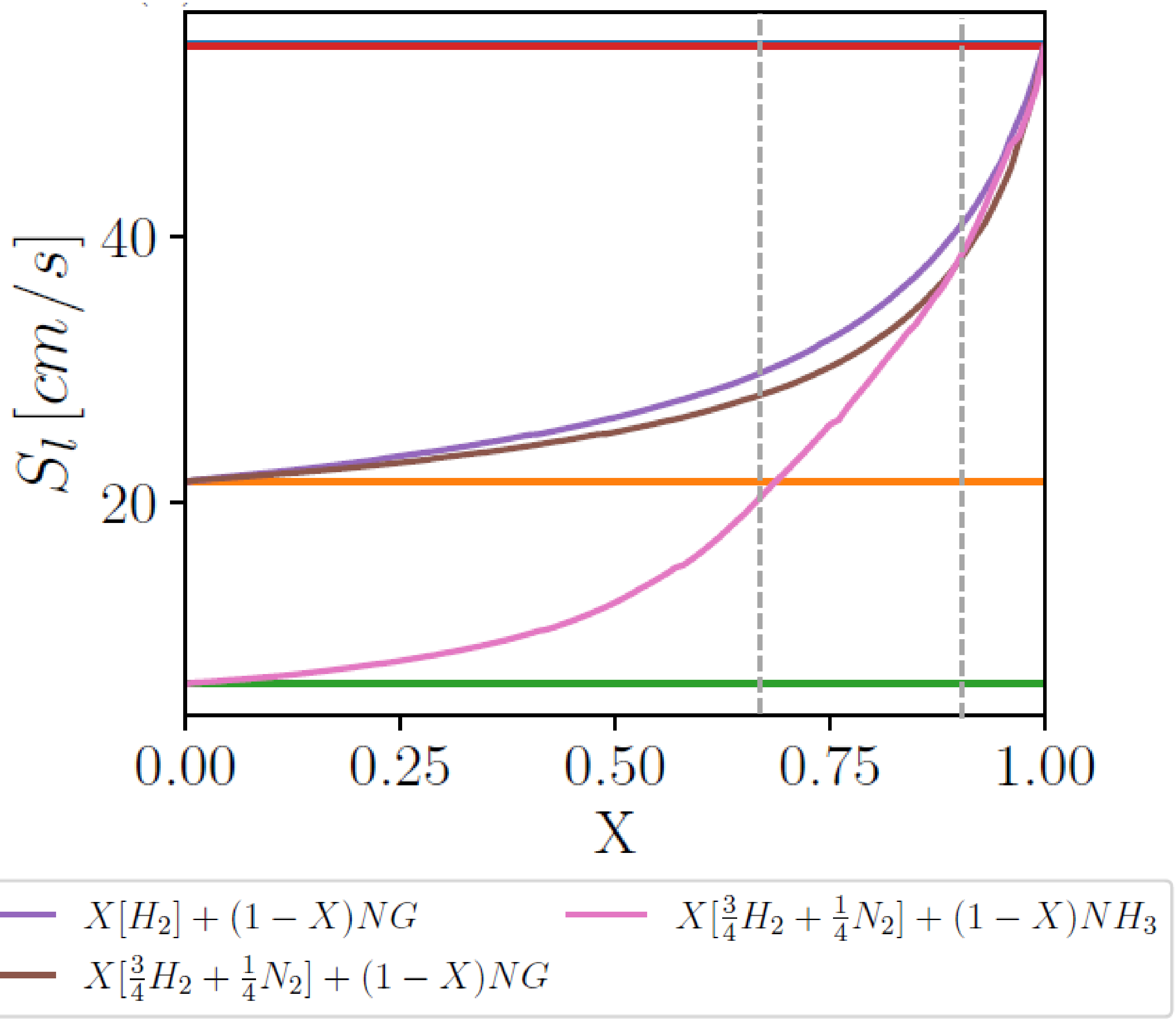
Premixed laminar flame speed (a) and variation in equivalence ratio for an adiabatic flame temperature of 1980 K (b).

$$\chi\left[\eta\left(\frac{3}{2}H_2 + \frac{1}{2}N_2\right) + (1-\eta)NH_3\right] + (1-\chi)NG$$

Fluid	χ	η	$\dot{m}_{max}\,[lb/s]$
H_2	0.9	0.9	0.01
N_2	0.9	0.9	0.05
NG	0.5	N/A	0.02
NH_3	0.9	0.4	0.04
Air	N/A	N/A	1

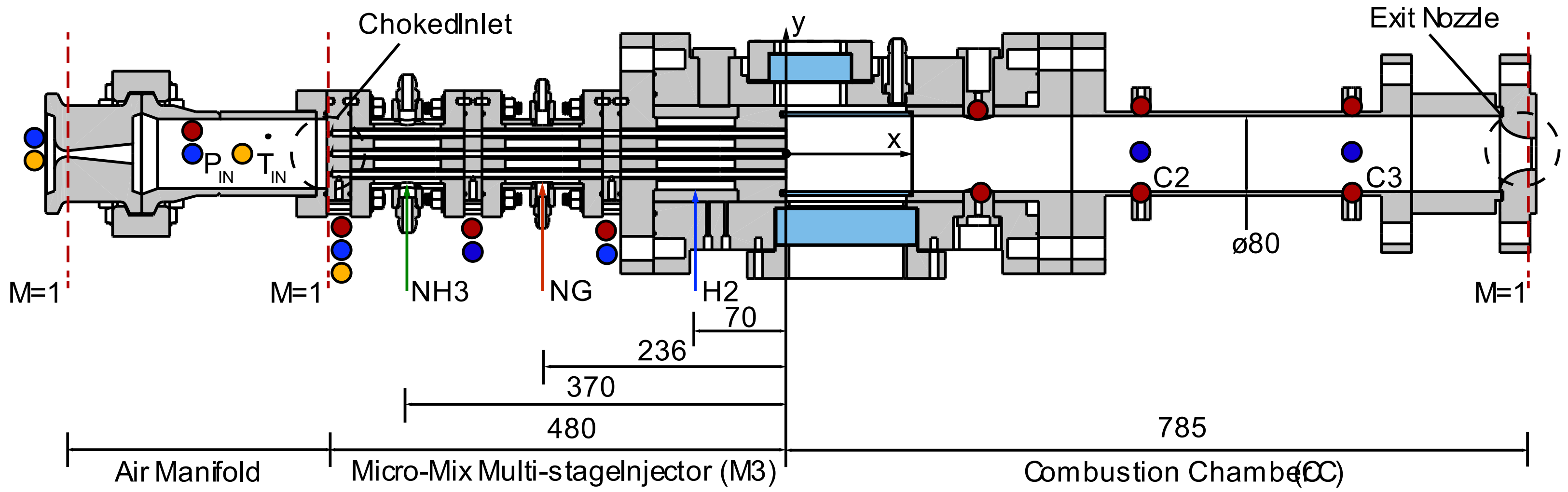
Natural Gas and Ammonia Effect on H_2 Combustion

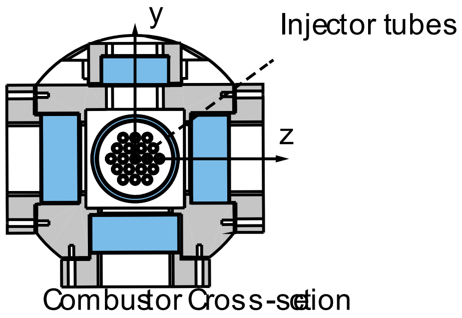
- Investigation of H_2 and NH_3 (H_2 carrier), and mixtures of these fuels with natural gas
- Significant reduction in flame speed with addition of either natural gas or ammonia to hydrogen
- Addition of even small amounts of ammonia to otherwise stable H_2/NG fuel mixtures has a dramatic effect on flame instabilities

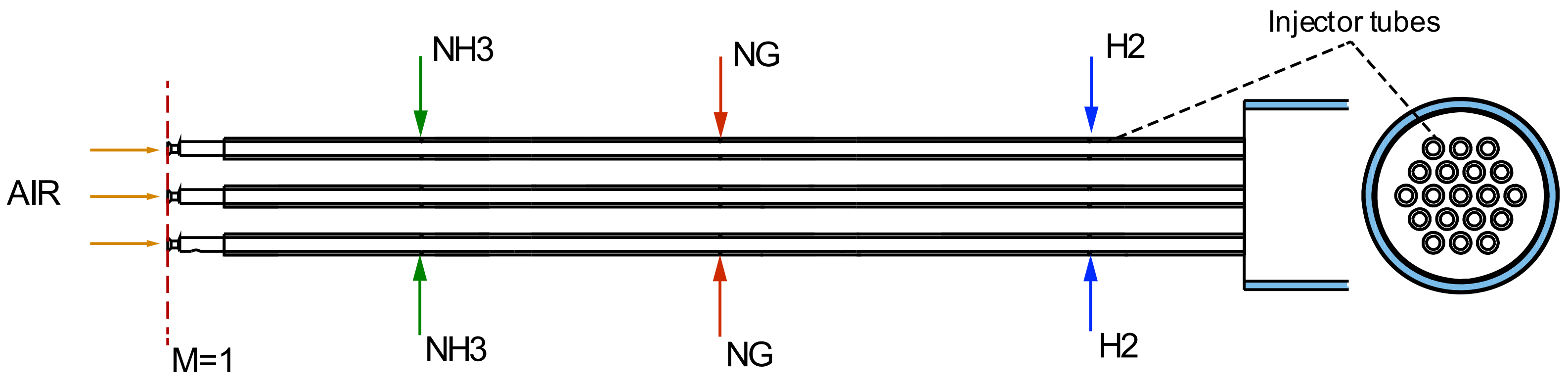


Combustor Design

- High-pressure (10-20 bar) optically accessible combustor
- Modular geometry to tune frequency and amplitude of dynamics with fuels of largely varying HRR
    - Characterization of fuel sensitivity to intrinsic flame instabilities with imposed (forced) dynamics
    - Well-defined flow and acoustic boundary conditions





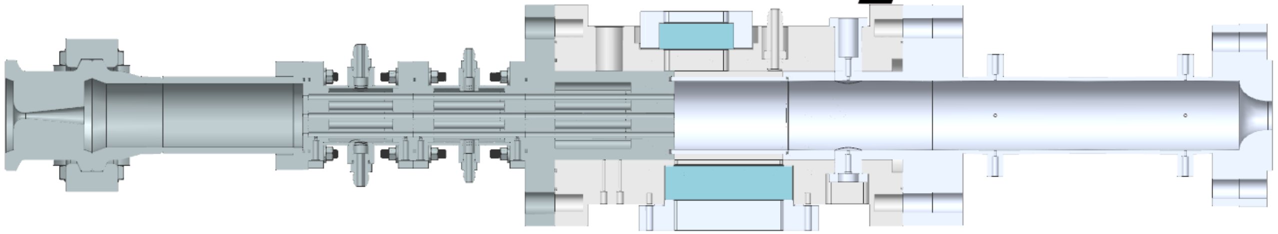


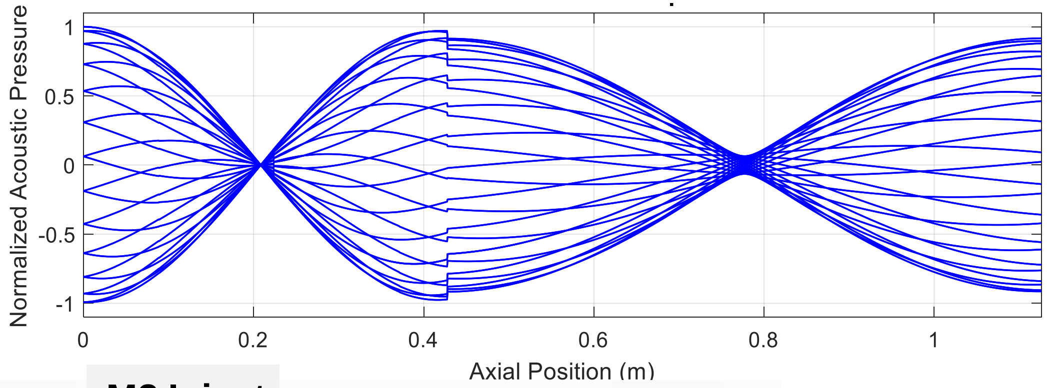
Premixed Staged Micromix Injection Elements (x19) **Injector Layout**

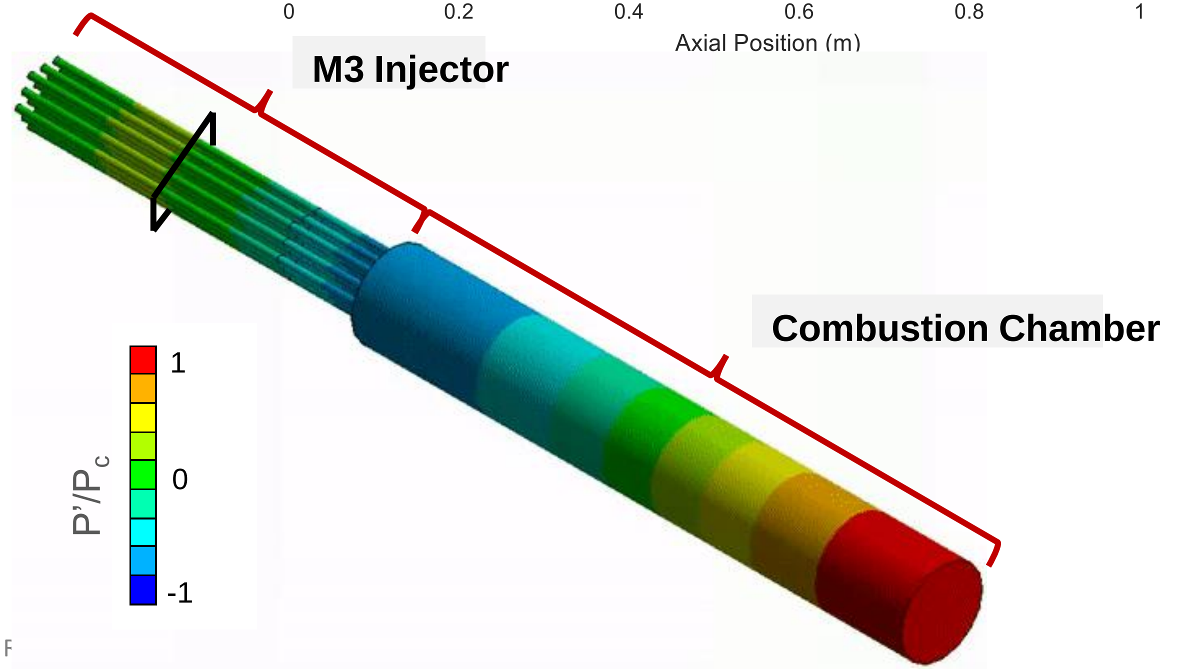
Injector Sizing

- Acoustic design based on linearized Euler equations using the Generalized Instability Model (GIM)
- Combustor dimensions designed to promote longitudinal mode combustion instability at 540 Hz (1L frequency)
  - Combustor residence time ~14.5 ms
- Combustor divided into domains representing NH_3, NG, H_2 injection regions and combustor
- Choked inlet and exit boundaries
- Injector designed as a ½ wave resonator at the chamber acoustic frequency

Domain Lengths [in]	
Air	4.31
NH3/Air	5.30
NG/NH3/Air	6.55
H2/N2/NG/NH3/Air	2.75
Combustor	31.00







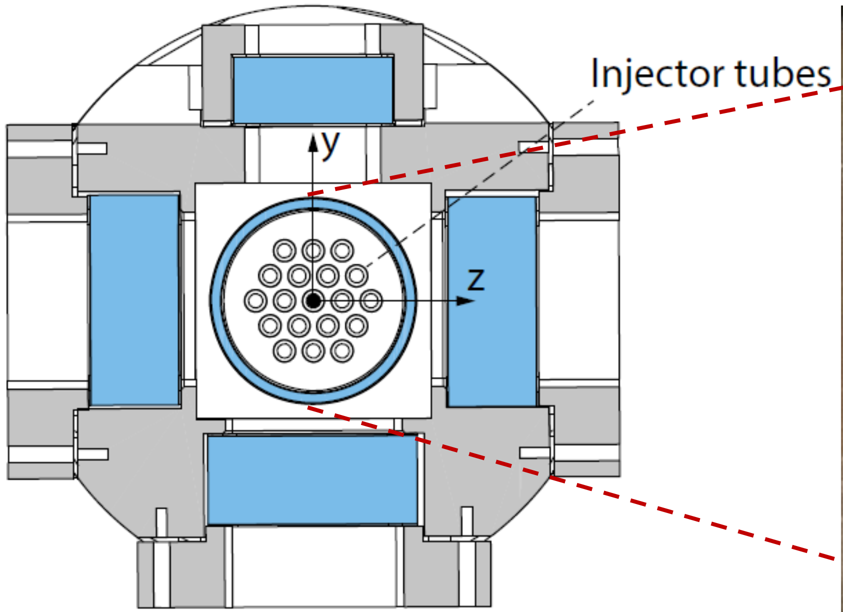
Injector Design

- Premixed multi-stage, multi-tube, micromix (M^3) injectors distributed in an uniform array in cylindrical combustion chamber
  - Discrete axially staged sections for NH_3, NG and H_2 injection
  - 19 injector elements with jet in crossflow reactant injection
  - Uniform inter-element separation
  - Injector Mach number between 0.25 – 0.28 at typical flow conditions

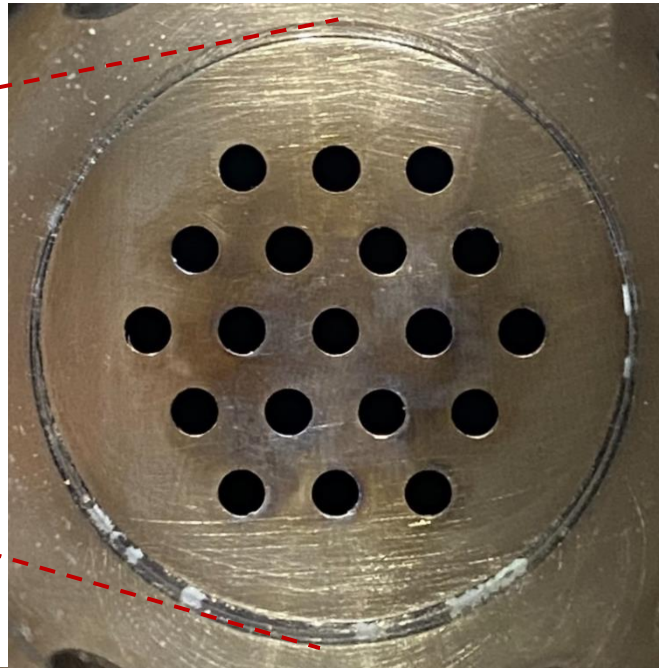
Injector Geometry	
$\emptyset_{element}$	0.245 [in]
Velocity	300 – 400 [ft/s]

Mach Number		η	
		0.4	0.9
χ	0.5	0.25	0.25
	0.9	0.27	0.28

Velocity		η	
		0.4	0.9
χ	0.5	432 [ft/s]	439 [ft/s]
	0.9	490 [ft/s]	514 [ft/s]

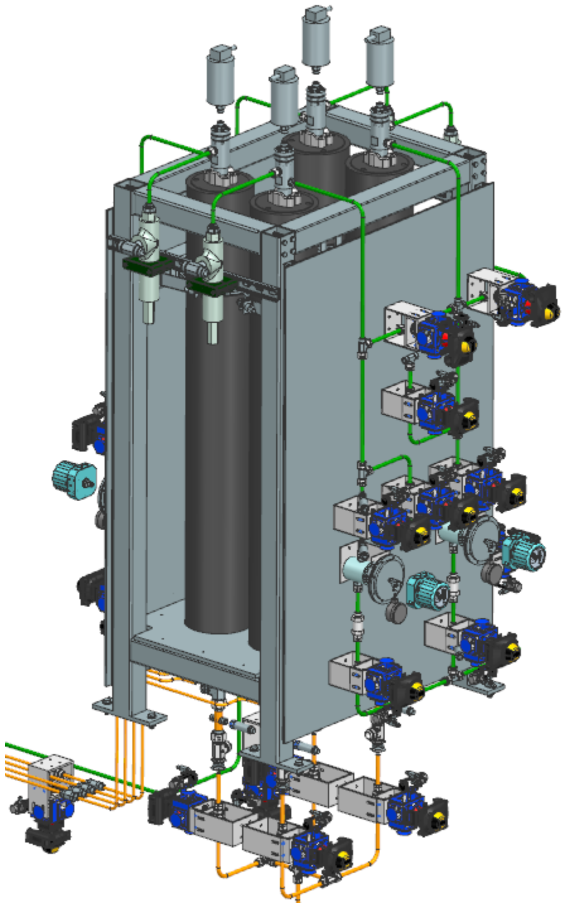


Combustor Cross-section

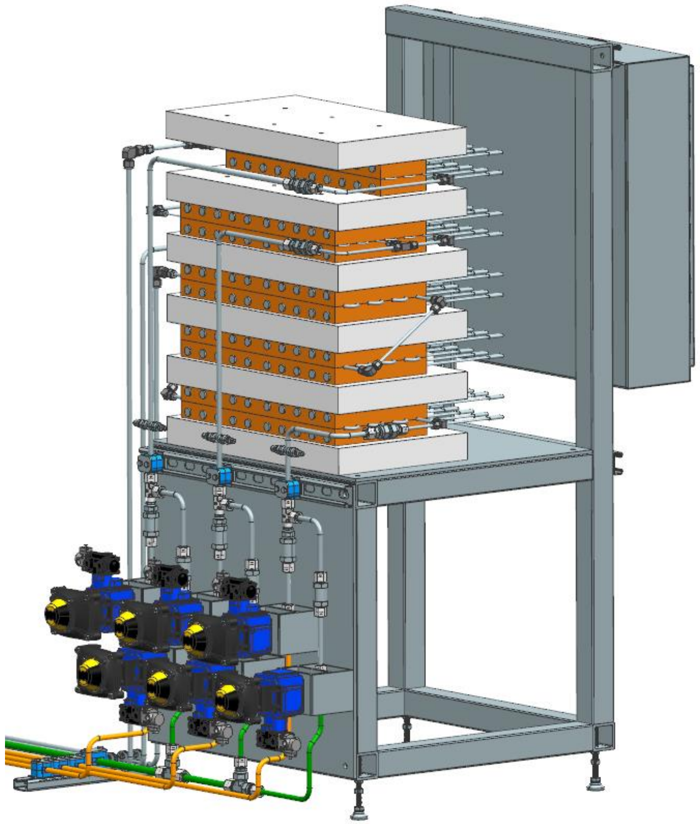


Ammonia System Design

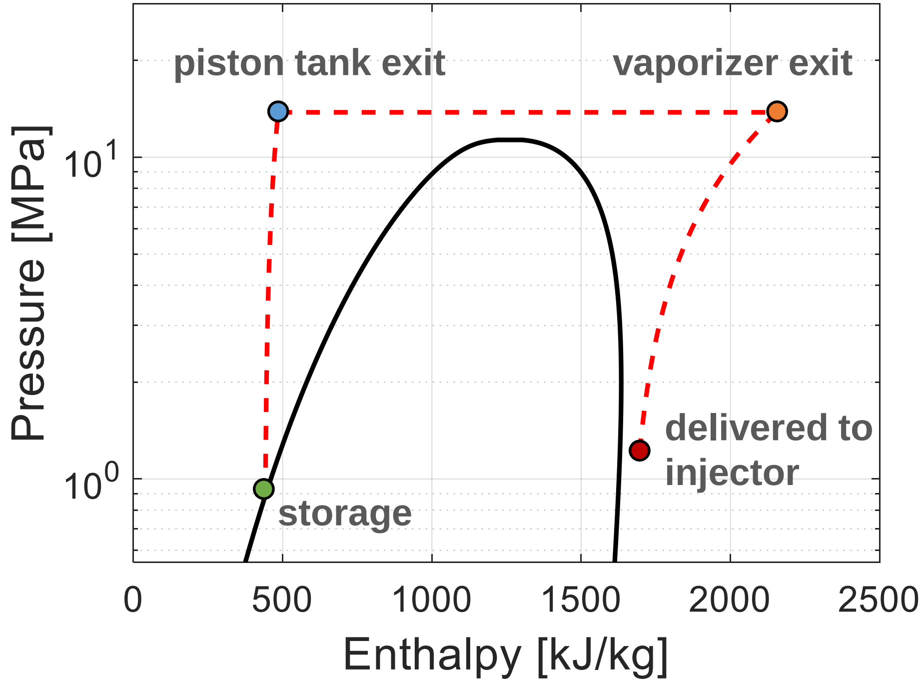
- Ammonia delivered in saturated state pressurized to target conditions in a piston tank
  - 70 kg of ammonia available per test at maximum supply pressure of 345 bar
- Ammonia delivered to steady state vaporizer prior to injection
  - Accommodates liquid NH_3 injection



NH_3 Piston Tanks

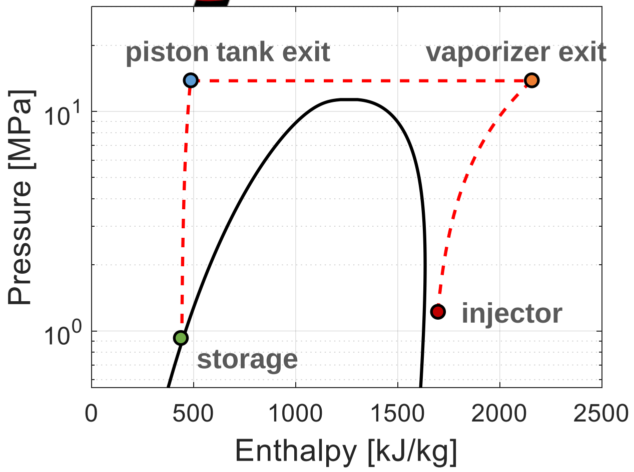


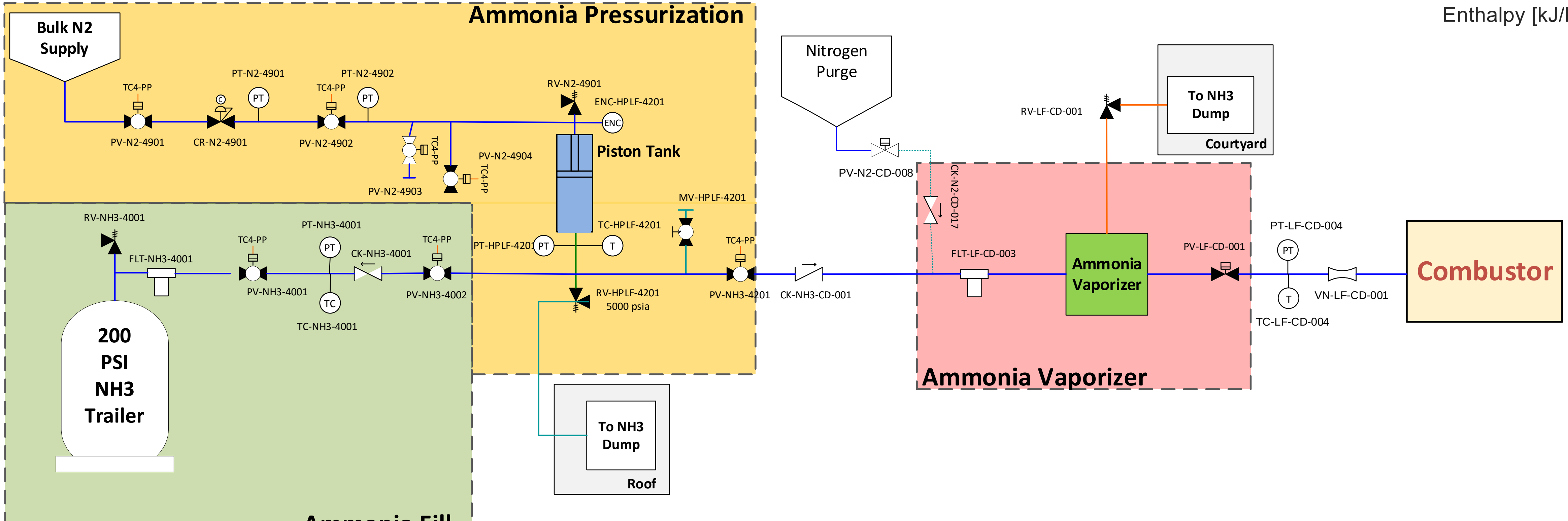
NH_3 Vaporizer



Ammonia System Design

- Ammonia filled into piston tank at saturated state into piston tank
- Piston tank pressurized with gaseous nitrogen (<345 bar)
- Liquid ammonia delivered from piston tank to steady state vaporizer
  - Linear encoder provides position feedback from piston
- Gaseous ammonia injected into combustor through JICF injector at target conditions
- Ammonia flowrate metered using cavitating (liquid) and sonic nozzles (vapor)

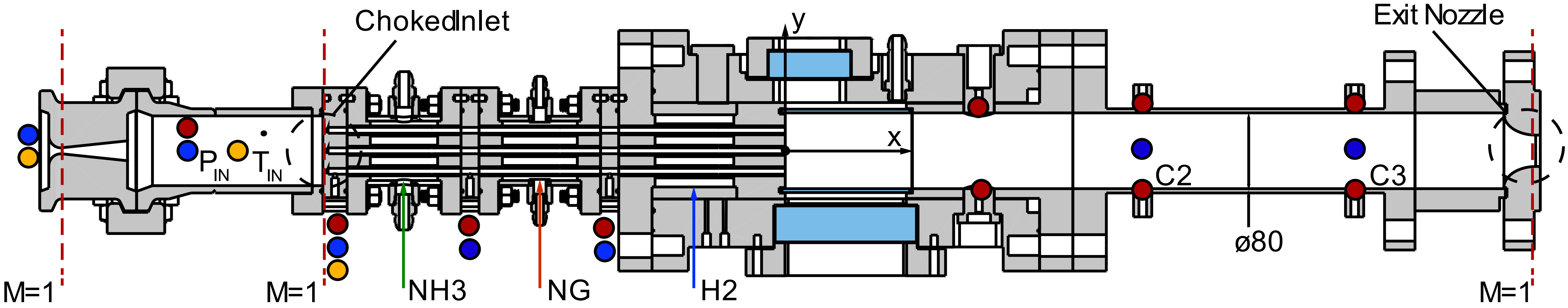




Instrumentation Layout

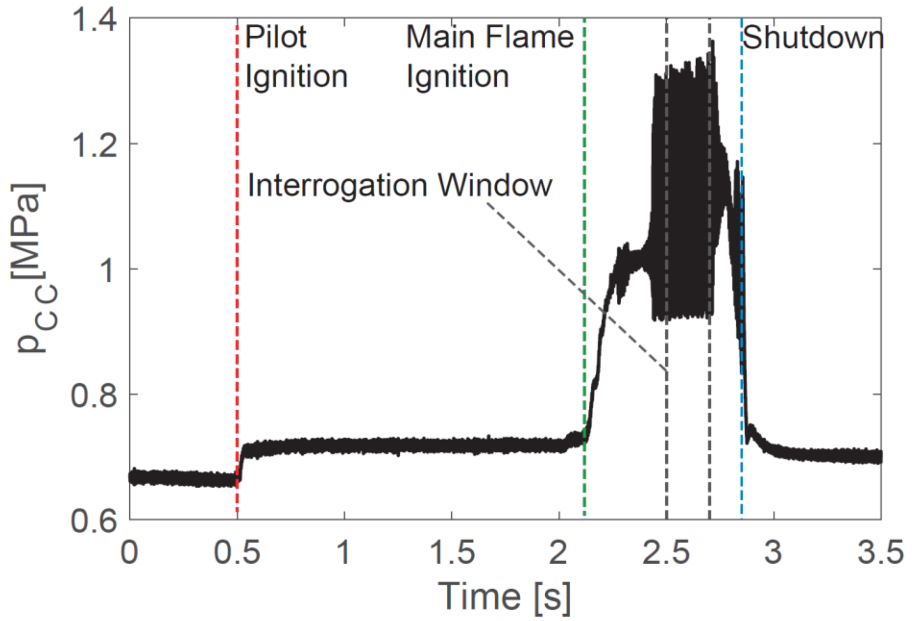
Measurement	Instrumentation	Range	Accuracy
LF Pressure (blue)	GE Sensing UNIK50E6	35 bar (test article), 70 bar (feed system)	0.04% FSO
HF Pressure (red)	Kulite WCT-312M-35/70BARA	35/70 bar	0.1% FSO
Temperature (yellow)	K-type thermocouple (GKMQIN-062G-06)	< 1250°C	2.2°C or 0.75%

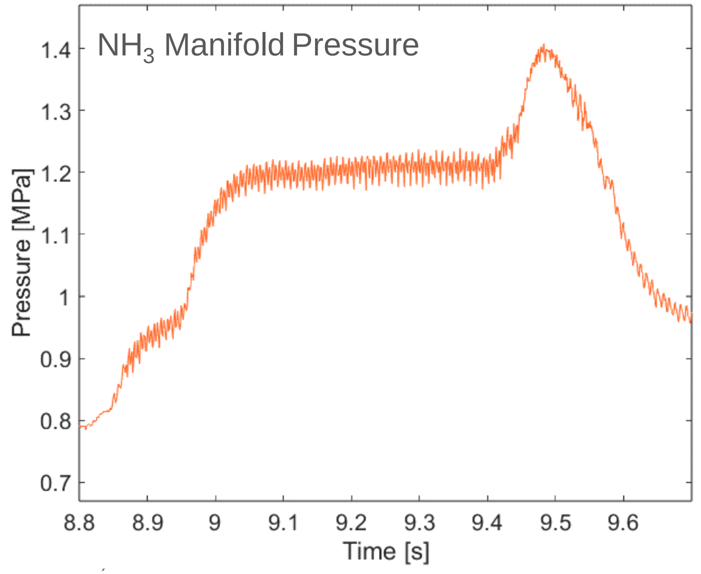
Diagnostic	Equipment
OH* Chemiluminescence Imaging	Phantom V2512 + Lambert HiCATT25 320±20 nm band-pass filter

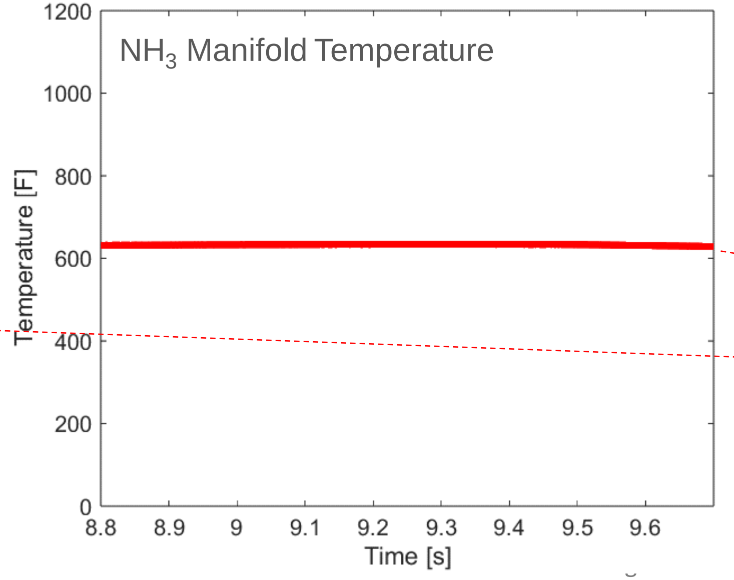


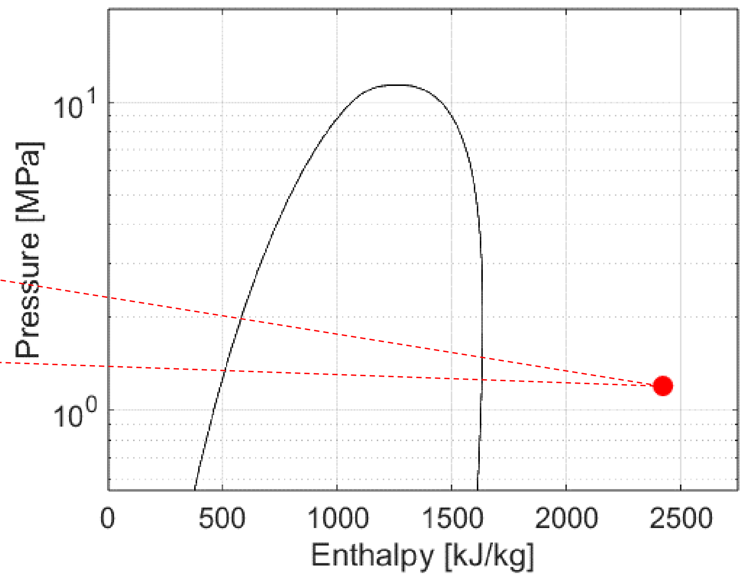
Results – Test Operation

- Experiments performed with dynamics configuration to illustrate influence of fuel composition
  - Mean chamber pressure 10 -12 bar
  - Ignition achieved using laser induced spark with a single-element operating with premixed hydrogen-air
  - Pre-vaporized ammonia delivered from piston tanks at target pressure
  - Natural gas and hydrogen delivered from bulk systems
  - All reactants metered with critical flow venturis upstream of injector







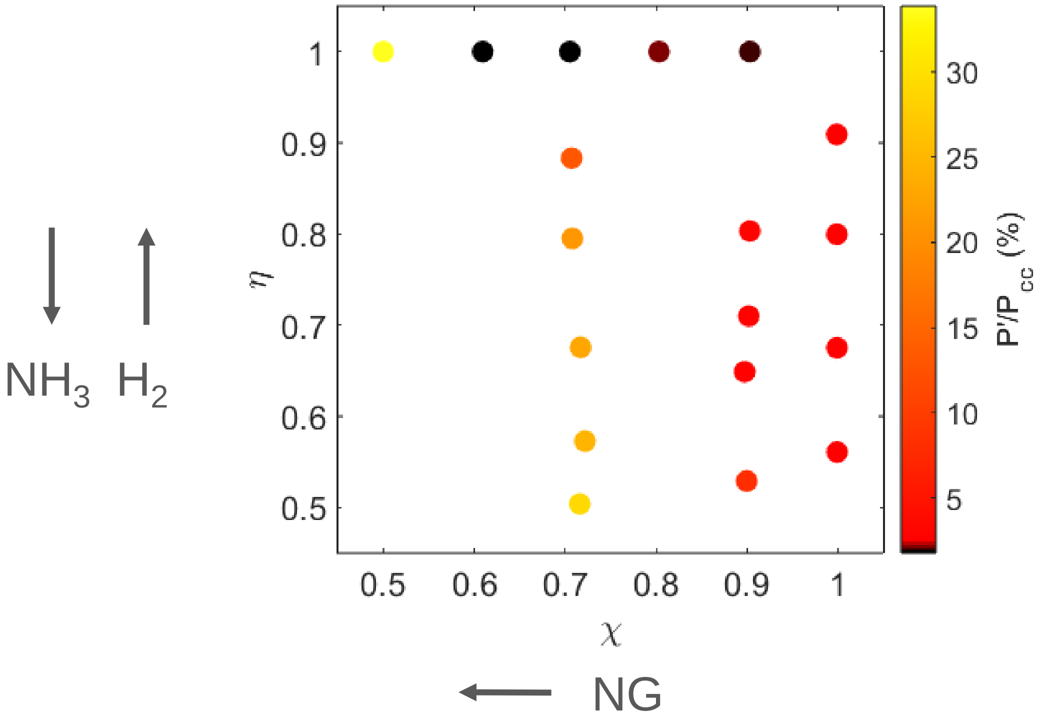


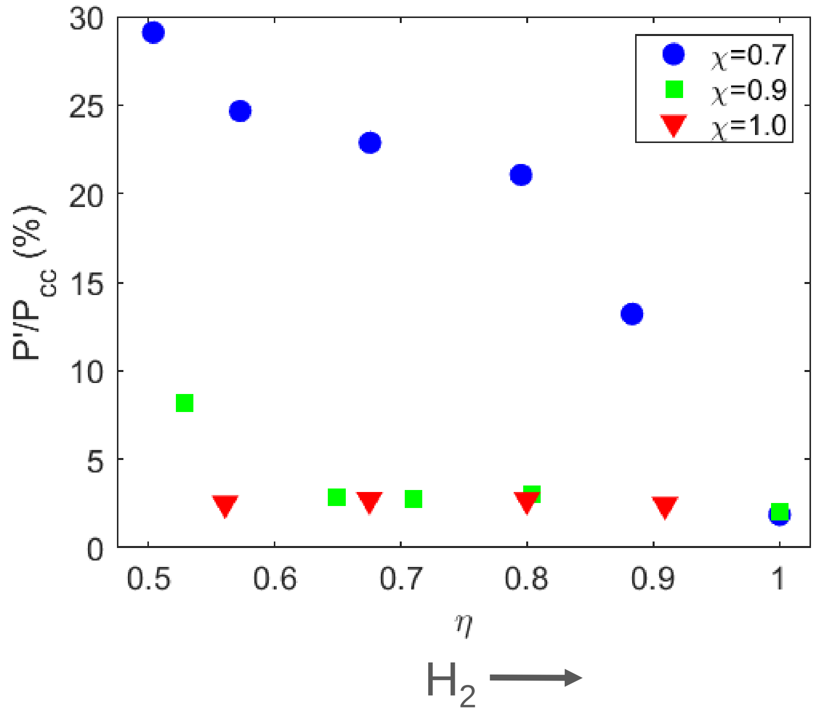
Results

- Systematic variation of χ and η to investigate influence of hydrogen and ammonia addition on combustion dynamics
- Hydrogen addition observed to suppress combustion instabilities
- Combustion instability amplitude is largely invariant to the addition of ammonia in absence of natural gas addition
- As hydrogen content is decreased, the addition of ammonia increases combustion instability amplitudes

Fuel Composition:

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$



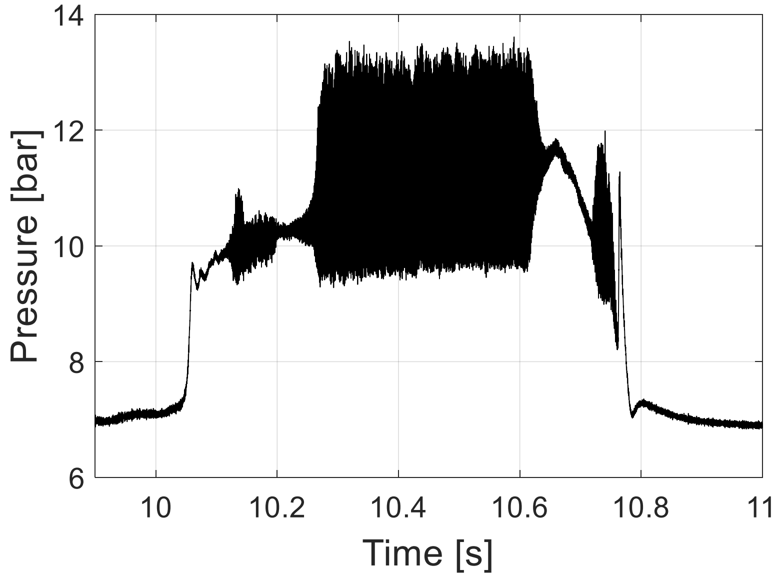


Results: H_2 Addition

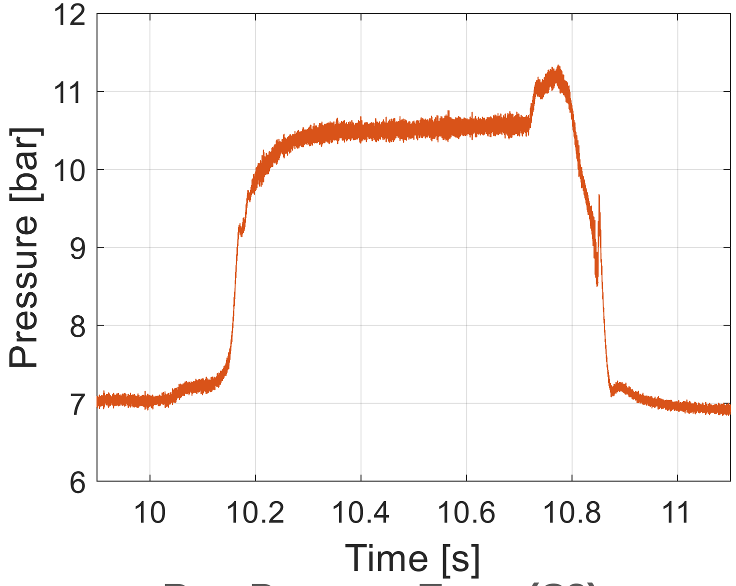
- Addition of H_2 is shown to suppress combustion instability (decreasing χ)
- At $\chi = 0.5$, p'/p_c of ~30% observed, with a longitudinal mode instability at the 2L frequency ~1075 Hz
- At $\chi = 0.7$, p'/p_c of ~2% observed, with the longitudinal mode instability dampened significantly

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$

$X = 0.5$, $\eta = 1.0$ — **H_2 addition** → **$X = 0.7$, $\eta = 1.0$**



Raw Pressure Trace (C3)



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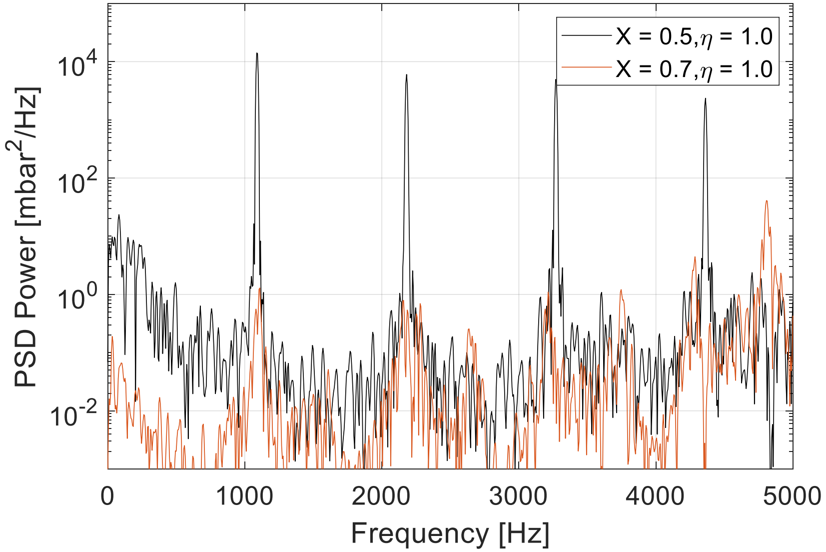
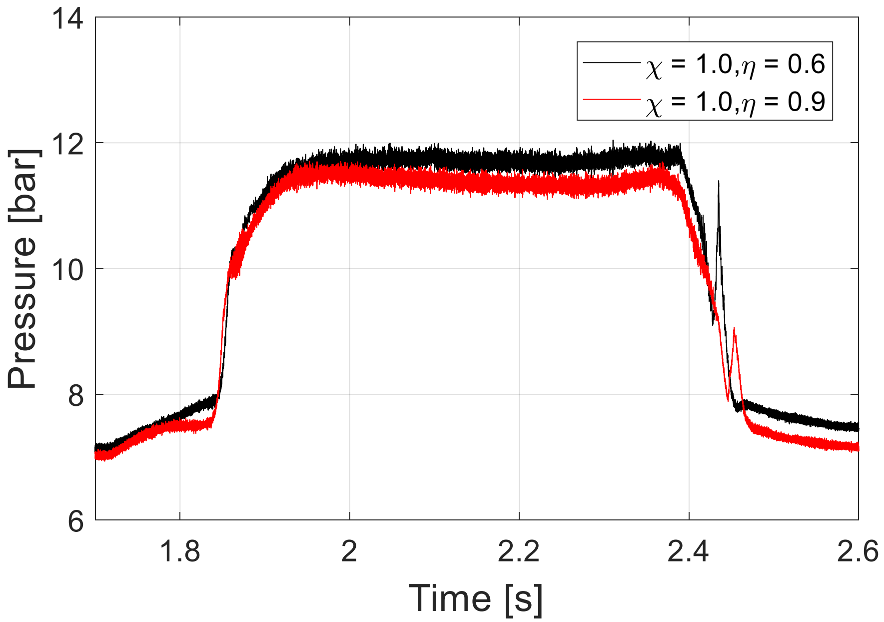


Power Spectral Density

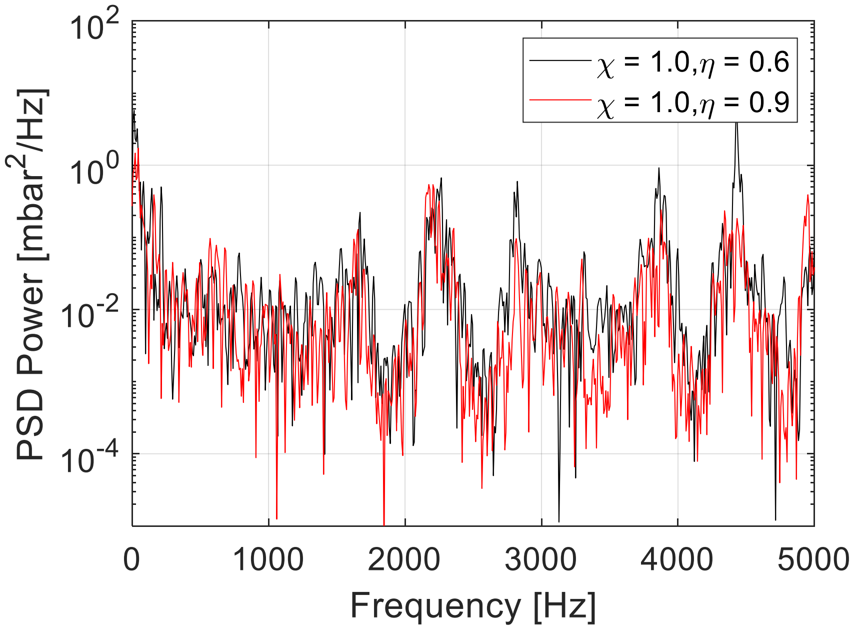
Results: NH_3 Addition

- Combustion instability amplitude is largely invariant to addition of NH_3 without NG present
- Fuel fraction of H_2 based fuel is at a maximum (χ = 1.0), while NH_3 decomposition efficiency is varied (η = 0.6 – 0.9)
- Chamber pressure fluctuations are low (p'/p_c of ~2%)
- Absence of longitudinal mode instabilities

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$



Raw Pressure Trace (C3)



Power Spectral Density

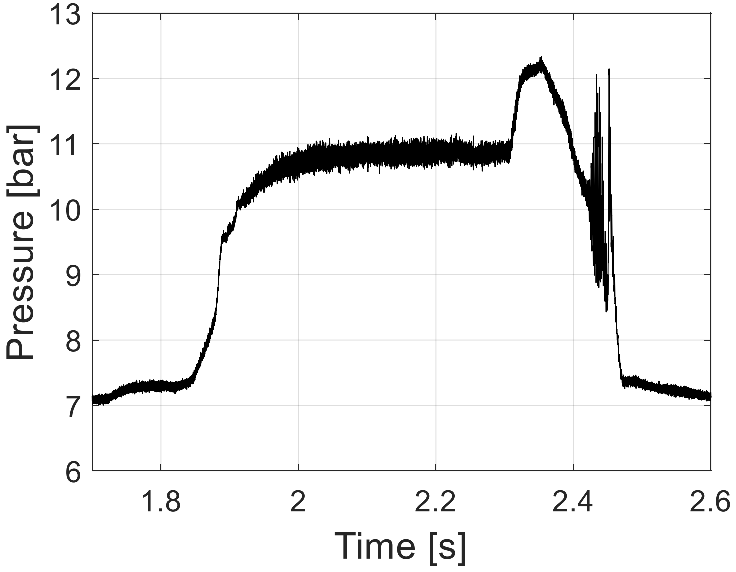
Results: NH_3 Addition

- With NG present (30%), small amounts of NH_3 addition increases combustion instability amplitude
- At η = 1.0, p'/p_c of ~2.5% observed, with a weak longitudinal mode instability at the 2L frequency ~1075 Hz
- At η = 0.9, p'/p_c of ~13% observed, with the longitudinal mode instability strength increased

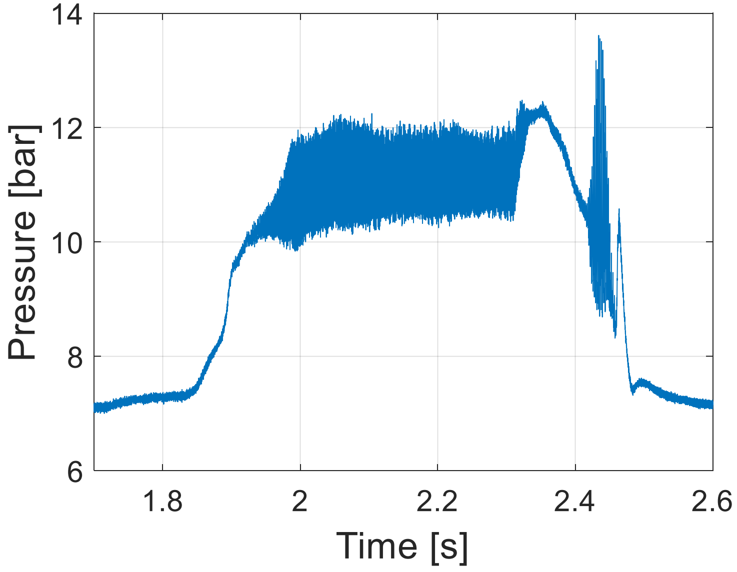
$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$

0.7 (↑ χ) 0.7 (↑ $(1-\chi)$)

χ = 0.7, η = 1.0 **NH_3 addition** → **χ = 0.7, η = 0.9**



Raw Pressure Trace (C3)



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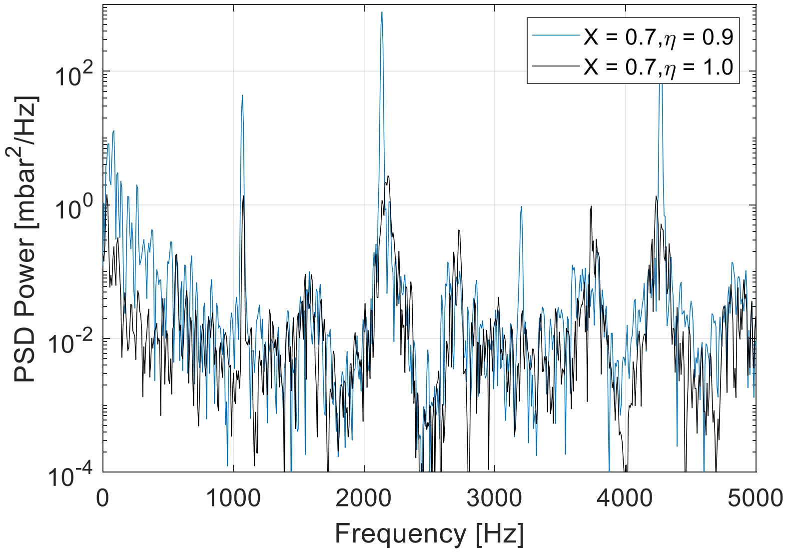


Power Spectral Density

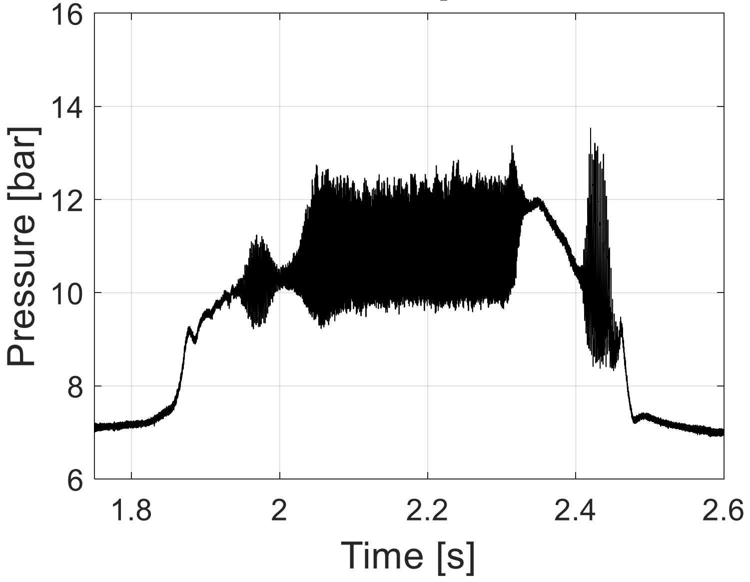
Results: NH_3 Addition

- Further NH_3 addition shifts the dominant longitudinal instability mode from 2L to 1L
- At η = 0.7, p'/p_c of ~24% observed, with a strong longitudinal mode instability at the **2L** frequency ~1075 Hz
- At η = 0.5, p'/p_c of ~29.1% observed, with a strong longitudinal mode instability at the **1L** frequency ~575Hz

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$

0.7 (χ) 0.7 ($1-\chi$)

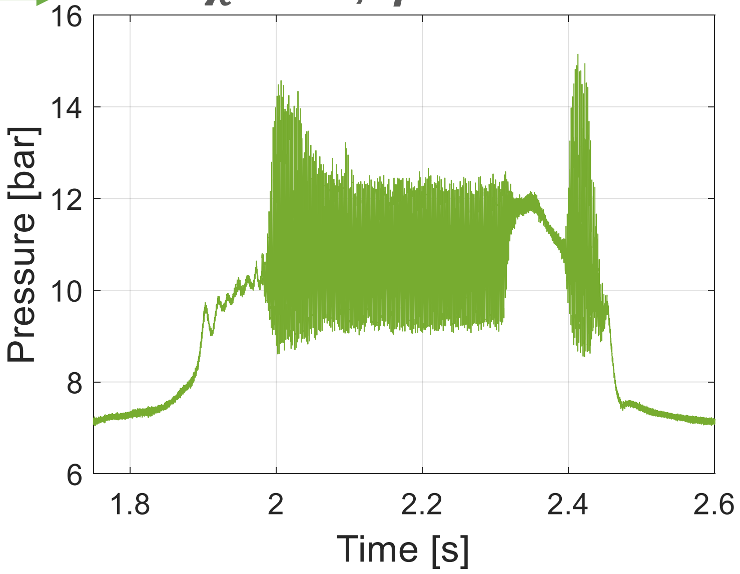
χ = 0.7, η = 0.7



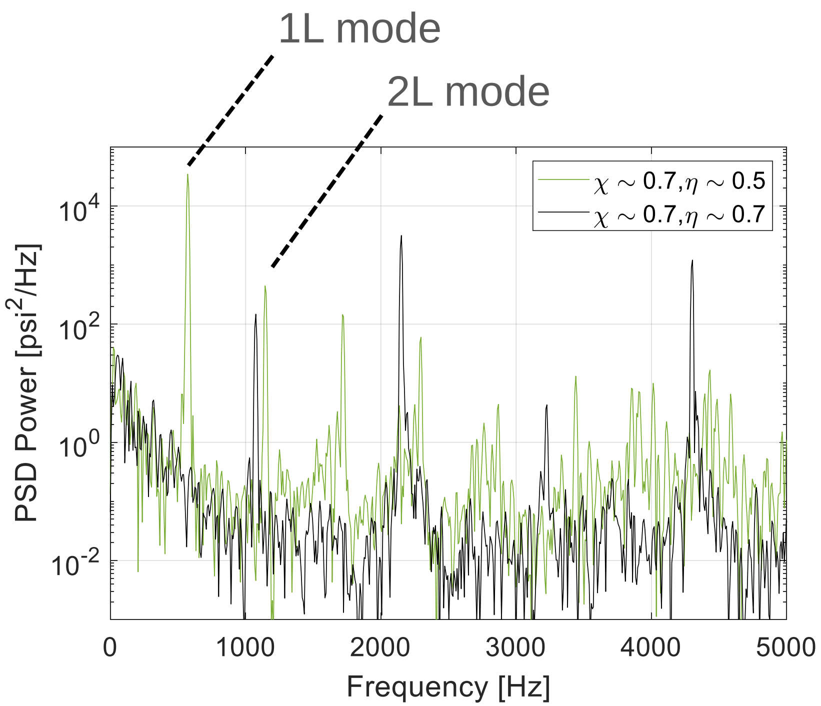
Raw Pressure Trace (C3)

NH_3 addition

χ = 0.7, η = 0.5



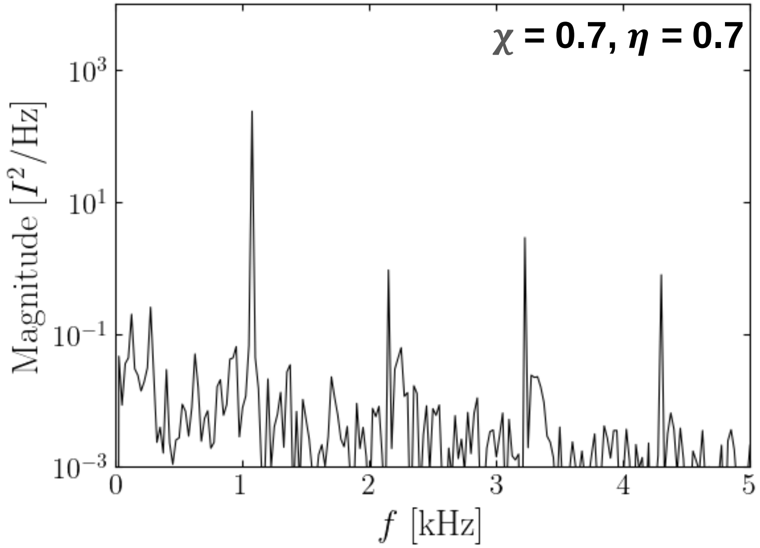
Raw Pressure Trace (C3)



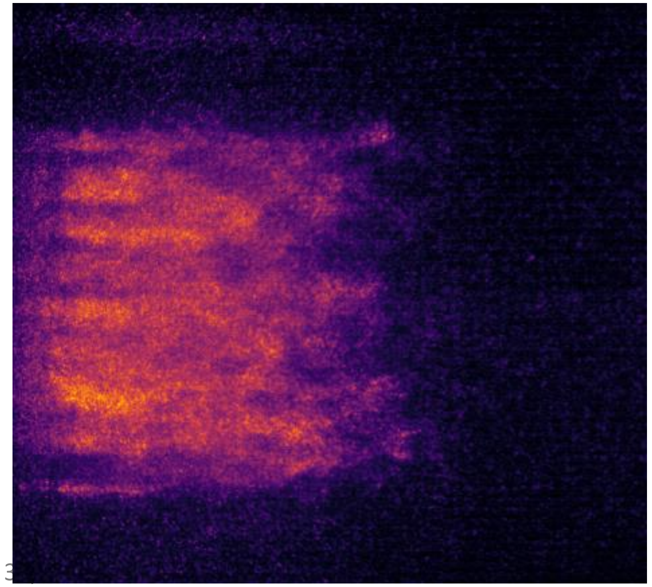
Power Spectral Density

Results: OH* Chemiluminescence

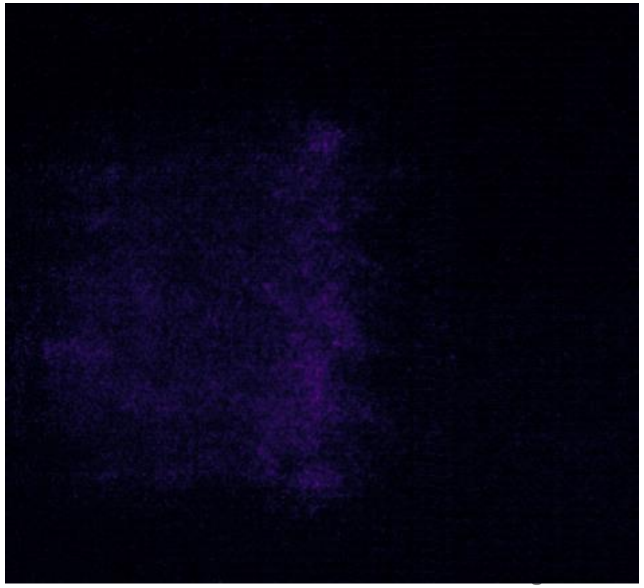
- OH* chemiluminescence measurements performed at 50kHz
- Time-averaged images provide a mean flame image using OH* as a marker for the heat release rate (I)
- Instability amplitude increases with increasing ammonia concentration
  - At η=0.5, the location of maximum heat release rate fluctuations shift downstream as 2L amplitude is significantly higher than 1L



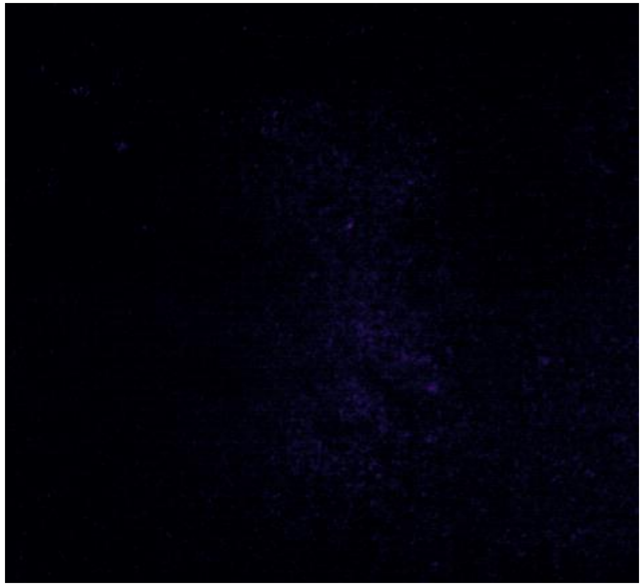
χ = 0.7, η = 1.0



χ = 0.7, η = 0.7



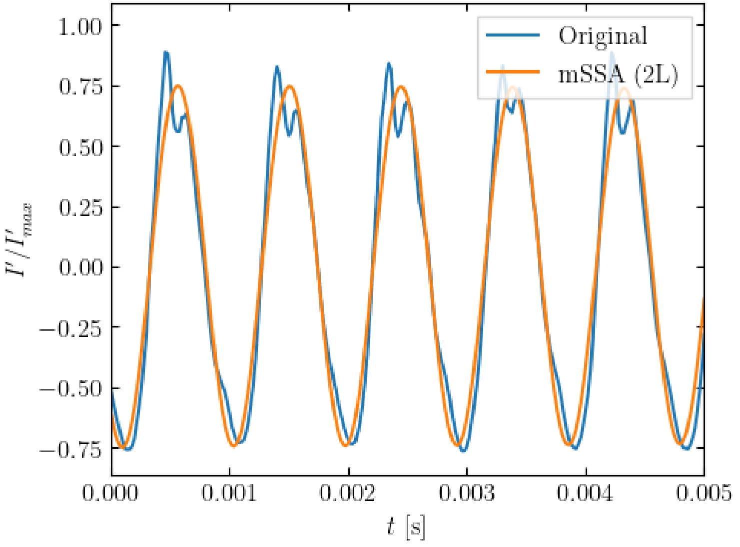
χ = 0.7, η = 0.5



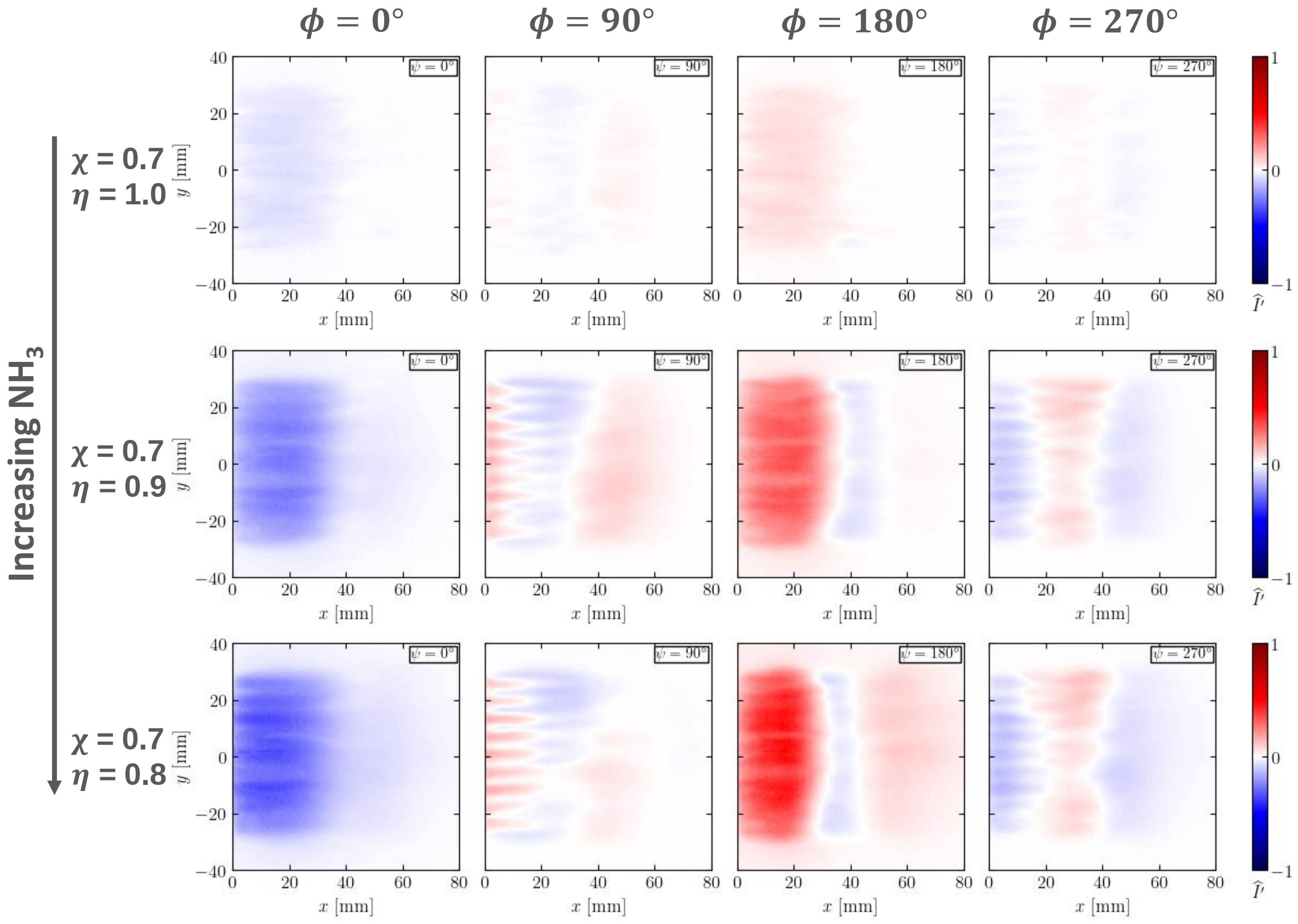
Results: Phase Averaged OH* CL

- Multivariate singular spectrum analysis (mSSA) performed to sync OH* CL fluctuations at the 2L frequency
- Phase averaged OH* CL results show the fluctuation of heat release as NH_3 is added
- Heat release fluctuations are strongest at x = 0 – 30 mm

χ = 0.7, η = 0.8



mSSA reconstruction of I' at the 2L mode frequency

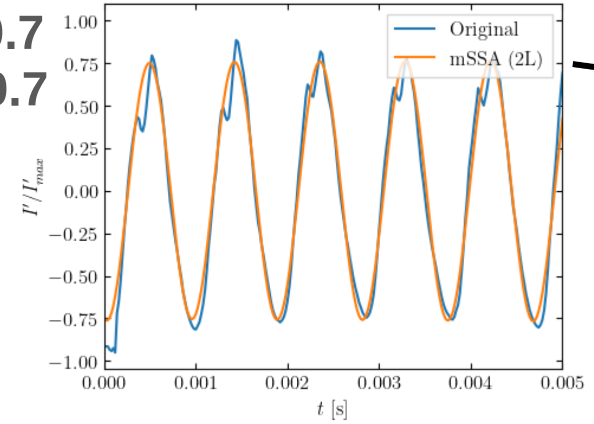


Results: Phase Averaged OH* CL

- Further increasing NH_3 addition causes an instability mode shift from 2L to 1L, changing the flame shape

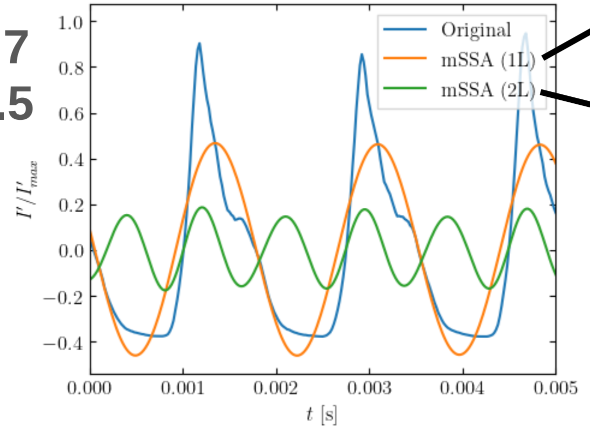
mSSA reconstruction of I' at the 2L mode frequency

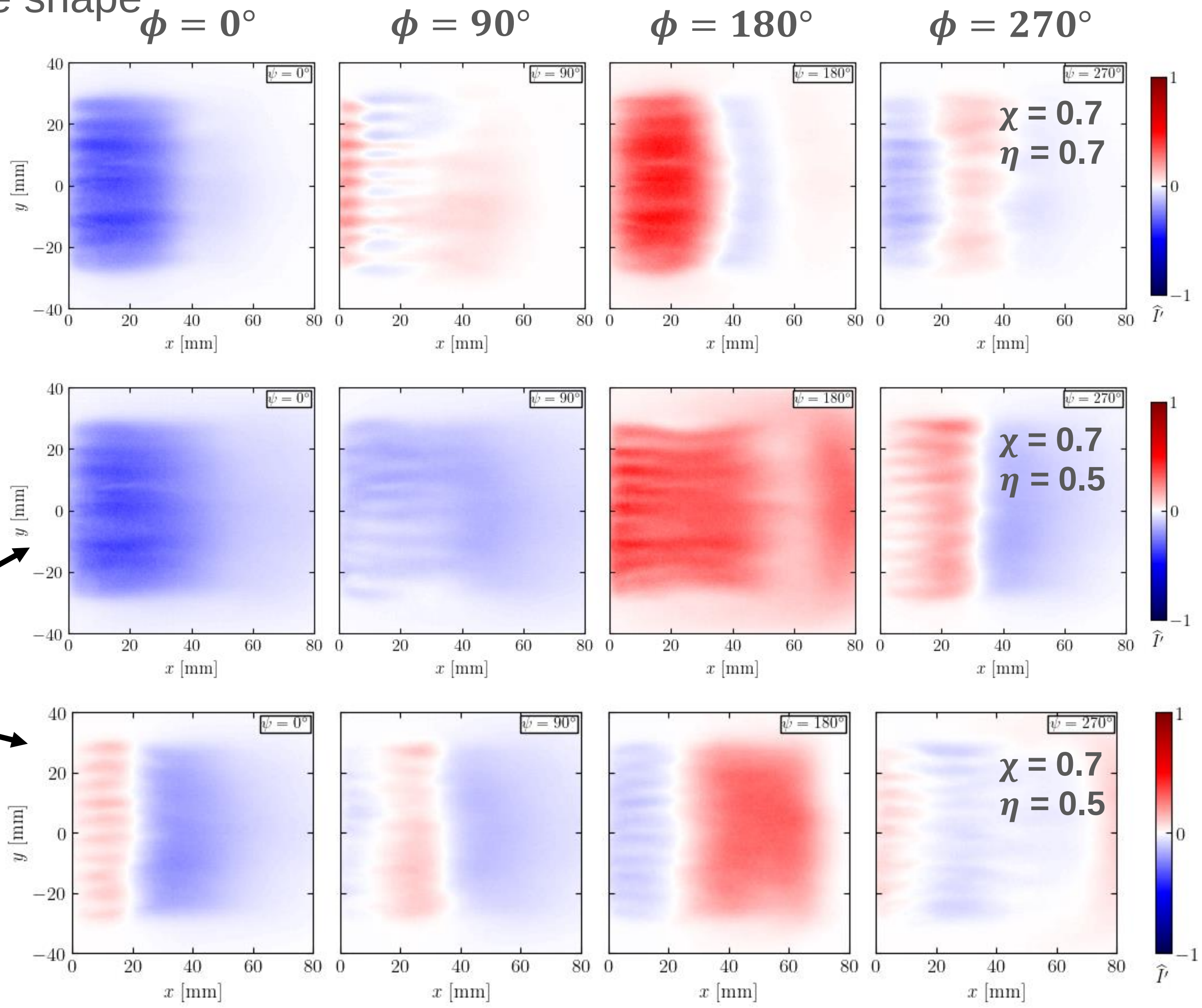
$\chi = 0.7$
$\eta = 0.7$



mSSA reconstruction of I' at the 1L and 2L mode frequency

$\chi = 0.7$
$\eta = 0.5$



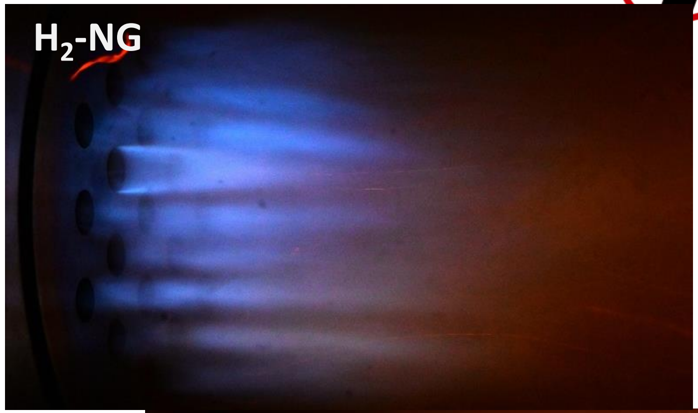


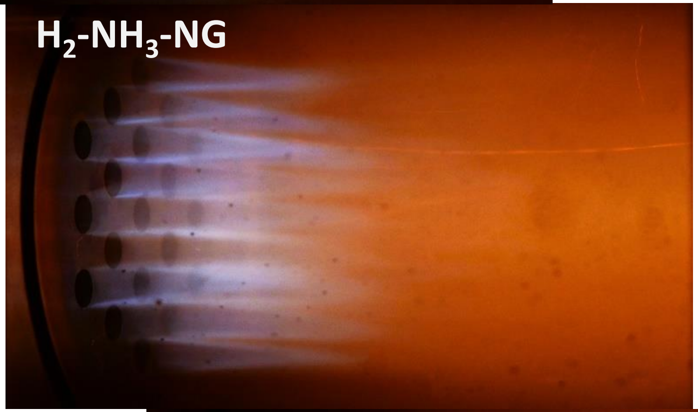
Summary

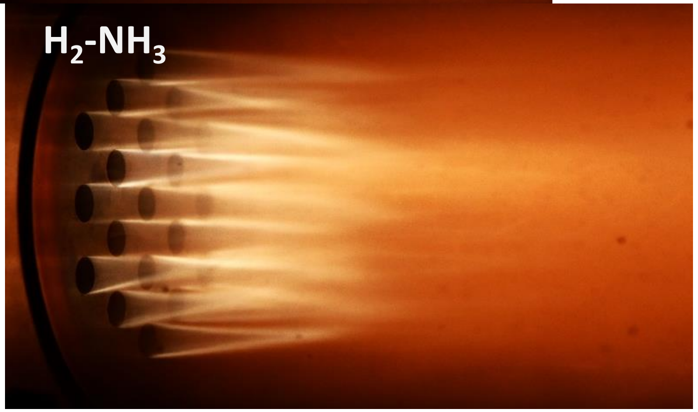
- Successfully developed and demonstrated operation of high-pressure ammonia system for combustion research with high hydrogen content fuels
- Characterized influence of ammonia and hydrogen addition on self-excited combustion instabilities at elevated pressure with a premixed multi-element micromix injector
  - Disparate flame speeds of ammonia and hydrogen allow stable combustion for a wide range of η
  - Addition of natural gas increases propensity for instability and sensitivity to ammonia addition
  - Additional tests and measurements planned to fully describe the behavior governing stability limits

Next Steps:

- Detailed characterization of flame structure and dynamics with application of chemiluminescence, PLIF, PIV, and CARS measurements
- Global emissions characterization using FTIR based extractive product gas sampling
- Collaborate with Sreenath Gupta and his group at Argonne National Labs on modeling of the ammonia combustion results







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