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HIGH-FREQUENCY TRANSVERSE COMBUSTION INSTABILITIES IN LOW-NOX GAS TURBINES (DE-FE0031285)

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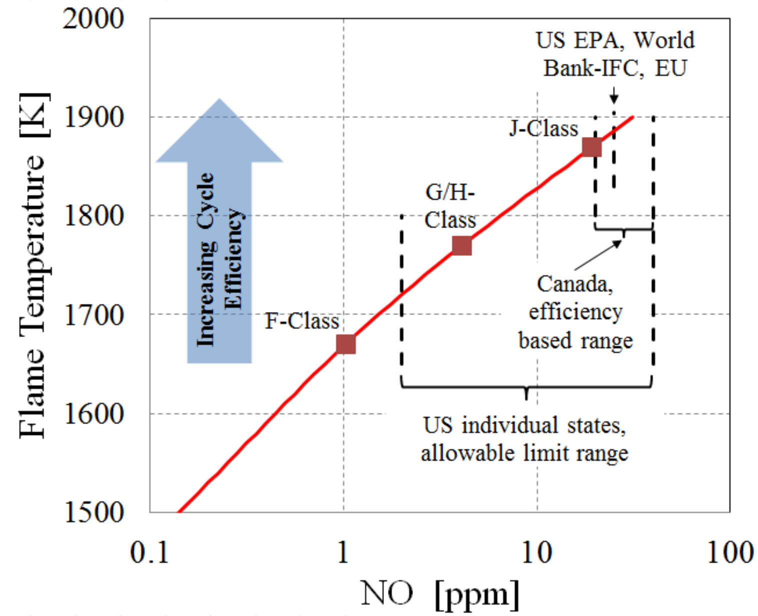
MOTIVATION FOR RESEARCH

- Combustion dynamics are a critical challenge in high efficiency gas turbines
  - Transverse, "screeching" instabilities are increasingly problematic

- **<u>Target architecture</u>** → Multi-nozzle can combustor configuration with interacting flames
  - Extensive research and literature to address longitudinal mode instabilities with acoustically compact flames

- <u>Focus of the proposed project</u> → **High-frequency transverse combustion instabilities in multi-nozzle can combustor configurations.**



Realistic multi-nozzle experiments and high frequency modeling capabilities needed

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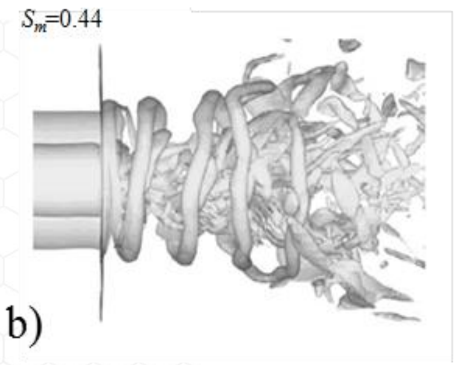
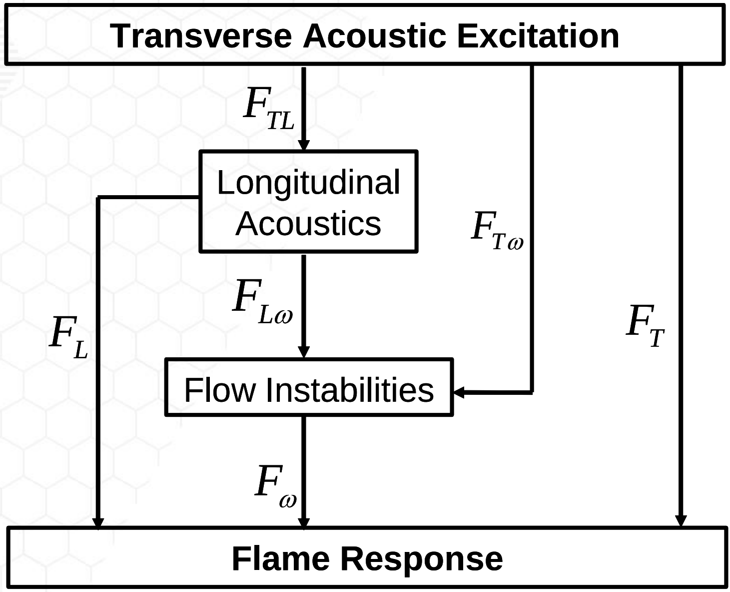
DISTINGUISHING FEATURES OF HIGH FREQUENCY, TRANSVERSE INSTABILITIES

- Acoustic wave motions perpendicular relative to main flow direction
  - intrinsic non-axisymmetric excitation
  - No direct net mass flow modulation of reactants (although indirect effect can be large, F_{TL} path on chart)
- Wave can be spinning or standing; nodal lines can move
- Acoustic wavelength of the order of heat release zone extent
  - Flame not compact; its spatial distribution matters
  - E.g., ideal heat release for 1-T mode has spatial integral of zero





EXPERIMENTS AND DATA ANALYSIS

TASK 2 ACCOMPLISHMENTS

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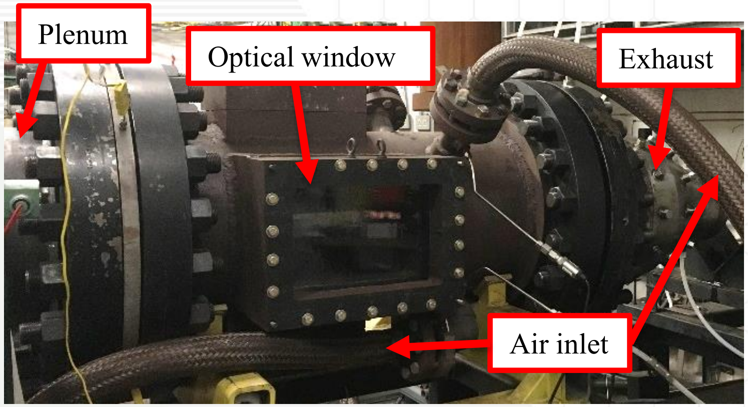
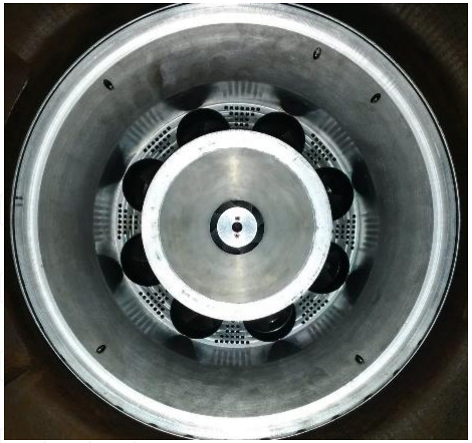
RESEARCH TASK 2

TASK 2.1 – EXPERIMENT

- D=29 cm combustor
  → capture accurate high-frequency acoustics

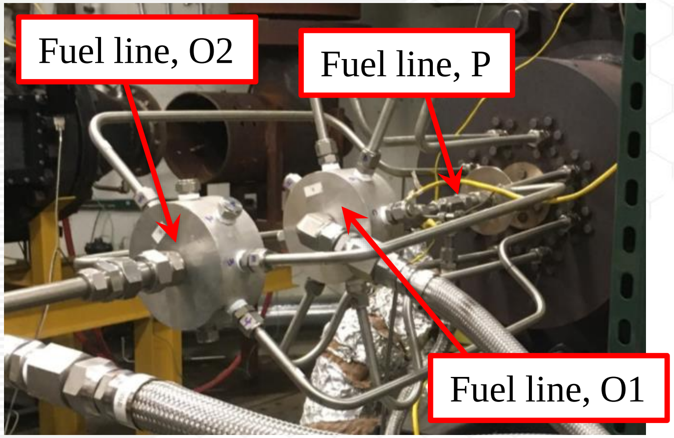


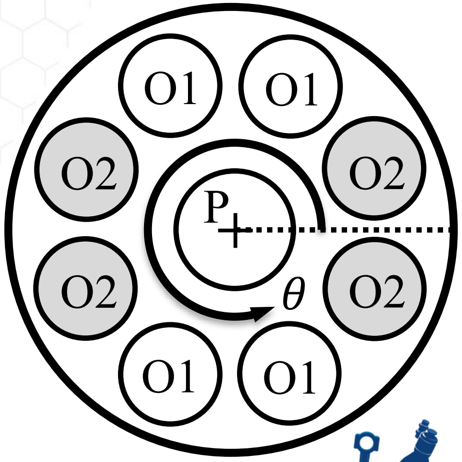


- Multiple nozzles
  → capture flame-flame interactions.

- Optical accessibility using quartz
  → spatio-temporal flow and flame characterization

- Ability to vary heat release distribution in radial and azimuthal direction
  → 3 fuel circuits (P, O1, O2)

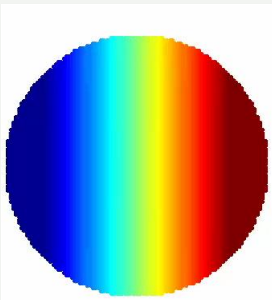




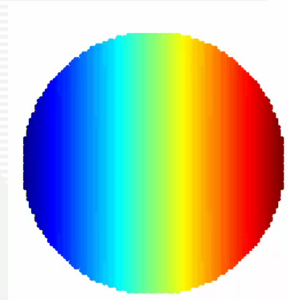
RESEARCH TASK 2

TASK 2.2 – MODAL DYNAMICS

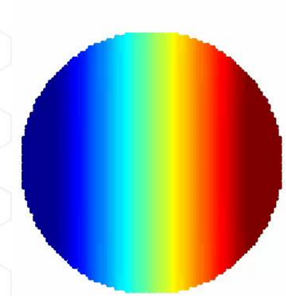
- Modal nature of transverse instabilities (e.g., $m = 1$ transverse mode)
  - Standing vs spinning: characterized by SR



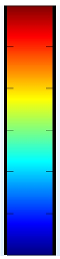
Standing wave
($SR = 0$)



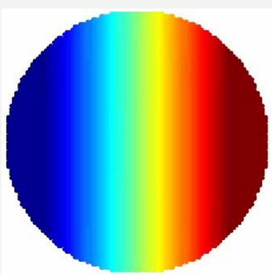
Spinning wave
($SR = 1$)



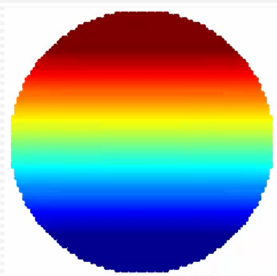
Mixed wave
($SR = 0.5$)



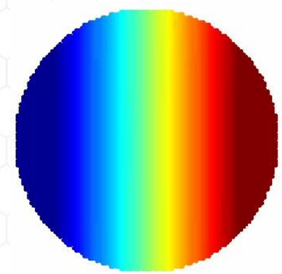
  - Orientation of anti-nodal line: characterized by φ_{FG} ($\theta_a = -\frac{\varphi_{FG}}{2}$)



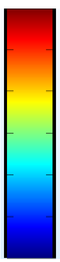
Horizontal
($\varphi_{FG} = 0$)



Vertical
($\varphi_{FG} = \pi$)



Func of time
($\varphi_{FG} = \varphi_{FG}(t)$)



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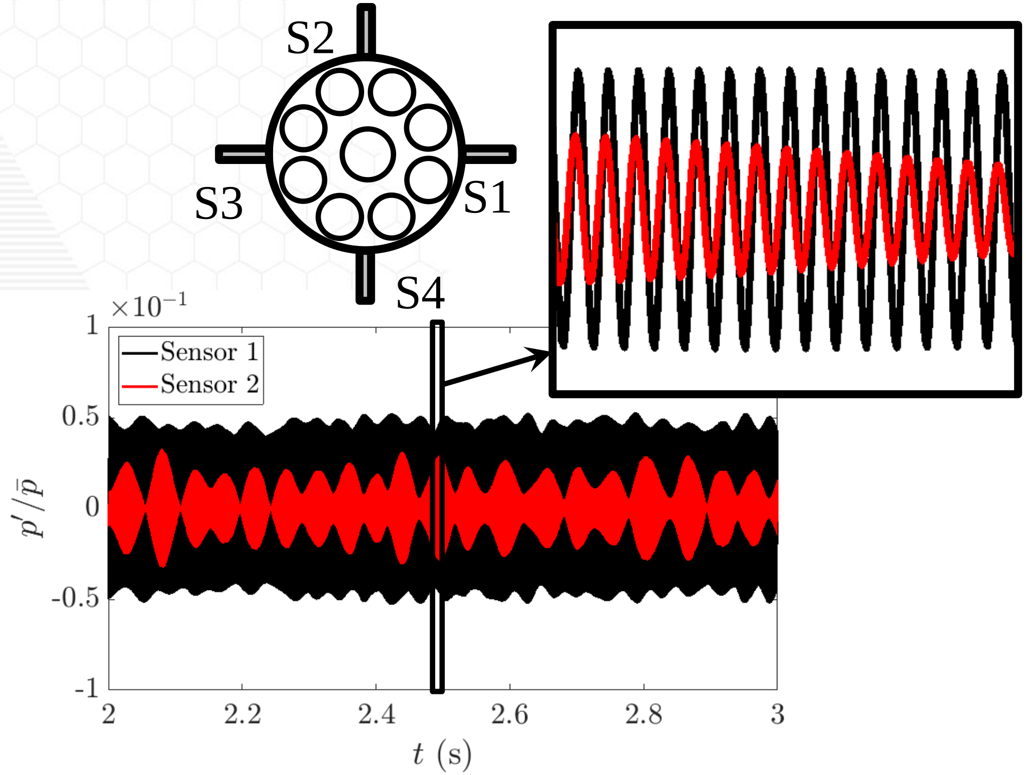
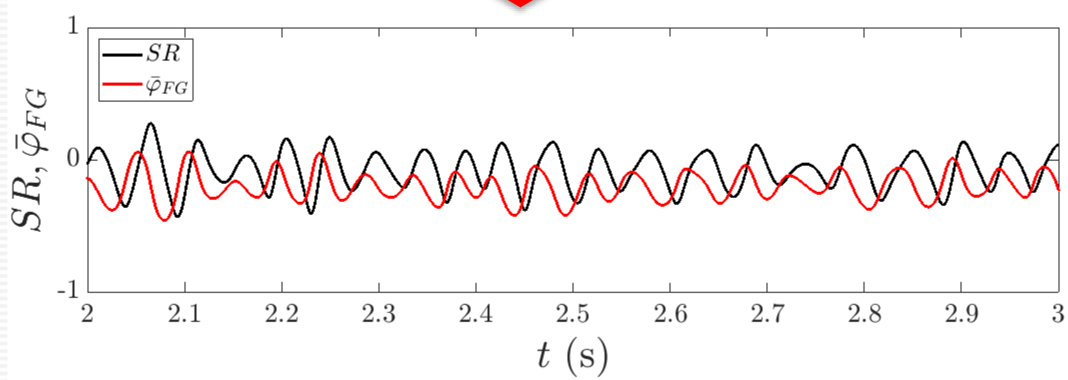
RESEARCH TASK 2

TASK 2.2 – MODAL DYNAMICS

- Pressure signal is harmonically oscillating.
- Magnitude (envelope) of pressure signal is oscillating.
  → Quasi-periodicity
- Spin ratio and phase difference (anti-nodal line) are oscillating.
  → The wave is predominantly a standing wave ($SR = 0$), but it periodically oscillates around it.
  → Anti-nodal line is oscillating around its averaged location (reason for pressure magnitude oscillation).
  → Modal nature is periodically oscillating.





RESEARCH TASK 2

KEY TAKEAWAYS

- ✓ Developed multi-nozzle facility with radial/azimuthal fuel staging capabilities
- ✓ Identified range of conditions with 1-T mode, with various dominant standing and spinning wave dominant conditions
- ✓ Phase portraits show different types of dominant attractors, leading to substantively different pressure sensor measurements
- ✓ Magnitudes of pressure and heat release fluctuations are positively correlated, and their phase difference satisfies the Rayleigh criterion.
- ✓ Non-uniform azimuthal fuel staging reduces the overall instability amplitude
- ✓ Non-uniform azimuthal fuel staging provides a standing wave with anti-node at a fixed location

MODELING THE DYNAMICS DURING HIGH-FREQUENCY INSTABILITIES

TASK 3 ACCOMPLISHMENTS

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RESEARCH TASK 3.1
MODELING FRAMEWORK

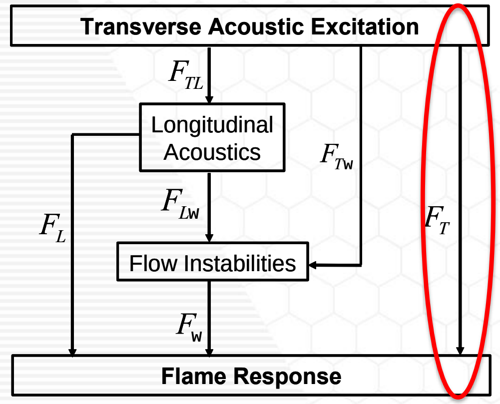
High-frequency → Non-compact flames

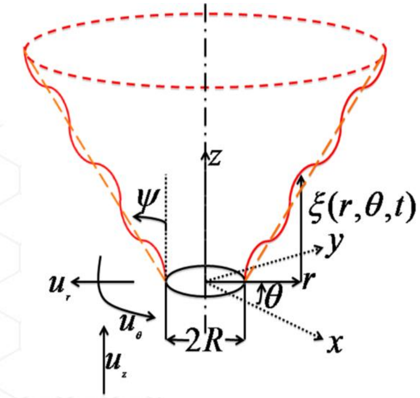
- Cannot use global heat release dynamics
- Acoustic energy dynamics

$$\frac{\partial}{\partial t}\int_V e_1 dV = \frac{\gamma-1}{\gamma p_0}\int_V \left(p_1\dot{q}_1\right)dV - \int_S p_1\left(\vec{u}_1\cdot d\vec{S}\right)$$

A necessary condition for the Rayleigh Integral:

$$RI = \int_t\int_V p_1\dot{q}_1 dV dt > 0$$





➢ Explicit flame dynamics

$$\frac{\partial\xi}{\partial t} + u_r\frac{\partial\xi}{\partial r} + \frac{u_\theta}{r}\frac{\partial\xi}{\partial\theta} + s_L\left[\left(\frac{\partial\xi}{\partial r}\right)^2 + \frac{1}{r^2}\left(\frac{\partial\xi}{\partial\theta}\right)^2 + 1\right]^{1/2} = u_z$$

➢ Normalized Rayleigh Index

$$\Re = \frac{RI}{2E}$$

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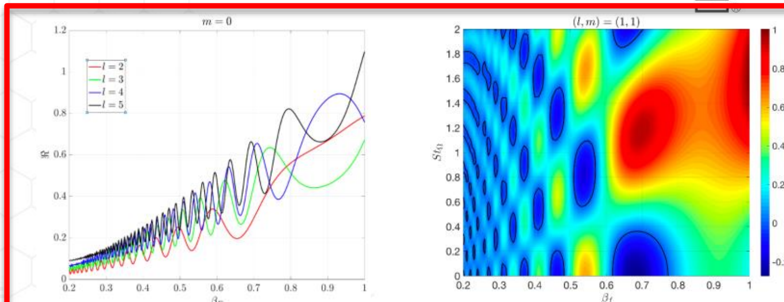
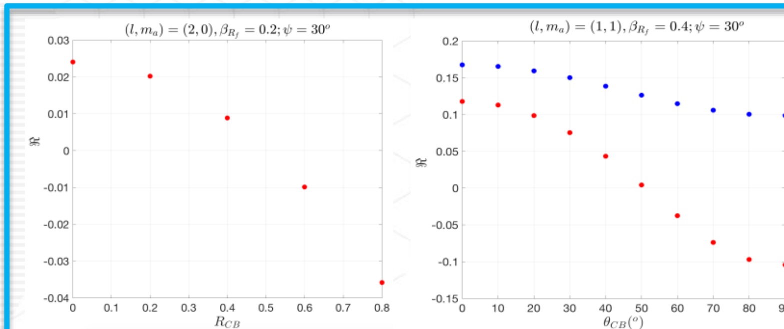
RESEARCH TASK 3.1

SUMMARY OF PRIOR RESULTS

- Stability for low-frequency compact flames: global flame transfer function
- Stability for high frequency non-compact flames: Rayleigh index
- Prior modeling studies on single flames
  - Axisymmetric mean flames centered in combustor
  - Axisymmetric mean flames offset from combustor axis
  - Non-axisymmetric mean flame effects
  - Comparison to induced axial excitation

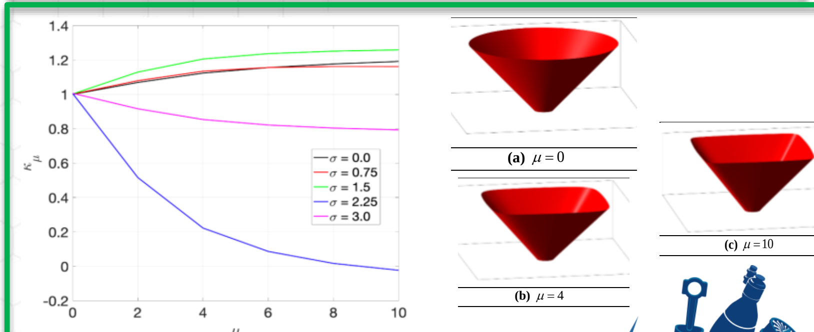


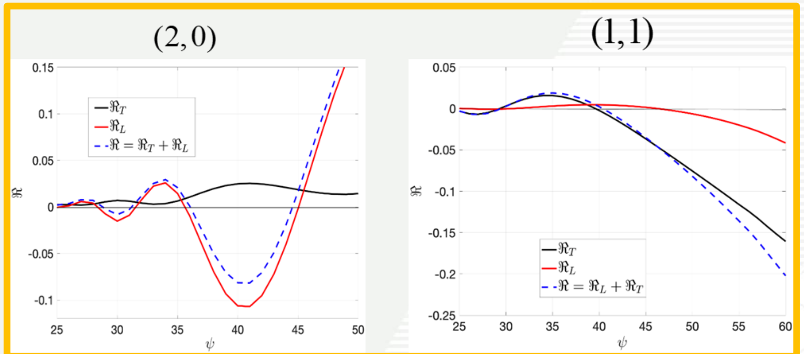
Radial modes – always unstable! (1,1) – islands of stability



Outward radial offset increases stability

Azimuthal offset increases stability

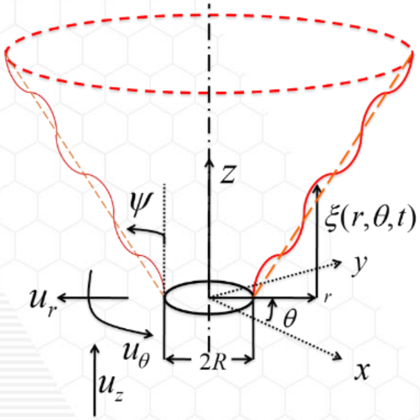




RESEARCH TASK 3.1

PRIOR WORK → OPTIMIZATION STUDIES

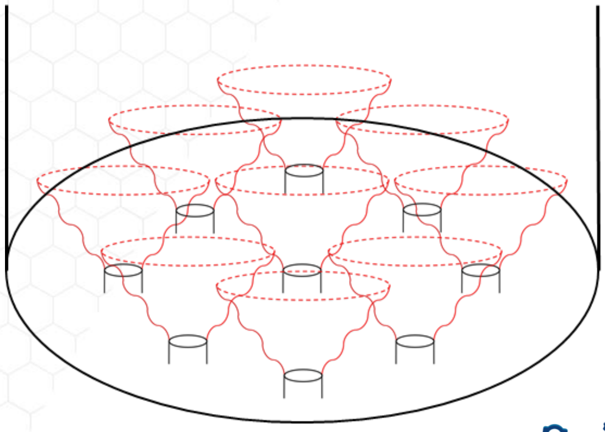
- Prior work was for single flames only



- What about multiple flames/multi-nozzle systems?

➢ **How to optimally position nozzles for stability?**

➢ **How to optimally operate given nozzles for stability?**

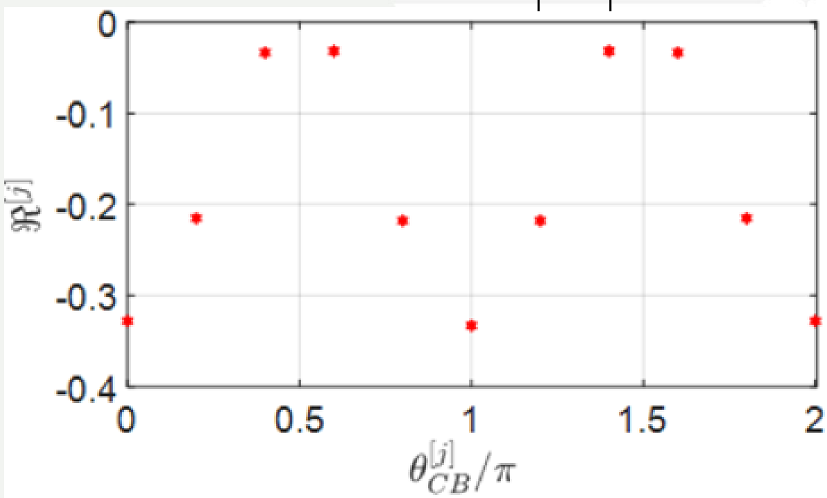


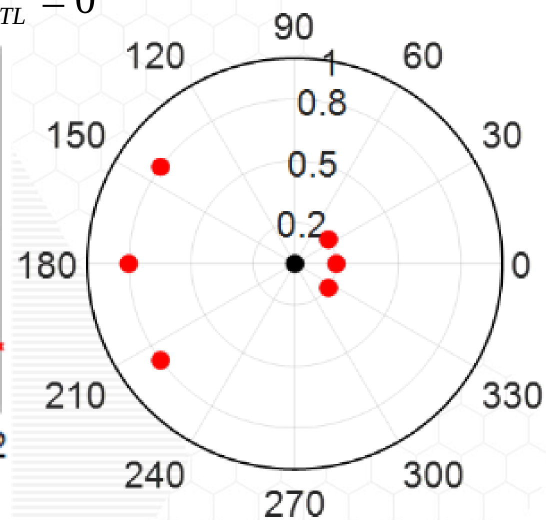
RESEARCH TASK 3.1

NOZZLE POSITION OPTIMIZATION FOR 1-T MODE

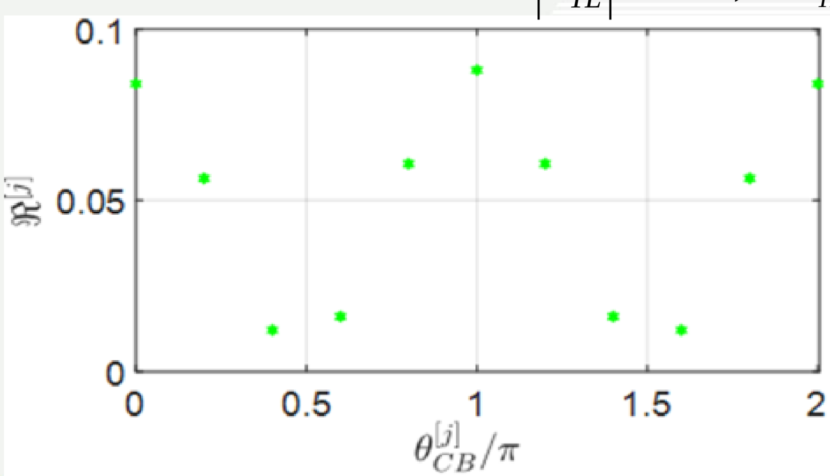
For a fixed set of flame/flow parameters, what is the optimal positioning for the multiple nozzles

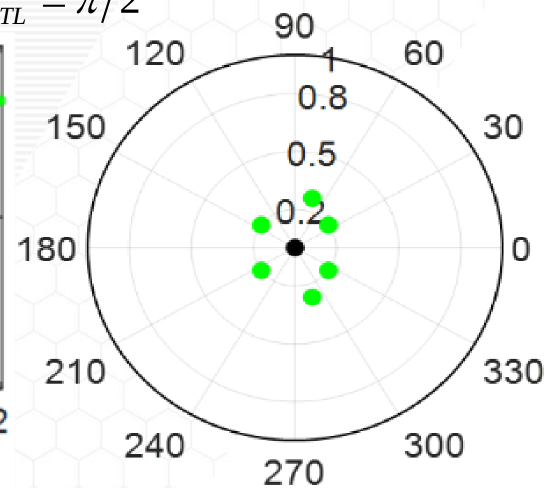
$$\left|\hat{Z}_{TL}\right| = 10.0\,,\ \angle\hat{Z}_{TL} = 0$$





$$\left|\hat{Z}_{TL}\right| = 10.0\,,\ \angle\hat{Z}_{TL} = \pi/2$$





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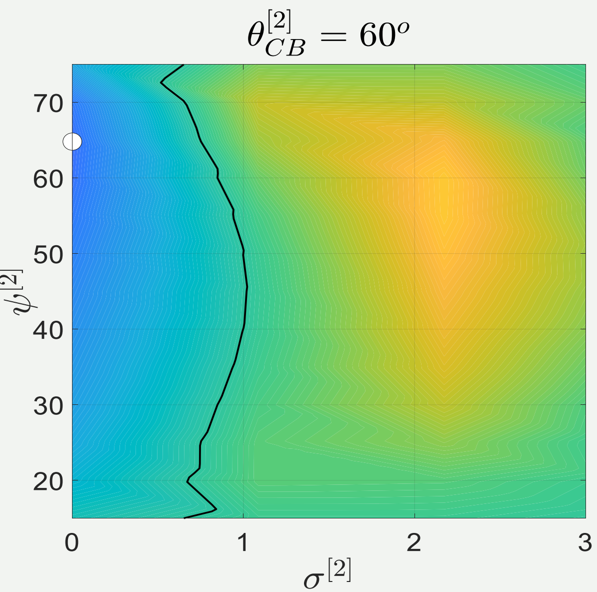
RESEARCH TASK 3.1

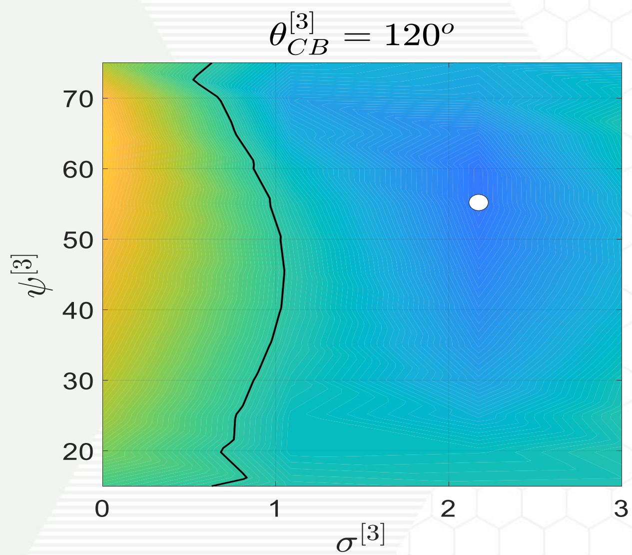
NOZZLE PARAMETER OPTIMIZATION FOR 1-T MODE

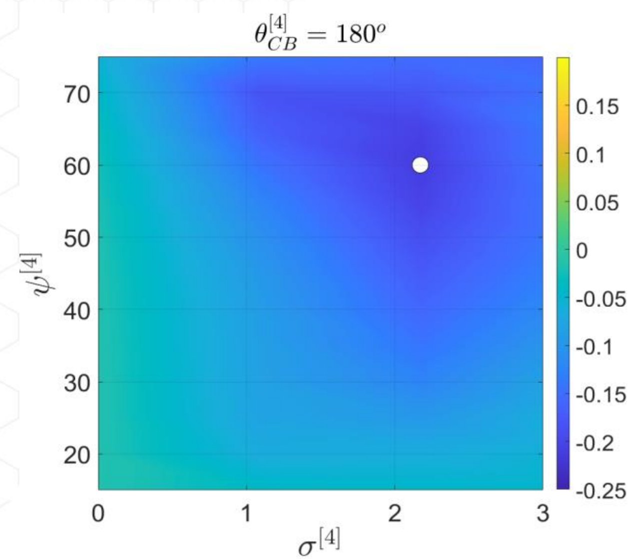
For a fixed set of nozzle locations, what is the optimal operating flame/flow parameters

$$\left|\hat{Z}_{TL}\right| = 1.0\,,\ \angle \hat{Z}_{TL} = 0$$

6 equally distributed nozzles, showing only 2-4







RESEARCH TASK 3.1

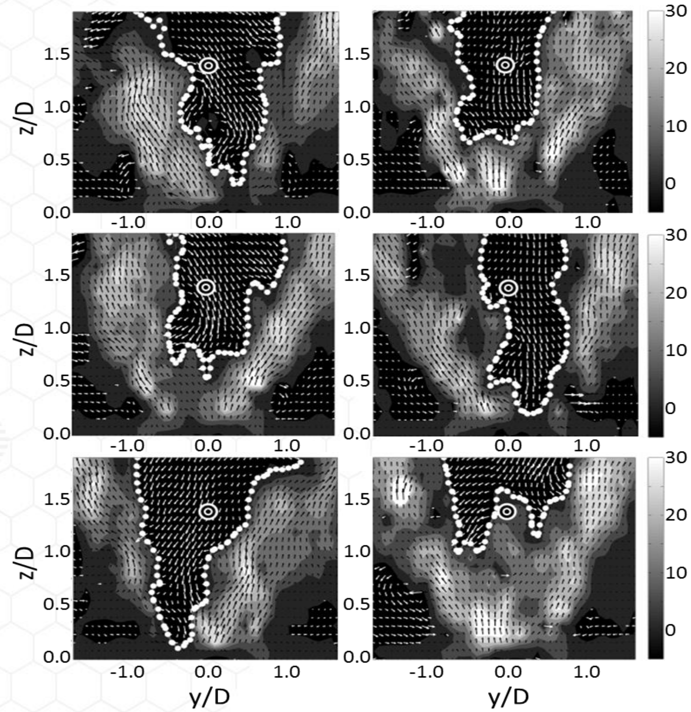
OPTIMIZATION STUDY TAKEAWAYS

- <u>**Nozzle optimization study (fixed operating parameters, move nozzles around)**</u>
  - 1-R mode → minimal RI at $0.6R_C$ (pressure node) → nozzles distributed symmetrically
  - 1-T mode → non-axisymmetric → radial offset depends on angular location in mode
    - Optimal distribution unlike conventional symmetric nozzle placements.
    - Indicates lowest possible *RI* requires drastically different nozzle placements.
- <u>**Parameter optimization study (fixed nozzle placements, optimize operating parameters)**</u>
  - 1-R Mode → optimal flame angle/swirl → large parameter space with negative *RI*.
  - 1-T mode (6 around 1) → 4 different operating parameters for outer nozzles → similar to nozzle staging.
- ***Additional considerations***
  - Fixed mode shape relative to the nozzle placements (extend to dynamic mode-shapes)
  - Only axisymmetric flames (on-going work to extend to non-axisymmetric flames)
  - Vortical flow fluctuations → nozzle flow/swirler optimization for hydrodynamics/vortical-acoustic interactions that minimize RI → on-going work.

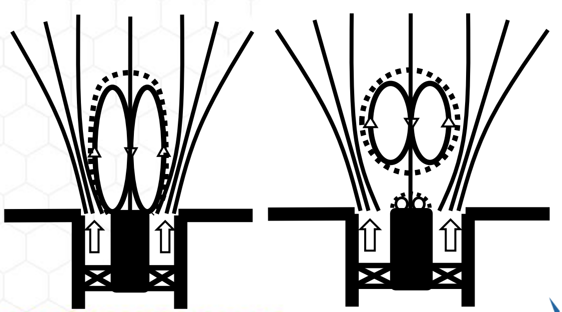
RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

- Swirling flows and flames in annular geometries exhibit range of topologies.
- Complex flow dynamics strongly affect flame stabilization and shape:
  - Flame aerodynamically stabilized in front of vortex breakdown stagnation feature.
  - Flame anchoring position highly unsteady, in contrast to stabilization at edges/corners.
  - Response of flame to imposed disturbance is materially different.



- Under what circumstances can such flames exist?
  - Not always observed; flames may blowoff directly without reverting to a “free floating” configuration
  - Flow must have interior stagnation point



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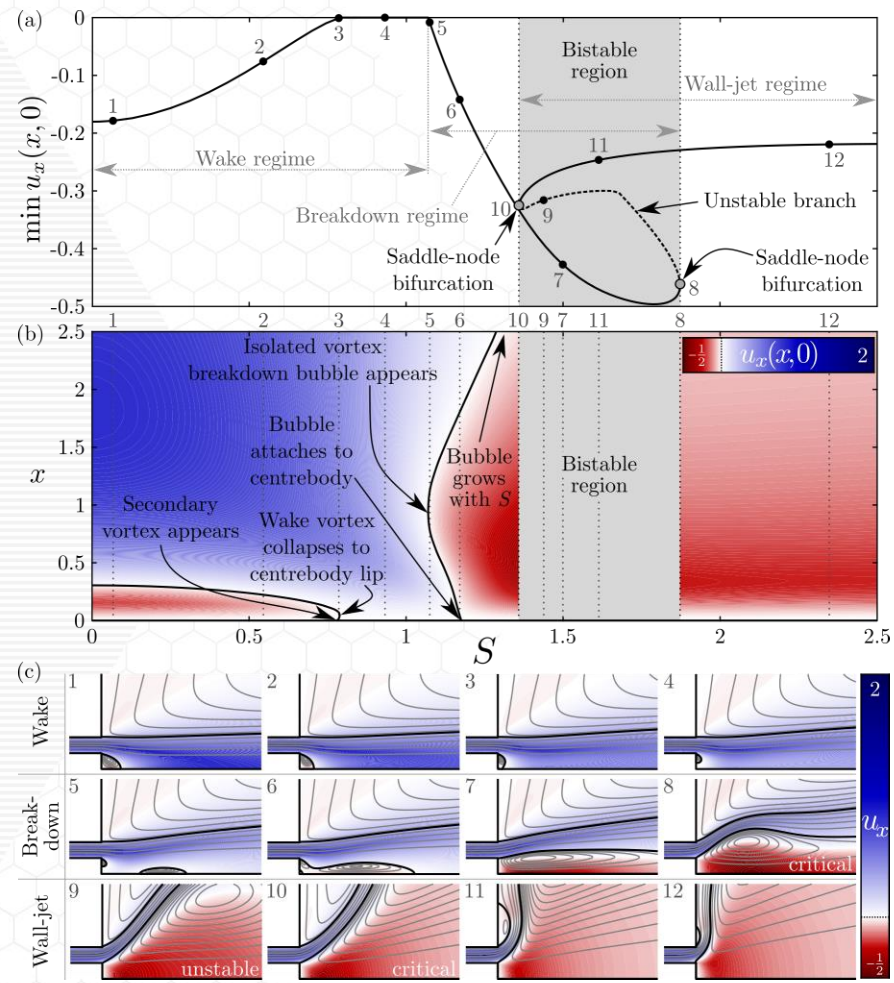
RESEARCH TASK 3.2
HYDRODYNAMIC STABILITY MODELING

- Nonlinear bifurcation analysis
  - Saddle-node bifurcations -> hysteresis

When are certain families of solutions possible?

What types of solutions are possible?



RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

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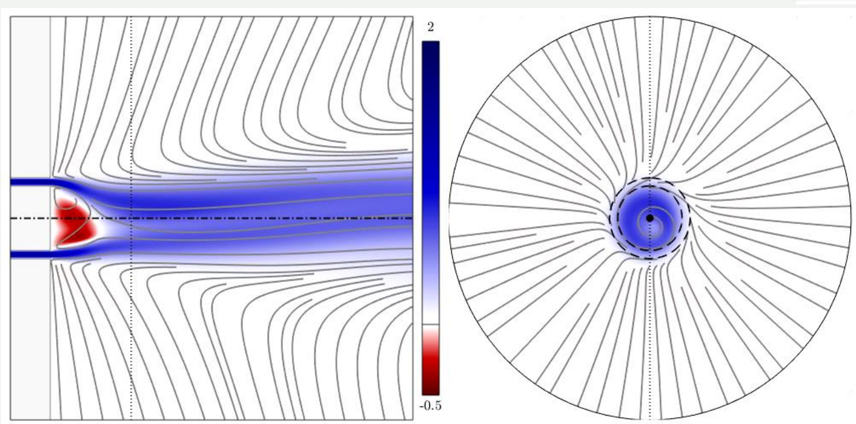
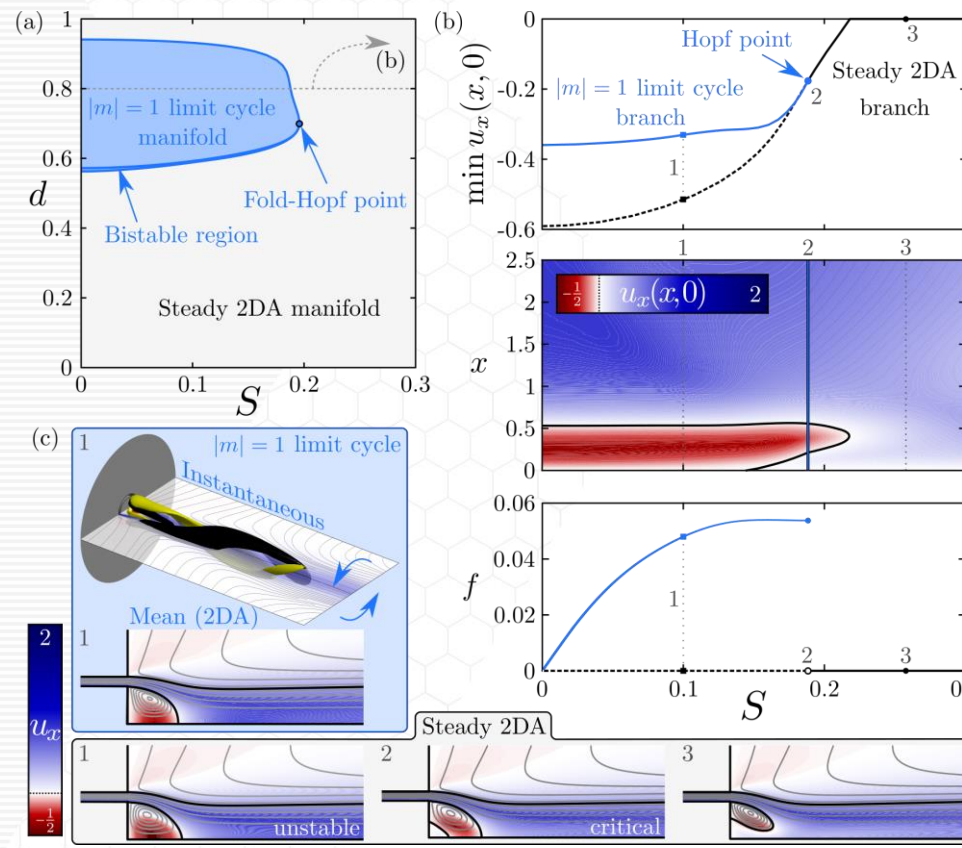
- Nonlinear bifurcation analysis
  - Saddle-node bifurcations -> hysteresis
  - Hopf bifurcations -> limit cycles

Low swirl: wake regime





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RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

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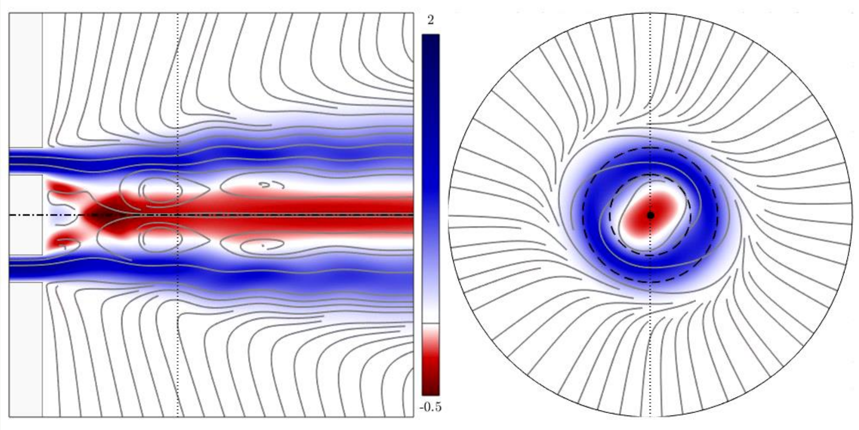
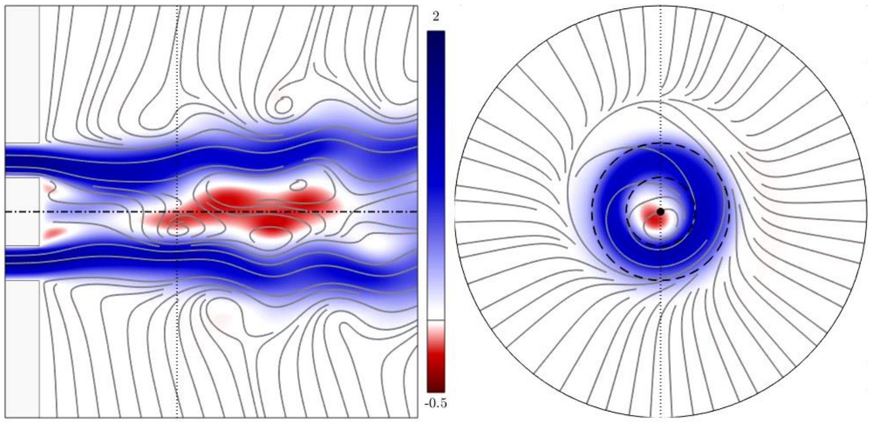
- Nonlinear bifurcation analysis
  - Saddle-node bifurcations -> hysteresis
  - <u>Hopf bifurcations -> limit cycles</u>

<u>Strong swirl: vortex breakdown regime</u>





|*m*|=2 limit cycle

|*m*|=1 limit cycle

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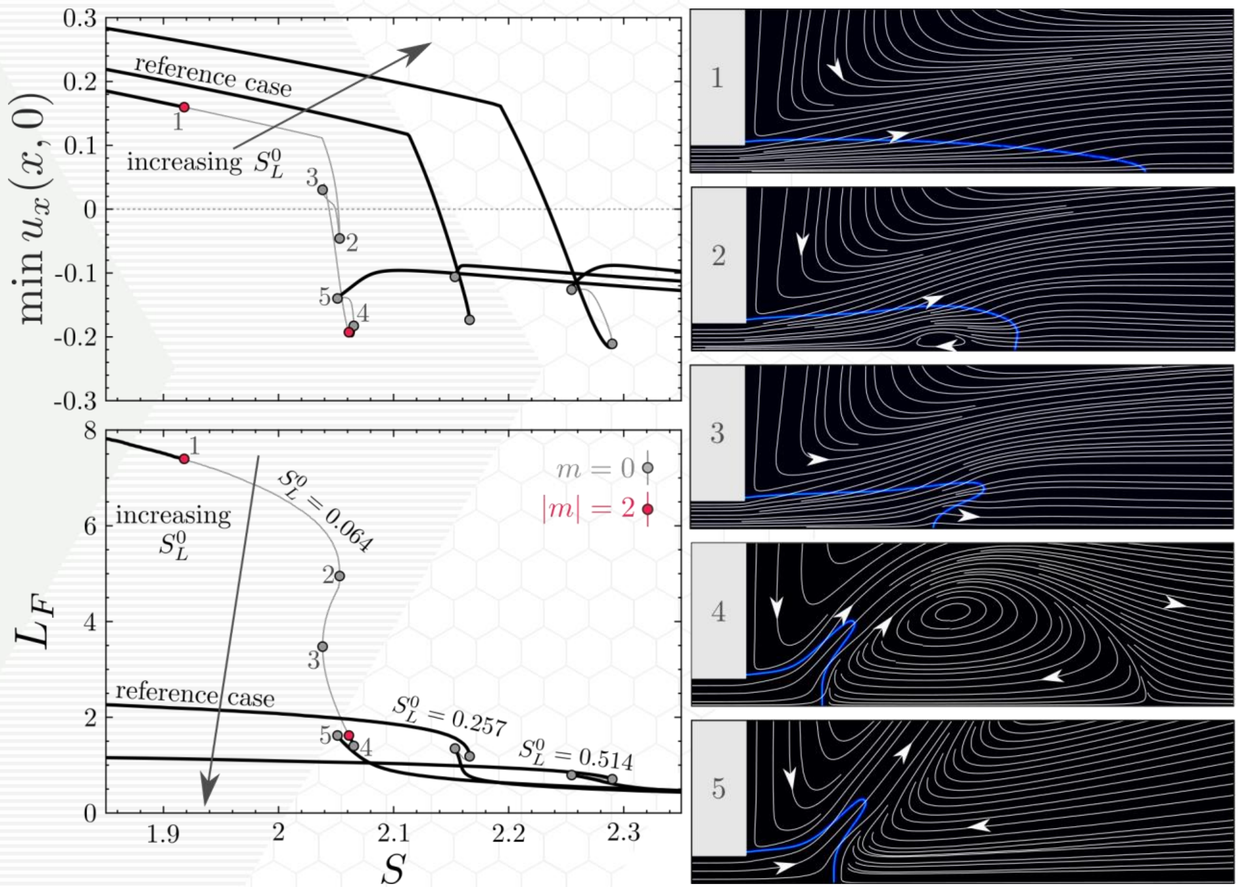
RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

Nonlinear bifurcation analysis

- Saddle-node bifurcations
  -> hysteresis
- Hopf bifurcations
  -> limit cycles
- Introduce lean-premixed reactions
  → add additional, coupled flame dynamics (e.g. flashback)



RESEARCH TASK 3.2

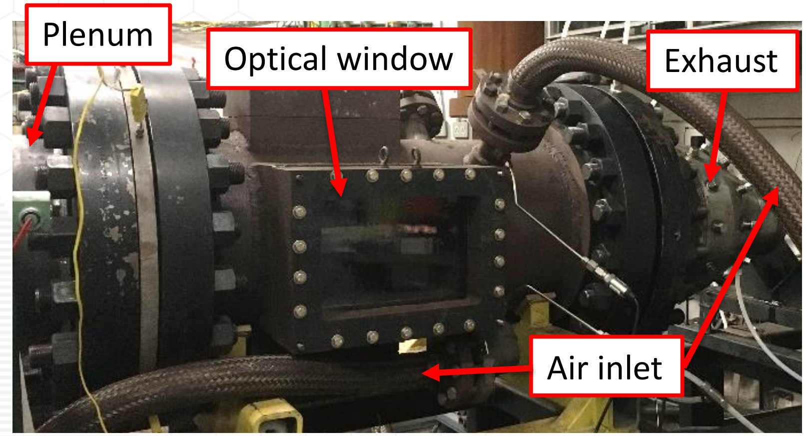
TAKEAWAYS

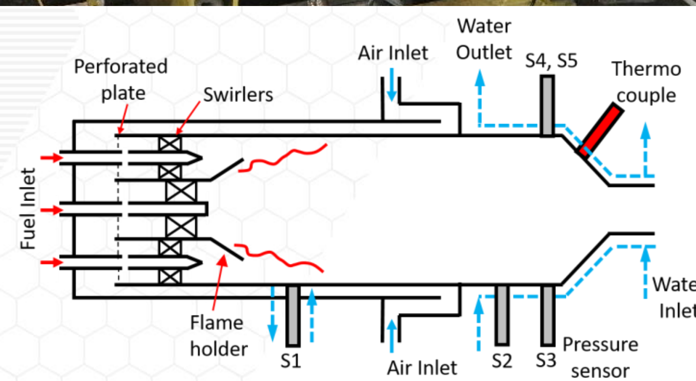
- Flame shape and stabilization cannot be predicted reliably without excellent understanding of underlying fluid mechanics.

- Annular swirling flows exhibit strong hysteresis and three-dimensionality, influencing both flame position and nature of flow disturbances exciting the flame

KEY ACCOMPLISHMENTS FROM EXPERIMENTS

- ✓ Designed a multi-nozzle can combustor experiment with
  - Radial/azimuthal fuel staging to control modal dynamics
  - Multiple pressure taps to characterize multi-dimensional transverse mode shapes
  - Chemiluminescence characterization for heat release
- ✓ Established new data analysis methods to understand the dynamic nature of the transverse modes through statistical, correlation and Fourier based analysis
- ✓ Understood correlation between heat release and excited mode during high-frequency transverse instabilities through simultaneous flame-pressure measurements
- ✓ Investigated the effects of azimuthal fuel staging on instability amplitude and its modal nature





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KEY ACCOMPLISHMENTS FROM MODELING

- ✓ Flame response modeling framework
  - ✓ Response to Direct Acoustic Excitation from natural transverse modes & Induced axial excitation
  - ✓ Multiple flame configurations- axisymmetric, non-axisymmetric, variable flame location in combustor
  - ✓ Analyzed mode amplification (non-dimensional growth rate) for different flames to different modes to understand stability bands
  - ✓ Nozzle and Parameter optimization studies for individual nozzle distribution and operation
- ✓ Hydrodynamic stability modeling
  - Internal tool developed to study hydrodynamic stability in reacting flows using FreeFEM++
  - Modeling of swirling flow instabilities