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H_2 enrichment of CH_4 blends in lean premixed gas turbine combustion: An experimental study on effects on flame shape and thermoacoustic oscillation dynamics.

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4. Isothermal flow characterization.
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Motivation: Characterizing the thermoacoustic behavior of a gas turbine combustor using an approriate mixture property.

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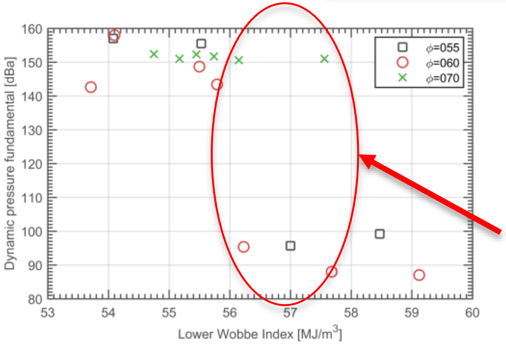
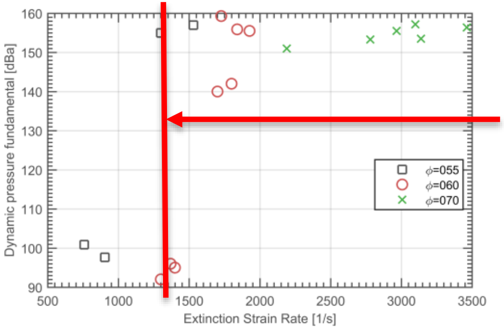


Lower Wobbe Index: Non-unilateral thermoacoustic behavior



Extinction strain rate: thermoacoustic transitional threshold

- Lower Wobbe Index (LWI) is used as an interchangeability index between gas fuels.
- However, it cannot unilaterally describe the thermoacoustic operational state of gas turbine combustors.
- Experiments enriching CH_4 with H_2 at three different equivalence ratios composed of up to 40 vol% H_2 show that within a 5% LWI range the combustor may demonstrate rich thermoacoustic behavior.
- In this context we examine an additional mixture property, the extiction strain rate, to further characterize operatability limits.

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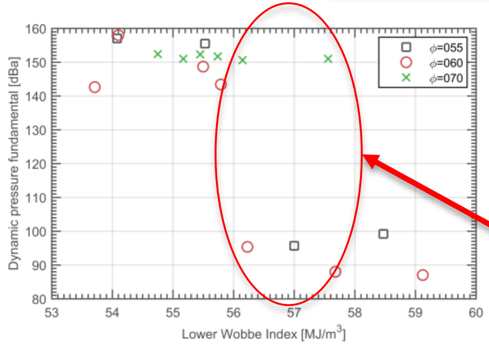
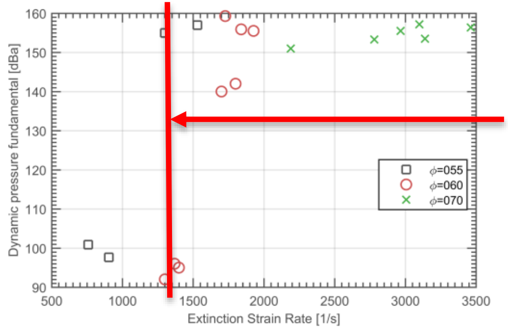
Motivation: Characterizing the thermoacoustic behavior of a gas turbine combustor using an approriate mixture property.



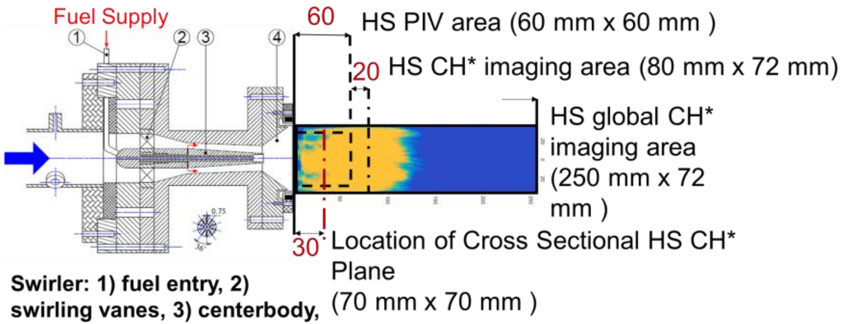
Lower Wobbe Index: Non-unilateral thermoacoustic behavior



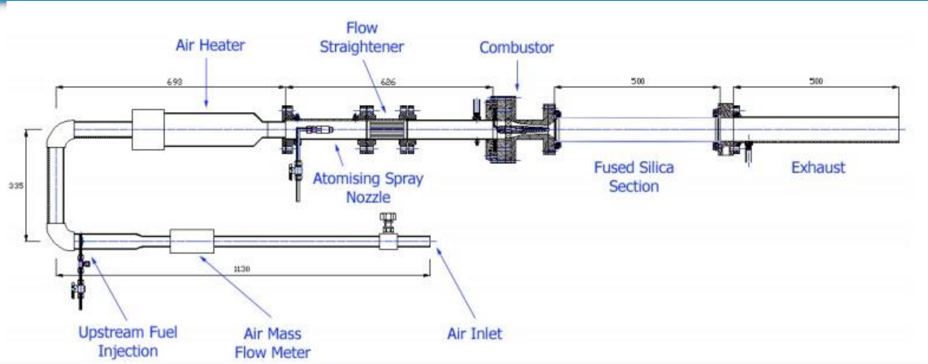
Extinction strain rate: thermoacoustic transitional threshold

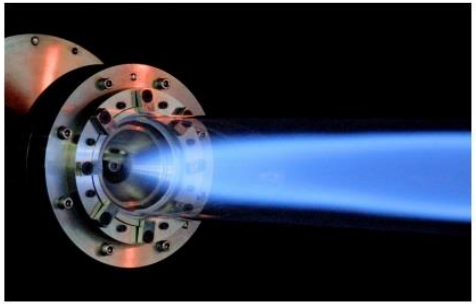
- The extinction strain rate is a mixture property that can be easily calculated as a function of the equivalence ratio and the mixture composition.
- It can dictate the flame anchoring regions in the combustor by comparing it to local flow imposed time scales.
- In the current experimental campaign by testing fuels with increasing H_2 vol% hence increasing k_{ext} , the combustor bifurcates into the following dynamic states: quiescent, intermittent, Period 1 limit cycle, Period 2 limit cycle.

Experimental Configuration



Swirler: 1) fuel entry, 2) swirling vanes, 3) centerbody, 4) diffuser.





Long exposure image of the combustor

- Swirl premixed stabilized combustor with 360º optical access to the flame.
- Swirl number is approximately 0.7.
- Flow field is fully turbulent, as Reynolds numbers up to 30000 have been examined.
- Experimental techniques: Dynamic pressure measurement, integral heat release rate via a PMT measuring CH*, OH*, C_2^* radiation intensity, high speed imaging of CH^* chemiluminescence, high speed PIV measurements.

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Experimental Test Matrices

Mixture ID	Vol %CH_4	Vol %H_2	Equivalence Ratio	Reynolds Number	Extinction Strain Rate [1/s]	Thermoacoustic State
055_1	100	0	0.55	19000	274	Susceptible to blow off
055_2	90	10	0.55	19000	759	Quiescent, lifted
055_3	80	20	0.55	19000	905	Quiescent, attached to centerbody
055_4	70	30	0.55	19000	1127	Intermittent
055_5	60	40	0.55	19000	1530	Limit Cycle-Period 1

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060_4	77	23	0.60	19000	1839	Intermittent
060_6	75	25	0.60	19000	1927	Intermittent
060_7	65	35	0.60	19000	2435	Limit Cycle:Period 1
060_8	62.5	37.5	0.60	19000	2588	Limit Cycle: Period 1

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Experimental Test Matrices

Mixture ID	Vol %CH_4	Vol %H_2	Equivalence Ratio	Reynolds Number	Extinction Strain Rate [1/s]	Thermoacoustic State
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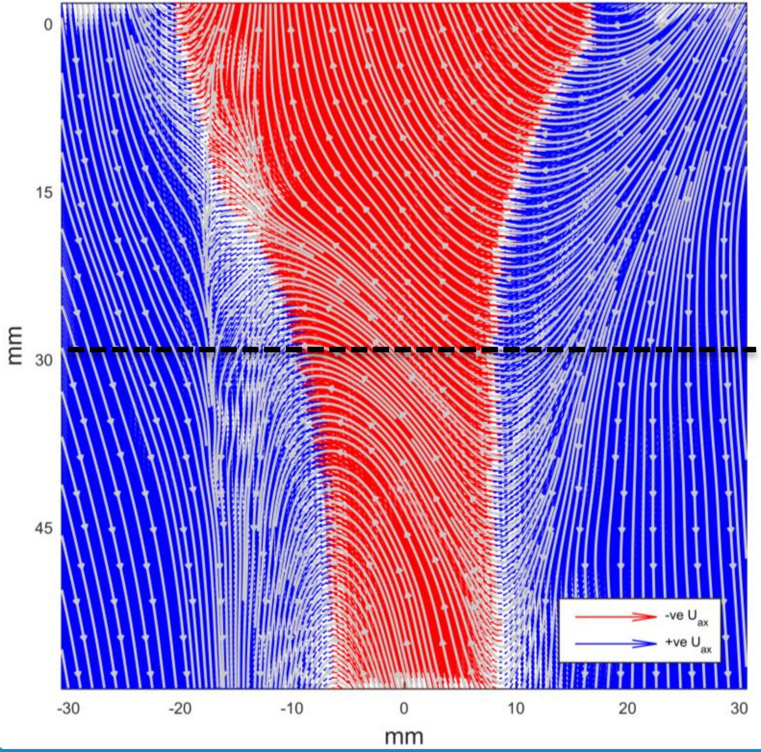
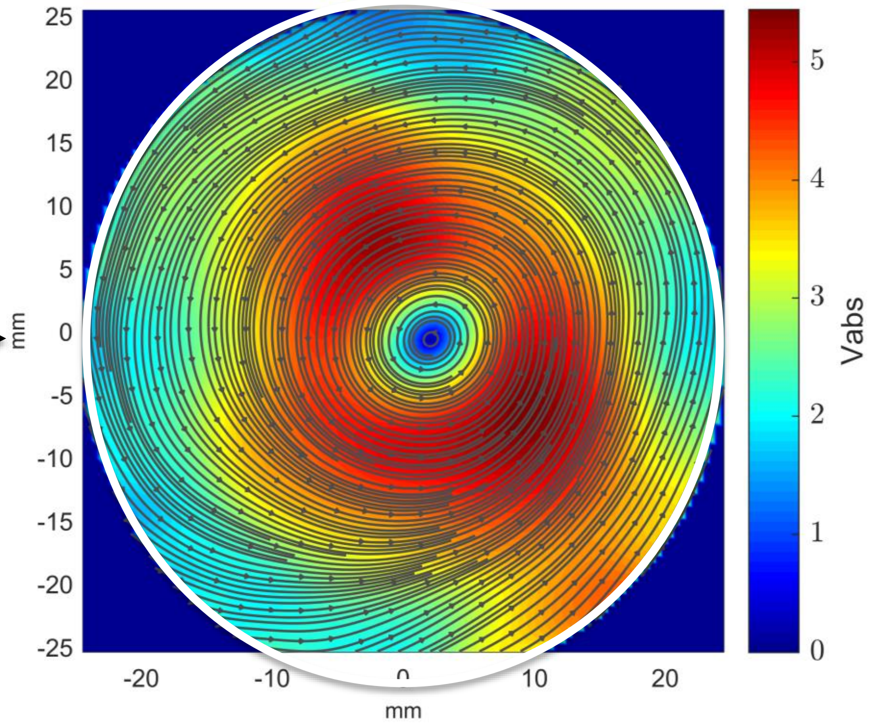
070_5	83	17	0.70	19000	3120	Period 2
070_6	80	20	0.70	19000	3263	Period 2

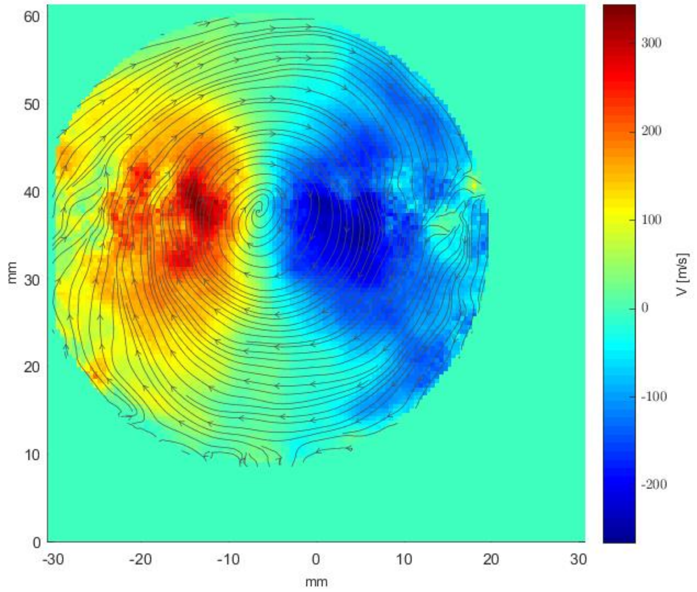
Isothemal Flow: Axial – Radial FOVs

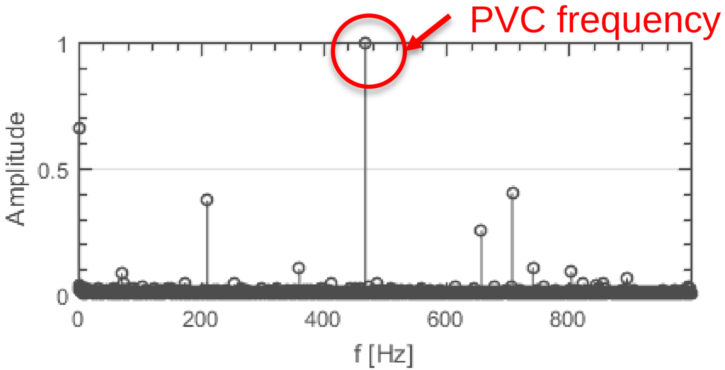


Radial Slice



Isothemal Flow: Precessing Vortex Core through DMD





- The isothermal flowfield demonstrates a self excited global instability known as Precessing Vortex Core (PVC).
- DMD helps us identify the natural PVC frequency in the isothermal flowfield at 420 Hz.
- DMD reconstruction at the mode corresponding at this frequency aids in visualizing the PVC.

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Experimental Test Matrices

Mixture ID	Vol %CH_4	Vol %H_2	Equivalence Ratio	Reynolds Number	Extinction Strain Rate [1/s]	Thermoacoustic State
055_1	100	0	0.55	19000	274	Susceptible to blow off
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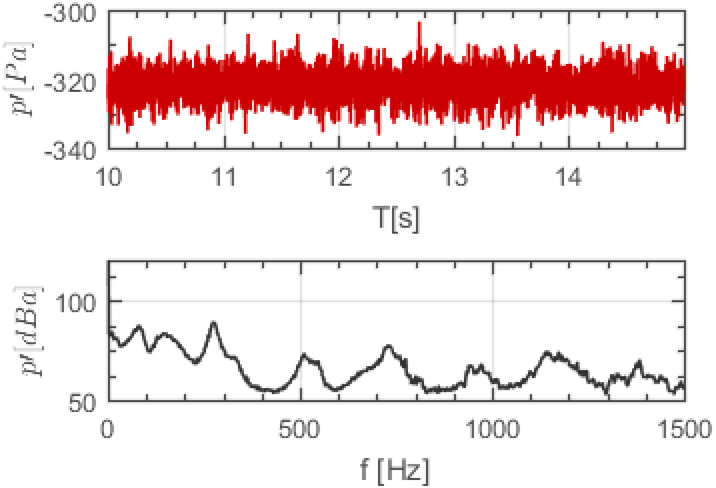
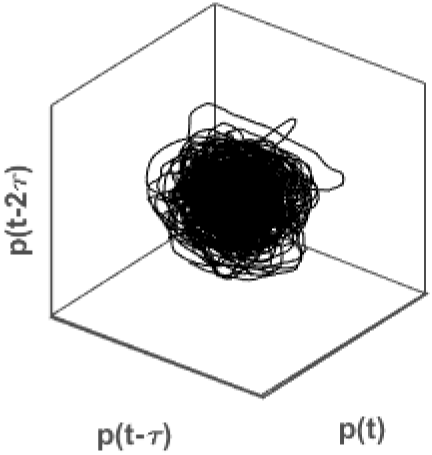
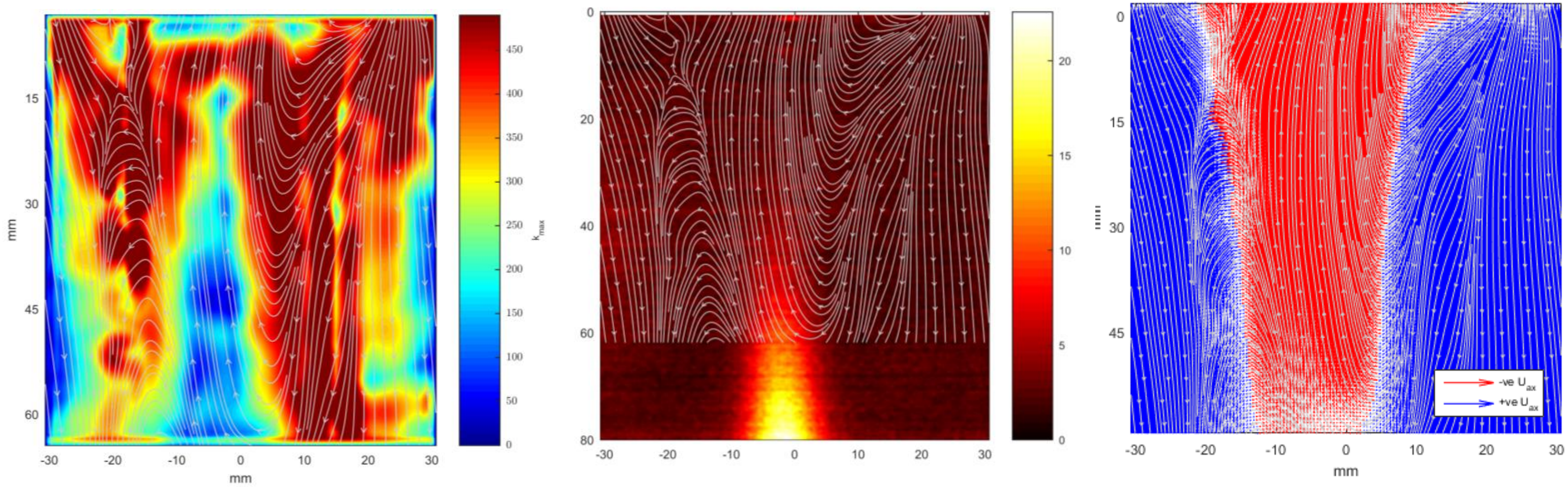
Dynamic States Encountered: Quiescent Flame - Lifted





- ➢No high amplitude dynamics encountered.
- ➢Phase space reconstruction of the flow field shows attraction towards a fixed point in phase space.

Dynamic States Encountered: Quiescent Flame - Lifted



- ➢The flame is anchored ~40mm away from the centerbody.
- ➢High strain rate areas surround the flame anchoring locations.
- ➢Flame anchoring locations are characterized by low strain rates.

Experimental Test Matrices

Mixture ID	Vol %CH_4	Vol %H_2	Equivalence Ratio	Reynolds Number	Extinction Strain Rate [1/s]	Thermoacoustic State
055_1	100	0	0.55	19000	274	Susceptible to blow off
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055_4	70	30	0.55	19000	1127	Intermittent
055_5	60	40	0.55	19000	1530	Limit Cycle-Period 1

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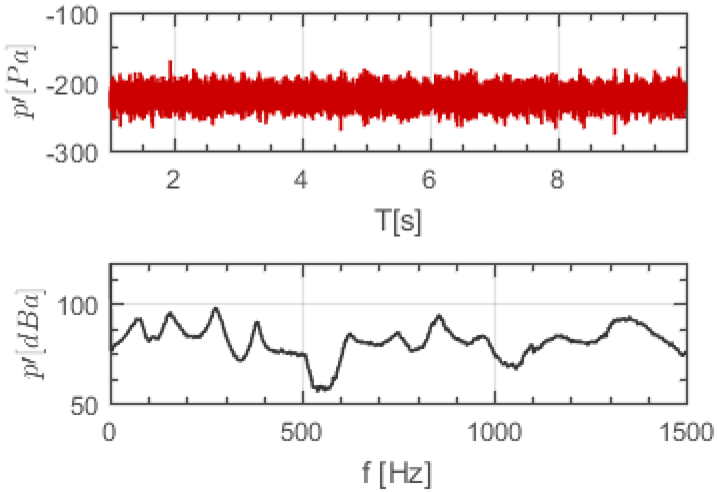
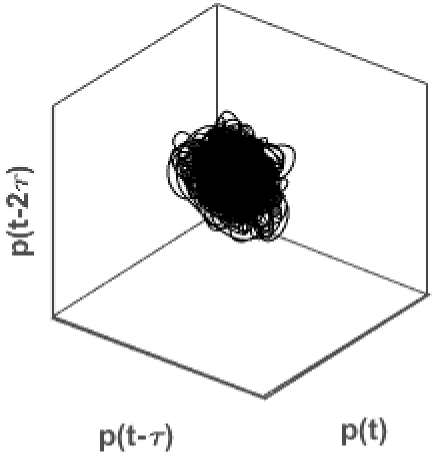
Dynamic States Encountered: Quiescent Flame – Attached to centerbody





- ➢No high amplitude dynamics encountered.
- ➢Phase space reconstruction of the flow field shows attraction towards a fixed point.

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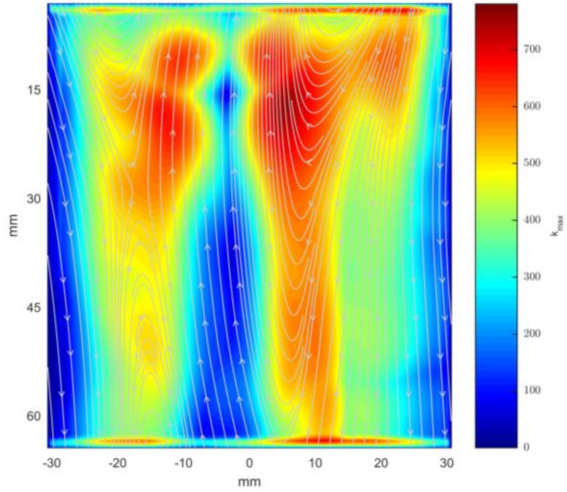
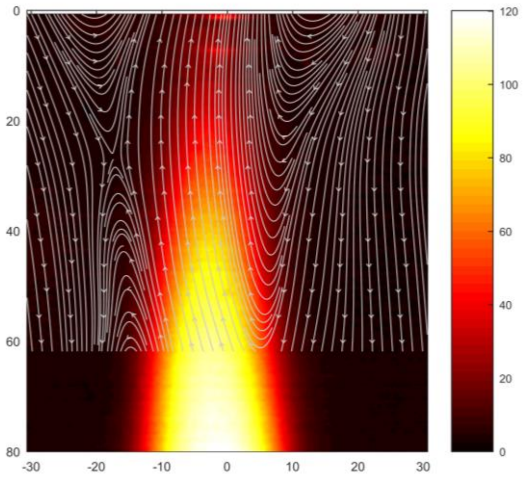
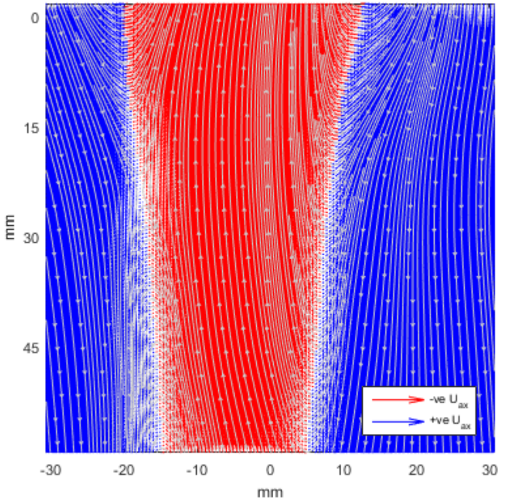
Dynamic States Encountered: Quiescent Flame - Lifted







- ➢The flame is anchored at the centerbody.
- ➢High strain rate areas surround the flame anchoring locations.The flame however can penatrate into the higher strain areas close to the centerbody.

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Experimental Test Matrices

Mixture ID	Vol %CH_4	Vol %H_2	Equivalence Ratio	Reynolds Number	Extinction Strain Rate [1/s]	Thermoacoustic State
060_1	100	0	0.60	19000	1043	Quiescent
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060_4	77	23	0.60	19000	1839	Intermittent
060_6	75	25	0.60	19000	1927	Intermittent
060_7	65	35	0.60	19000	2435	Limit Cycle:Period 1
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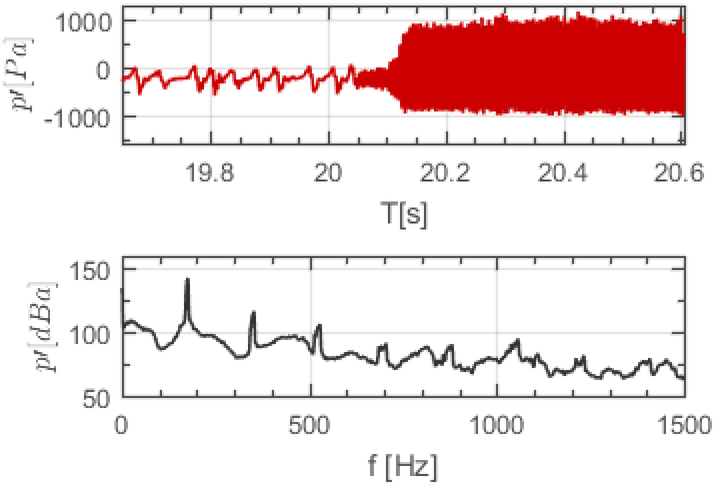
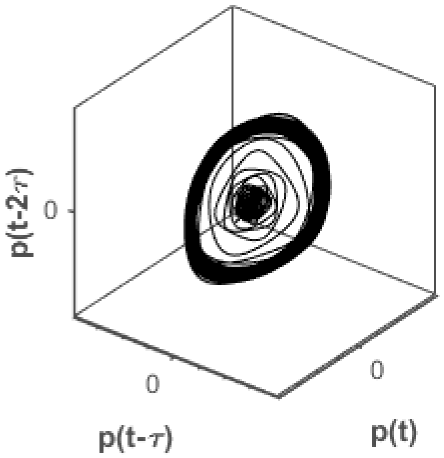
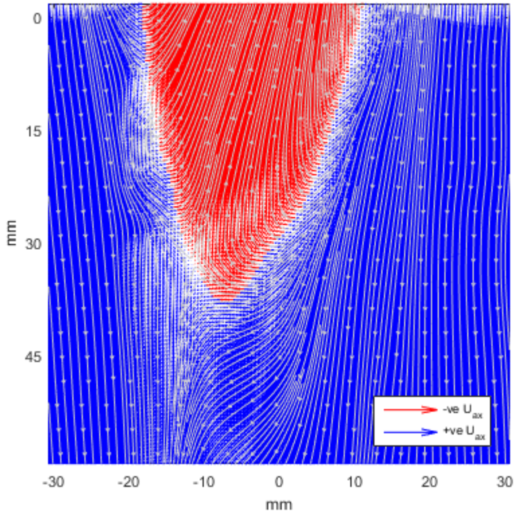
Dynamic States Encountered: Intermittent

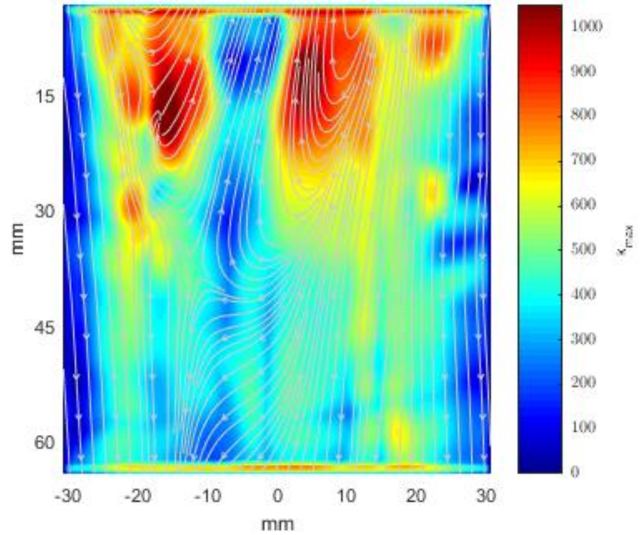




- ➢Intermittent injection of dynamics between a low amplitude and a high amplitude dynamic state.
- ➢The phase space reconstruction reveals a torroidal transition of the dynamics from a fixed point to a limit cycle.

Dynamic States Encountered: Intermittent





- ➢The mean flowfield demonstrates an assymmetry with the downstream stagnation recirculation point located away from the centerline.
- ➢Swirling jets impose significant strain rates whereas the freestream imposes low strain on the flame.
- ➢The flame is festly anchored on the centerbody therefore and it is susceptible to PVC undulations of the heat release rate.

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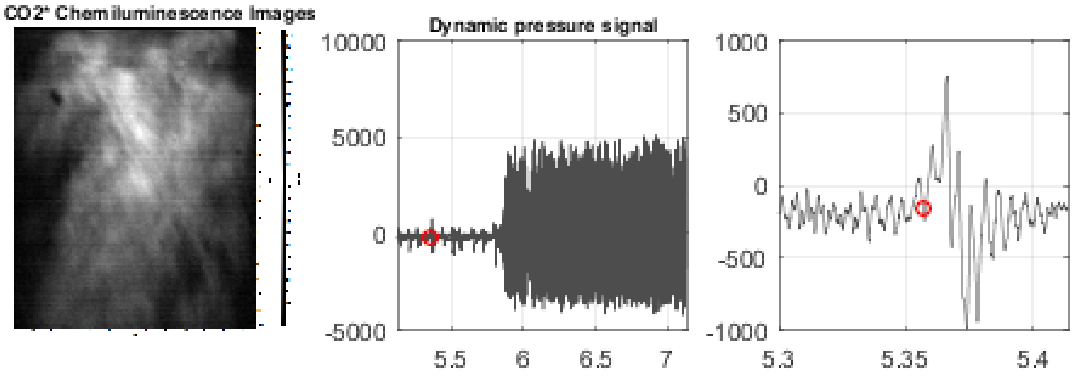
Dynamic States Encountered: Intermittent



- Parallel plotting of high speed CO_2^* chemiluminescence along with the dynamic pressure signal shows how the PVC affects the flame in the aperiodic parts of the signal.
- The flame is advected away from the central axis of the combustor in a spiral motion. Upon touching the walls of the combustor a high amplitude heat release burst is observed.

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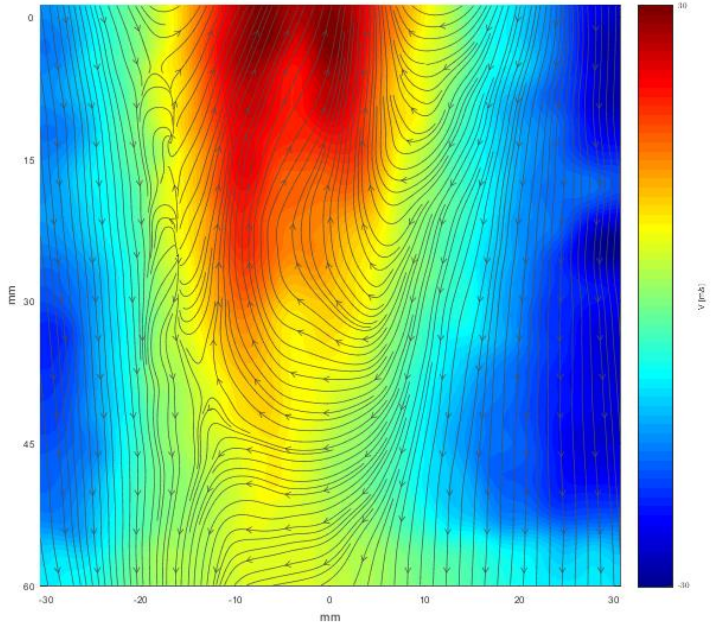
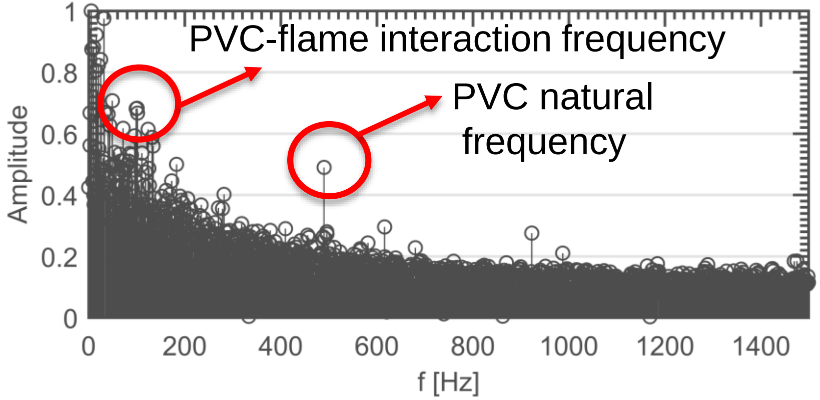
Dynamic States Encountered: Intermittent





- ➢The DMD power spectra reveal the existence of the PVC in the reacting flow at the same natural frequency f_n=420Hz.
- ➢The flame interacts with the PVC at 140Hz which is approximately $f_n/3$.

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060_8	62.5	37.5	0.60	19000	2588	Limit Cycle: Period 1

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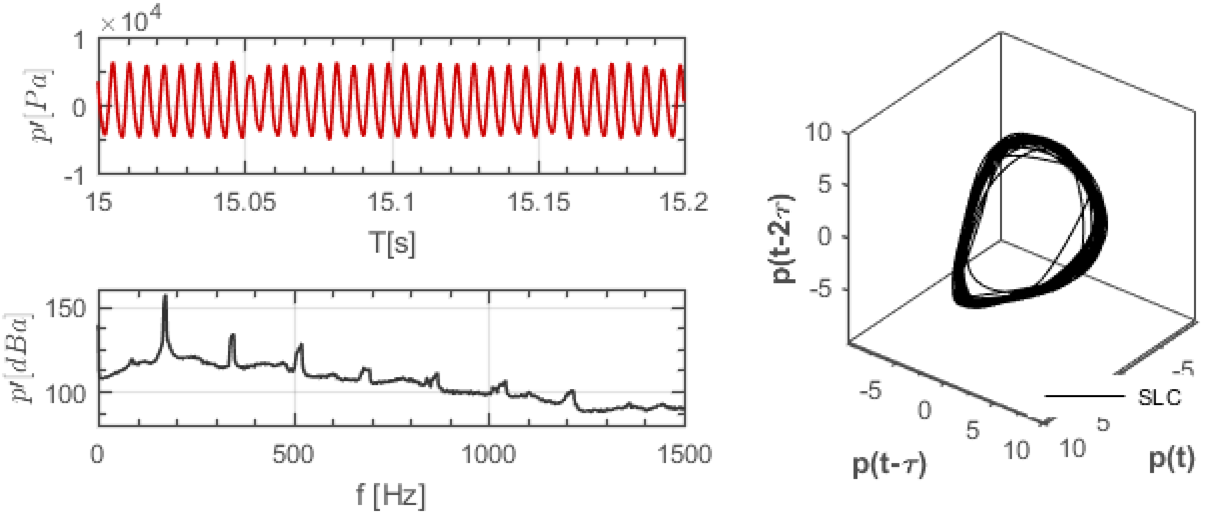
Dynamic States Encountered: Limit Cycle Period 1



- Dynamics are attracted towards a high amplitude ‘’single loop’’ limit cycle.
- The fundamental amplitude corresponds to the first quarter wave of the combustor.
- There are no hydrodynamic contributions into the limit cycle power spectra.

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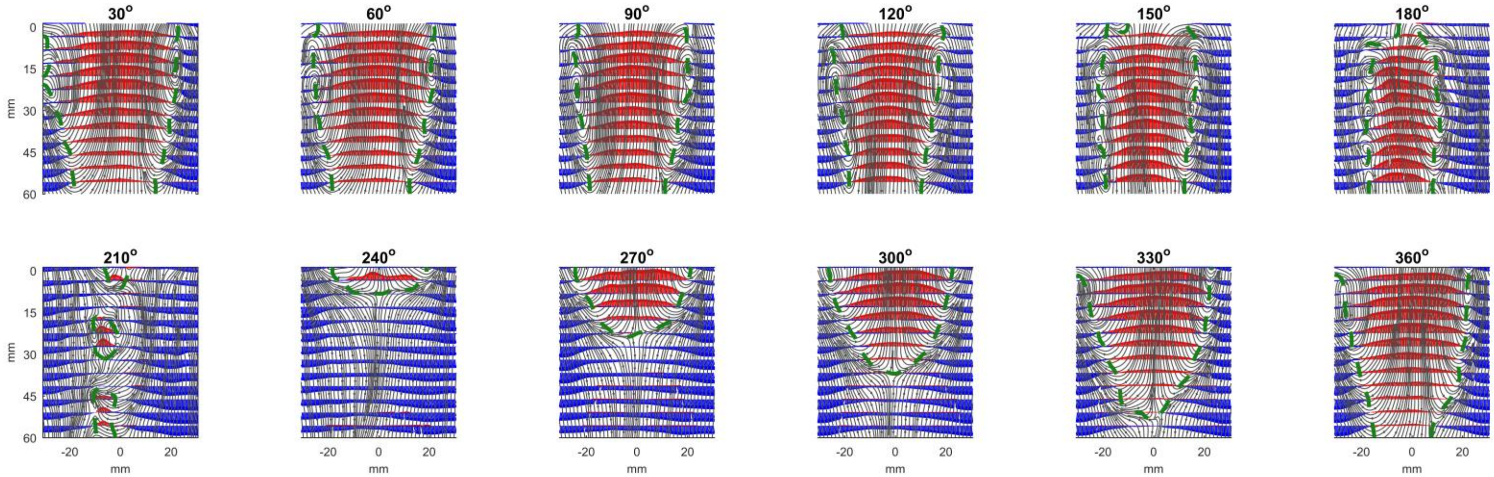
Dynamic States Encountered: Limit Cycle Period 1



- The extent of the recirculation zone during a period of instability is fluctuating.
- The jets are introduced when dynamic pressure is minimum (210^{O}) and the extent of the recirculation zone increases until the shear layers touch with the combustor walls.

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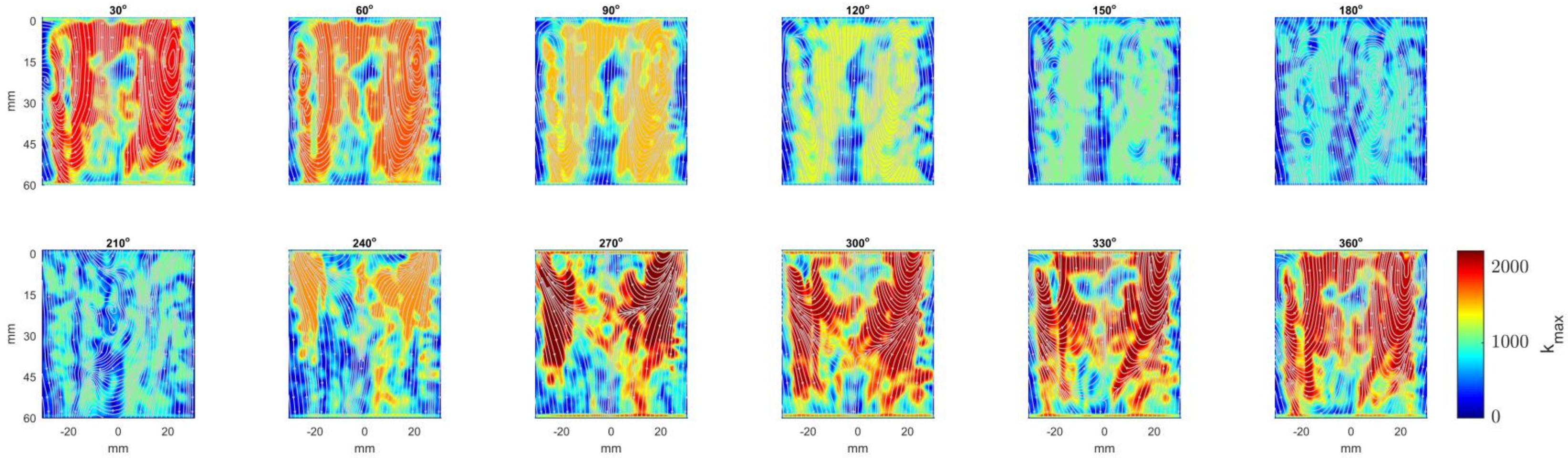
Dynamic States Encountered: Limit Cycle Period 1



➢Fluctuating extent of the recirculation zone imposes fluctuating velocity gradients. In comparison with flow dilatation due to combustion the strain rates the flate experiences is fuctuating as well.

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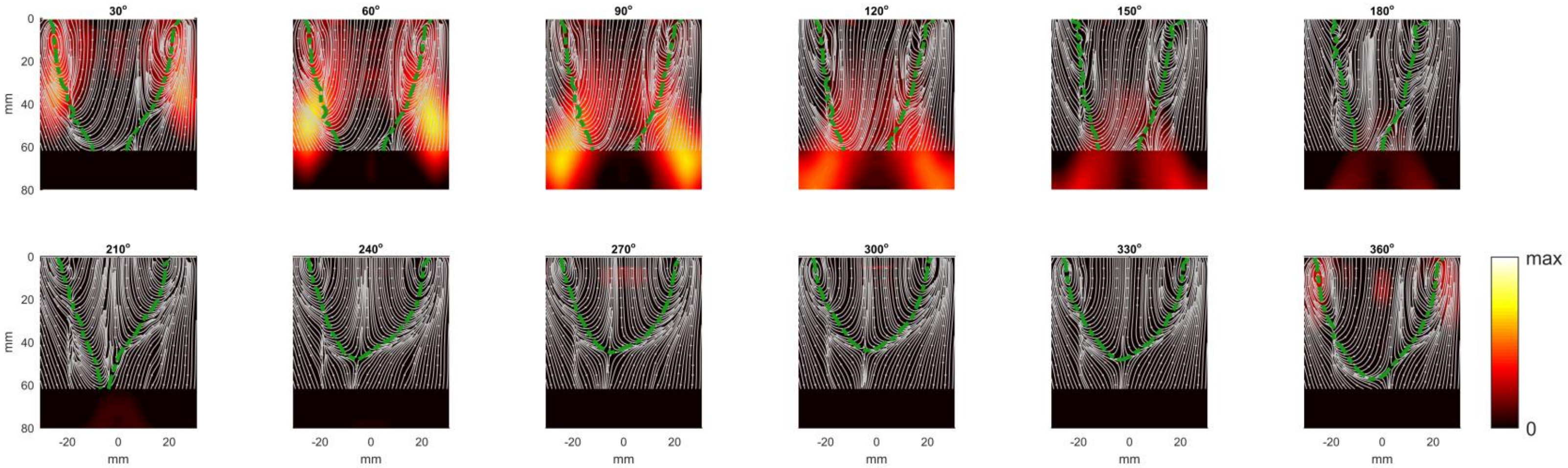
Dynamic States Encountered: Limit Cycle Period 1



➢From 210⁰ to 360º flame is introduced in the combustor chamber along the swirling jets,

➢From 30º to 180º the flame assumes a V shape as the flow imposed strain rates along the shear layers does not allow for further expansion in the inner shear layers. Flame root is extinguished as well.

Experimental Test Matrices

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070_1	100	0	0.70	19000	2191	Limit cycle: Period 2
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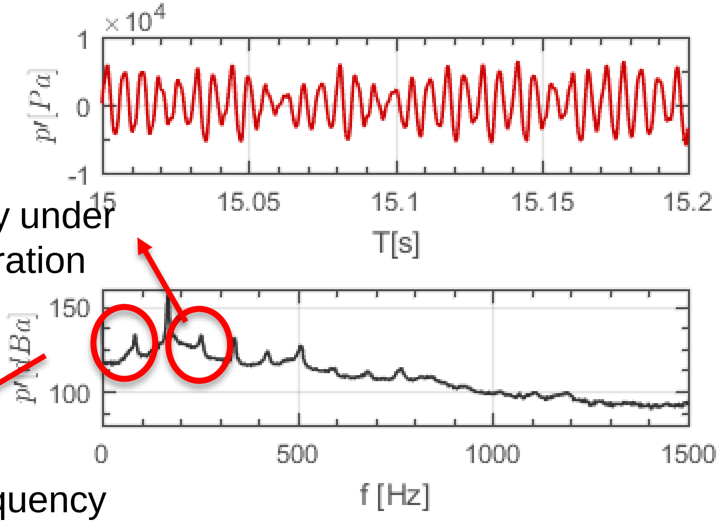
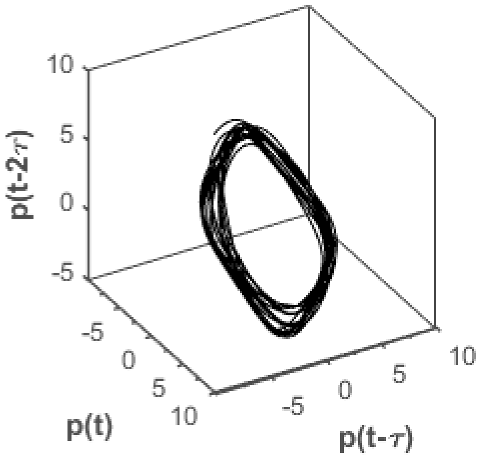
070_3	87	13	0.70	19000	2967	Period 2
070_4	85	15	0.70	19000	3099	Period 2
070_5	83	17	0.70	19000	3120	Period 2
070_6	80	20	0.70	19000	3263	Period 2-PVC suppression

Dynamic States Encountered: Limit Cycle Period 2



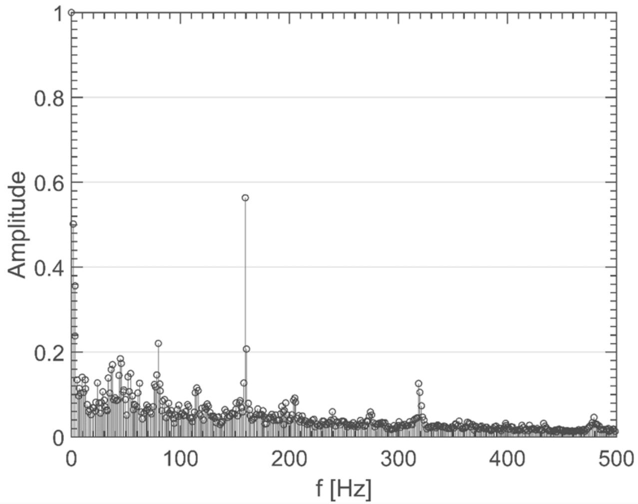
PVC frequency under limit cycle operation

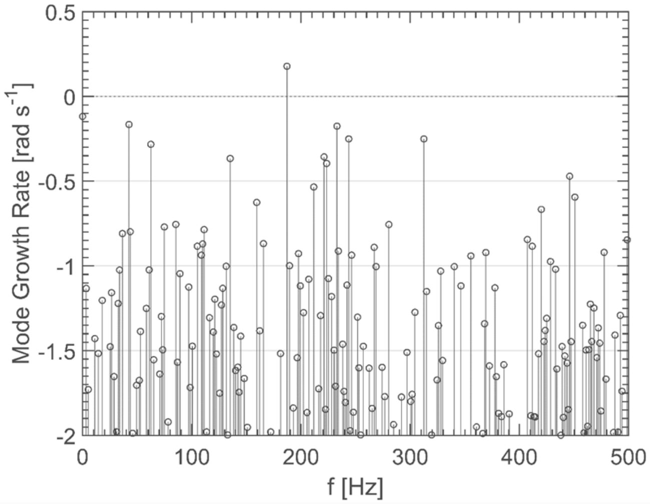
PVC-flame Interaction frequency



- ➢Dynamics are attracted towards a high amplitude 'double loop'' limit cycle.
- ➢Further to the fundamental f_1 a subharmonic frequency associated with the interaction of the flame with the PVC is observed at $f_2=f_1/2$.

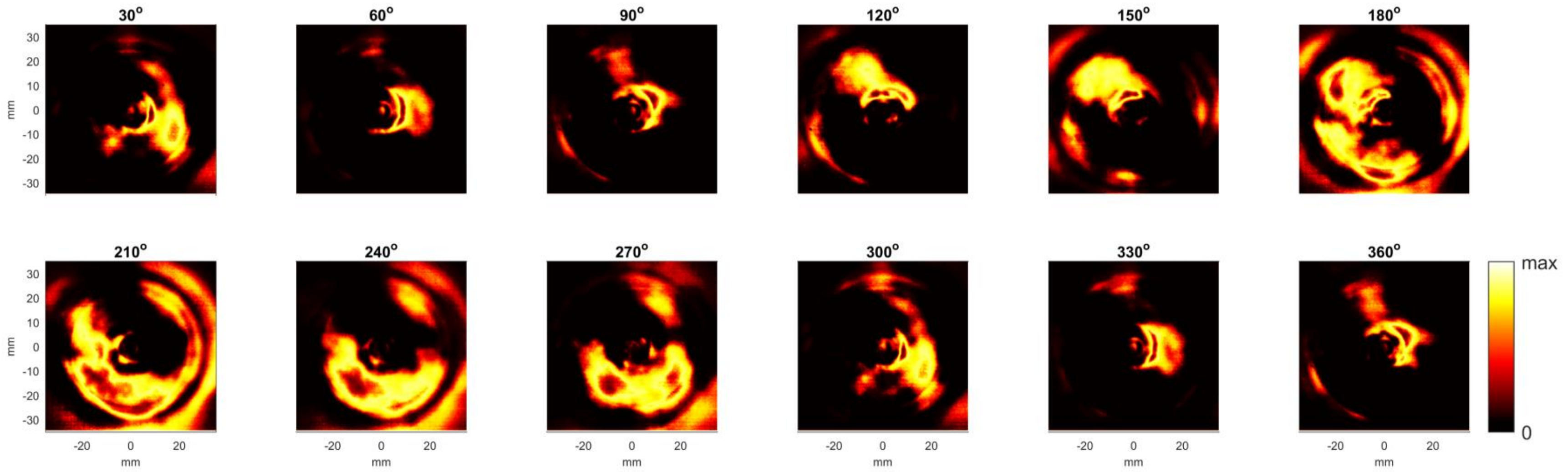
Dynamic States Encountered: Limit Cycle Period 2





- ➢The PVC natural frequency is frequency locked at $1.5f_{1.}$ and the interaction frequency with the flame at $f_2=0.5f_{1.}$
- ➢DMD allows for explicit depiction of the effect of PVC on the flame.
- ➢CH^* high speed imaging at a cross section of the combustor reveals the azimuthal recirculation of hot combustion products due to the helical modulation of the flame surface.

Dynamic States Encountered: Limit Cycle Period 2



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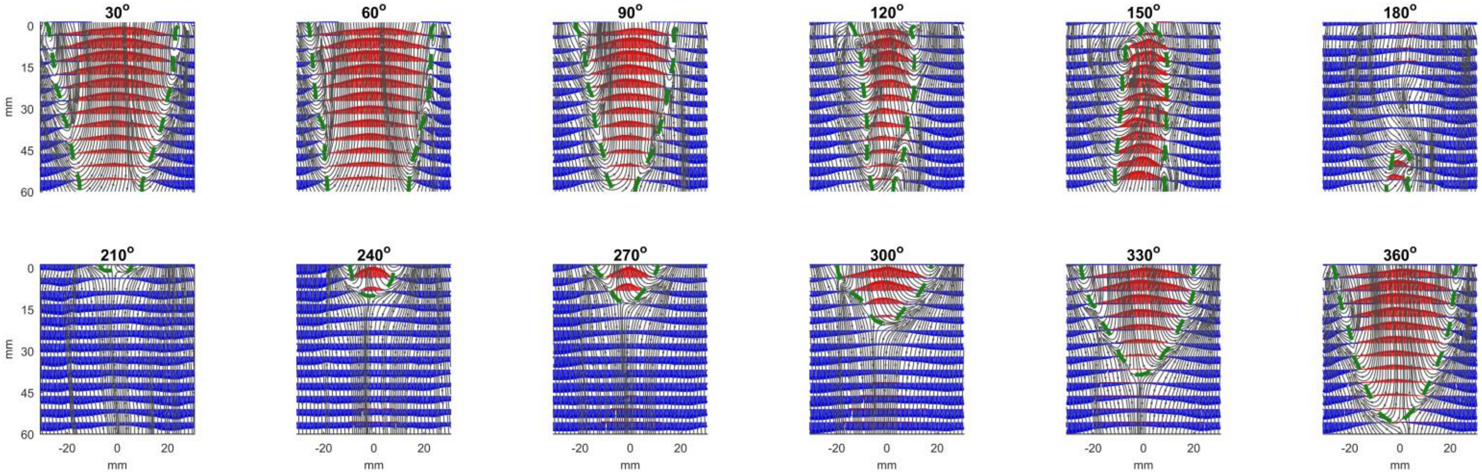
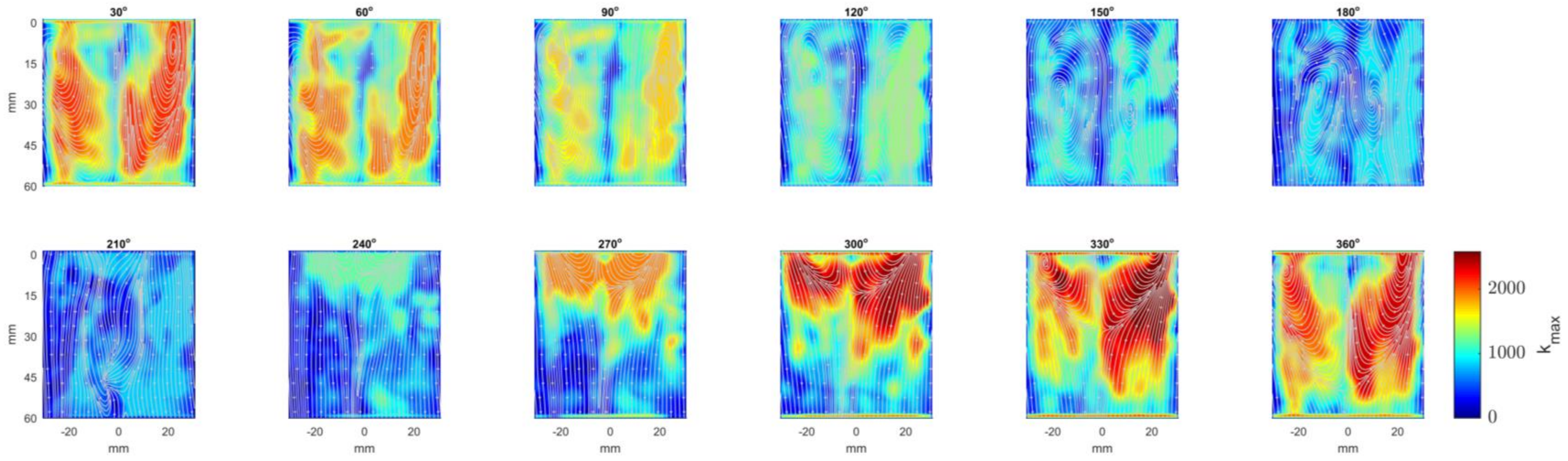


- In Period 2 oscillations the recirculation zone radial extent is limited in relation to Period 1.
- There is a growing assymetry of axial location of centers of coherent structures along the recirculation zone shear layers from 30^0 to 180^0.

Dynamic States Encountered: Limit Cycle Period 2



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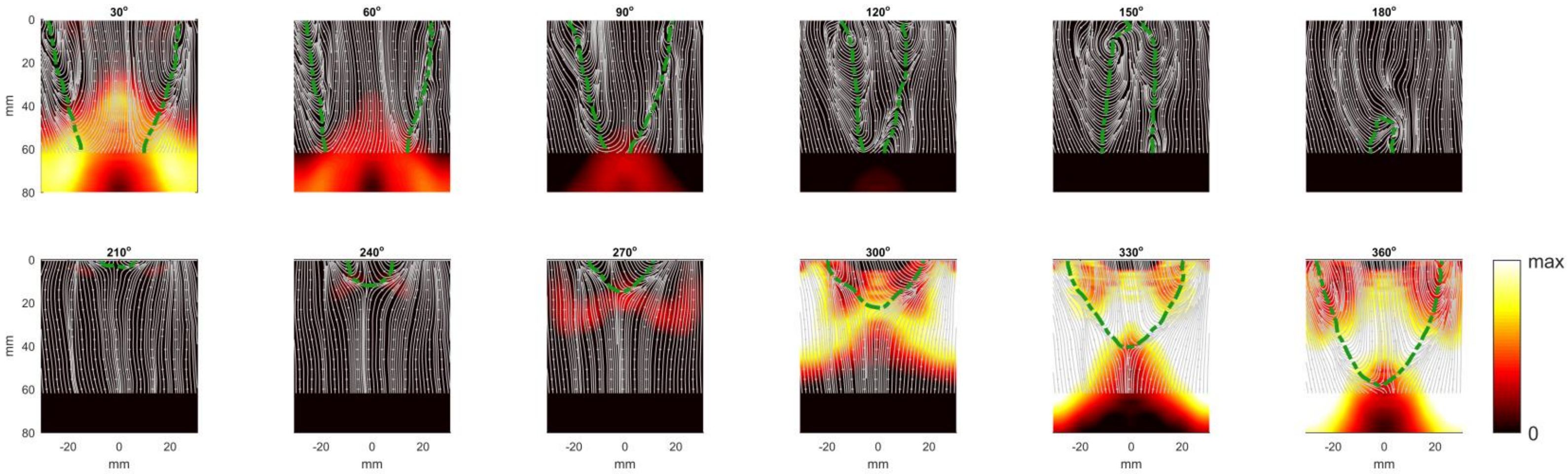
Dynamic States Encountered: Limit Cycle Period 2

PVC excitation



- M shape flame: In this case of Period 2 oscillations PVC is amplified.
- Vortices at 360º stretch the flame and extinguish the flame root so at 30^0 the flame appears lifted.
- Lifted flames are susceptible to PVC undulations of their surface.

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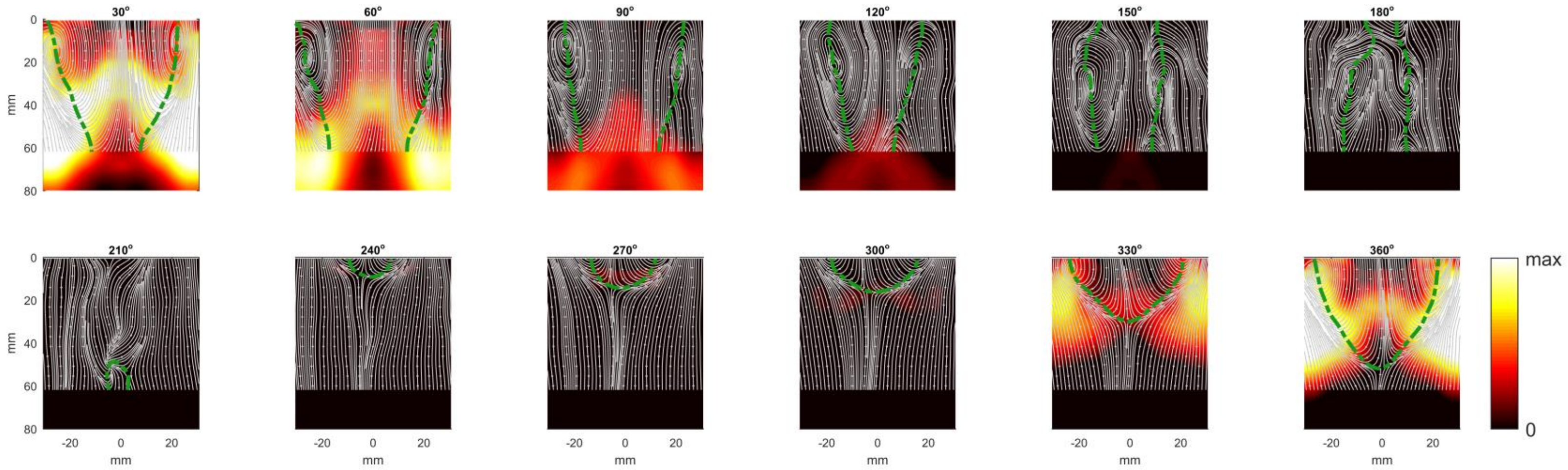
Dynamic States Encountered: Limit Cycle Period 2

PVC suppression



➢On further increasing H_2 content the flame is able to sustain stretching effects at the root and is anchored at the centerbody.

➢Stratification of temperature and density downstream of swirling jets suppresses the helical assymetry hence PVC is mittigated.

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Conclusions

- We suggest an additional mixture property the extinction strain rate, further to the Wobbe index as a fuel interchangeability parameter.
- On increasing equivalence ratio and hydrogen volumetric content different dynamic behaviors have been encountered.
- The relation between the extinction strain rate of the mixture and the flow imposed strain rate appears to dictate the interaction of the flame with the underlying hydrodynamic flowfield and hydrodynamic coherent structures.
- Flame shape bifurcations as well as exctiation or supression of the PVC are dictated by the relation of the flow imposed strain rate to the extinction strain rate of the mixture.