UKCTRF 2021

1 December 2021

Flowfield and Flame Structure during Thermoacoustic Intermittency

Experimental and Computational Study in a Turbulent Swirl Stabilized Combustor

Stathis Karlis, Yannis Hardalupas, Alex M. K. P. Taylor

D. Noh, E. Karlis, S. Navarro-Martinez, Y. Hardalupas, A.M.K.P. Taylor, D. Fredrich, W.P. Jones

Focal points

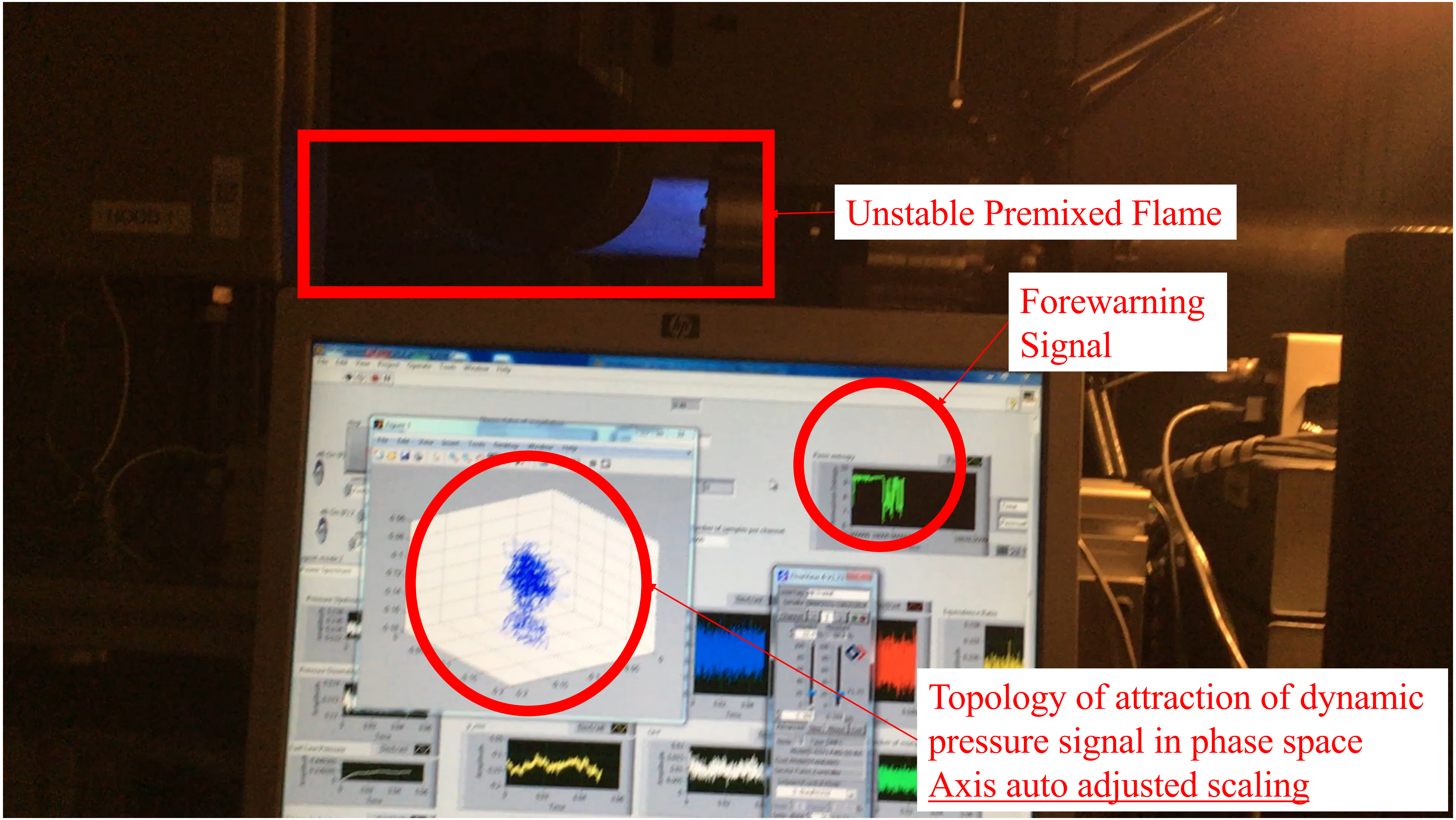
- Intermittency: precedes triggering of thermoacoustic oscillations (limit cycle).
- Intermittent bursts arise stochastically, hence it is difficult to predict their occurrence.
- It is important to gain knowledge of the flow/combustion phenomena causing the intermittent bursts.

Focal points:

- The flame precesses under the influence of the PVC before intermittent thermoacoustic bursts.
- The flame front becomes increasingly more wrinkled during transition into intermittency.

Structure

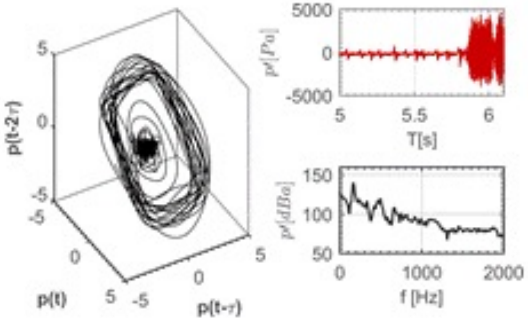
- Model gas turbine configuration and experimental instrumentation.
- Isothermal flow structure and quiescent flow and flame structure
- Flame and flowfield structure during intermittent transitions into thermoacoustic instabilities
- (Link between thermoacoustic dynamics and flame front curvature).
- Calculation of this flow


Unstable Premixed Flame
Forewarning Signal
Topology of attraction of dynamic pressure signal in phase space
Axis auto adjusted scaling

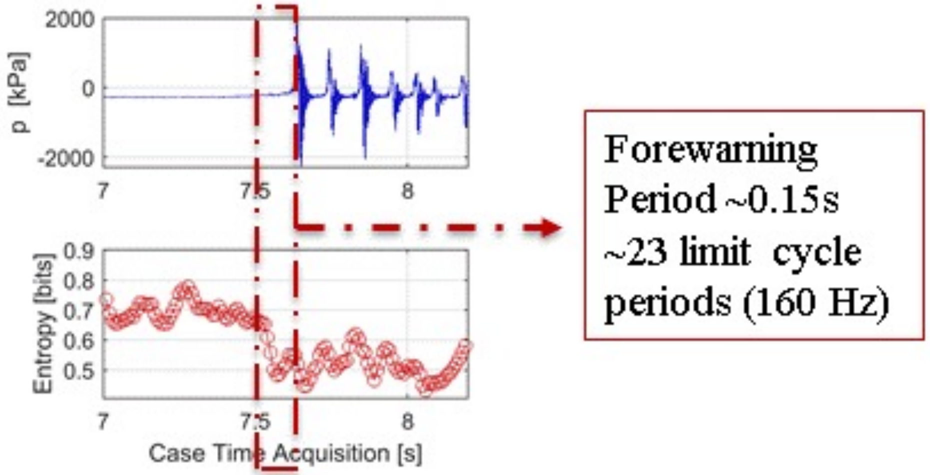
Imperial College London

Dynamic pressure signal time series and phase space structure

Intermittency



Permutation Entropy (forewarning method)



- Short term prediction techniques such as the permutation entropy are employed to detect the triggering of a thermoacoustic instability.

Description of dynamic states: Focus on the intermittent regimes

Global operational quantities:

Bulk Reynolds number Re = 19000
Equivalence ratio ϕ=0.55

On increasing extinction strain rate, the dynamics are driven from quiescent through intermittency into a limit cycle.

Karlis, E., Liu, Y. Hardalupas, Y., & Taylor, A. M. (2019d)

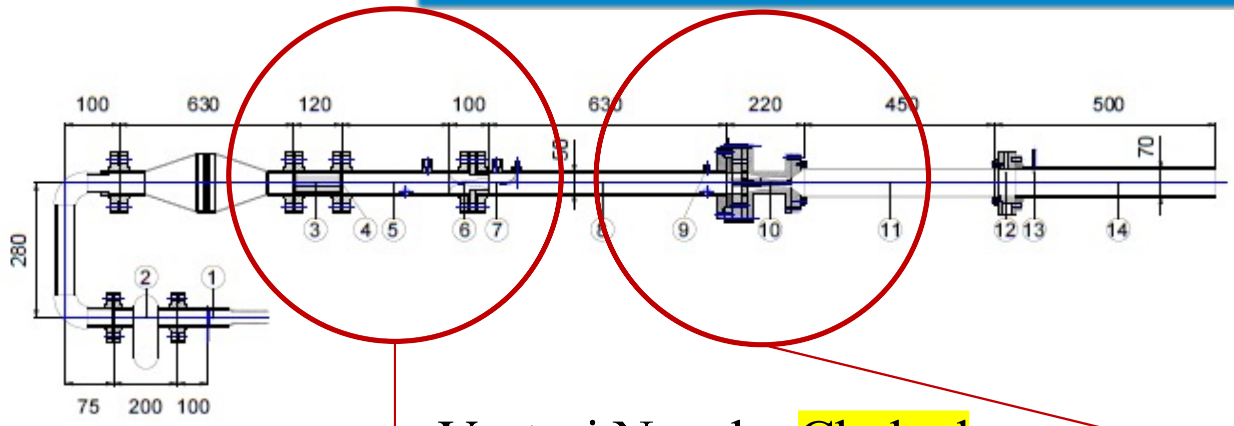
H_2 enrichment of CH_4 blends in lean premixed gas turbine combustion. Fuel, 254, 115524

Mixture ID	Methane molar percentage χ:CH_4	Hydrogen molar percentage χ:H_2	Extinction Strain Rate [1/s]	Dynamic State
Case A	1.000	0.000	273	Susceptible to blow off
Case B	0.900	0.100	652	Quiescent, lifted
Case C	0.800	0.200	759	Quiescent, lifted
Case D	0.700	0.300	1127	Intermittent
Case E	0.650	0.350	1250	Intermittent
Case F	0.625	0.375	1350	Intermittent
Case G	0.600	0.400	1540	Limit Cycle

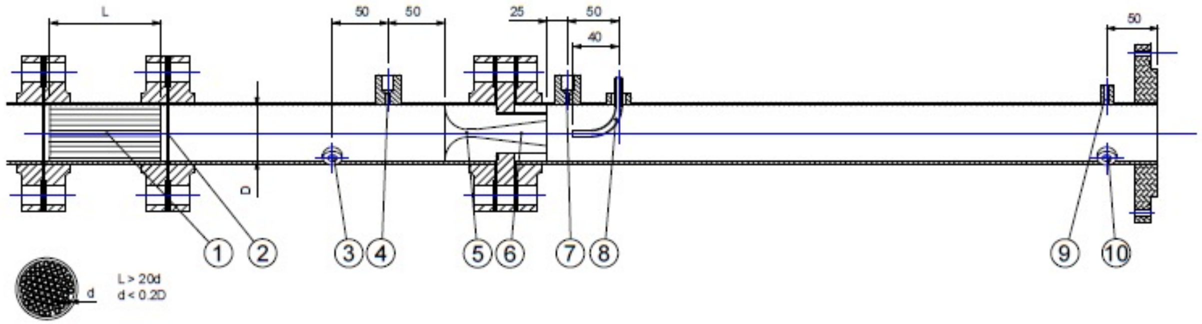
Experimental configuration-Instrumentation

Experimental Configuration

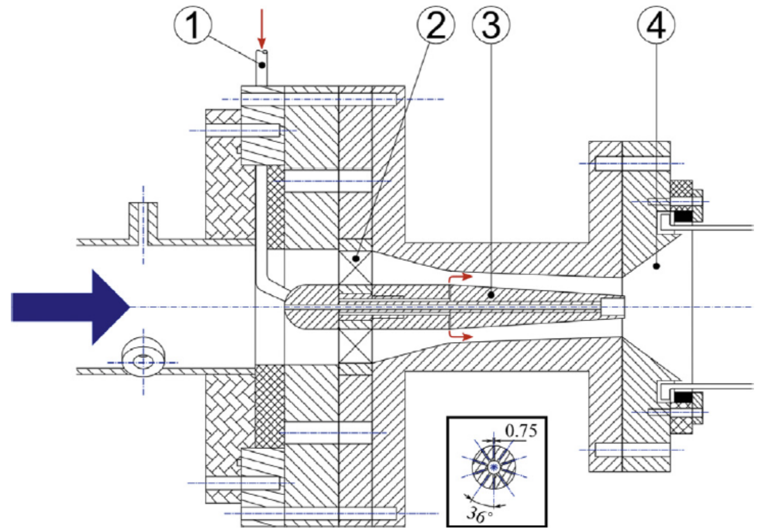
Boundary Conditions



Venturi Nozzle: Choked Air Flow

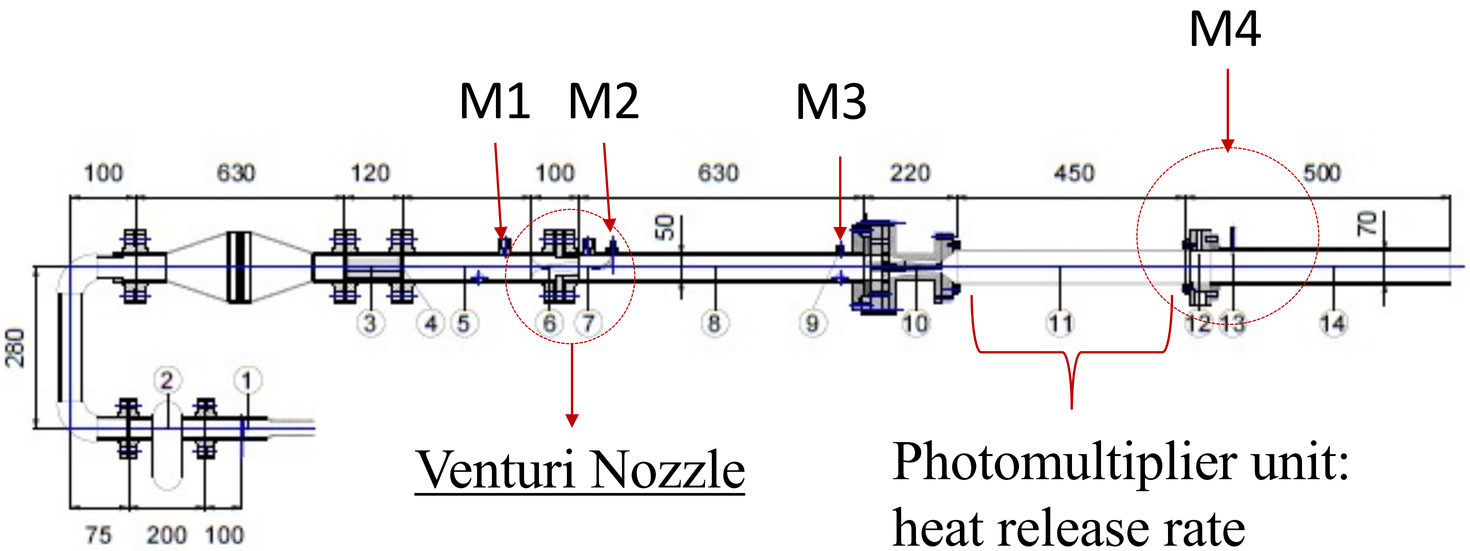


Burner: Choked Fuel Injection



Experimental Configuration

Measurement of fundamental quantities



Photomultiplier unit: heat release rate (CH^*, C_2^*, OH^*)

M1, M2: Monitor pressure drop across Venturi nozzle.

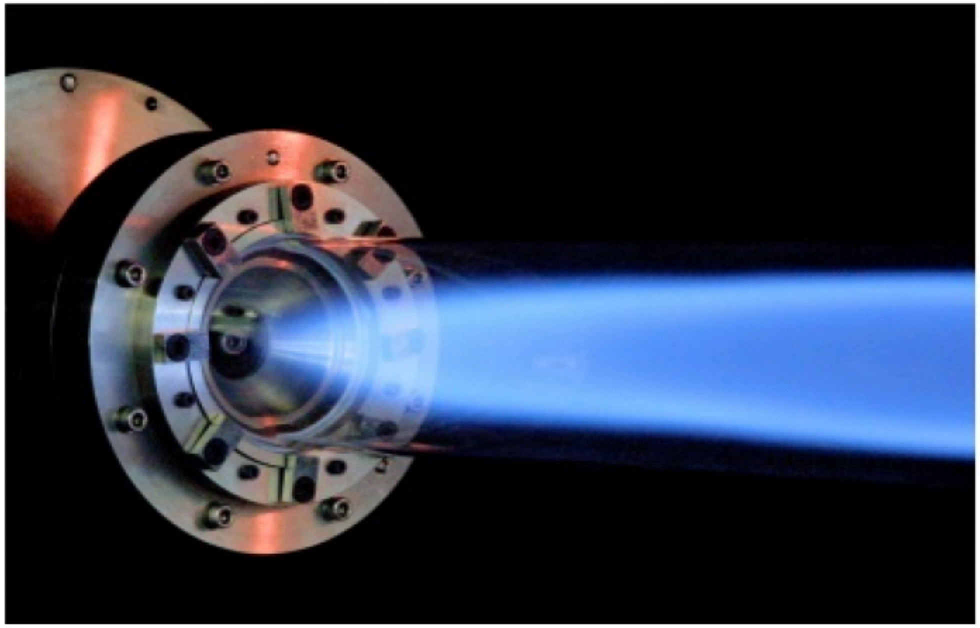
M2, M3: Acoustic wave amplitude inside duct (2-mic method)

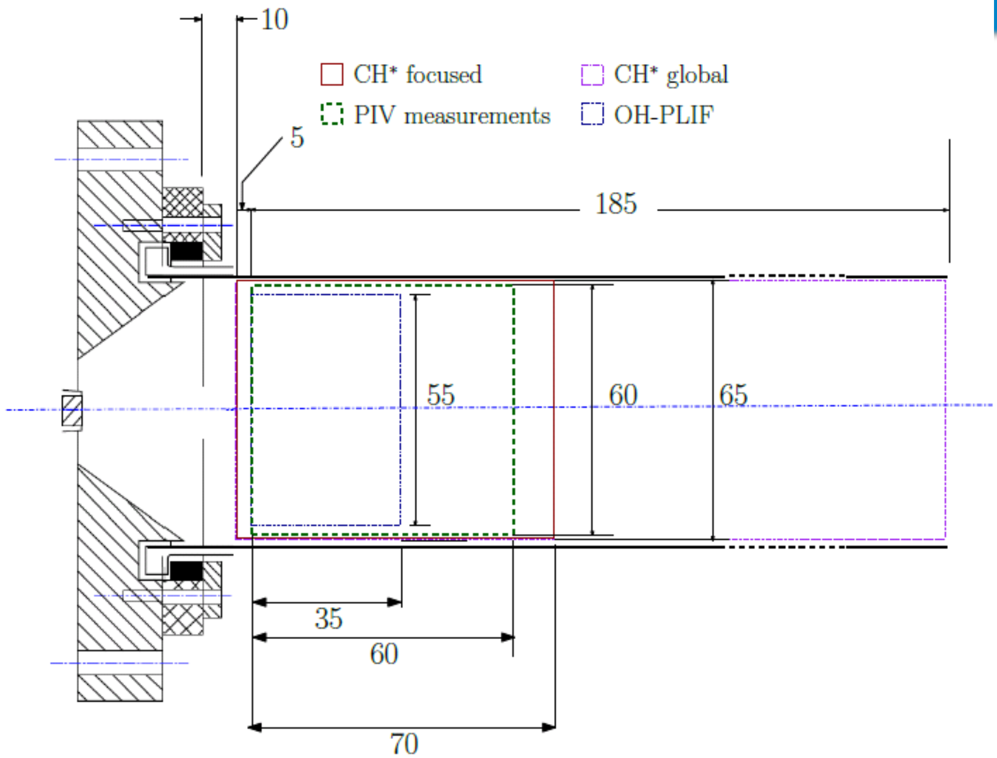
M4: Standing wave along combustor

M5 (not shown): Pressure in fuel supply line

Experimental Configuration

Swirler and Optically Accessible Combustion Window



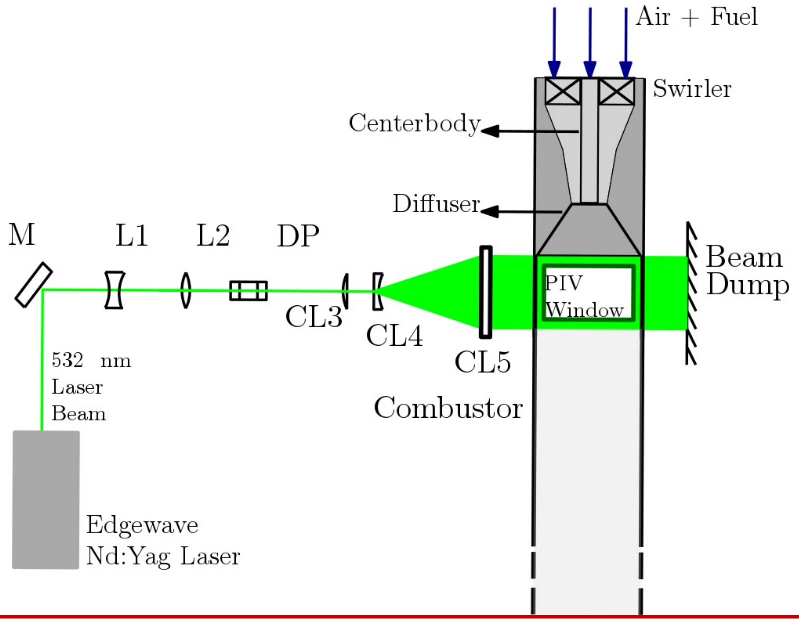


Measurement techniques: High speed CH* imaging (3000 Hz), High speed PIV (3000 Hz), OH-LIF (phase conditioned with acoustics)

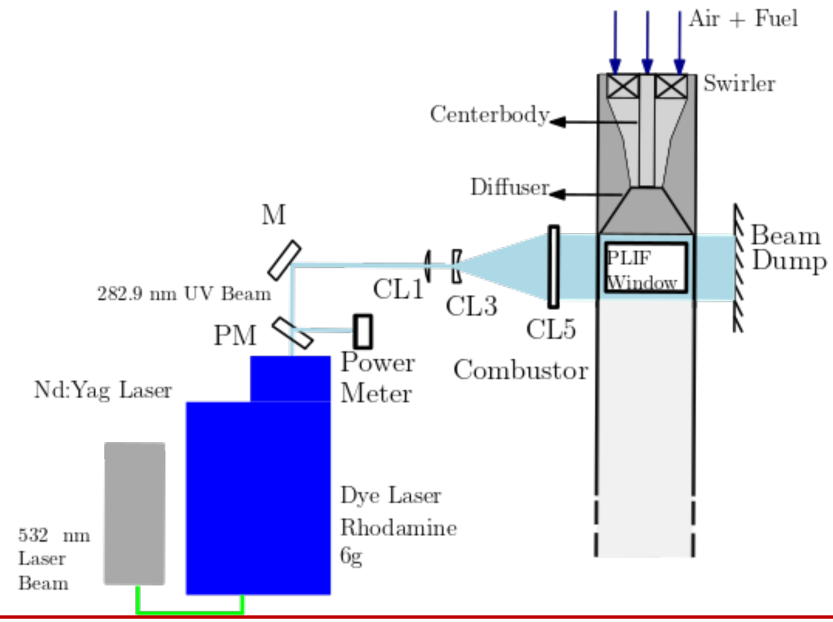
Experimental Configuration

Swirler and Optically Accessible Combustion Window

PIV Optical Configuration



PLIF Optical Configuration

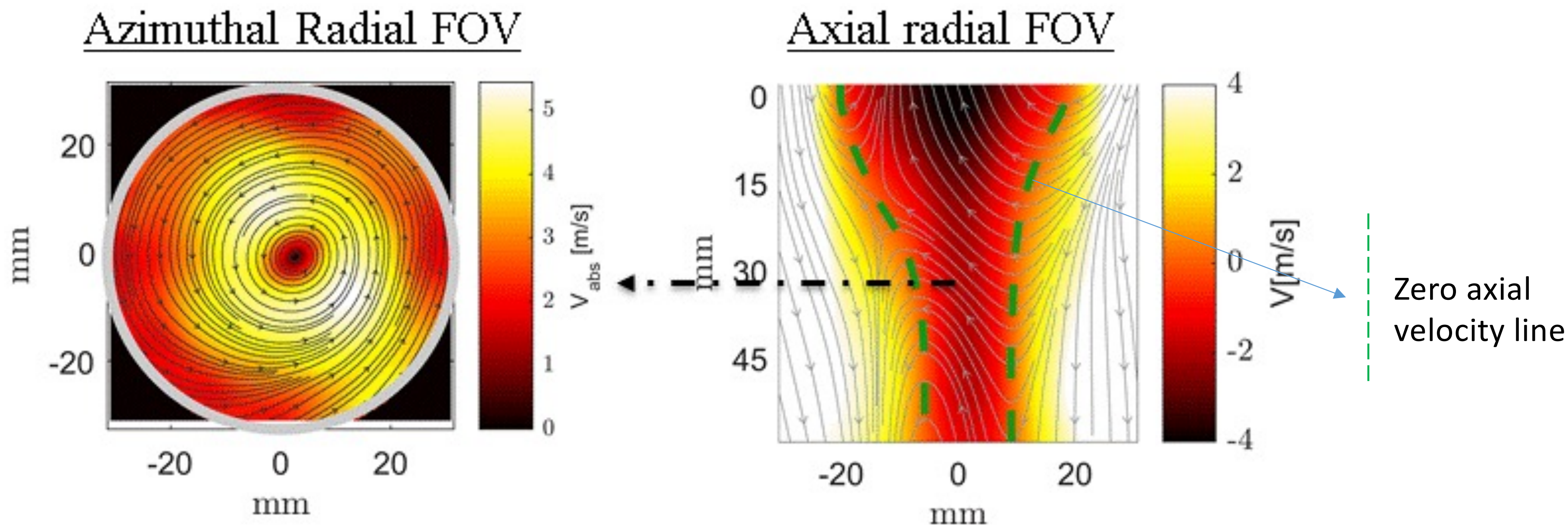


dt=4µs, 3000 Hz, FOV: 60 mm x 60 mm, Interrogation windows 16 x 16 pixels, 75% overlap, Resolution: 0.23 mm, Nominal uncertainty: 0.06 m/s. Cut-off Lengthscale in the flow=0.20mm (Poinsot 1991).

10 Hz, excitation $Q_1(6)$ transition line: $A^2\Sigma$-$X^2\Pi$ at 282.9 nm, light collected at 308 nm and 314 nm, dye laser output: 18mJ per pulse, field of view 35 mm x 35 mm, resolution of 5 line pairs / mm (curvature resolution)

Isothermal flowfield and quiescent flame structure

Isothermal flowfield structure



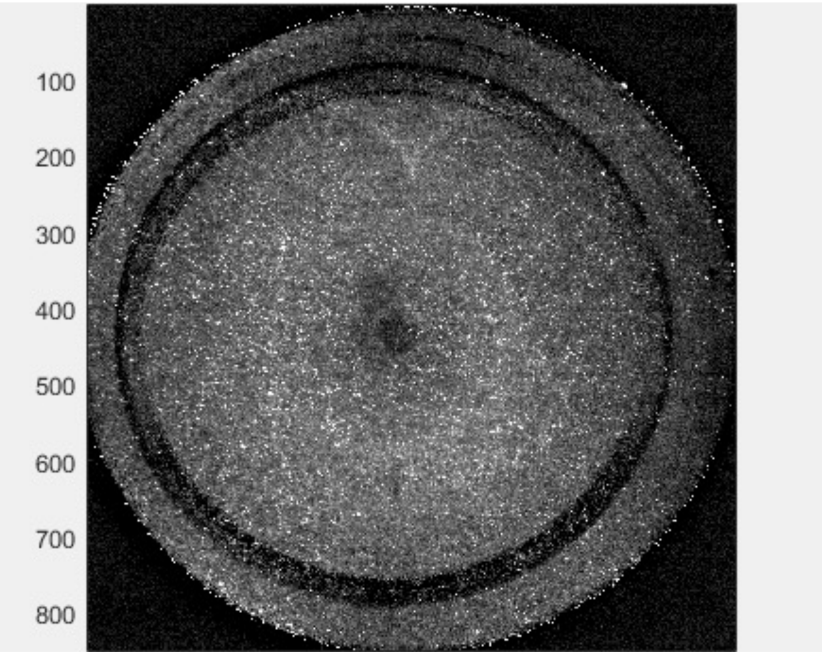
<u>Axial-radial plane:</u> isothermal flow features a recirculation zone with no downstream stagnation point, extending through all section of the PIV FOV

Imperial College London

Experimental Configuration

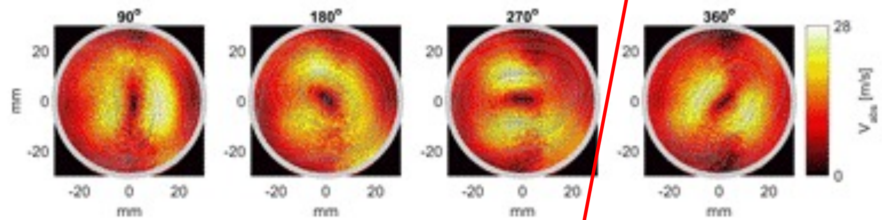
Isothermal flowfield dynamic coherent structures (PVC)

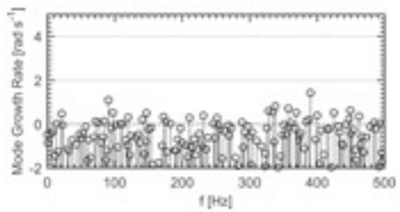
Mie Signal

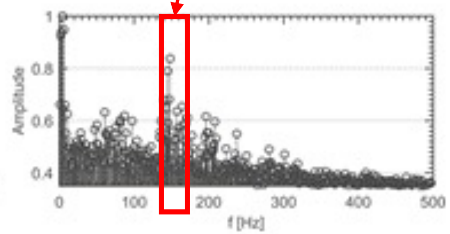


DMD analysis

DMD Filtering at 140 Hz







DMD growth rates

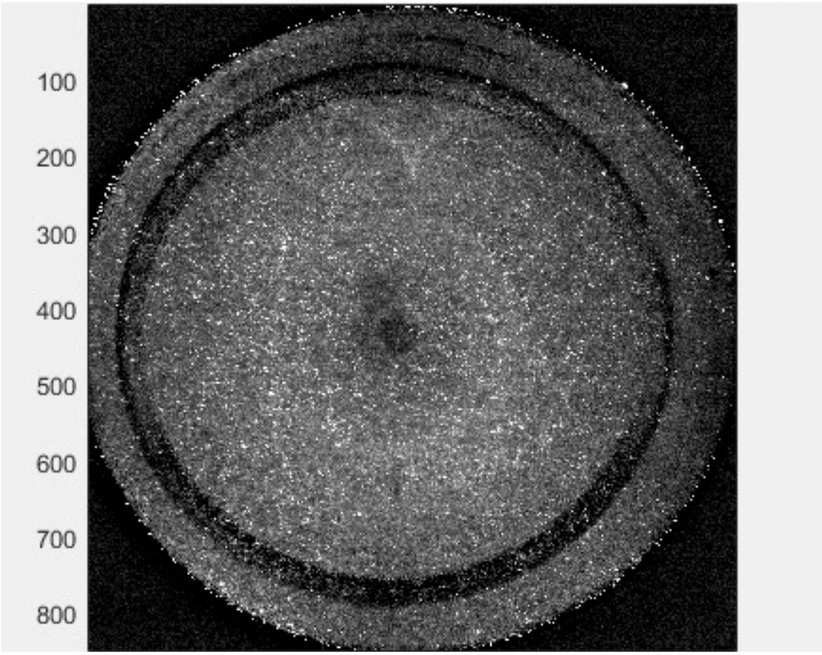
DMD amplitudes

Imperial College London

Experimental Configuration

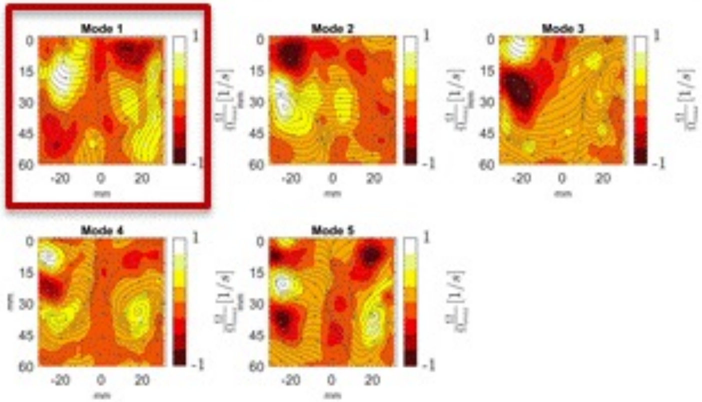
Isothermal flowfield dynamic coherent structures (PVC)

Mie Signal

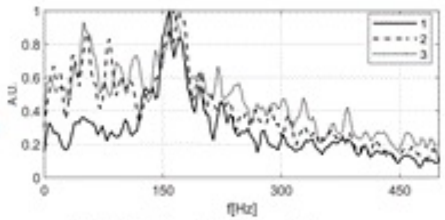


POD Modes (Normalized Vorticity)

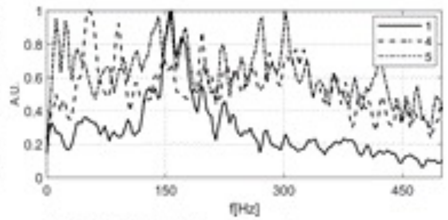
Wavemaker



POD analysis



POD Spectra Modes 1,2,3

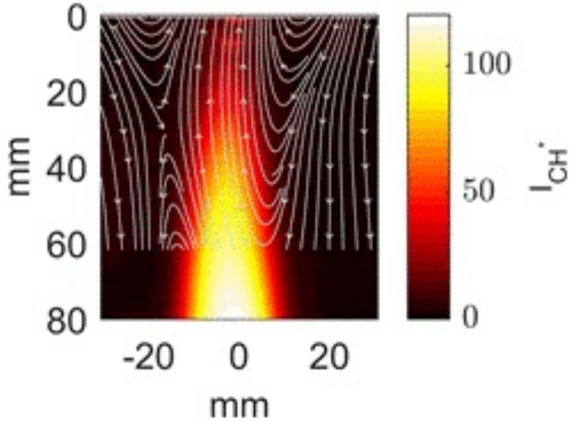


POD Spectra Modes 1,4,5

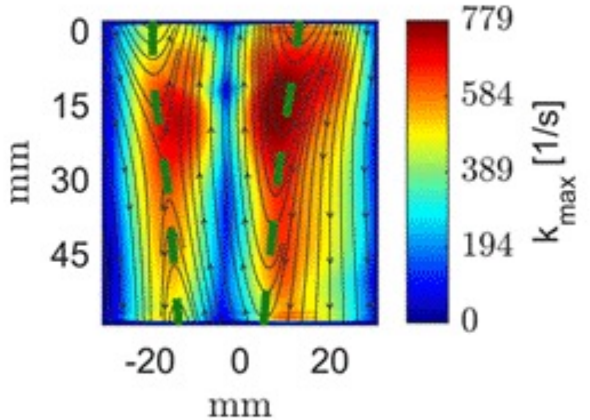
Imperial College London

Quiescent flame structure
Case C (χ_{H2}=0.20)

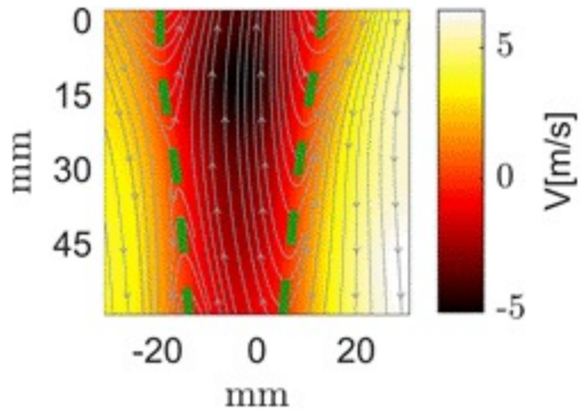
Quiescent flame



Axial-radial strain rate

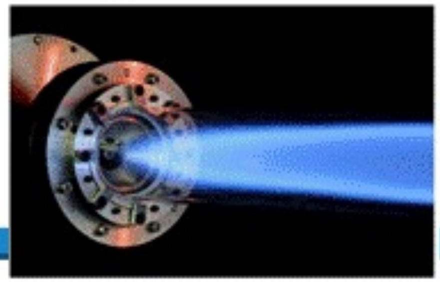


Axial Velocity



Long exposure image of a stable lean and elongated flame

- Flow structure similar to the isothermal.
- Flame anchoring within low strain rate regions



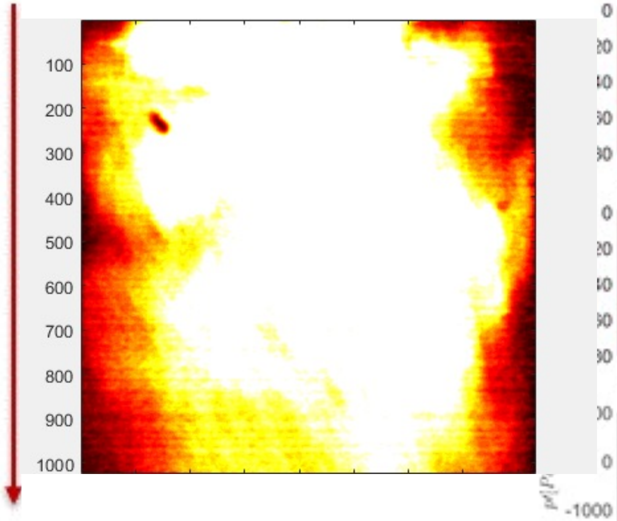
Flame and flowfield structure during triggering of intermittent thermoacoustic bursts

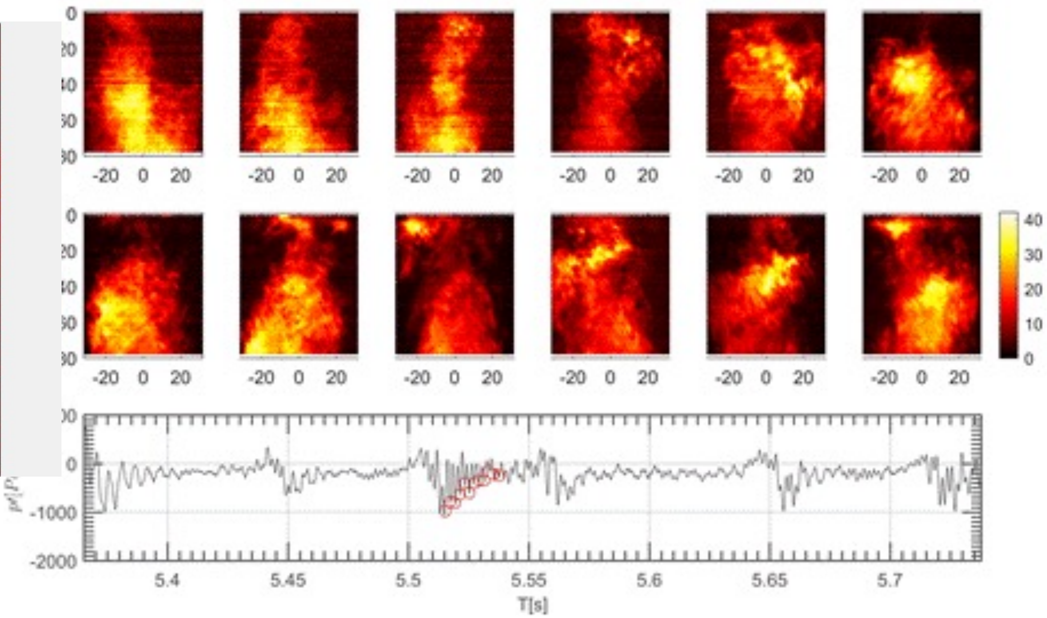
Imperial College London

Description of dynamic state transitions
Case D (χ_{H2}=0.30)
Instances of flame helical motion during thermoacoustic bursts

Intermittent Flame Dynamics

Flow Direction





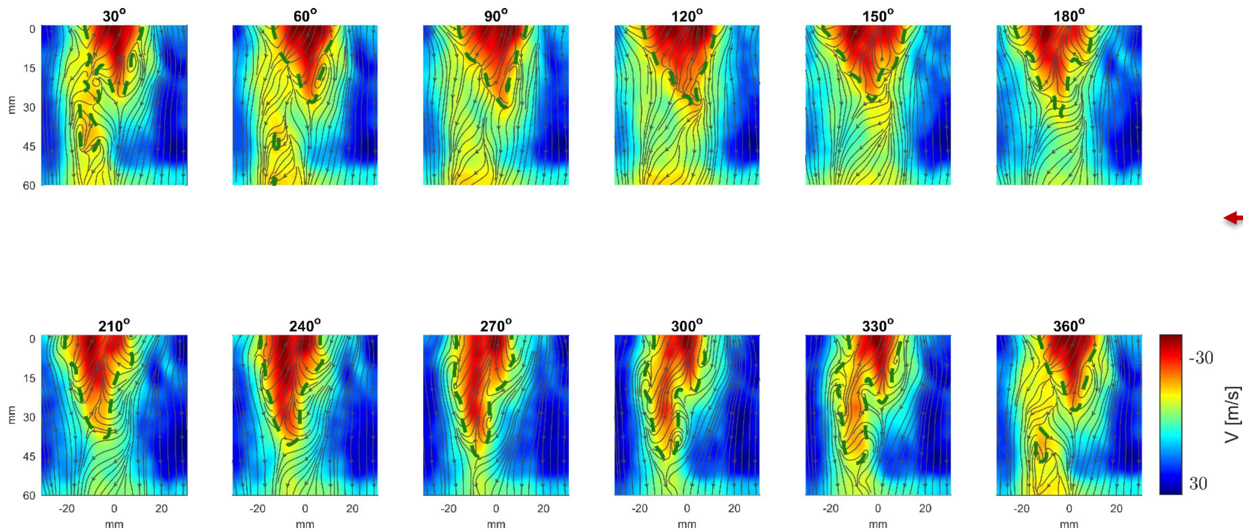
Dynamic pressure time series:

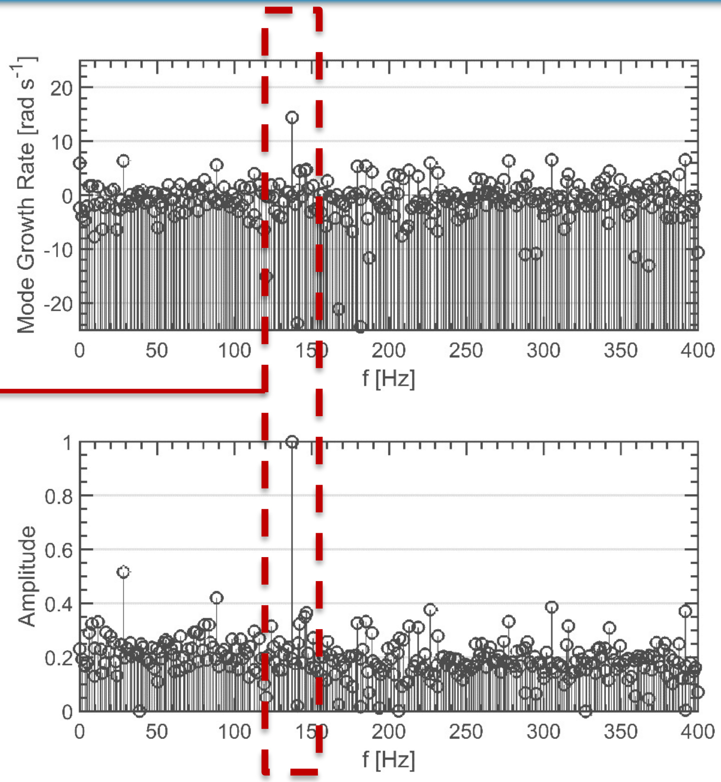
Note the red circles and corresponding snapshots

Description of dynamic state transitions
Case D (χ_{H2}=0.30)
Precession as extracted via DMD

Imperial College London

Filtering via DMD: Frequency of precession is very close to the isothermal PVC frequency of precession



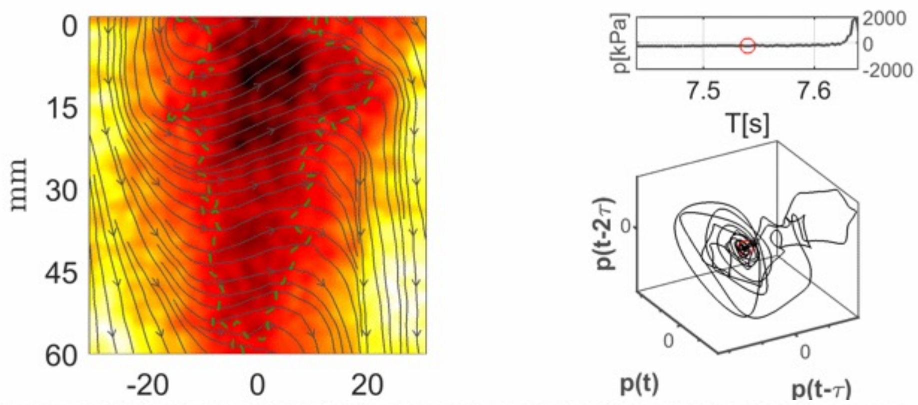


Frequency of precession: 137 Hz

Imperial College London

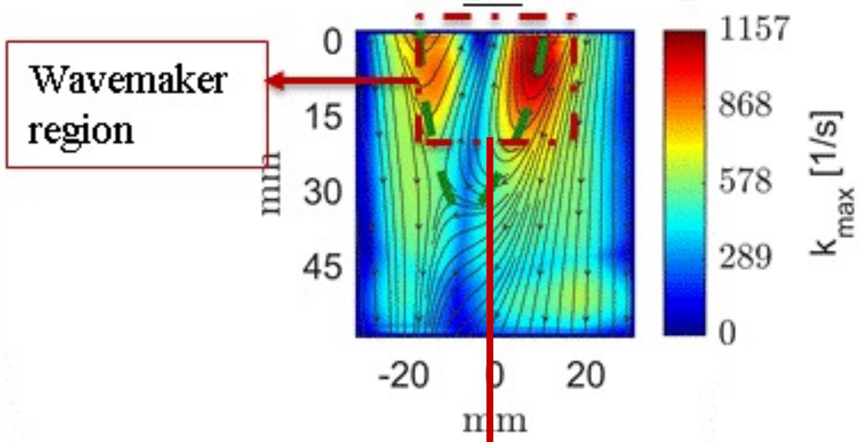
Description of dynamic state transitions
Case D (χ_{H2}=0.30)
Dynamic pressure phase space structure and intermittent flow dynamics

Intermittent Flow Dynamics



Contours of axial velocity

Mean strain rate (k_{flow}) during intermittency

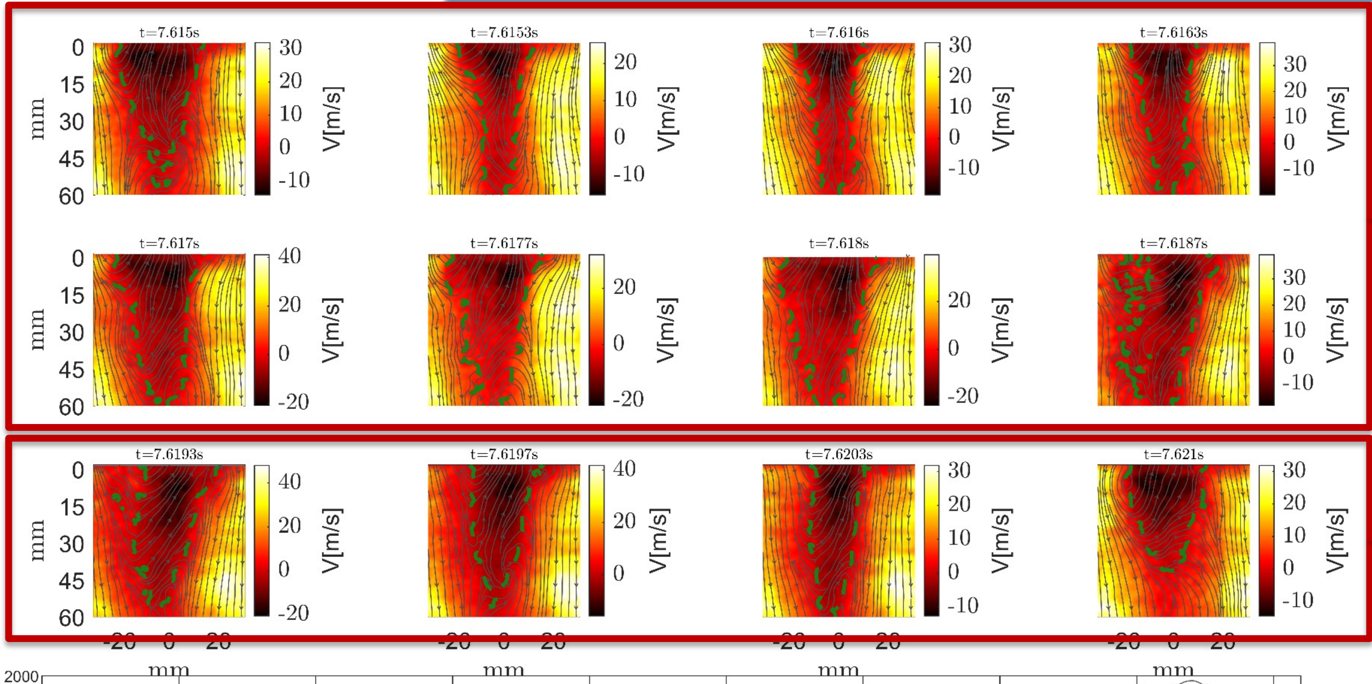


If the elongated flame survives straining, such that it anchors close to the region wherein the helical wavemaker exists, then the flame precesses under the influence of the helical coherent structure (PVC)

Description of dynamic state transitions

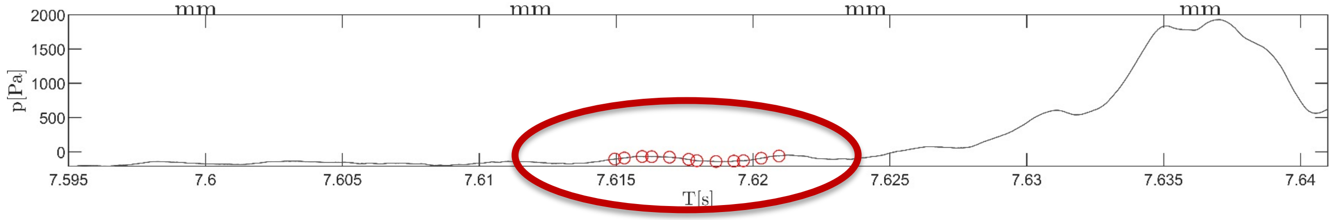
Breakdown of transition events: Pre-triggering

Imperial College London



Initiation of helical motion of recirculation zone under the effect of helical coherent structures along the shear layers.

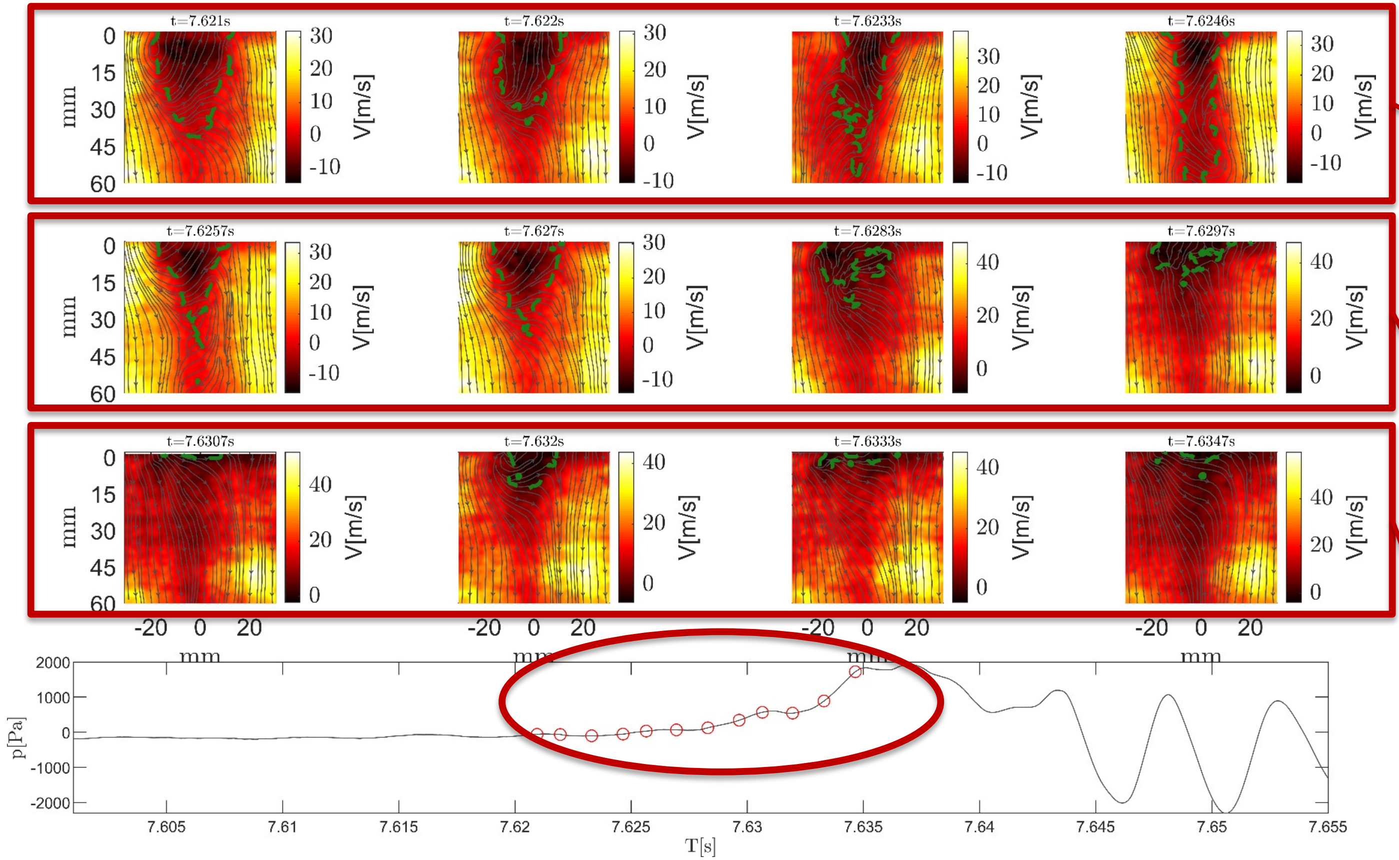
Initial formation of downstream axial stagnation point in the recirculation zone



Imperial College London

Description of dynamic state transitions

Breakdown of transition events: Thermoacoustic burst



Convection of high axial velocity amplitude disturbance causing the recirculation zone to form a downstream axial stagnation point.

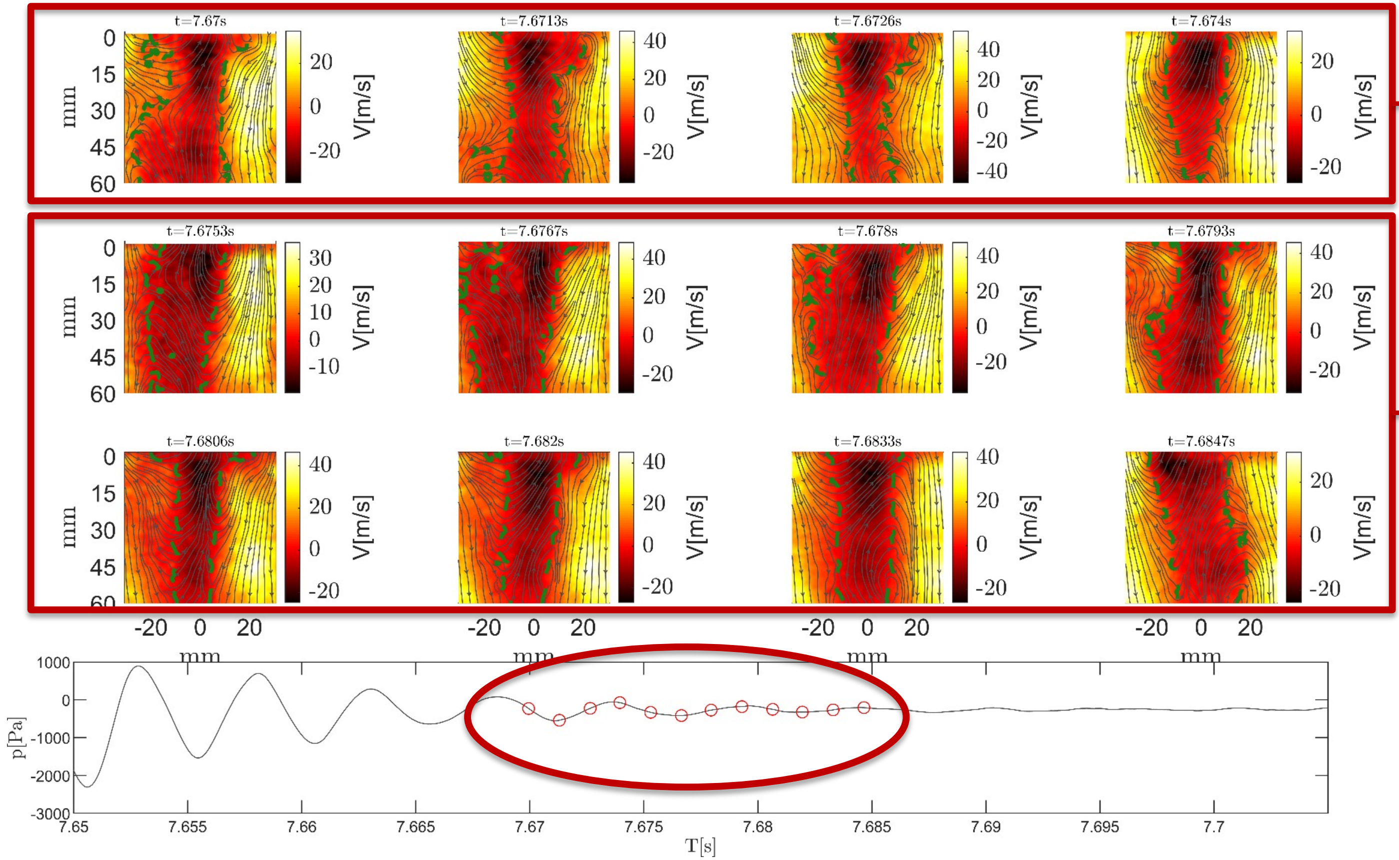
The downstream convection of the disturbance by the bulk flow decreases the axial and radial extent of the recirculation zone.

When the axial extent of the recirculation zone is minimum the dynamic pressure is maximum

Imperial College London

Description of dynamic state transitions

Breakdown of transition events: Requiescence

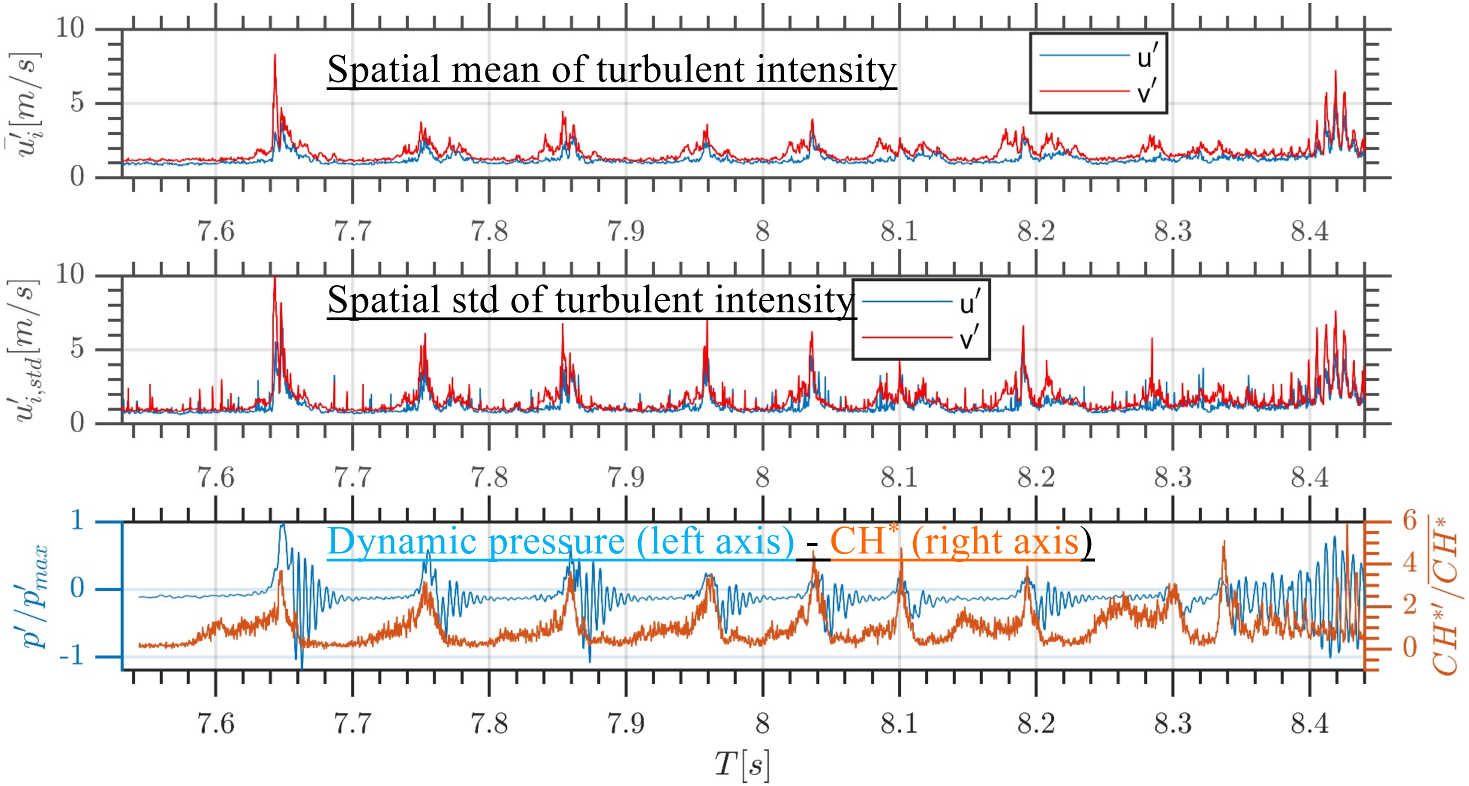


Decreasing rate of helical precession

Reestablishment of open ended recirculation zone with no downstream stagnation point

Imperial College London

Description of dynamic state transitions
Case D (χ_{H2}=0.30)
Spatial mean and standard deviations of turbulent intensity

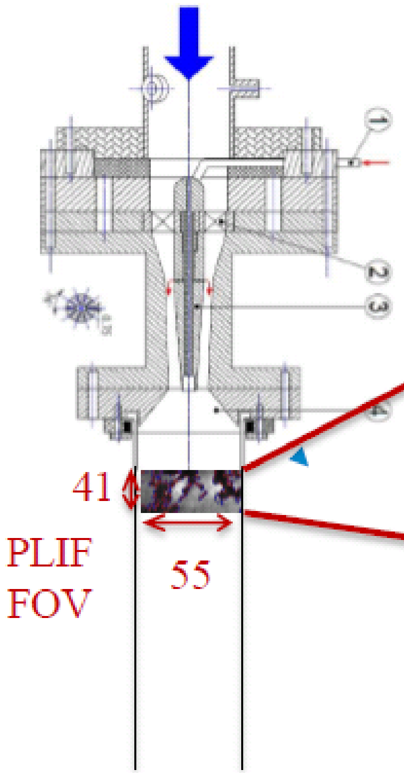


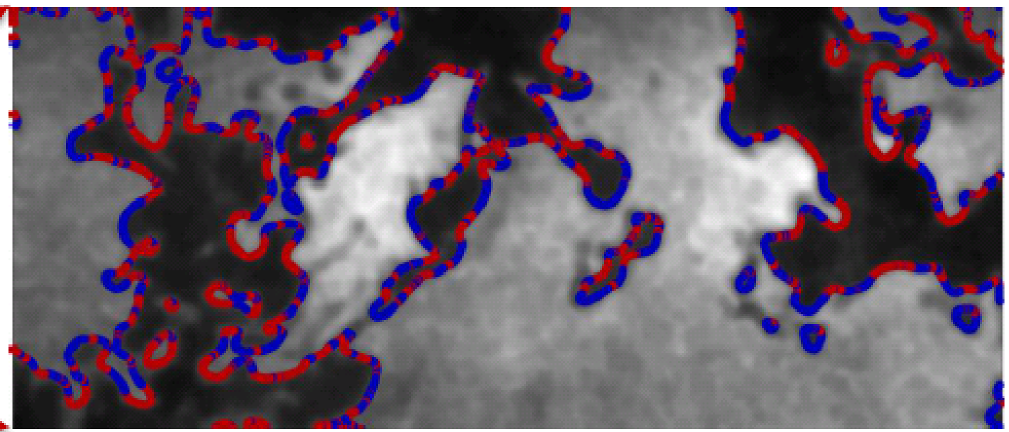
- The spatial mean and standard deviations of the turbulent intensities of the flowfield demonstrate spikes that coincide with the thermoacoustic bursts.
- The burning rate increases and the range of scales, with which the flame interacts, widens upon transitioning into thermoacoustic instability.

Flame front curvature analysis

Flame front detection algorithm

Method: [Bayley et al., 2012] Bayley, A. E., Hardalupas, Y., & Taylor, A. M. (2012). Local curvature measurements of a lean, partially premixed swirl-stabilised flame. Experiments in Fluids, 52(4), 963–983.





Burned (Unburned

Negative curvature

Burned) Unburned +

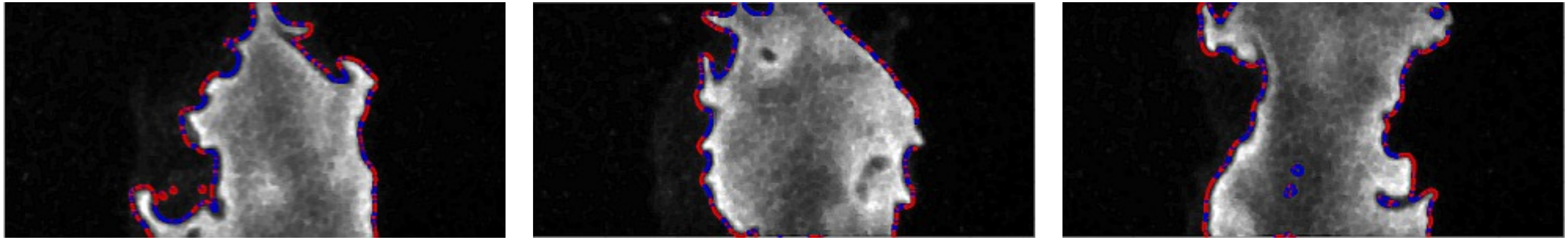
Positive curvature

Imperial College London

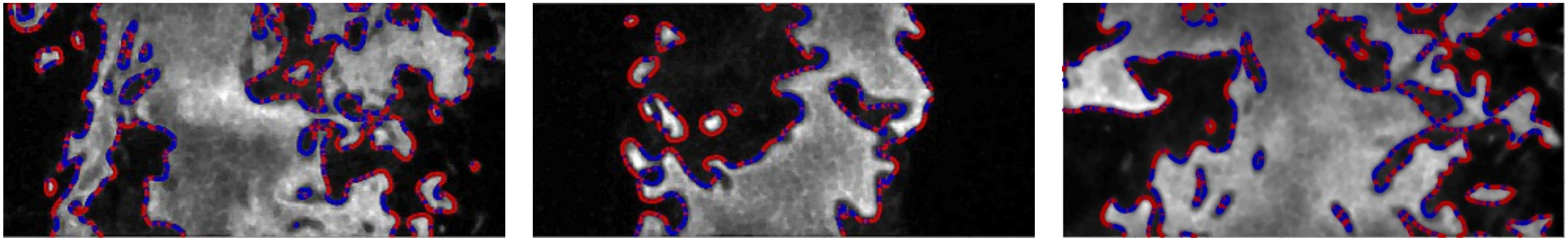
Description of dynamic state transitions

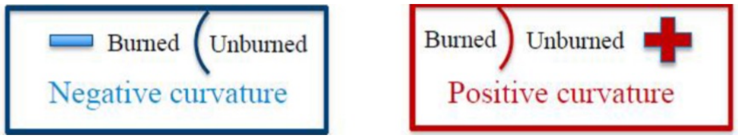
Flame front curvature characteristics of intermittent flame via OH-PLIF measurements

Quiescent flames-straight and elongated.



Transitional flames-more wrinkled and with greater radial extent



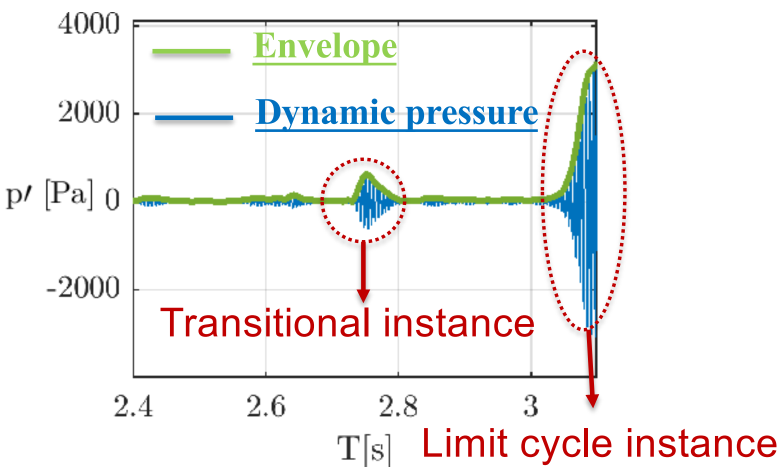


Reminder: Curvature convention

Imperial College London

Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Case ID Thermoacoustic state	$\bar{\kappa}$: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
D: Transitional	0.167	1.128	0.095	4.794
D: Limit Cycle	-0.036	1.416	-0.036	4.472
E : Quiescent	0.127	1.316	0.048	5.125
E: Transitional	0.087	1.330	0.047	4.755
E: Limit Cycle	-0.048	1.408	-0.031	4.577
F: Quiescent	0.122	1.264	0.027	5.344
F: Transitional	0.089	1.296	0.028	5.120
F: Limit Cycle	-0.024	1.402	-0.013	4.598

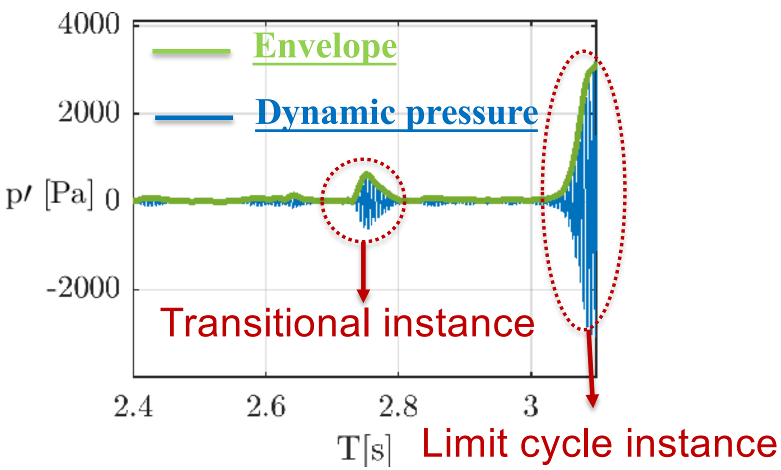
Distinction between dynamic states:
Quiescent: $p'_{envelope} < 300$ Pa
Transitional: $p'_{envelope} > 300$ Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope} > 300$ Pa for at least 20 thermoacoustic cycles

Upon transitioning from quiescence towards a limit cycle:
Mean curvature decreases towards near zero negative values

Imperial College London

Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Distinction between dynamic states:
Quiescent: $p'_{envelope} < 300$ Pa
Transitional: $p'_{envelope} > 300$ Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope} > 300$ Pa for at least 20 thermoacoustic cycles

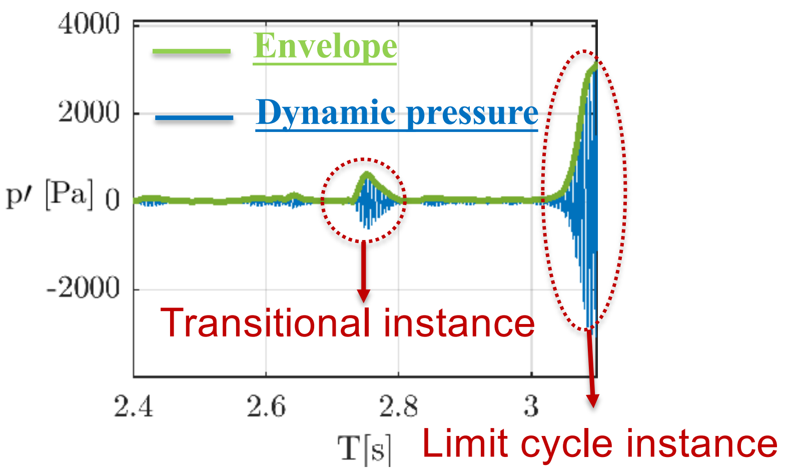
Case ID Thermoacoustic state	$\overline{\kappa}$: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
D: Transitional	0.167	1.128	0.095	4.794
D: Limit Cycle	-0.036	1.416	-0.036	4.472
E : Quiescent	0.127	1.316	0.048	5.125
E: Transitional	0.087	1.330	0.047	4.755
E: Limit Cycle	-0.048	1.408	-0.031	4.577
F: Quiescent	0.122	1.264	0.027	5.344
F: Transitional	0.089	1.296	0.028	5.120
F: Limit Cycle	-0.024	1.402	-0.013	4.598

Upon transitioning from quiescence towards a limit cycle:
Standard deviation strongly increases.

Imperial College London

Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Distinction between dynamic states:
Quiescent: $p'_{envelope} < 300$ Pa
Transitional: $p'_{envelope} > 300$ Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope} > 300$ Pa for at least 20 thermoacoustic cycles

Case ID Thermoacoustic state	$\overline{\kappa}$: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
D: Transitional	0.167	1.128	0.095	4.794
D: Limit Cycle	-0.036	1.416	-0.036	4.472
E : Quiescent	0.127	1.316	0.048	5.125
E: Transitional	0.087	1.330	0.047	4.755
E: Limit Cycle	-0.048	1.408	-0.031	4.577
F: Quiescent	0.122	1.264	0.027	5.344
F: Transitional	0.089	1.296	0.028	5.120
F: Limit Cycle	-0.024	1.402	-0.013	4.598

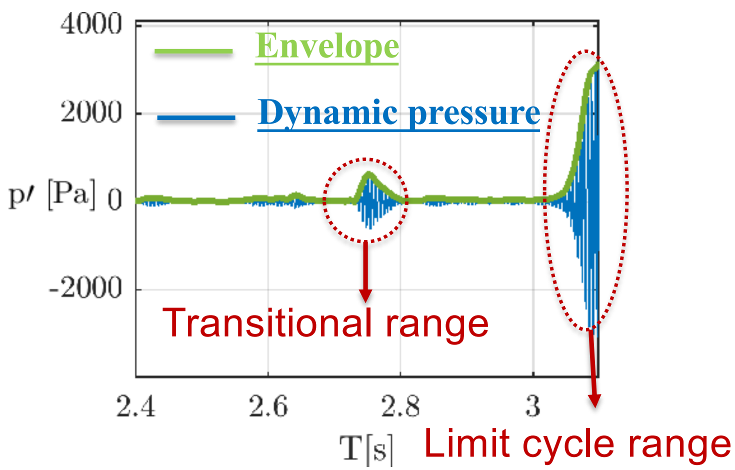
Upon transitioning from quiescence towards a limit cycle:
Standard deviation strongly increases.

Upon transitioning from quiescence towards a limit cycle:
Kurtosis decreases

Imperial College London

Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Distinction between dynamic states:
Quiescent: $p'_{envelope} < 300$ Pa
Transitional: $p'_{envelope} > 300$ Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope} > 300$ Pa for at least 20 thermoacoustic cycles

Case ID Thermoacoustic state	$\bar{\kappa}$: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
D: Transitional	0.167	1.128	0.095	4.794
D: Limit Cycle	-0.036	1.416	-0.036	4.472
E : Quiescent	0.127	1.316	0.048	5.125
E: Transitional	0.087	1.330	0.047	4.755
E: Limit Cycle	-0.048	1.408	-0.031	4.577
F: Quiescent	0.122	1.264	0.027	5.344
F: Transitional	0.089	1.296	0.028	5.120
F: Limit Cycle	-0.024	1.402	-0.013	4.598

Flames that experience subcrical Hopf bifurcations gradually become more wrinkled while transitioning through the transitional thermoacoustic state towards the limit cycle.

Imperial College London

Summary 1/2: During a subcritical Hopf bifurcation, how does the flame and flowfield structure bifurcate?

- Intermittency is observed when the flame is able to penetrate into, and anchor at, the "Wavemaker" region, close to the inlet of the burner. To do so, the flame needs to overcome increased strain rates in this region of the flowfield.
- Flames tolerant to extinction strain rates are more susceptible to demonstrating subcritical Hopf bifurcations.
- Transition into instability in the model gas turbine combustor is associated with:
  1. the PVC which imposes helical disturbances on the flame and the recirculation zone.
  2. Loss of randomness in the dynamic state: can be employed to forewarn of triggering.
- The role of the PVC is crucial. It exists both for the isothermal and the quiescent flowfields and it can instigate ("kick the system") thermoacoustic bursts that are promoted mainly by the flame-wall interactions.

Imperial College London

Summary 2/2: During a subcritical Hopf bifurcation, how does the flame and flowfield structure bifurcate?

- The flames of thermoacoustic systems demonstrating intermittency assume increasingly wrinkled forms. This is supported by both PIV and PLIF measurements:
  1. The standard deviation of the turbulent intensities during the transition into thermoacoustic instability increases.
  2. The standard deviation and the kurtosis of the flame front curvature increase.

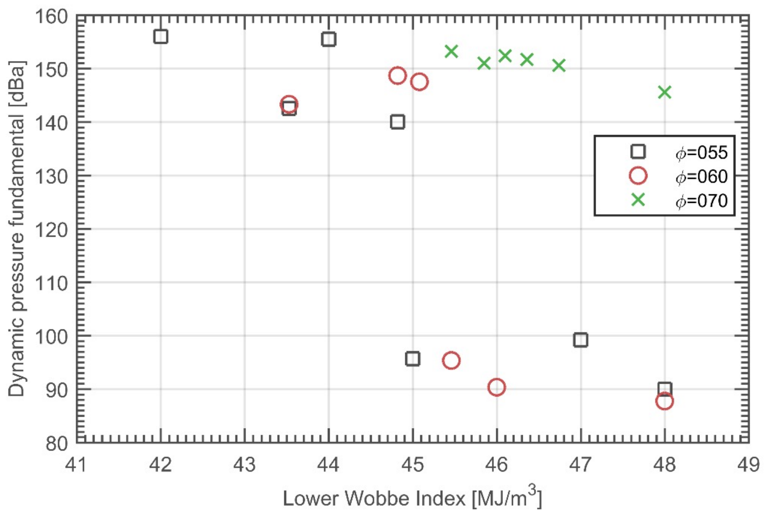
Imperial College London

Summary 2/2: During a subcritical Hopf bifurcation, how does the flame and flowfield structure bifurcate?

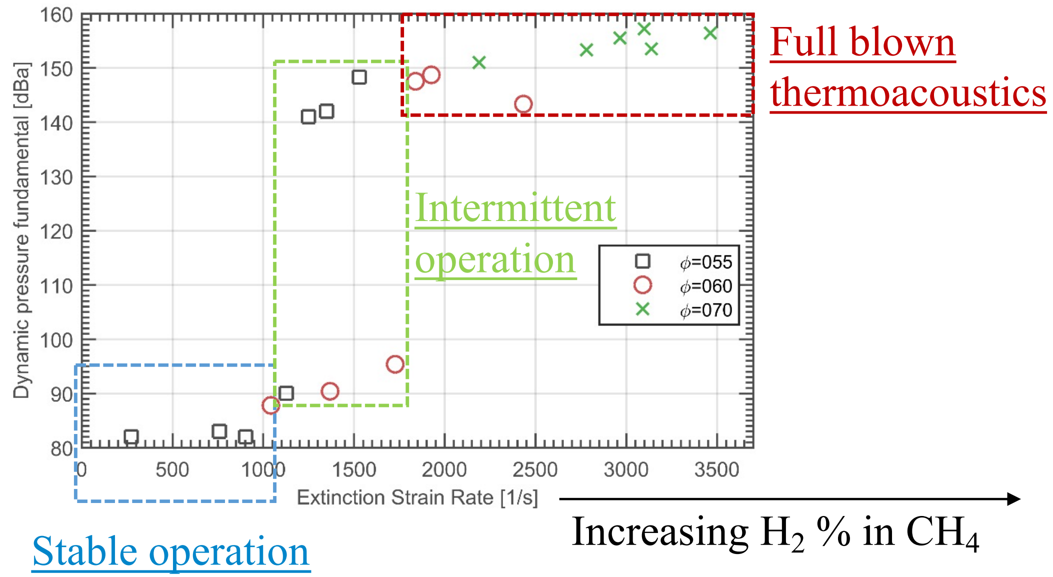
- Note that we have made no mention of
  - any acoustic frequency, Because the limit cycle has not been established yet in order to make a case about harmonics and subharmonics
  - a PVC (settles at the subharmonic) because its emergence is dependent on the limit cycle phase.
    - The PVC is suppressed when the flame moves back into the centerbody and detaches from its downstream half due to the strain rate. The PVC on the limit cycle, and has also been corroborated in the literature, appears at a natural frequency of 255 Hz- during the limit cycle - and gives a distinct heat release rate contribution at 85Hz - the subharmonic. It is the difference between f-pvc and the fundamental of the acoustics.

Motivation: Extinction strain rate is a mixture property collapsing dynamic state transitions (H_2 enriched CH_4 blends)

Collapsing dynamics with Wobbe index



Collapsing dynamics with extinction strain rate



Karlis, E., Liu, Y. Hardalupas, Y., & Taylor, A. M. (2019d) H_2 enrichment of CH_4 blends in lean premixed gas turbine combustion: An experimental study on effects on flame shape and thermoacoustic oscillations dynamics. Fuel, 254, 115524

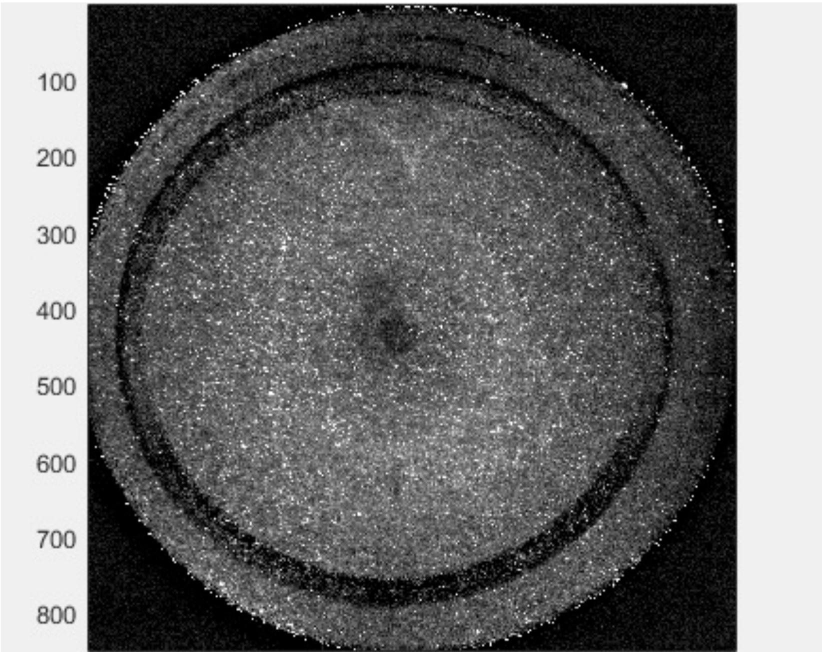
Supportive slides

Imperial College London

Experimental Configuration

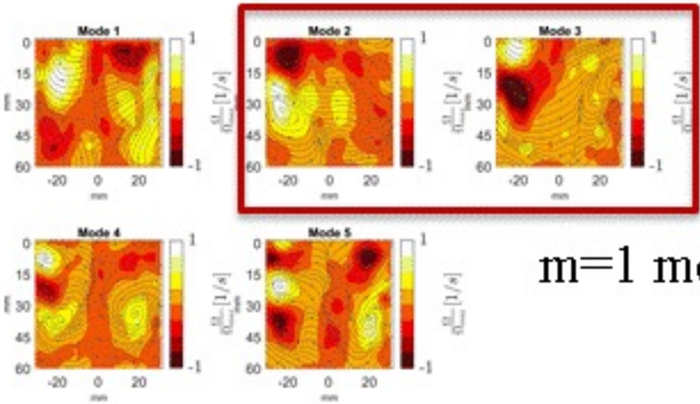
Isothermal flowfield dynamic coherent structures (PVC)

Mie Signal

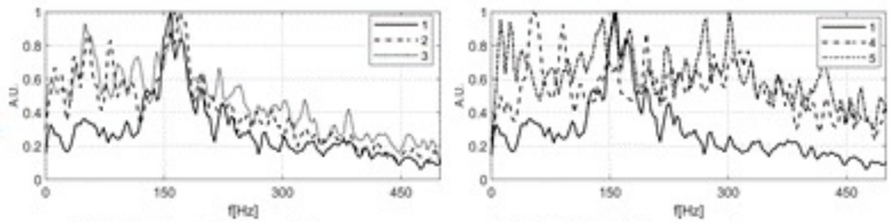


POD analysis

POD Modes (Normalized Vorticity)



m=1 modes



POD Spectra Modes 1,2,3

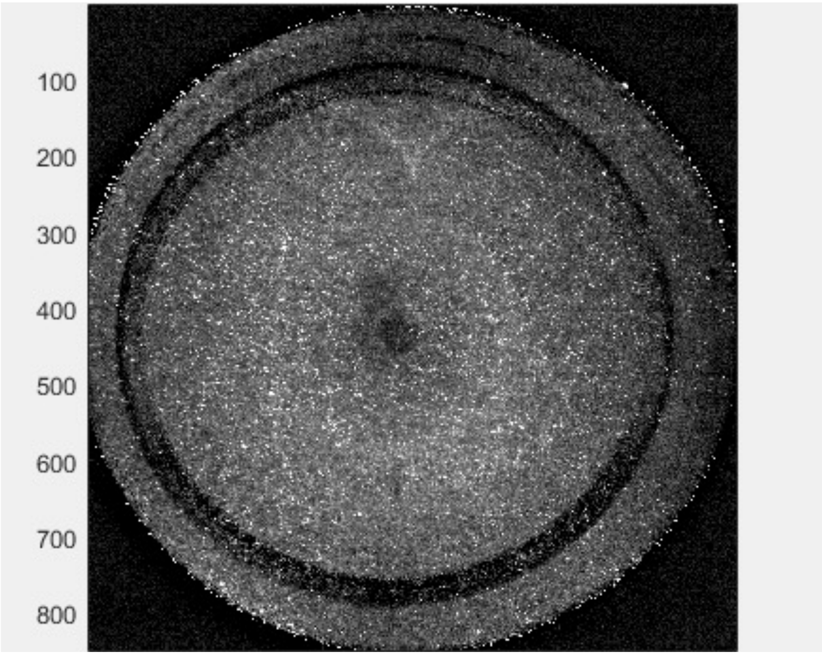
POD Spectra Modes 1,4,5

Imperial College London

Experimental Configuration

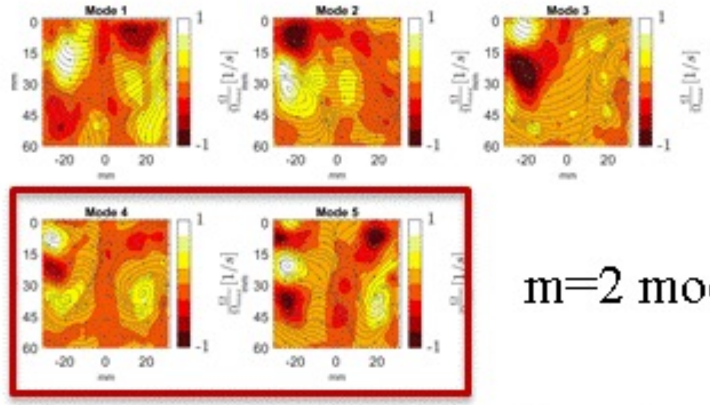
Isothermal flowfield dynamic coherent structures (PVC)

Mie Signal

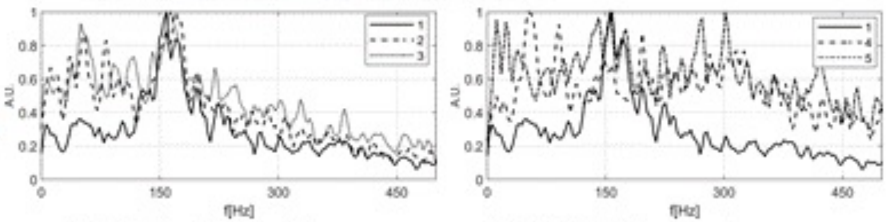


POD Modes (Normalized Vorticity)

POD analysis



m=2 modes



POD Spectra Modes 1,2,3

POD Spectra Modes 1,4,5

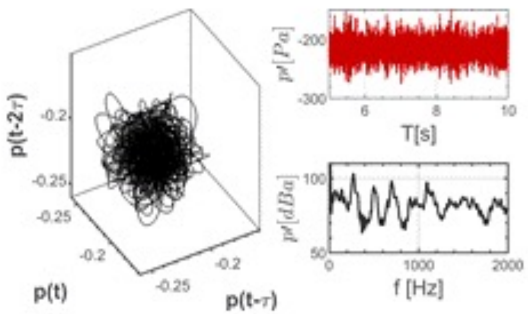
Intermittency: Interpretation of transitional dynamics
Phase space representation

Imperial College London

Quiescence-Intermittency-Limit Cycle

Case study: H_2 enrichment of CH_4

Quiescence



Dynamic Pressure

Fourier Spectra

Cases B, C

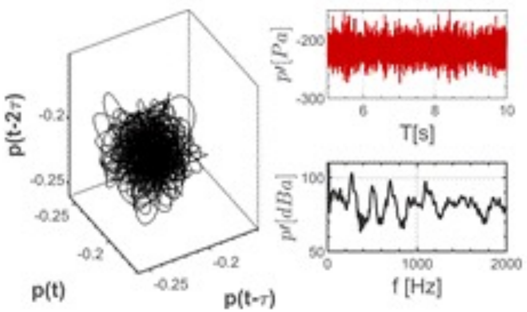
Dynamics: Attracted to fixed point and demonstrate stochastic low amplitude pressure fluctuations.

Imperial College London

Quiescence-Intermittency-Limit Cycle

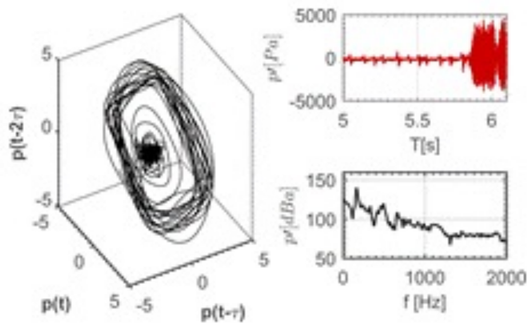
Case study: H_2 enrichment of CH_4

Quiescence



Cases B, C

Intermittency



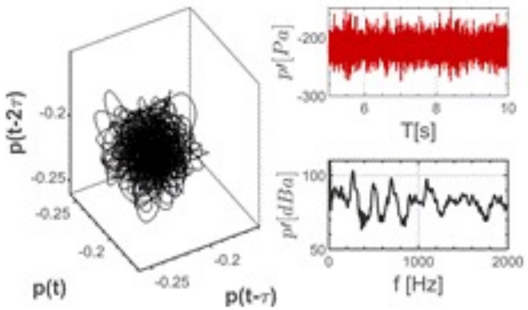
Case D

Dynamics: Toroidal transition between limit cycle and fixed point. Emergence of coherent dynamics amidst a quiescent background.

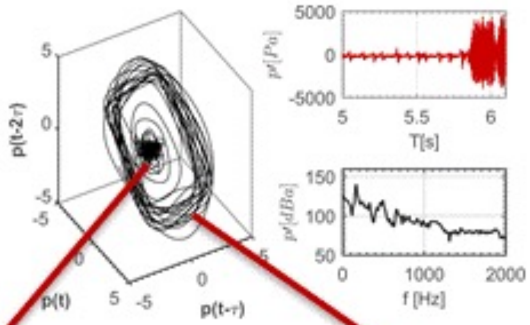
Imperial College London

Quiescence-Intermittency-Limit Cycle
Case study: H_2 enrichment of CH_4

Quiescence

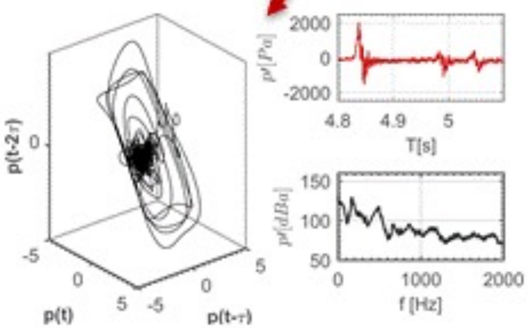


Intermittency

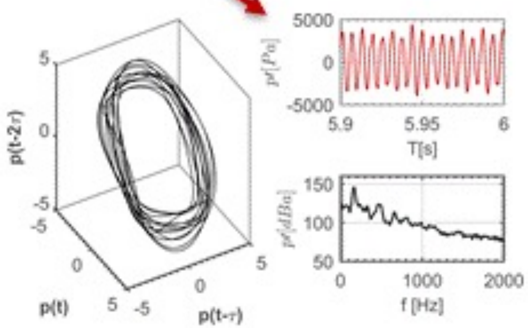


Cases B, C

Dynamics: Fixed point and toroidal transition



Case D



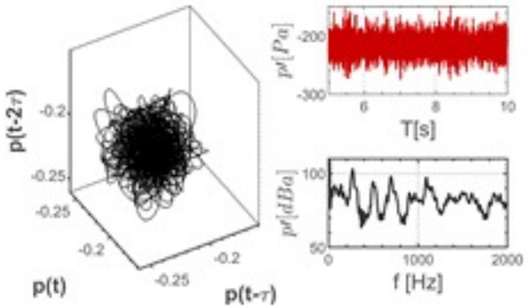
Dynamics: Limit cycle

Imperial College London

Quiescence-Intermittency-Limit Cycle

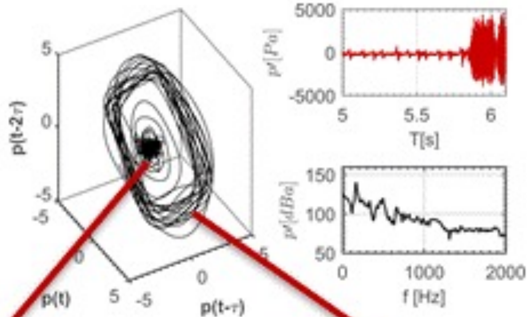
Case study: H_2 enrichment of CH_4

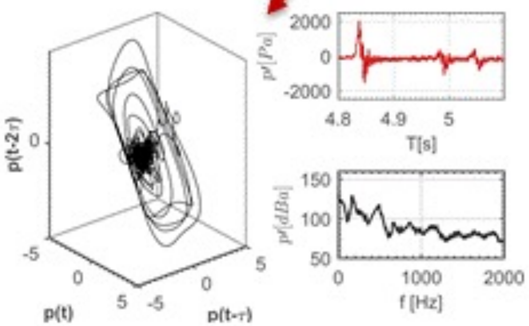
Quiescence



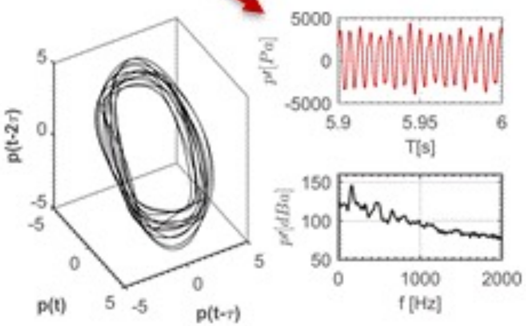
Cases B, C

Intermittency

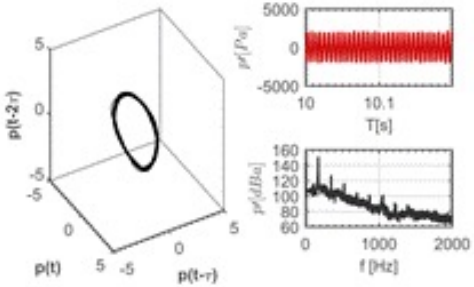




Case D



Limit Cycle



Case G

Dynamics:
Consistent attraction to limit cycle.