Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

Project DE-FE0025495, Oct. 2015 – Sept. 2018
Program Monitor: Steve Richardson

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Overview of presentation

- Project motivation and objective
- Technical background
- Technical approach
- Next steps

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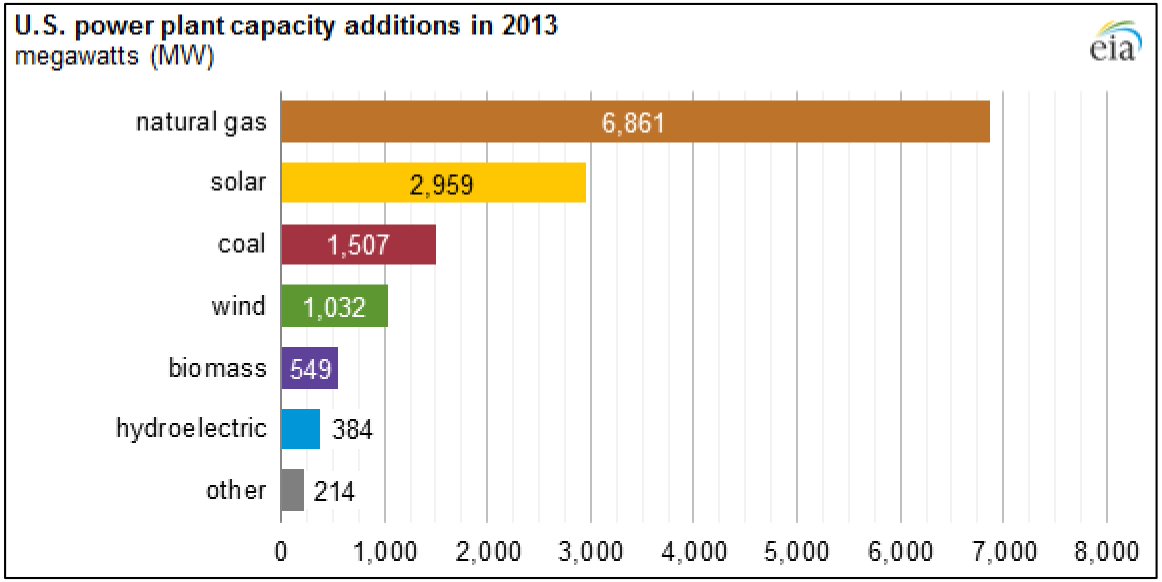
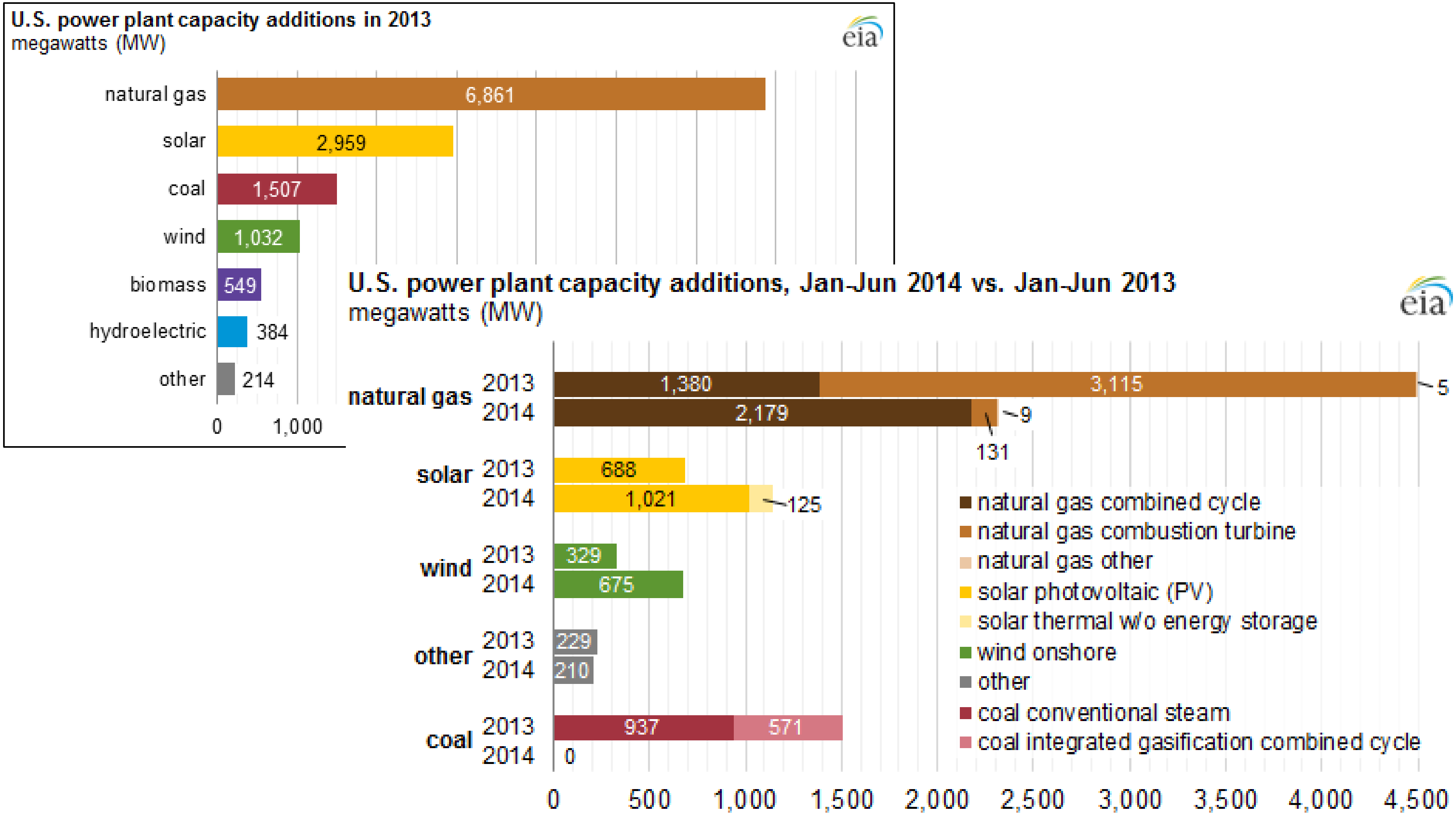
In 2013, 50% of new power generation capability came from natural gas, which was used in gas turbine power plants



Source: eia.gov

These additions were split between "peaking plants" and combined cycle plants, both of which use gas turbines



Source: eia.gov

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

Objective of the program will be achieved through experimental study and close ties with industry

— Experimental program that includes two separate, complementary facilities

— Development of quantification and prediction frameworks will aid in applying the results from this work to other facilities, including industrial hardware

— Cost-share and partnership from GE Global Research will provide industry feedback and internship opportunities for students on project

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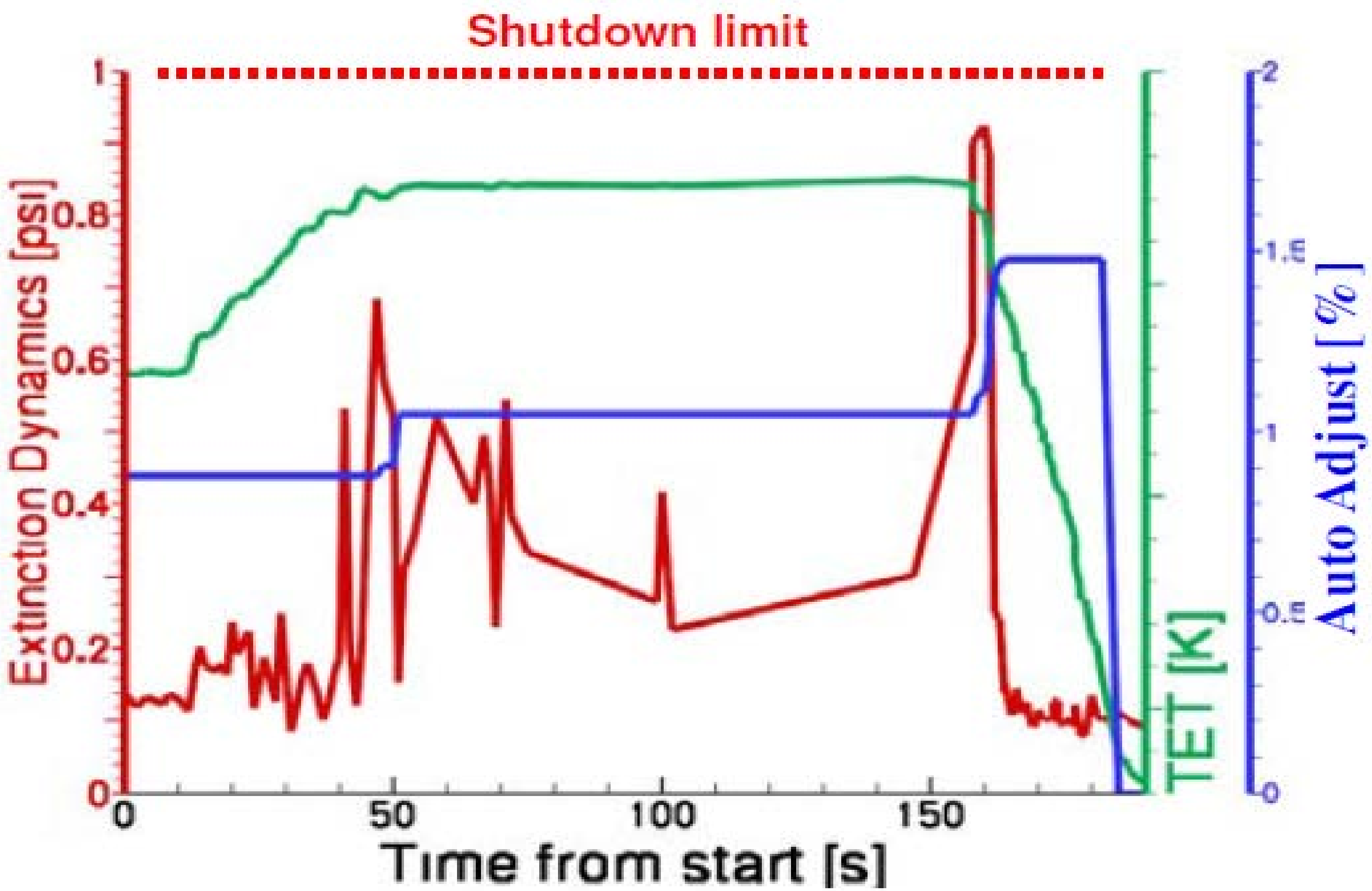
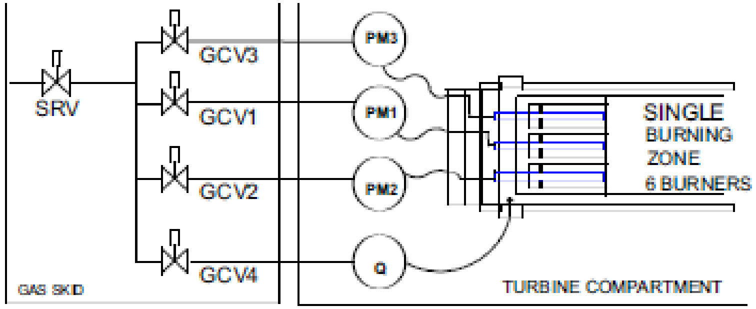
Very few studies have discussed the onset or control of instabilities during transient operation, but it's a common issue



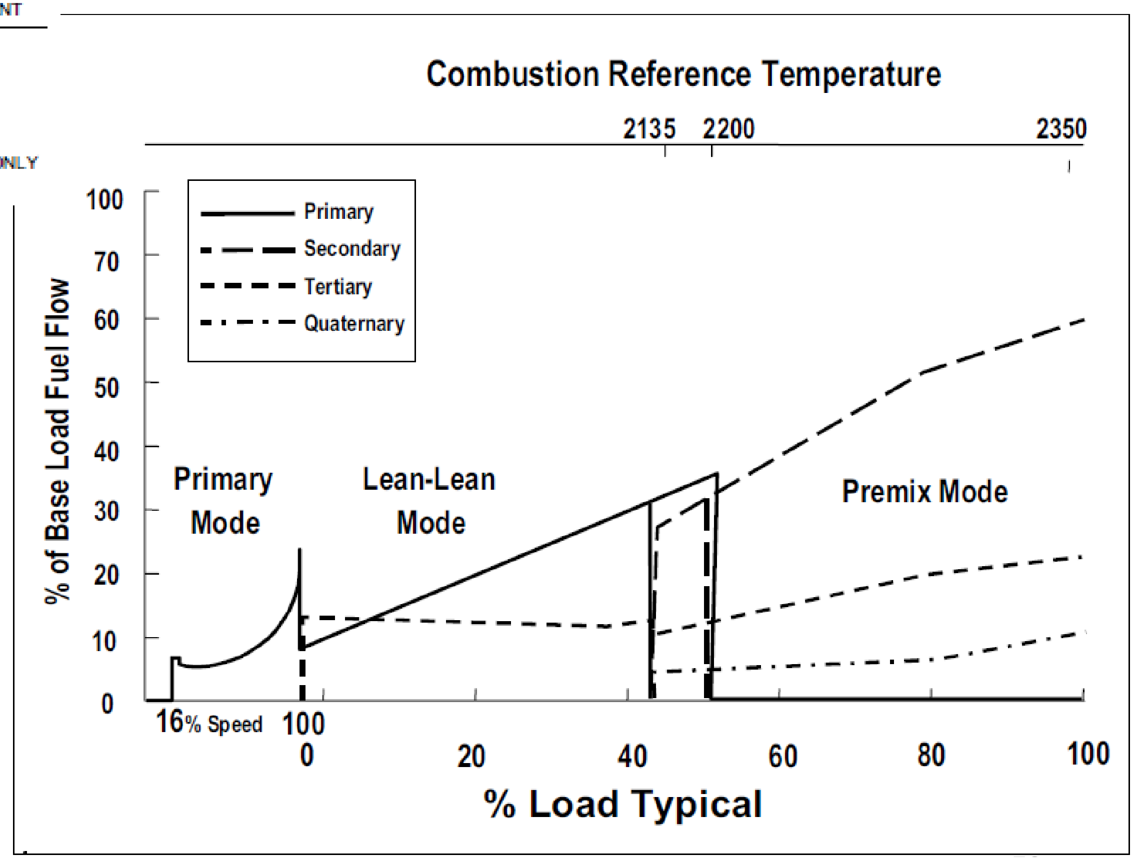
Transient operation of a Siemens SGT-200 (Bulat *et al.* 2007)

Engine load is typically varied by either varying fuel staging or the equivalence ratio of certain fuel nozzles



SRV SPEED/RATIO VALVE
GCV1 GAS CONTROL PM1
GCV2 GAS CONTROL PM2
GCV3 GAS CONTROL PM3
GCV4 GAS CONTROL Quaternary

PM3 - 3 NOZ. PRE-MIX ONLY
PM2 - 2 NOZ. PRE-MIX ONLY
PM1 - 1 NOZ. PRE-MIX ONLY
Q - QUAT MANIFOLD, CASING, PRE-MIX ONLY



Source: Davis and Black, "Dry Low NO_x Combution Systems for GE Heavy-Duty Gas Turbines"

Most of the focus on transient operation has been on hysteretic or triggering behavior in combustion systems

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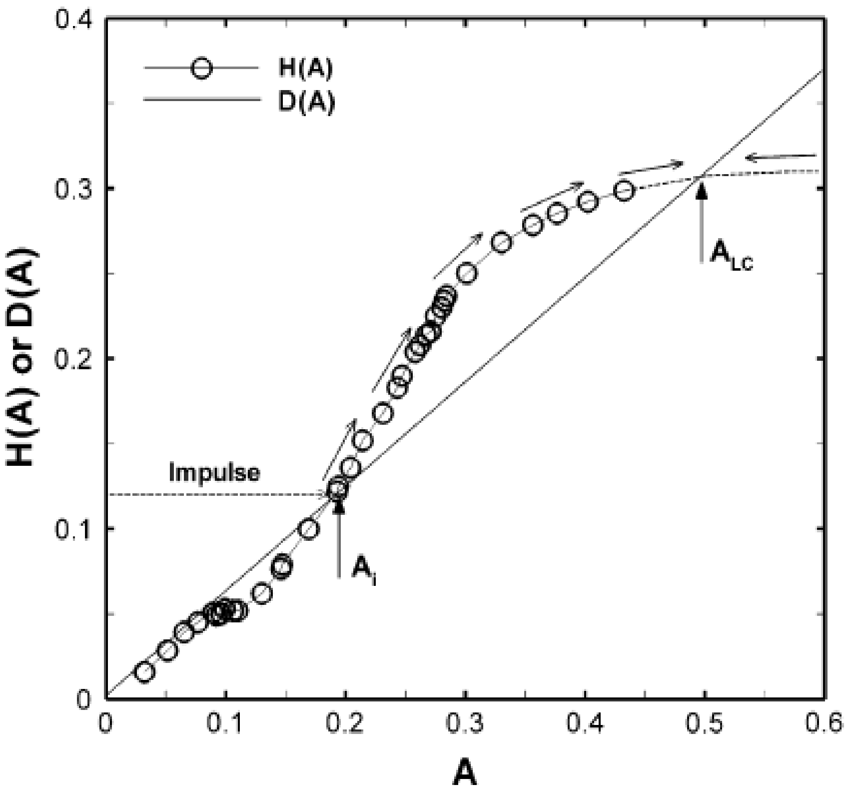
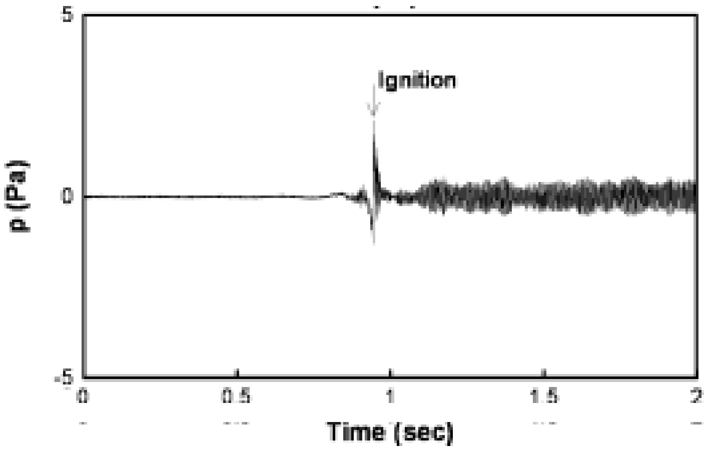
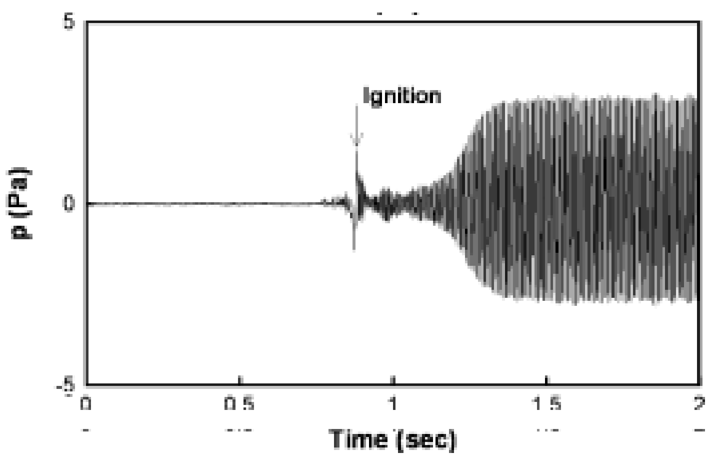
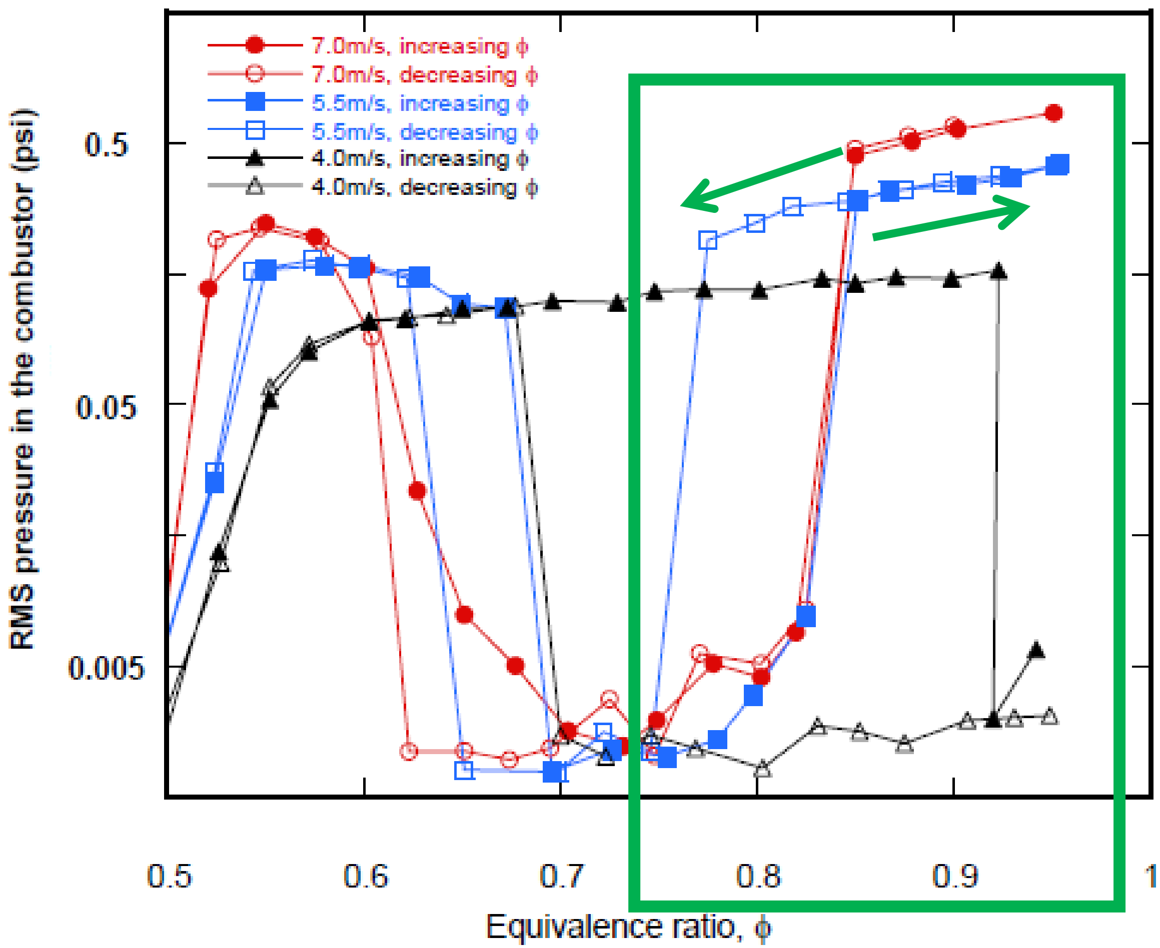






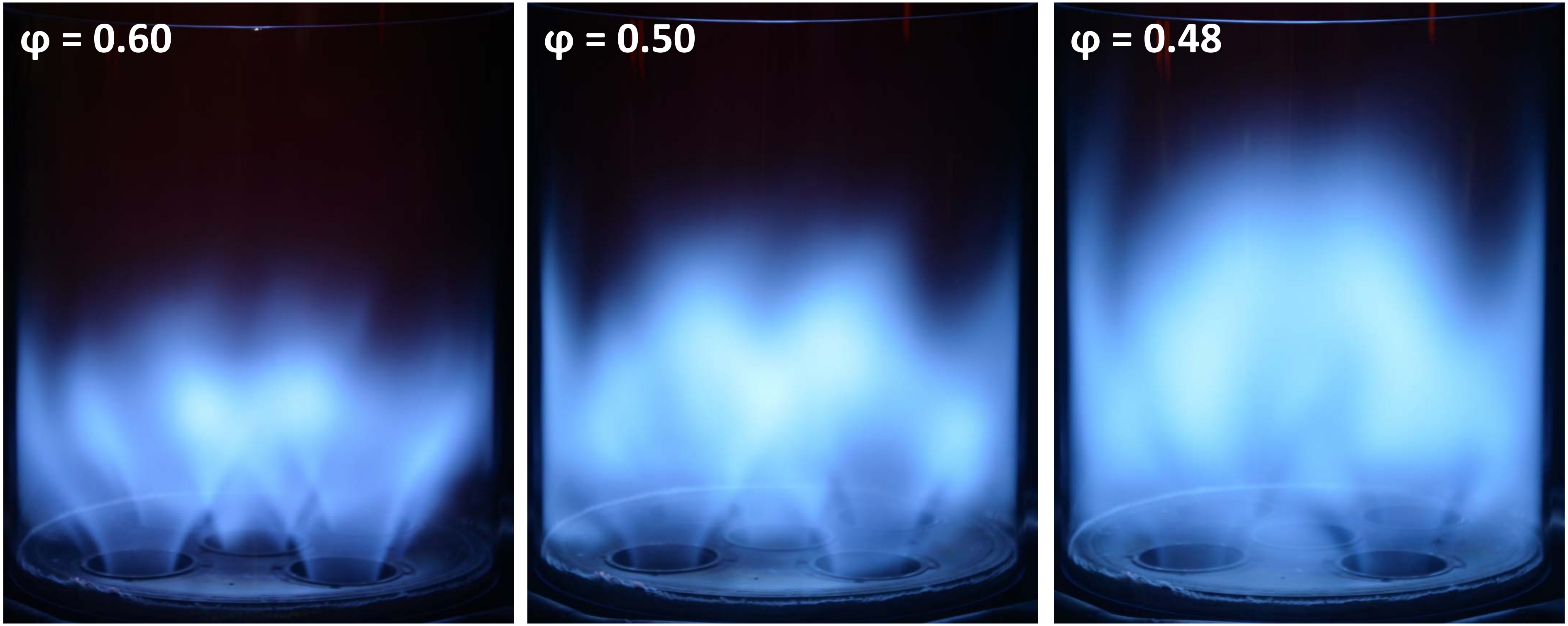
Kim and Hochgreb, 2012

Most of the focus on transient operation has been on ***hysteretic*** or triggering behavior in combustion systems



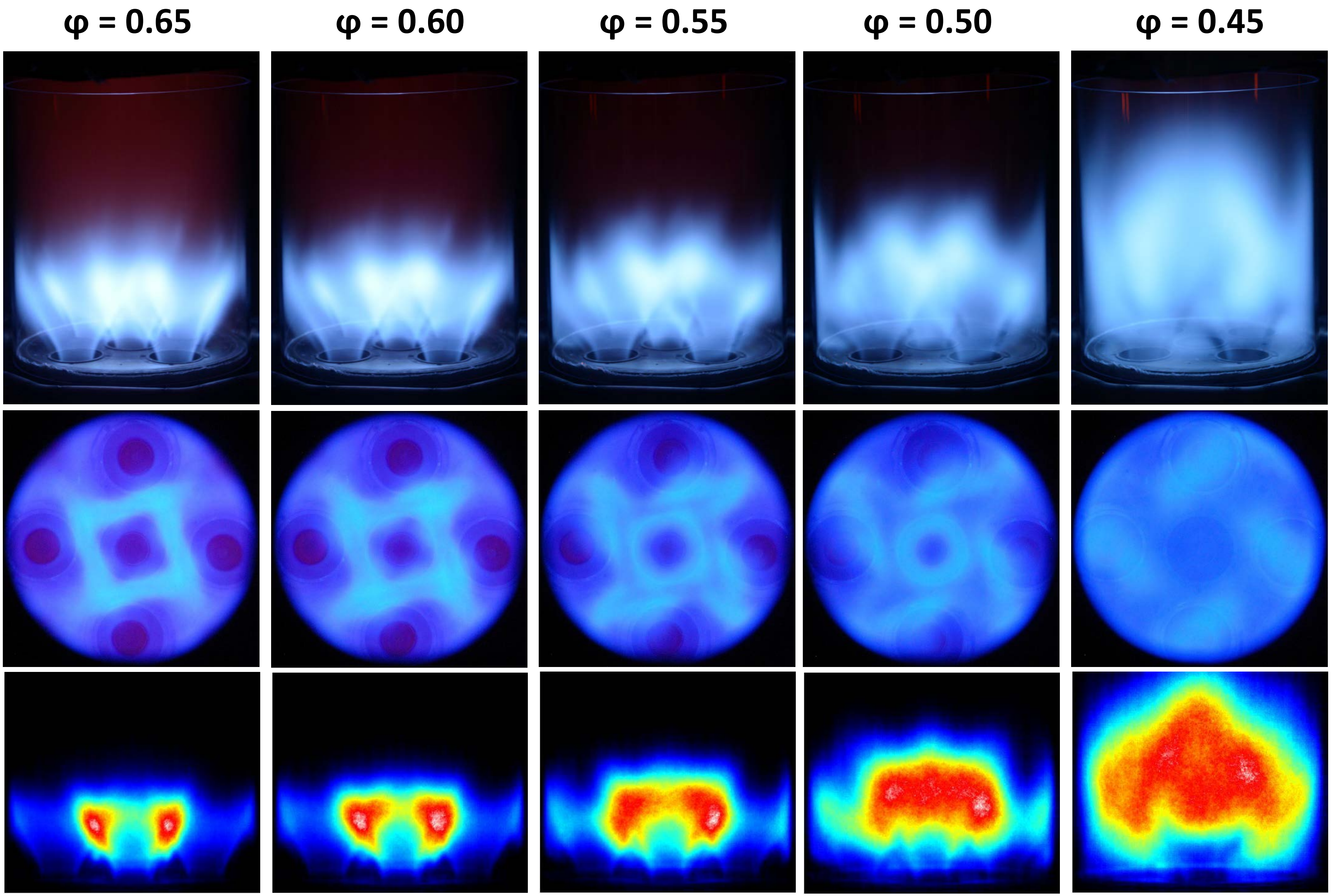
AIAA Paper No. 2004-0825, B-J Lee, J-G Lee and D. Santavicca

Instabilities may arise as a result of changes in flame shape and flame anchoring that occur with variation in equivalence ratio



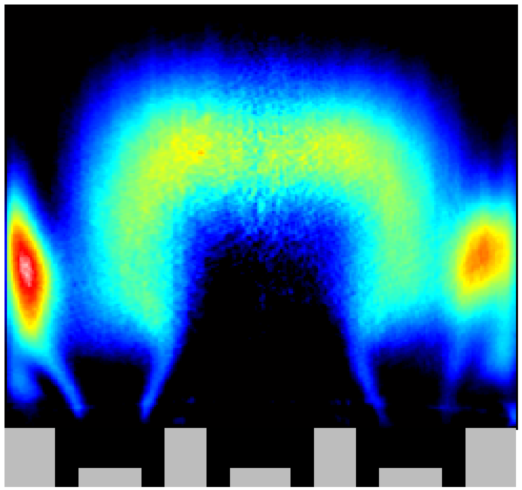
Photographs of multi-nozzle flame at U = 25 m/s, T_{in} = 200°C

U = 22.5 m/s, T_{in} = 200°C, fully premixed, unforced

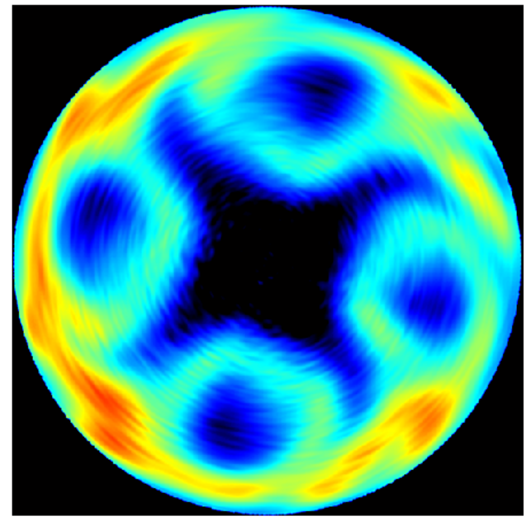


To further investigate the structure of the multi-nozzle flame, 3-D image sets were obtained at $\phi = 0.60$ and $\phi = 0.48$

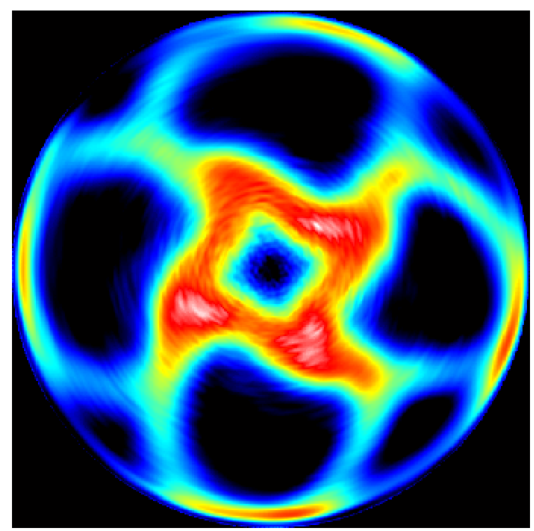
ϕ = 0.48



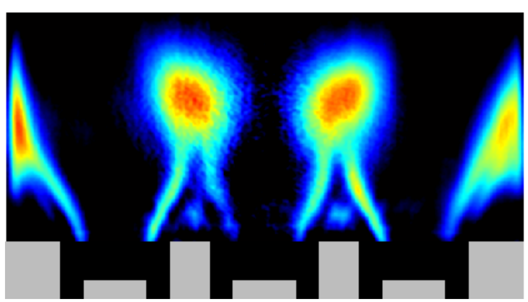
ϕ = 0.48



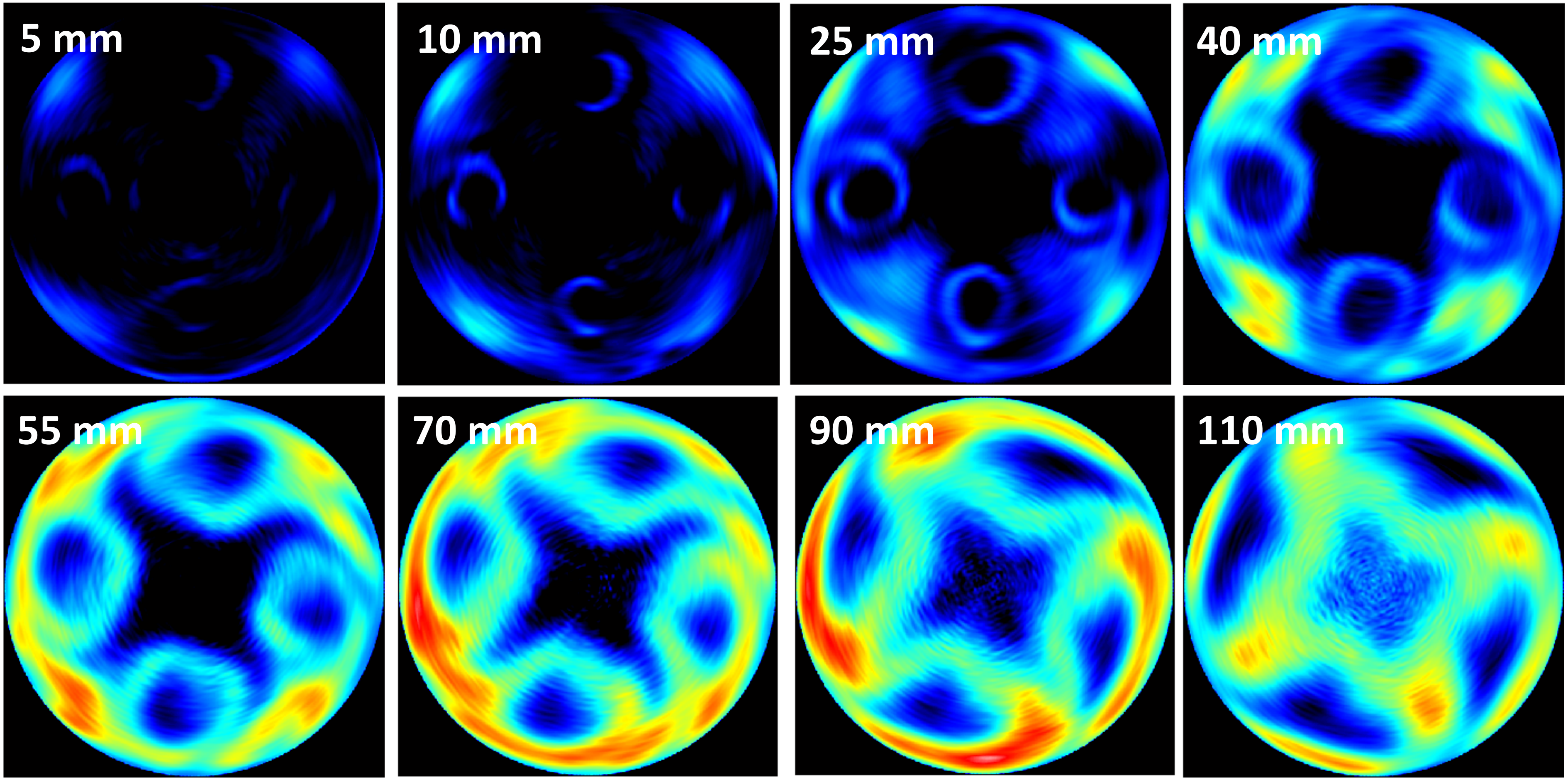
ϕ = 0.60



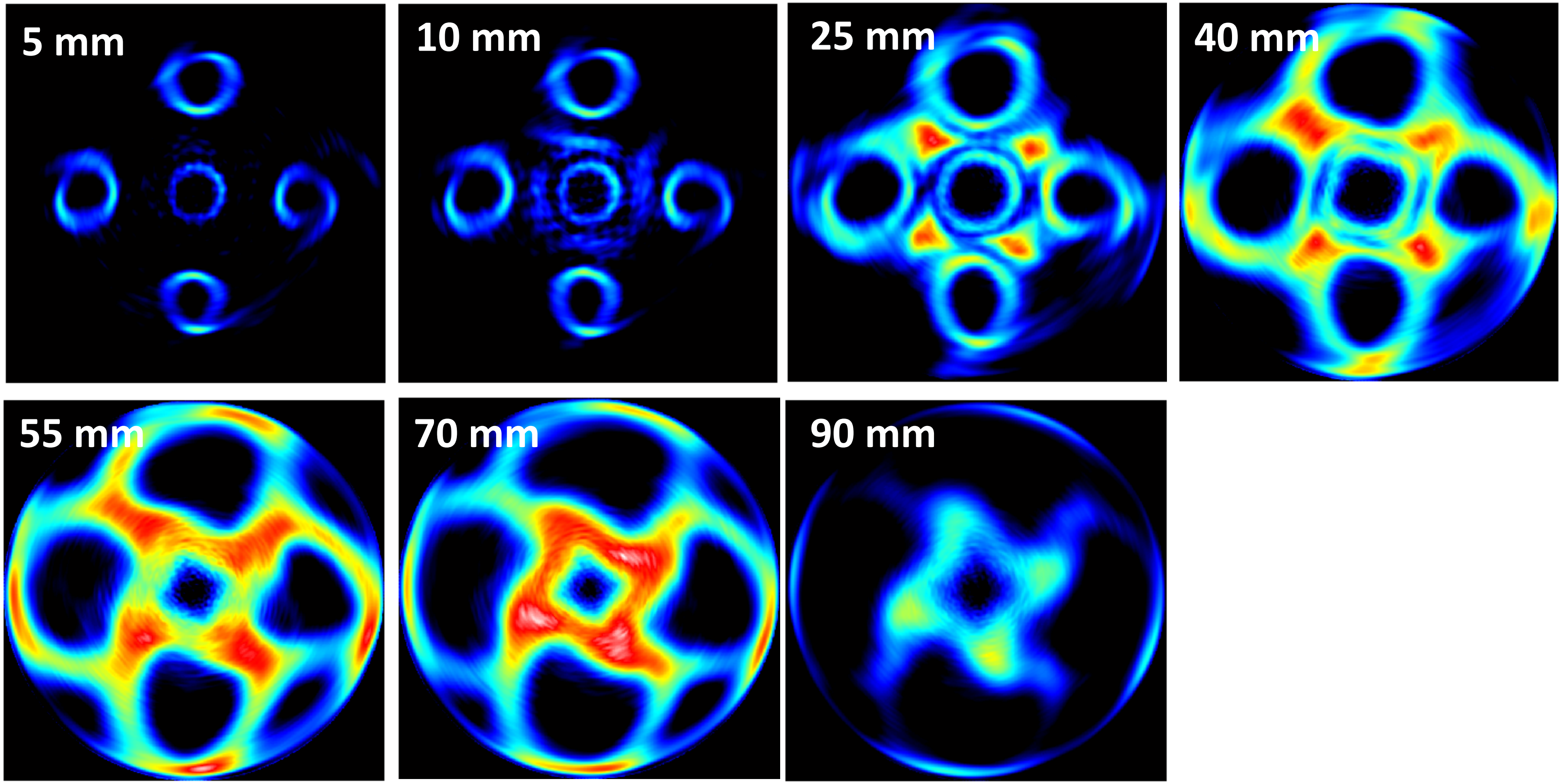
ϕ = 0.60



Slides through the flame shows center flame lift-off and significant flame-wall interaction at ϕ = 0.48

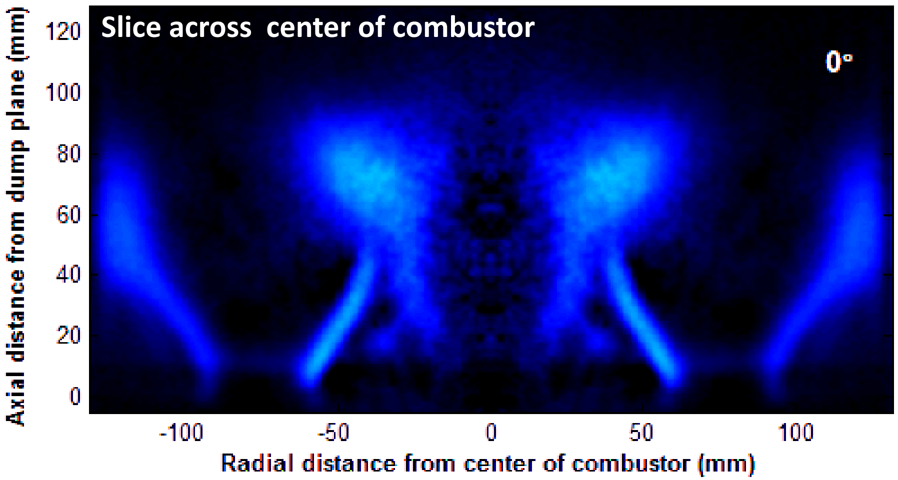


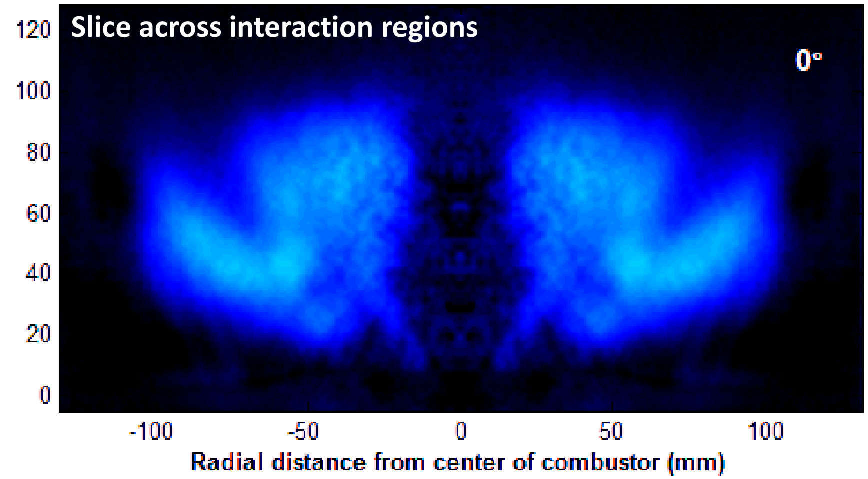
Flame-flame interaction dominates at ϕ = 0.6 and center flame, now attached, shows significant non-axisymmetry



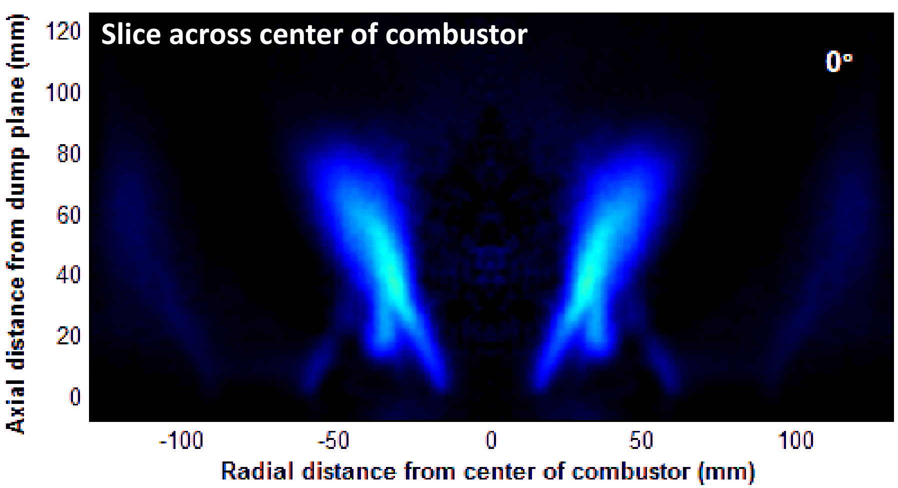
Data from our multi-nozzle combustor shows that fuel splitting changes flame structure and oscillation during instability

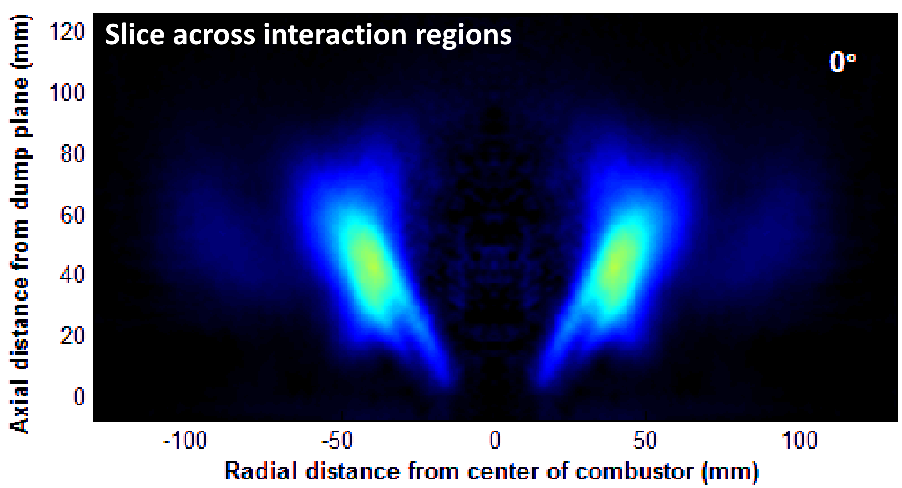
ϕ = 0.6 in all nozzles





ϕ = 0.5 in outer nozzles, ϕ = 0.8 in middle nozzle





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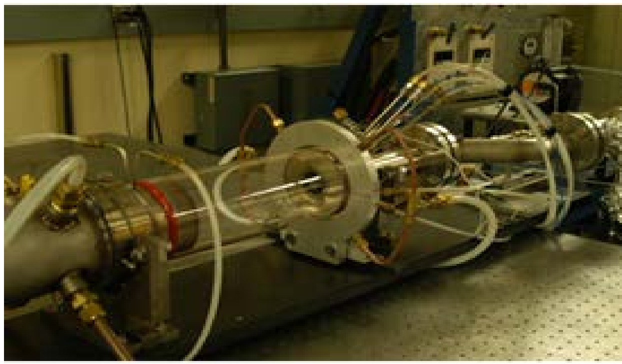
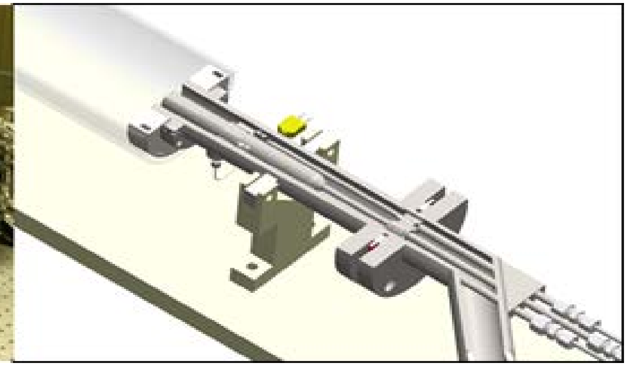
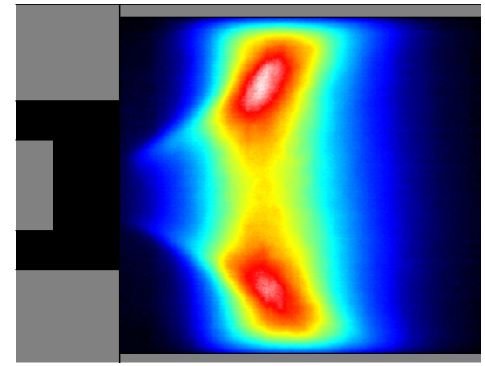
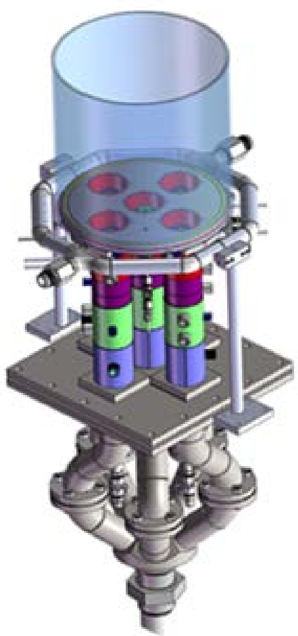
Experimental facilities include both a single-nozzle and multi-nozzle combustor, fuel splitting on multi-nozzle only





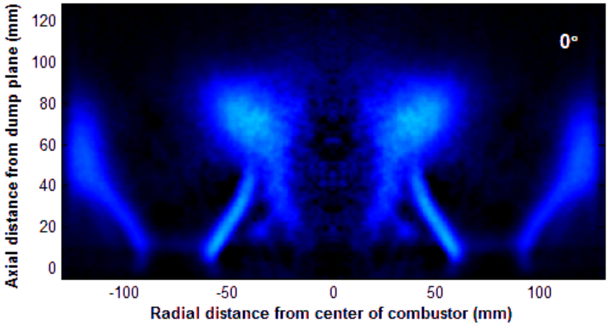




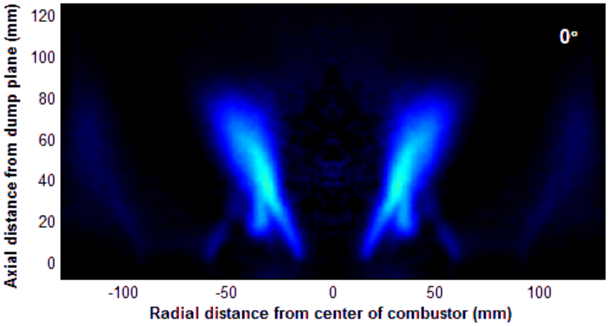
Three types of transients will be considered in the program that mimic the types of transients used in operational turbines

Fuel Splitting

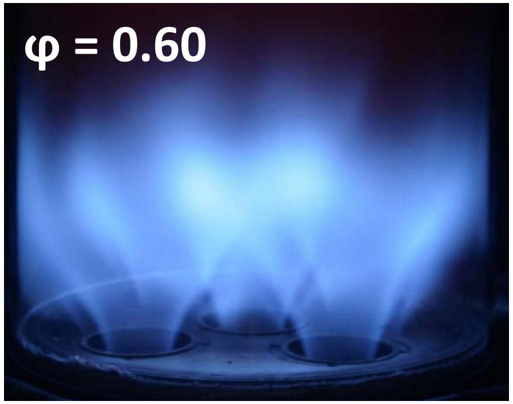
ϕ = 0.6 in all nozzles



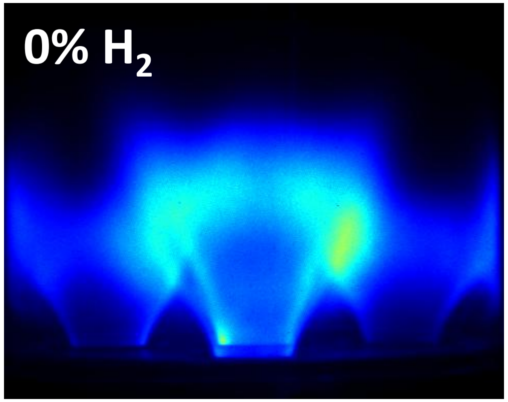
ϕ = 0.5 in outer nozzles,
ϕ = 0.8 in middle nozzle

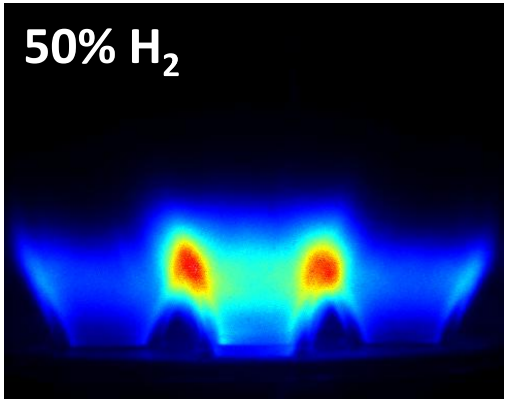


Equivalence Ratio



Fuel Composition

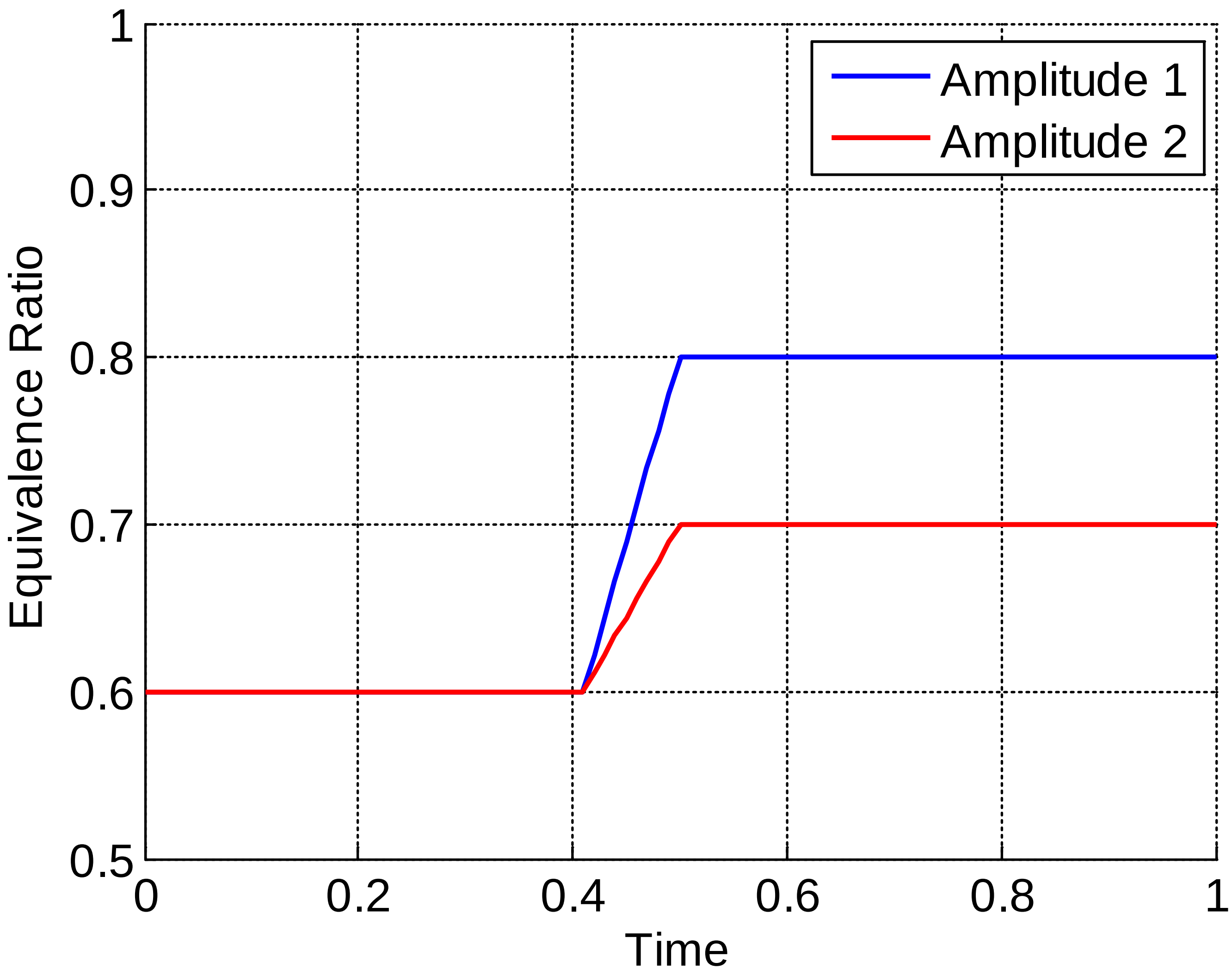




Images obtained from work done by Alex De Rosa (2011)

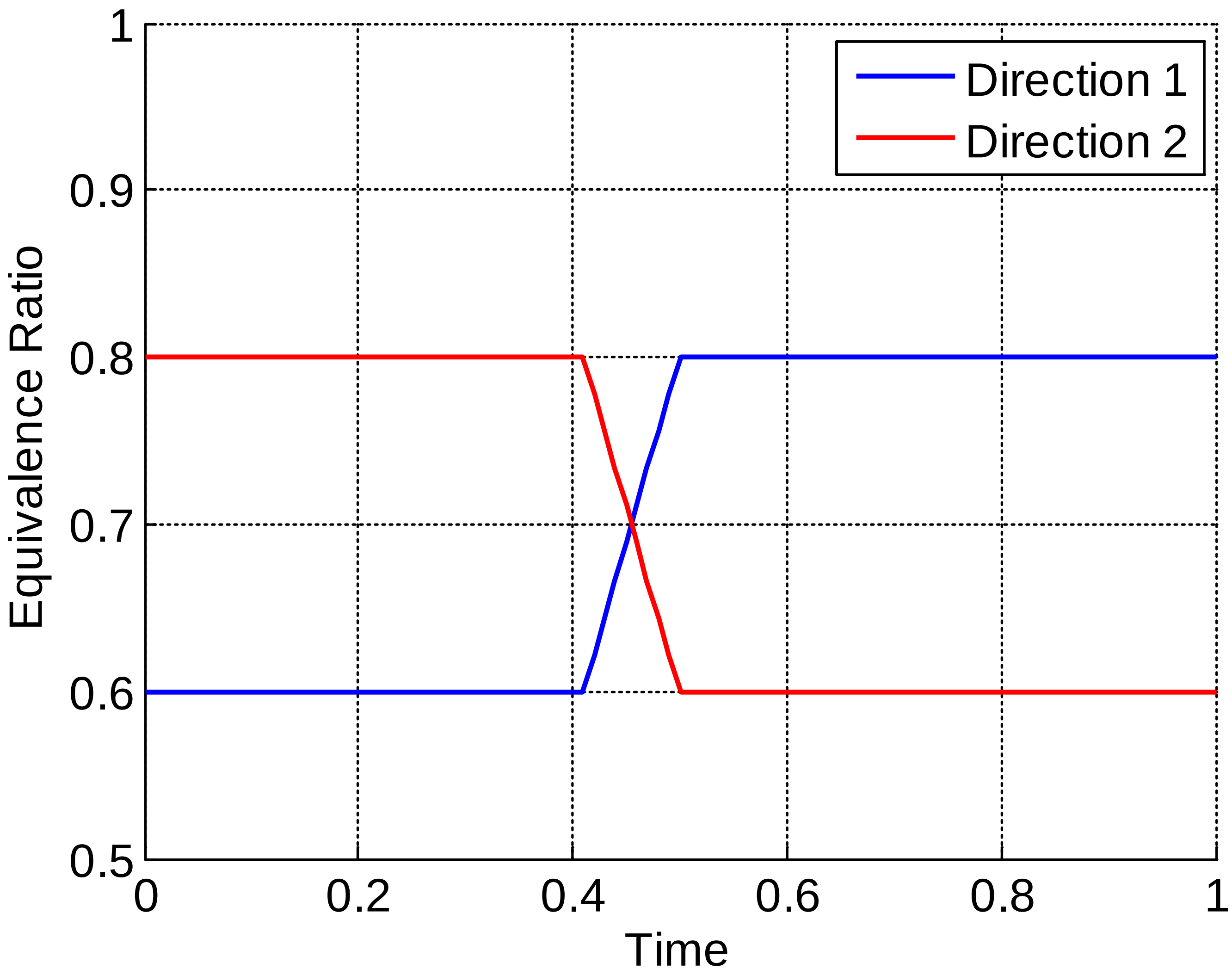
The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

Amplitude



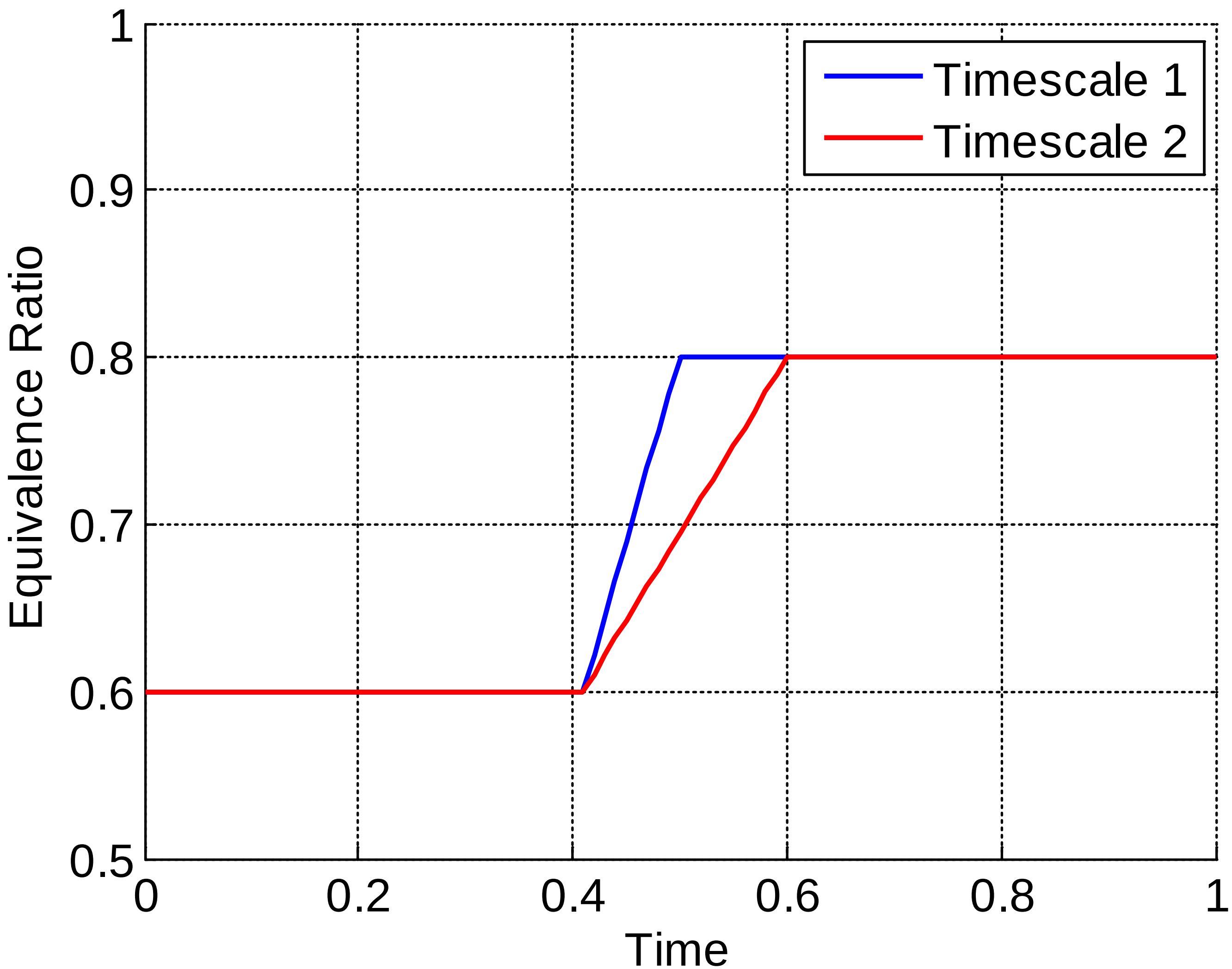
The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

Direction

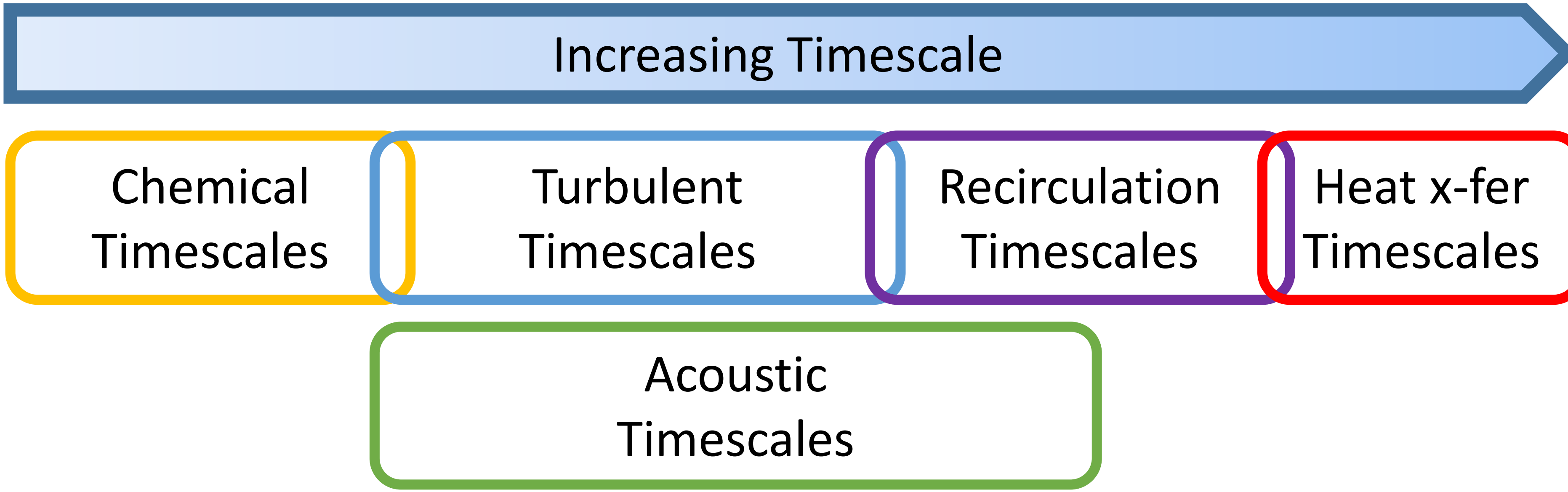


The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

Timescale



Competition of timescales defines the path of the transient and could impact the final state of the transient event



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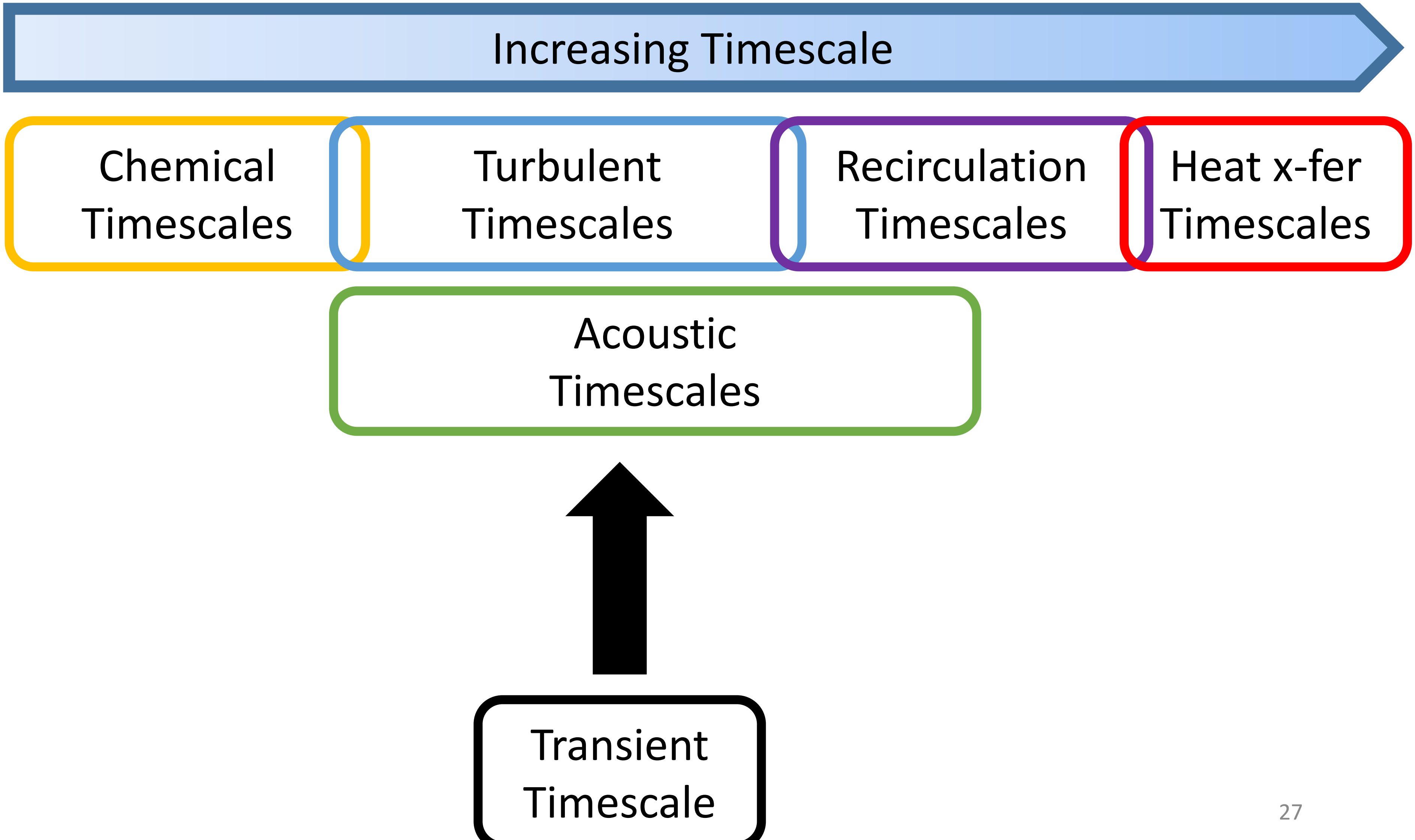

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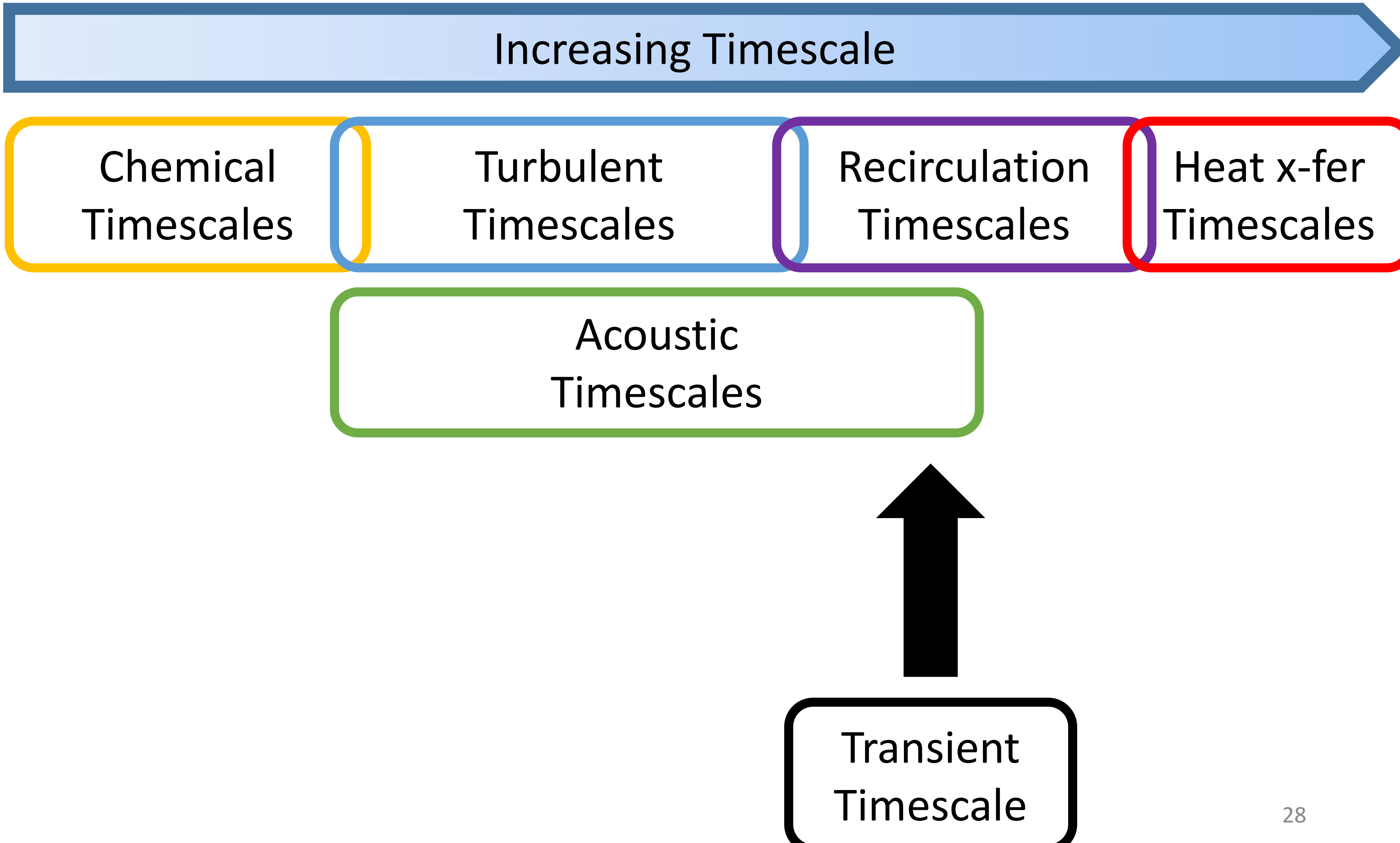

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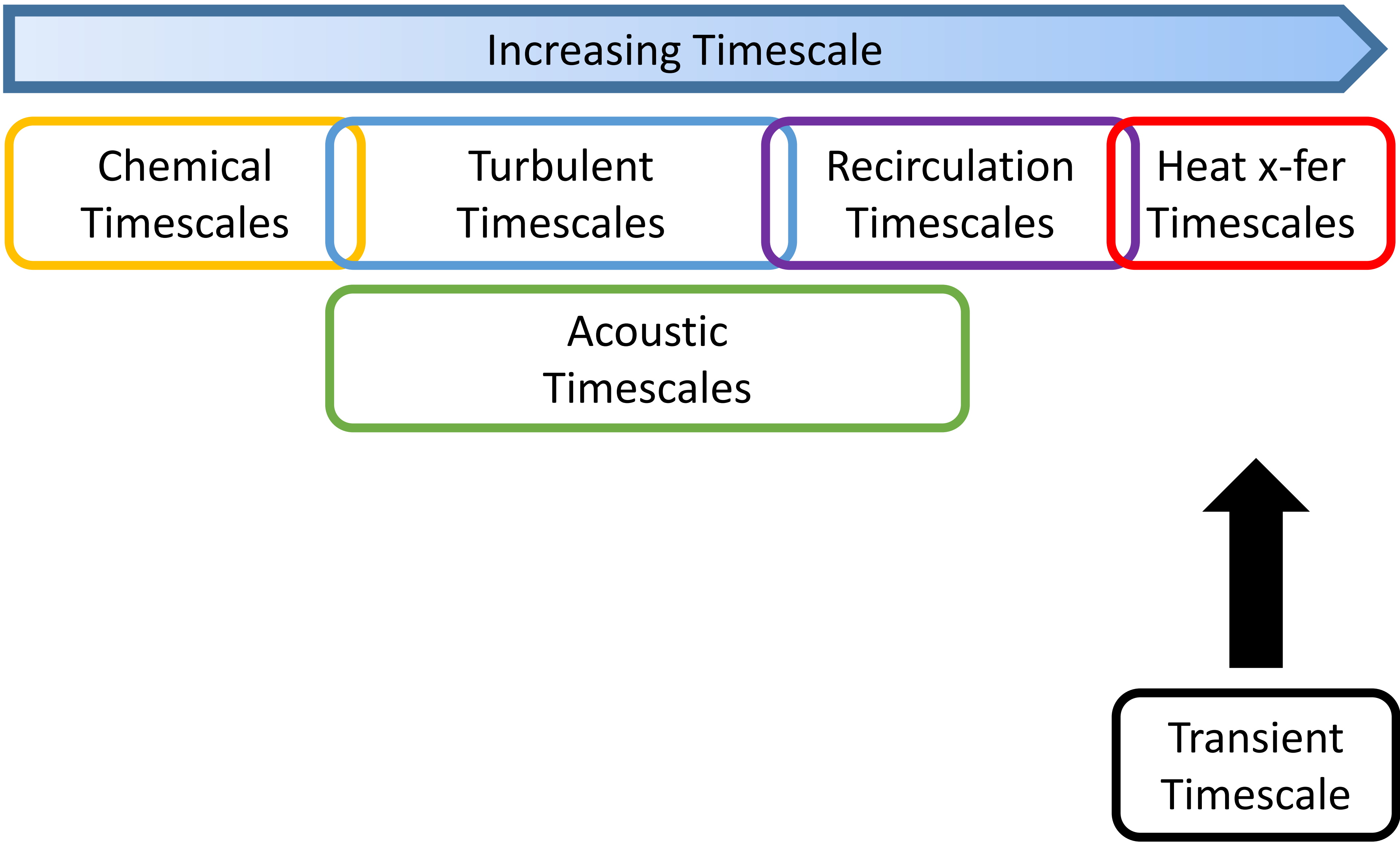
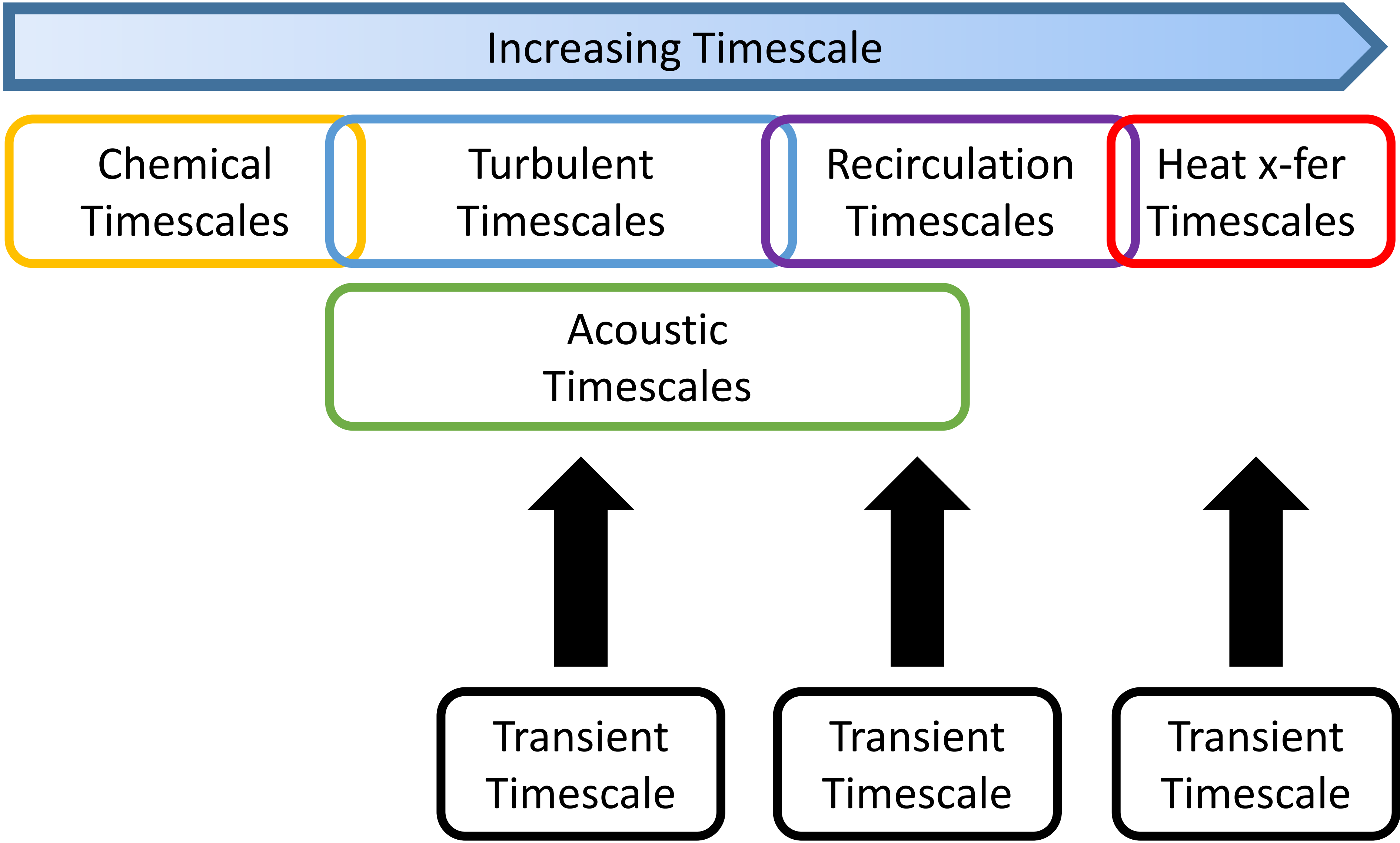
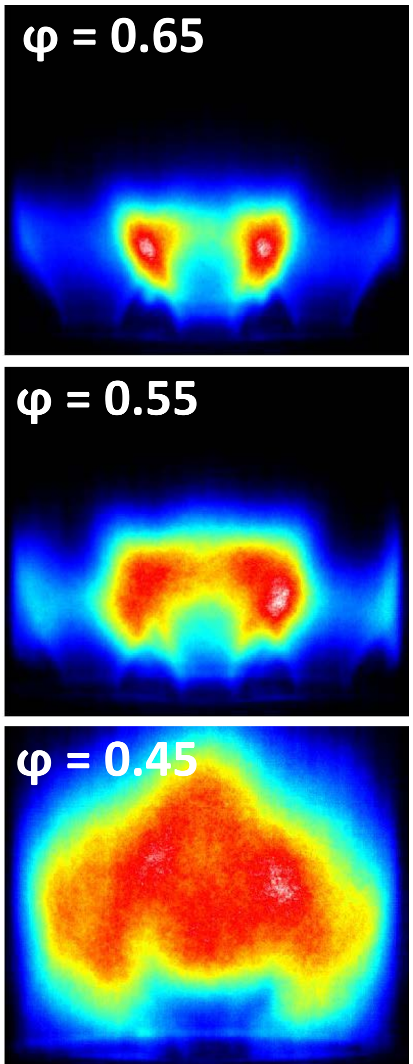


Varying the transient timescales allows for different processes to equilibrate during the transient, changing the path

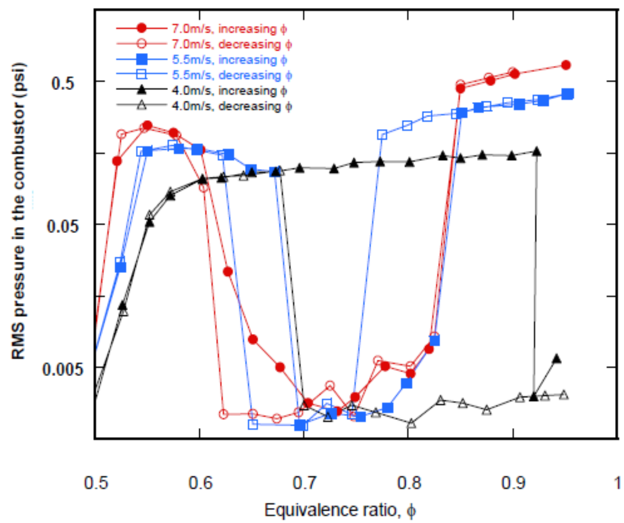


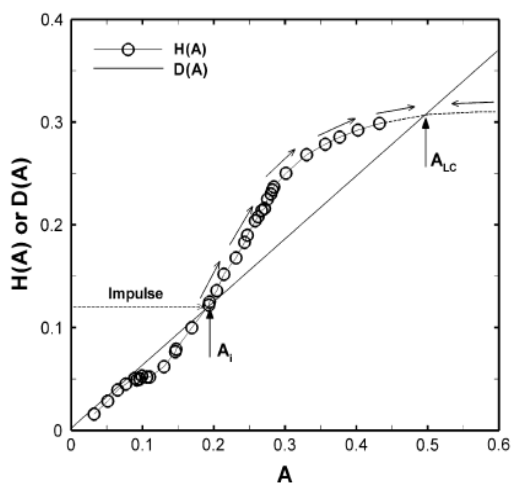
Project structure includes three stages of experimentation: mapping, transients, and quantification

Mapping



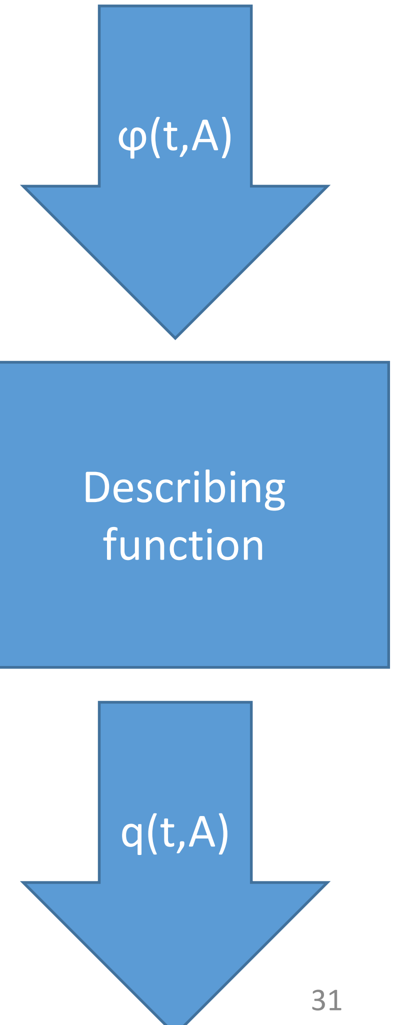
Transients





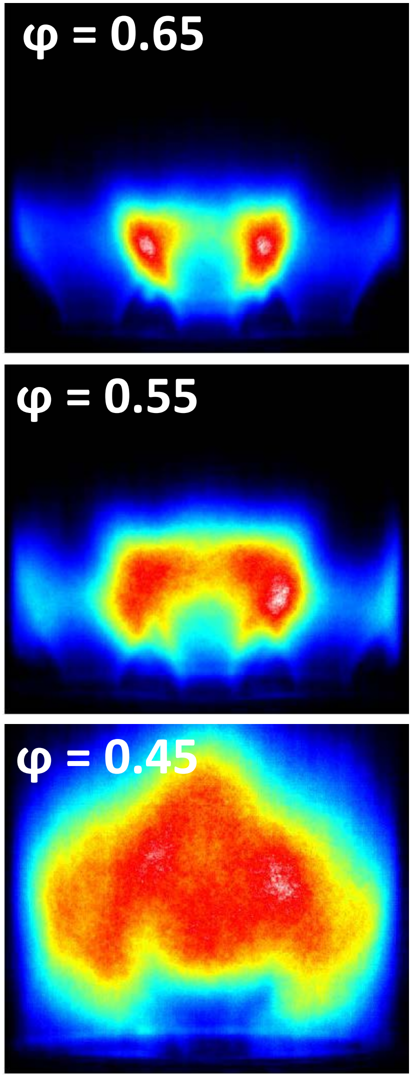
Kim and Hochgreb, 2012

Quantification



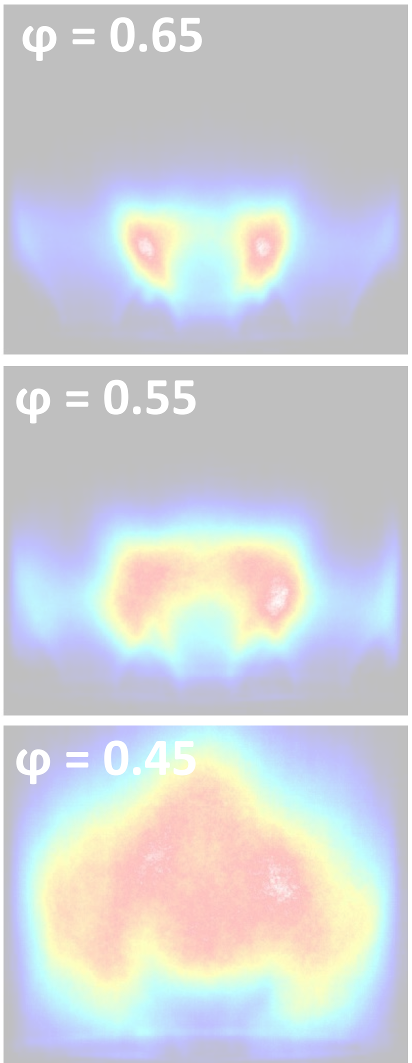
Mapping will include characterization of stability and important combustor timescales

Mapping

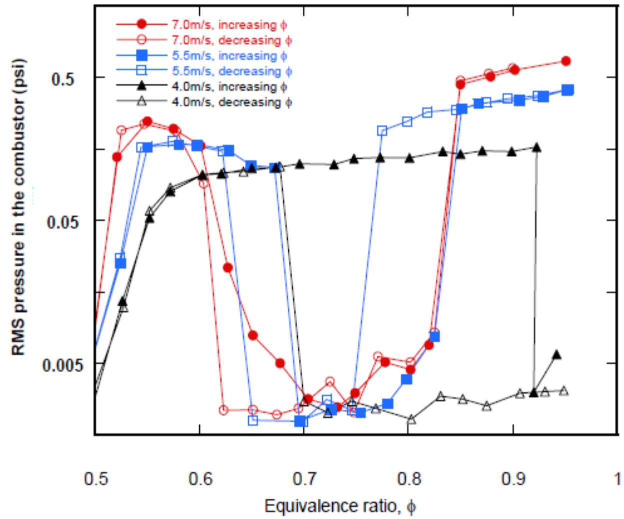


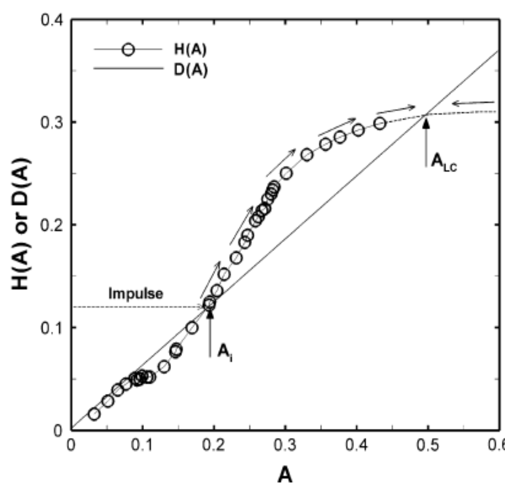
Transient experiments will be designed based on the mapping, varying the transient *amplitude, direction,* and *timescale*

Mapping



Transients

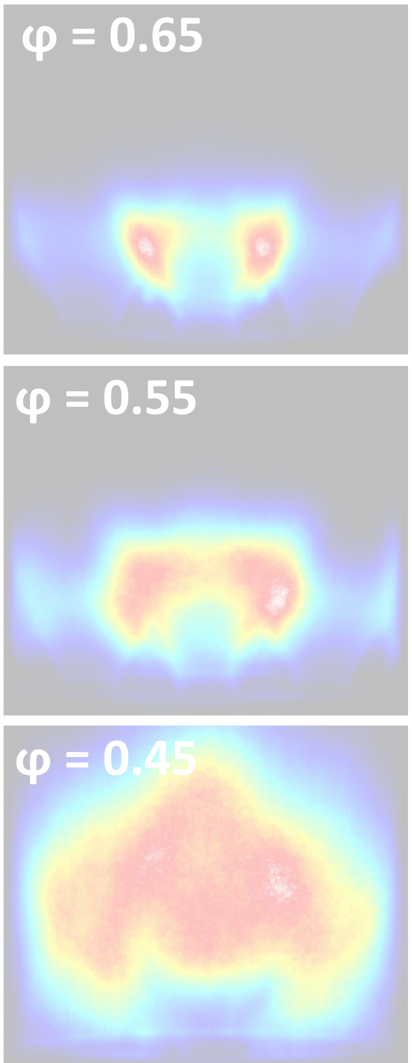




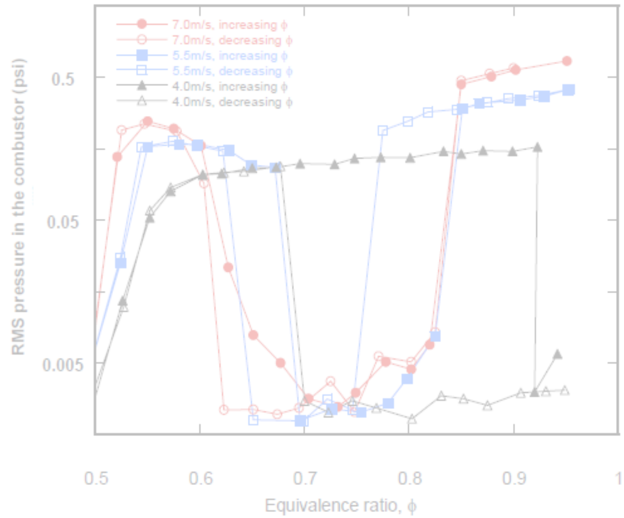
Kim and Hochgreb, 2012

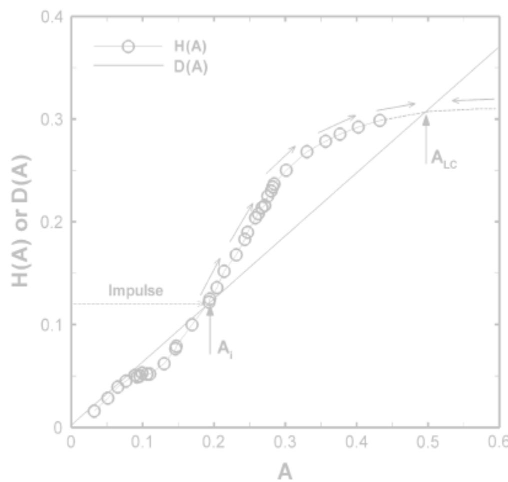
Both the transient input and the combustor response will be quantified and a describing framework will be developed

Mapping



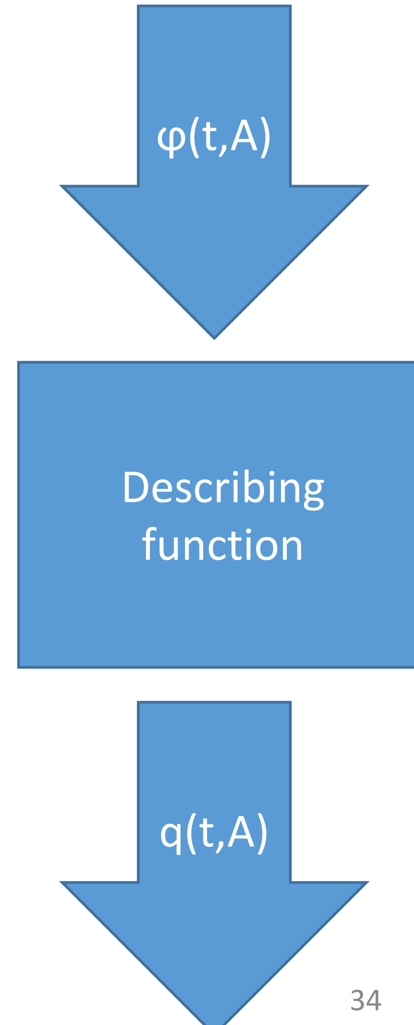
Transients



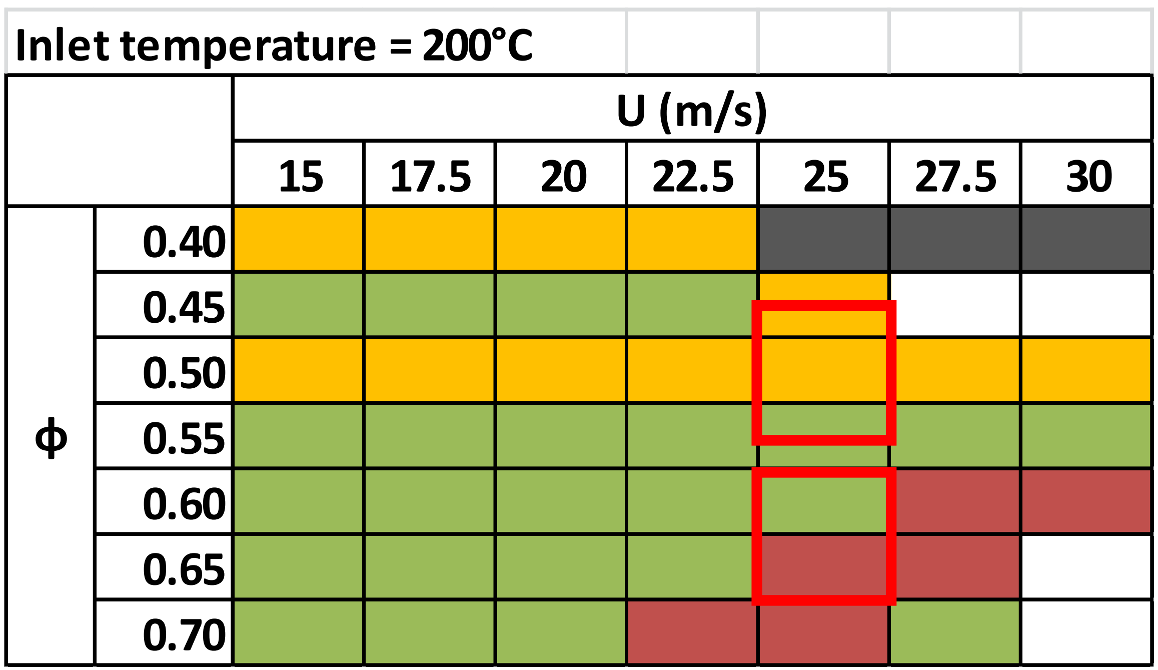


Kim and Hochgreb, 2012

Quantification



Stability limits of certain operating points are already known, current work focuses on mapping instability with fuel splits



Stable | Unstable | Poor Stabilization | Cannot Achieve Condition

Measurements include:

- Flow rates
- Dynamic pressure
- Surface temperatures
- Time-averaged flame imaging

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Project Management Plan

- 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
- Task 6 – Equivalence ratio transients
- Task 7 – Fuel composition transients
- Task 8 – Data analysis and determination of prediction/quantification framework

Questions?

Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

Project DE-FE0025495, Oct. 2015 – Sept. 2018
Program Monitor: Steve Richardson

PI: Jacqueline O'Connor, Ph.D.
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Graduate students: Janith Samarasinghe and Wyatt Culler

Mechanical and Nuclear Engineering
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Backup slides

Multi-nozzle steady-state fuel-staging tests

What is the purpose of these tests? What do we expect to learn?

- To determine the steady state flame structure at various fuel splits.
- To characterize the different flame structures that exist when fuel splitting is varied, understand the fluid mechanic features that lead to those structures and the nature of the transitions between flame structures.
- To determine the influence of fuel-splitting on self-excited instabilities.

Questions to answer from the steady-state fuel staging tests

- What causes changes in flame structure with fuel splits? Does fuel splitting change the flow-field, flame phenomena (e.g. flame speed or heat of reaction), or both?

- How can we characterize thermal boundary conditions? What temperatures do we need to monitor?

- Can increasing fuel to the middle nozzle during an unstable test condition make it stable?

- Are there cases where increasing fuel to the middle nozzle during a stable test condition makes it unstable?

- Can fuel staging improve flame stability such that the combustor can be operated closer to the LBO limit than without staging?

Data from unforced and forced flames are available in a range of operating conditions

Stable | Unstable | Poor Stabilization | Cannot Achieve Condition

Inlet temperature = 100°C

		U (m/s)						
		15	17.5	20	22.5	25	27.5	30
Φ	0.40							
	0.45							
	0.50							
	0.55							
	0.60							
	0.65							
	0.70							

Inlet temperature = 150°C

		U (m/s)						
		15	17.5	20	22.5	25	27.5	30
Φ	0.40							
	0.45							
	0.50							
	0.55							
	0.60							
	0.65							
	0.70							

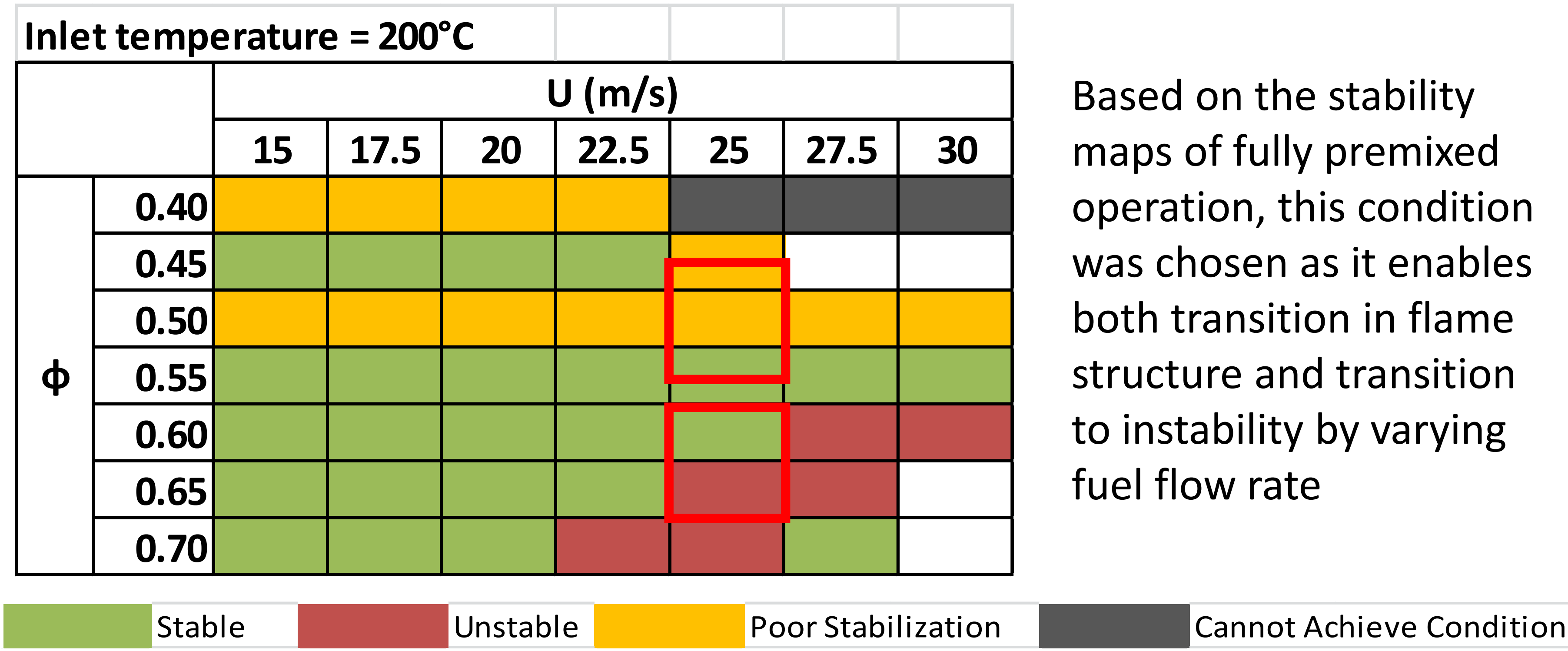
Inlet temperature = 200°C

		U (m/s)						
		15	17.5	20	22.5	25	27.5	30
Φ	0.40							
	0.45							
	0.50							
	0.55							
	0.60							
	0.65							
	0.70							

Inlet temperature = 250°C

		U (m/s)						
		15	17.5	20	22.5	25	27.5	30
Φ	0.40							
	0.45							
	0.50							
	0.55							
	0.60							
	0.65							
	0.70							

An inlet temperature of 200°C and an inlet velocity of 25 m/s was chosen for the steady-state tests



Based on the stability maps of fully premixed operation, this condition was chosen as it enables both transition in flame structure and transition to instability by varying fuel flow rate

Stability map for GE-15 single-nozzle experiment (TPM)

	T_{in} = 100°C			T_{in} = 200°C			T_{in} = 275°C	
ϕ	**25 m/s**	**30 m/s**	**35 m/s**	**25 m/s**	**30 m/s**	**35 m/s**	**30 m/s**	**35 m/s**
0.50				LBO	LBO	LBO	LBO	LBO
0.525		LBO	LBO	57 Hz	72 Hz	81 Hz	97 Hz	106 Hz
0.55	LBO	68 Hz	84 Hz	78 Hz	86 Hz	111 Hz	105 Hz	116 Hz
0.60	71 Hz	96 Hz	117 Hz	94 Hz	110 Hz	124 Hz	111 Hz	125 Hz
0.65	89 Hz	114 Hz	124 Hz	101 Hz	115 Hz	125 Hz	117 Hz	127 Hz
0.70	104 Hz	117 Hz	129 Hz	112 Hz	118 Hz	128 Hz	129 Hz	145 Hz

	stable		unstable		estimate lean blow-off

Stability map for GE-15 single-nozzle experiment (FPM)

	Tin=100 C			Tin=150 C			Tin=200 C		
ϕ	20 m/s	25 m/s	30 m/s	20 m/s	25 m/s	30 m/s	20 m/s	25 m/s	30 m/s
0.50		LBO	LBO	LBO	LBO	LBO	LBO		LBO
0.55	LBO								
0.60									
0.65									
0.70									
0.75									

	stable		unstable		estimate lean blow-off

Measurements that will be made in steady state tests

- Flame structure will be characterized using digital photographs and line-of-sight CH* chemiluminescence images.
- K-type thermocouples will be used to make necessary temperature measurements to determine thermal BCs.
- Static pressure will be measured upstream and downstream of the swirler to obtain the mean velocity in each nozzle.
- PCB pressure transducer mounted on dump plane will measure pressure fluctuation in the combustor.
- Additional measurements? PLIF?

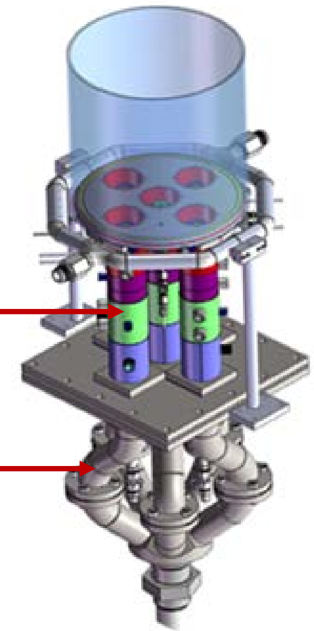
PLIF: May provide useful information about the nature of flame-flame interaction along the center plane

Fuel injection strategy for staging

Two options for adding additional fuel to middle nozzle:

(1) Inject fuel at swirler → technically premixed

(2) Inject fuel at air manifold with a choke → fully premixed



Poravee showed using acetone PLIF, that the fuel and air are well mixed at the nozzle exit of the GE-15 nozzle

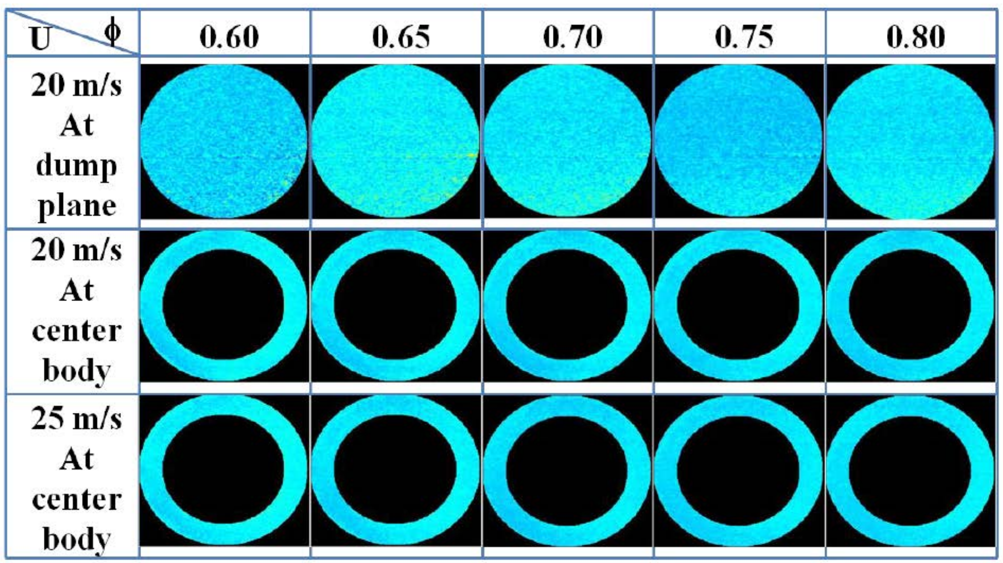
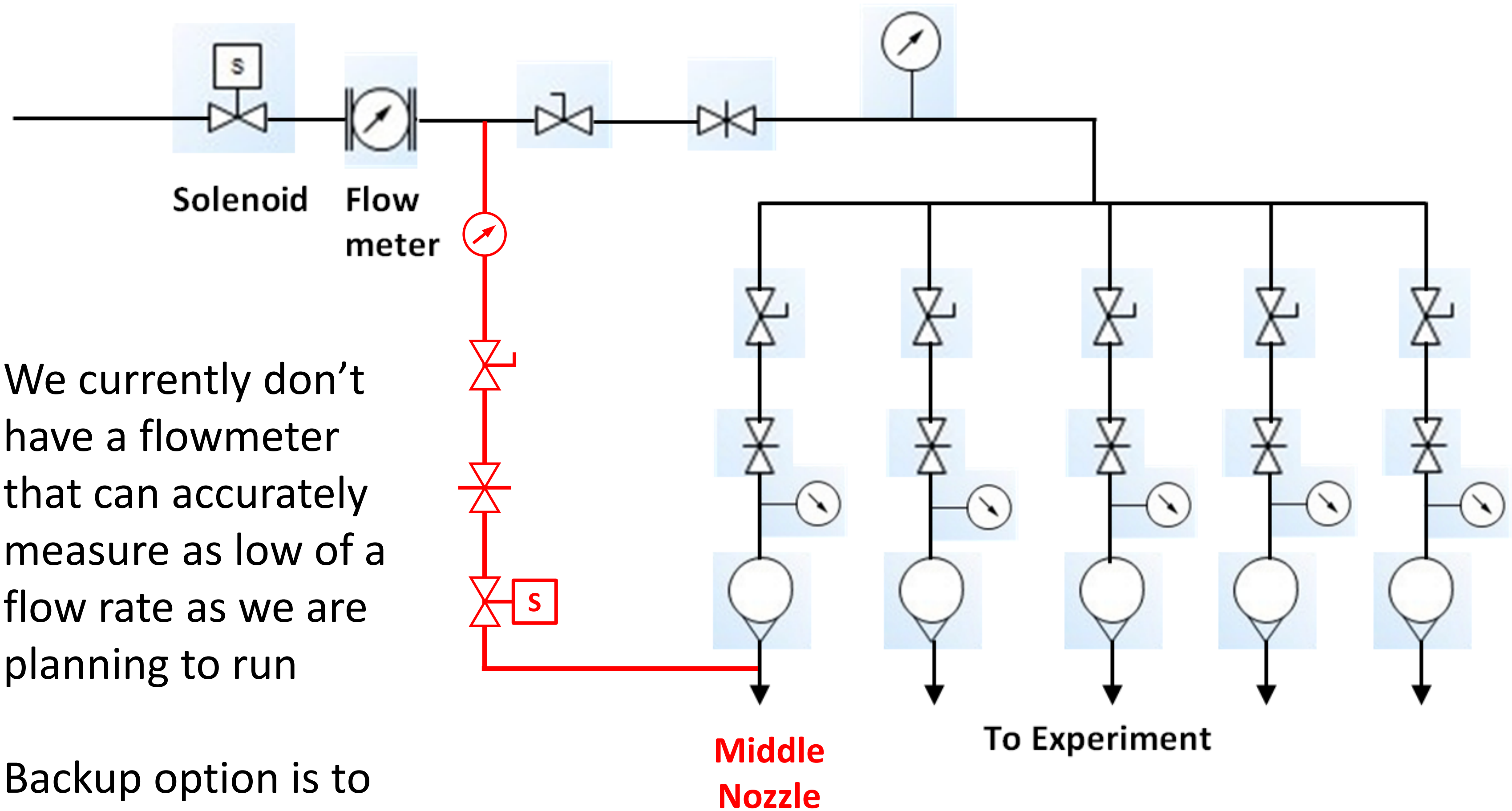


Figure B-4. Spatial distribution of fuel-air mixture results.

The main difference between these then becomes the type of governing mechanisms during the unstable flame case

Fuel injection strategy for staging

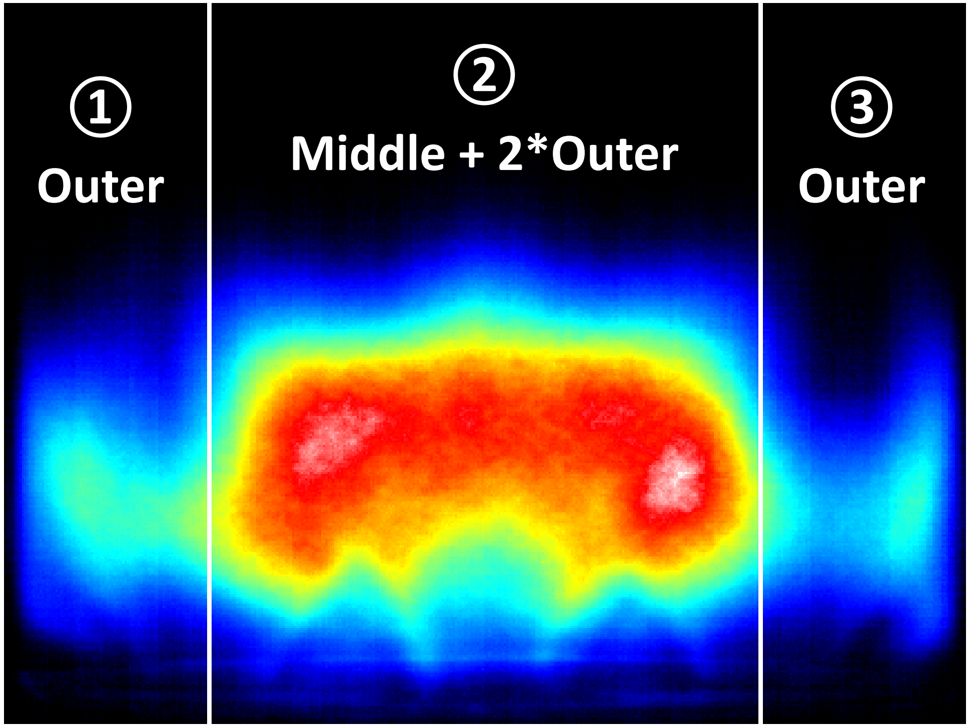


We currently don't have a flowmeter that can accurately measure as low of a flow rate as we are planning to run

Backup option is to use a rotameter

Flame-flame and flame-wall regions are separated from the line-of-sight images to look at relative contribution to Q'

The regions are separated based on the locations of the centers of the outer nozzles



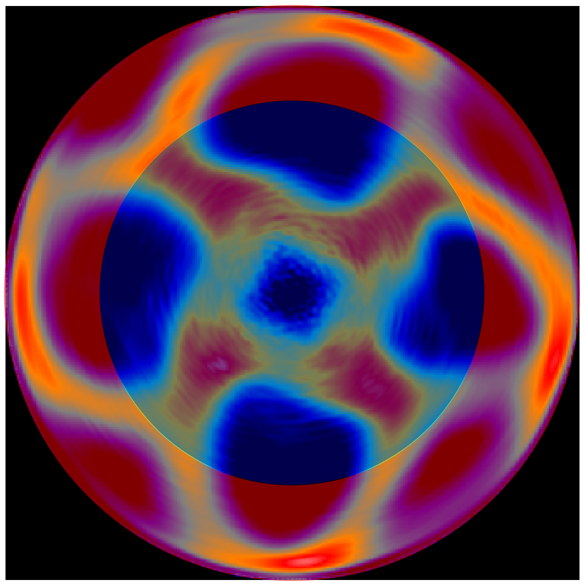
Chemiluminescence emission from flame-flame interaction region

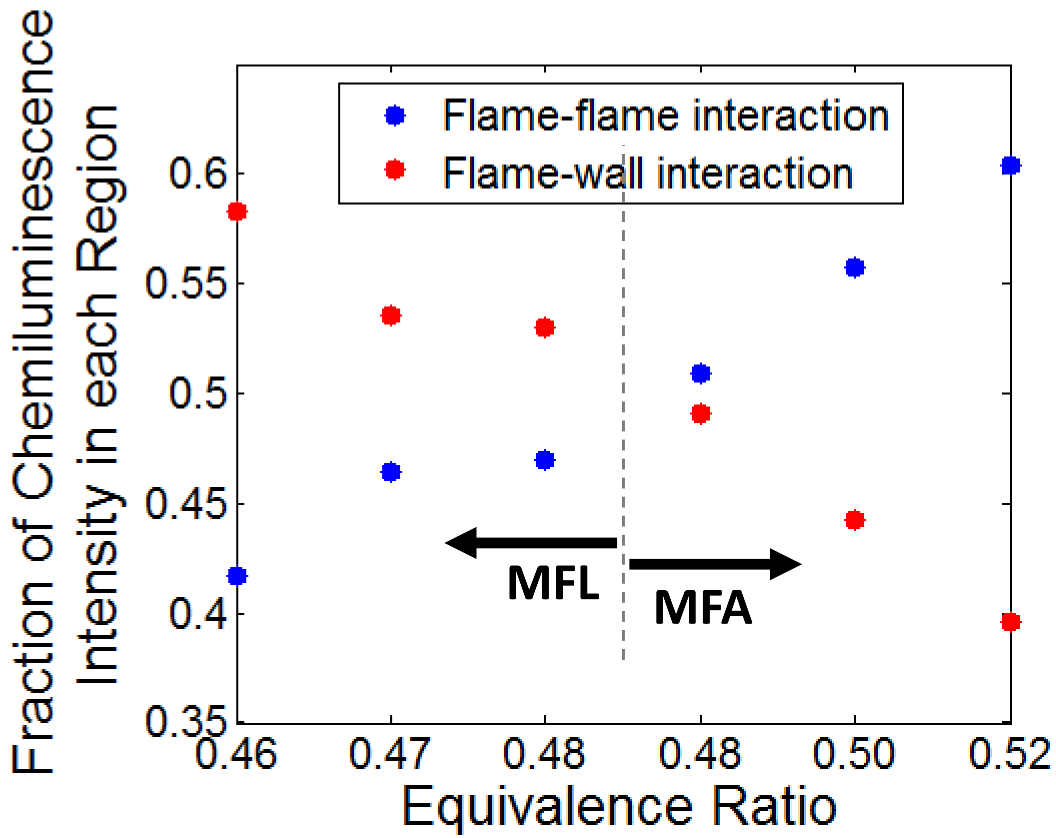
$$CH^*_{F\text{-}F} = ② - [①+③]$$

Chemiluminescence emission from flame-wall interaction region

$$CH^*_{F\text{-}W} = CH^*_{Total} - CH^*_{F\text{-}F}$$

The majority of heat release rate occurs in the flame-flame interaction region when the middle flame is attached





Very limited data is available on the behavior of flames at different fuel splits except in the cases of flame piloting

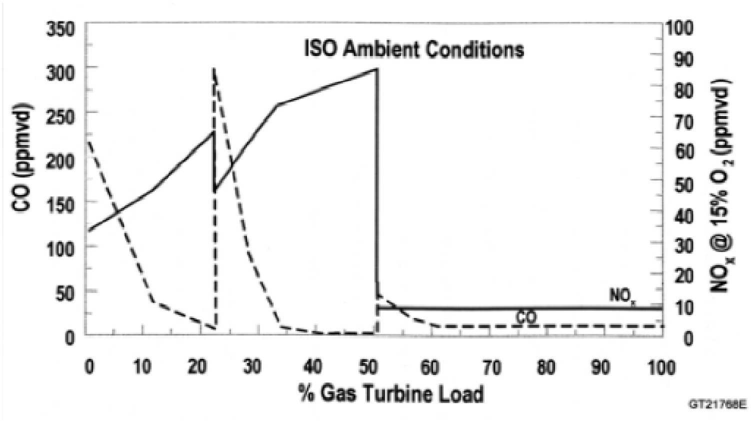


Figure 9. MS7001EA/MS9001E emissions - natural gas fuel

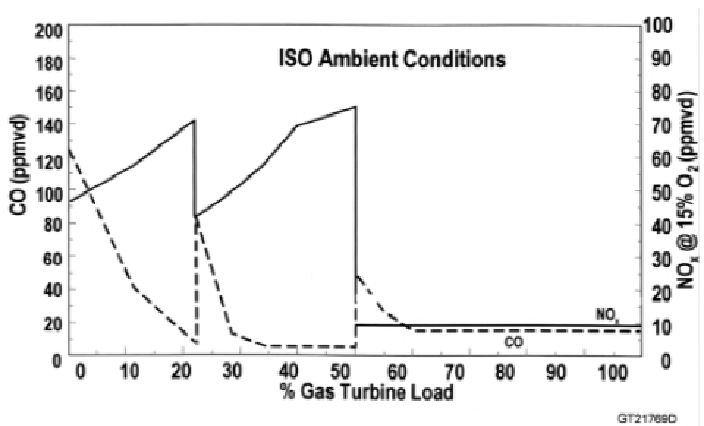
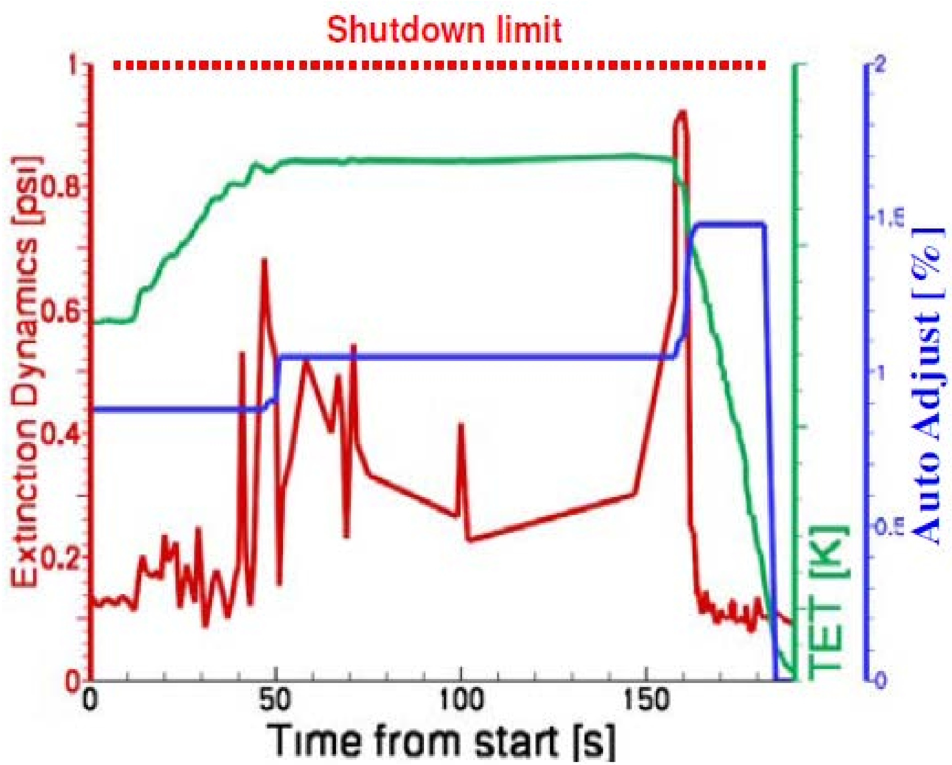


Figure 10. MS6001B emissions - natural gas



Transient operation of a Siemens SGT-200 (Bulat *et al.* 2007)

Source: Davis and Black, "Dry Low NO_x Combution Systems for GE Heavy-Duty Gas Turbines"