Near Lean Blowout Simulations of a Model Gas Turbine Combustor

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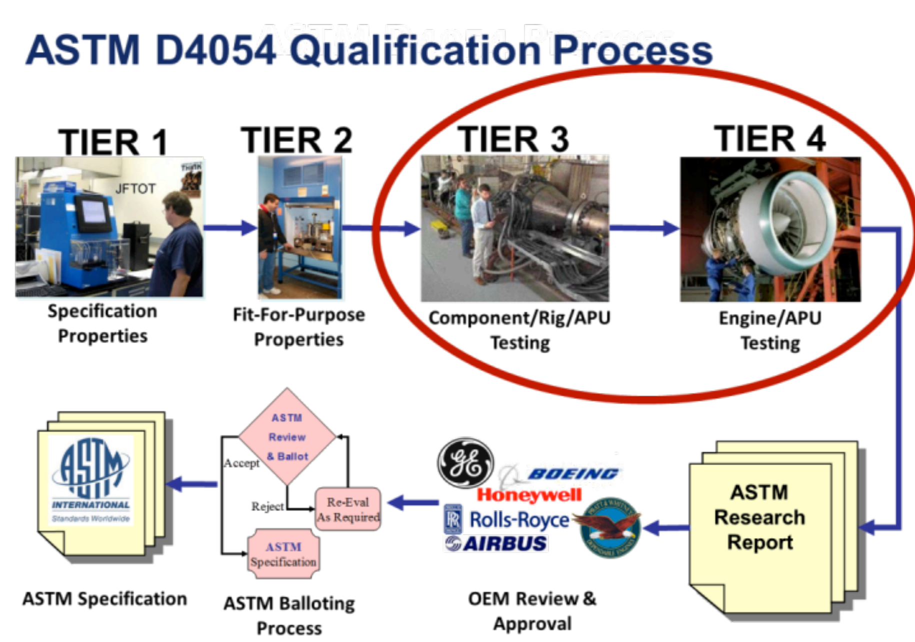
Background and Motivation

- Modern gas turbines operate at lean conditions to increase efficiency and reduce emissions
- Operating at lean conditions make the gas turbines susceptible to blowout as the flame stabilization mechanisms are weakened
- Fuel supply uncertainty and environmental concerns promote need for alternative fuels
- Drop-in fuels (readily usable with current technologies) must be certified
- 3 combustion performance targets
  - Cold start
  - Altitude relight
  - **Lean blowout (LBO)**

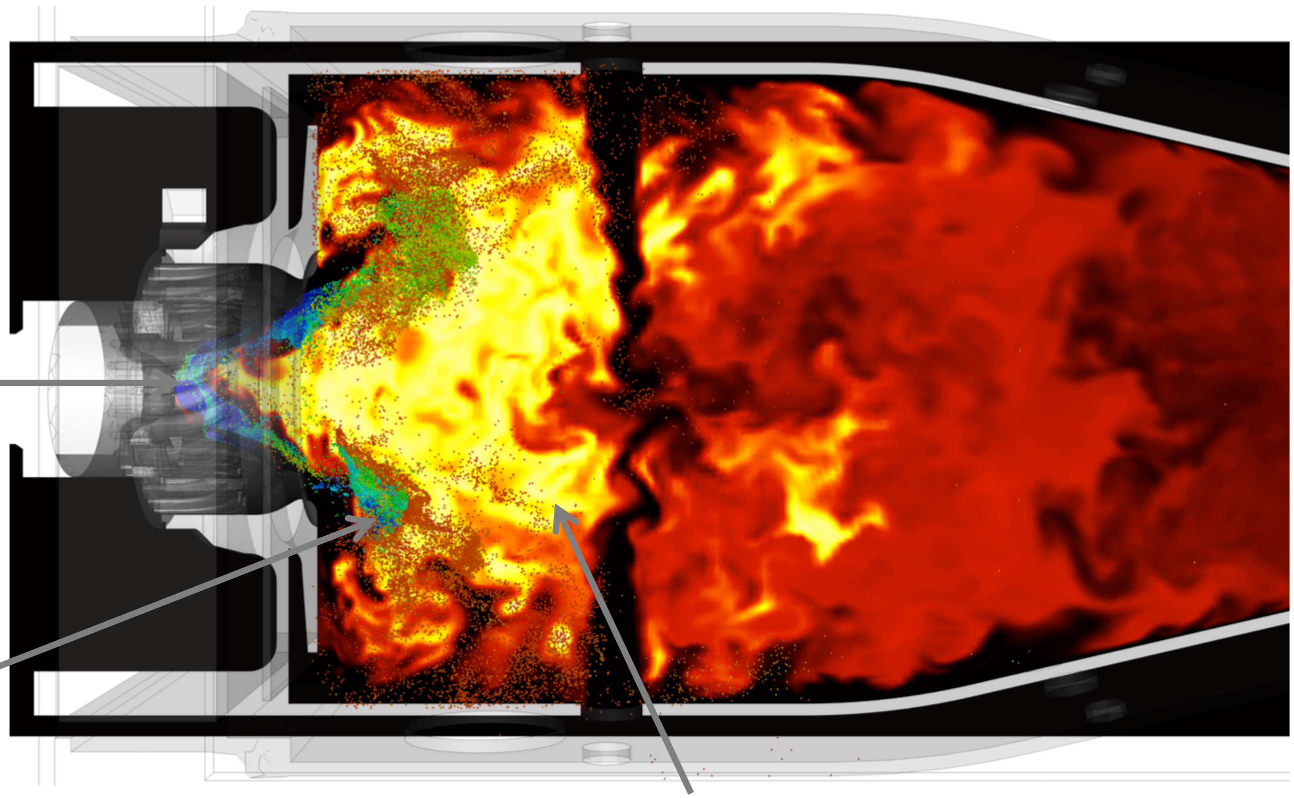


Background and Motivation

Processes impacting LBO:

Spray formation, droplet breakup

Multicomponent droplet evaporation



Chemistry

Background and Motivation

- Multi-institutional collaboration in partnership with OEM, NASA and the FAA
- Each institution using different numerical codes

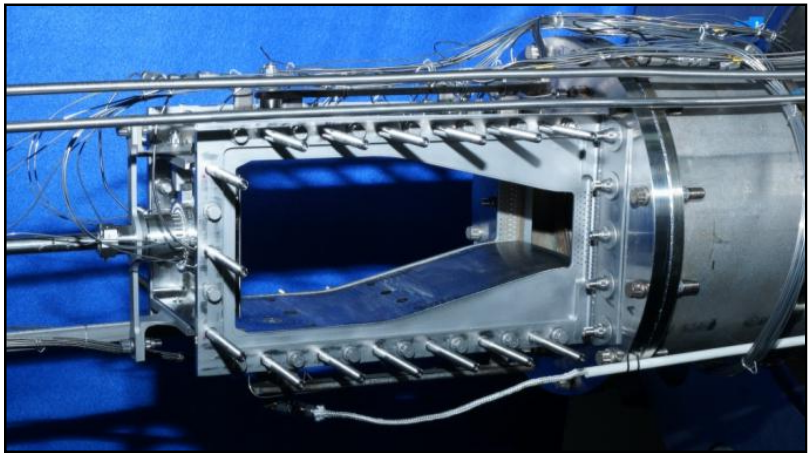
Differences	Similarities
Numerics	Mesh
Closure models	Boundary conditions
Combustion models	Fuels

- Investigation of importance of secondary droplet breakup and the impact of the initial droplet distribution on near lean blowout (LBO) predictions.

Experimental Set-up

Referee-rig combustor (NJFCP):

- Important feature of real combustors:
  - Hybrid pressure-swirl/air-blast injector
  - dilution holes
  - multiperforated liner
- Pressurized combustor
- Optical access



NJFCP referee-rig combustor

Cat-A2 fuel operated at $\varphi = 0.1$

Diagnostics

- Air flow split (measured on a separate test bench)
- High-speed chemiluminescence (OH*, CH*)
- PDPA data: SMD, droplet velocity

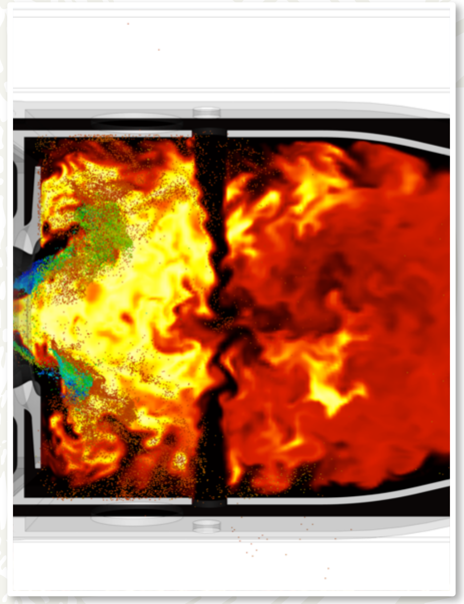
Candidate fuel description

Three selected fuels:

- Cat-A2: Conventional petroleum-derived Jet-A (POSF10325)
- Cat-C5: Narrow boiling characteristic candidate (POSF12345)
- Cat-C1: Small DCN candidate (POSF11498)

	Mol. Weight [kg/kmol]	Composition (mass fraction [%]) Aromatics	*iso*-Paraffins	*n*-Paraffins	Cycloparaffins	Alkenes
Cat-A2	159	18.66	29.45	20.03	31.86	<0.001
Cat-C5	135	30.68	51.58	17.66	0.08	<0.001
Cat-C1	178	<0.01	99.63	<0.001	0.05	0.32
	H/C	Δh_c [MJ/kg]	DCN	T_{10} [K]	$T_{90} - T_{10}$ [K]	μ_l(322 K) [mPa s]
Cat-A2	1.90	43.1	48.3	450.0	67.8	1.17
Cat-C5	1.93	43.0	39.6	434.7	2.9	0.56
Cat-C1	2.16	43.8	17.1	452.1	45.5	0.98

Baseline FPV Simulations



LES numerical Details

Numerical Methodology

- Low-Mach solver VIDA
- Mesh: patched version of Multi-block grid from UTRC (20M cells)
- $2^{nd}/4^{th}$ order in space on regular/hex mesh
- Predicter/corrector scheme in time
- Poisson solver for pressure
- 3^{rd} order RK scheme for dispersed phase

Closures

- WALE subgrid model
- FPV with presumed PDF for chemistry and turbulence-chemistry interactions

Spray Models

Reaction chemistry and transport properties

- Detailed chemistry (Hai Wang) for Cat{A2,C1,C5}
- Reported liquid transport properties from T. Edwards, Fuel Handbook

Combustion model

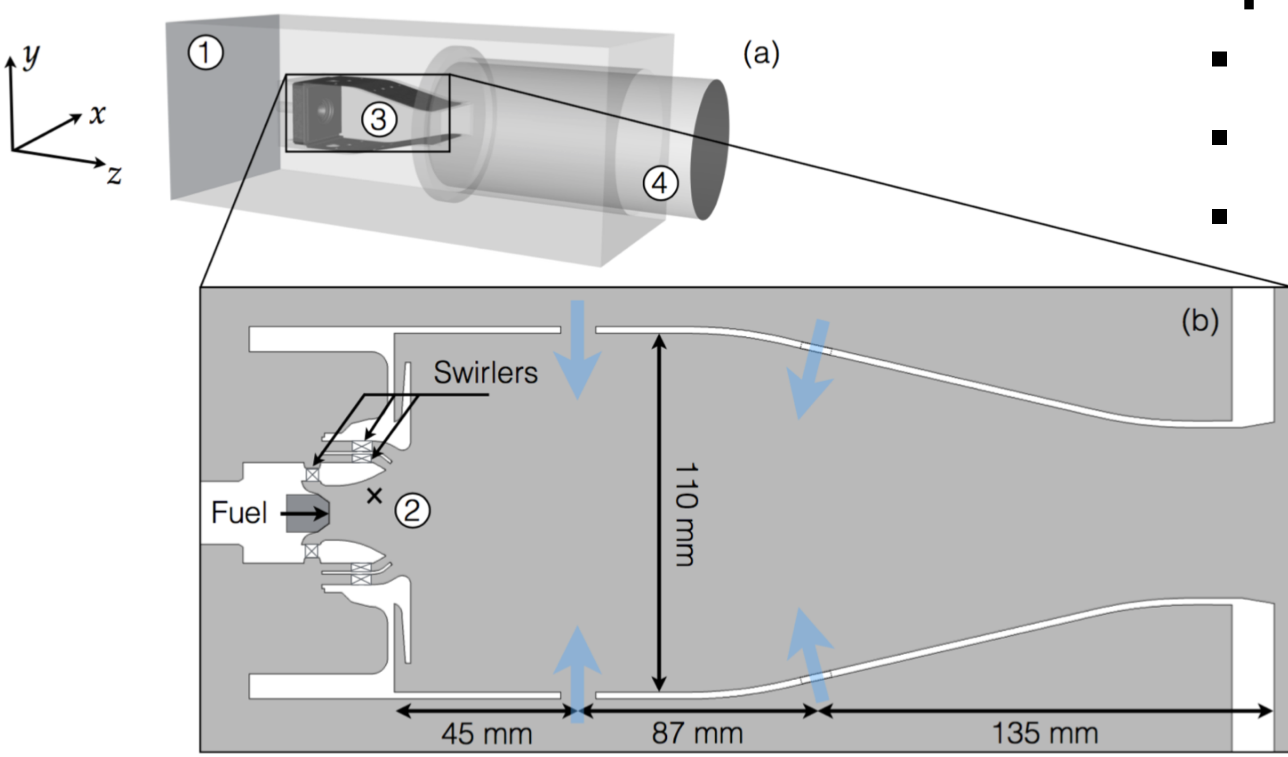
- FPV with presumed PDF for turbulence/chemistry interaction
- Consideration of latent heat of vaporization in spray-combustion

Droplet model

- Deterministic Lagrangian model
- Stochastic model for secondary droplet breakup

Geometry and Boundary Conditions

Referee-rig combustor configuration[1]



Operating conditions:

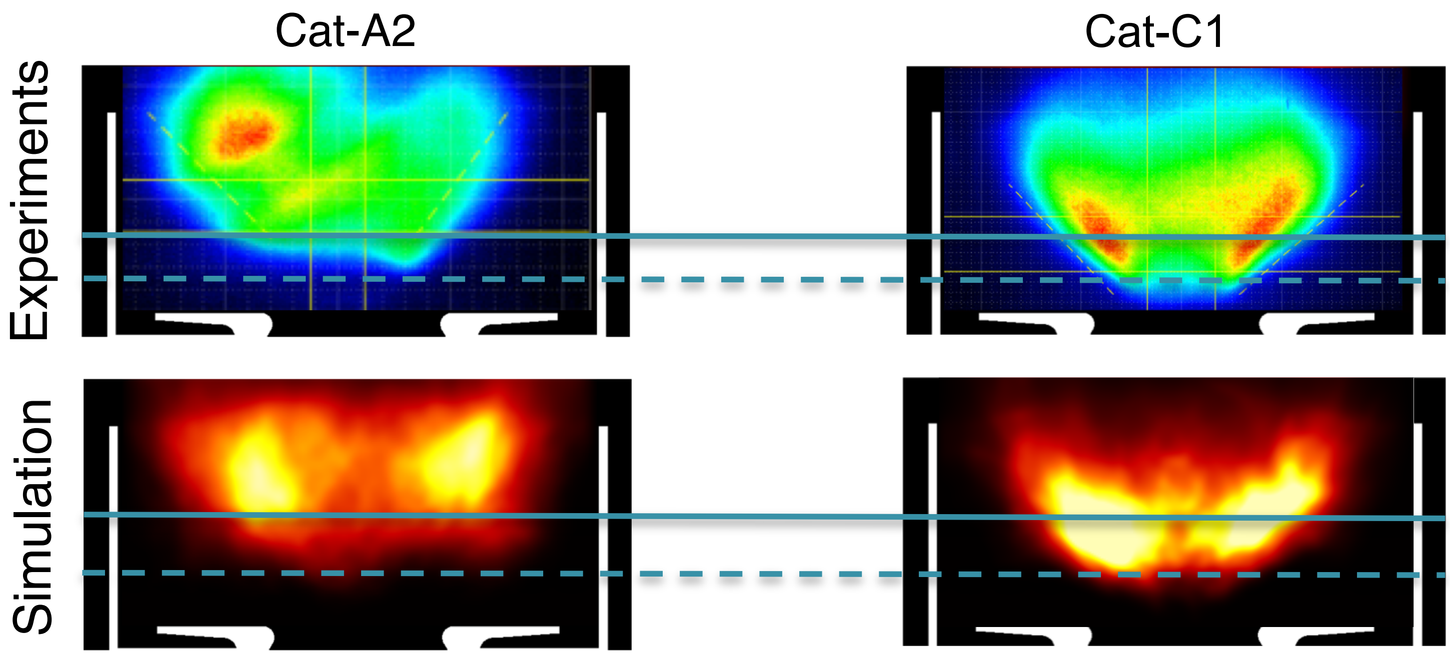
- T_{air}: 394.0 K, T_{liq}: 322.0 K
- Pressure: 2 atm
- Air inflow: 3% ΔP -> 391 g/s

1. Pressurized plenum
2. Injection system
3. Combustion chamber
4. Exhaust plenum

S. Stouffer et al., UDRI

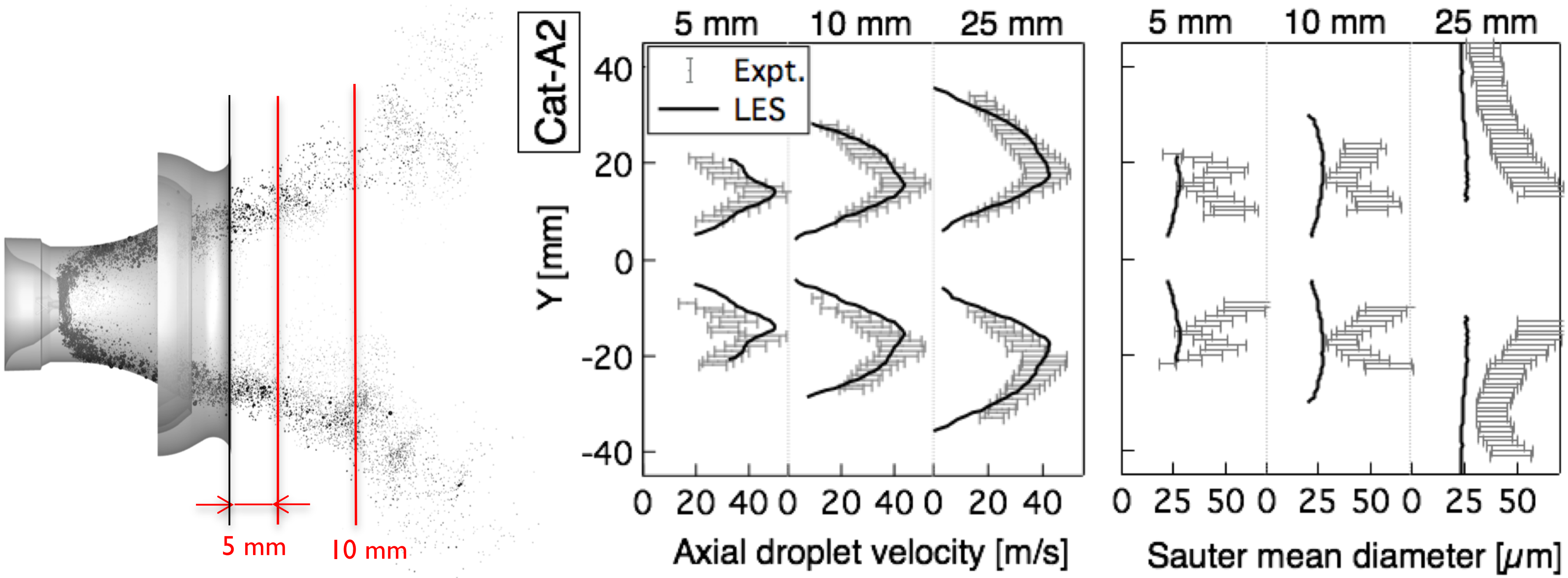
Stable Reacting Condition: Flow-Field Results

OH* Chemiluminescence



LES at stable conditions near LBO

- Comparison with PDPA measurements in reacting conditions:



L. Esclapez et al., CnF 2017

LES at stable conditions near LBO

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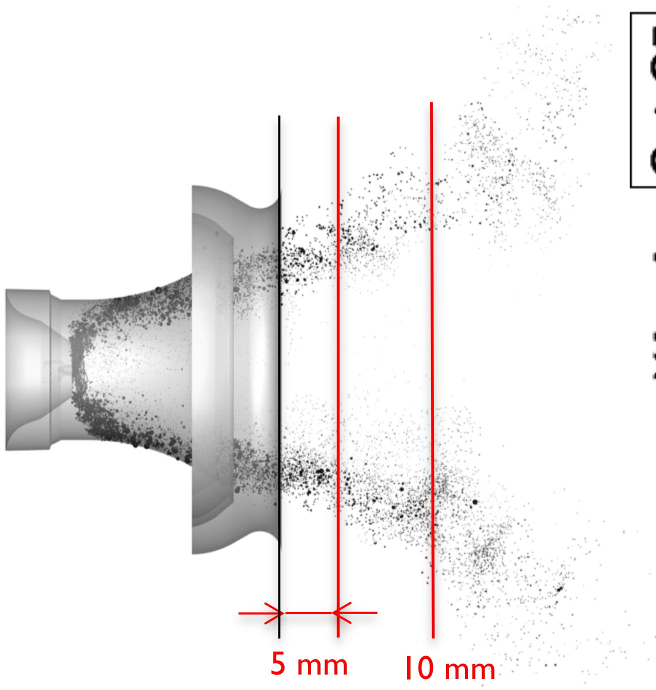

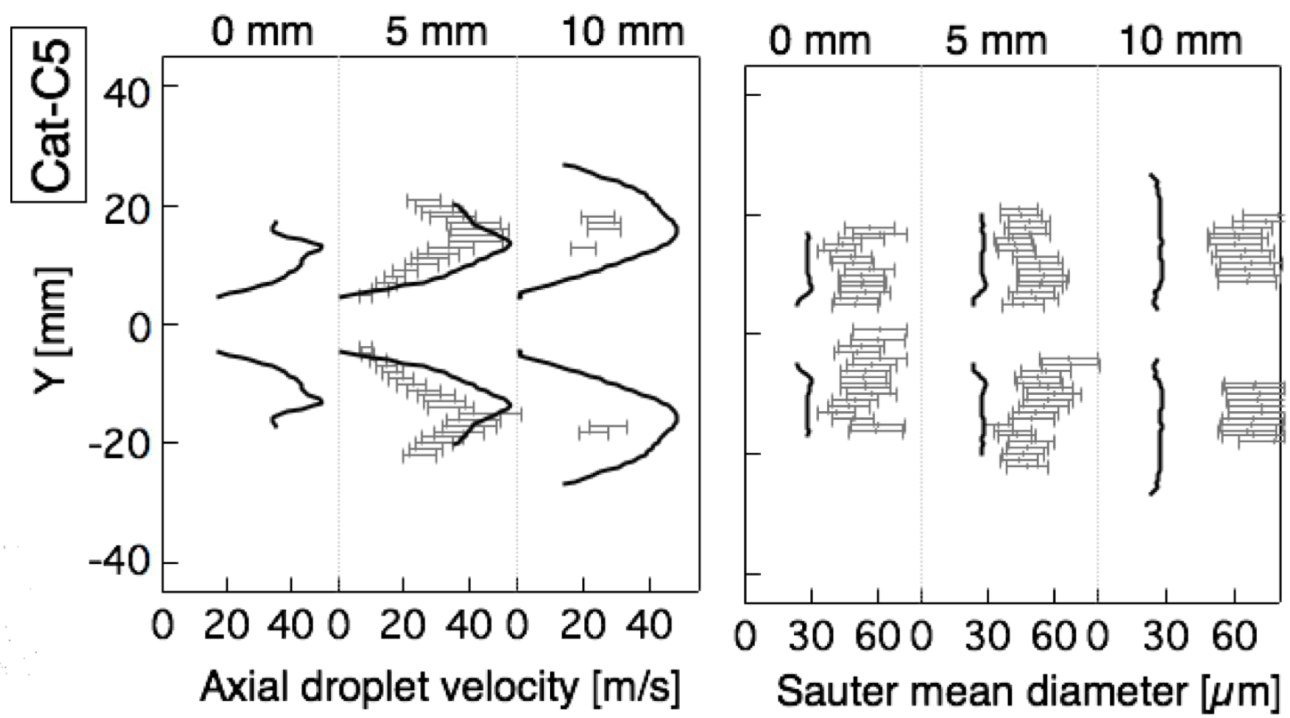

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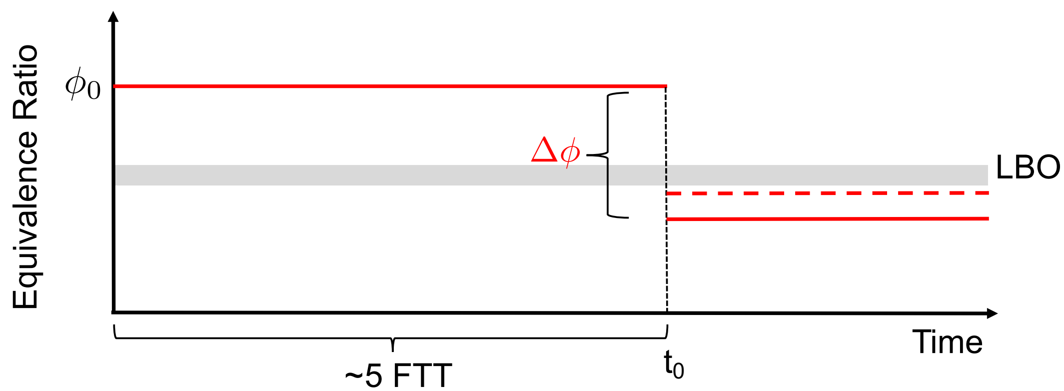
Transient LBO simulations

- Objective: observe LBO-equivalence ratio after step-change in equivalence ratio (reduction of fuel mass flow-rate)
- Approach: step-response to change in equivalence ratio

$$\phi = \phi_0 - \Delta\phi \, \delta(t - t_0)$$

- Change $\Delta\phi$ until LBO is found



Transient LBO simulations

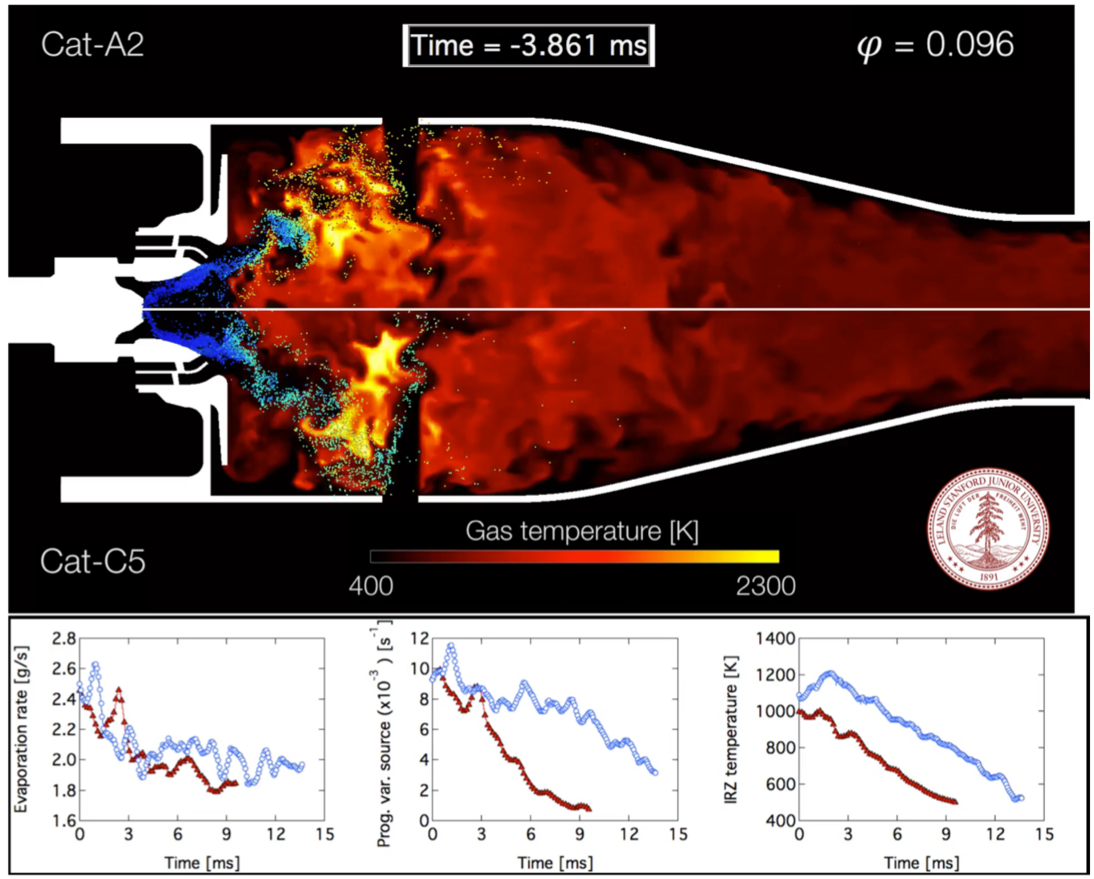
Cat-A2 and Cat-C5 at $\phi = 0.08$

- Temporal evolution of combustor state indicators:
  - Evaporation rate
  - Chemical source term
  - IRZ mean temperature

- Cat-A2 is found to blow-out faster than Cat-C5

- Partial recovery of the flame is observed at times, but burn gases are convected downstream

- Similar cooling rate of the IRZ

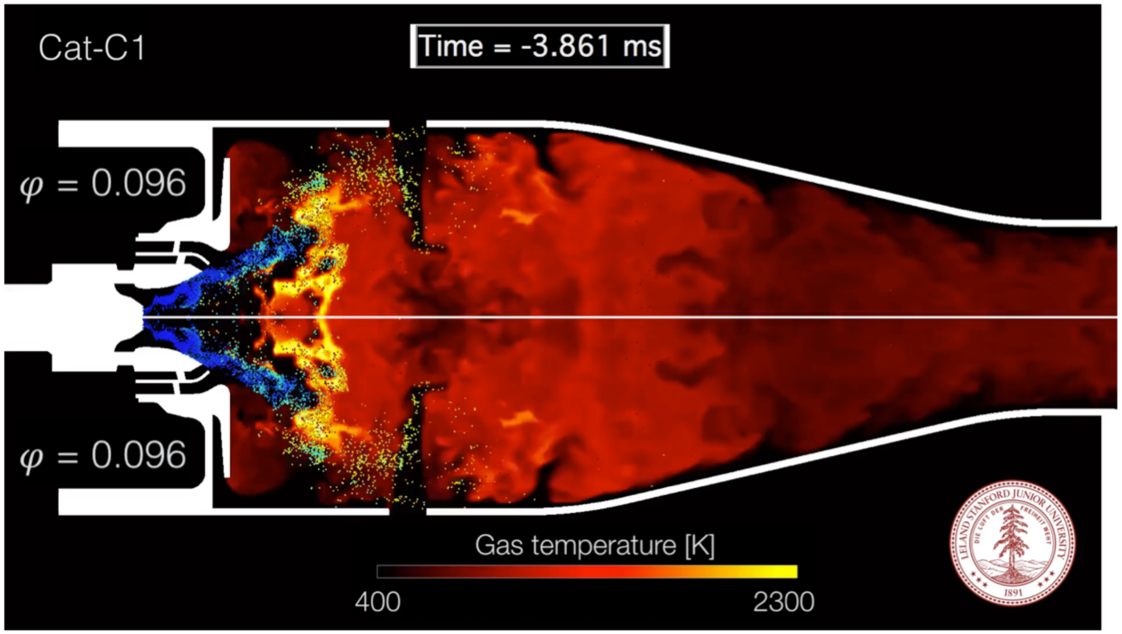


L. Esclapez et al., CnF 2017

Transient LBO simulations

Transient blow-out simulation: comparison of Cat-C1 at ϕ = 0.09 and ϕ = 0.08:

- No significant differences before 2 ms after injection rate change
- Larger droplet density at ϕ = 0.09 induces formation of near stoichiometric pocket
- More hot gases recirculated at ϕ = 0.09 maintain a hot IRZ, enhancing evaporation



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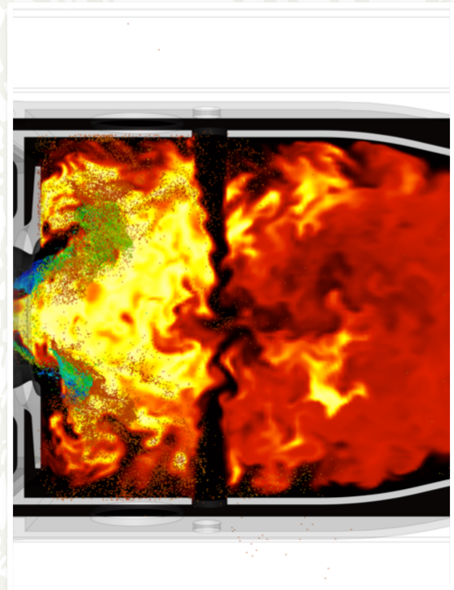
Transient LBO simulations

Computed LBO-limits

ϕ	Cat-A2		Cat-C5		Cat-C1	
	Exp.	LES	Exp.	LES	Exp.	LES
0.096	✓	✓	✓	✓	✓	✓
0.093	✓	✓	✓	✓	✓	–
0.090	✓	✗	✓	✗	✗	✓
0.085	✓	–	✓	–	✗	✗
0.080	✗	✗	✗	✗	✗	✗

- Consistent trends for Cat-A2 and Cat-C5

Importance of secondary droplet breakup



Secondary break up model

Stochastic droplet breakup model:

- Breakup of parent drops into secondary governed by the Fokker–Planck (FP) differential equation

$$\frac{\partial T(x,t)}{\partial t} = -\nu\langle\zeta\rangle\frac{\partial T(x,t)}{\partial x} + \frac{1}{2}\nu\langle\zeta^2\rangle\frac{\partial^2 T(x,t)}{\partial x^2}$$

with $x = ln(r)$

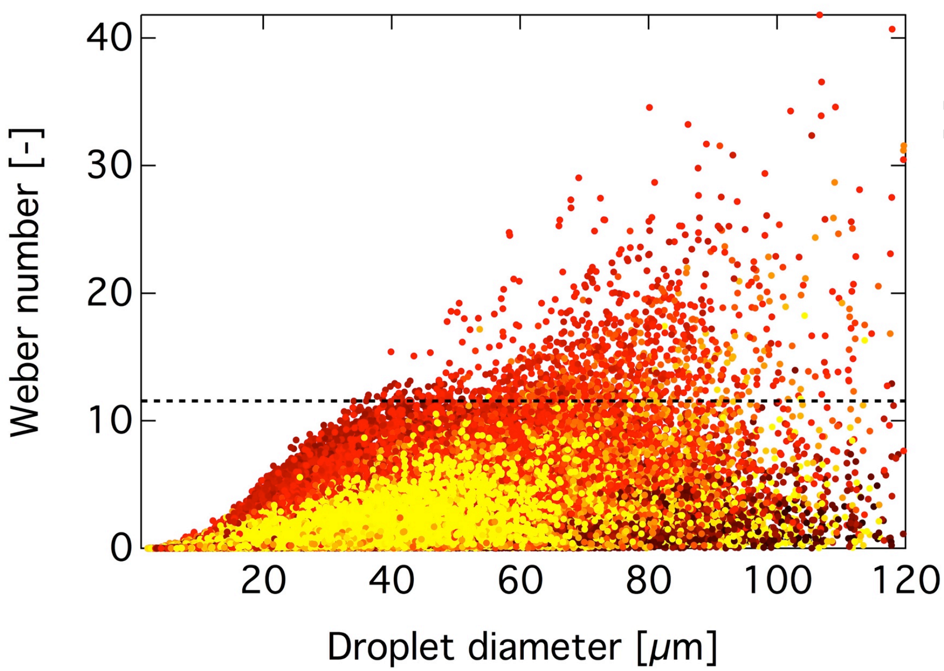
- Steady state distribution given by

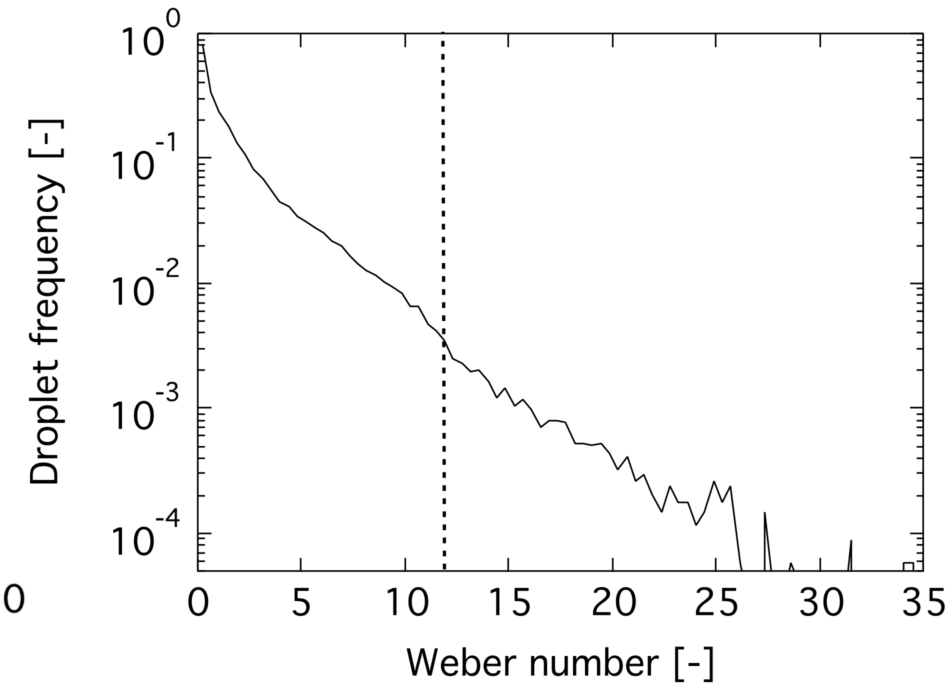
$$T_j(x,t+1) = \frac{1}{2}\left[1 + erf\left(\frac{x - x_j - \langle\zeta\rangle}{\sqrt{2\langle\zeta^2\rangle}}\right)\right]$$

- Closure needed for $\langle\zeta\rangle$ and $\langle\zeta^2\rangle$ which are given by

$$\langle\zeta^2\rangle = -0.1log\left(\frac{We_{cr}}{We_j}\right), \qquad \langle\zeta\rangle = -0.1$$

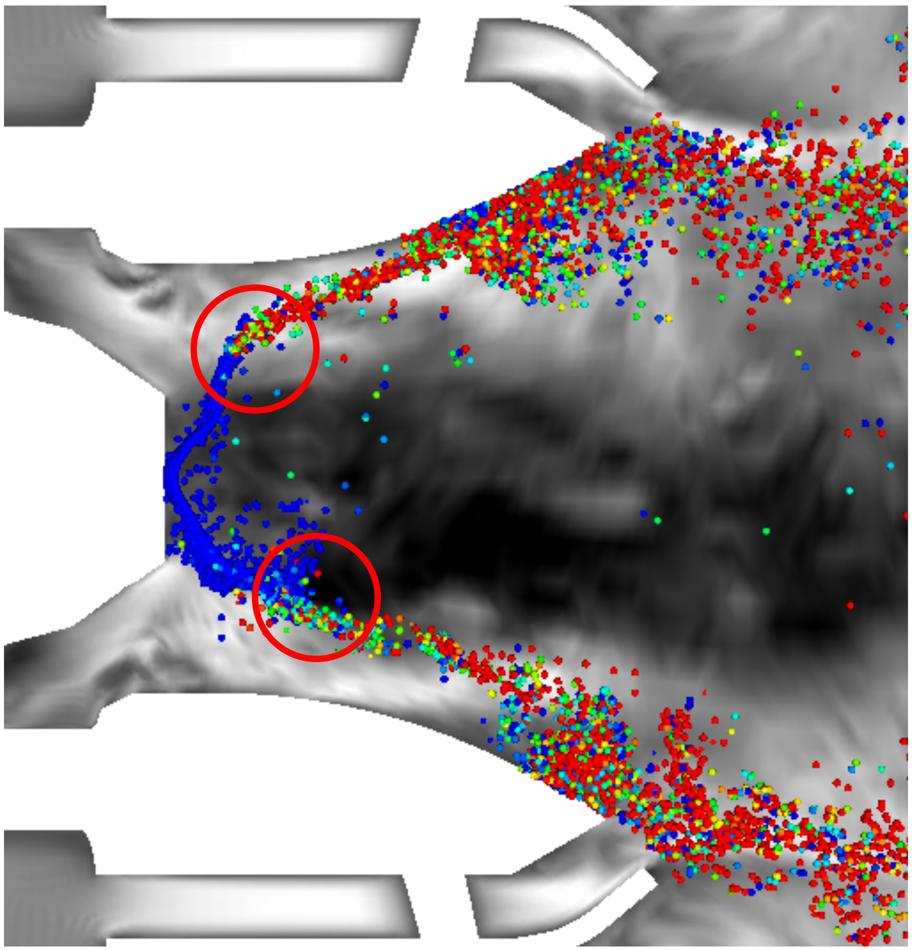
Sensitivity to secondary break-up

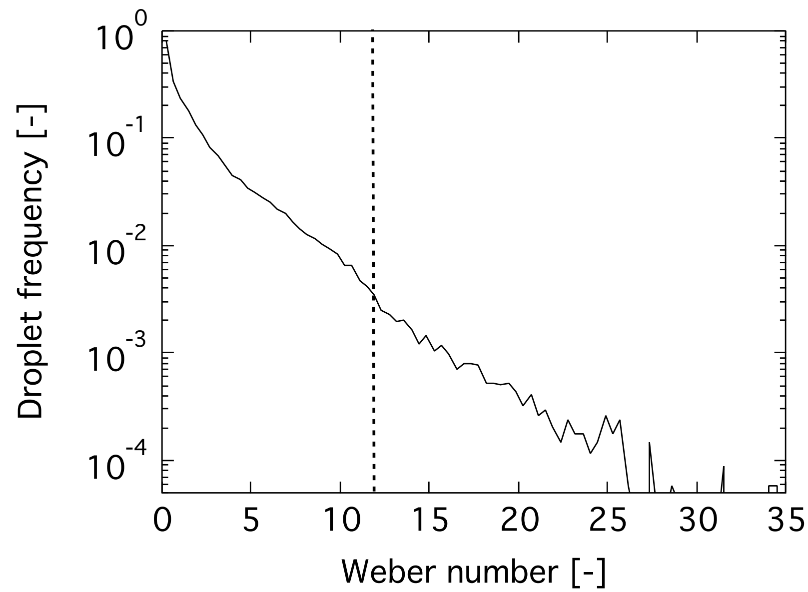




Although the instantaneous number of droplets above critical We is low, most of the droplet with Dp > 60μm experiences Web > 12 following the injection

Secondary break-up position





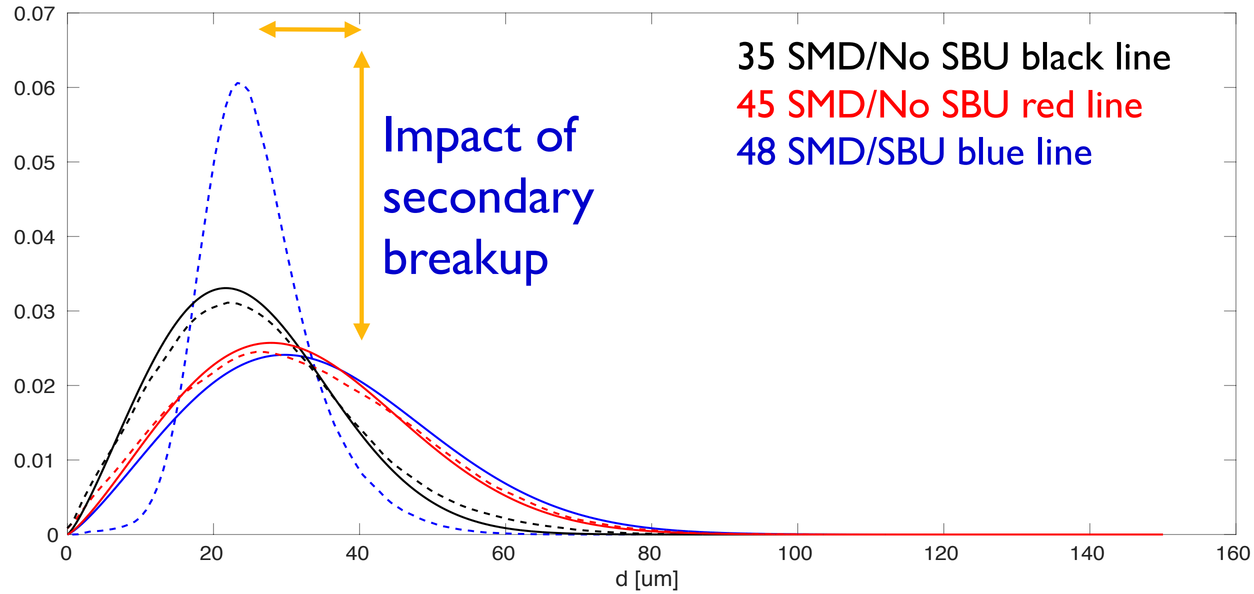
- Secondary break-up mainly in the radial swirler flow/IRZ shear layer
- Droplet Weber number larger than the critical value (ongoing break-up)

Spray Boundary Conditions

	Stable	New
Fuel	A2	
Spray injection location	0.25 mm downstream of spray nozzle	
Spray injection point	Ring injection with ring radius of r=0.9 mm	
Spray injection speed	8.6 m/s	8 m/s
Drop size distribution	Rosin-Rammler, q = 2.25	
	SMD: 54 microns	SMD: 45 microns
Full spray angle	90 degrees	80 degrees
Secondary breakup model	Yes	No

Impact of Secondary Break-up

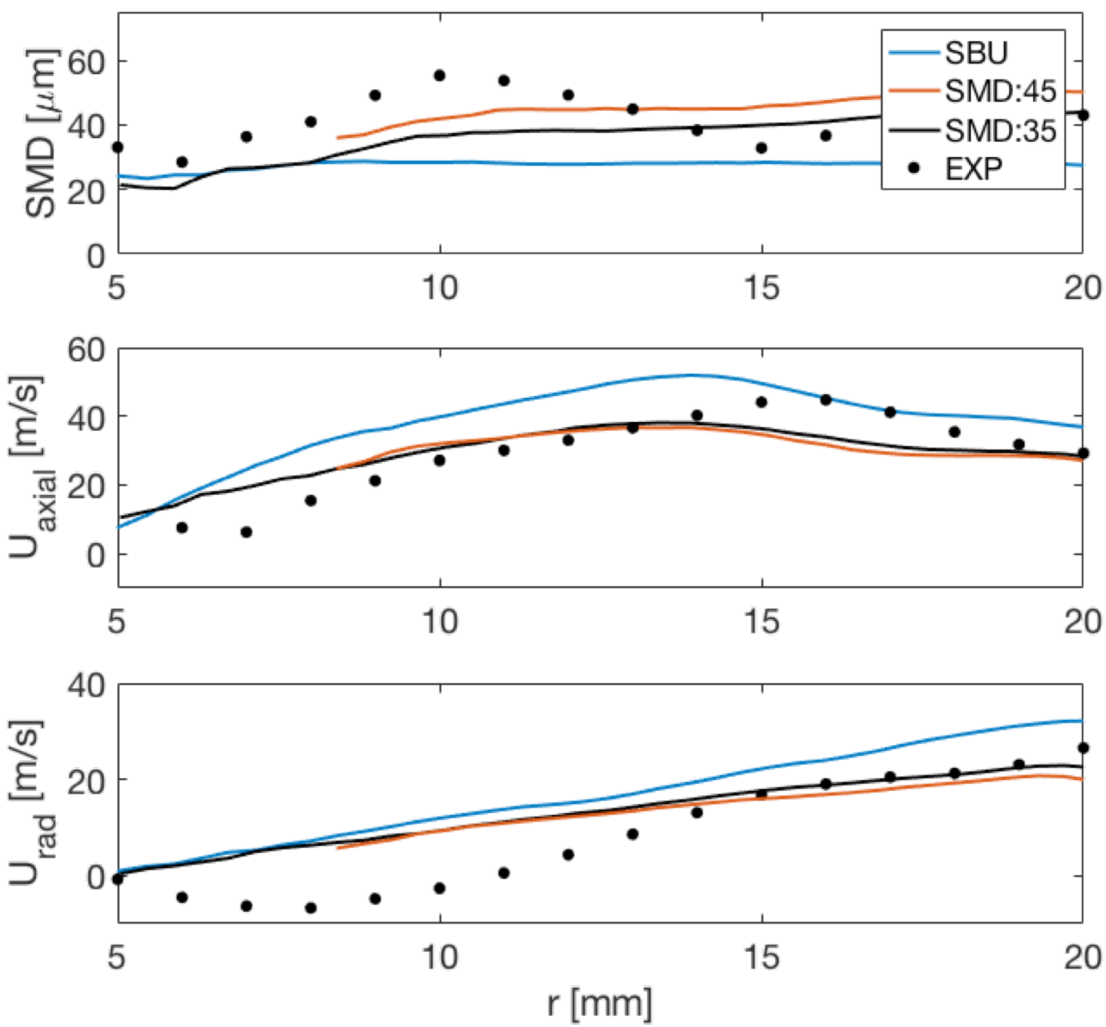
- Importance of initial particle distribution defined at injector (solid line-injector, dashed line particle distribution at -5mm



- Large difference between SBU and no SBU
- SBU particle distribution at -5 mm defined completely by SBU model
- For No SBU model distribution at -5mm defined completely by boundary condition

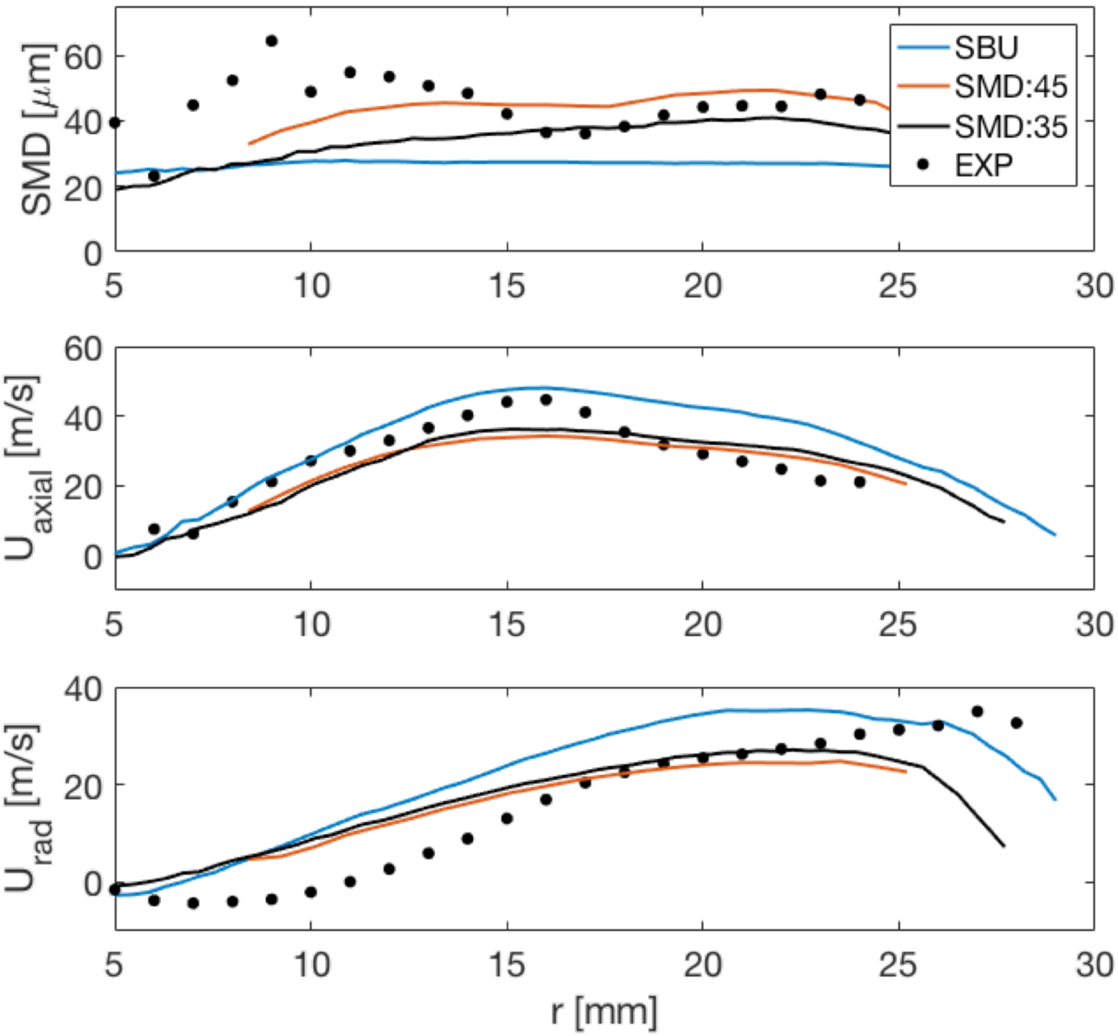
Comparison to PDPA measurements

5 mm



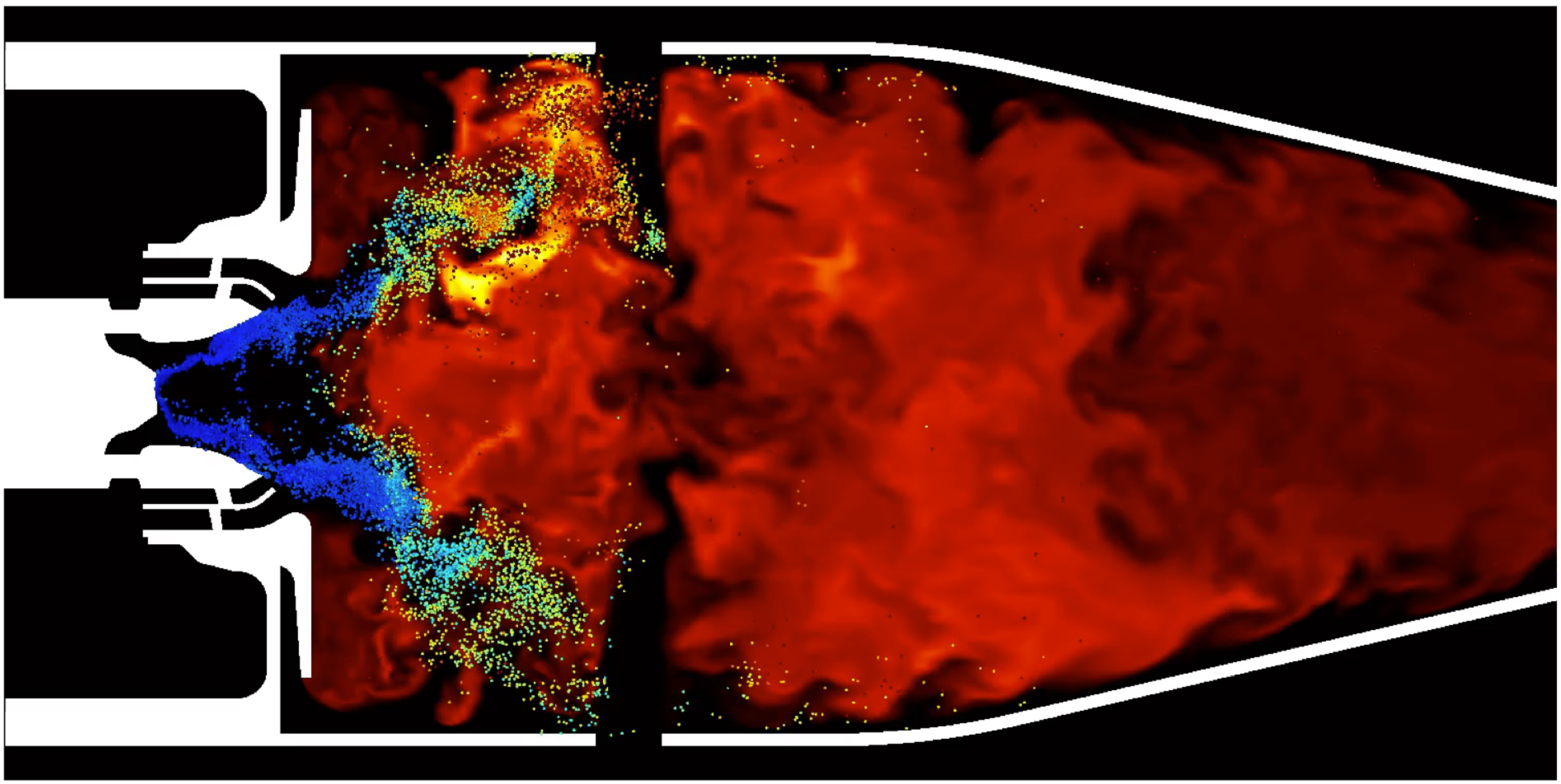
Comparison to PDPA measurements

10 mm



Effect of variation in SMD

Near blow-out simulation (phi=0.096); no secondary break-up: SMD=45um



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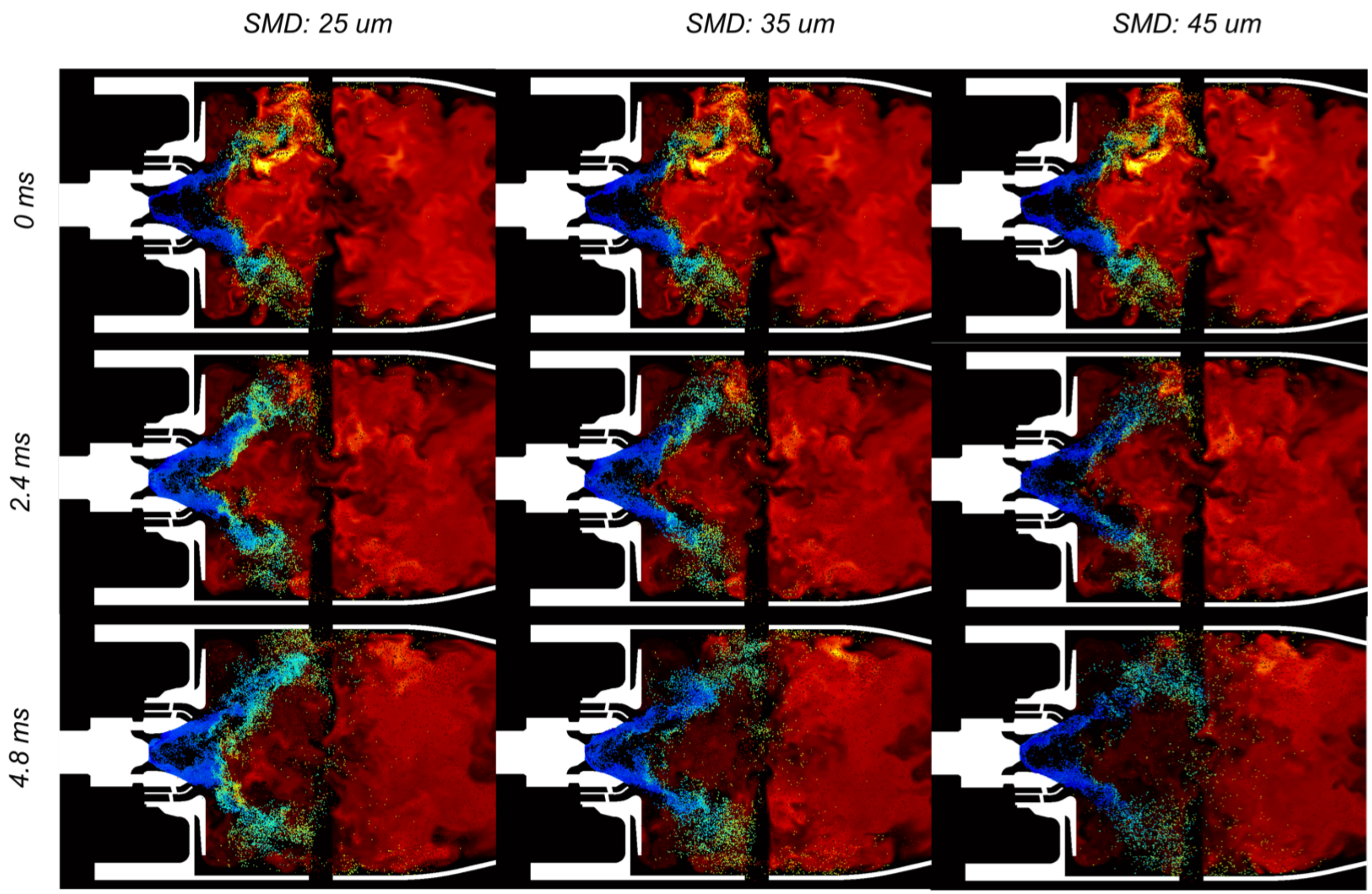
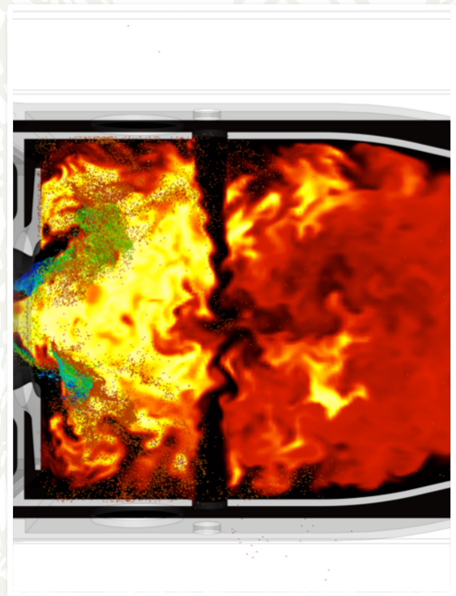


Investigation of Spray Injection on LBO Predictions



Investigation of Spray Injection on LBO Predictions

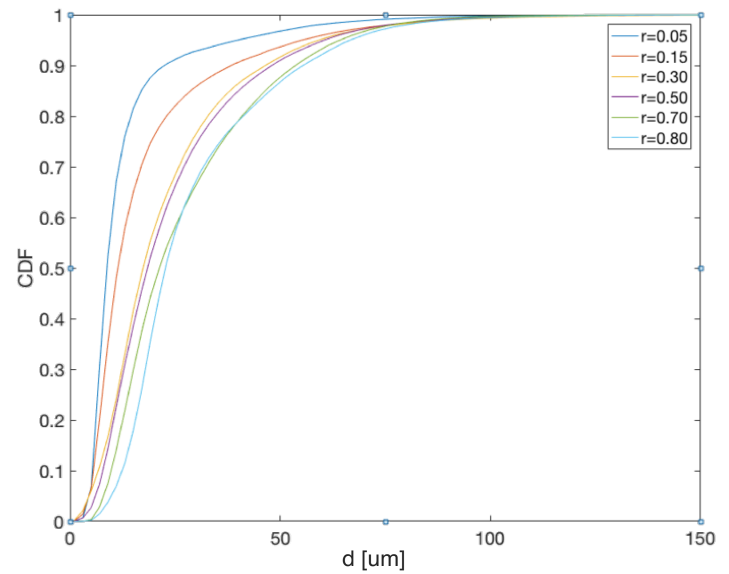
	Case 1	Case 2
Fuel	A2/C1	
Spray injection location	0.25 mm downstream of spray nozzle	2 mm downstream of spray nozzle
Spray injection point	Ring injection with ring radius of r=0.9 mm	Multi-ring injection
Spray injection speed	8.6 m/s	Variable
Drop size distribution	Rosin-Rammler, q = 2.25	Based on experimental data
	SMD: 54 microns	Variable
Full spray angle	90 degrees	Variable
Secondary breakup model	Yes	No
Evaporation model	Default	Default
Mass flow rate	Nominal	Nominal

New spray boundary conditions

Spray injected 2 mm from injector face

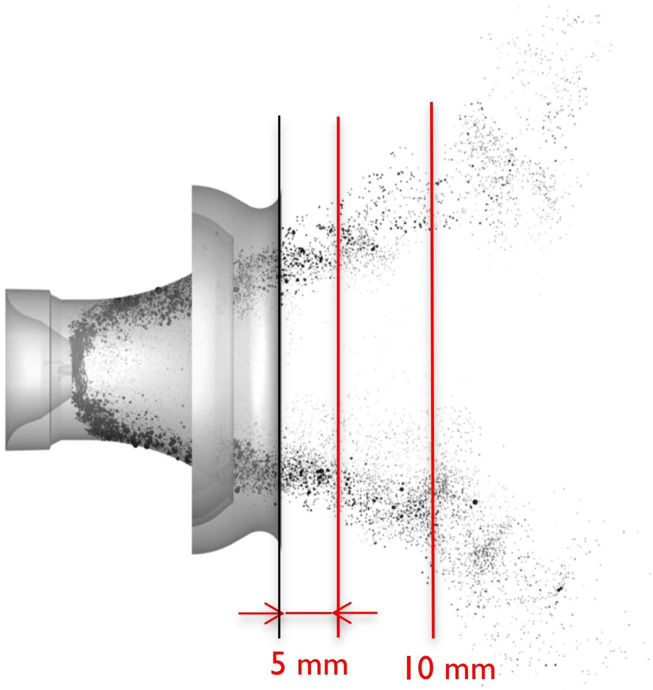
Spray broken into 6 concentric rings with unique:

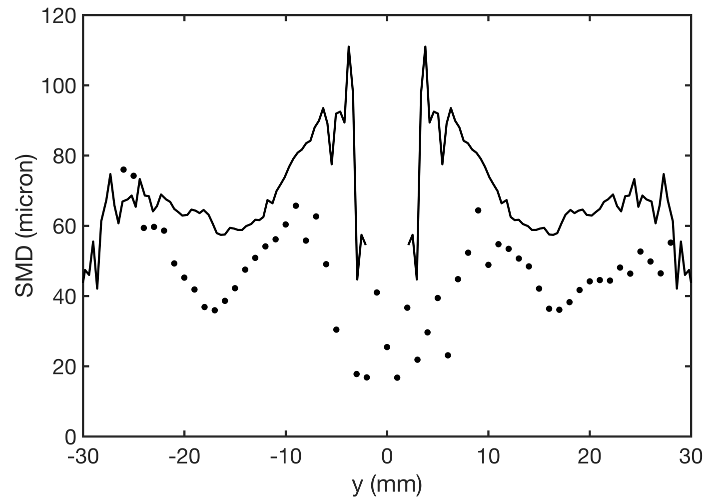
- Spray angle
- Droplet diameter distribution
- Velocity
- Mass flow rate

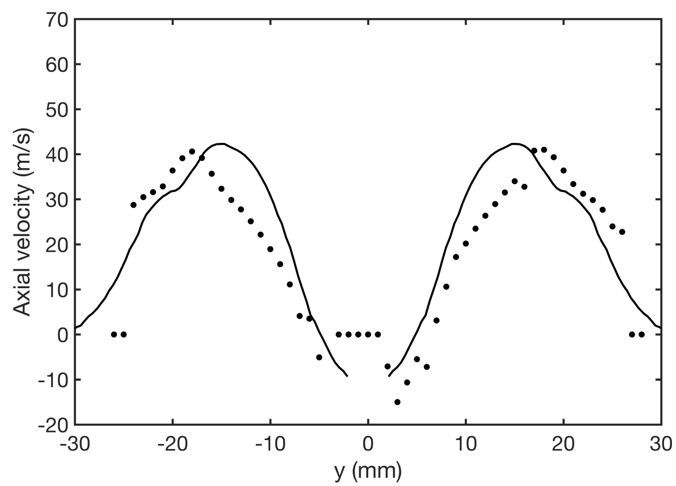


All properties estimated using downstream PDPA measurements

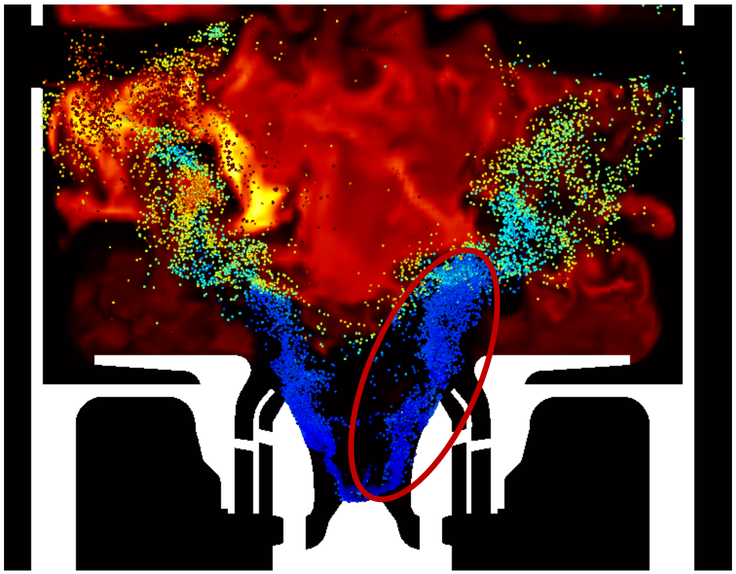
PDPA Measurements (10 mm)



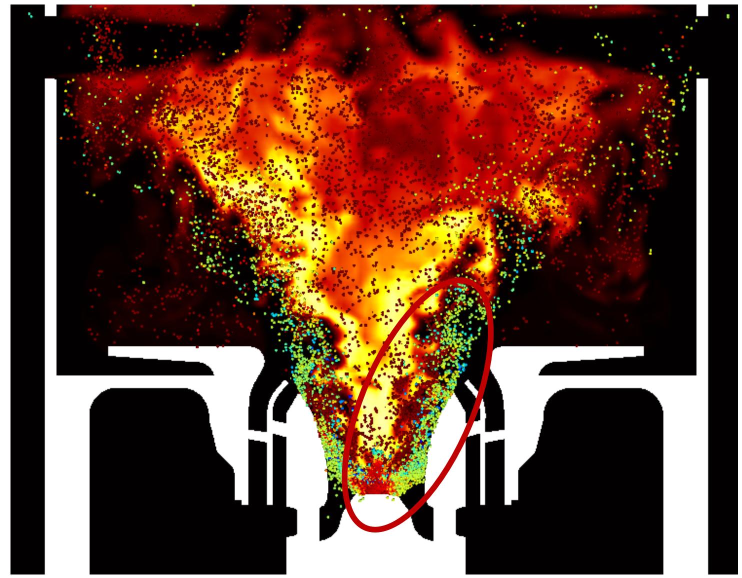




Droplet behavior



Case 1

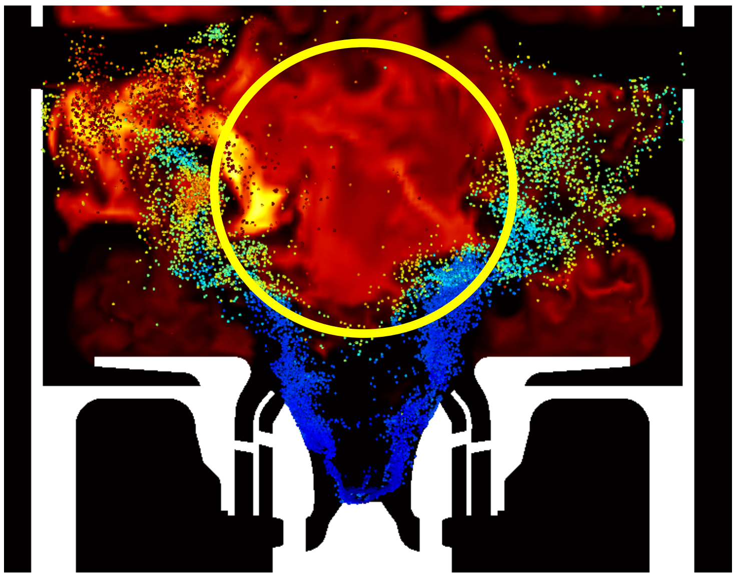


Case 2

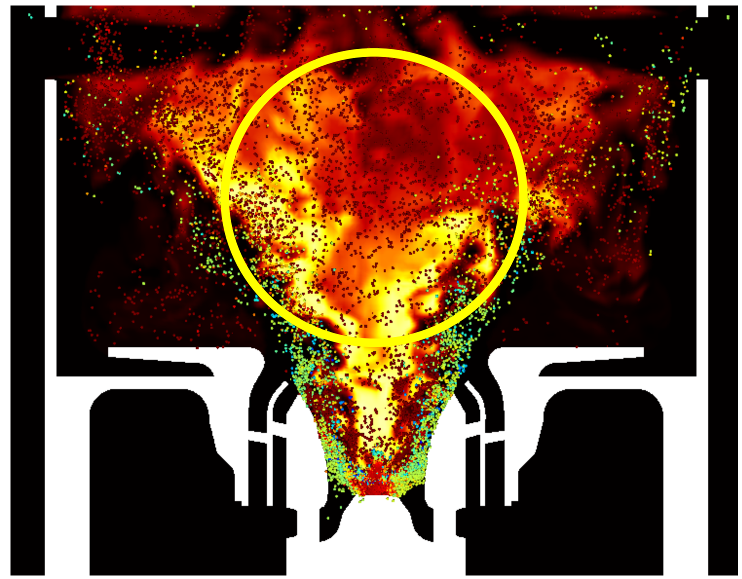
New BC:

- Broader “spray angle” near injector face

Droplet behavior



Case 1

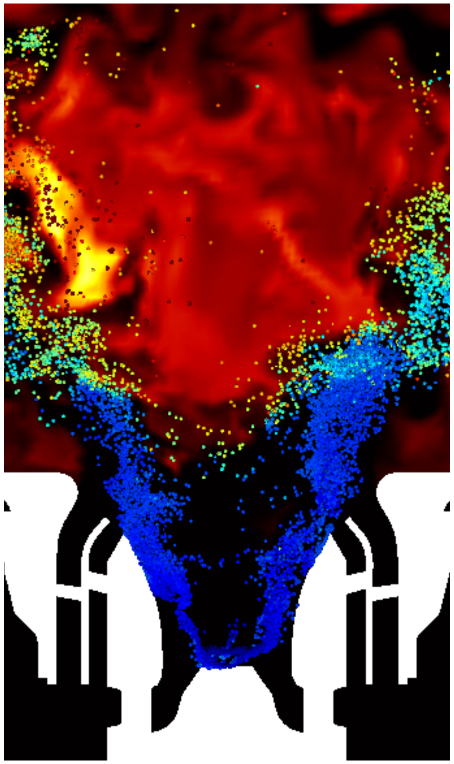


Case 2

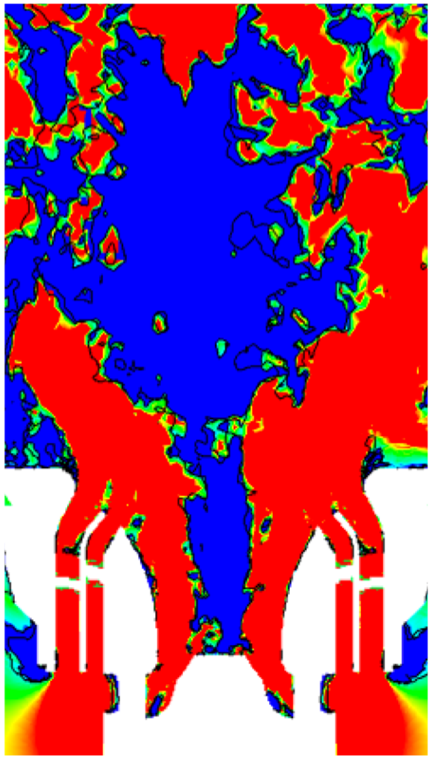
New BC:

- Higher concentration of droplets within inner recirculation

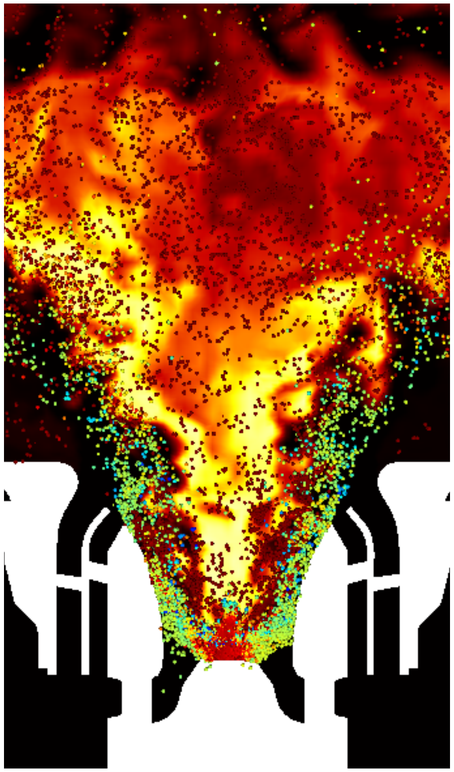
Recirculation Zone



Case 1



Axial velocity

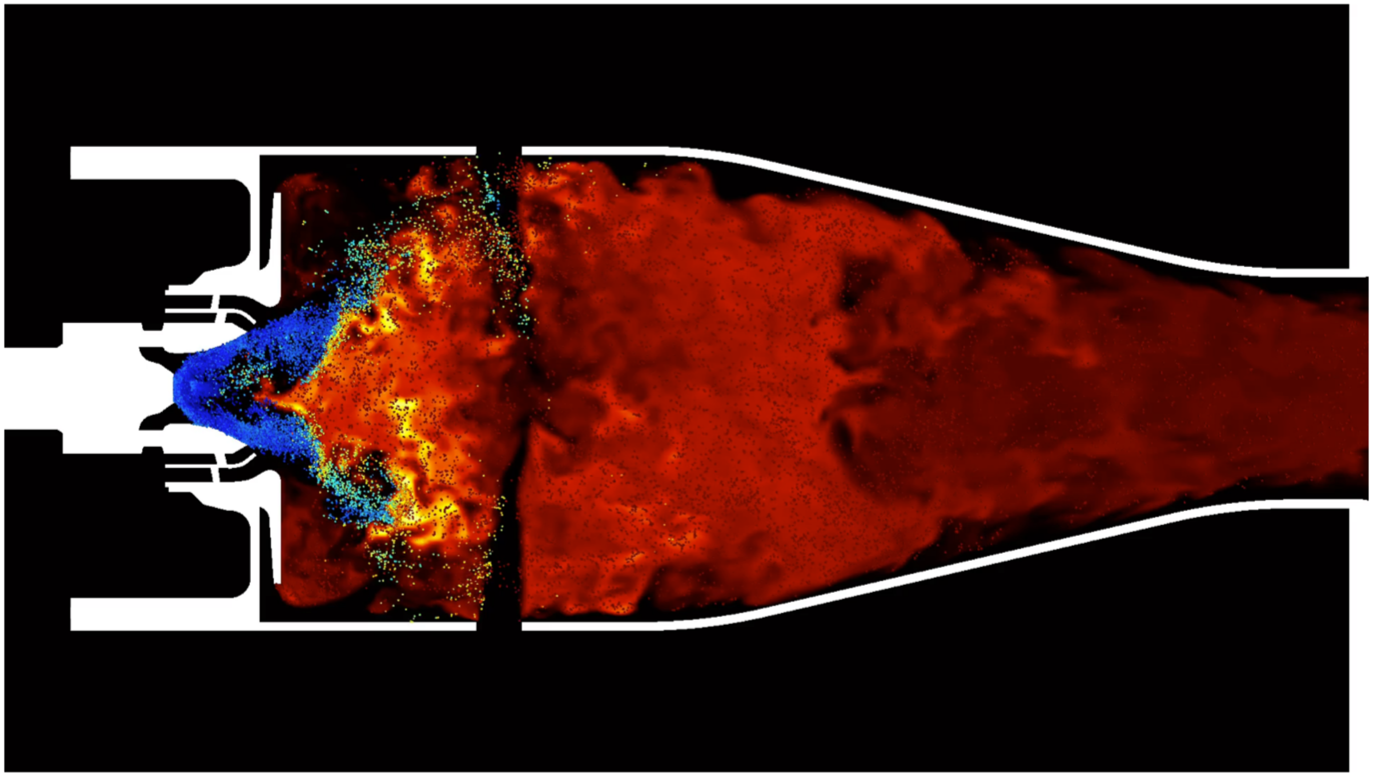


Case 2

Large number of droplets injected into inner recirculation zone (blue region)

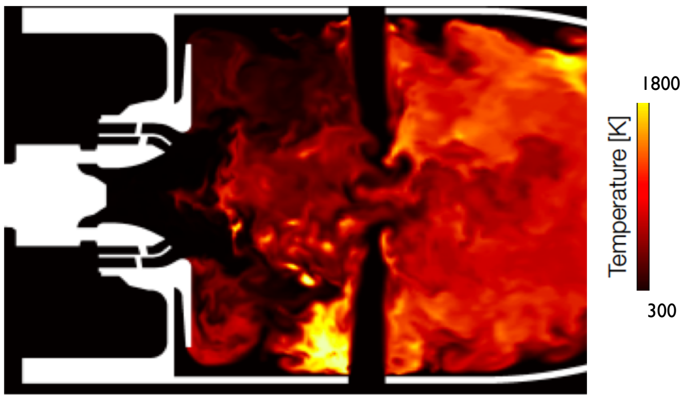
Droplets spend significant time in inner recirculation zone before evaporating

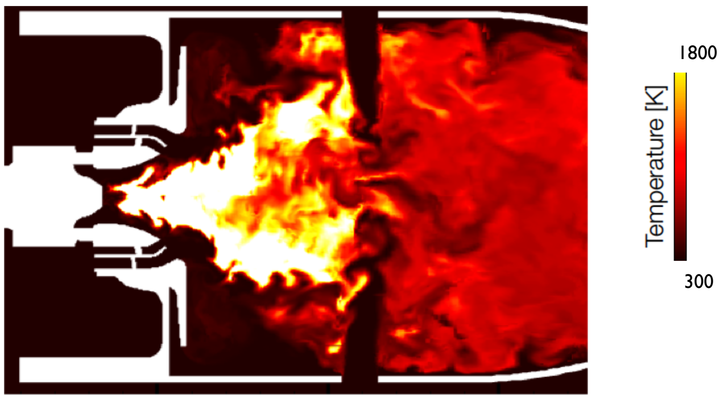
Flame behavior

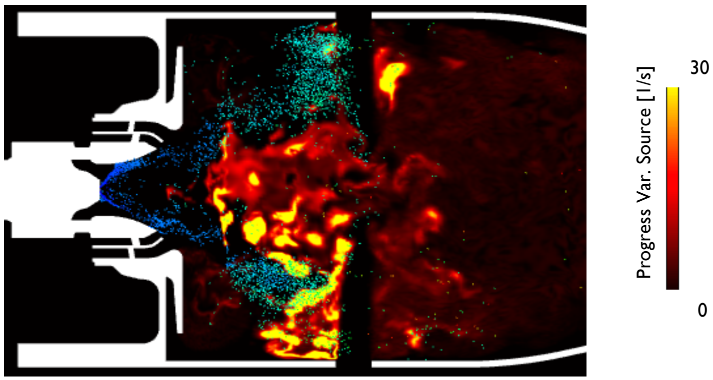


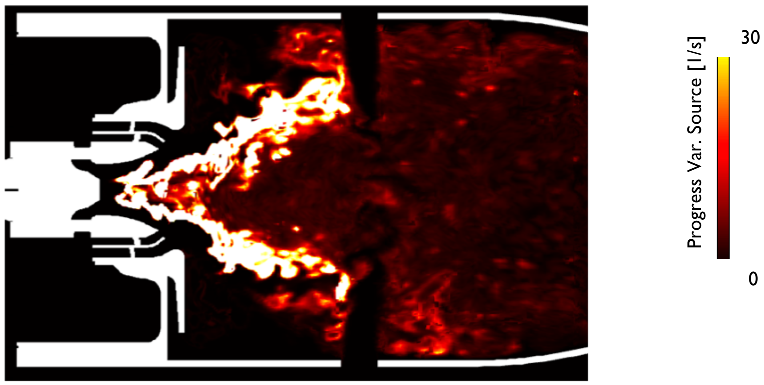
Instantaneous behavior

Case 1	Case 2

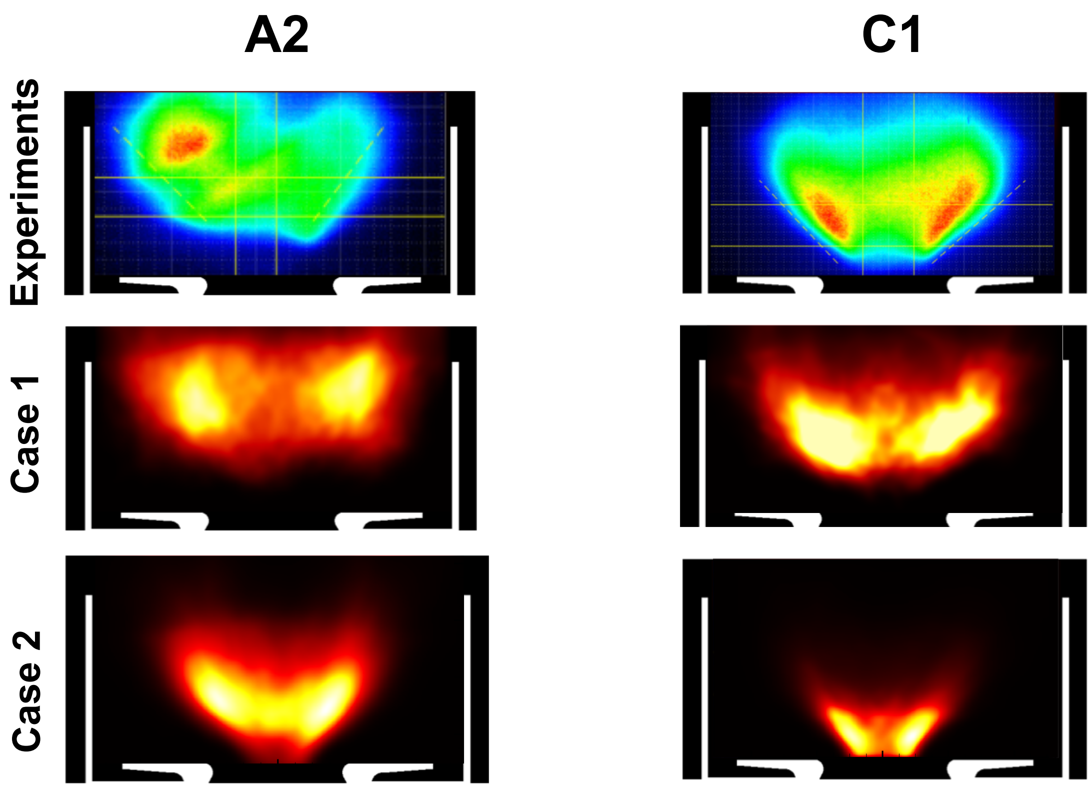




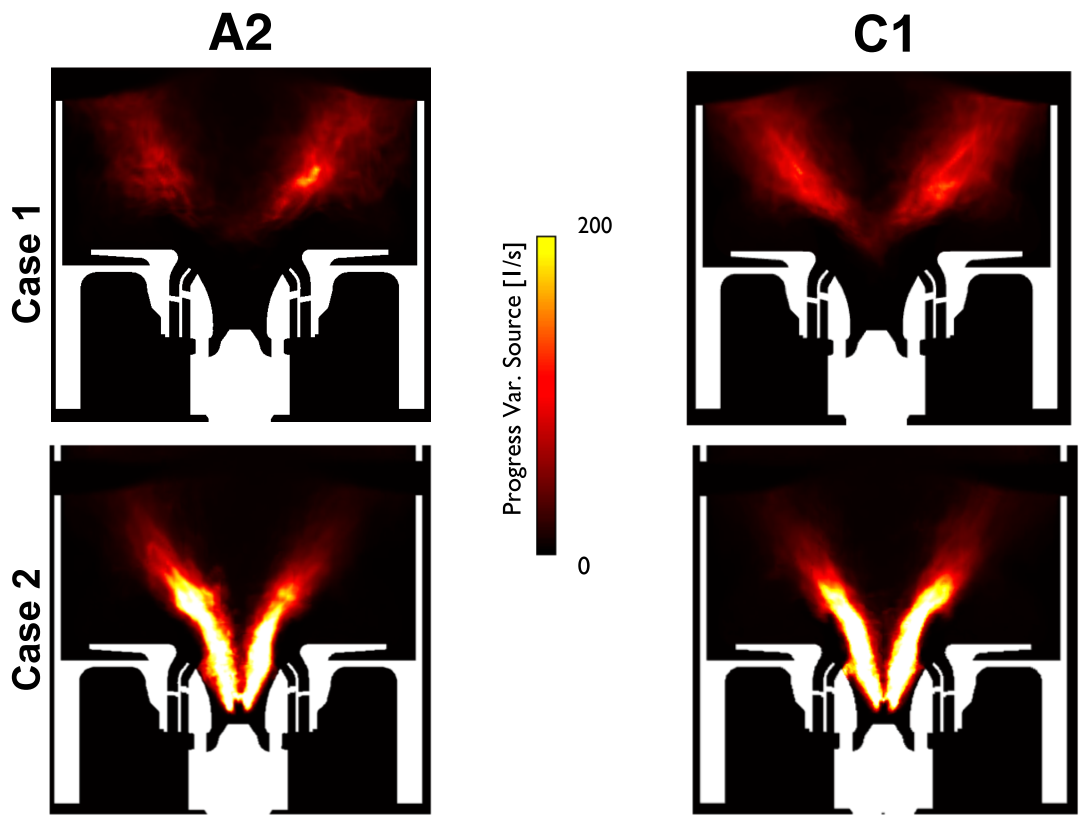




Time averaged OH*

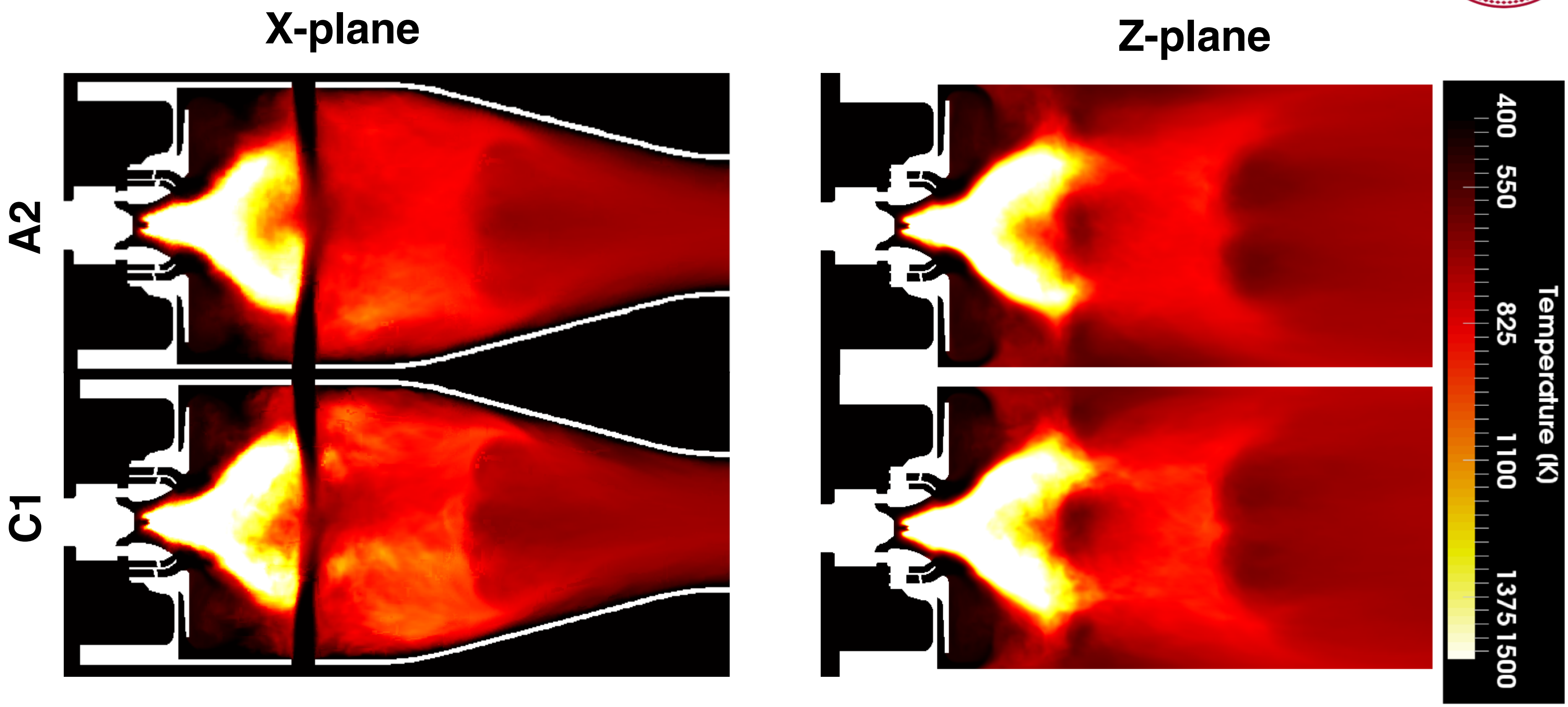


Time-averaged Progress Source Term



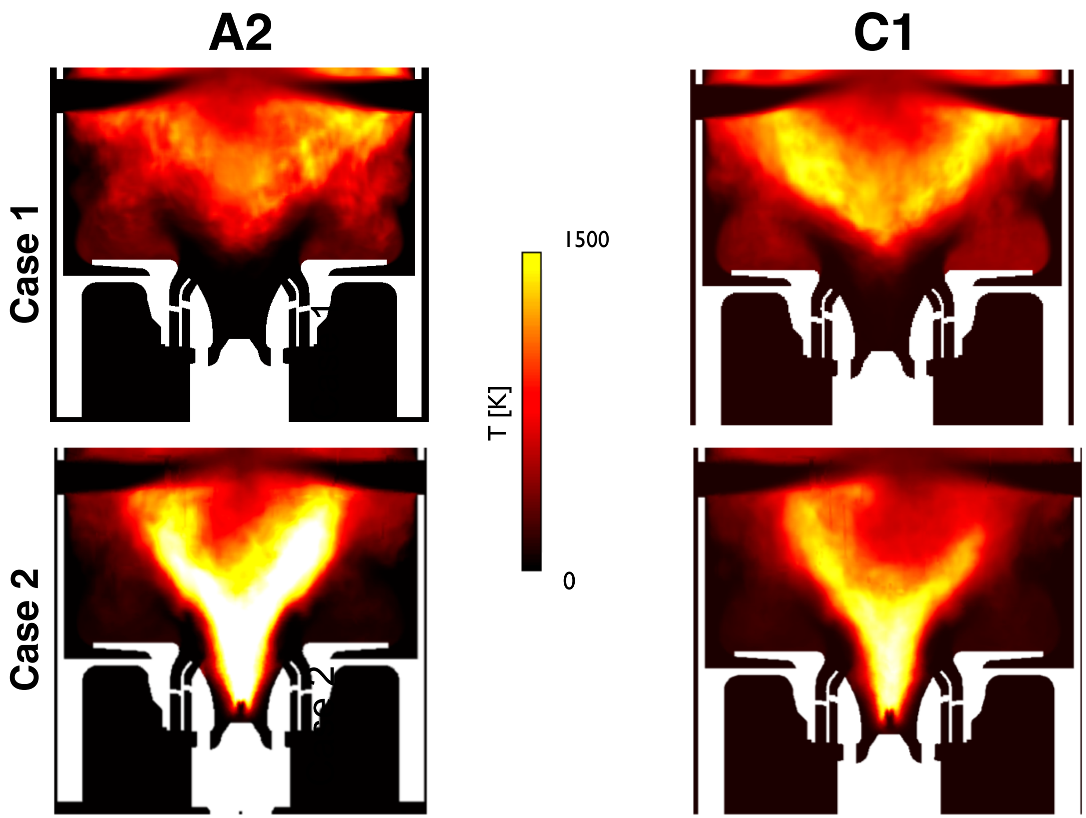
- Referee-rig simulations sensitivity to spray injection:
  - Location of stabilization
  - Degree of reactivity
  - Shape and width of reaction zone
- Similar trends observed for both fuels

Time-averaged Temperature (Case 2)



- Observable impact of fuel on mean temperature
- Both flames share similar characteristics
  - Lifted flame stabilized within swirler, low temperature in ORZ

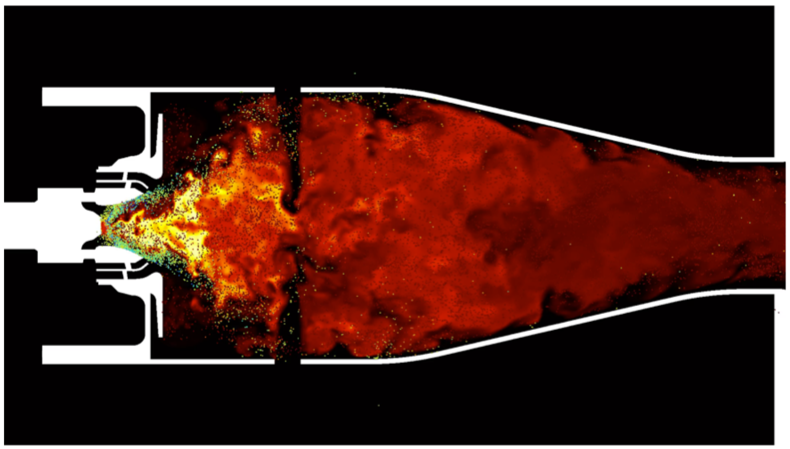
Time-averaged Temperature



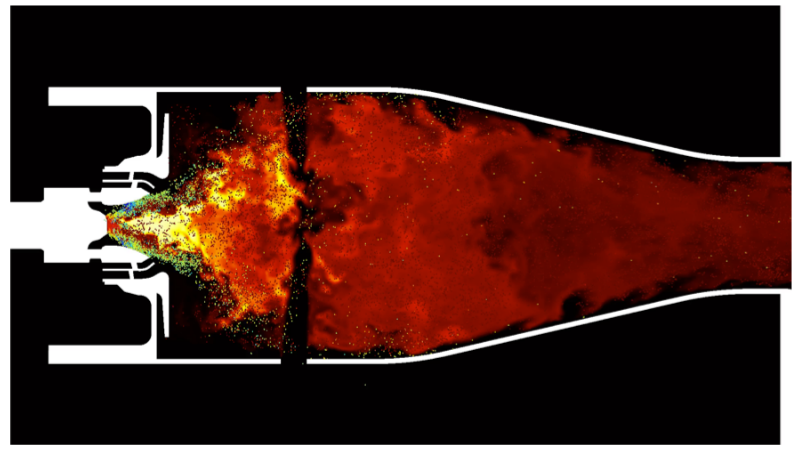
- Referee-rig simulations sensitivity to spray injection:
  - Temperature of ORZ
  - Temperature within swirler
- Similar trends observed for both fuels
- Higher temperature observed for Case 2 which produces a more stable flame

A2 and C1 transient behavior (Case 2)

A2

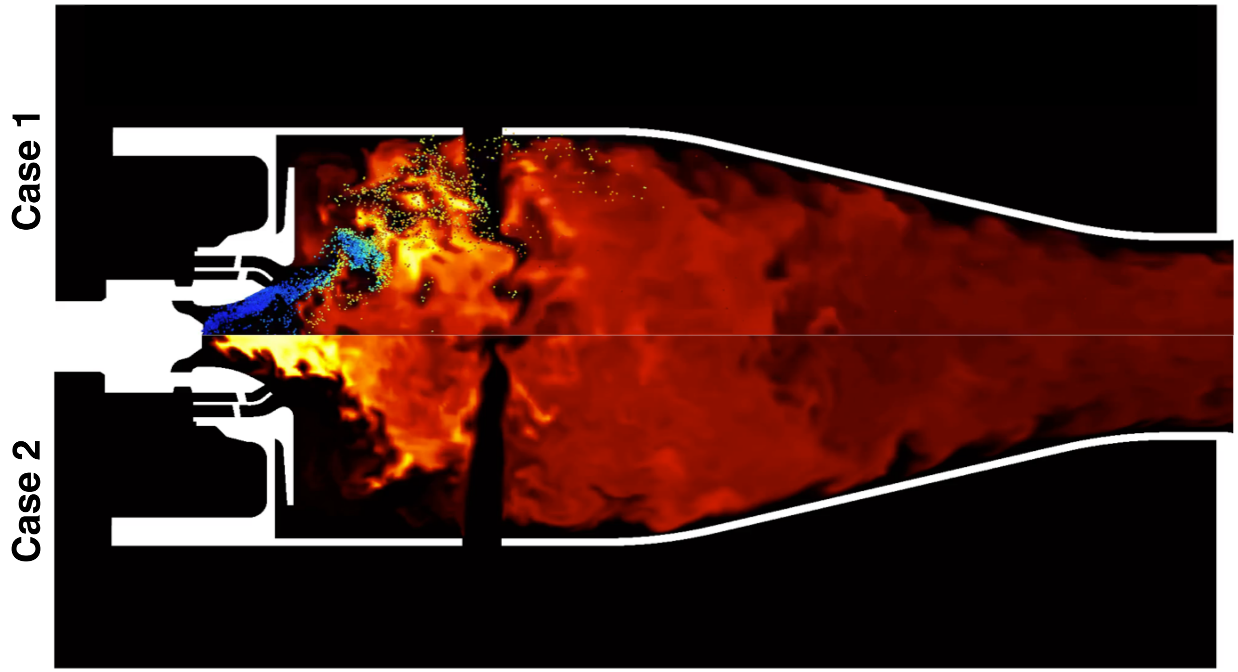


C1



- Transient behavior for both fuels are similar at stable operating condition.
  - Low temperature in ORZ
  - Reaction occurring within swirler and in IRZ
  - Similar bending of dilution jets
  - Size of IRZ similar

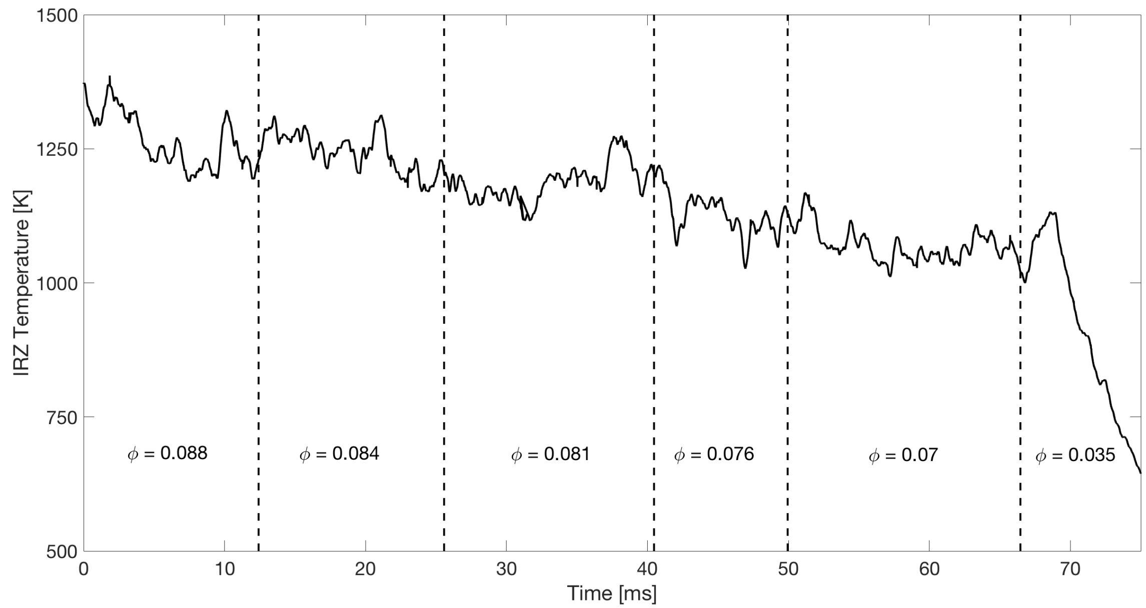
Impact of Spray injection on A2 Blow-out



A2 Temperature at Different ϕ (Case 2)

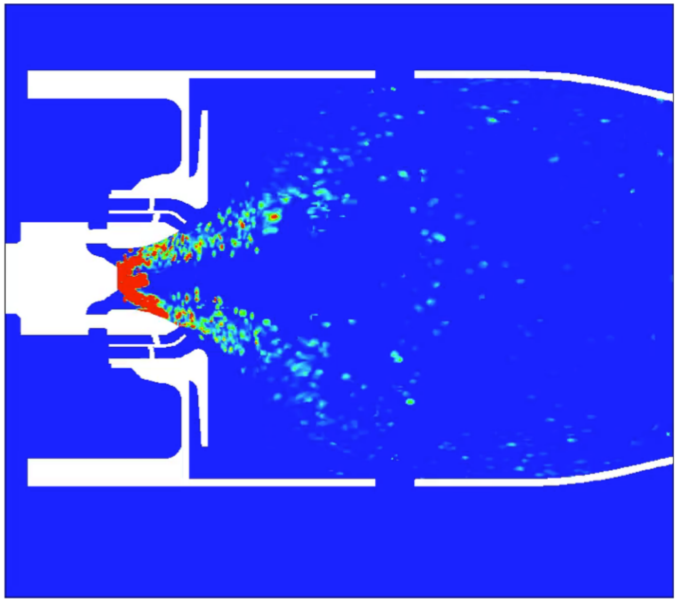
- Instantaneous temperature for ϕ=0.096 (left), 0.081 (center) and 0.035 (right)
  - All equivalent ratios show flame stabilized in swirler where near stoichiometric conditions are present
  - Lower equivalent ratios result in lower temperatures in the inner recirculation region
  - Shows a flame that is very stable

A2 IRZ temperature



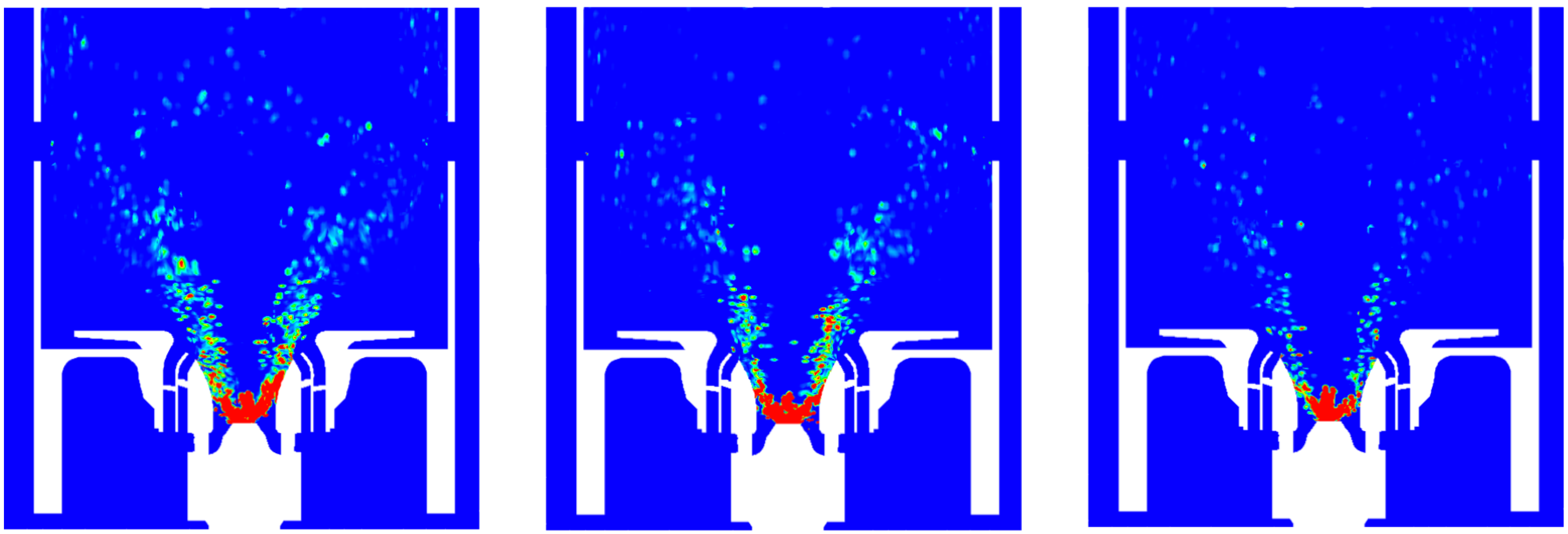
- Six step reductions from ϕ = 0.096 to 0.035
  - Starting IRZ temperature much higher when compared to old Stanford approach to LBO study
  - Large variation in instantaneous temperature is observed
  - Sharp IRZ temperature decrease for ϕ = 0.035

A2 Evaporation Rate (Case 2)



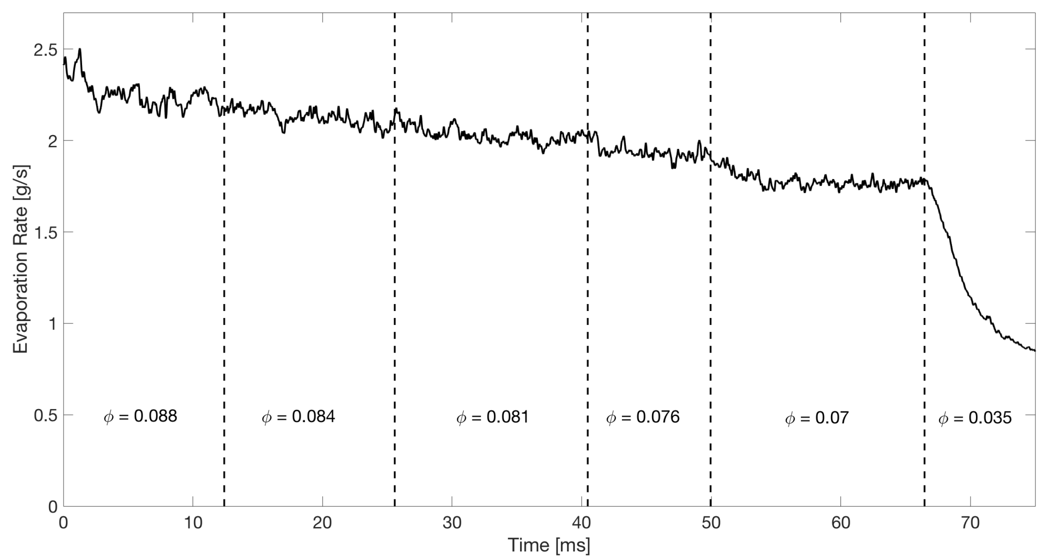
- Instantaneous evaporation rate during LBO
  - Evaporation occurs within the swirler and within the combustion chamber
  - As ϕ decrease less evaporation is observed in the combustion chamber

A2 Evaporation Rate at Different ϕ (Case 2)



- Instantaneous evaporation rate for ϕ=0.096 (left), 0.081 (center) and 0.035 (right)
  - Evaporation occurs within the swirler and within the combustion chamber
  - As ϕ decrease less evaporation is observed in the combustion chamber

A2 Evaporation Rate at Different ϕ (Case 2)



Six step reductions from ϕ = 0.096 to 0.035

- Each simulation held until "steady" evaporation rate observed
- Flame still very stable in the swirler where flame is stabilized
- LBO occurs between ϕ = 0.07 and ϕ = 0.035

Conclusions

- Current numerical tools and models able to predict fuel effect
  - Near LBO behavior
  - Transient LBO behavior

- Impact of secondary breakup significant on stability and simulation behavior
  - Droplet velocity insensitive to SBU
  - SBU reduces SMD, producing many smaller droplets which evaporate and stabilizes flame

- Stabilization location influenced by spray injection boundary conditions
  - Different flame behavior at near LBO and transient LBO simulations

Thank You !