Lean blowoff of kerosene swirl spray flames using LES-CMC

Jenna M. Foale[1], Andrea Giusti[2], Epaminondas Mastorakos[1]

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UKCTRF Annual Meeting

30/03/2021

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Current Research Focus

SR71 – afterburner blowout

- Current emphasis on fuel-lean-combustion designs to reduce emissions
  - Lean blowoff (LBO) is a critical factor
  - Lean designs increase instabilities
- Alternative jet fuels are being developed with dramatically different and unique compositions
- Fuel-chemistry observed to have largest effect at lean conditions[1]

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[1] M. Colket et al. Overview of the National Jet Fuels Combustion Program. AIAA Journal 55.4 (2017)
Image: Campbell J, Chambers J. Patterns in the sky: natural visualization of aircraft flow fields. NASA SP-514, National Aeronautics and Space Administration; 1994.

Research Objectives

- Evaluate the LES-CMC turbulence combustion model using novel detailed kerosene chemical mechanisms
- Model lean blow-off and extinction phenomena
- Analyze intermediate species trends, particularly for soot precursors

Image: https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-1000.aspx#/

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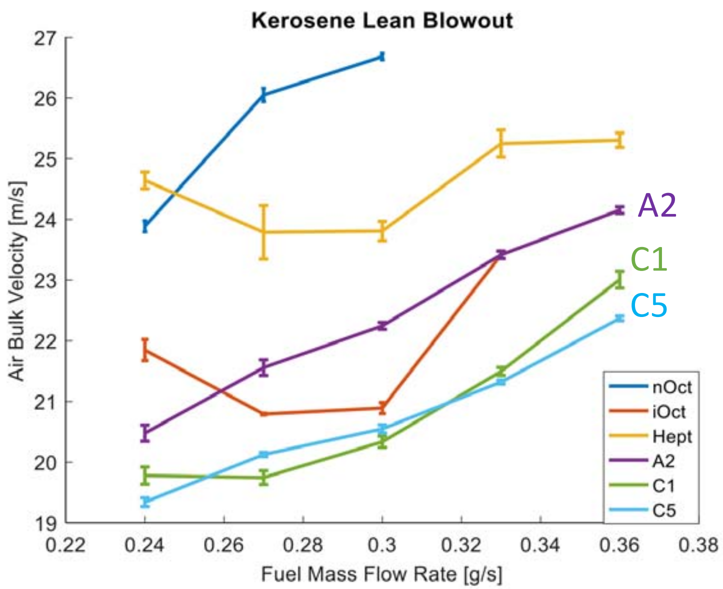
Outline

1. Context and Objectives
2. **Setup and Methods**
3. LES-CMC Results
    - Comparison with Experiments
    - Global blow-off
    - Local extinctions
4. Conclusions
5. Current/Future Work

Setup – Relevant Literature

Experiments:

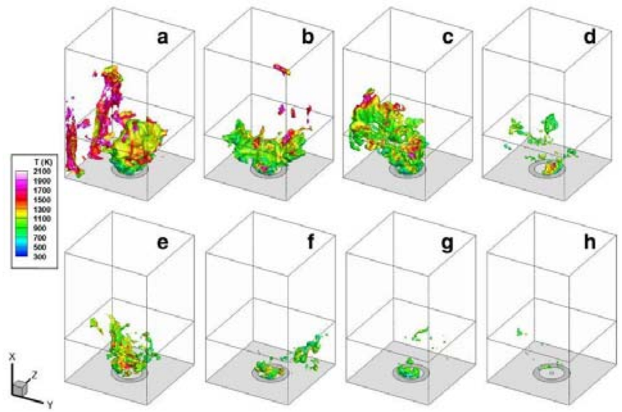
- Sidey et al. 55th AIAA Meeting. (2017)
- Allison et al. AIAA Proceedings. (2018)



Allison et al. AIAA Proceedings. 2018.

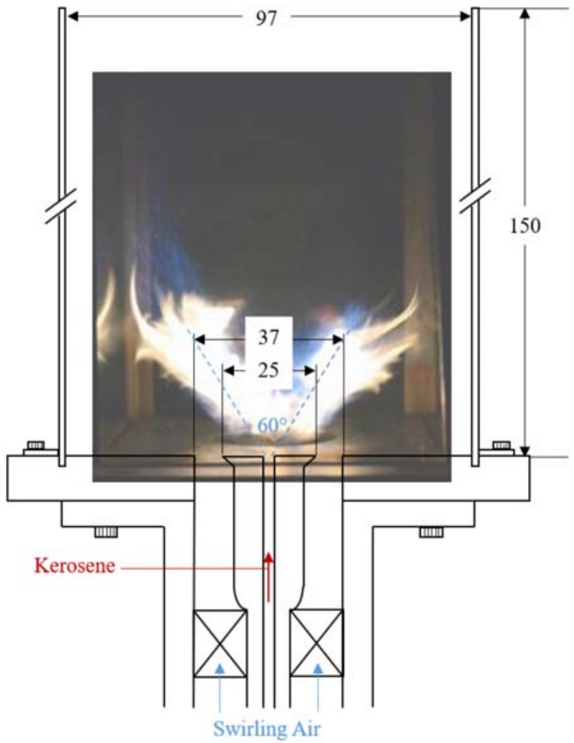
Simulations involving blow-off:

- Tyliszczak, Cavaliere & Mastorakos. Flow Turb. Comb. (2014)
  - Blow-off of n-heptane swirl flame using LES-CMC
- Zhang & Mastorakos. Flow Turb. Comb. (2016)
  - Blow-off of methane swirl flame using LES-CMC
- Giusti & Mastorakos. PROCI. (2017)
  - Blow-off of ethanol swirl spray flame using LES-CMC



Zhang & Mastorakos. FTC. 2016.

Burner Setup



- Cambridge bluff body non-premixed swirl-stabilized burner

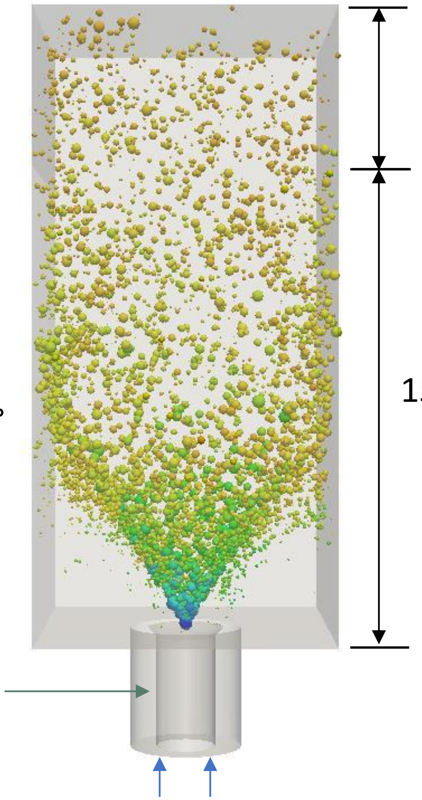
- Hollow cone kerosene spray was injected from centre of bluff body at 60° using Rosin-Rammler distribution with SMD of 60 µm based on experiments [1-2]

Kerosene Fuel:
❖ A2: conventional Jet A, $C_{11}H_{22}$

Flow conditions

$\Phi_{overall}$	U_b Air [m/s]	$\dot{m}_{fuel}$ [g/s]
0.36	15.85	0.27
0.25	22.7	0.27

Domain



[1] Sidey, J.A.M. et al., 2017, 55th AIAA Aerospace Sciences Meeting.
[2] Allison, P. M et al., *AIAA Sci-Tech 2018*, , No. AIAA 2018-1421, 2018.

Numerical Methods and Chemical Mechanism

Large Eddy Simulation (LES) - Conditional Moment Closure (CMC)

LES

- Mixture fraction $\tilde{\xi}$ and sub-grid scale $\widetilde{\xi''^2}$ transport equations

Time step: 1e-6 s
Pressure: 1 atm
T_{fuel}: 300 K
T_{air}: 300 K

CFD Solver

Mesh: 5.2 million cells, structured

OpenFOAM 2.3.1

U, ξ →

← ρ, Y_α, T, H ...

Combustion Model

CMC[3]

Mesh: 5714 cells

of η nodes: 51

Evaporation: Abramzon and Sirignano[1]
Fuel properties: Esclapez et al.[2]

CMC

- In-house unstructured CMC code with spray terms [3]
- Amplitude Mapping Closure model for scalar dissipation rate $\widetilde{N|\eta}$

T_{fuel}: 475 K
T_{air}: 300 K
$N_{0,max}$: 30 s^{-1}

HyChem "A2" kerosene mechanism [5]: lumped pyrolysis, single-component fuel, 119 species, 843 reactions

- ➢ Main products of pyrolysis are: ethylene, propene, iso-butene, 1-butene, benzene, toluene, hydrogen and the methyl radical
- ➢ Oxidized with detailed mechanism USC-Mech II (not pictured)

```
POSF10325    =>                   1.7426762C2H4 + 0.8190578C3H6 + 0.0871338iC4H8 + 0.2614014C4H81 + 0.1700C6H6 + 0.1633333C6H5CH3 + 0.5H + 1.5CH3
POSF10325+H  =>    H2 + 0.45CH4 + 1.5945764C2H4 + 0.7494509C3H6 + 0.0797288iC4H8 + 0.2391865C4H81 + 0.2465C6H6 + 0.2368333C6H5CH3 + 0.3H + 0.7CH3
POSF10325+CH3=>         1.45CH4 + 1.5945764C2H4 + 0.7494509C3H6 + 0.0797288iC4H8 + 0.2391865C4H81 + 0.2465C6H6 + 0.2368333C6H5CH3 + 0.3H + 0.7CH3
POSF10325+OH =>   H2O + 0.45CH4 + 1.5945764C2H4 + 0.7494509C3H6 + 0.0797288iC4H8 + 0.2391865C4H81 + 0.2465C6H6 + 0.2368333C6H5CH3 + 0.3H + 0.7CH3
POSF10325+O2 =>   HO2 + 0.45CH4 + 1.5945764C2H4 + 0.7494509C3H6 + 0.0797288iC4H8 + 0.2391865C4H81 + 0.2465C6H6 + 0.2368333C6H5CH3 + 0.3H + 0.7CH3
POSF10325+HO2=>  H2O2 + 0.45CH4 + 1.5945764C2H4 + 0.7494509C3H6 + 0.0797288iC4H8 + 0.2391865C4H81 + 0.2465C6H6 + 0.2368333C6H5CH3 + 0.3H + 0.7CH3
POSF10325+O  =>    OH + 0.45CH4 + 1.5945764C2H4 + 0.7494509C3H6 + 0.0797288iC4H8 + 0.2391865C4H81 + 0.2465C6H6 + 0.2368333C6H5CH3 + 0.3H + 0.7CH3
```

[1] Abramzon, B., & Sirignano, W. Int. J. Heat Mass Transfer, 32, (1989).
[2] Esclapez, L. et al., Combust. Flame, 181, (2017).
[3] Giusti, A. and Mastorakos, E., Proc. Combust. Inst., 36, (2017).
[4] Perini, F. et al., Energy and Fuels, 26, (2012)
[5] Wang, H. et al. Combust. and Flame, 193 (2018).

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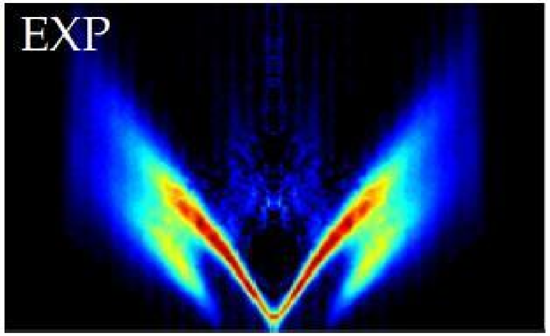
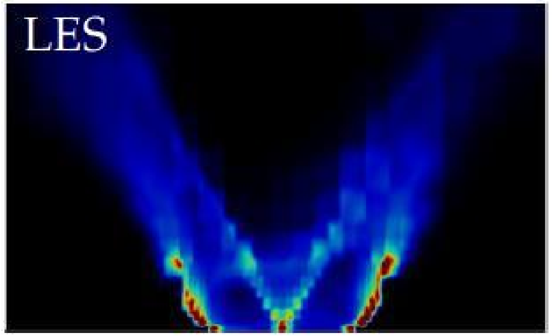
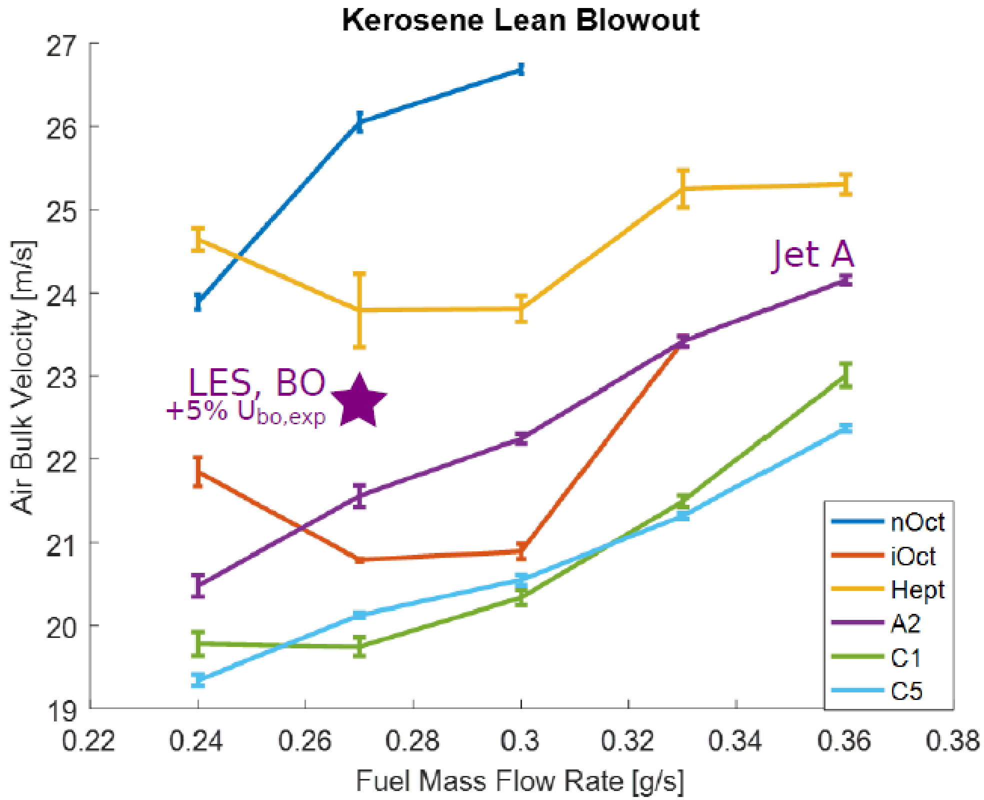
Results – Comparison with experiment

Inverse Abel-transformed time-averaged OH*



Time-averaged 2D cut-plane of OH*

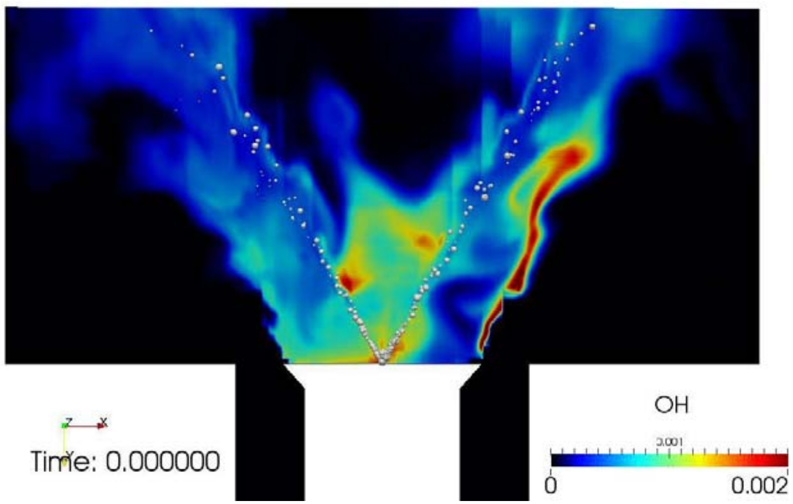




[1] Sidey, J.A.M. et al., 2017, 55th AIAA Aerospace Sciences Meeting.
[2] Allison, P. M et al., *AIAA Sci-Tech 2018*, , No. AIAA 2018-1421, 2018.

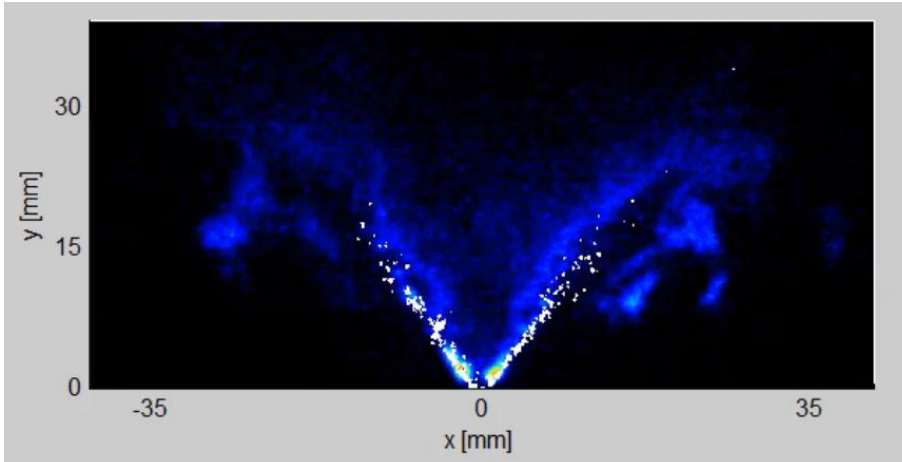
Results – Comparing with experiment

Simulation



LES-CMC of Lagrangian spray and gaseous OH

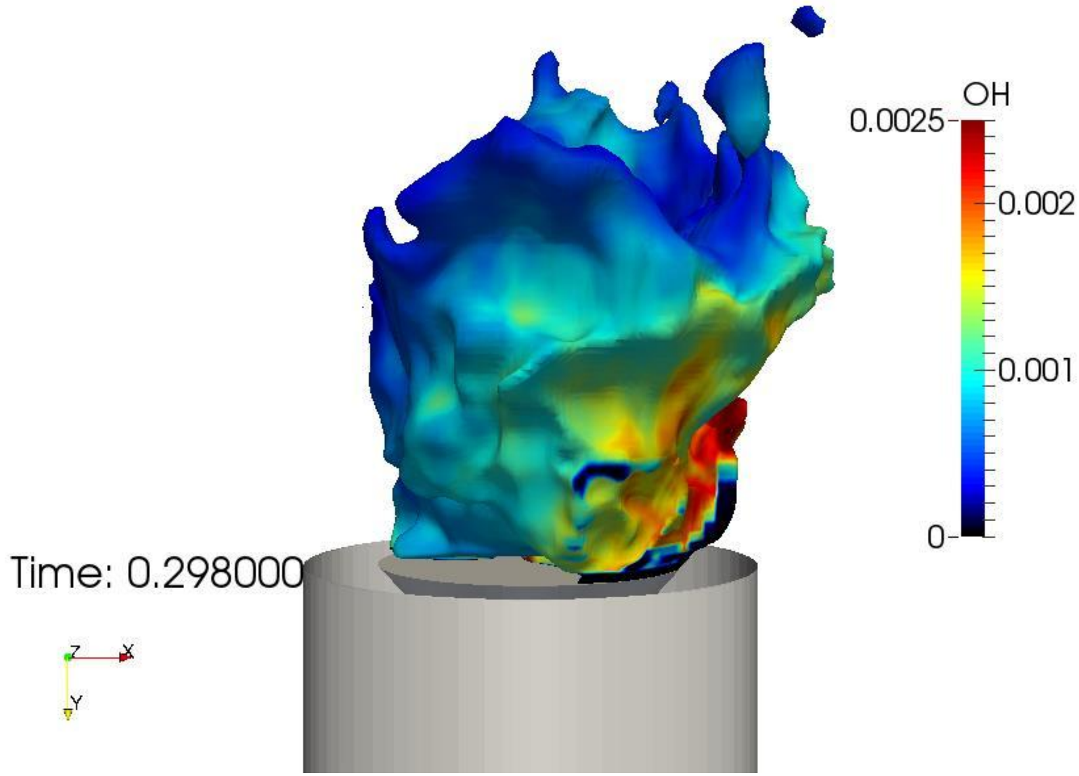
Experiment



OH-PLIF Mie of Jet-A [1]

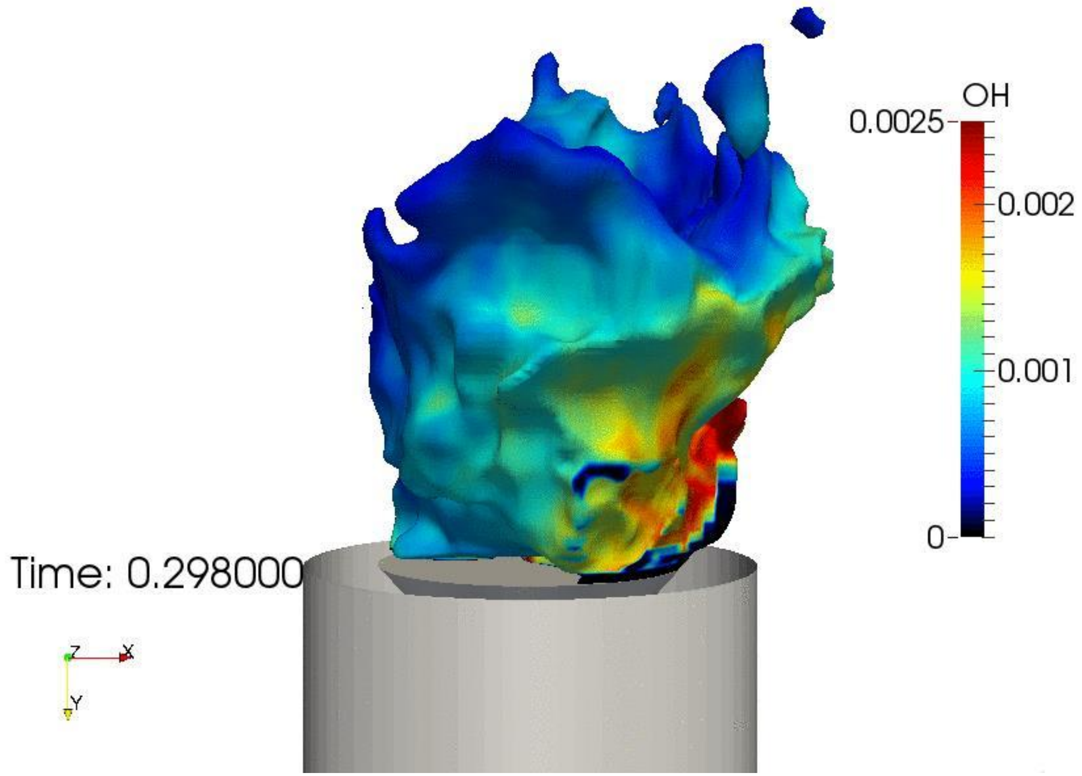
[1] Sidey, J.A.M. et al., 2017, 55th AIAA Aerospace Sciences Meeting.

Results – Global blowoff



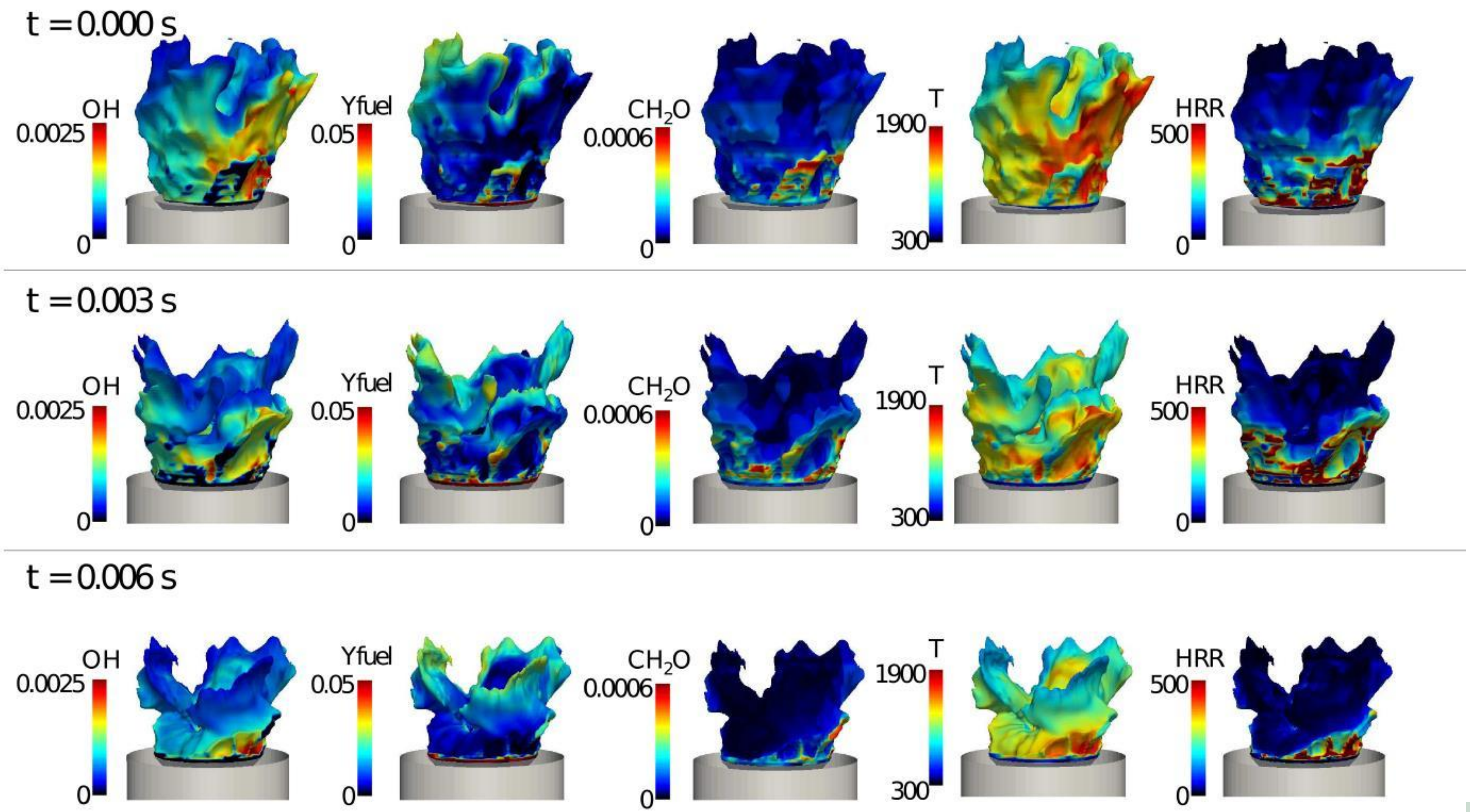
ξ_{st} isosurface colored with OH mass fraction

Results – Global blowoff

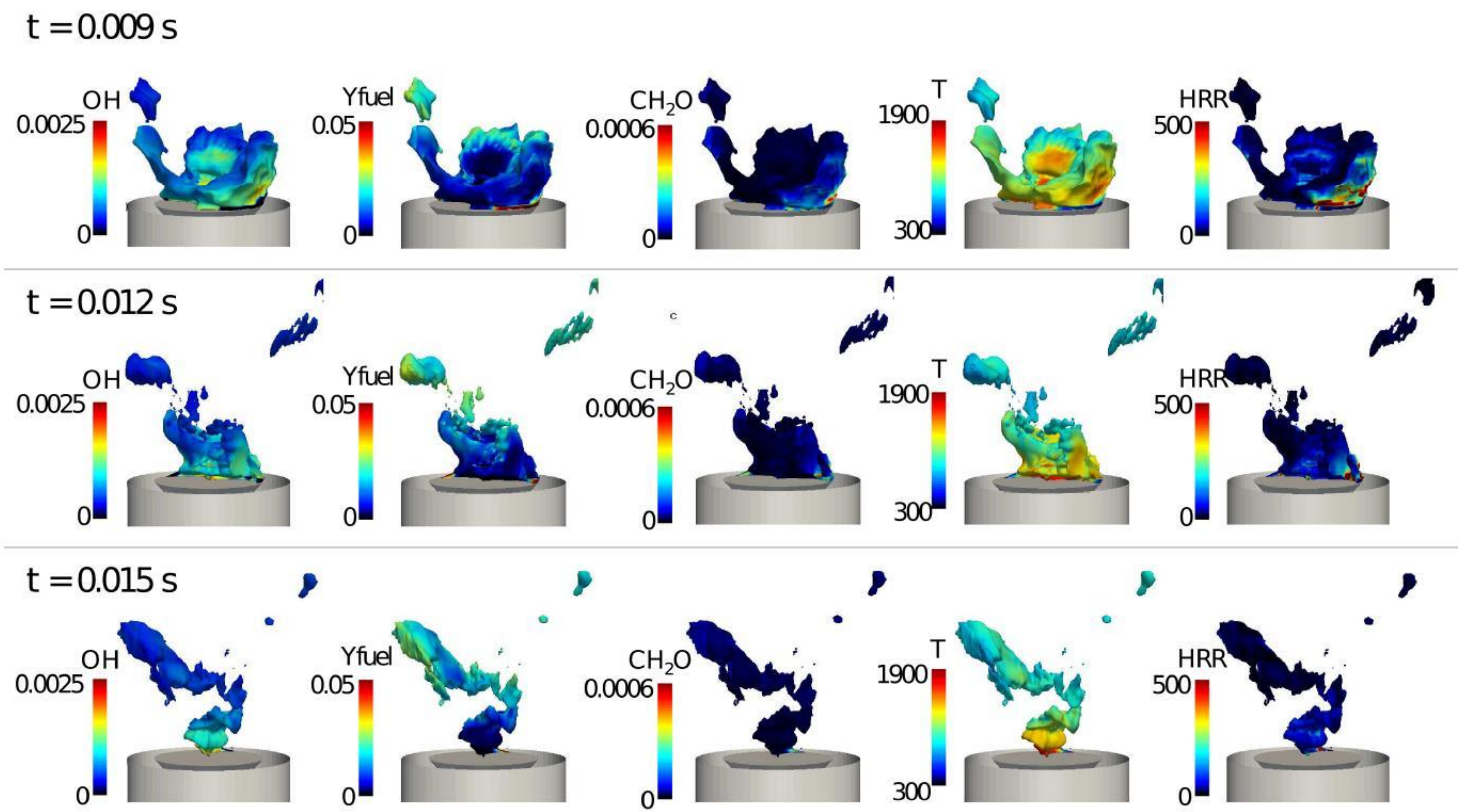


ξ_{st} isosurface colored with OH mass fraction

Results – Global blowoff



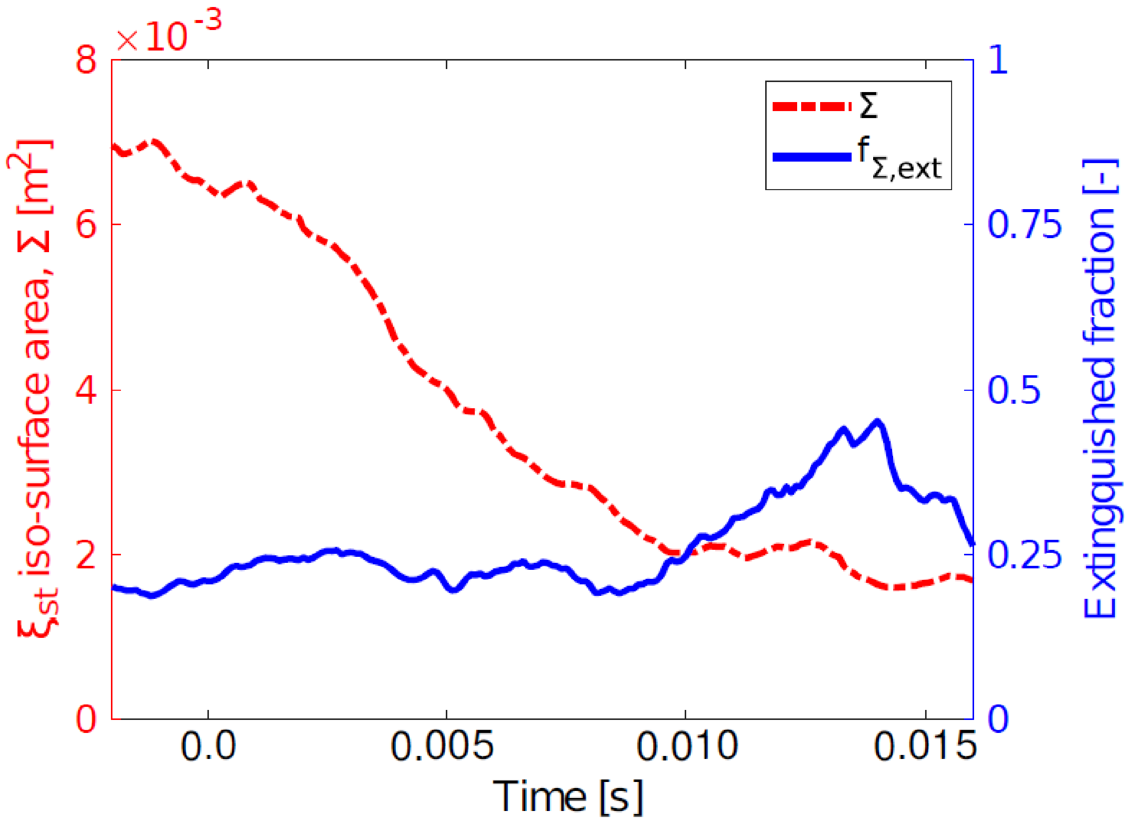
Results – Global blowoff



Results – Extinguished fraction

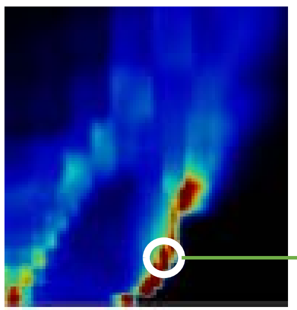
$$f_{ext} = \frac{\Sigma|\left(\widetilde{Y_{OH}|\xi_{st}} < 0.00045\right)}{\Sigma}$$ [1]

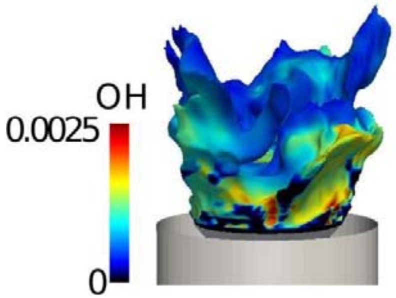
- The extinguished fraction, f_{ext}:
- f_{ext} = 1 is complete extinction
- f_{ext} = 0 is fully burning

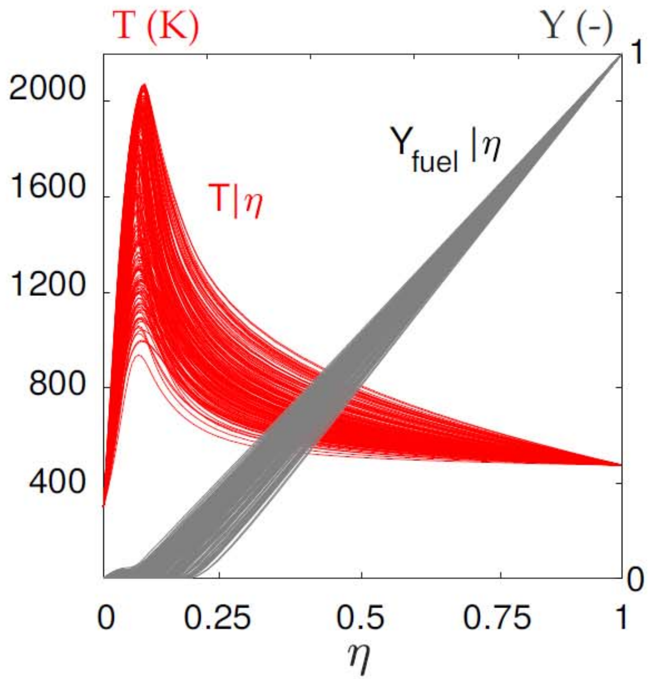


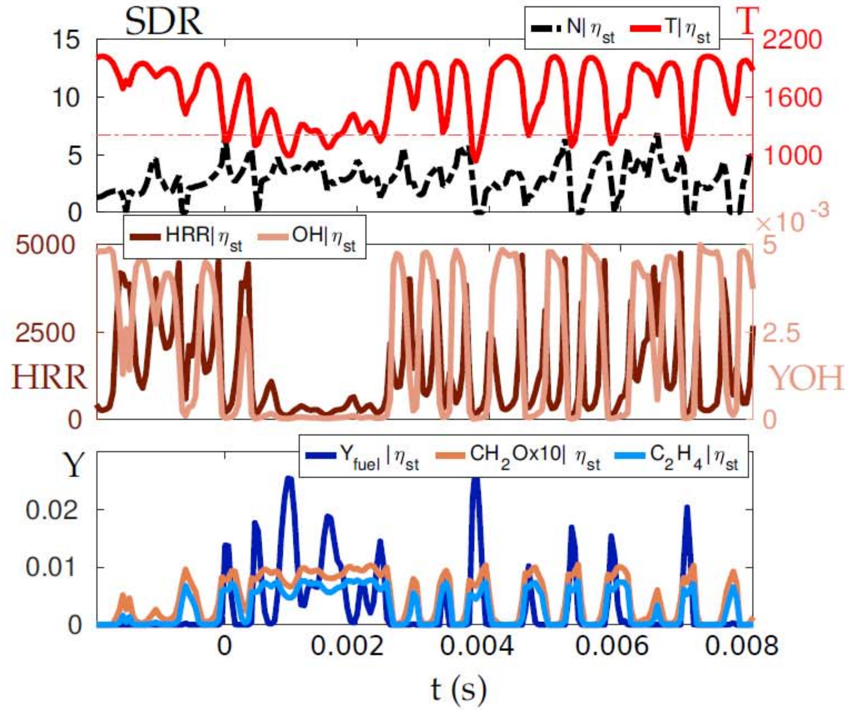
[1] Zhang & Mastorakos. Flow, Turbulence and Combustion. 2016.

Results – Local extinction



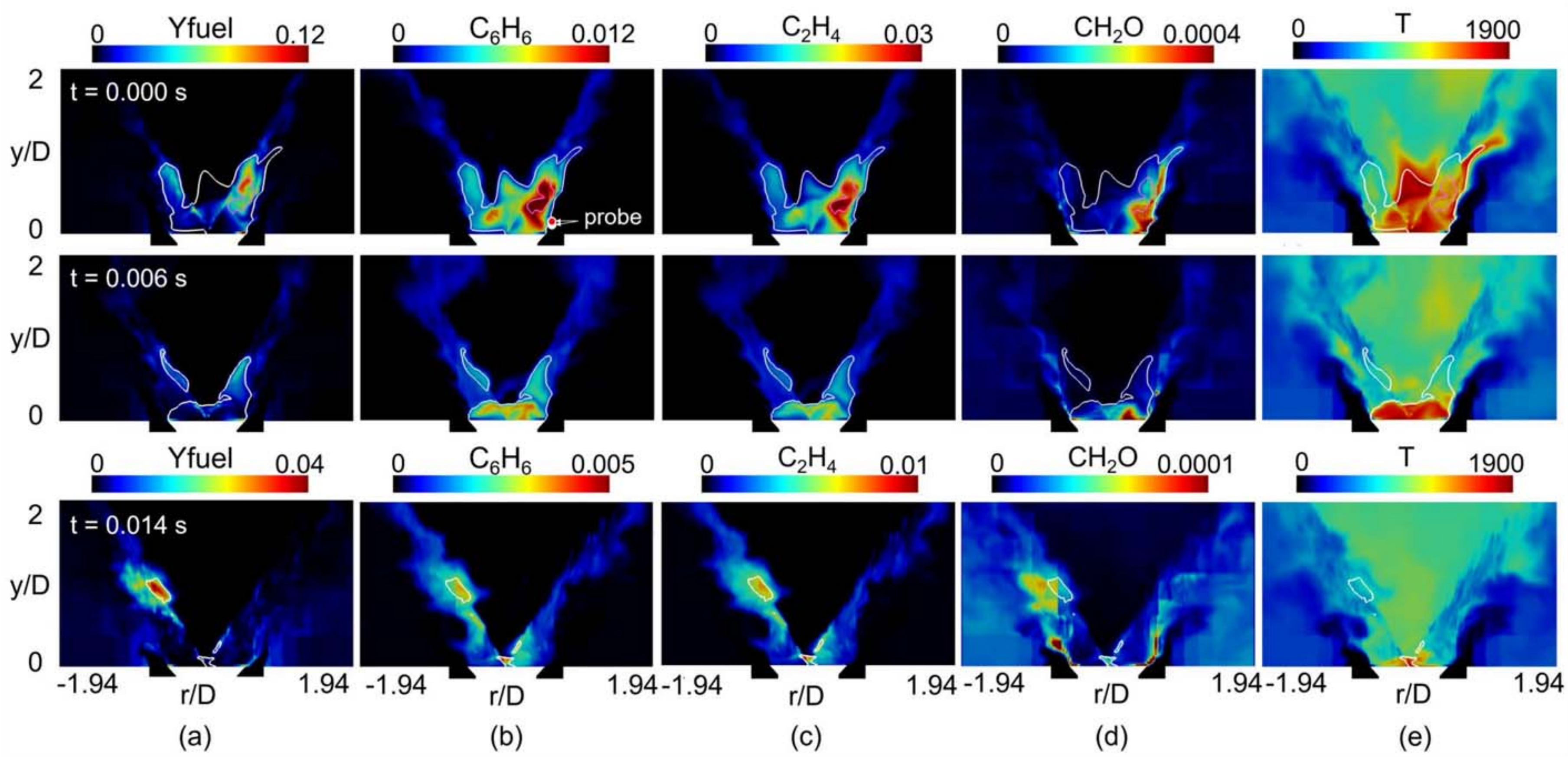




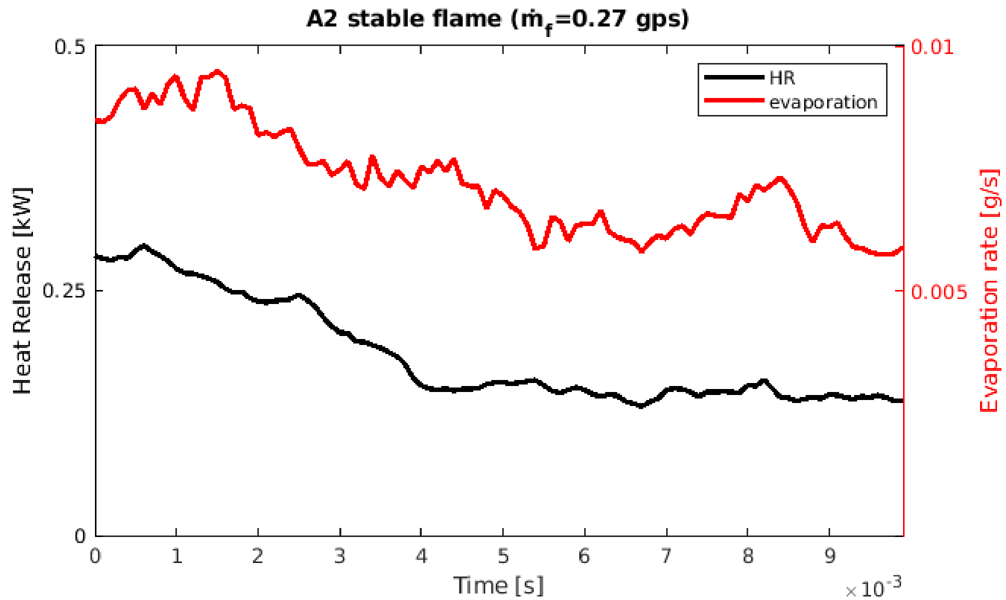


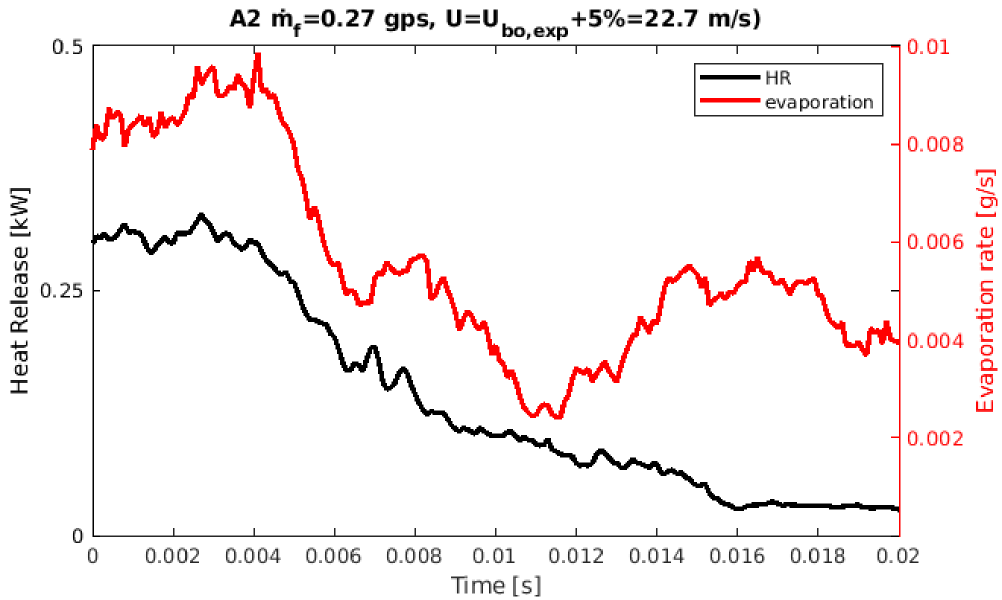
- Probe of CMC cell along the shear layer showing quantities in mixture fraction space

Results – Intermediate species



Results – Heat release and evaporation rate





Local volume integrated heat release rate and evaporation using volume of cells around the stoichiometric mixture fraction isosurface

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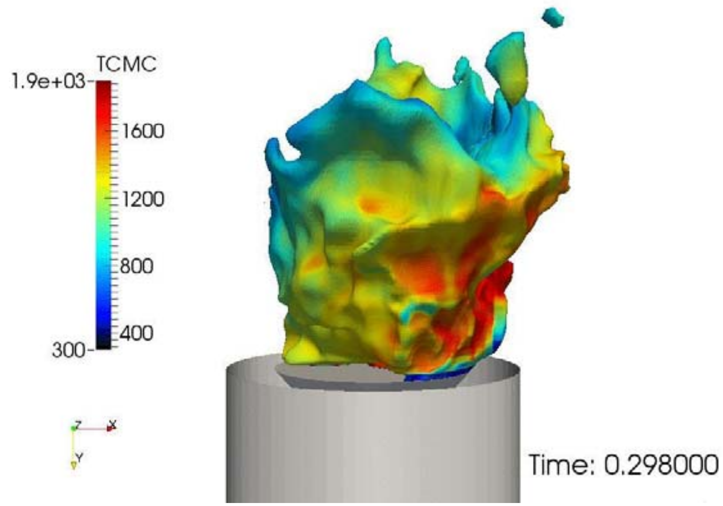
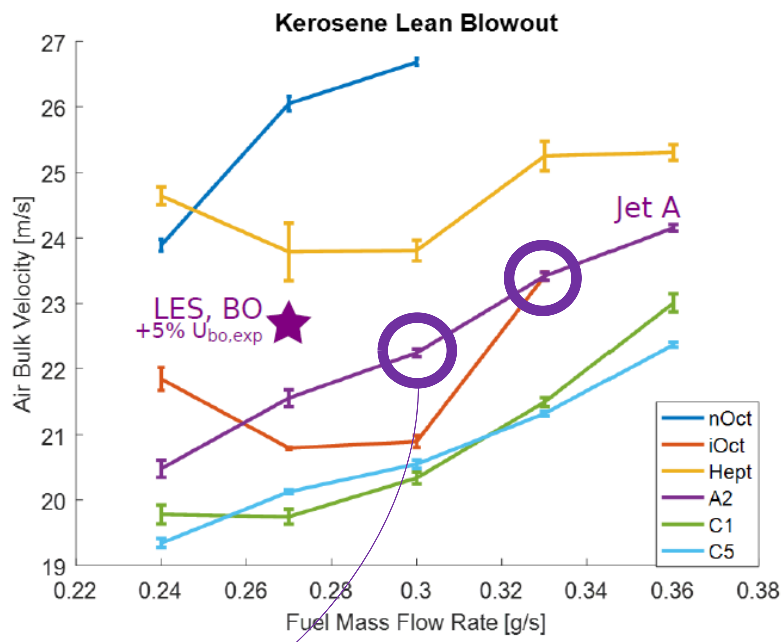
Conclusions

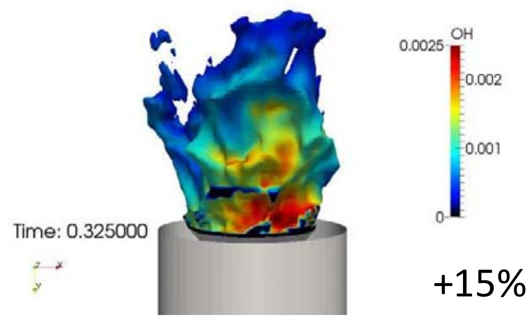
- Simulated the blowoff transient of a Jet-A swirl spray flame using detailed chemistry
- Captured local extinctions visually and quantitatively
- Flame appeared to blowoff because of both fuel starvation and local extinctions
- Observed blowoff of the flame within +5% of experimental air bulk velocity
- Affirmed capability of LES-CMC to model blowoff of real fuels



Current & Future Work

- Two more mass flow rate conditions from Jet-A blowoff curve being simulated
    - ➢ Want full simulated blowoff curve for kerosene
- Simulation of alternative jet fuel C1 from National Jet Fuels Combustion Program, comparison with Jet-A and experiments





+15% of experimental blowoff velocity

Acknowledgments

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Thank you for listening!

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