UNIVERSITY OF CAMBRIDGE

LES/CMC of unsteady flames

Andrea Giusti, Huangwei Zhang, Philip M. Sitte & E. Mastorakos

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Department of Engineering

Motivational slide for combustion scientists and to convince EPSRC that we are not that useless…

1960s

2010s

B787

Outline

- Lean Blow Off

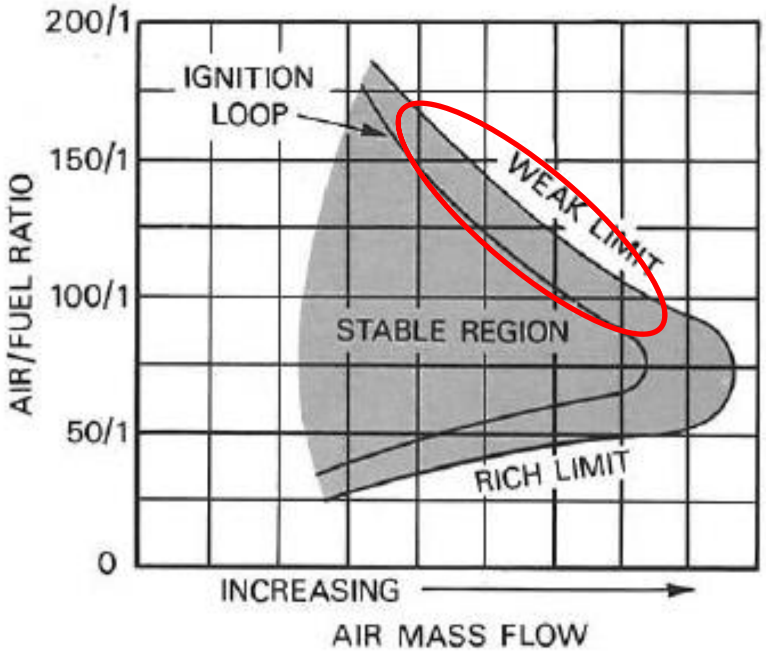
- LES/CMC – equations & modelling

- Edge flame propagation in non-premixed systems
- Local extinction – Sandia F, Cambridge swirl CH_4; Sydney swirl CH_4
- Local extinction – sprays
- Global extinction – Cambridge swirl CH_4
- Global extinction – spray swirl ethanol

- Using LES/CMC for discovery/explanation of physics

- Concluding remarks

Lean Blow Out: important practical problem



Capturing extinction is one of the “Holy Grails” of turbulent combustion theory.

Can we predict blow-off curve with CFD? This talk shows evidence we are making good progress.

Finite-rate kinetics effect - extinction

- Model must have “good enough” chemistry to predict extinction: test on laminar flames.
- Model must include spatial and temporal fluctuation of strain and mixing rates.

- Available models that fit the bill (to various degrees):

  Conditional Moment Closure

  Transported PDF (Lagrangian or Eulerian)

  Progress variable – mixture fraction flamelet

  Stirred reactor

  Linear Eddy Model

Conditional Moment Closure

$$\frac{\partial Q_\alpha}{\partial t} = \langle N|\eta\rangle \frac{\partial^2 Q_\alpha}{\partial \eta^2} + \langle \dot{w}_\alpha|\eta\rangle - \left[\tilde{u}_j - D_t \frac{1}{\widetilde{\xi''^2}} \frac{\partial \tilde{\xi}}{\partial x_j}\left(\eta - \tilde{\xi}\right)\right]\frac{\partial Q_\alpha}{\partial x_j}$$

$$+ \frac{1}{\bar{\rho}\tilde{P}(\eta)} \frac{\partial}{\partial x_j}\left[\bar{\rho}\tilde{P}(\eta) D_t \frac{\partial Q_\alpha}{\partial x_j}\right]$$

$$+ \langle S|\eta\rangle - \langle S|\eta\rangle Q_\alpha - (1-\eta)\langle S|\eta\rangle \frac{\partial Q_\alpha}{\partial \eta}$$

Steady flamelet model

Transient flamelet model

Terms responsible for flame propagation, heat losses to walls, stabilization etc.

$\langle N|\eta\rangle$ Conditional scalar dissipation. Model needed.

Droplet interactions. Model for <S|η> needed.

Scalar dissipation rate (for LES)

$$\widetilde{N} = \underbrace{D\left(\frac{\partial \tilde{\xi}}{\partial x_i}\right)^2}_{\text{resolved}} + \underbrace{\frac{1}{2} C_N \frac{\nu_t}{\Delta^2} \widetilde{\xi''^2}}_{\text{subgrid}}$$

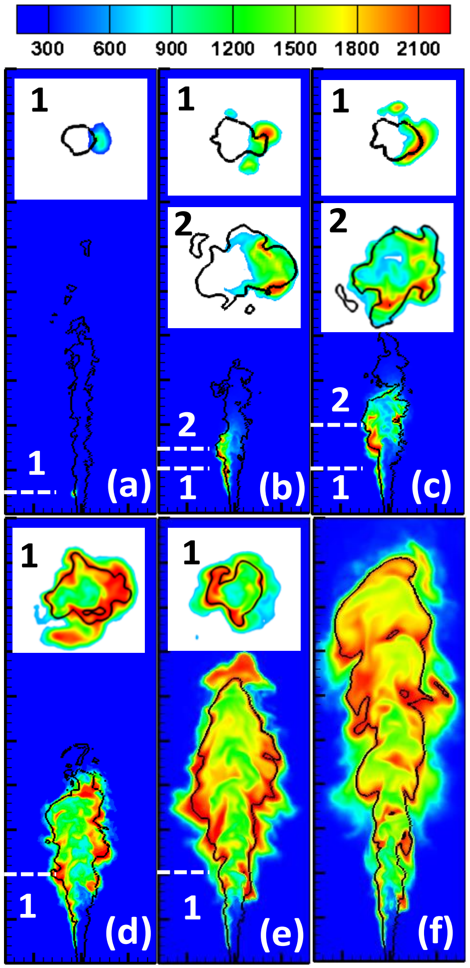
$$\widetilde{N|\eta} = N_0 G(\eta),$$

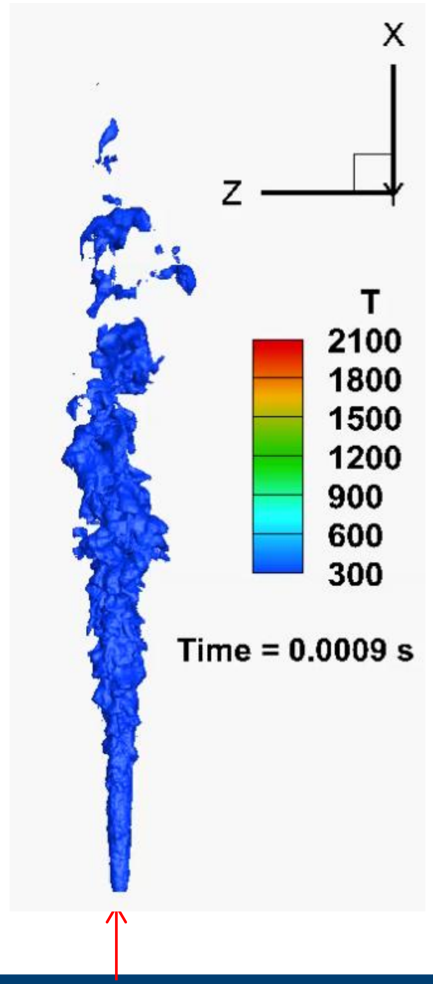
$$G(\eta) = \exp\left(-2\left[\operatorname{erf}^{-1}(2\eta - 1)\right]^2\right)$$

$$N_0 = \frac{\widetilde{N}}{\int_0^1 G(\eta)\widetilde{P}(\eta)d\eta}$$

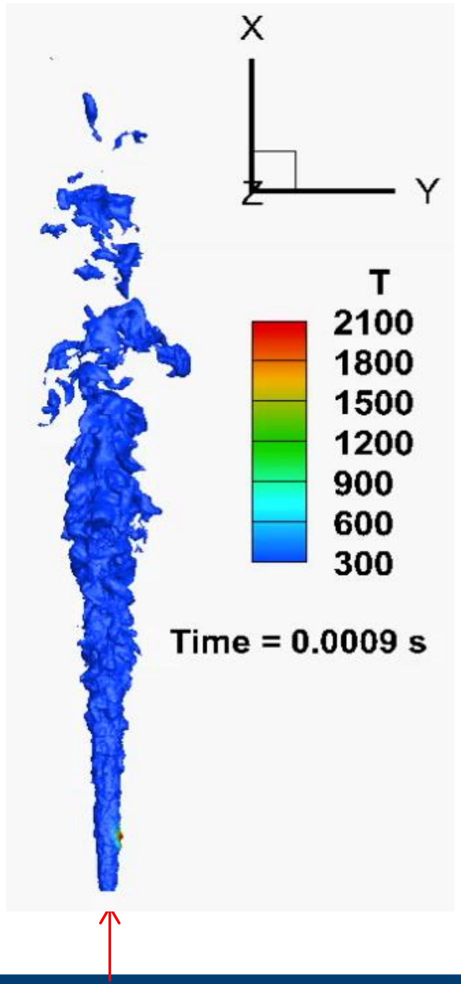
C_N=42.0

Flame propagation in non-premixed systems





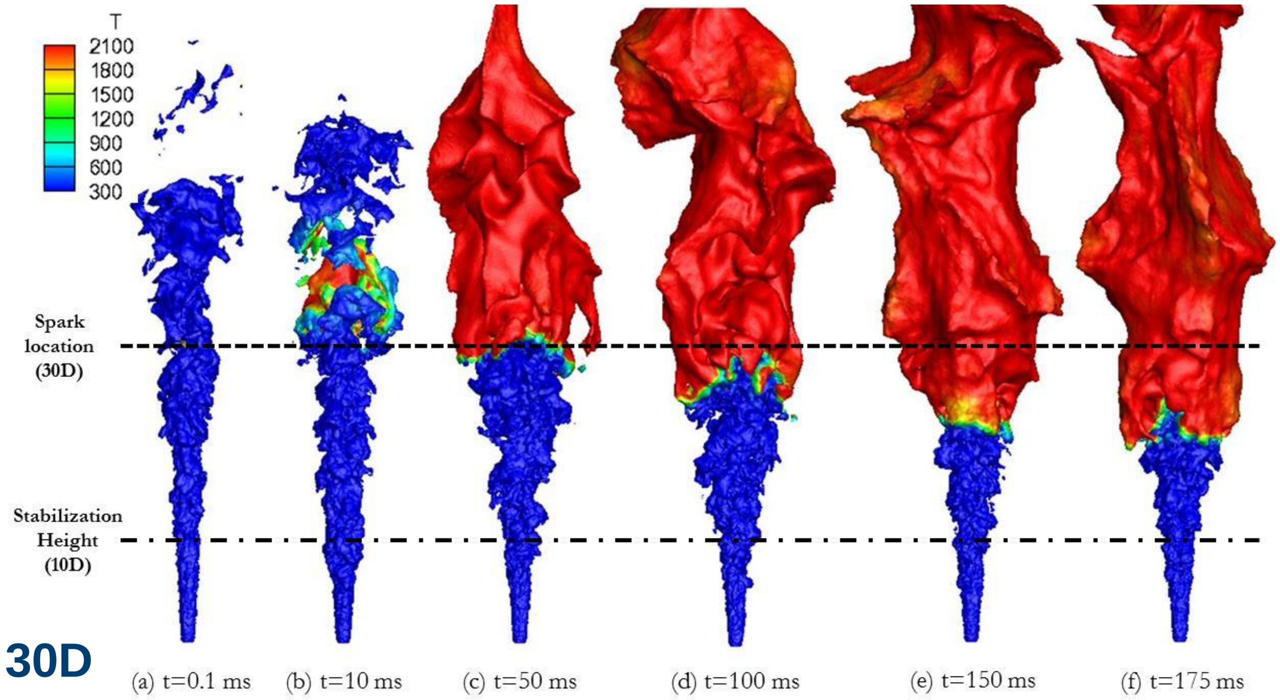
Air-diluted CH_4

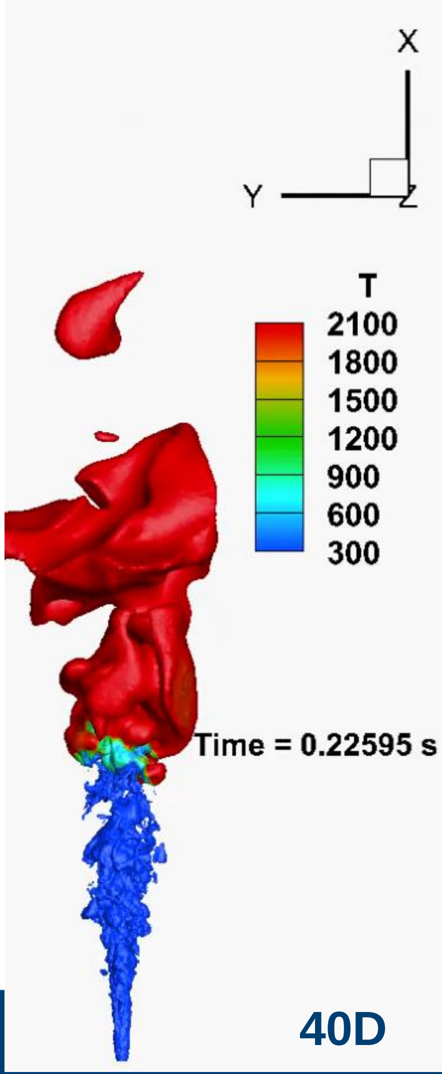


Air-diluted CH_4

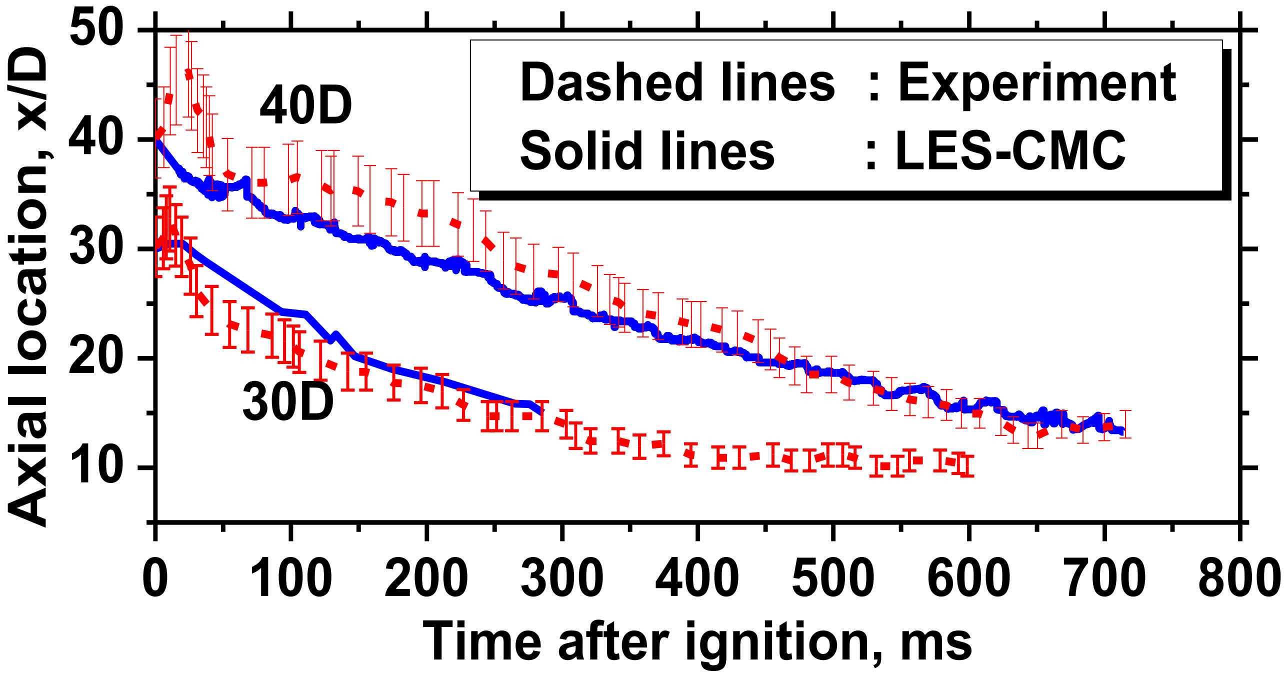
Flame development

3D iso-surfaces of stoichiometric mixture fraction colored by resolved temperature



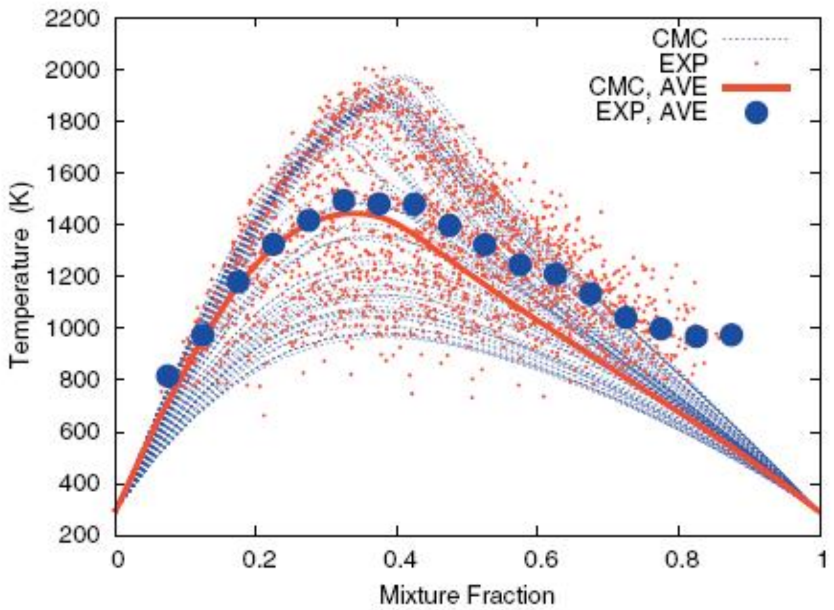


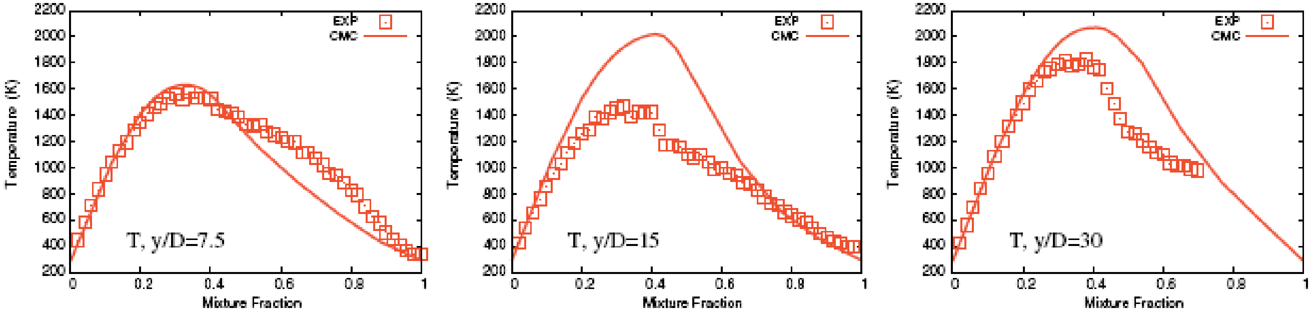
Flame development



- LES/CMC predicts the time series of the flame edge locations reasonably well.
- The lift-off height shows good agreement with the measured data.

Local extinction: Sandia F (PROCI 33)

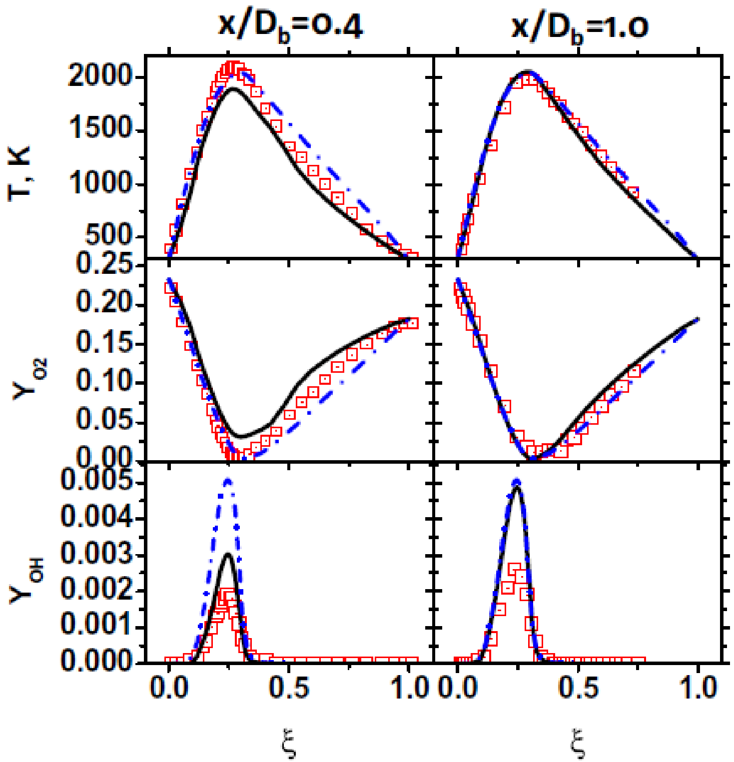




Overall very good agreement for Sandia D & F

Local extinction at Sydney swirl flame

LES/CMC of the CH_4 non-premixed Sydney flame (Zhang & Mastorakos, PROCI 36, 2017)



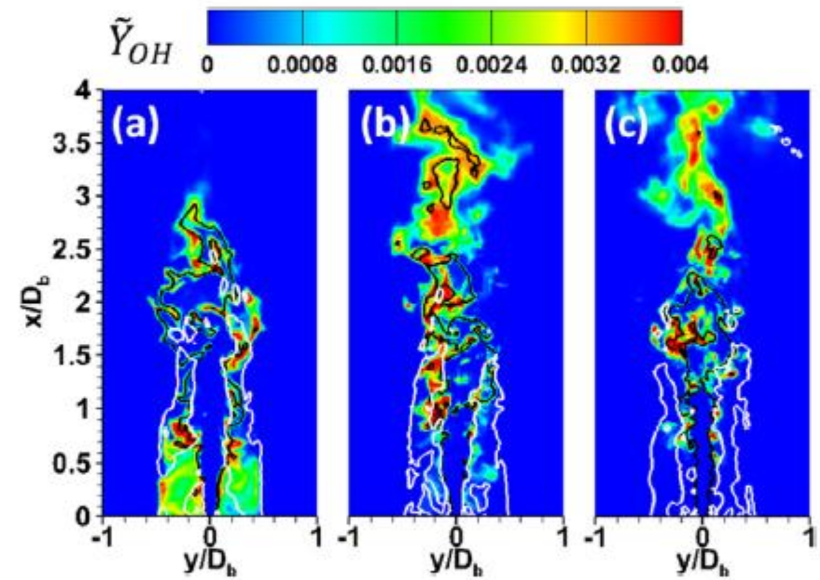


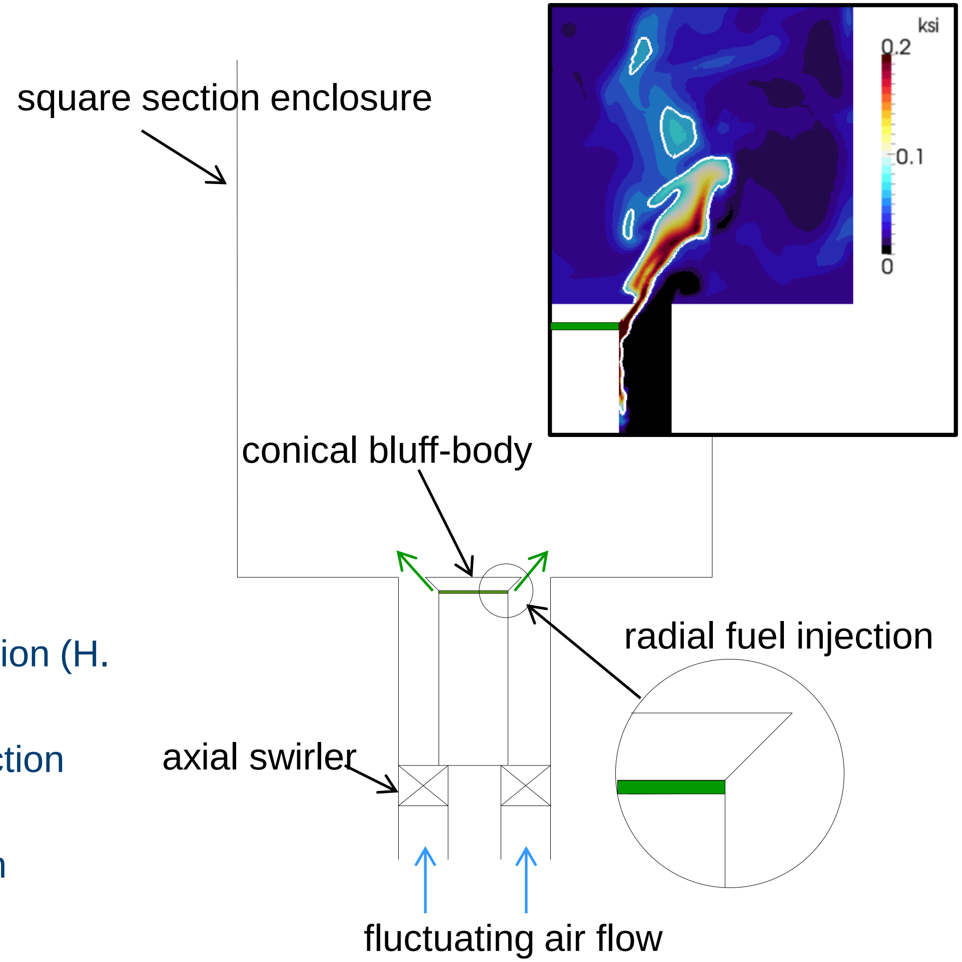
Fig. 6. Contours of $\tilde{Y}_{OH}$ from (a) SMA2, (b) SMA3 and (c) SMA4. Black lines: stoichiometric mixture fraction; white lines: zero axial velocity.

Localised extinction captured correctly.

Validation against unconditionally- and conditionally-averaged quantities

Experiments & simulations at Cambridge

- One burner, many flames
  - a) Premixed flame
  - b) Non-premixed with axial injection
  - c) Non-premixed with radial injection
  - d) Spray flames
- Overall objective of research
  - Can we predict the blow-off condition?
  - Investigate the flame response to pulsations



- Simulations

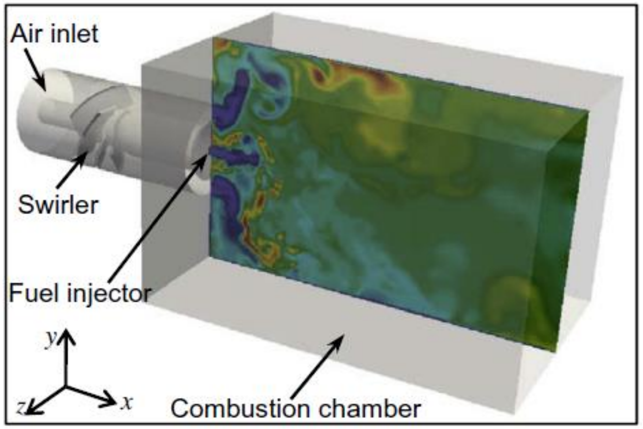
  LES/CMC – axial injection of CH_4, focus on extinction (H. Zhang, FTaC 2016)

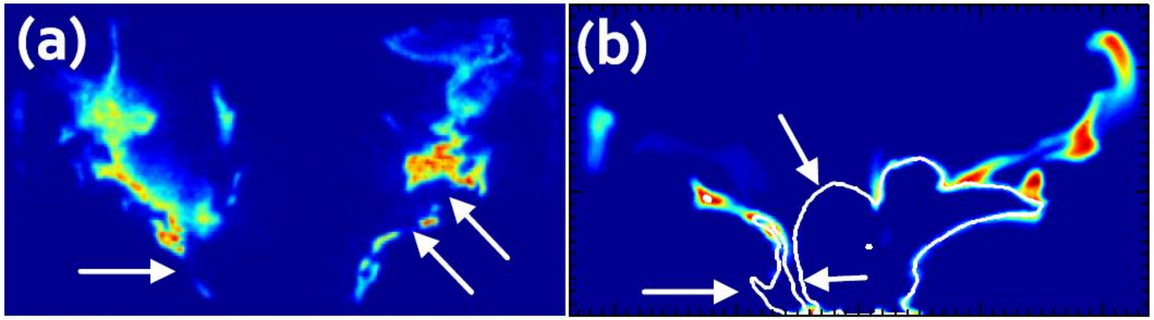
  LES/CMC – radial injection of CH_4, focus on extinction (A.Giusti)

  LES/CMC – spray of liquid fuel, focus on extinction (A.Giusti)

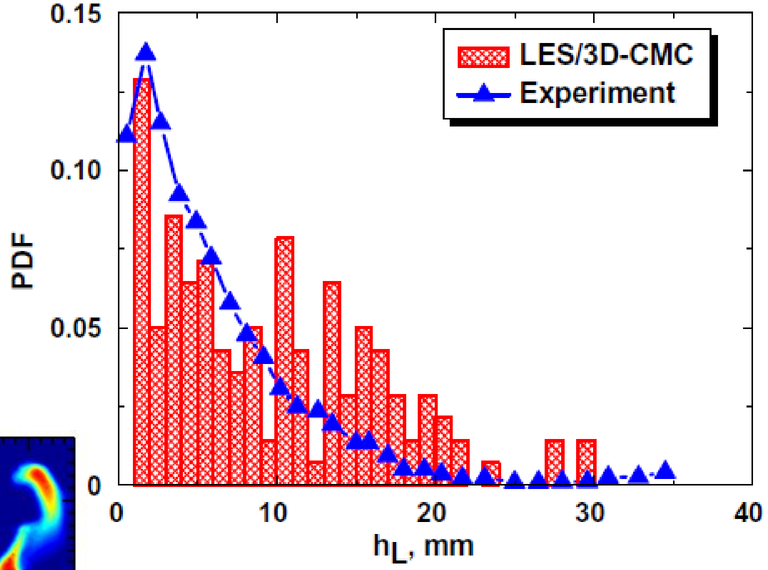
Local extinction at Cambridge swirl flame

LES/CMC of the CH_4 non-premixed Cambridge flame (Zhang & Mastorakos, PROCI 35, 2015)



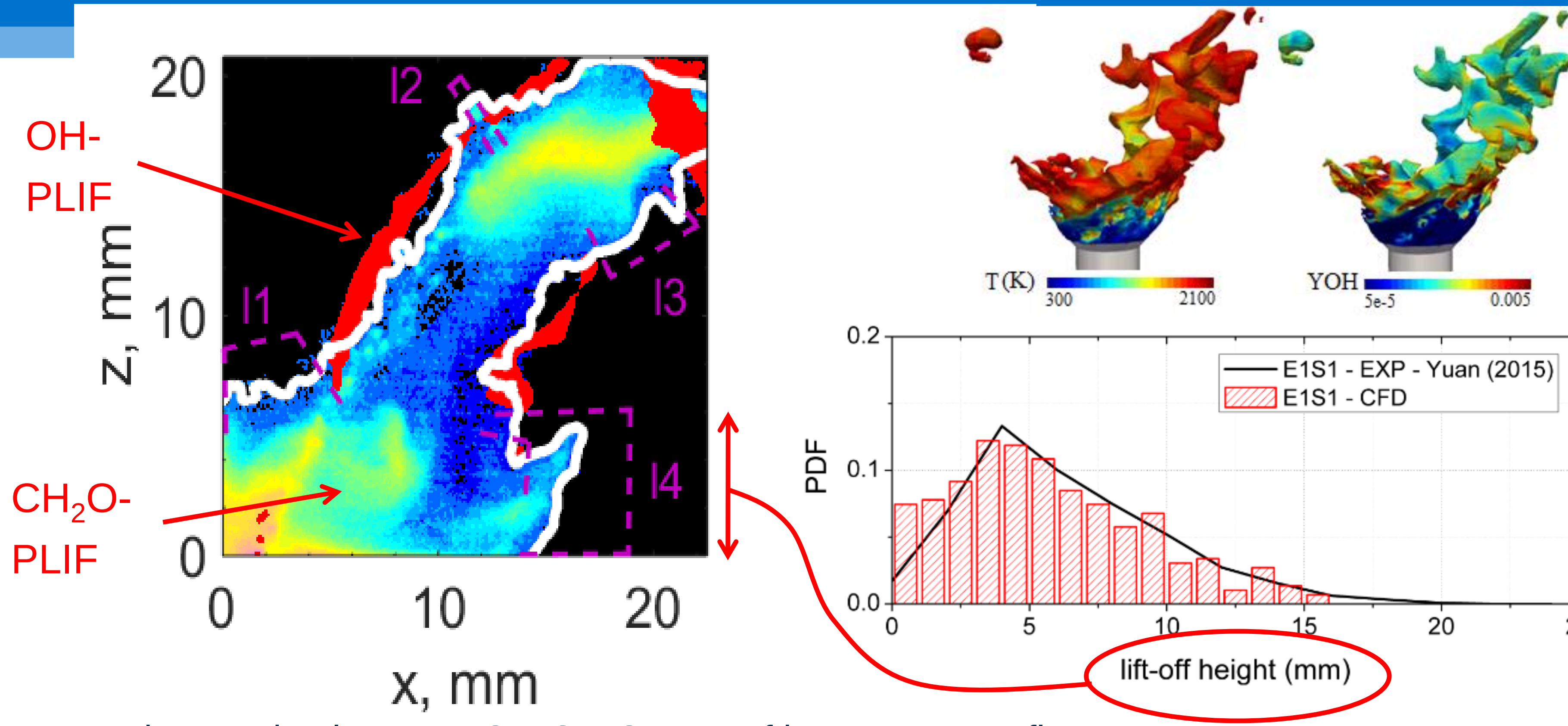


OH-PLIF (Exp) OH (LES)



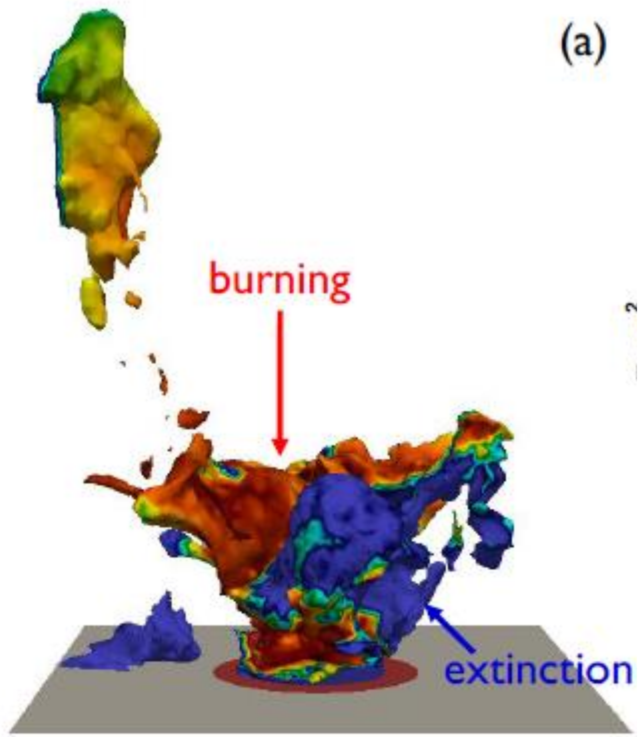
Flame lift-off captured OK

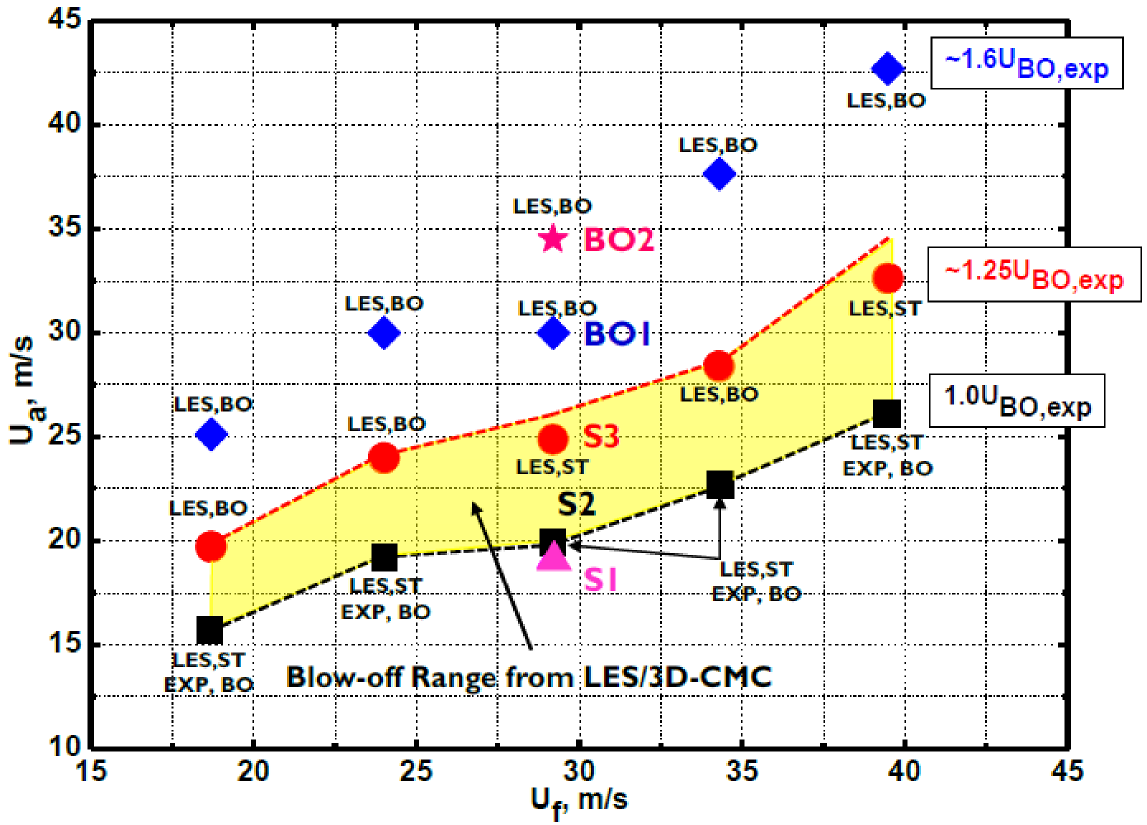
Spray flames close to blow-off (Yuan et al, PROCI 35; Giusti et al, PROCI 36)



- Experiment: simultaneous OH-CH_2O PLIF of heptane spray flame
- Laminar flame simulations suggest that CH_2O boundary $\approx \xi_{st}$. Close to blow-off: percentage of quenched ξ_{st} iso-surface increases. Statistical metric for model validation.
- LES reproduces experimental measurements of lift-off height at corner.

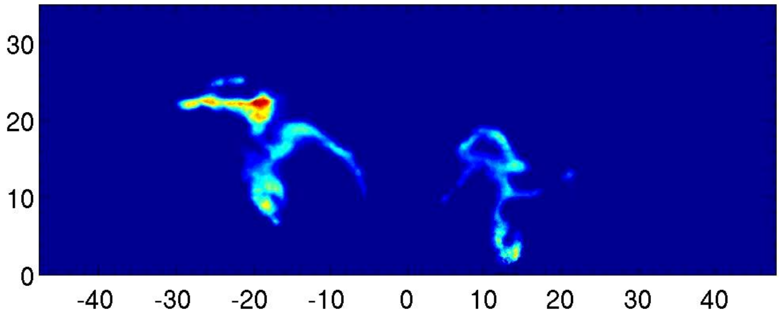
Global extinction (Zhang & Mastorakos, FTaC 2016)



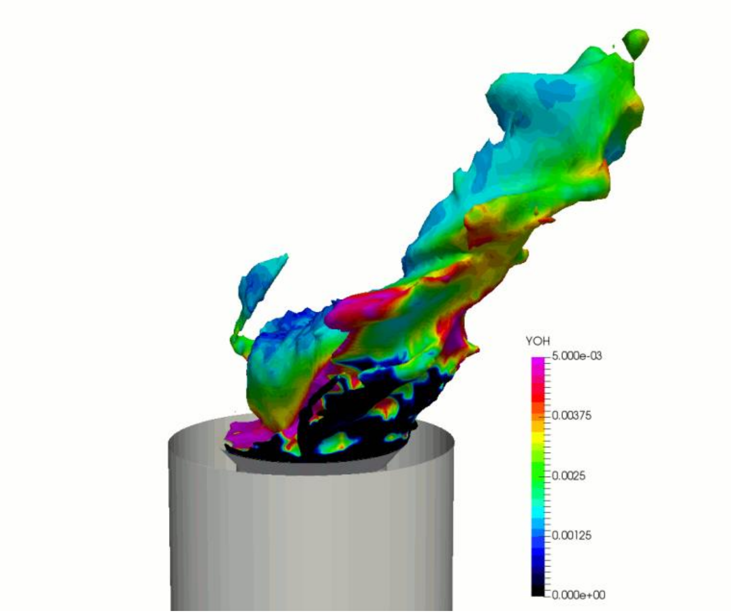


For CH_4 flame, full blow-off curve predicted to within 25% !

Blow-off transient – ethanol spray flame



OH-PLIF from the experiment (R. Yuan, 2015)

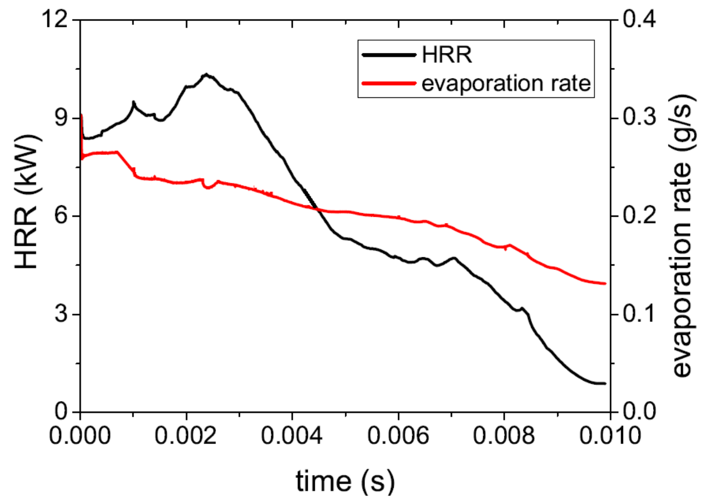


a) **The flame sheet becomes more and more fragmented**

b) **The initial V-shape is completely destroyed**

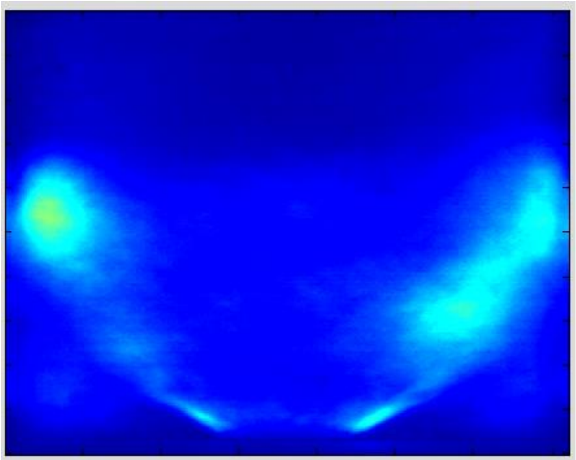
c) **The last surviving flame appears close to the injection location**

Blow-off was achieved by imposing an air mass-flow rate 20% higher than the experimental blow-off velocity



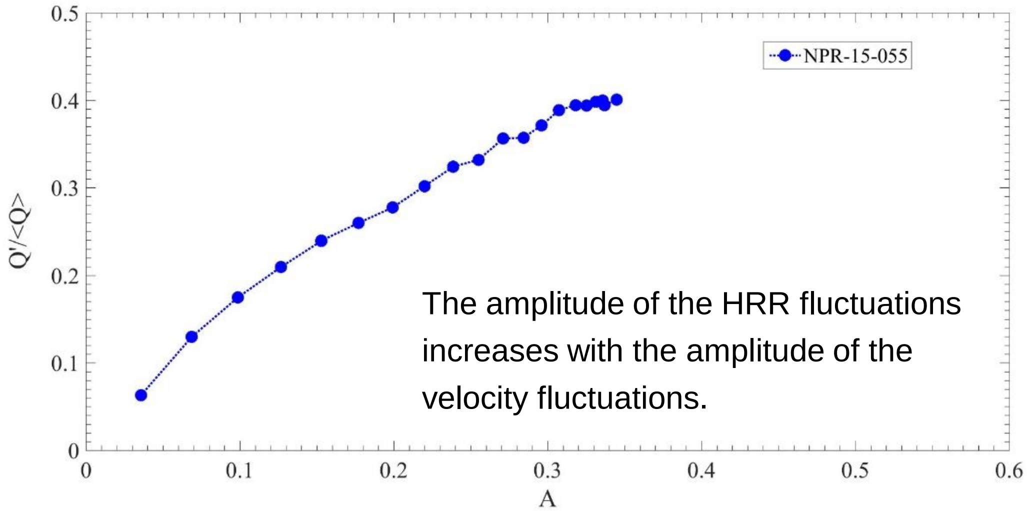
Unsteady behaviour - thermoacoustics

- …from the experiment



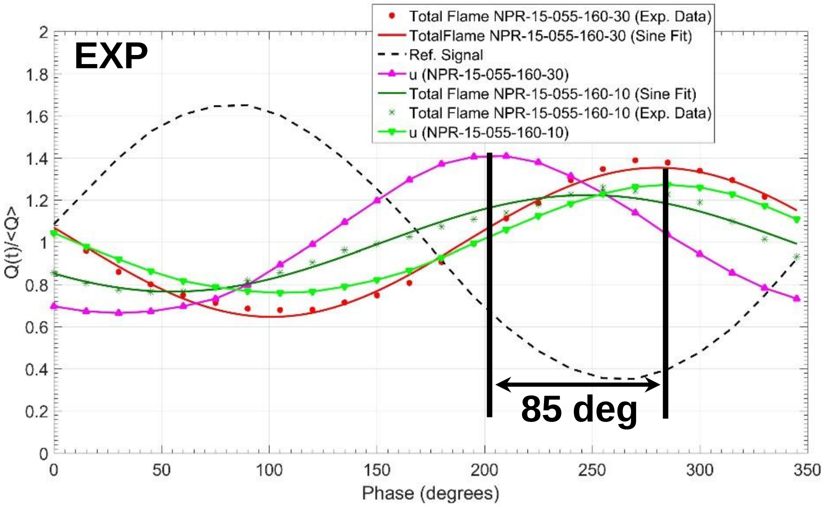
Phase-locked OH* chemiluminescence signal

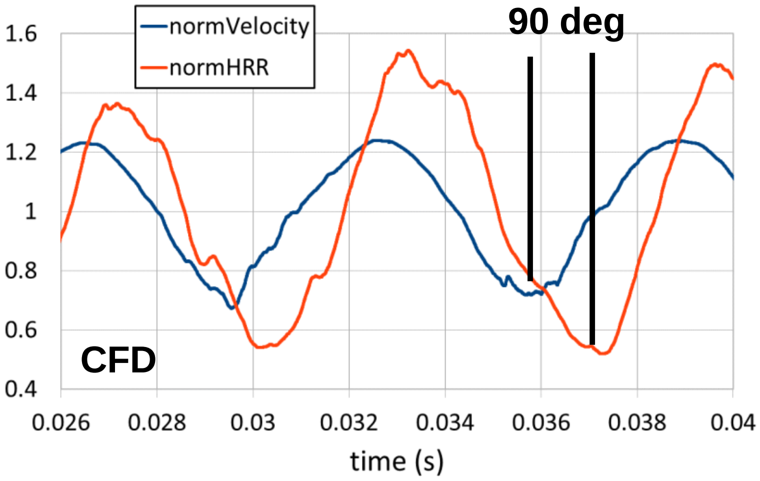
- ➢ F = 160 Hz
- ➢ A = 0.3
- ➢ Ub = 15 m/s
- ➢ Global eq. ratio = 0.55



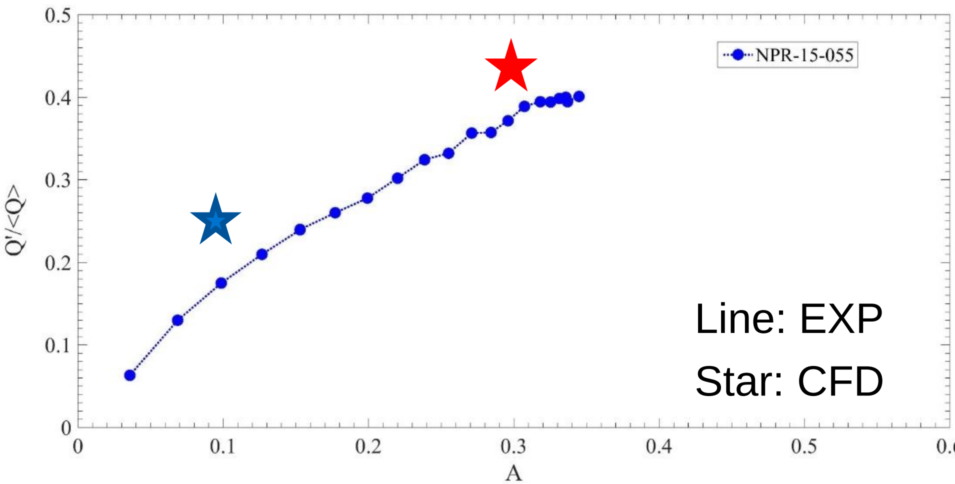
- Some observations:
  a) The flame seems to pulsate in the axial direction
  b) Regions with high OH* chemiluminescence signal appear at mid-height and close to the walls
  c) The opening of the flame brushes on the two sides of the bluff-body changes in time

Dynamic behavior of the flame structure



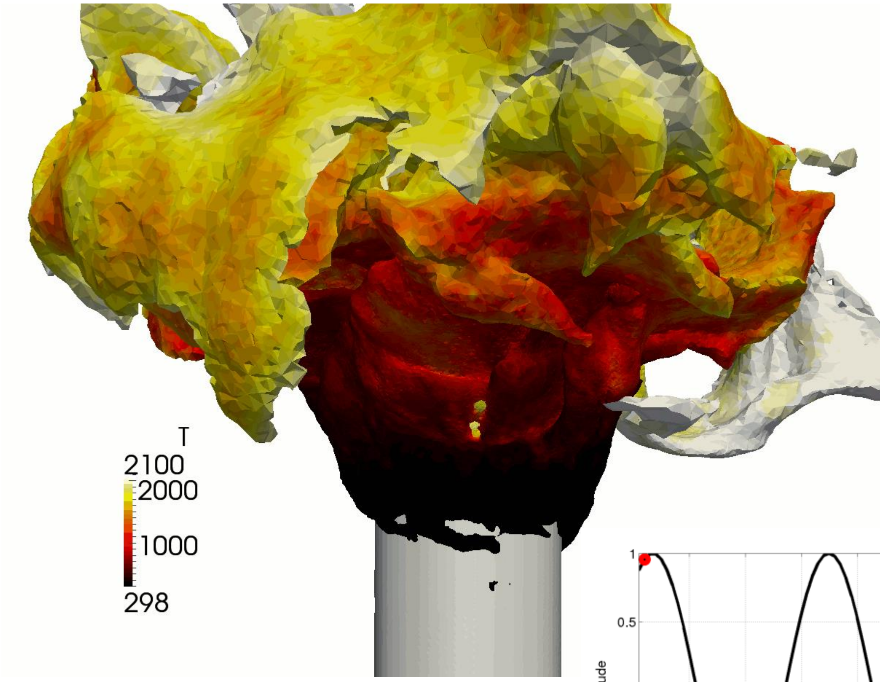


- Can we predict the heat release rate fluctuations?
  - Good prediction of the phase lag
  - Good prediction of the HRR fluctuations

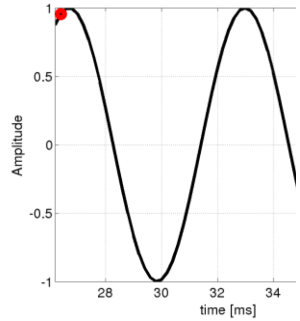


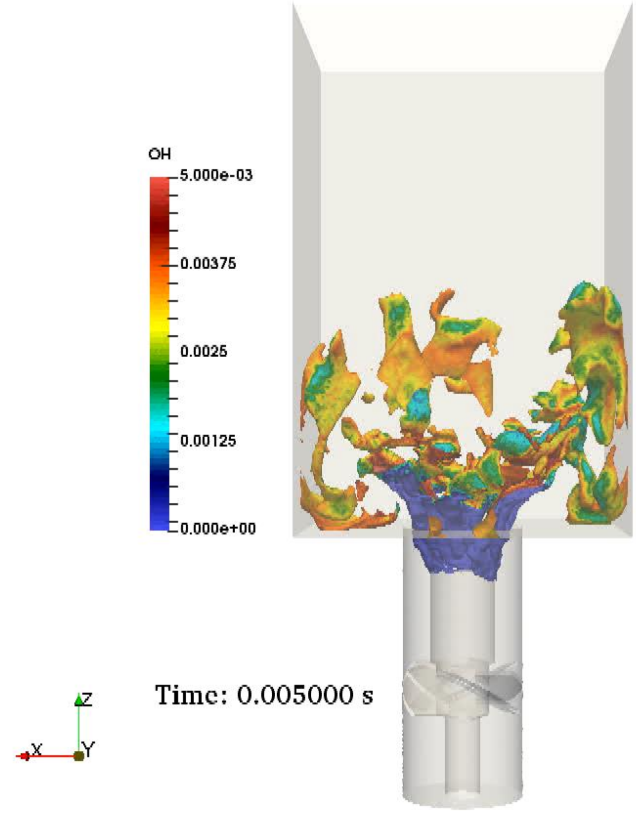
Dynamic behavior of the flame structure

- What is the mechanism leading to heat release rate fluctuations?

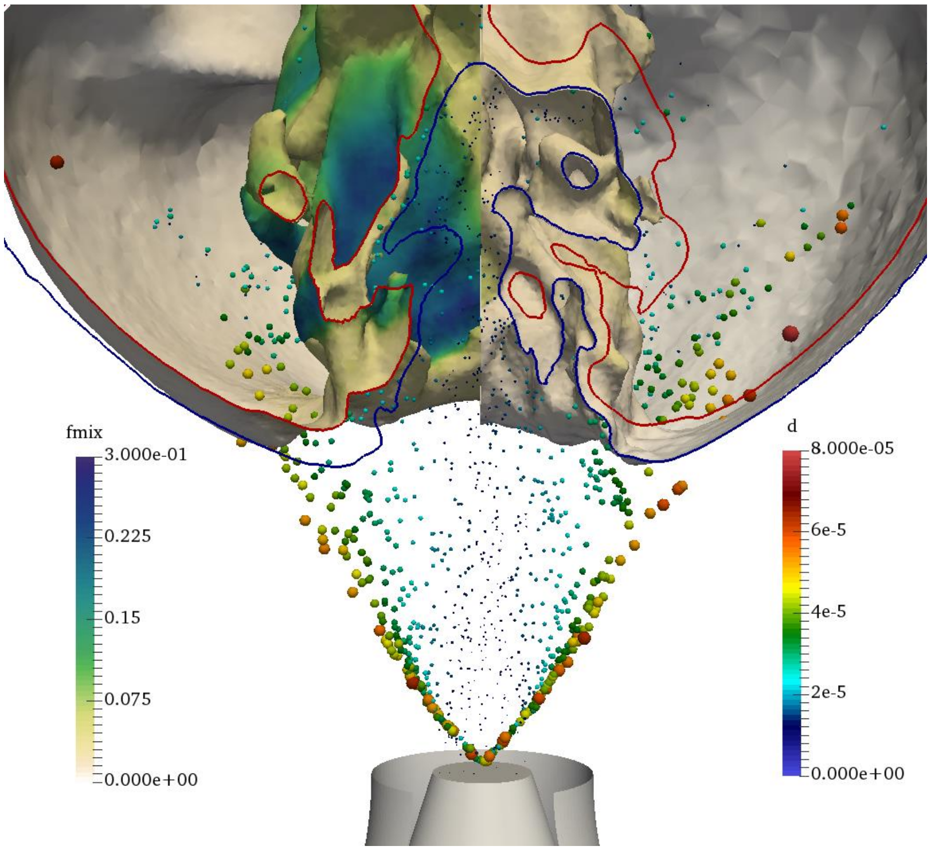


Stoichiometric mixture fraction isosurface coloured with temperature





Double conditioned moment closure for sprays (Sitte & Mastorakos, submitted CNF)



Conclusions

- LES/CMC is very expensive, but allows local and global extinction to be quantitatively predicted.
- Sub-models and validation needed for sprays (ξ variance, N, conditional N, P(η), etc)
- Cannot avoid having a lot of chemistry; real fuel chemistry needed for kerosene
- Model with local extinction allows confidence to attack complex problems