Modelling Blow-Off Dynamics of Gas Turbine Flames

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(Acknowledgment to Prof. Epaminondas Mastorakos)

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Outline

- Clean combustion technology and flame extinction
- Conditional moment closure modelling in large eddy simulation
- Predictions of localized and global extinctions in turbulent swirling flames
  - ❖ *Global extinction in confined turbulent swirling flames*
  - ❖ *Extinction in a model gas turbine combustor with dual swirlers*
- Conclusions and future work

Flame extinction: state of the art

Turbulent Non-premixed Flames

Local extinction ⟺ Global extinction

Experiment

- Transported PDF
- Flamelet
- CMC

✓ Work around 1990 by Bilger, Masri, Dibble and Barlow

✓ Recent experimental work using state-of-the-art diagnostics:
- Sandia Flames D and F (Barlow and Frank, PCI 1998)
- Sydney Swirl Flames (Masri et al. CNF 2004)
- Hult et al. PCI 2005
- Sutton and Driscoll, PCI 2007
- Kaiser and Frank, PCI 2009
- Steinburg et al., PCI 2011
- Cavaliere et al. FTC 2013

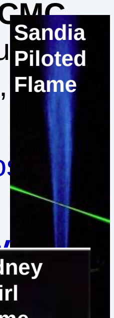
✓ Doubly-conditional CMC: Cha et al., PoF 2001.

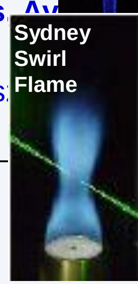
✓ Higher order CMC: Cha and Pitsch, CTM 2002.

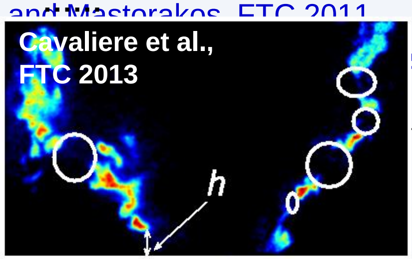
✓ Tabulation with 2D manifold for CMC chemistry: Kronenburg and Papou PCI 2005, Kronenburg and Kostka, 2005.

✓ Sandia F, Garmory and Mastorakos 2011.

✓ Delft-III natural gas jet flames, Av and Mastorakos, FTC 2011







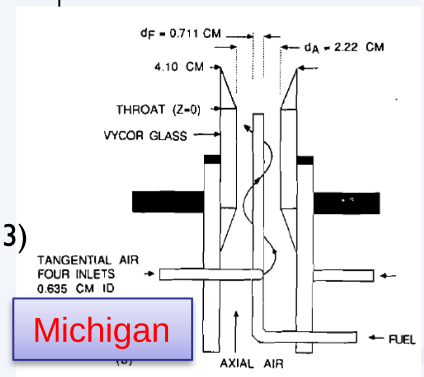
Blow-out / Blow-off

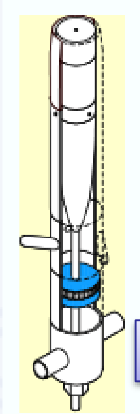
(Chen et al. CST 1990)

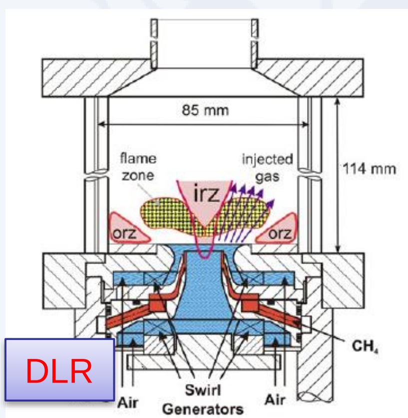
(Masri et al. CNF 2004)

(Meier et al. CNF 2006)

(Cavaliere et al. FTC 2013)

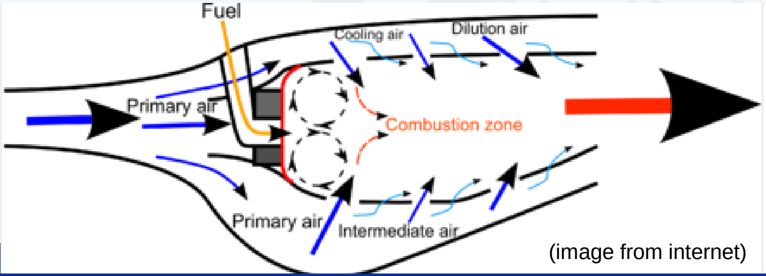






Scientific challenges

- <u>Predictability</u>: *Highly unsteady and stochastic; evolution modes subject to flow configurations (e.g. lift-off or recirculating flames?); Burner-to-burner interaction in annular gas turbine combustors.*
- <u>Evolving combustion modes</u>: *Different levels of turbulence, reactant mixing and flame dynamics (e.g. localized extinction) as the flame blows off?*
- <u>Interaction with multiple physics</u>: *Spray of liquid fuels? Soot formation or oxidation? Gas pollutant emissions? Radiation heat loss?*
- <u>Post-extinction dynamics</u>: *Spark ignition? High-altitude relight? Spray injection and evaporation?*
- <u>Modelling or measurement approaches</u>: *How to quantify blow-off transients? How do the current combustion models (e.g. Flamelet, CMC and PDF) work? Are our measurement methods sufficient?*



(image from internet)

Large Eddy Simulation (LES) for turbulent combustion

◆ Filtered governing equations for LES:

$$\partial_t\bar{\rho} + \nabla\cdot\left(\bar{\rho}\widetilde{U}\right) = 0$$ Continuity

$$\partial_t\bar{\rho}\widetilde{U} + \nabla\cdot\left(\bar{\rho}\widetilde{U}\otimes\widetilde{U}\right) = -\nabla\cdot\bar{p} + \nabla\cdot\left(\bar{S} - \bar{S}_{sgs}\right)$$ Momentum

$$\partial_t\bar{\rho}\tilde{\xi} + \nabla\cdot\left(\bar{\rho}\widetilde{U}\tilde{\xi}\right) = \nabla\cdot\left(\bar{\Xi} - \bar{\Xi}_{sgs}\right)$$ Mixture fraction

$$\boxed{\partial_t\bar{\rho}\tilde{Y}_i + \nabla\cdot\left(\bar{\rho}\widetilde{U}\tilde{Y}_i\right) = \nabla\cdot\left(\bar{\Theta} - \bar{\Theta}_{sgs}\right) + \bar{\rho}\widetilde{\omega}_i}$$ Species mass fraction

Difficult to close!

$$\widetilde{\omega_\alpha} \neq \omega_\alpha\left(\tilde{Y}_1 \ldots \tilde{Y}_n, \tilde{T}\right)$$

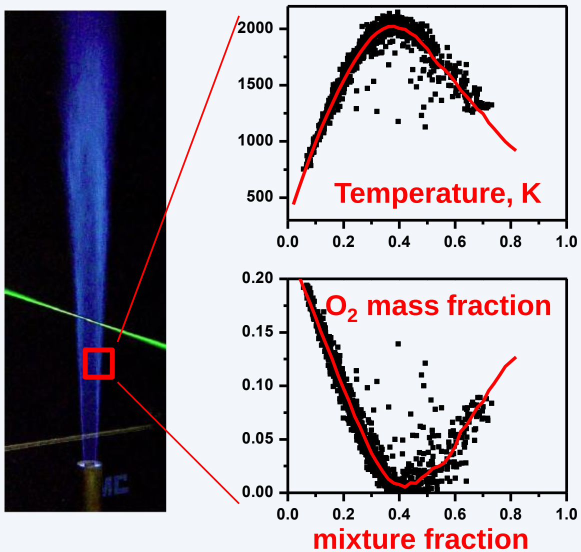
Scalar Dissipation Models

$$\widetilde{N}_{fil} = \widetilde{N}_{res} + \widetilde{N}_{sgs}$$

$$\widetilde{N}_{res} = D\nabla\tilde{\xi}\cdot\nabla\tilde{\xi} \qquad \widetilde{N}_{sgs} = C_N\mu_t\widetilde{\xi''}/2\bar{\rho}\Delta^2$$

$$\widetilde{\xi''} = C_V\Delta^2\nabla\tilde{\xi}\cdot\nabla\tilde{\xi}$$

Conditional Moment Closure (CMC) for turbulent non-premixed flames



Sandia flame D
Barlow and Frank, Proc. Combust. Inst. 1998

$$\widetilde{\omega_\alpha} \neq \omega_\alpha\left(\tilde{Y}_1 \ldots \tilde{Y}_n, \tilde{T}\right)$$

$$\widetilde{\omega_\alpha|\eta} \approx \widetilde{\omega_\alpha}\left(\widetilde{Y_1|\eta}, \ldots, \widetilde{Y_n|\eta}, \widetilde{T|\eta}\right)$$

First-order CMC model

- **Five-dimensional Eqs. of species mass fraction ($\widetilde{Y_\alpha|\eta}$) and energy ($\widetilde{h|\eta}$):**

$$\underbrace{\int_{\Omega\mathrm{CMC}} \frac{\partial Q_\alpha}{\partial t}\,\mathrm{d}\Omega}_{T_0} + \underbrace{\int_{\Omega\mathrm{CMC}} \nabla \cdot \left(\widetilde{\mathbf{U}|\eta} Q_\alpha\right)\mathrm{d}\Omega}_{T_1} =$$

$$\underbrace{\int_{\Omega\mathrm{CMC}} Q_\alpha \nabla\cdot\widetilde{\mathbf{U}|\eta}\,\mathrm{d}\Omega}_{T_2} + \underbrace{\int_{\Omega\mathrm{CMC}} \widetilde{N|\eta}\frac{\partial^2 Q_\alpha}{\partial^2 \eta}\,\mathrm{d}\Omega}_{T_3} + \underbrace{\int_{\Omega\mathrm{CMC}} \widetilde{\omega_\alpha|\eta}\,\mathrm{d}\Omega}_{T_4} + \underbrace{\int_{\Omega\mathrm{CMC}} \nabla\cdot\left(D_t \nabla Q_\alpha\right)\mathrm{d}\Omega}_{T_5}$$

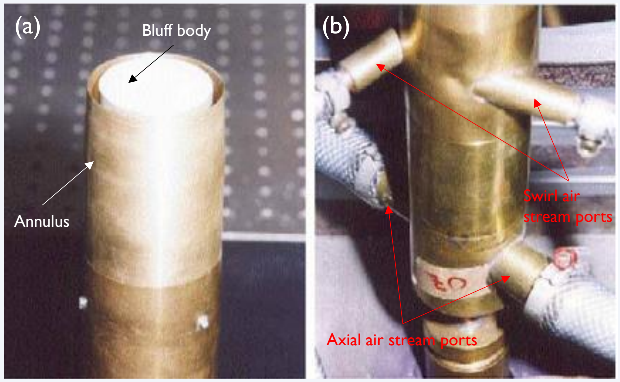
T1: Convection; *T2*: Dilatation; *T3*: Micro-mixing;
T4: Chemistry; *T5*: Turbulent Scalar Flux

Modeled Terms

- ✓ $\widetilde{\mathrm{U}|\eta} = \tilde{\mathrm{U}}$
- ✓ $\widetilde{N|\eta}$: amplitude mapping closure (AMC)
- ✓ $\tilde{P}(\eta)$: presumed beta-function
- ✓ $\widetilde{\omega_\alpha|\eta}$: **first order CMC closure, detailed chemistry, ARM2 mechanism**
- ✓ a gradient model used for sub-grid scale scalar flux

Target swirling flames for blow-off studies

Target flame	Measurement	Flame phenomenon
Sydney swirling flame	detailed pointwise species and velocity measurements	open jet flame, increased local extinction by increased fuel velocity, lift-off
Cambridge swirling flame	Images for OH-PLIF and OH* chemiluminescence, blow-off time and transients	confined swirling methane flame, blow-off by increased air bulk velocity, severe local extinction
DLR (German Aerospace Center) swirling flame	detailed pointwise species and velocity measurements, and images for CH-PLIF, OH-PLIF and OH* chemiluminescence	Close to aircraft and stationary gas turbine combustion, fuel-lean, lift-off and flashback, severe local extinction, periodic blowout

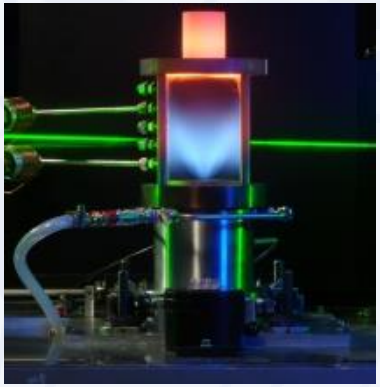


Sydney swirling flame

Masri et al, Combust. Theor. Model. 2007.
Masri et al, Combust. Flame 2004.

Cambridge swirling flame

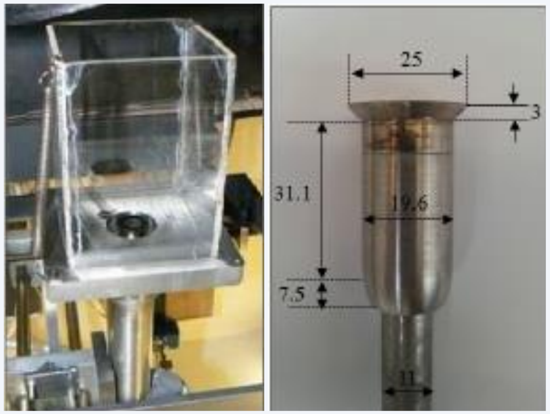
Cavaliere et al. Flow Turb. Combust. 2013.



DLR swirling flame

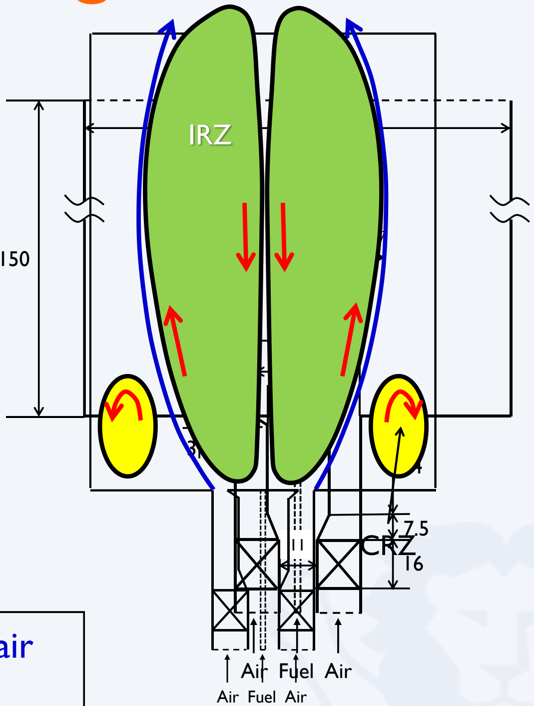
Weigang et al. Combust. Flame 2006.
Meier et al. Combust. Flame 2006

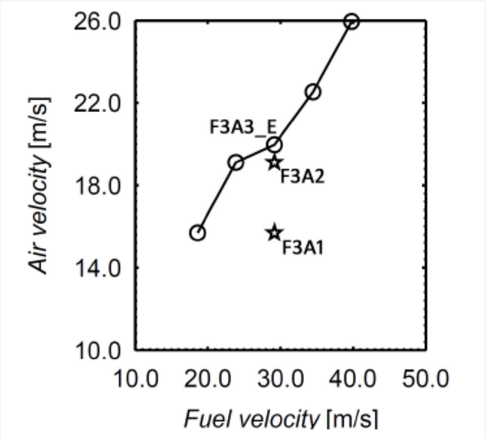
Global extinction in confined swirling flames



(a) Chamber *(b) Bluff body*

Schematic of experimental setup



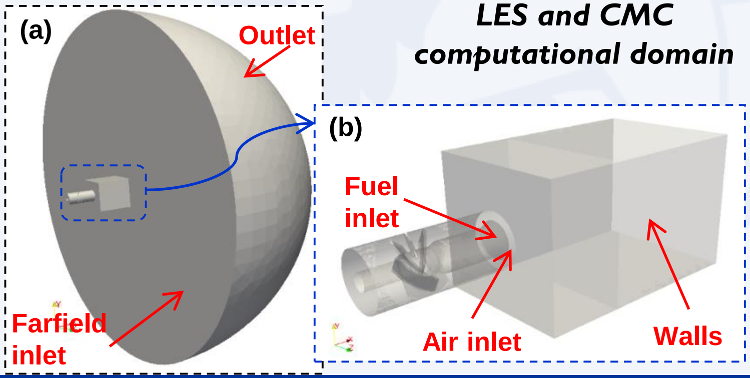


Blow-off curve

- Fuel/oxizider: pure methane (non-swirling) and air (swirling)
- The swirl number S_N is calculated following Beer and Chigier's method (Applied Science 1972):

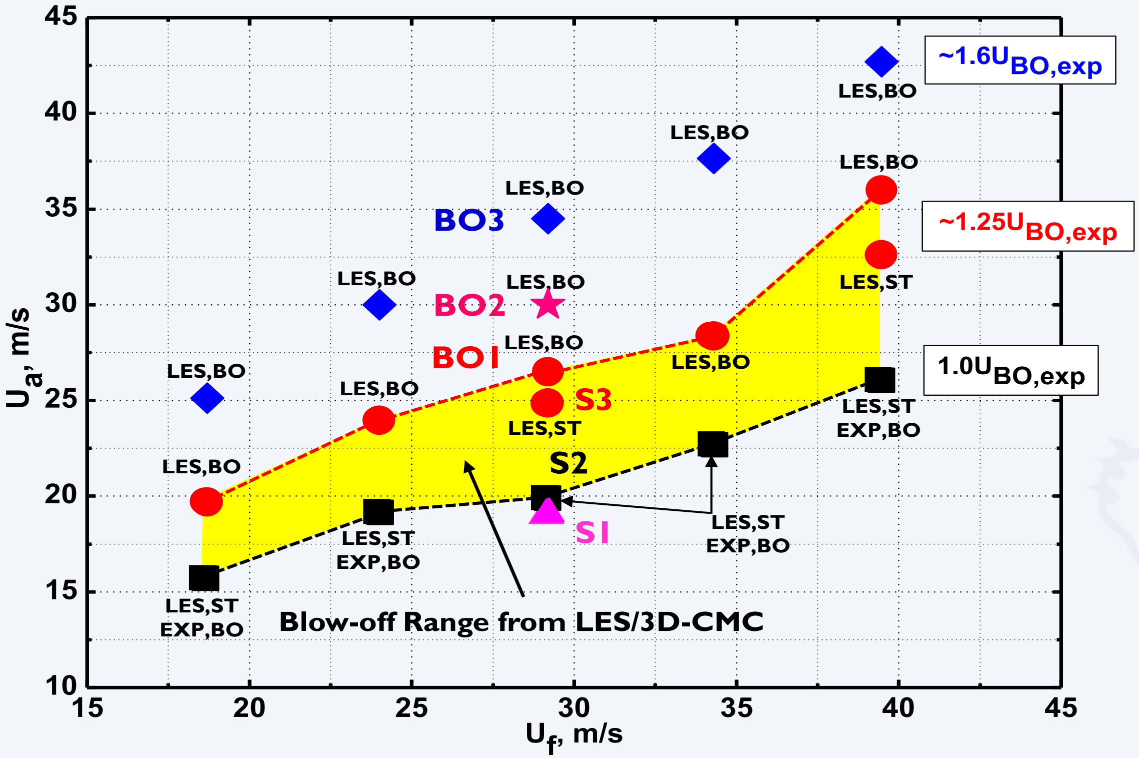
$$S_N = \frac{2}{3}\frac{1-(D_{hub}/D_{sw})^3}{1-(D_{hub}/D_{sw})^2}\tan\theta = 1.23$$

LES and CMC computational domain



Experimental data from: Cavaliere et al. Flow Turb. Combust. 2013.

Prediction of global extinction (blow-off) condition



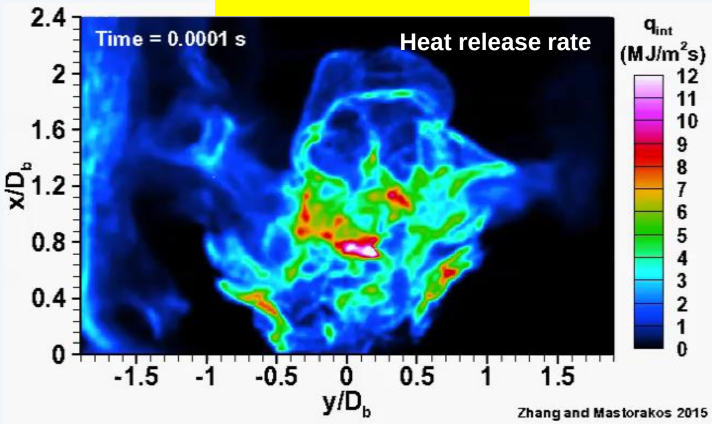
- Prediction of the full blow-off curve is still one of the targets of combustion CFD.
- Capturing the blow-off condition with LES has not been demonstrated yet.

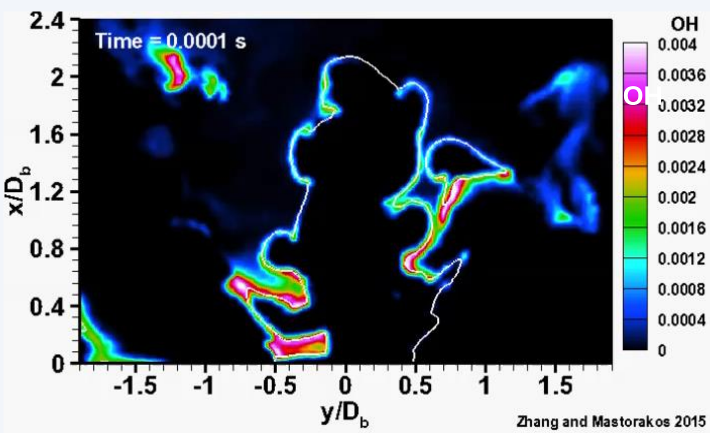
- The LES/CMC model shows the reasonably good accuracy to predict the global extinction conditions over a range of fuel/air mass flow rates.

Zhang and Mastorakos, Flow Turb Combust 2016.

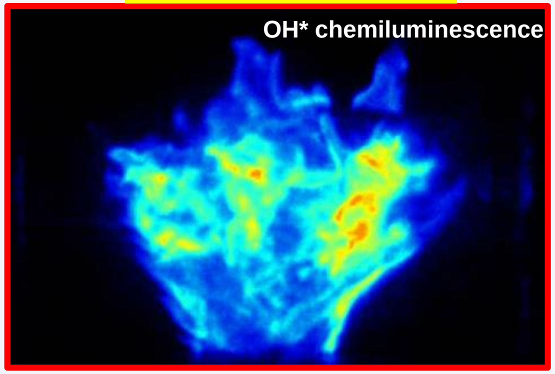
Blow-off transient: LES vs. experiment

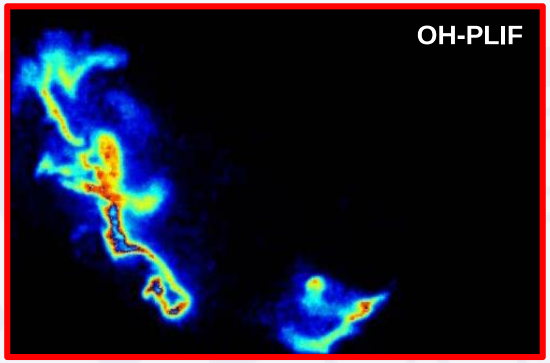
Simulation





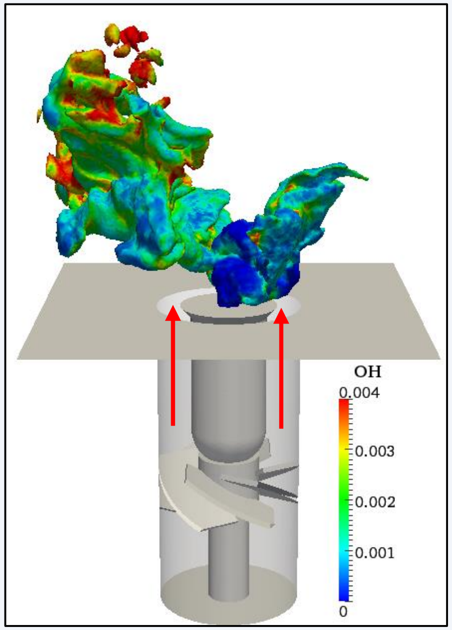
Experiment



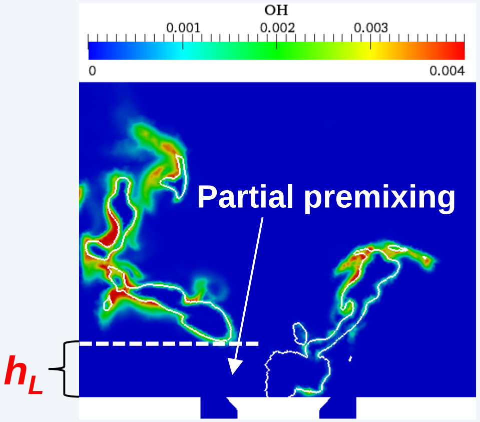


(Cavaliere et al. Flow Turb. Combust. 2013)

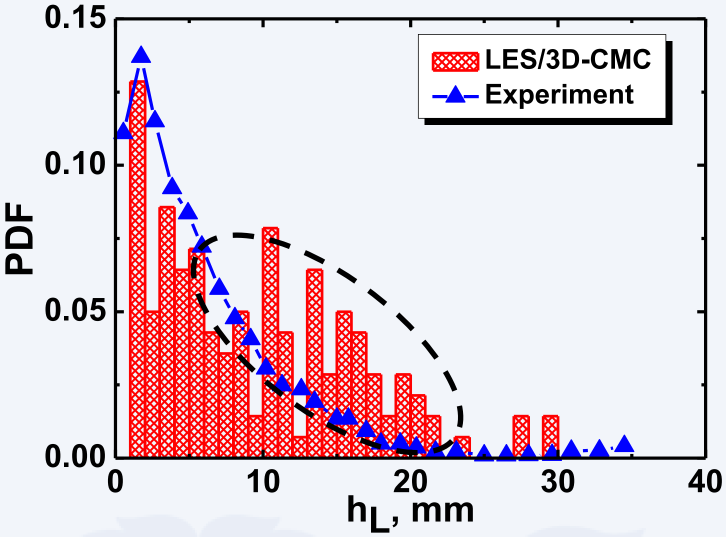
Lift-off height statistics



3D instantaneous contours of stoichiometric mixture fraction colored by OH mass fraction

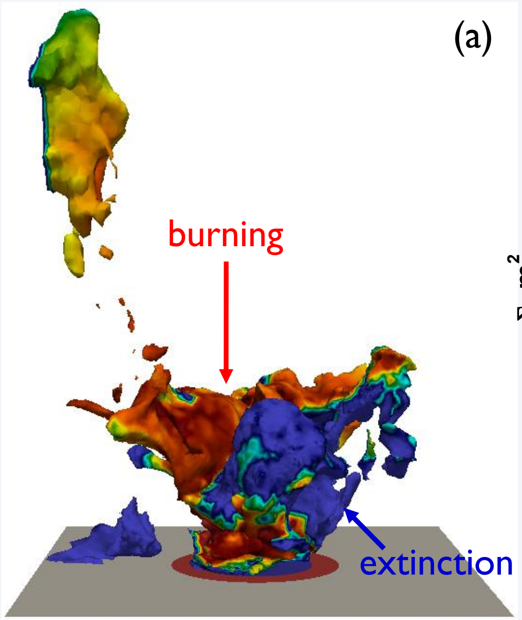


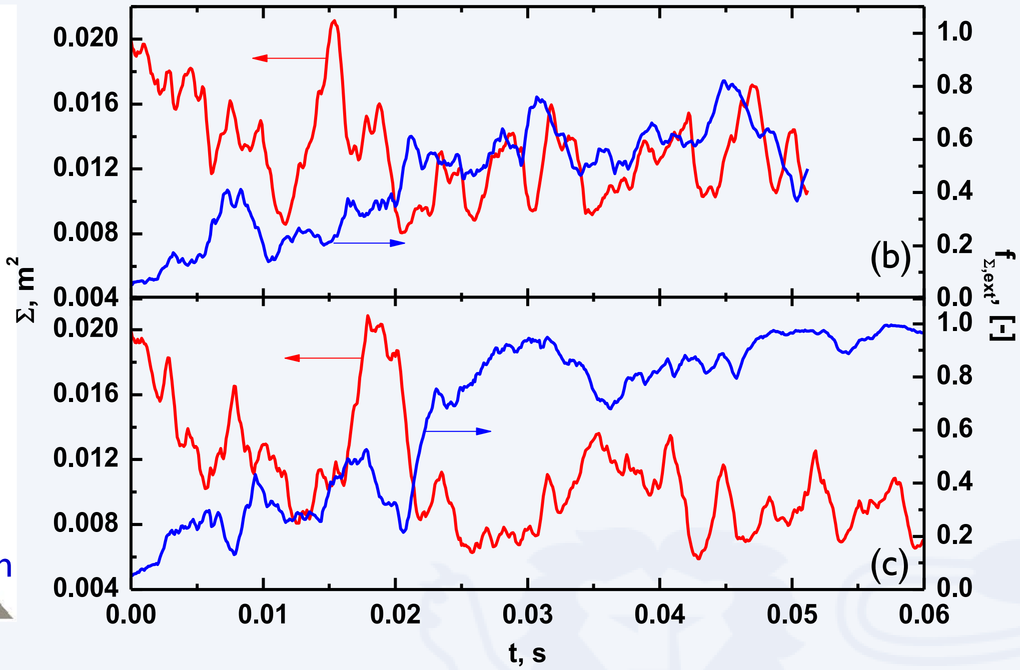
Instantaneous distributions of OH mass fraction. White lines: stoichiometric mixture fraction.



- **Flame lift-off from the bluff body: (i) local extinction along stoichiometric mixture fraction at the flame base or (ii) iso-lines of stoichiometric mixture fraction detached from the bluff body edge.**
- **The shape of PDF(h_L) demonstrates the overall consistency with the experimental result (Cavaliere et al. 2013).**
- **The high PDF for h_L = 10-20 mm from LES/CMC is expected to be caused by the over-prediction of turbulence intensity close to the annulus exit.**

Localized extinction during blow-off





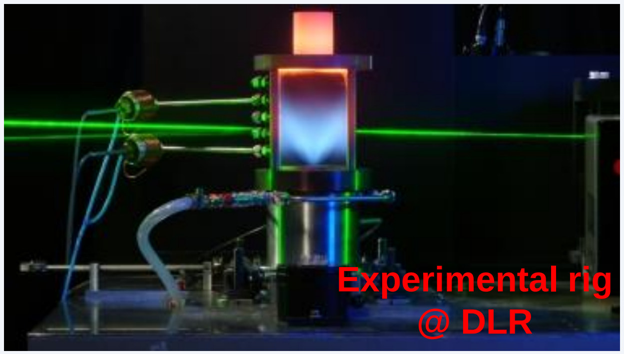
Metrics for quantifying flame extinction:

- ❖ **Area of the stoichiometric mixture fraction iso-surface Σ**
- ❖ **Extinguished fraction $f_{\Sigma,ext}$**

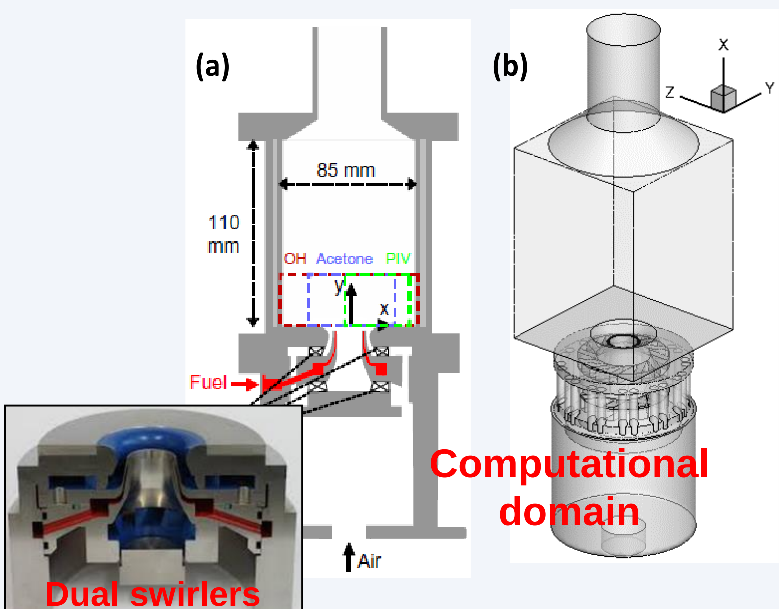
$$f_{\Sigma,ext} = \frac{extingsuihed\ area}{total\ stiochiometric\ area}$$

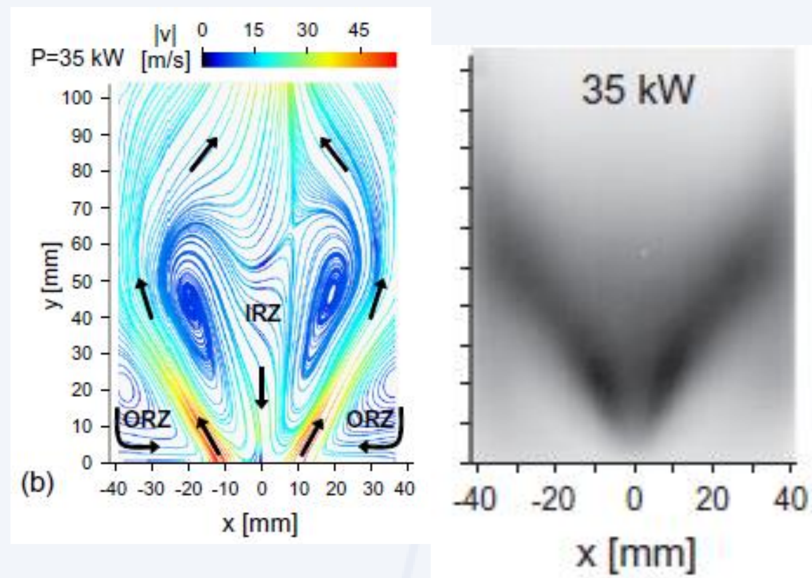
Zhang and Mastorakos, Flow Turb Combust 2016.

DLR (German Aerospace Center) model gas turbine combustor



Case	Fuel mass flow rate (kg/s)	Air mass flow rate (kg/s)	Swirl number	Thermal power (kW)	Global equivalence ratio
A	0.000697	0.018	0.9	34.9	0.65
C	0.00015	0.0047	0.55	7.6	0.55

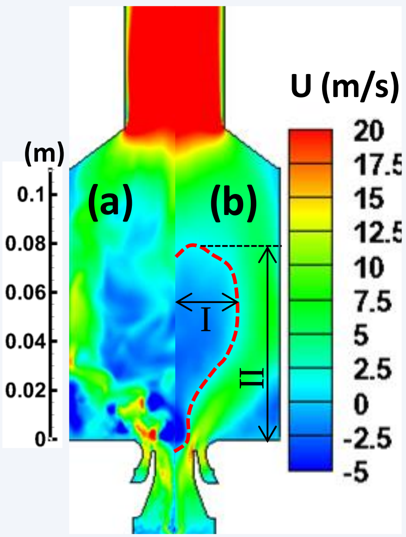




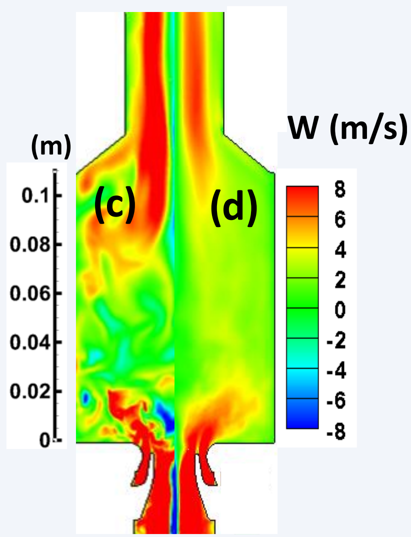
Experimental visualizations of flow pattern and reaction zone of Flame A case

Weigand et al. Combust Flame 2006.
Stohr et al. Combust. Flame 2012.

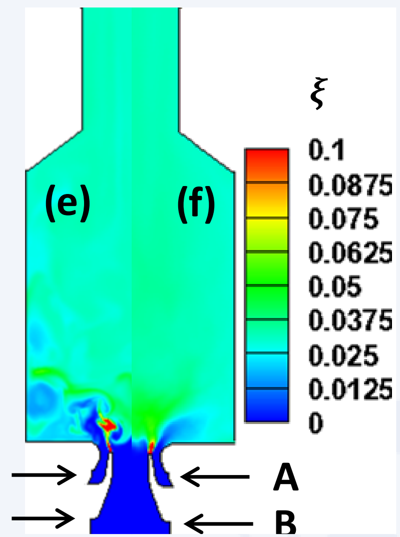
General flame characteristics



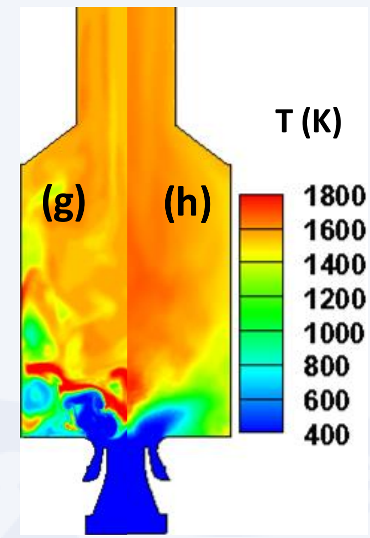
Mean axial velocity



Mean swirl velocity



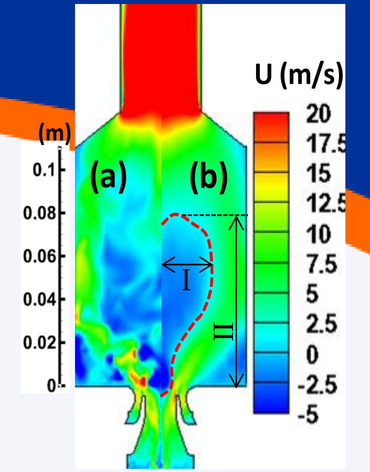
Mean mixture fraction



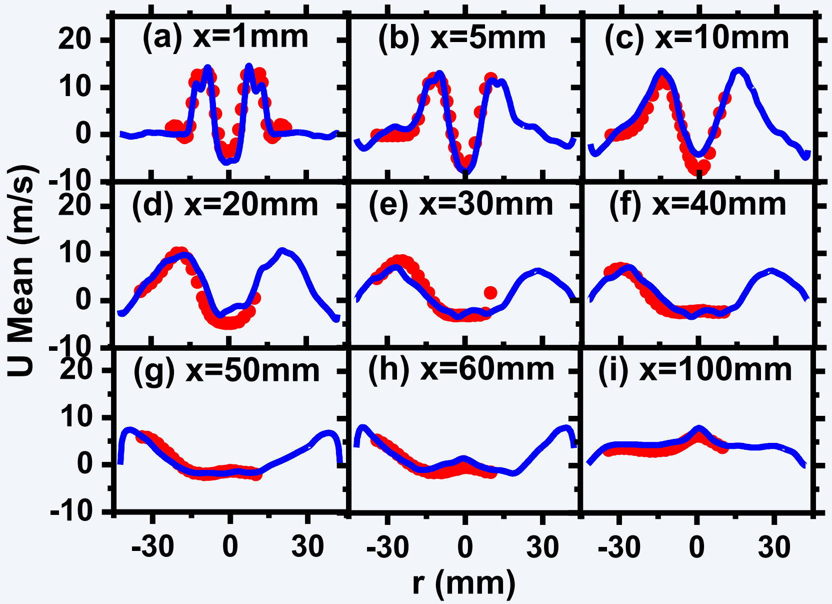
Mean temperature

- The central and corner recirculation zones are accurately captured in the LES/CMC simulations.
- The resolved mixture fraction in the combustor is close to the global mixture fraction, due to the strong mixing caused by the swirling motions.

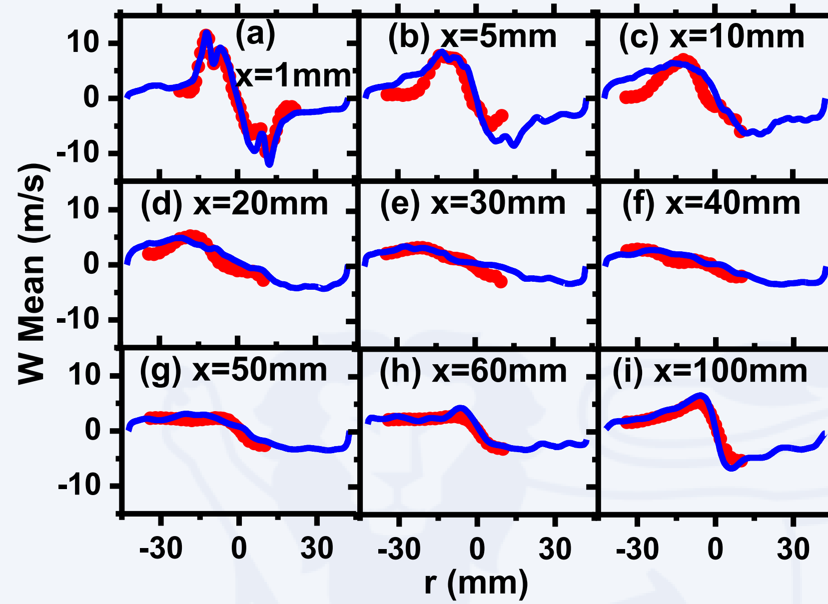
Velocity statistics



Lines: LES/CMC
Symbols: Exp. Data (Weigand et al. Combust Flame 2006)



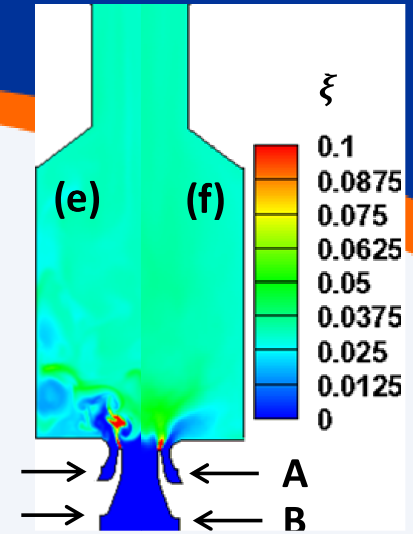
Mean axial velocity



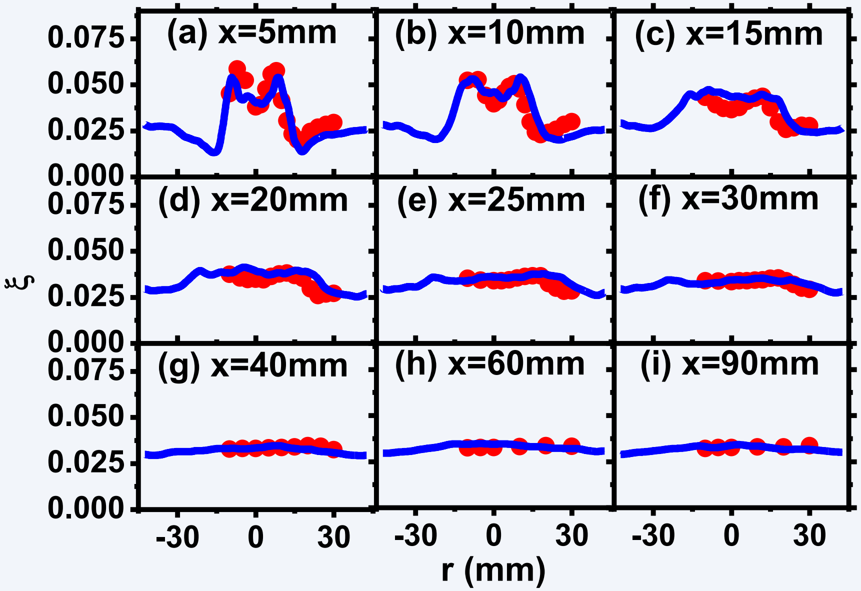
Mean swirl velocity

- The spanwise distributions of mean axial and swirl velocities are accurately predicted for different streamwise locations.
- The main aerodynamic features are obtained, including the recirculation zones and swirling motion.

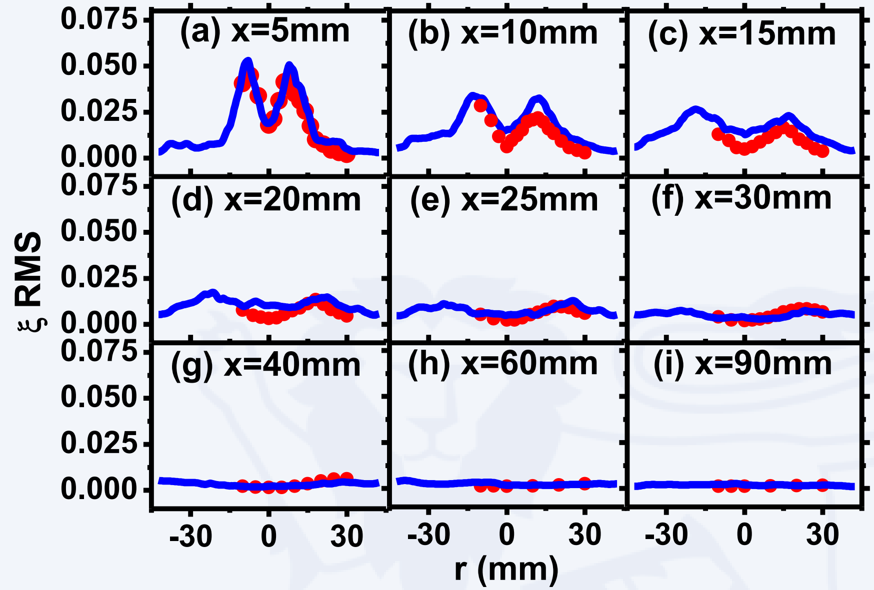
Conserved scalar statistics



Lines: LES/CMC
Symbols: Exp. Data (Weigand et al. Combust Flame 2006)

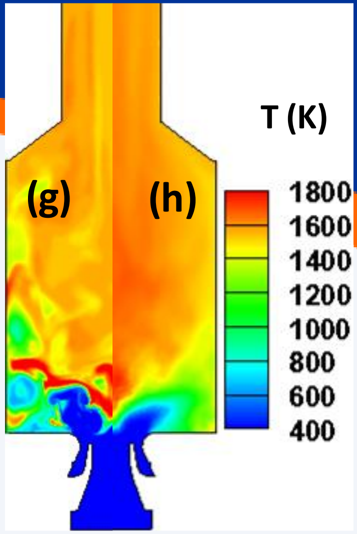


Mean mixture fraction

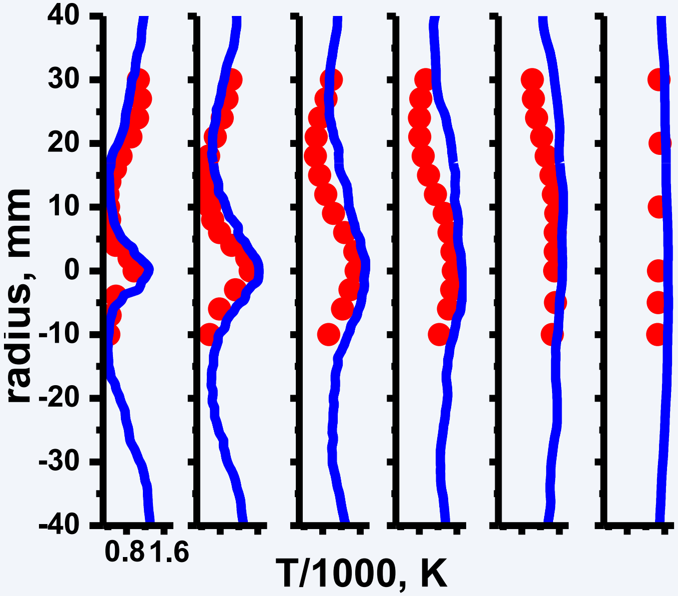


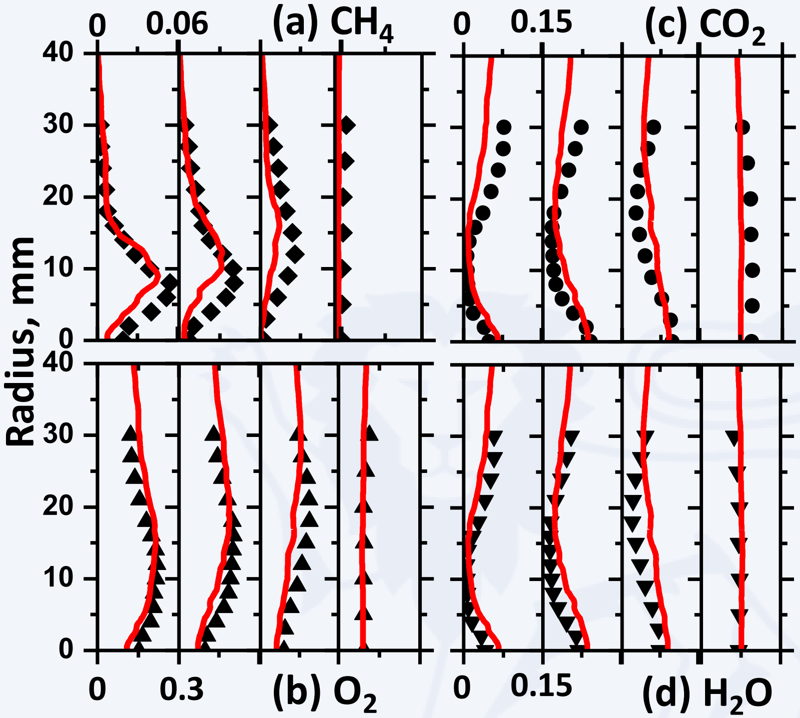
Mixture fraction RMS

Reactive scalar statistics

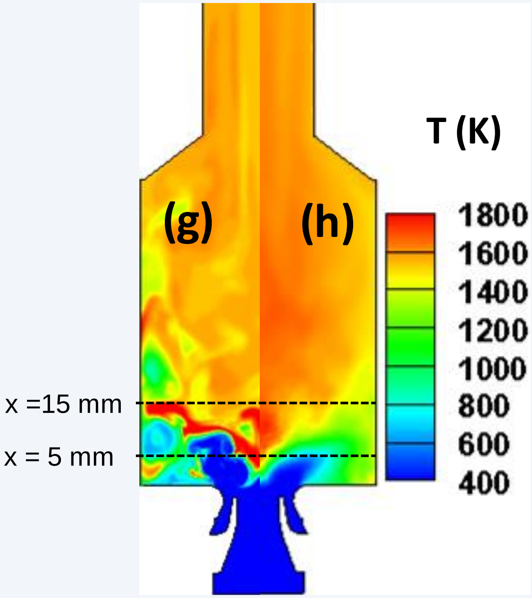


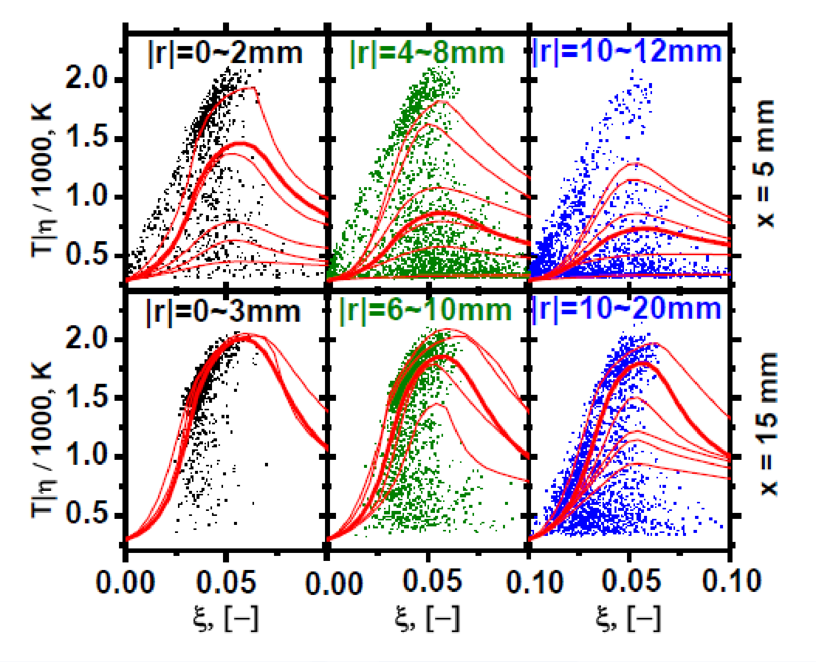
Lines: LES/CMC
Symbols: Exp. Data (Weigand et al. Combust Flame 2006)





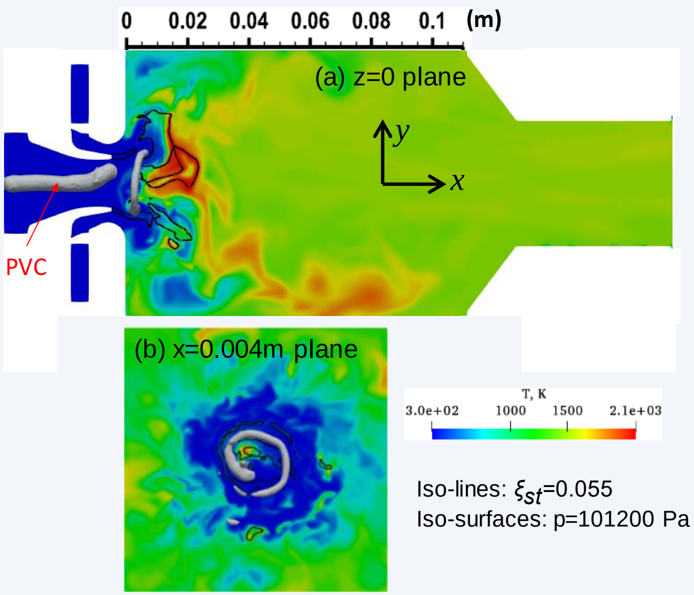
Reactive scalar statistics (mixture fraction space)

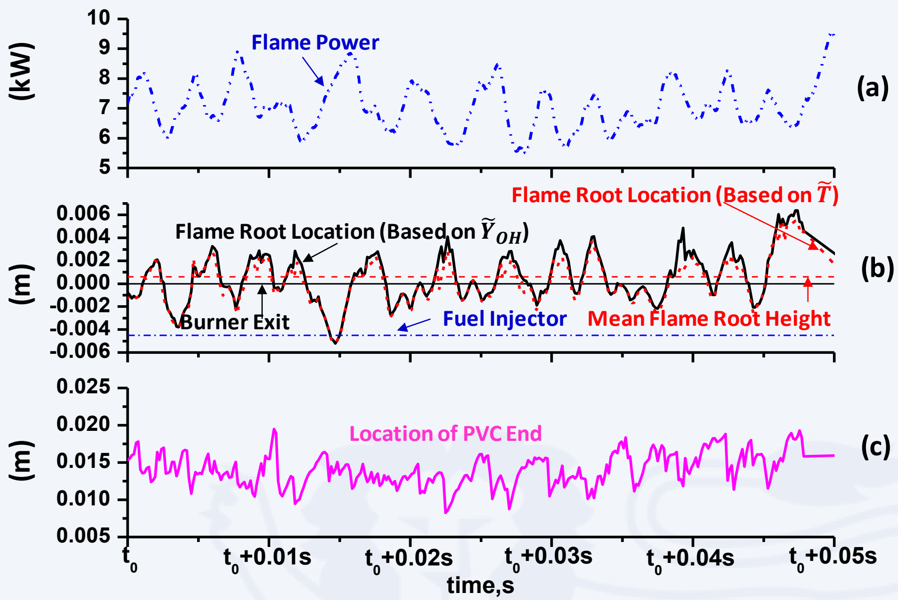




- Most of the scatters are found to be less than 0.1 in mixture fraction space, indicating that the good mixing occurs for the upstream of the combustor.
- Lots of the low-T scatters can be found around the stoichiometric mixture fraction. Quenched or never reacted?

Flame root dynamics





- Flame root dynamics is the significant indicator for occurrence of global extinction in this combustor (as discussed in the experiments).

Conclusions and Future Work

- The conditional moment closure modelling in the context of large eddy simulation demonstrates the ability for accurately predicting the flame extinction dynamics in turbulent combustion. It successfully predicts the localized extinction and blow-off dynamics for the shown three types of turbulent swirling flames.
- Blow-off process is affected by different concurrent flame dynamics, e.g. localized extinction, re-ignition, flame base lift-off and partial premixing.
- The CMC model can perform well in predicting the global fuel-lean flames in gas turbine combustors in which quick fuel/air mixing occurs.
- **Future work:** (1) Higher order CMC model? (2) More understanding about blow-off physics?

Acknowledgement

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Dr Wolfgang Meier

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archer

National Supercomputing Centre
NSCC SINGAPORE

Thank you and Question?

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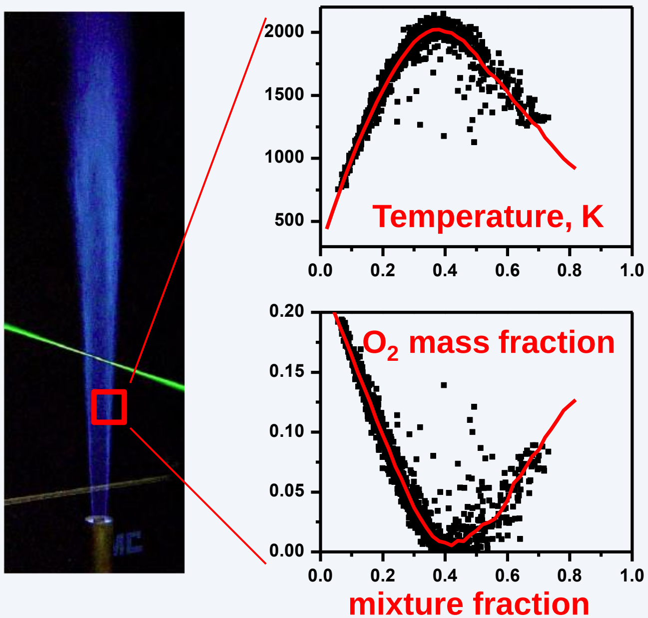
Backup slides

Conditional Moment Closure (CMC) for turbulent non-premixed flames



Sandia flame D
Barlow and Frank, Proc. Combust. Inst. 1998

$$\widetilde{\omega_\alpha} \neq \omega_\alpha\left(\tilde{Y}_1 \ldots \tilde{Y}_n, \tilde{T}\right)$$

$$\widetilde{\omega_\alpha|\eta} \approx \widetilde{\omega_\alpha}\left(\widetilde{Y_1|\eta}, \ldots, \widetilde{Y_n|\eta}, \widetilde{T|\eta}\right)$$

First-order CMC model

- **Five-dimensional Eqs. of species mass fraction ($\widetilde{Y_\alpha|\eta}$) and energy ($\widetilde{h|\eta}$):**

$$\underbrace{\int_{\Omega\mathrm{CMC}} \frac{\partial Q_\alpha}{\partial t} d\Omega}_{T_0} + \underbrace{\int_{\Omega\mathrm{CMC}} \nabla\cdot(\widetilde{\mathbf{U}|\eta} Q_\alpha) d\Omega}_{T_1} =$$

$$\underbrace{\int_{\Omega\mathrm{CMC}} Q_\alpha \nabla\cdot\widetilde{\mathbf{U}|\eta} d\Omega}_{T_2} + \underbrace{\int_{\Omega\mathrm{CMC}} \widetilde{N|\eta} \frac{\partial^2 Q_\alpha}{\partial^2 \eta} d\Omega}_{T_3} + \underbrace{\int_{\Omega\mathrm{CMC}} \widetilde{\omega_\alpha|\eta} d\Omega}_{T_4} + \underbrace{\int_{\Omega\mathrm{CMC}} \nabla\cdot(D_t \nabla Q_\alpha) d\Omega}_{T_5}$$

T1: Convection; *T2*: Dilatation; *T3*: Micro-mixing;
T4: Chemistry; *T5*: Turbulent Scalar Flux

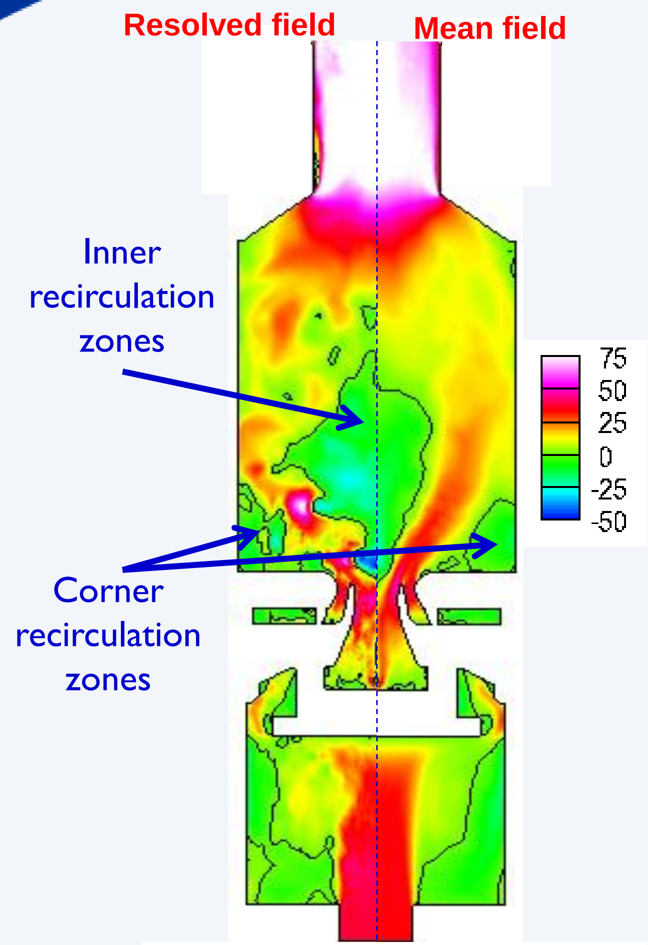
Modeled Terms

- ✓ $\widetilde{U|\eta} = \tilde{U}$
- ✓ $\widetilde{N|\eta}$: amplitude mapping closure (AMC)
- ✓ $\tilde{P}(\eta)$: presumed beta-function
- ✓ $\widetilde{\omega_\alpha|\eta}$: **first order CMC closure, detailed chemistry, ARM2 mechanism**
- ✓ a gradient model used for sub-grid scale scalar flux

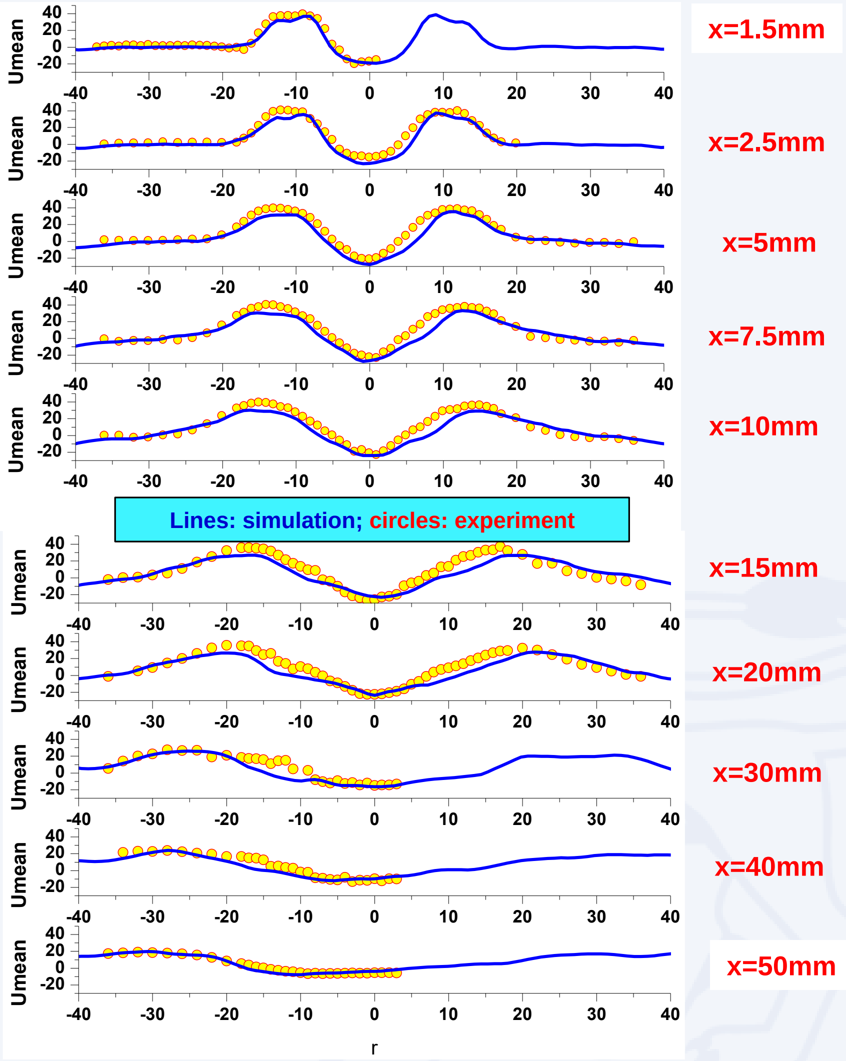
Zhang et al., Proc. Combust. Inst. 2015.
Zhang and Mastorakos, Flow Turb Combust 2016.
Garmory and Mastorakos, Proc. Combust Inst 2015.

Sung et al., Proc. Combust. Inst. 1998.
Klimenko and Bilger, Prog. Combust. Energy Sci. 1999.

Axial mean velocity distribution



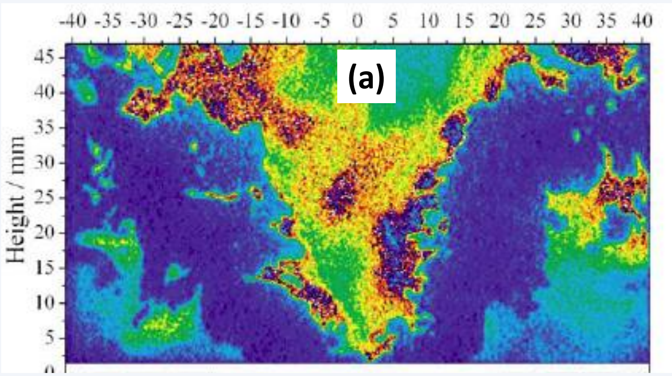
Contours of resolved (left) and mean (right) axial velocity for Flame A case.



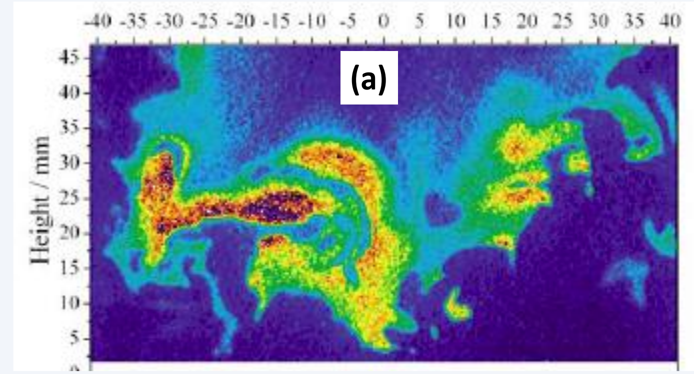
OH mass fraction vs. OH-PLIF

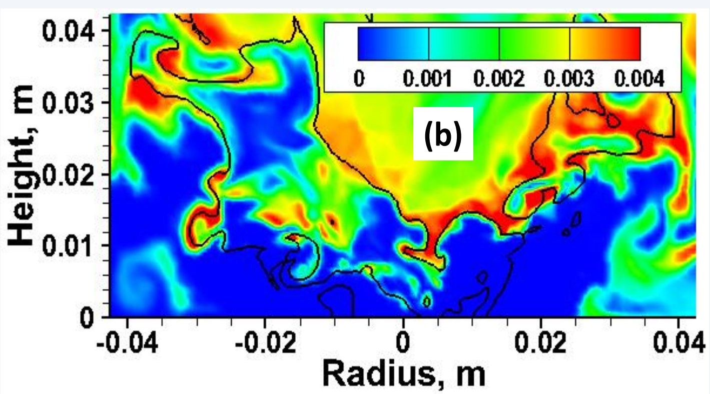
Flame A

Flame C

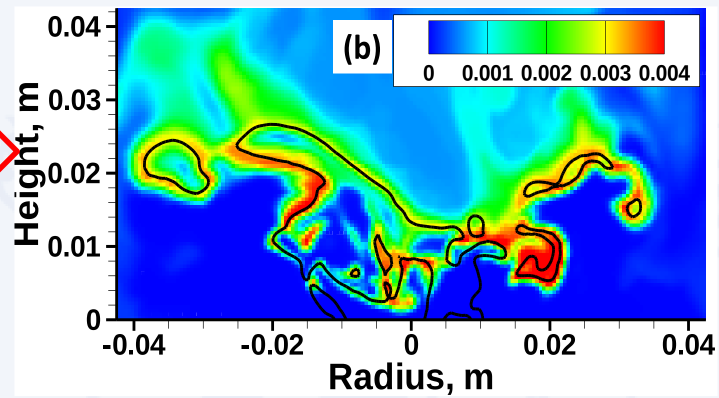


Experiment
(Weigand et al. Combust. Flame 2006)





Simulation



- ✓ **Localized extinction?**
- ✓ **Lean blowout?**
- ✓ **Partially premixed?**

Clean Combustion Technology

- **Decrease pollutant emission (mainly nitrogen oxides NOx)**
- **Increase combustion efficiency**

Innovative combustion Technologies ⟺ **Alternative Fuels**