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Modelling Spark Ignition of Turbulent Jet Flows with LES/CMC

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Outline

- Background and previous work
- Large eddy simulation and conditional moment closure (LES/CMC) modelling
- Results and discussion
  - Cold flow validation
  - Ignition of turbulent jet methane flames
- Conclusions and future work

Background and previous work

Spark ignition of turbulent jet flows

- **ignition probability ⇔ flammability limit**: Birch et al.
- **Flame kernel growth, propagation and stabilization**: Ahmed and Mastorakos
- **Upstream flame propagation**: Lyons: et al.
- ……

Author	Combustion model	Ignition model
Lacaze et al.	Thickened flame model	Volumetric energy deposition
Jones & Prasad	PDF	
Chen et al.	Partially premixed flamelet	Fully burned flamelet deposition

✓ **Main findings from Ahmed jet ignition experiments:**

- Three different events for spark ignition
- Flame expansion sequence
- Diagram of ignition probability with different conditions
- Correlation between successful ignition and local fields

Motivations ?

Birch et al. PROCI 1981
Birch et al. PROCI 1986
Ahmed and Mastorakos, CNF2006

Lacaza et al. CNF 2009
Jones and Prasad, PROCI 2011
Chen et al. PROCI 2016

LES/3D-CMC modelling

- **Governing Equations for LES**

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

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

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

Scalar Dissipation Models

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

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

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

- **Conservative Governing Equations for CMC** ($\boldsymbol{Q_\alpha = \widetilde{Y_\alpha|\eta}}$, $\boldsymbol{Q_h = \widetilde{h|\eta}}$)

$$\underbrace{\partial Q_\alpha/\partial t}_{T0} + \underbrace{\nabla\cdot\widetilde{\mathrm{U}|\eta}Q_\alpha}_{T1} = \underbrace{Q_\alpha\nabla\cdot\widetilde{\mathrm{U}|\eta}}_{T2} + \underbrace{\widetilde{N|\eta}\,\partial^2 Q_\alpha/\partial\eta^2}_{T3}$$

$$+ \underbrace{\widetilde{\omega_\alpha|\eta}}_{T4} - \underbrace{\nabla\cdot\left[\bar{\rho}\tilde{P}(\eta)\left(\widetilde{Y_\alpha\mathrm{U}|\eta} - \widetilde{\mathrm{U}|\eta}Q_\alpha\right)\right]/\bar{\rho}\,\tilde{P}(\eta)}_{T5}$$

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

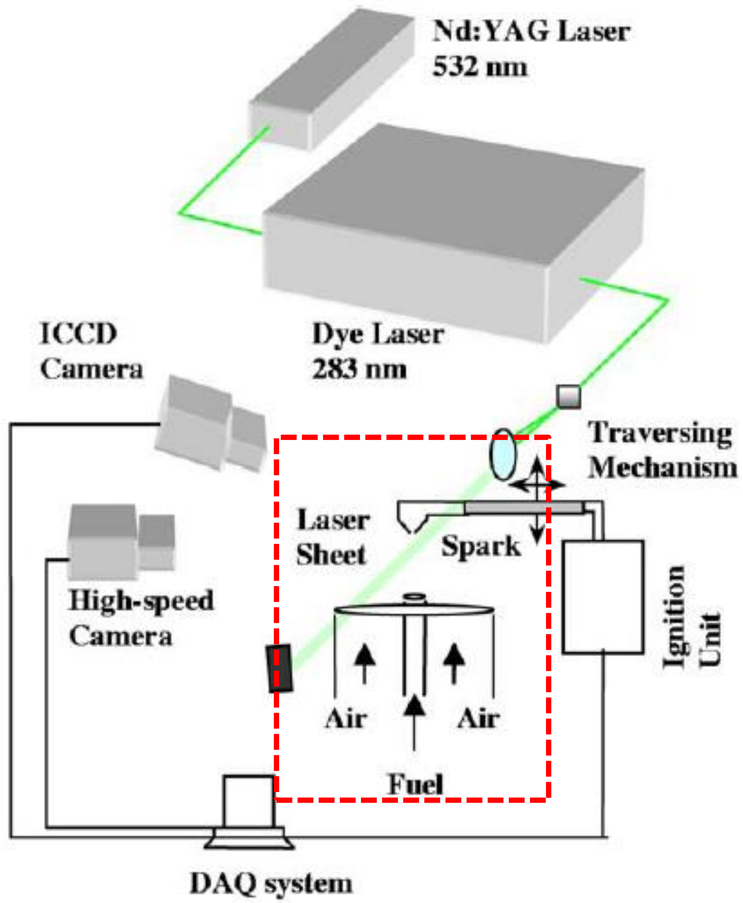
Modeled Terms

- ✓ $\widetilde{\mathrm{U}|\eta} = \tilde{\mathrm{U}}$
- ✓ $\widetilde{N|\eta}$: amplitude mapping closure (AMC)
- ✓ $\tilde{P}(\eta)$: presumed beta-function
- ✓ $\widetilde{\omega_\alpha|\eta}$: **first order CMC closure, ARM2 mech.**
- ✓ a gradient model used for *T5*

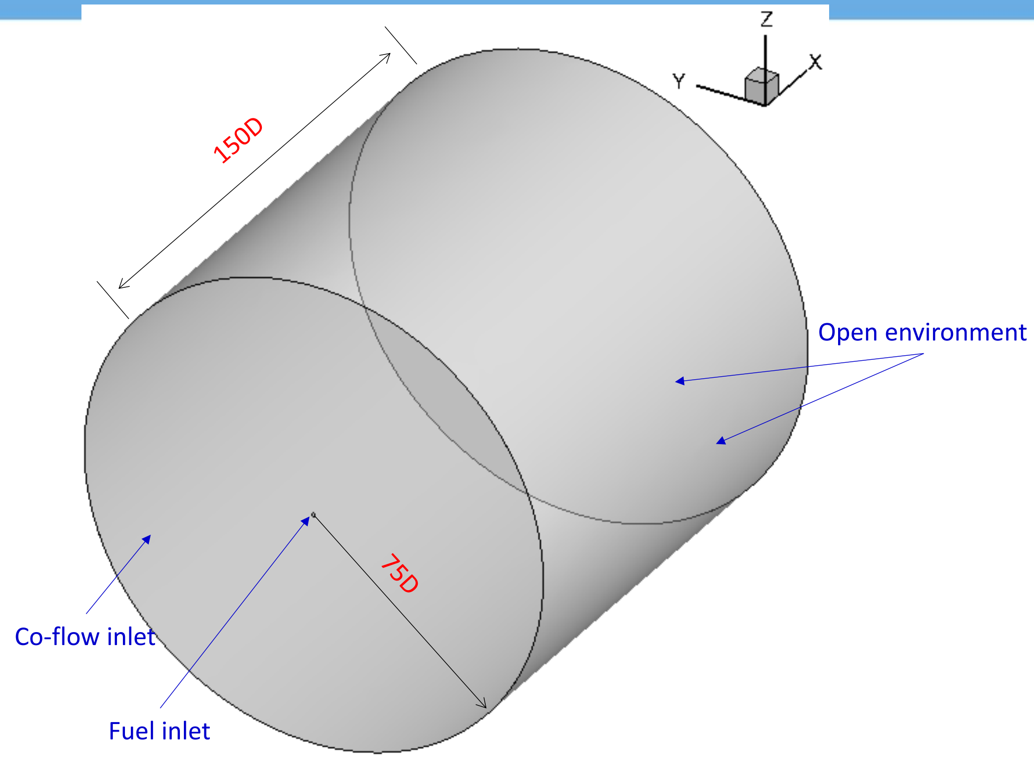
Zhang et al., PROCI 2015.
Garmory and Mastorakos, PROCI 2015.

Sung et al., PROCI 1998.
Pera et al., CNF 2006.
Garmory and Mastorakos, PROCI 2011.

Experimental and computational setup

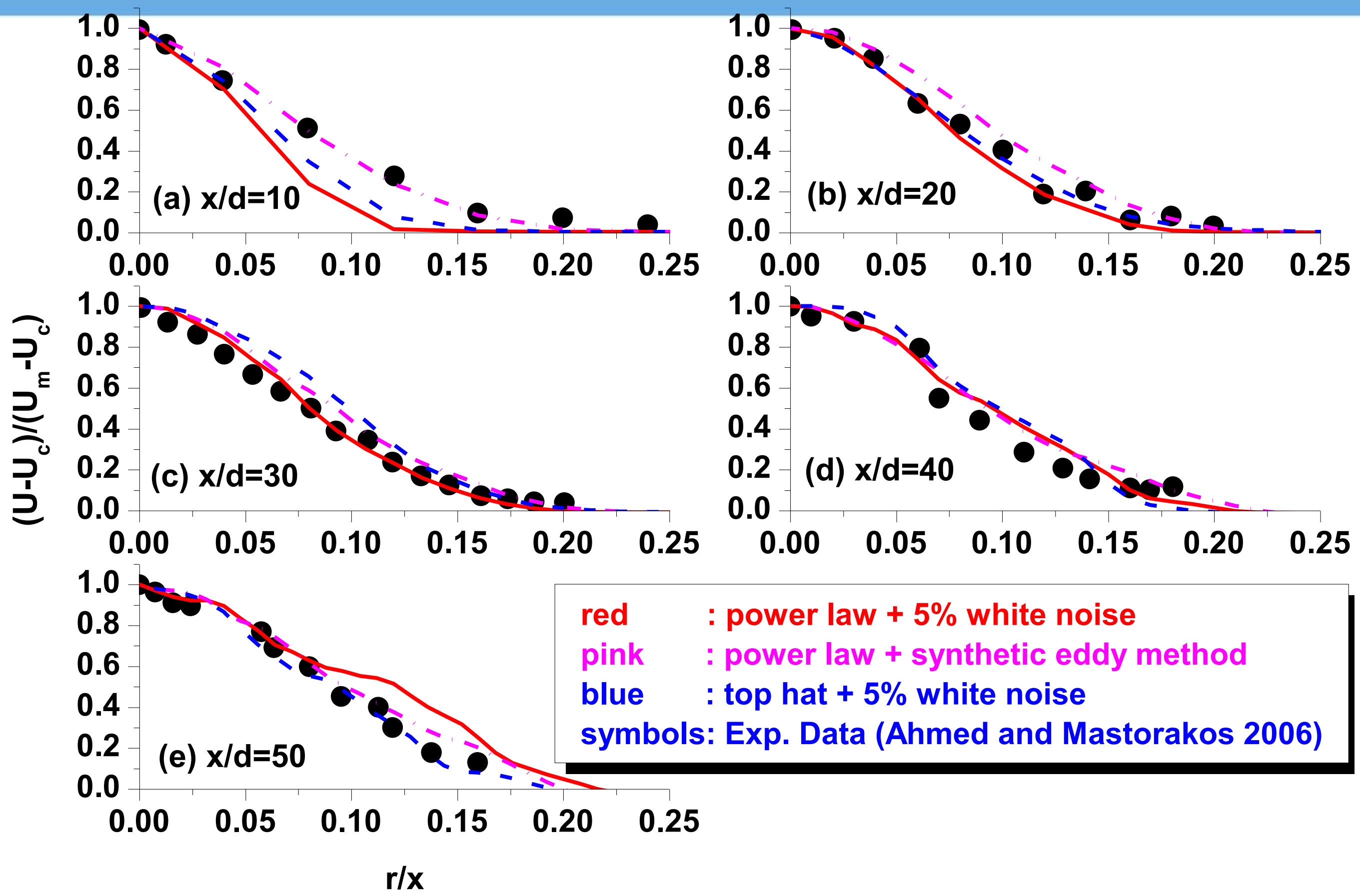


Schematic of the test rig (Ahmed and Mastorakos CNF 2006)



- **Fuel**: 70% CH_4, 30% air by volume
- **LES cells**: 13 m; **CMC cells**: 160 k
- **Spark location:** centerline and off-axis

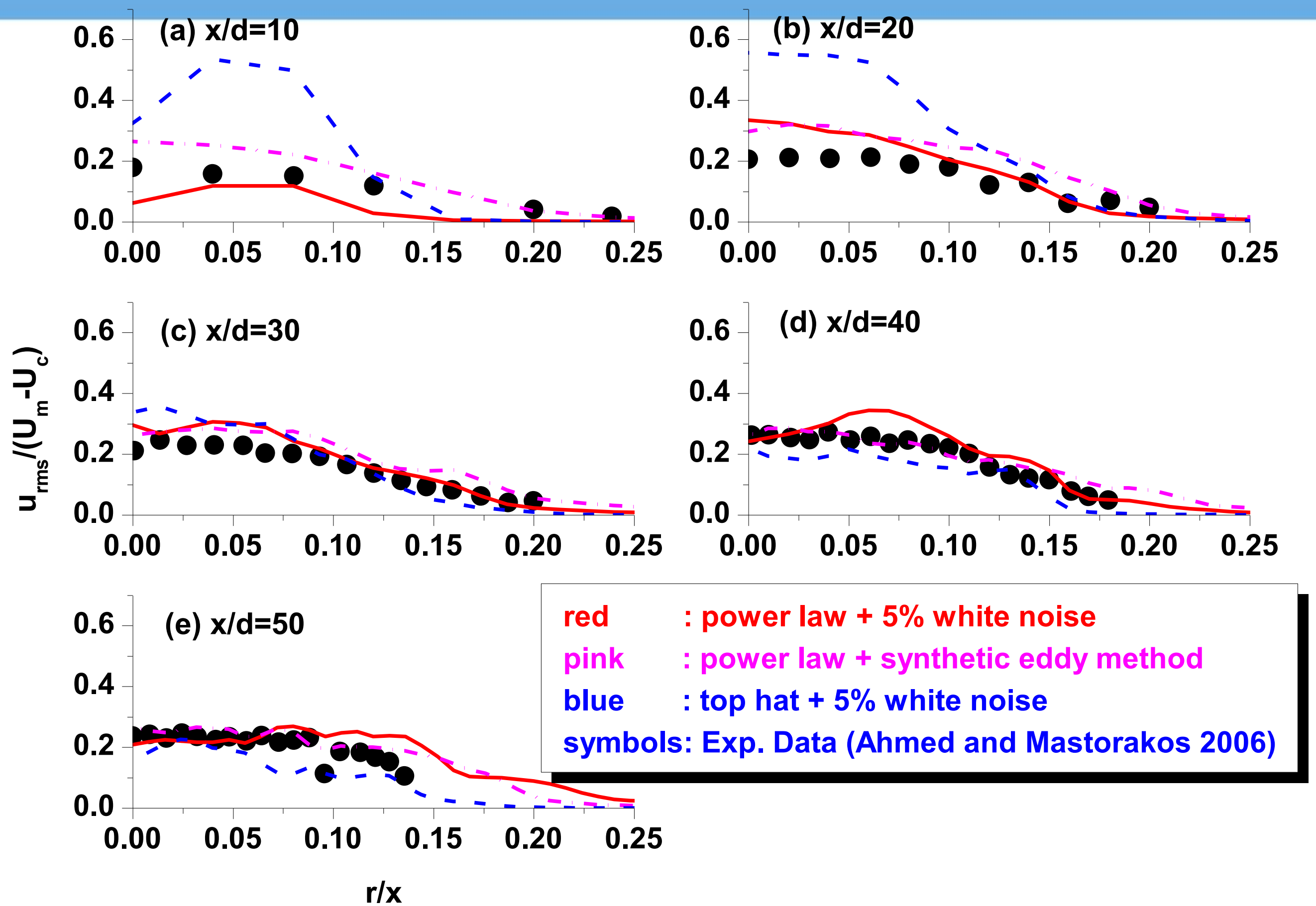
Non-reacting flow field



- The effect of inlet turbulence in the LES of non-reacting flows is only shown in x/D=10.
- Inclusion of the synthetic eddy method may have influence on the flame stabilization after spark ignition.

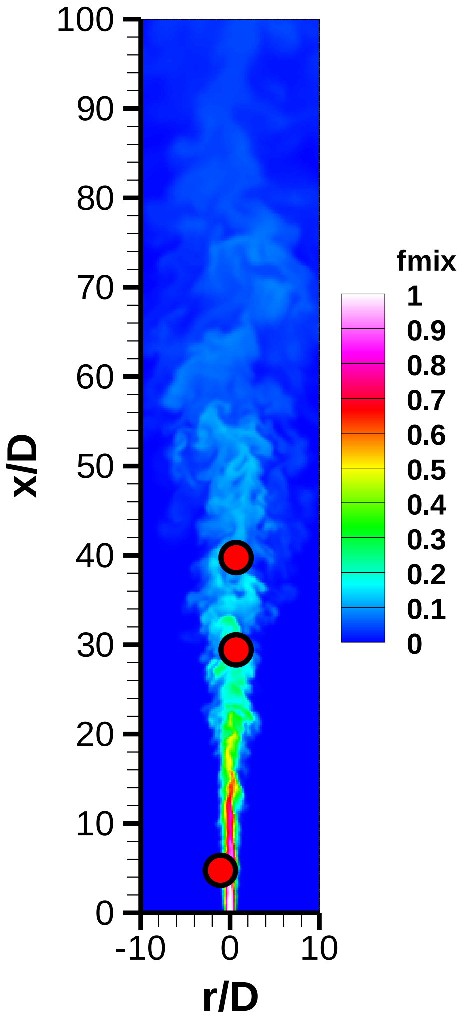
Experimental data: Ahmed and Mastorakos, CNF 2006.

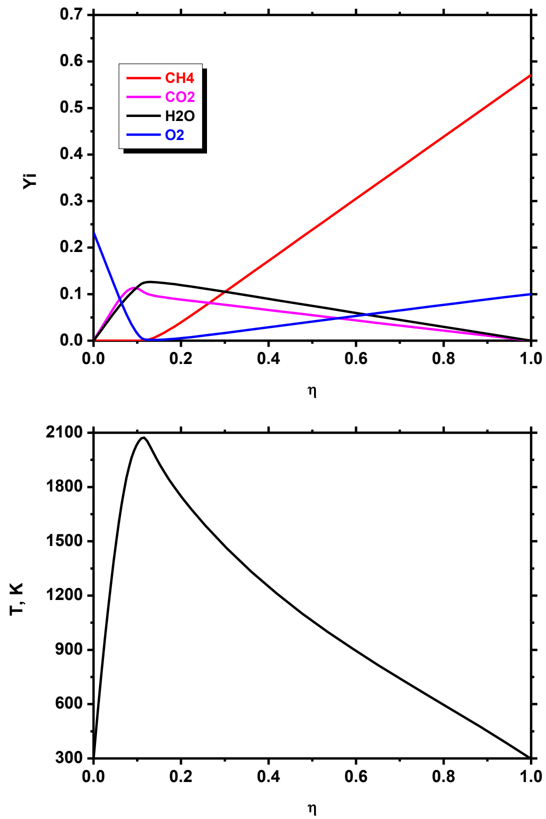
Non-reacting flow field



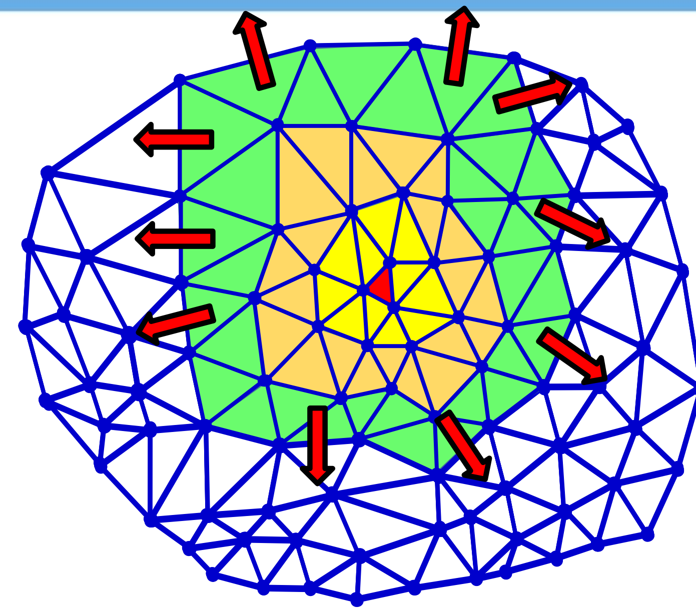
- The near-field turbulence (e.g. at x/D=10) is well reproduced by the synthetic eddy method.

Spark location





Flame kernel structure from CMC model

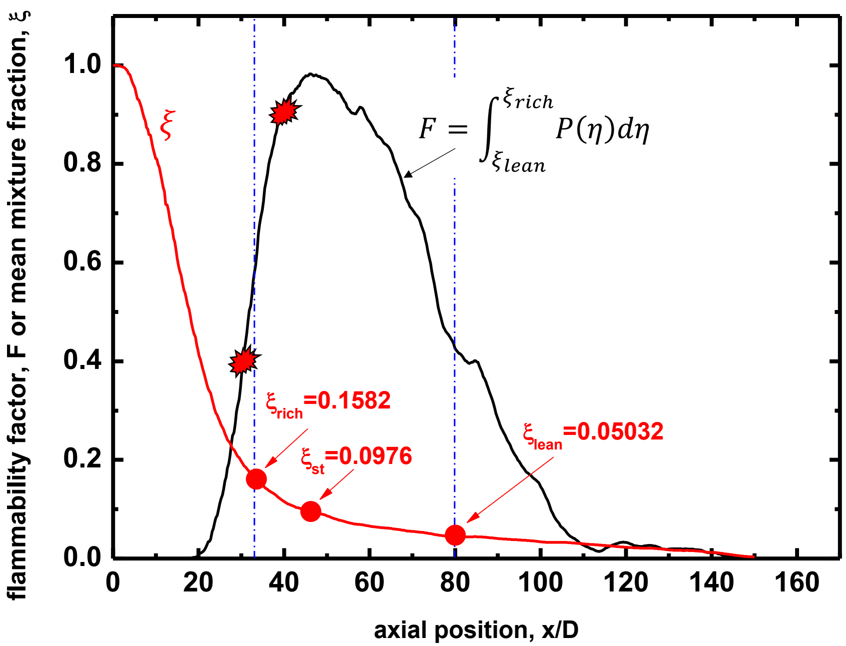


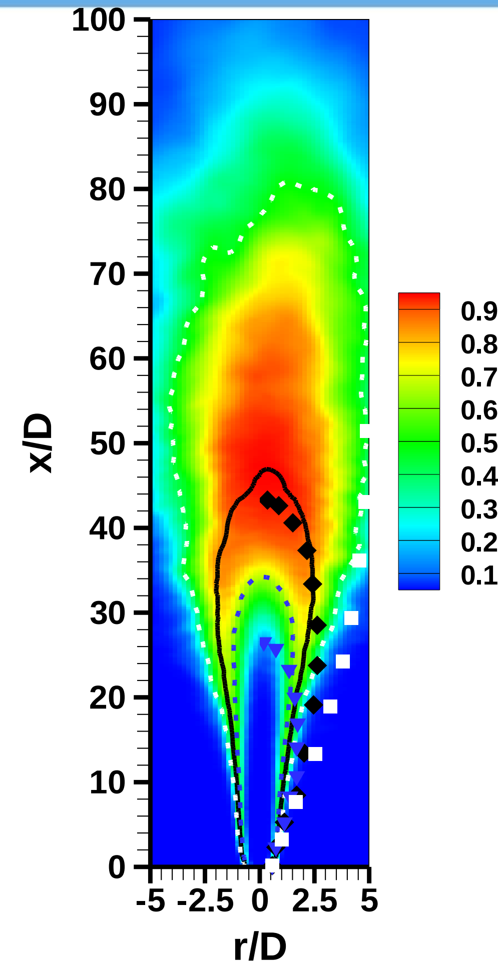
- Three cases with different spark locations are simulated.
- Flame kernel is mimicked by depositing the fully reactive flame structures in mixture fraction space.

Flammability factor

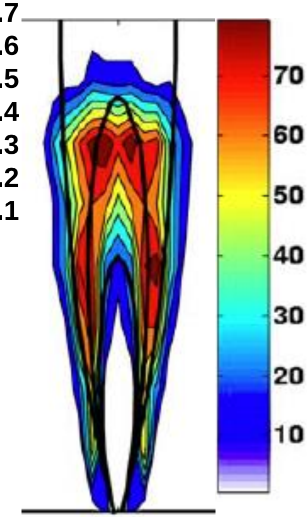
- Flammability factor ⇔ probability to achieve flame kernel

$$F = \int_{\xi_{lean}}^{\xi_{rich}} P(\eta)d\eta$$





Flammability factor

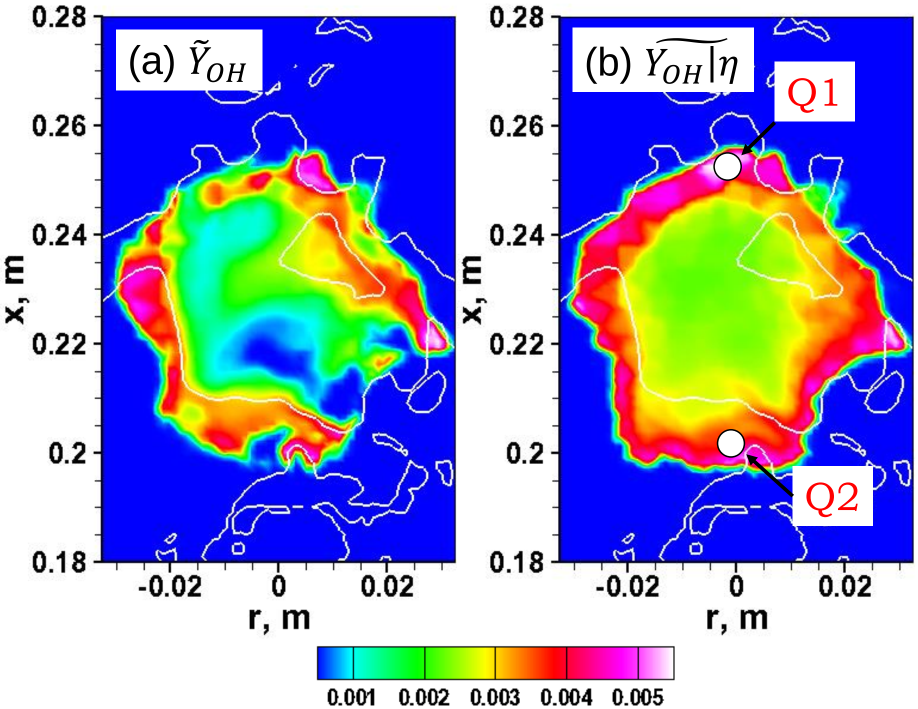


Ignition probability (Ahmed and Mastorakos 2006)

Birch et al. PROCI 1981
Birch et al. PROCI 1986
Ahmed and Mastorakos, CNF 2006.

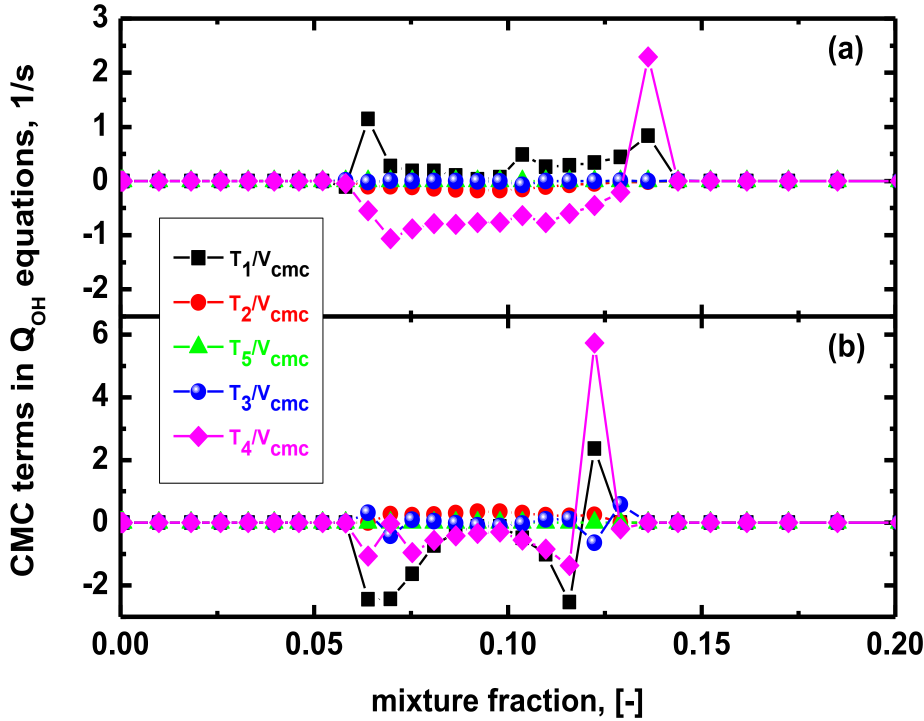
Flame kernel growth

Spark location at x/D=40



White iso-lines: stoichiometric mixture fraction

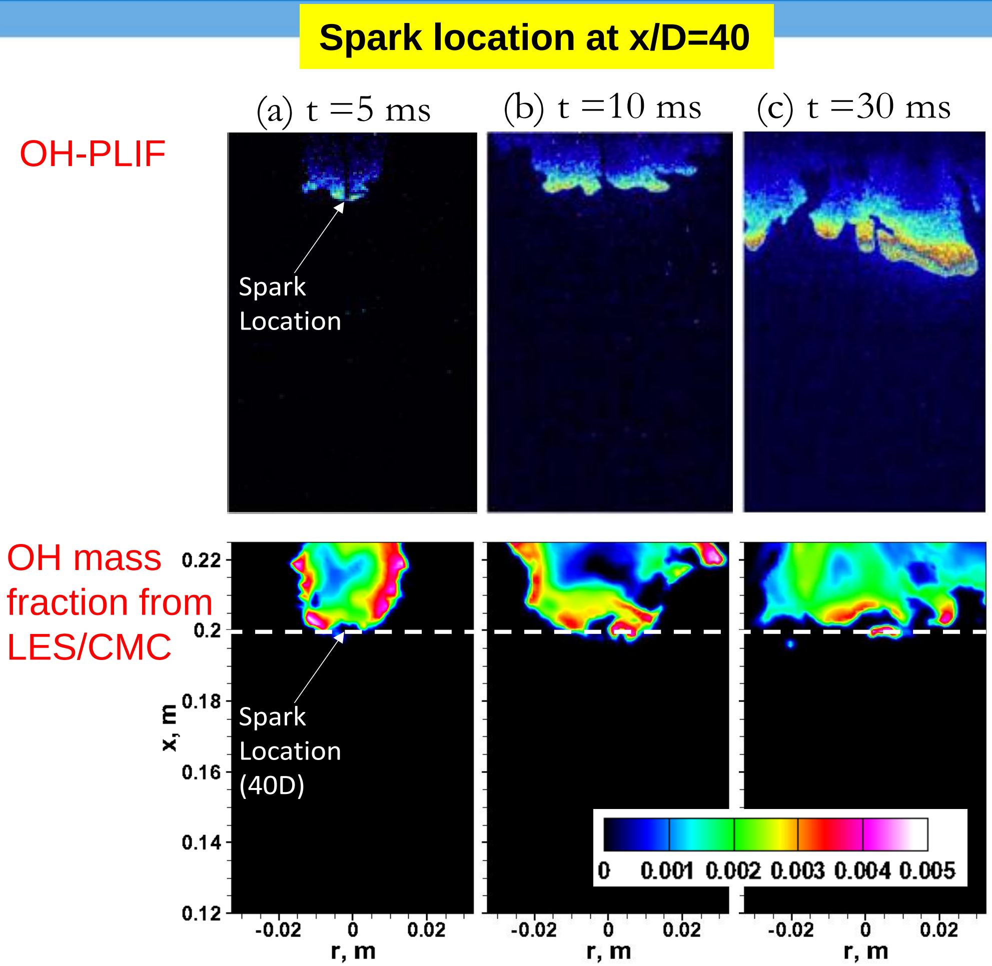
Budget analysis of CMC terms

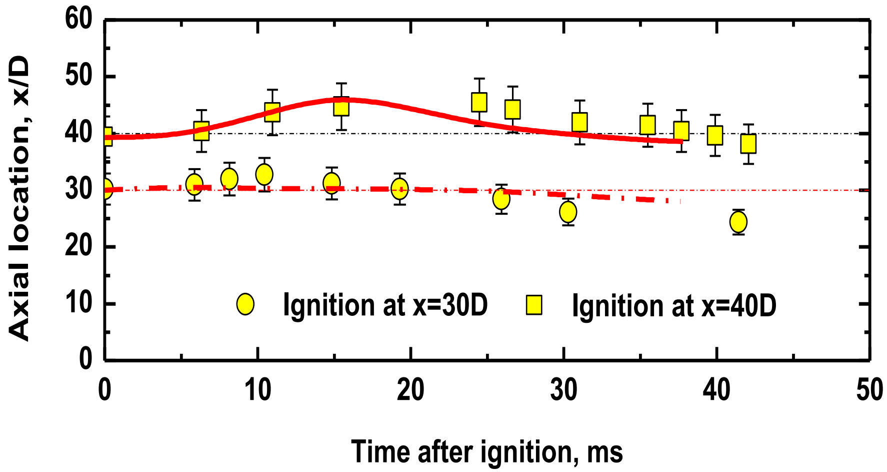


T_1: convection; T_2: dilatation; T_3: micro-mixing; T_4: reaction; T_5: sub-grid scale diffusion

- The conditional convection in mixture fraction space play a significant role for flame kernel growth.

Initial flame propagation

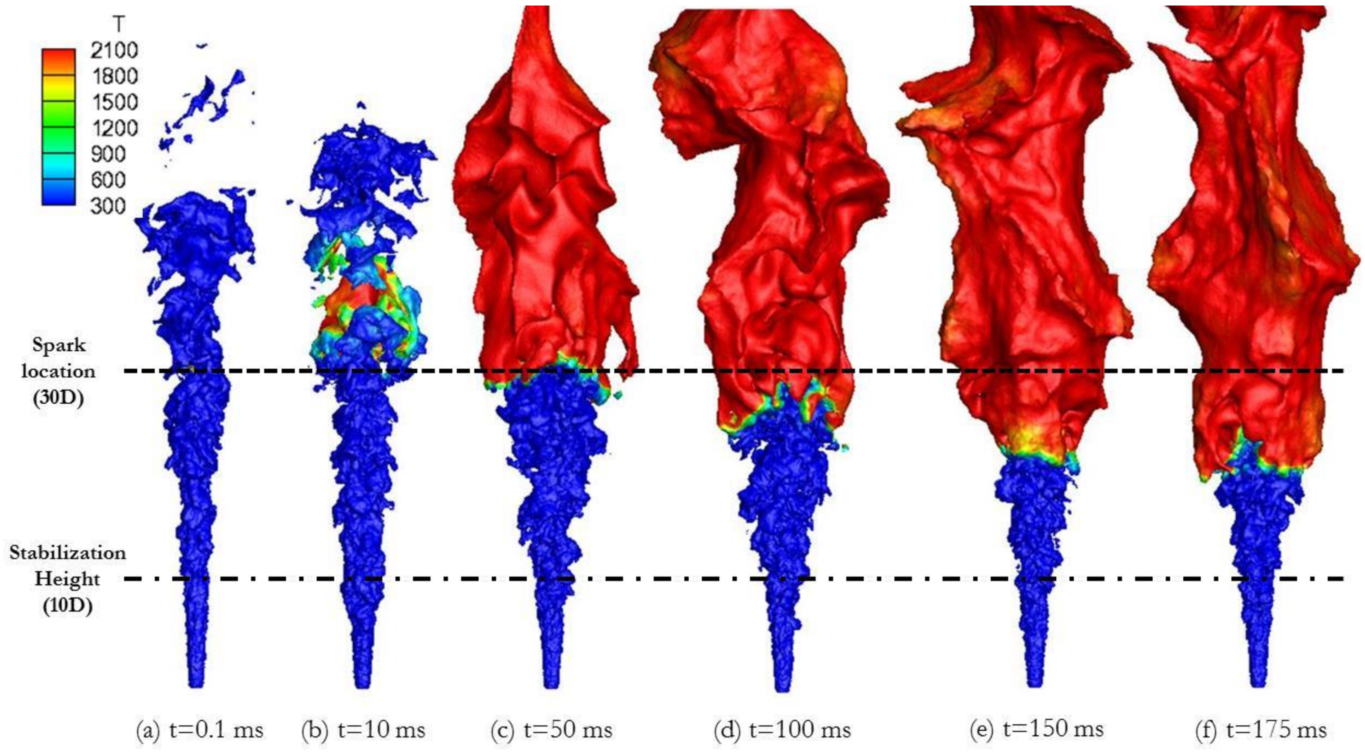


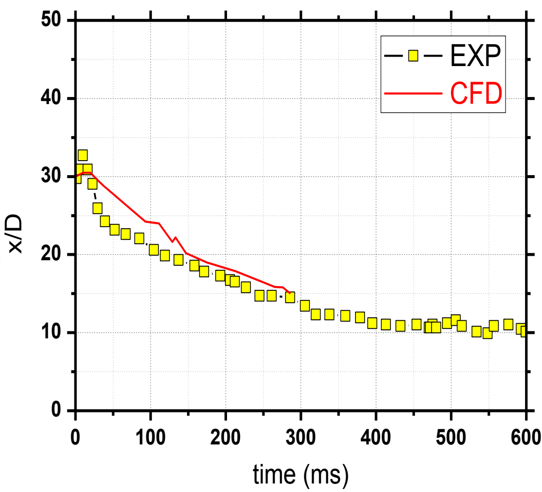


- The distribution of OH mass fraction during the stage of initial expansion of the flame kernel is reasonably predicted by LES/CMC.
- In the ignition of x = 40D case, the propagation speed of the upstream edge of the flame is under-predicted.

Flame propagation towards stabilization

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





Conclusions and future work

- The large eddy simulation is applied for simulating the spark ignition process of turbulent methane jet flows with sub-grid scale conditional moment closure model.
- The flow and mixing fields in the inert flows before ignition are validated with the experimental data and good agreement is achieved. Based on the mixing fields, flammability factor is estimated to indicate the probability of flame kernel formation.
- The initial growth of the flame kernel is analyzed based on the budget analysis of the individual terms of the CMC governing equations. It is found that the convection dominates.
- The time history of the flame edge propagation is compared with the corresponding the measured data and the good agreement is achieved. This confirms the capacity the CMC model and the current implementations.

Future work:

✓ Investigate the different flame propagation history for the three simulated ignition cases.

✓ Analyze the mechanism for the flame edge propagation based on the LES/CMC modelling.

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archer

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Thank You for Your Attention !