Case 5: Flame Extinction

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Acknowledgements

- Dr. James P. White (FM Global)

Overview

- Experimental Setup
  - Turbulent Line Burner (TLB) Facility
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    - Suppression
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- Simulation Results
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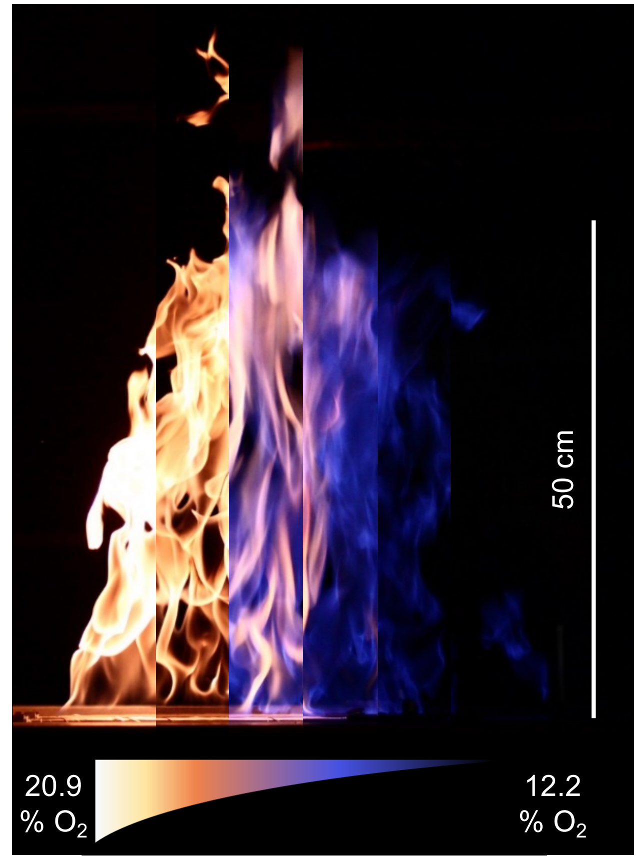
    - O_2 Profiles
    - Flame Height
    - Combustion Efficiency
- Concluding Remarks
  - Experimental Issues
    - Flame Anchor Effects
    - Ventilation
      - Entrainment
      - Exhaust Flow Distribution
    - Mist Details
  - Experimental Advancements
    - New Configurations
    - New Measurements
  - Simulation Issues
- Open Discussion

TLB Facility

Overview

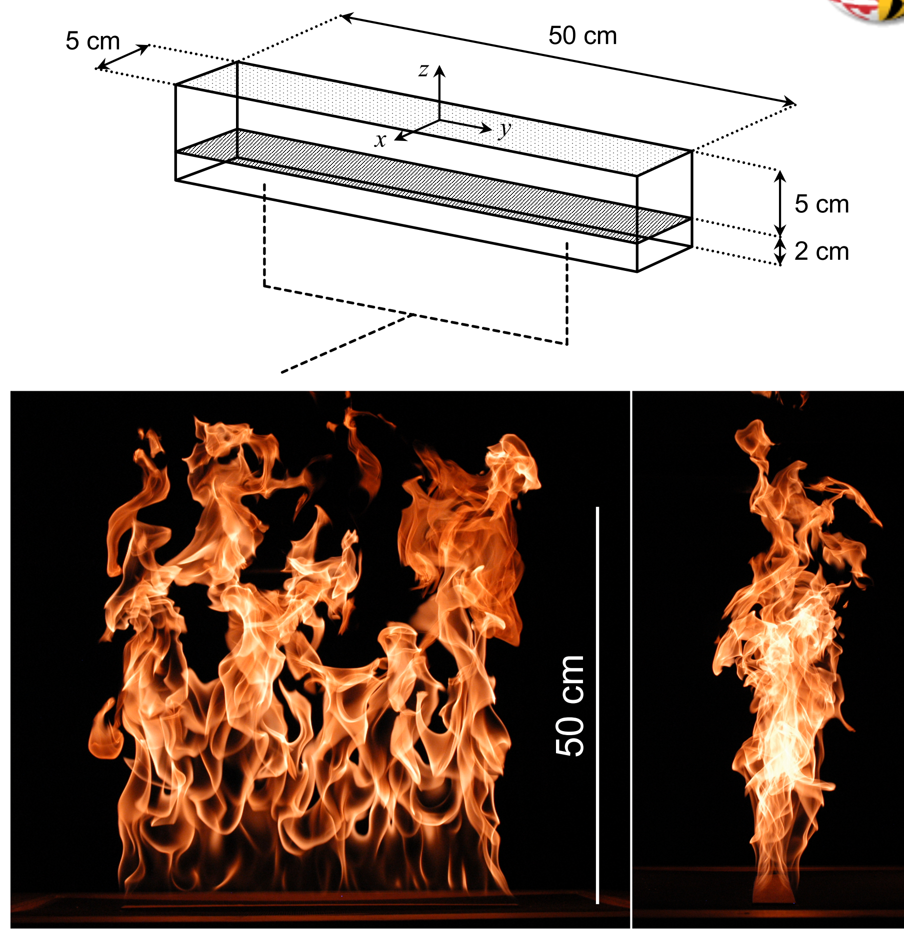
- Canonical lab-scale facility
- Well-characterized inlet and boundary conditions
- Integral and local diagnostics
  - Global HRR / combustion efficiency
  - Global radiative loss fraction
  - Mean flame height
  - Local temperature & O_2 profiles
- Suppression capabilities
  - Nitrogen dilution of oxidizer
  - Water-mist



TLB Facility

Flame Details

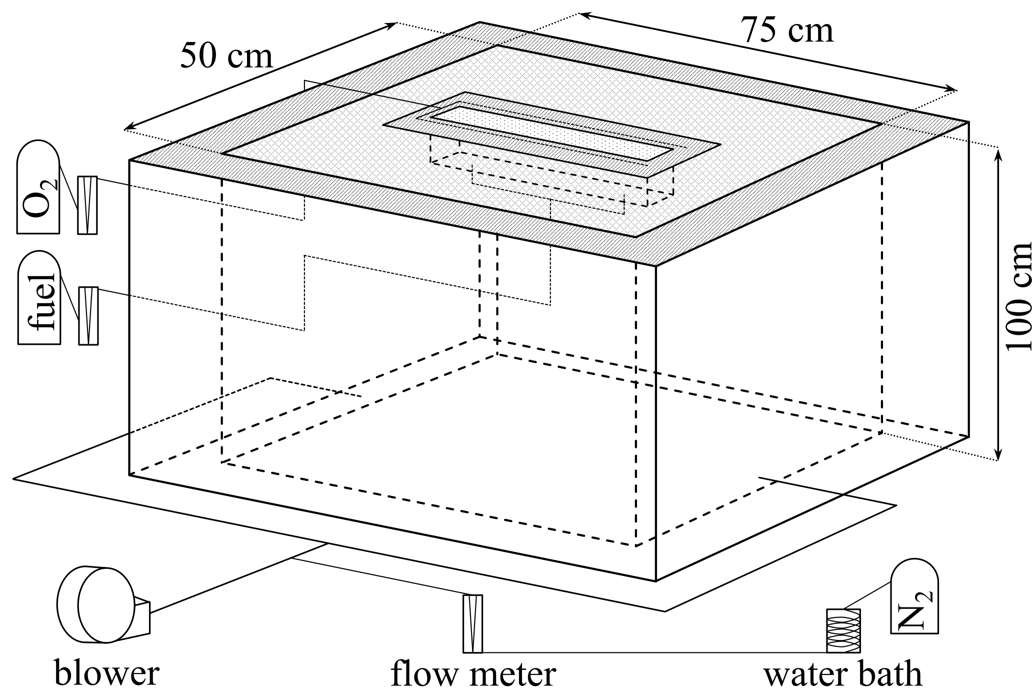
- Flame features
  - Line-fire geometry
  - Buoyancy driven
  - Fully turbulent
- Gaseous fuels
  - Methane (CH4) 1.00 g/s, 5.4 cm/s
  - Propane (C3H8) 1.08 g/s, 2.1 cm/s
- ~50 kW total HRR



TLB Facility

Suppression Details

- Co-flowing oxidizer
  - Steady, uniform flow (85 g/s, 25 cm/s)
  - Controlled suppressant delivery
- Nitrogen suppression
  - N_2 gas via pressurized Dewar
  - 0-40 g/s N_2 (X_{O_2} : 0.21-0.11)
  - Oxygen anchor
    - ➢ 0.08 g/s O_2 (~2% combustion)
    - ➢ Prevents liftoff extinction



TLB Facility

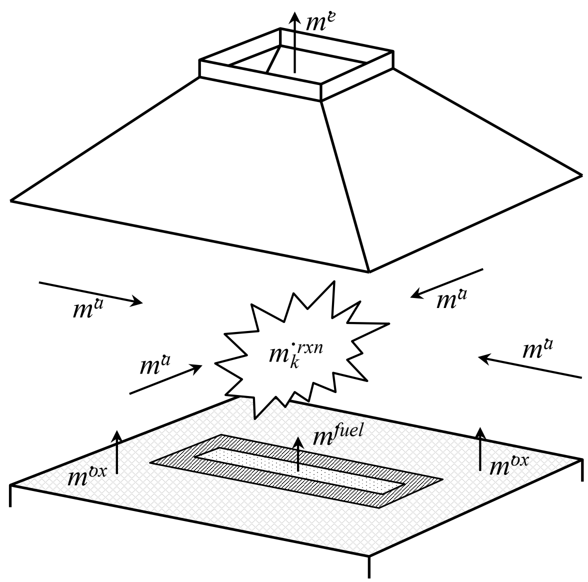
Measurement Details

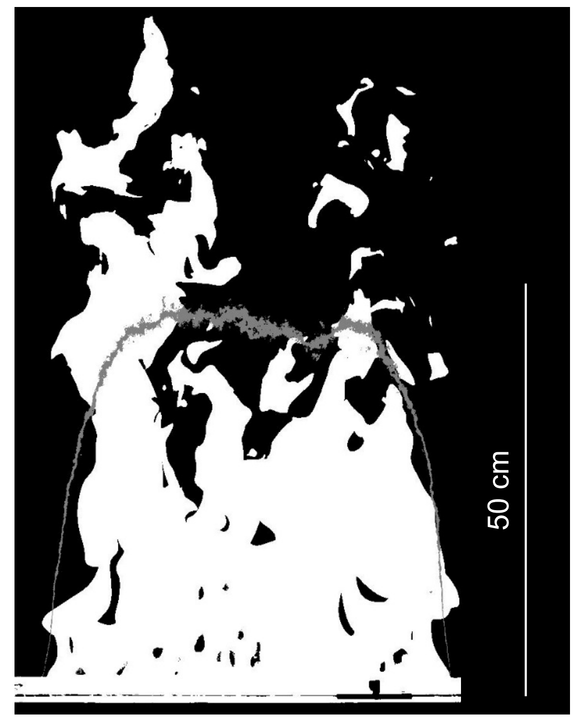
- Local point-measurement profiles
  - Cross-flame profiles, 12.5 cm and 25 cm elevation
  - Partially diluted oxidizer (X_{O2} ~ 0.18)
  - TC temperature
    - K-Type thermocouples, ~1 mm bead diameter
    - Uncertainty ±2 K
  - O_2 concentration
    - 1/8” OD copper tube sampling probe
    - Servomex 540E paramagnetic O_2 analyzer
    - Uncertainty ±1250 ppm

TLB Facility

Measurement Details

- Flame height
  - Video camera
  - 50% intermittent visible flame location
  - Uncertainty ±1.5 cm
- Combustion efficiency
  - OC and CDG calorimetry
  - Uncertainty ±1.5 kW





Simulation Results

Contributing Teams

- FM Global (Ning Ren)
- University of Maryland (A. Marchand, S. Verma and A. Trouvé)
- NIST (Randall McDermott)

Simulation Results

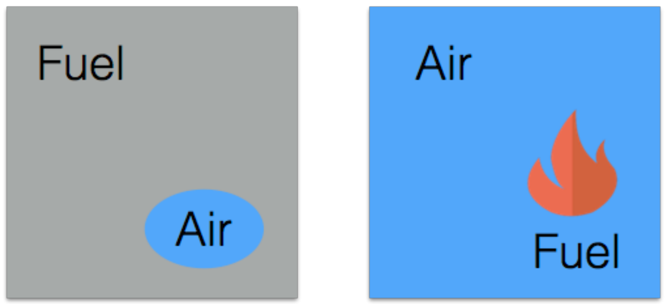
Summary Modeling Information

Institution	Model Domain (m) DX (mm)	Radiation Model	Turbulence Model	Combustion Model	Extinction Model	Re-ignition Model
FM Global	FireFOAM-dev 1.6 x 1.4 x 2.0 5.0	fvDOM Gray Xr*Q N_DO=16	Deardorff MU_t 1-Eqn ksgs SC_t = 1.0 PR_t = 1.0	EDC C_EDC = 4.0 C_DIFF = 6.0	Reactive Volume Fraction Model Vilfayeau (2 fuel)	
UMD	FireFOAM-dev 2.0 x 0.85 x 2.0 4.2				Critical Damköhler Number	T_IGN = 1100 K Vilfayeau (2 fuel)
NIST	FDS 6.5.3-dev 1.65 x 2.0 x 1.5 3.125	fvDOM Gray Xr*Q N_DO=700	Deardorff MU_t Algebraic ksgs SC_t = 0.5 PR_t = 0.5	EDC C_U = 0.4 C_D = 1.0	Critical Flame Temperature T_OI (SFPE)	Pilot Zone AIT (SFPE)

Critical Flame Temperature Model

J. Vaari et al. CFD Simulations on Extinction of Co-Flow Diffusion Flames. In 10th IAFSS, 2011.

Diluents include excess Fuel, but not excess Air

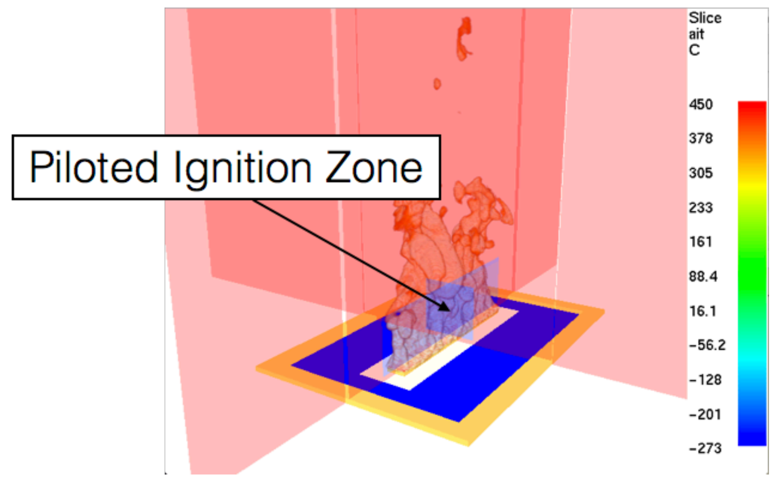


$$\underbrace{m_F \Delta h^\circ_{f,F} + m_A \Delta h^\circ_{f,A} - m_P \Delta h^\circ_{f,P}}_{\sum_\alpha m_\alpha \Delta h^\circ_{f,\alpha} \equiv Q} + m_F \int_{T_{ref}}^{T_0} C_{p,F}\,\mathrm{d}T + m_A \int_{T_{ref}}^{T_0} C_{p,A}\,\mathrm{d}T + m_D \int_{T_{ref}}^{T_0} C_{p,D}\,\mathrm{d}T$$

$$= m_P \int_{T_{ref}}^{T_f} C_{p,P}\,\mathrm{d}T + m_D \int_{T_{ref}}^{T_f} C_{p,D}\,\mathrm{d}T$$

$$m_F h_{s,F}(T_0) + m_A h_{s,A}(T_0) + m_D h_{s,D}(T_0) + Q < m_P h_{s,P}(T_{CFT}) + m_D h_{s,D}(T_{CFT})$$

Reignition Model



J.P. White, S. Vilfayeau, A.W. Marshall, A. Trouvé, R.J. McDermott. Modeling flame extinction and reignition in large eddy simulations with fast chemistry. Fire Safety Journal, 2017.

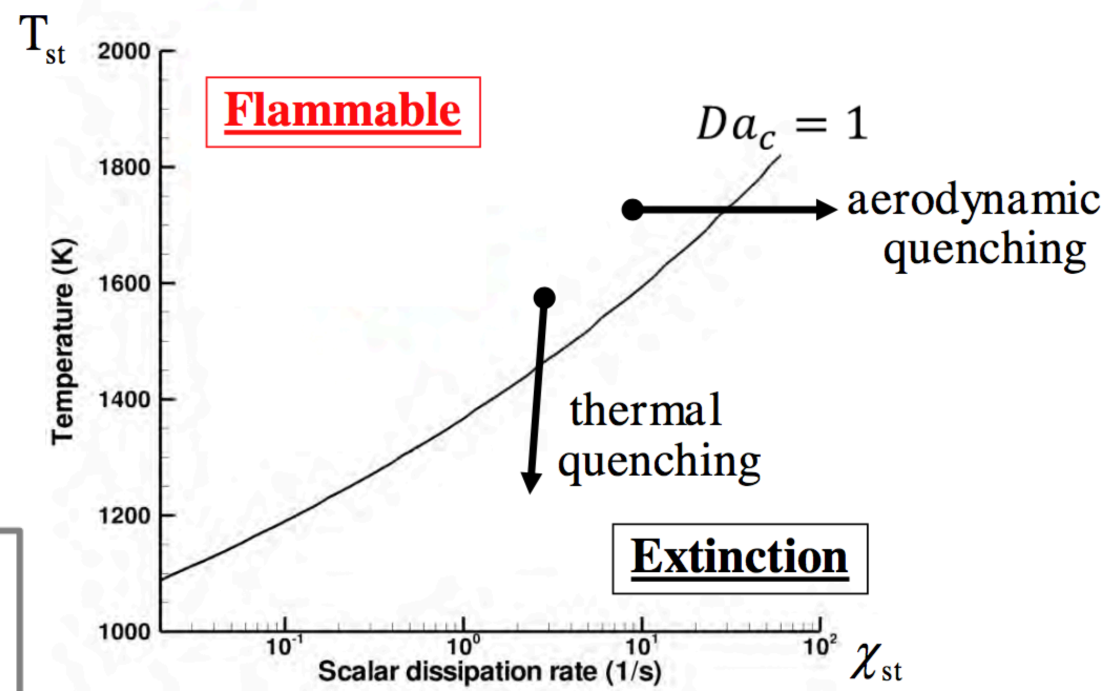
Critical Damköhler Number Model

S. Vilfayeau et al. Large eddy simulation of flame extinction in a turbulent line fire exposed to air-nitrogen co-flow. *Fire Safety Journal*, 2016.

- UMD model
  - Provide a framework that allows a separate treatment of **extinction** and reignition

$$Da = \frac{\tau_{mixing}}{\tau_{chemical}}$$

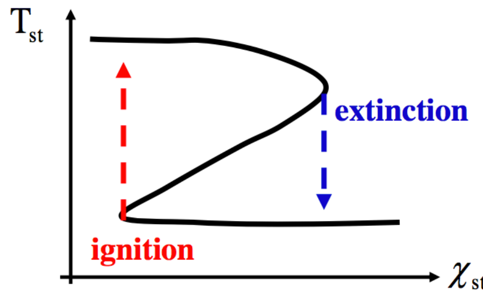
$$Da = C\frac{\exp(-Ta/T_{st})}{\chi_{st}} \leq Da_c$$



Reignition Model

S. Vilfayeau et al. Large eddy simulation of flame extinction in a turbulent line fire exposed to air-nitrogen co-flow. *Fire Safety Journal*, 2016.

- UMD model
  - Provide a framework that allows a separate treatment of extinction and **reignition**



$$\overline{\dot{\omega}'''_{R_1}} = (1 - FEF) \times \overline{\dot{\omega}'''_{EDC}}$$

$$\overline{\dot{\omega}'''_{R_2}} = FEF \times \overline{\dot{\omega}'''_{EDC}}$$

$$\overline{\dot{\omega}'''_{R3}} = FIF \times (\overline{\dot{\omega}'''_{EDC}})^*$$

R1: $C_nH_mO_p + \left(n + \frac{m}{4} - \frac{p}{2}\right) O_2 \rightarrow nCO_2 + \frac{m}{2} H_2O$

R2: $C_nH_mO_p + \left(n + \frac{m}{4} - \frac{p}{2}\right) O_2 \rightarrow C_nH_mO_p^* + \left(n + \frac{m}{4} - \frac{p}{2}\right) O_2$

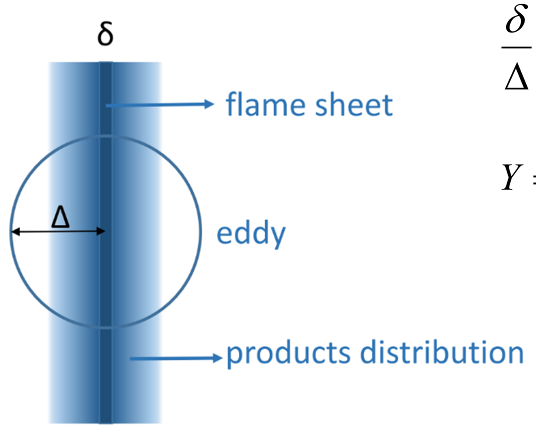
R3: $C_nH_mO_p^* + \left(n + \frac{m}{4} - \frac{p}{2}\right) O_2 \rightarrow nCO_2 + \frac{m}{2} H_2O$

FEF Flame extinction factor
FIF Flame re-ignition factor

$\boxed{FIF = H(\tilde{T} - T_{ign})}$ and $T_{ign} = 1100$ K

Reactive Volume Fraction Model

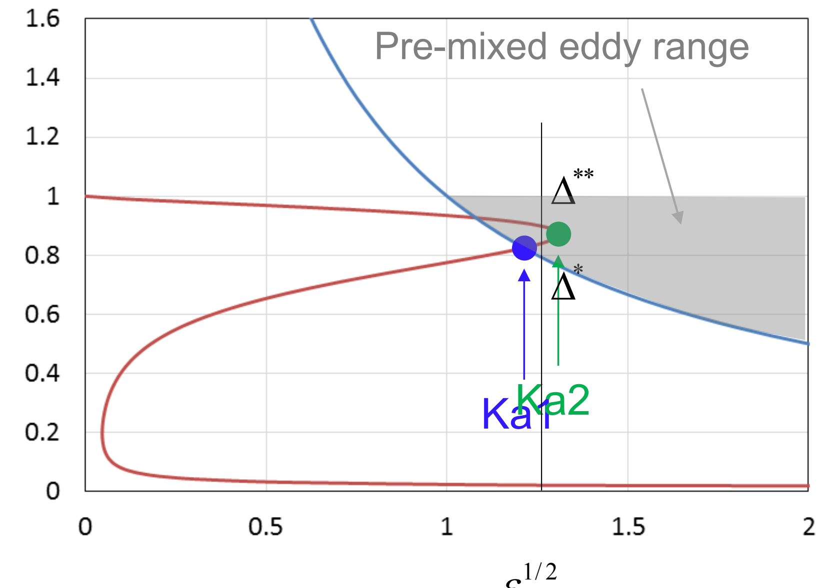
S. Dorofeev. Thermal quenching of mixed eddies in non-premixed flames. In Proceedings of the Combustion Institute, 2016.



$$\frac{\delta}{\Delta} = 1 - Y = 1 - \frac{\theta}{\beta}$$

$$Y = \frac{T_b - T}{T_b - T_u} = \frac{\theta}{\beta}$$

$$x = \frac{\delta}{\Delta}$$



$$Ka = c\delta^2 \frac{\varepsilon^{1/2}}{\nu^{3/2}}$$

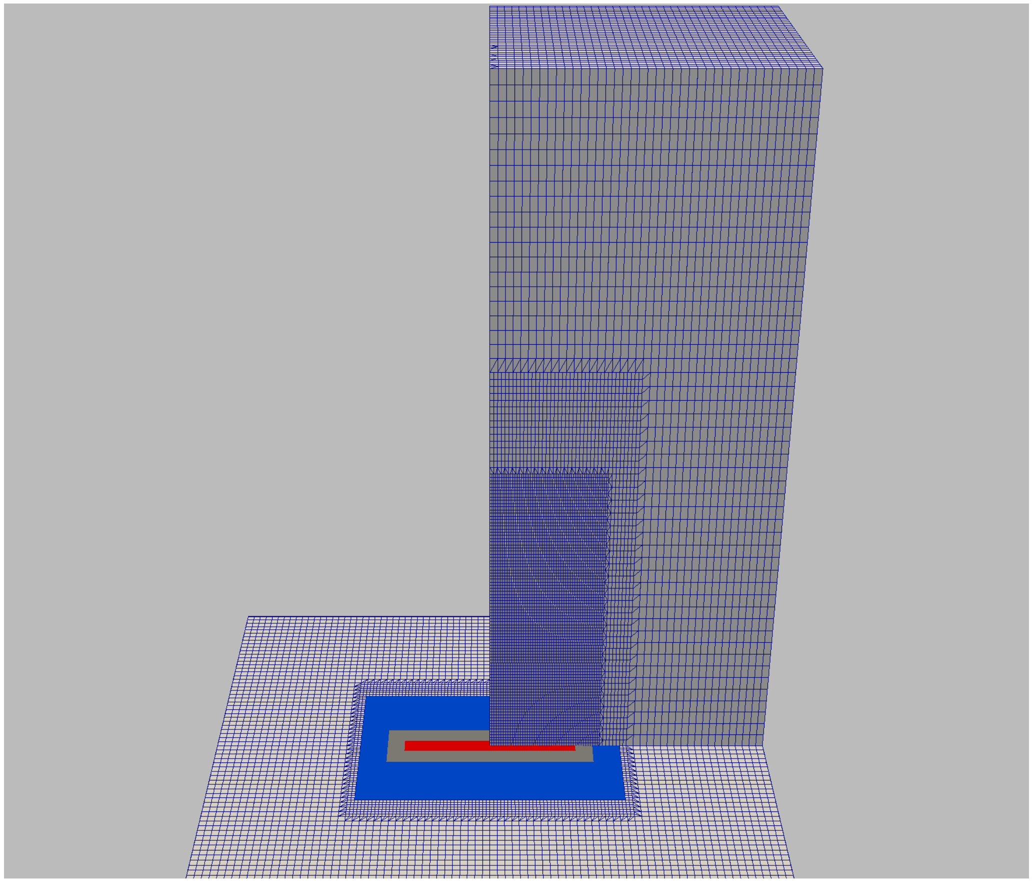
$$-\frac{d\theta}{d\tau} = -\frac{(\beta - \theta)}{Da} + \theta^n e^{-\theta} = 0$$

$$\theta = \frac{E_a (T_b - T)}{T_b^2} \qquad \beta = \frac{E_a (T_b - T_u)}{T_b^2} \qquad \tau = t\beta^{1-n} k_1 e^{-\frac{E_a}{T_b}} \qquad Da = \frac{\beta^{1-n} k_1 e^{-\frac{E_a}{T_b}}}{3\Delta^{-2}(\chi_T + \chi_R)}$$

Computational Domain

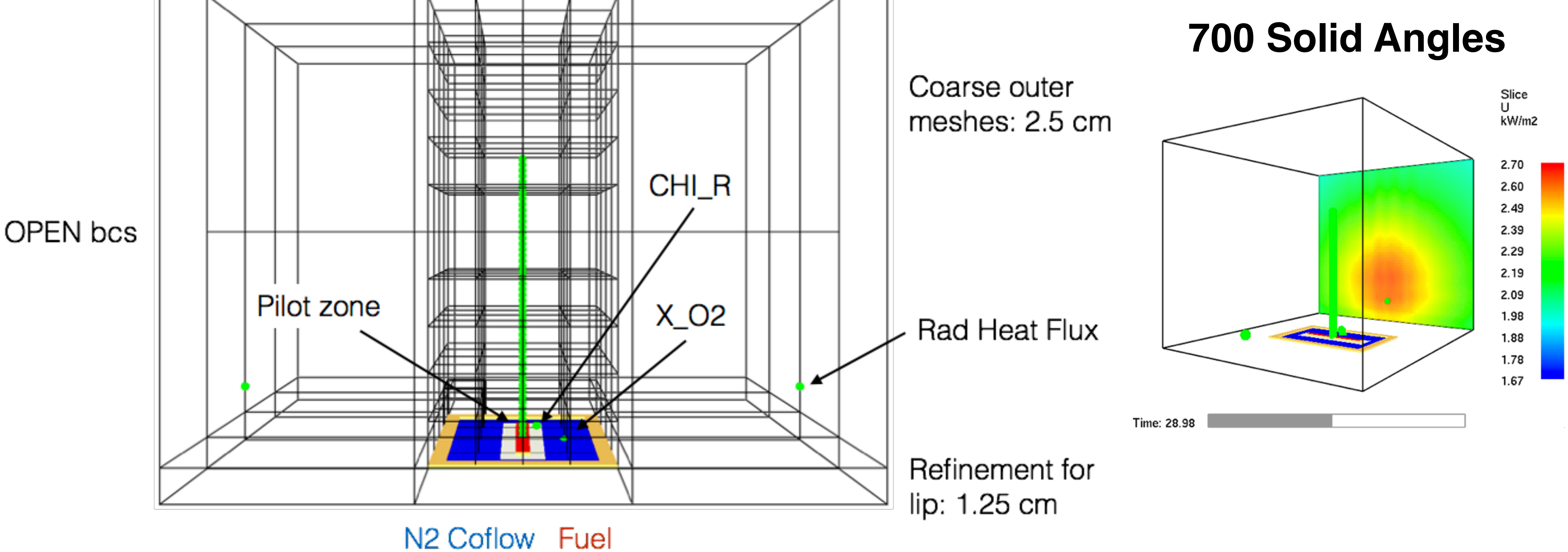
FireFOAM (FM Global)

- CH_4 and C_3H_8
- 1.6 x 1.4 x 2.0 m
- 5 mm grid in the flame region
- 2 cm grid in the far-field



Computational Domain

FDS (NIST)



Simulation Videos

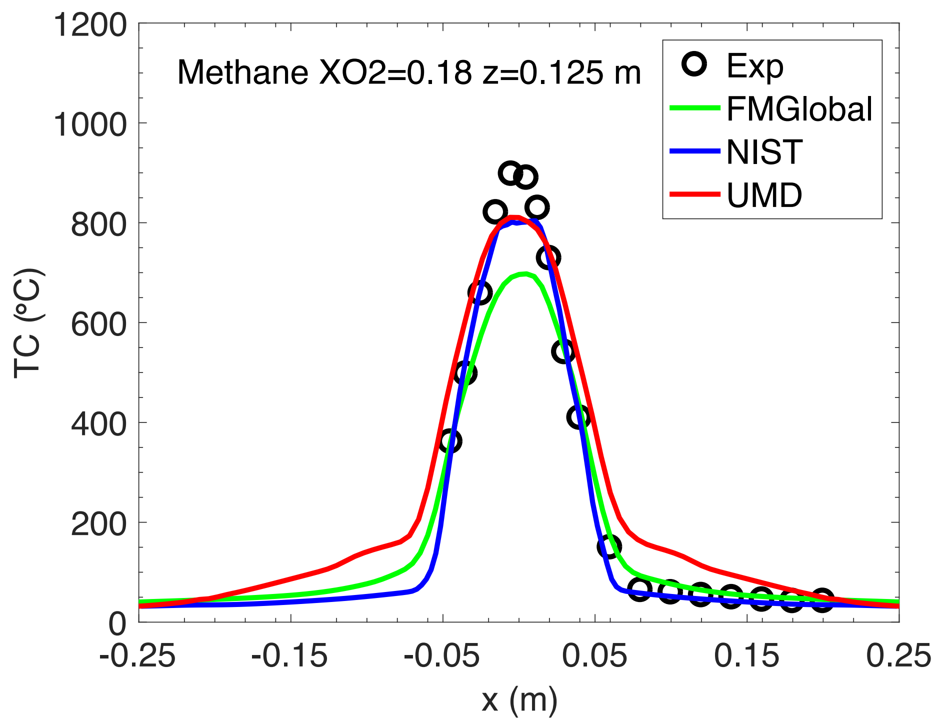
Simulation Results

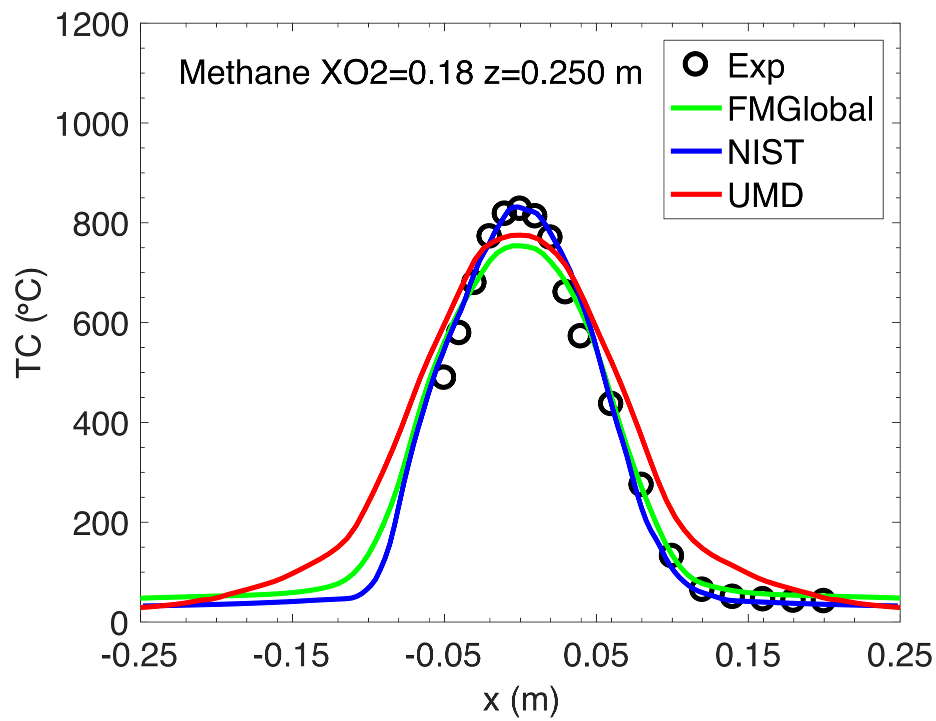
Comparisons

- Temperature Profiles
- O_2 Profiles
- Flame Height
- Combustion Efficiency
- Radiative Heat Flux

Simulation Results

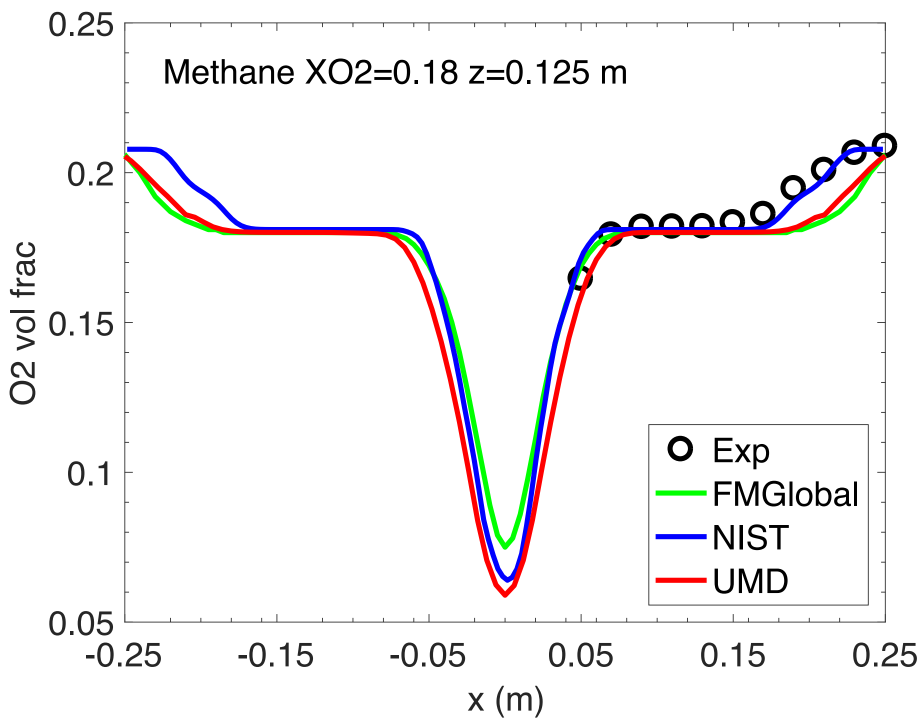
Temperature Profile Comparisons

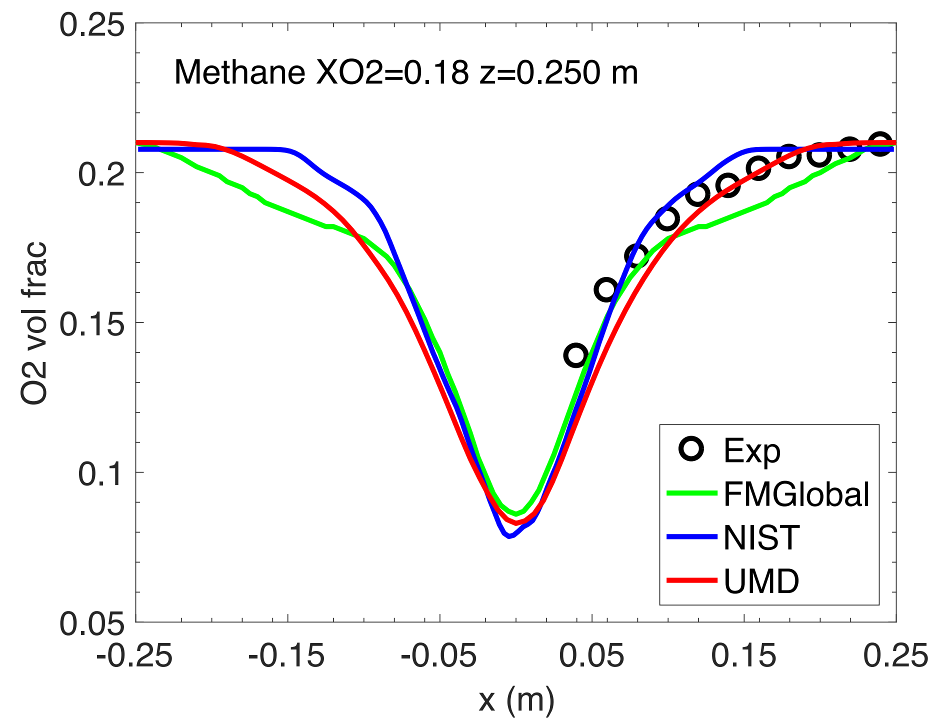




Simulation Results

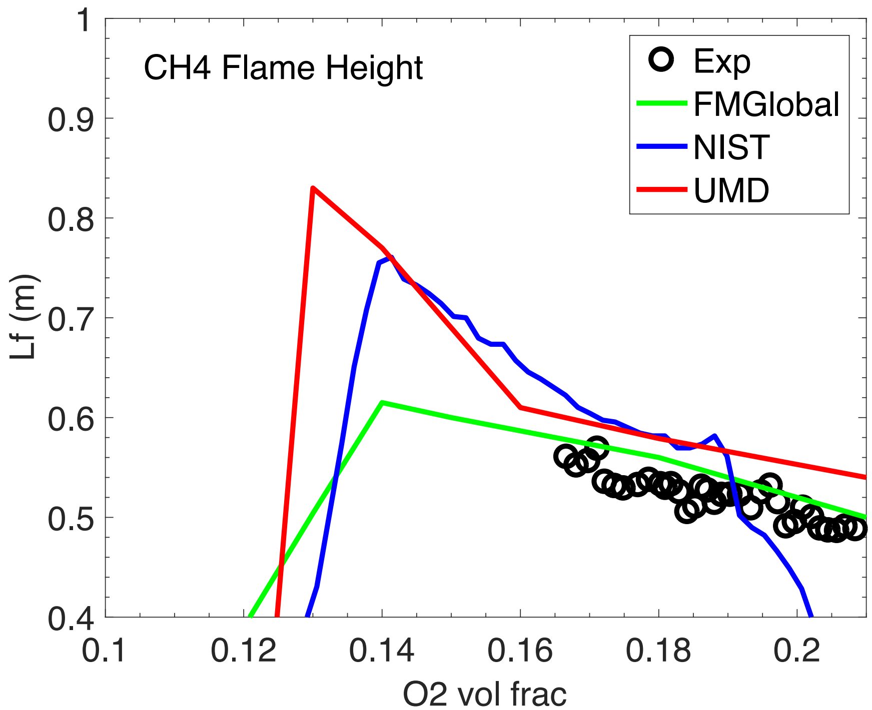
O_2 Profile Comparisons

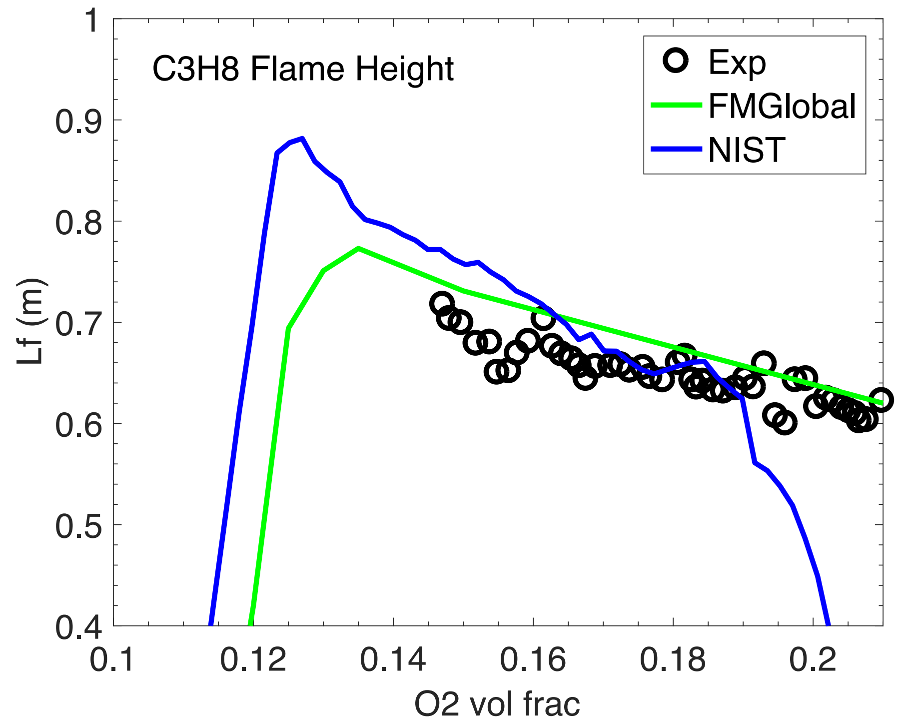




Simulation Results

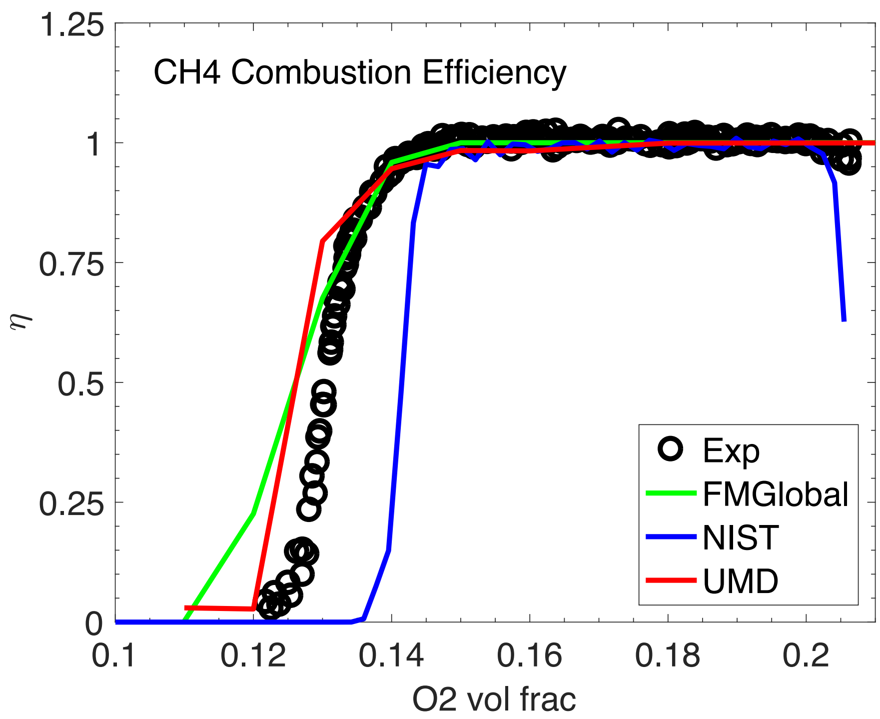
Flame Height Comparisons

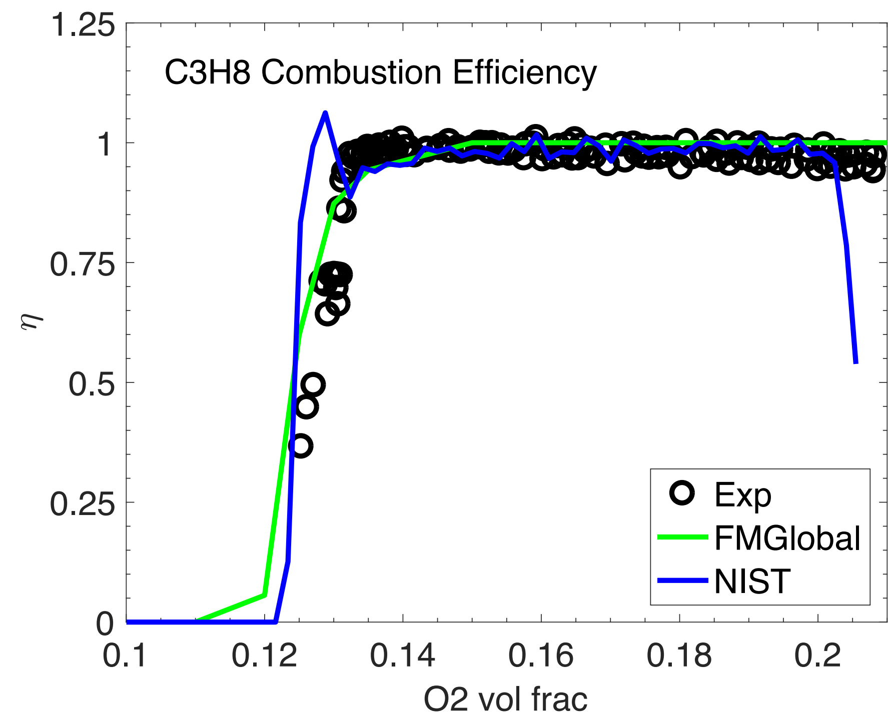




Simulation Results

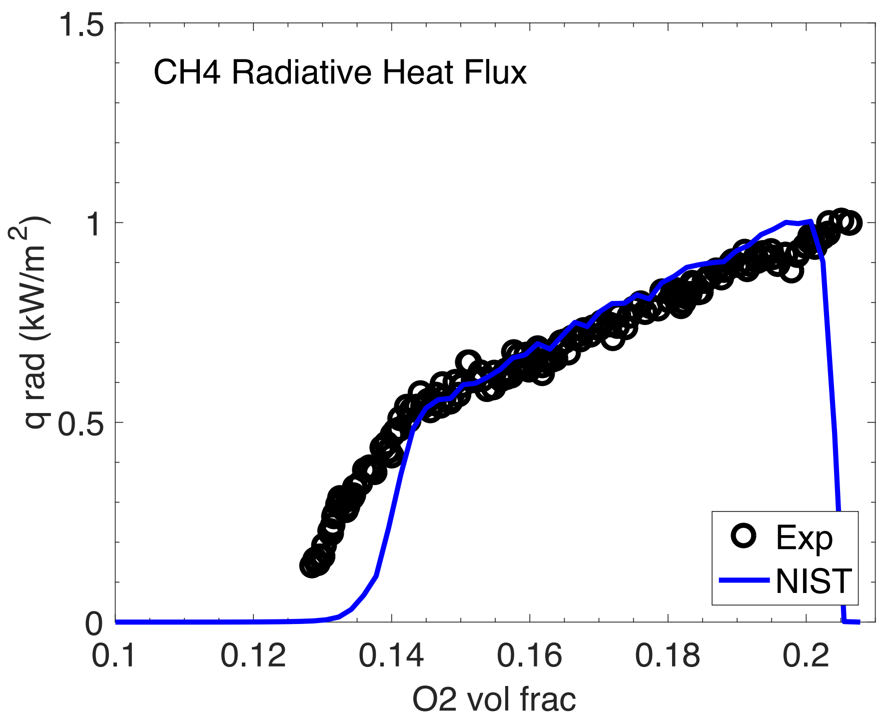
Combustion Efficiency Comparisons

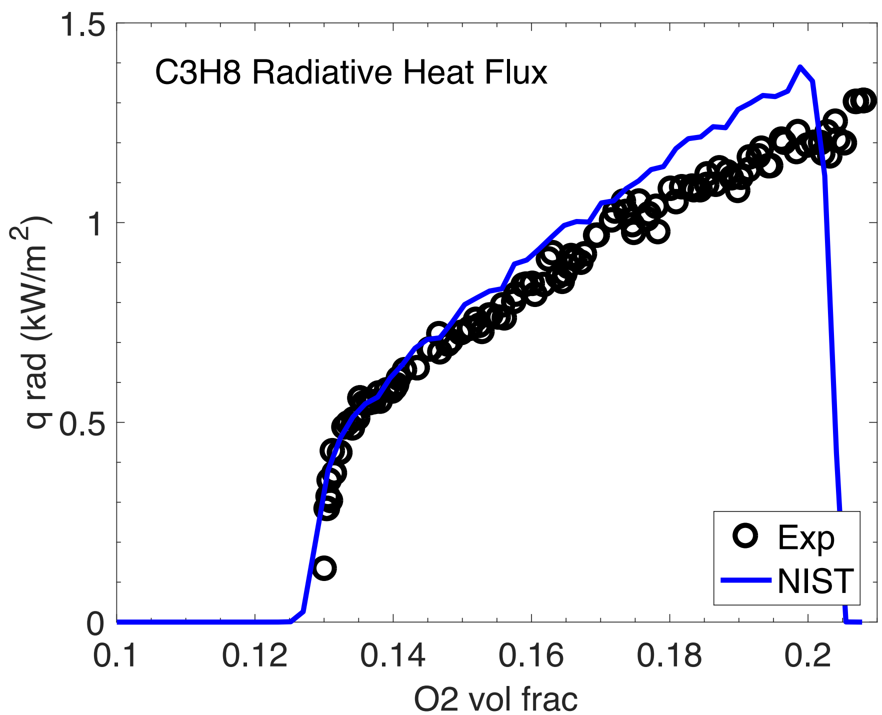




Simulation Results

Radiative Heat Flux Comparisons

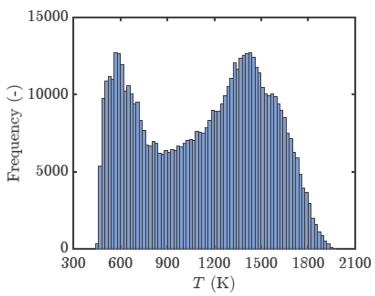


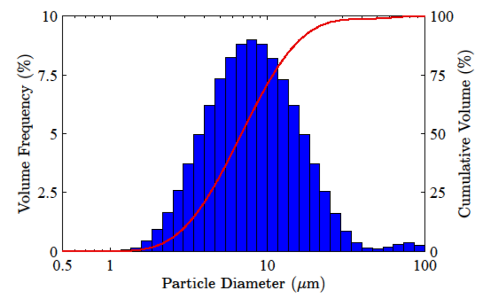


Concluding Remarks

- Experimental Issues
  - Flame Anchor Effects
  - Ventilation
    - Entrainment
    - Exhaust Flow Distribution
  - Mist Details

- Experimental Advancements
  - New Configurations
  - New Measurements
    - Micro-TC data
      - S-Type TC probes
      - 12.7 um junctions (~1 ms)
    - Water-mist suppression data
      - Drop size distribution (Malvern)
      - Combustion efficiency vs. Y_{wm}





Concluding Remarks

- Simulation Issues
  - Prediction of radiative fraction
  - Robust extinction model parameters
    - Broaden range of experimental targets:
      - Fuels
      - Diluents
      - Strain rates

Open Discussion

[MaCFP, 2017]