Effects of Exhaust Gas Recirculation (EGR) on Turbulent Combustion Emissions in Advanced Gas Turbine Combustors with High Hydrogen Content (HHC) Fuels

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Hasti Veeraraghava Raju - CFD simulations
Jupyoung Kim – PIV

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Content

1. **Piloted Axisymmetric Reactor Assisted Turbulent (PARAT) burner development and testing under atmospheric and high-pressure conditions**

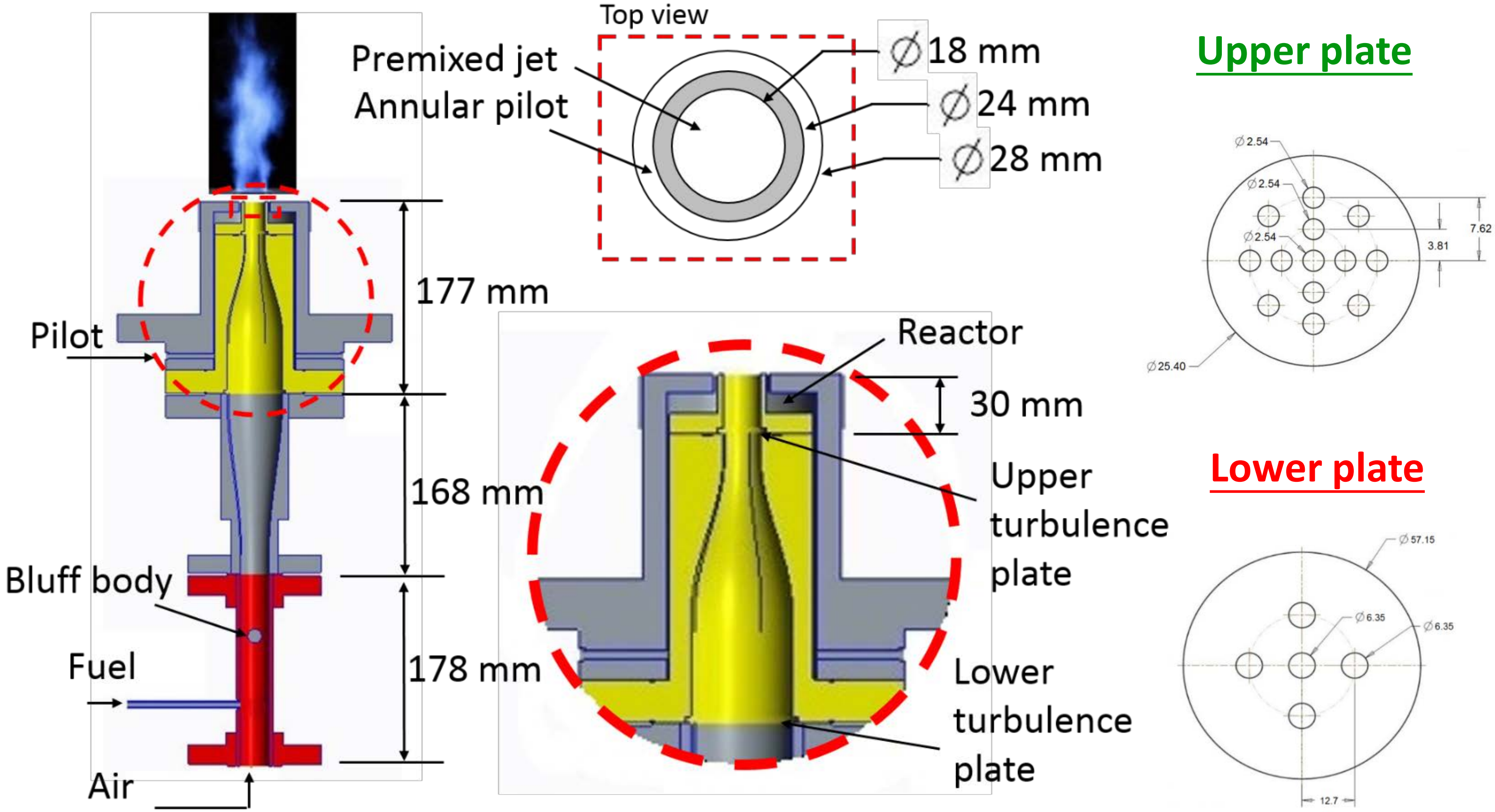
2. **Effects of CO_2 addition on turbulent flame structure and burning velocity**

3. **Temperature and velocity measurements in CH_4 /air/CO_2 flames with different levels of CO_2 addition using CARS and PIV**

4. **Development and validation of LES model for H_2 piloted CH_4 /air/CO_2 premixed turbulent flames**

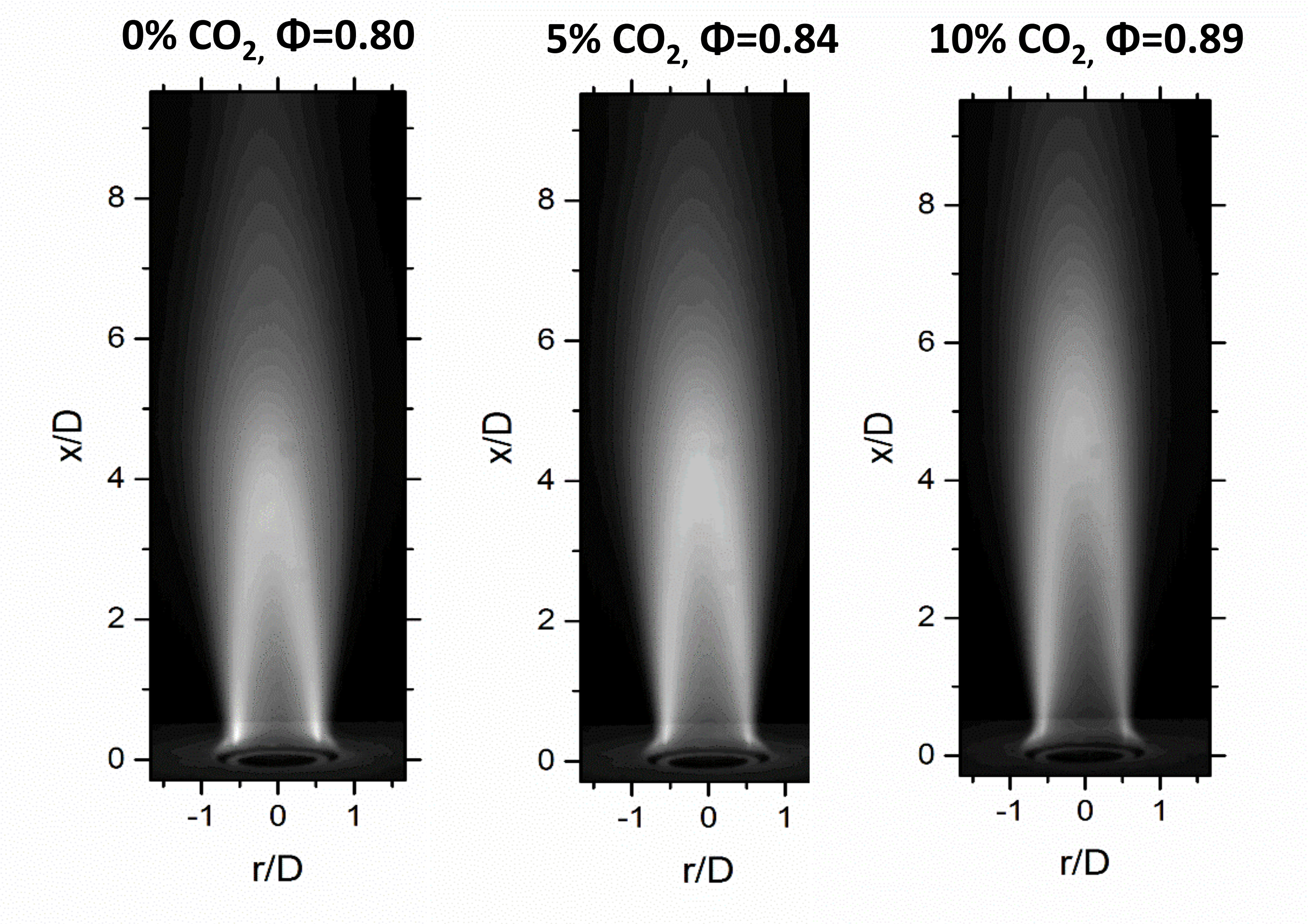
5. **CH PLIF and IR imaging for turbulent premixed flames**

Experimental Apparatus: PARAT Burner



Flames with varying levels of CO_2 addition

Re=10,000, T_{ad}=2030 K, Le=1, P=1 bar

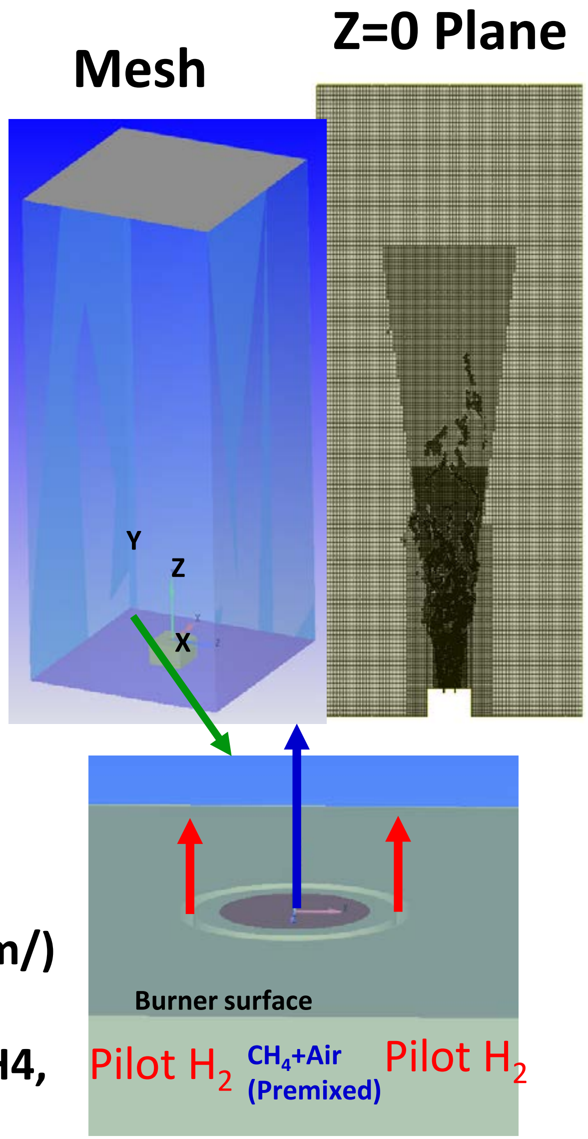


Flames designed to minimize thermal and transport effects on NOx

Large Eddy Reacting Flow Simulations

CFD Summary

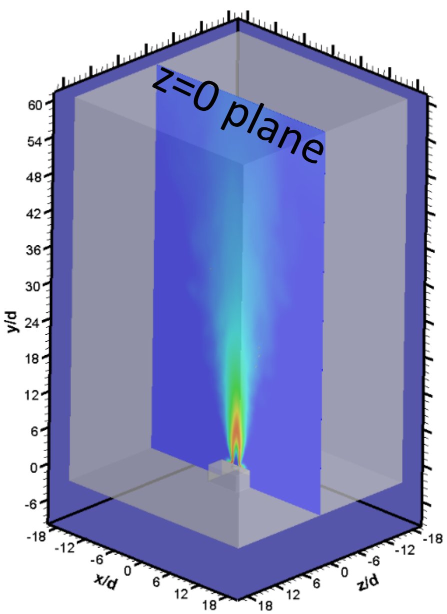
- Premixing tube simulated separately and the solutions patched
- Jet Reynolds number – 10000
- Domain (D= 18 mm): 36D x 64D x 36 D
- Detailed chemistry solver with DRM19 mech. Turbulence – 1 eq. dynamic structure model
- Sensitivity study with base grid : 10 x 8 x 6 mm
- 4 Level Adaptive Mesh Refinement based on Velocity and Temperature, Max. 15 M cells
- Mesh sensitivity studied with Max. 30 M cells



Chemistry

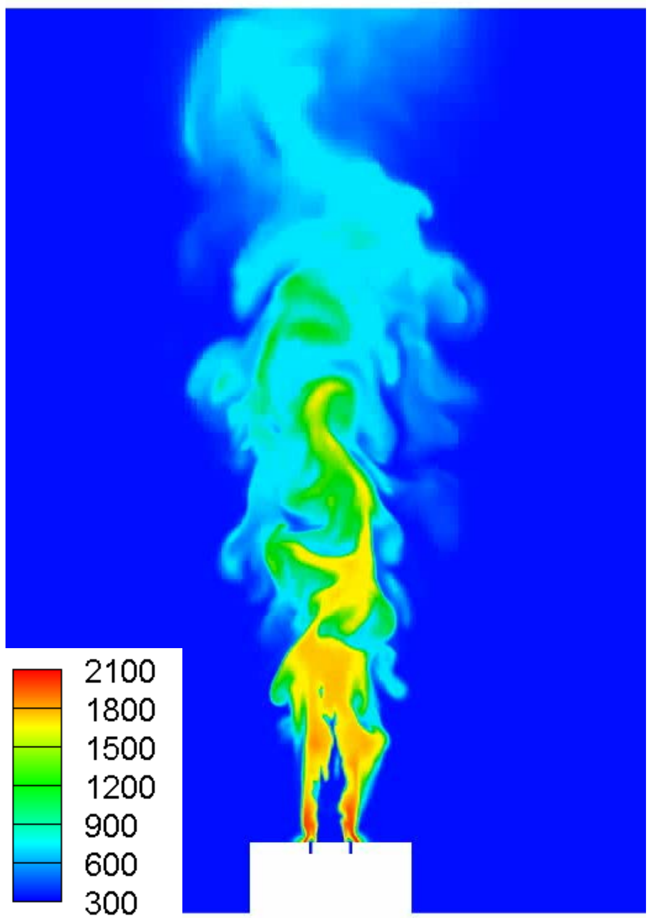
- DRM19 Mechanism: (http://combustion.berkeley.edu/drm/)
- Elements : O, H, C, N, AR
- Species: H2, H, O, O2, OH, H2O, HO2, CH2, CH2(S), CH3, CH4, CO, CO2, HCO, CH2O, CH3O , C2H4, C2H5, C2H6, N2, AR
- Number of Reactions: 84

Large Eddy Simulations

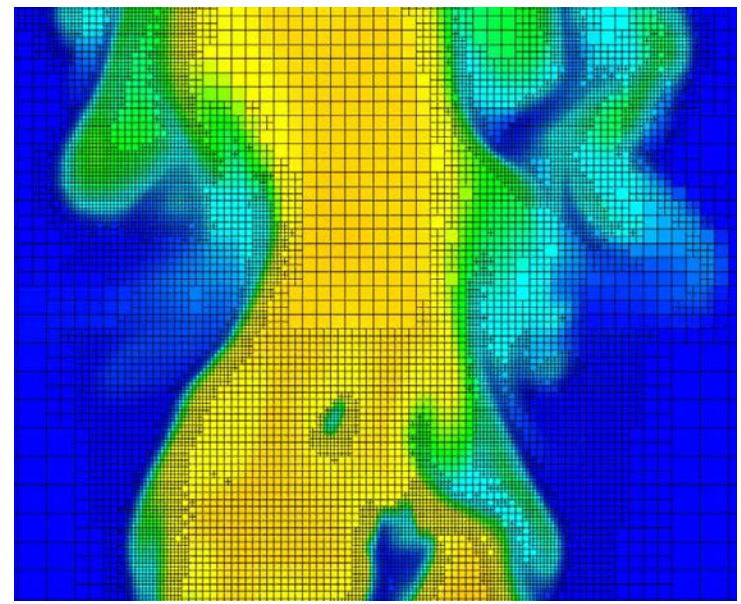


Mean Temperature [K]

Instantaneous Temperature [K]

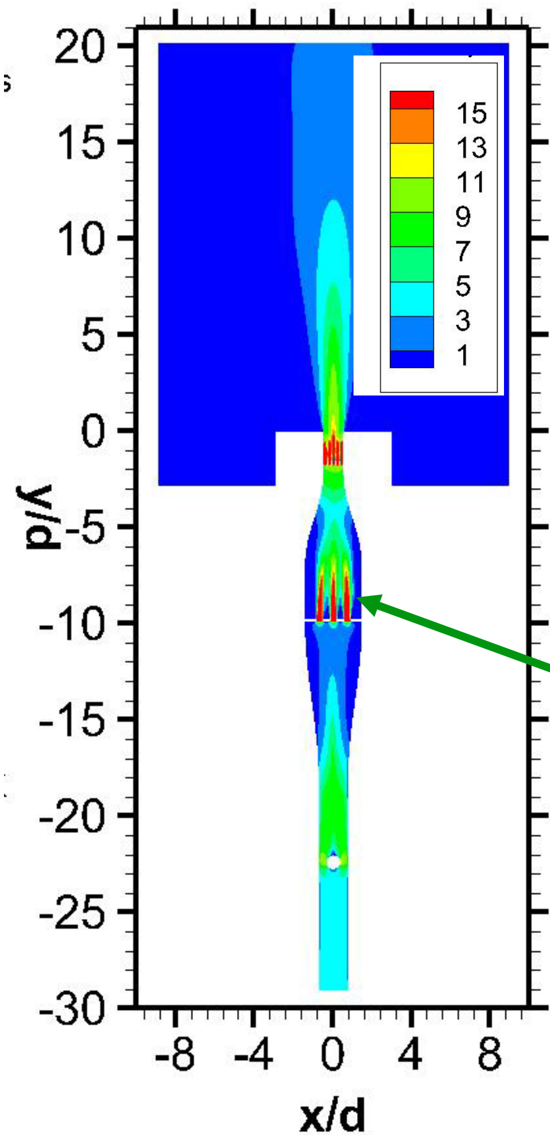


Computational Grid

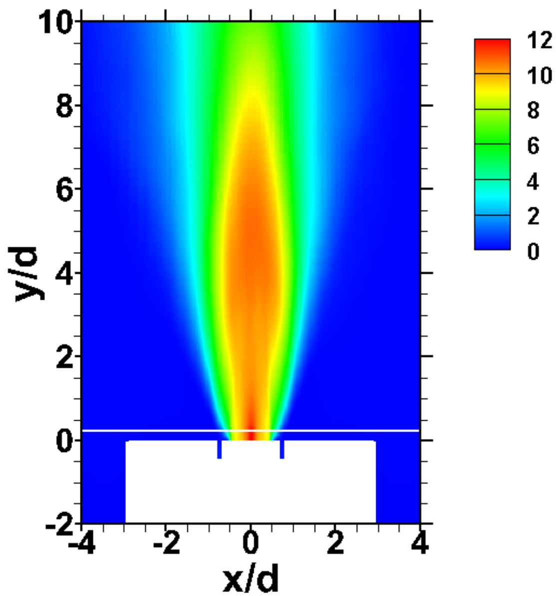


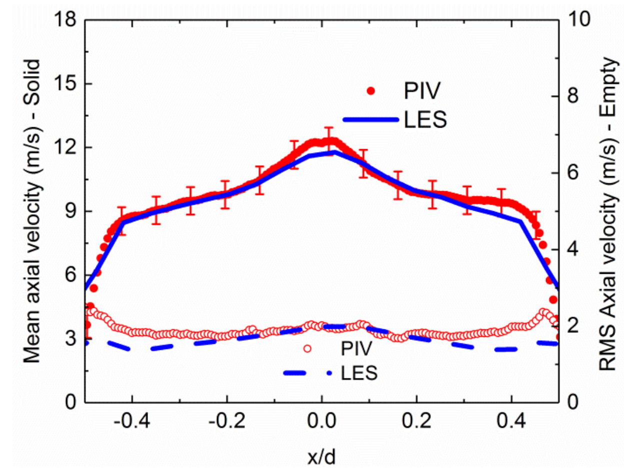
Region: 5 < y/d < 6

Inlet Boundary Conditions LES Comparison with Experiments

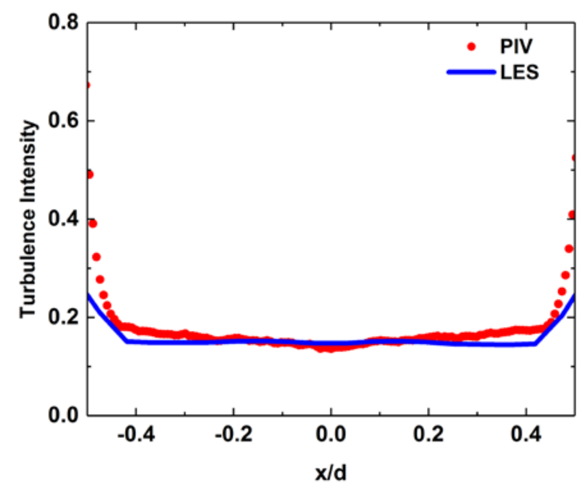


Flame 1 velocity contour



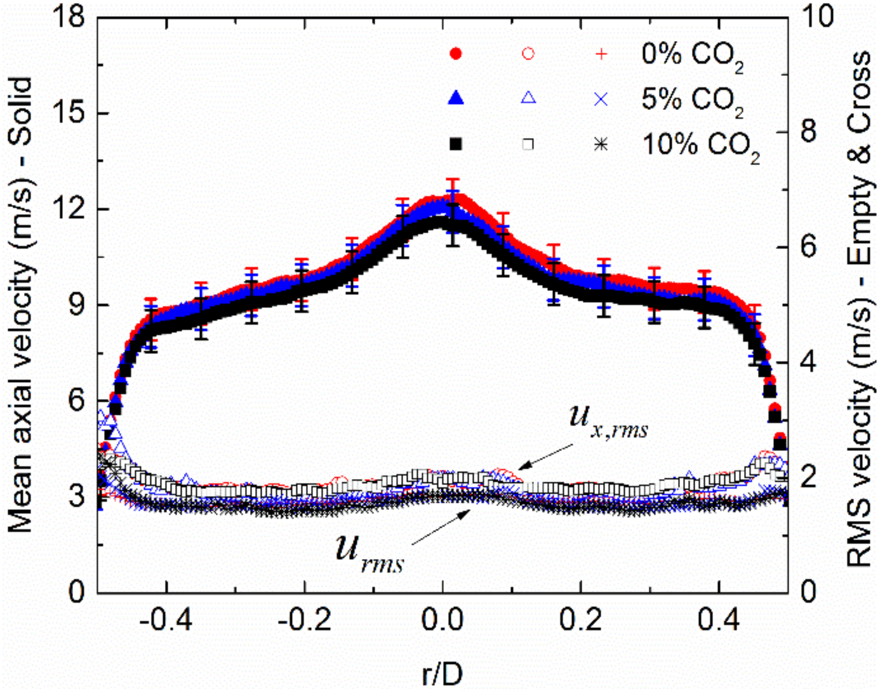


Non reacting flow simulation for jet velocity profiles at the burner exit

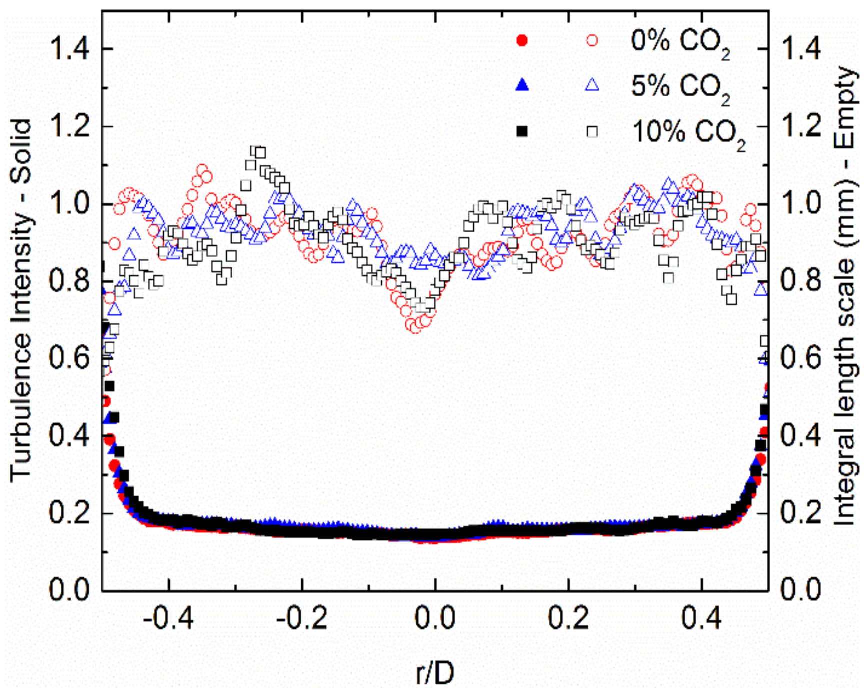


Boundary Condition & Turbulence Intensity at x/D=0.2

Mean & RMS velocity profiles



Integral length scale & turbulence intensity



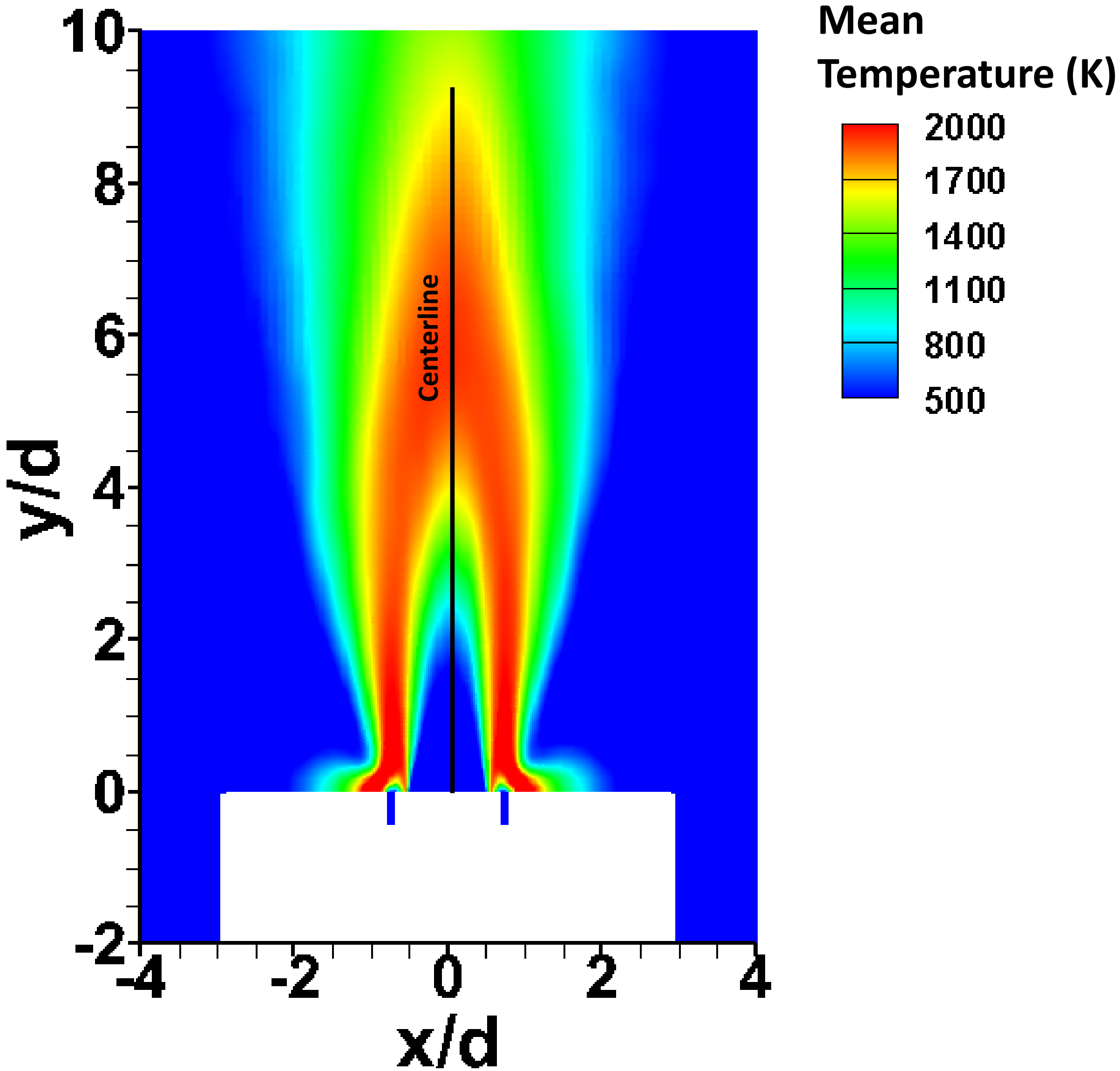
Integral length scale

$$l(r) = \int_0^\infty \rho(r, r^*) dr^* \quad \rho(r, \Delta r) = \frac{\overline{u'_x(r) u'_x(r+\Delta r)}}{\overline{u'^2_x(r)}}; \Delta r = |r - r^*|$$

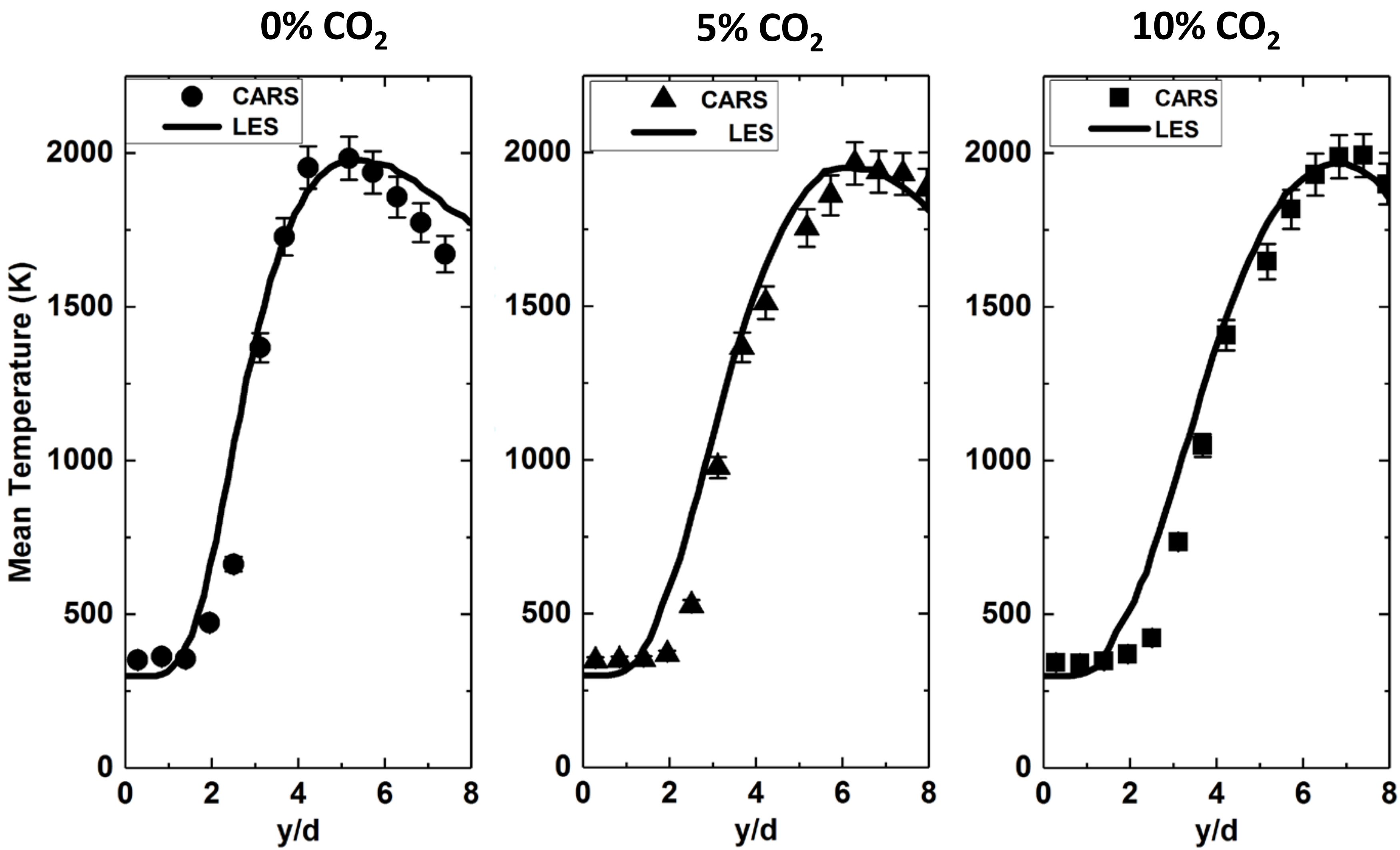
Turbulence intensity

$$T.I. = \frac{u_{rms}}{u_{mean}}$$

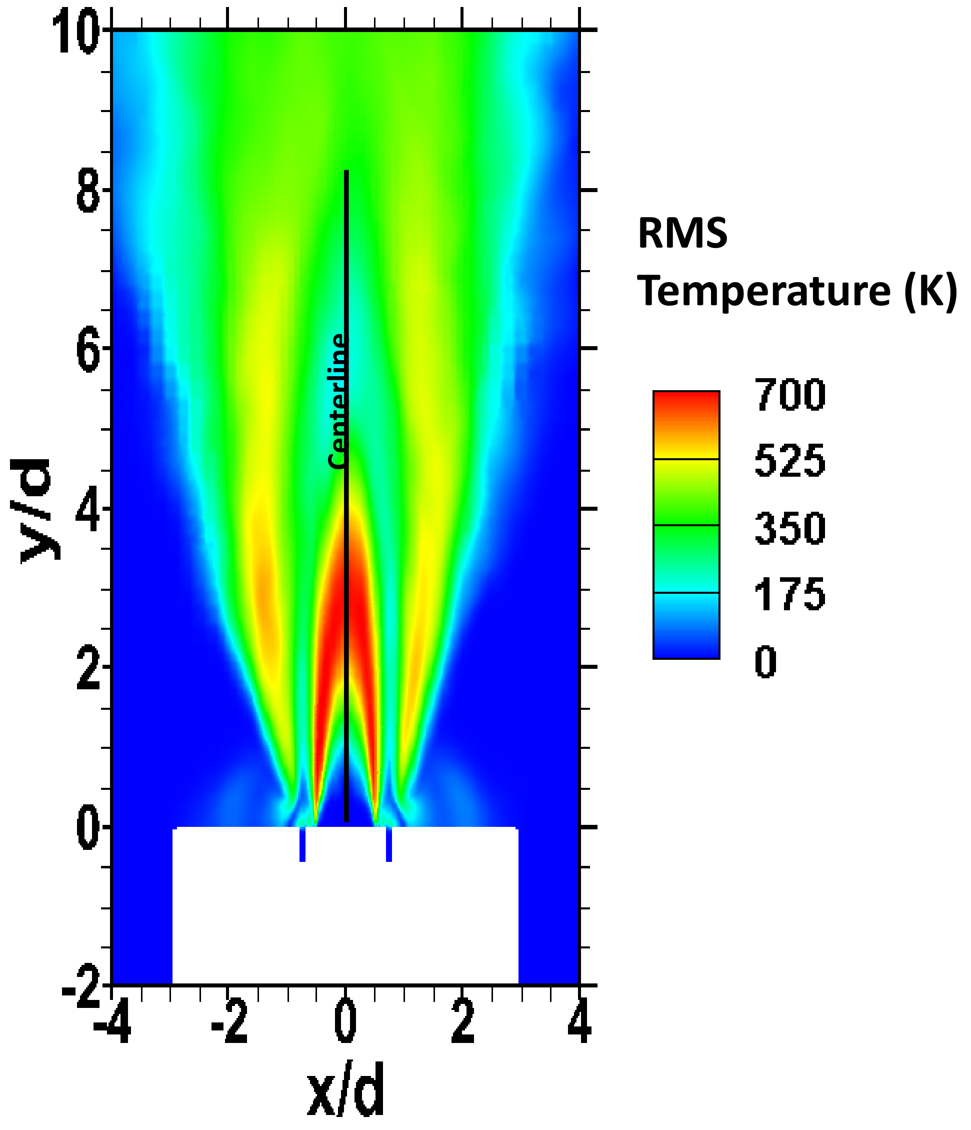
LES Mean Temperature Contours on Z=0 Plane



Axial Temperature Profiles with CO2 Addition

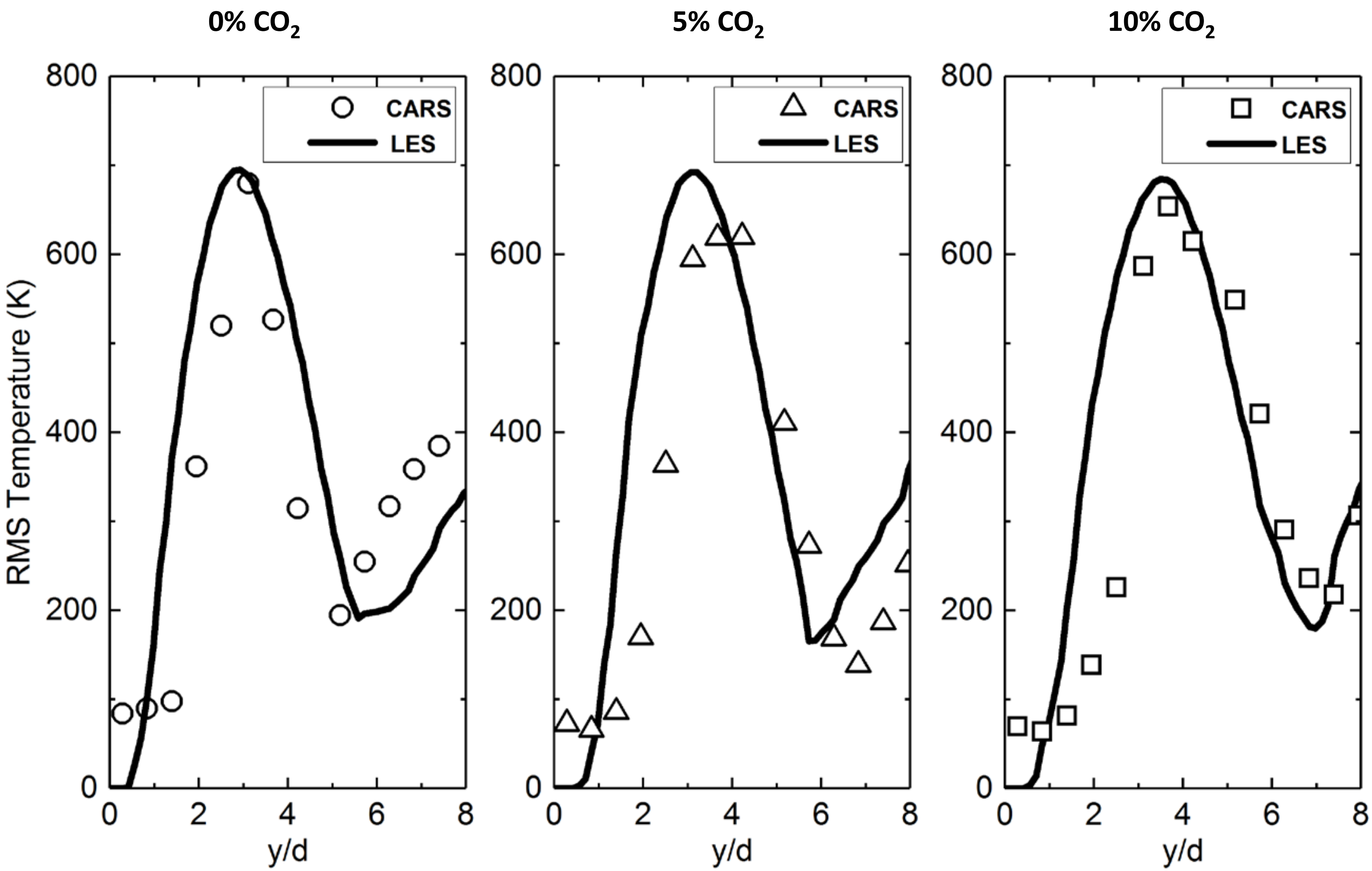


LES RMS Temperature on Z=0 plane

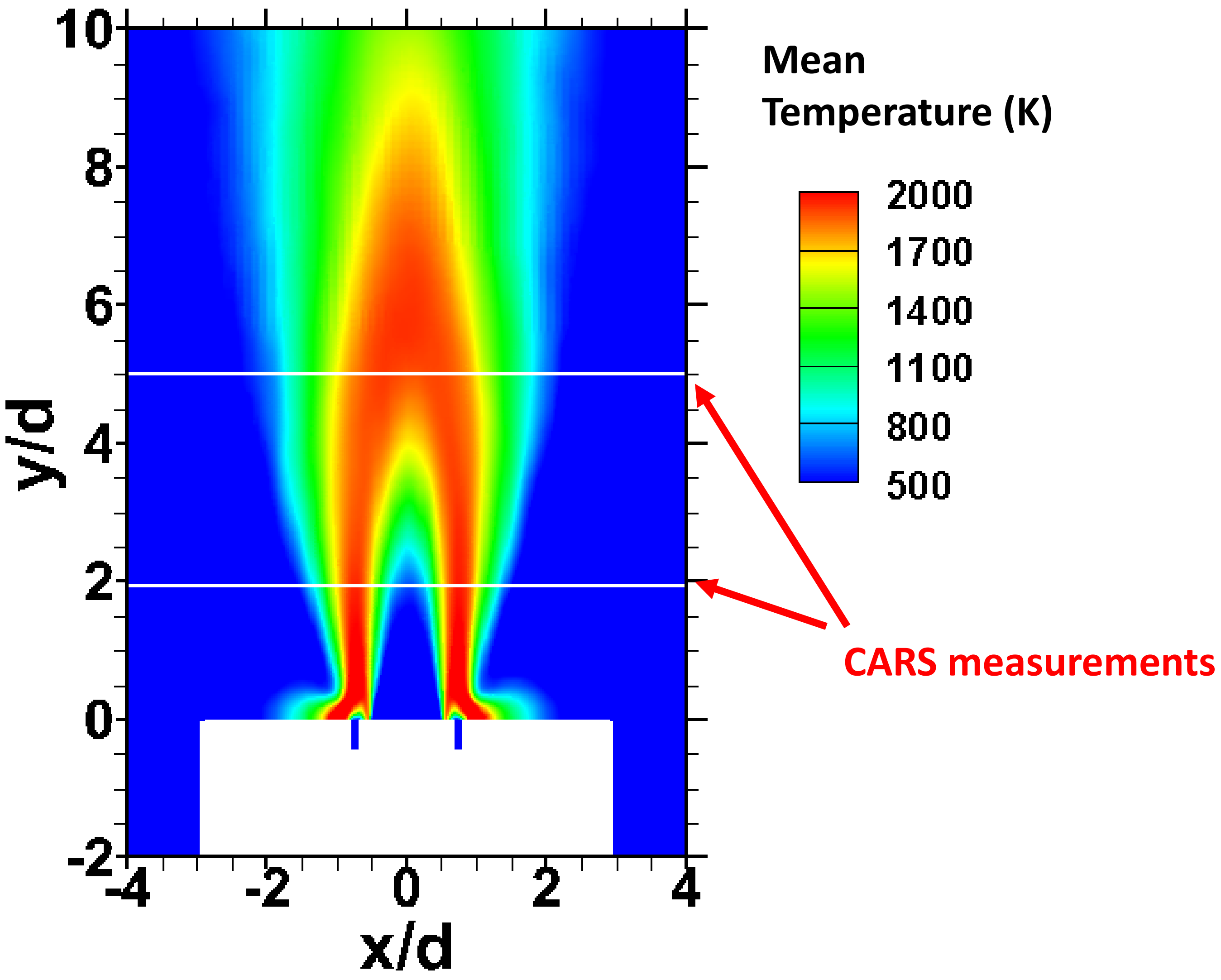


T_RMS comparison between CARS and LES

Centerline RMS temperature

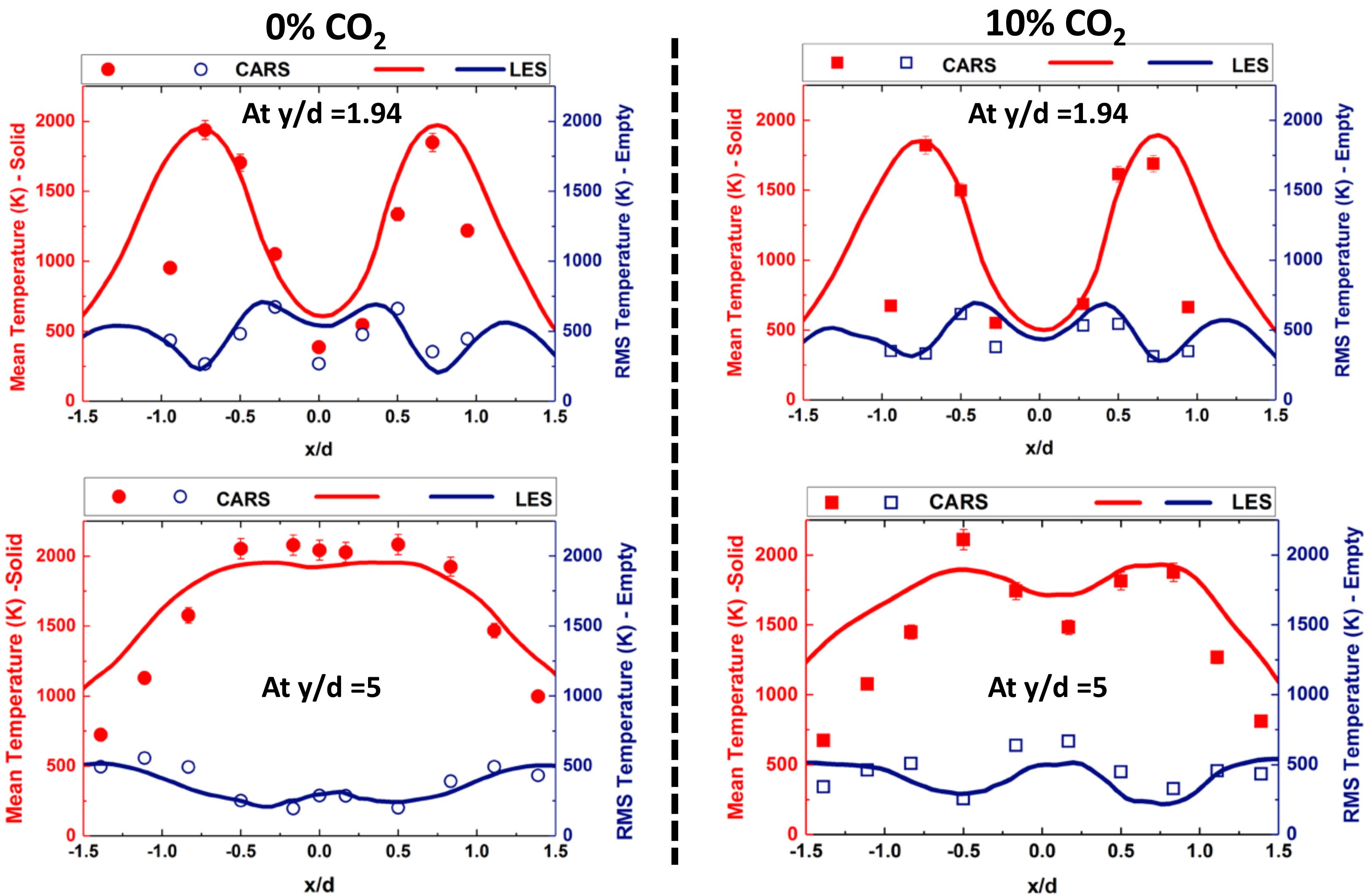


Temperature comparison between CARS and LES

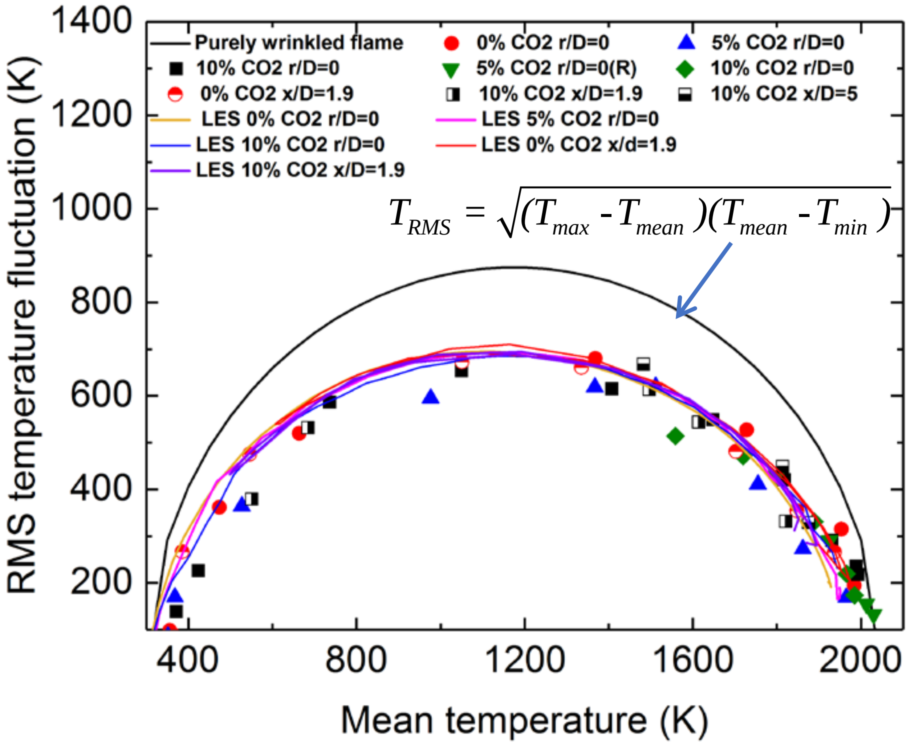


Temperature comparison between CARS and LES

Radial mean and RMS temperature



Thin or Purely Wrinkled Flame Assumption *is not adequate!*



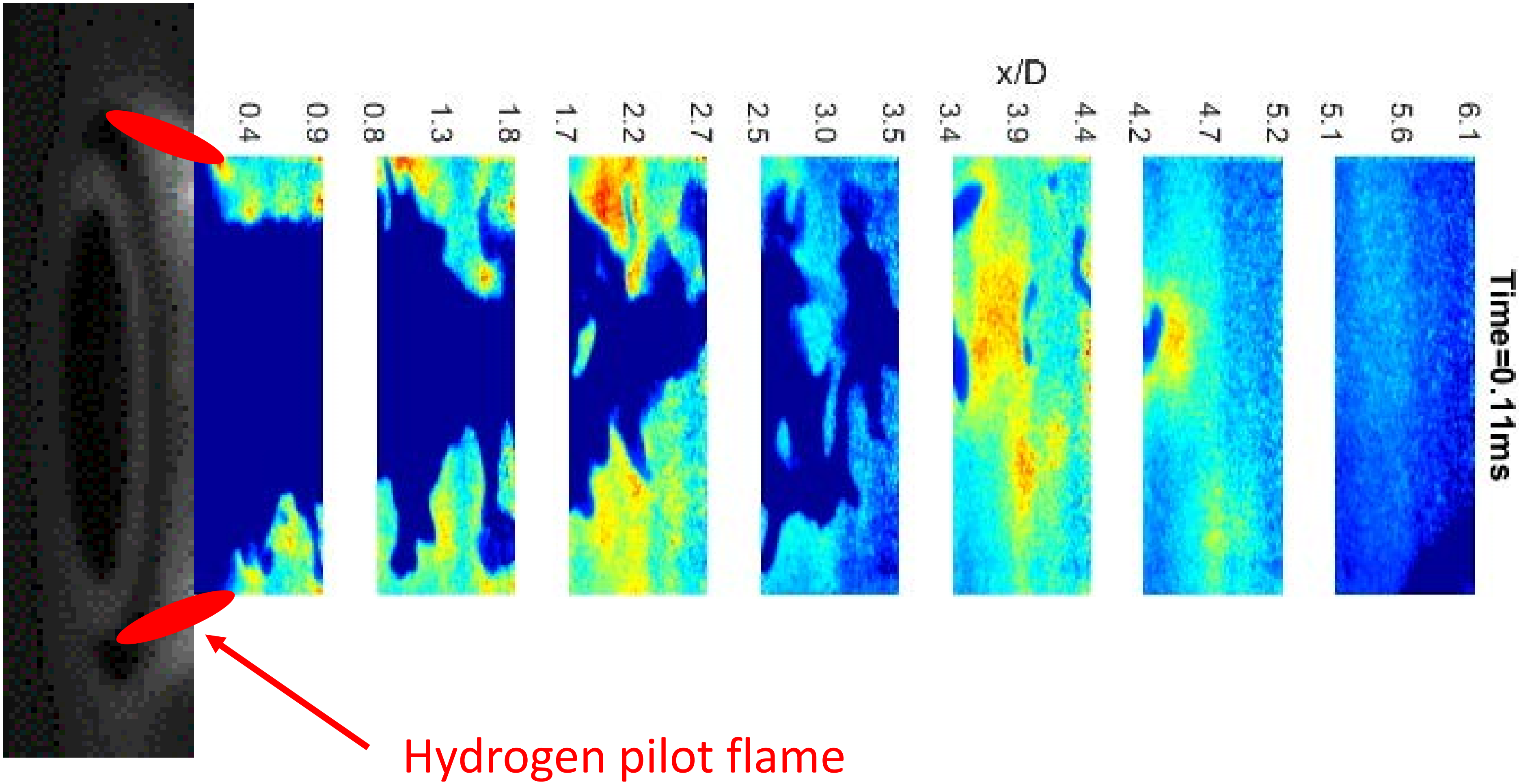
$$\lambda = \frac{D_u}{S_L^0} \qquad \eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

CO_2 levels	Characteristic flame thickness, λ (μm)	Kolmogorov length scale η, (μm)
0%	70	50
5%	80	52
10%	90	55

Effect of CO2 on the chemistry of turbulent flames with EGR are captured in the present computations!

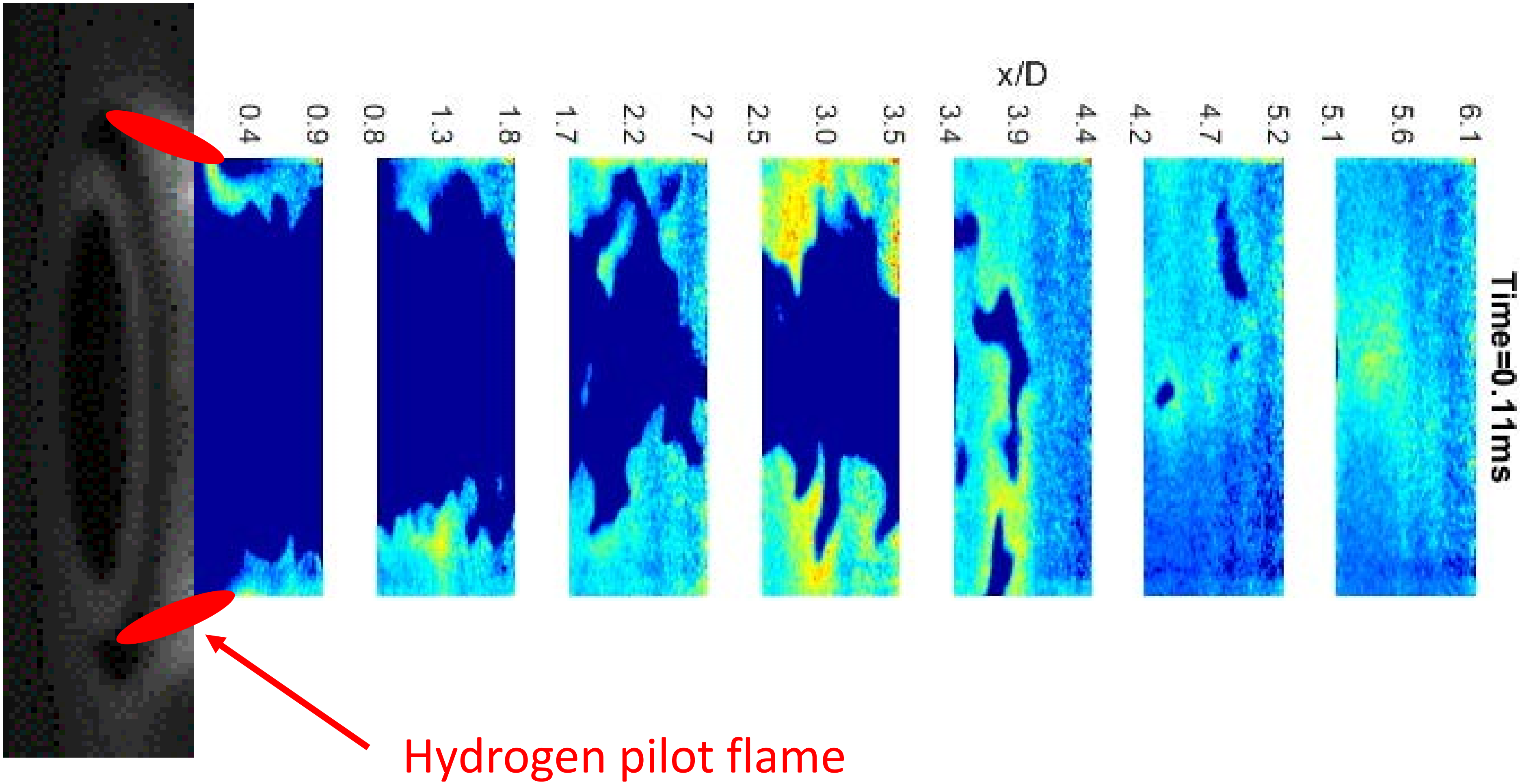
OH PLIF video for flame with 0% CO_2 addition

Φ=0.8, Re=10000



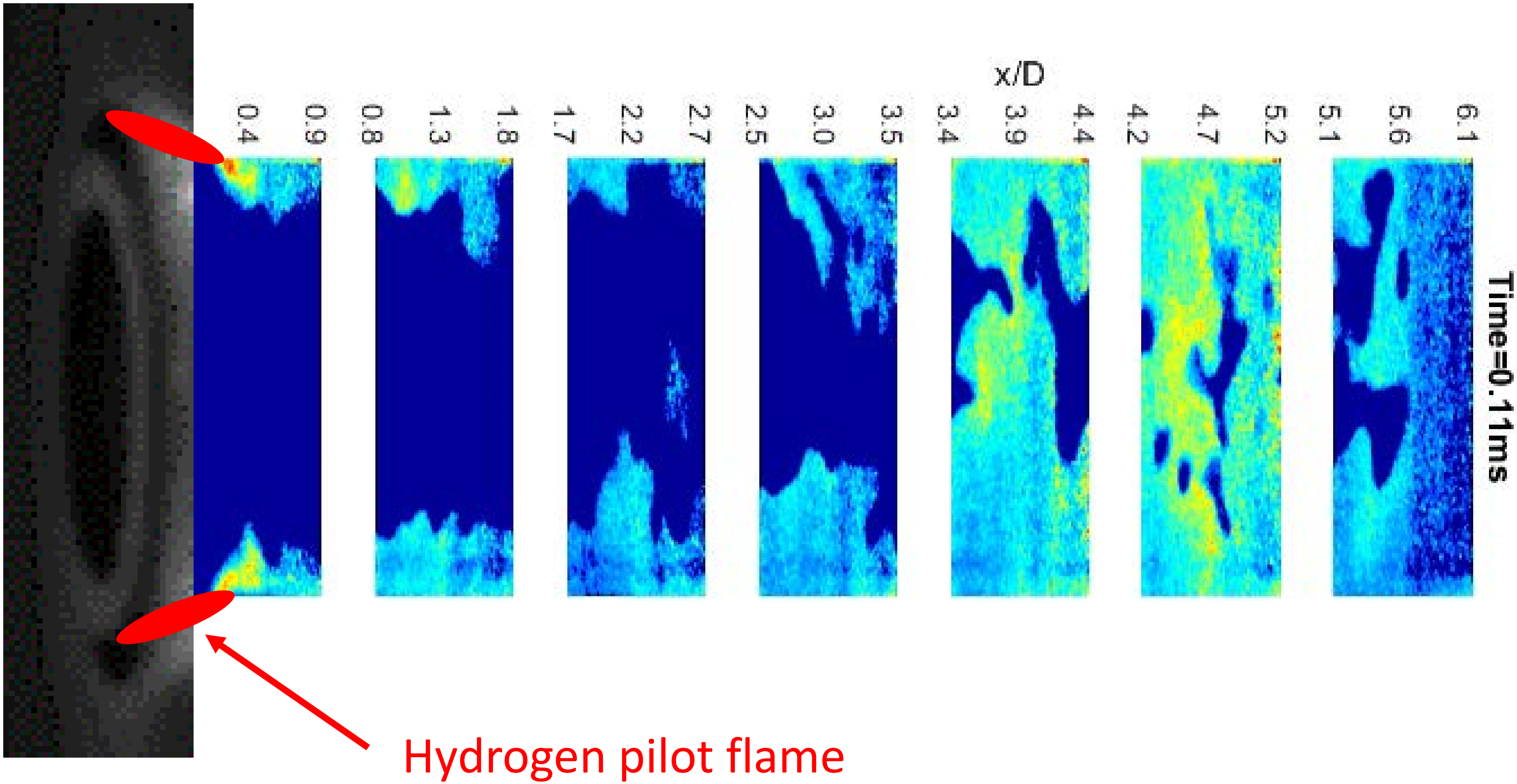
OH PLIF video for flame with 5% CO_2 addition

Φ=0.84, Re=10000



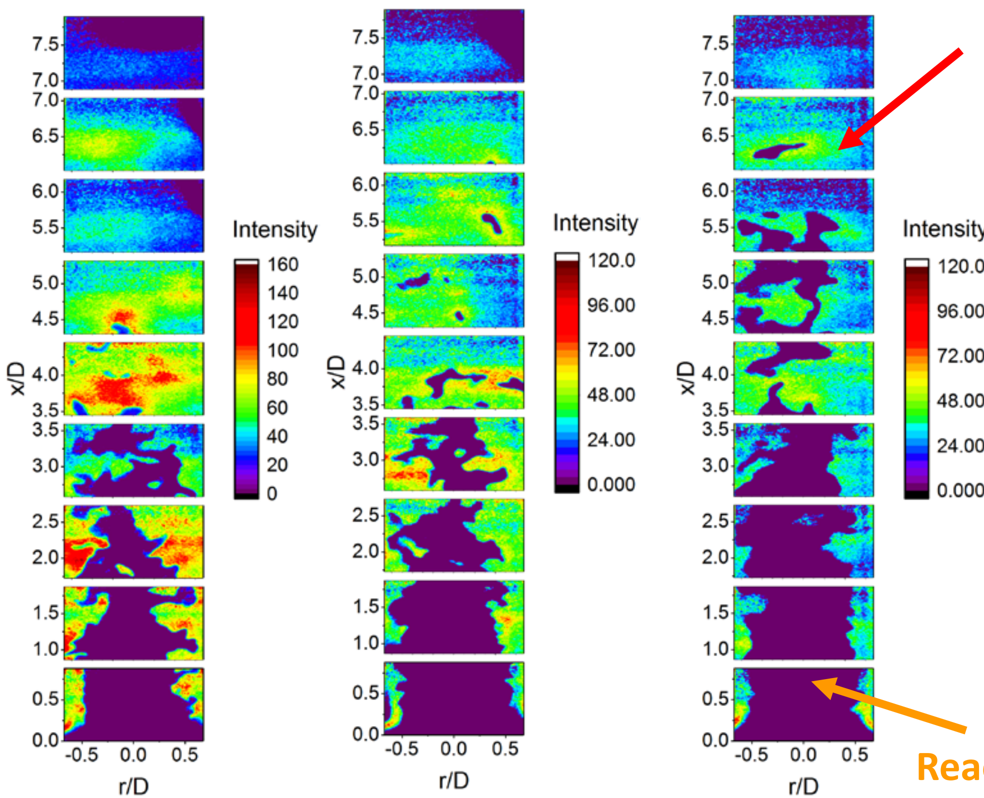
OH PLIF video for flame with 10% CO_2 addition

Φ=0.89, Re=10000



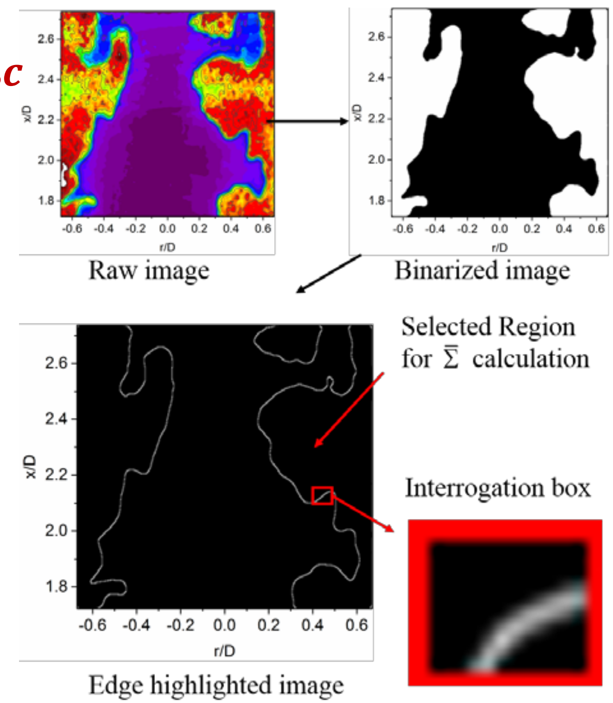
OH PLIF Images & Data Processing

0% CO_2 5% CO_2 10% CO_2



Products $c = 1$

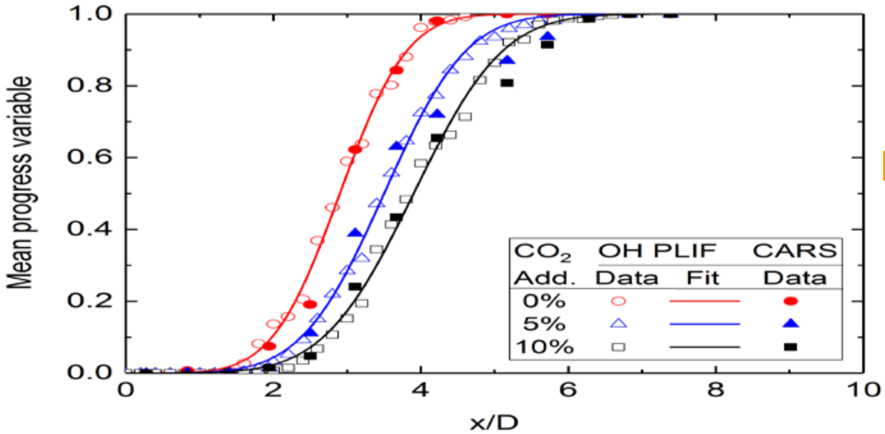
Reactants $c = 0$



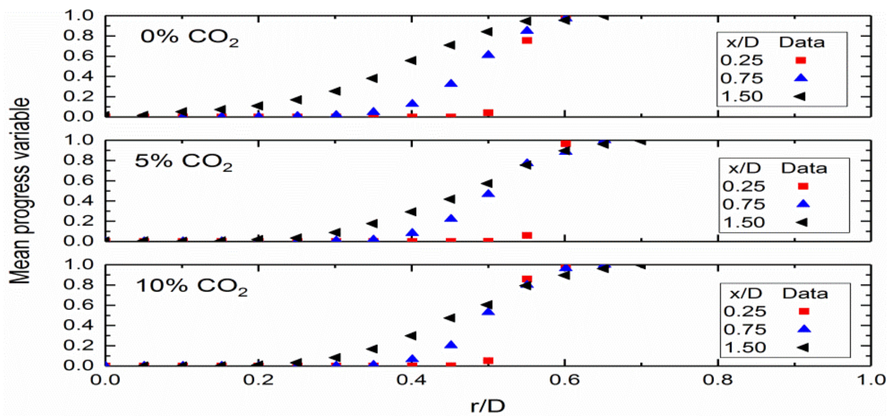
Flame surface density $$\bar{\Sigma} = \frac{1}{n}\sum_{i=1}^{n}\frac{L_i(c)}{A_i(c)}$$

Mean Reaction Progress

Axial direction



Radial direction



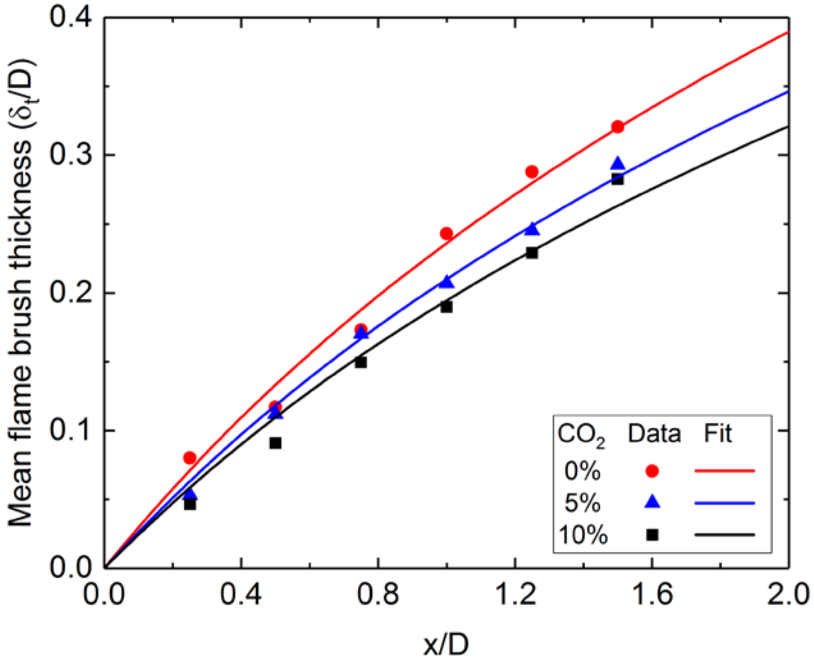
Mean progress variable

$$\overline{c}(x,r) = \frac{1}{n}\sum_{i=1}^{n} c_i(x,r)$$

Flame brush development & Taylor's theory

Data $$\delta_{T,r} = \max{}^{-1}\left(\frac{d\overline{c}}{dr}\right)$$

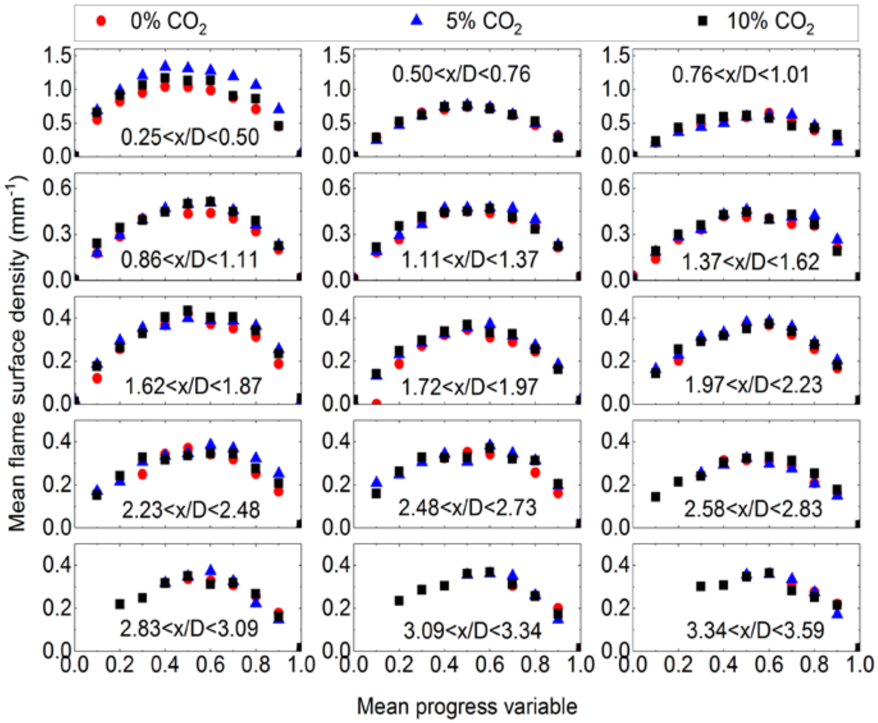
Fit $$\delta_{T,r} = \alpha\left(2u'l\tau\right)^{1/2}\left\{1-\frac{l}{u'\tau}\left[1-\exp\left(-\frac{\tau u'}{l}\right)\right]\right\}^{1/2}$$



Flame Surface Density

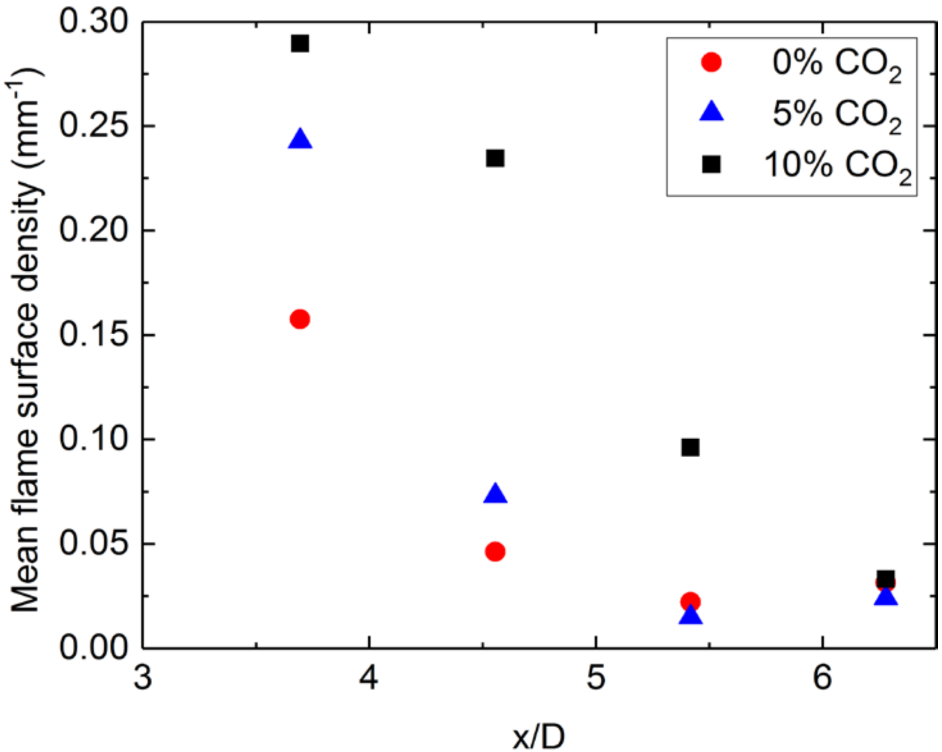
Radial flame brush development

0 < x/D < 3.6



Axial flame brush development

3.6 <x/D<6.5

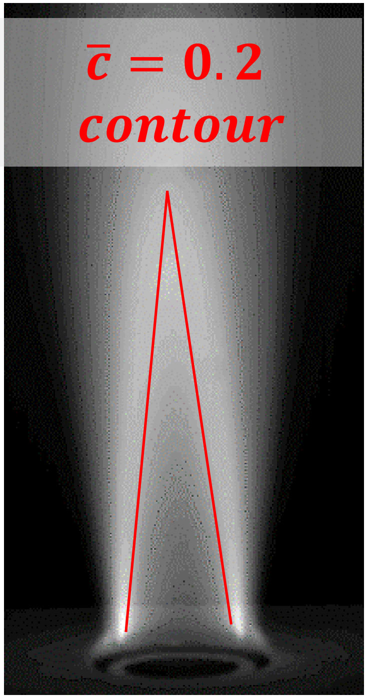


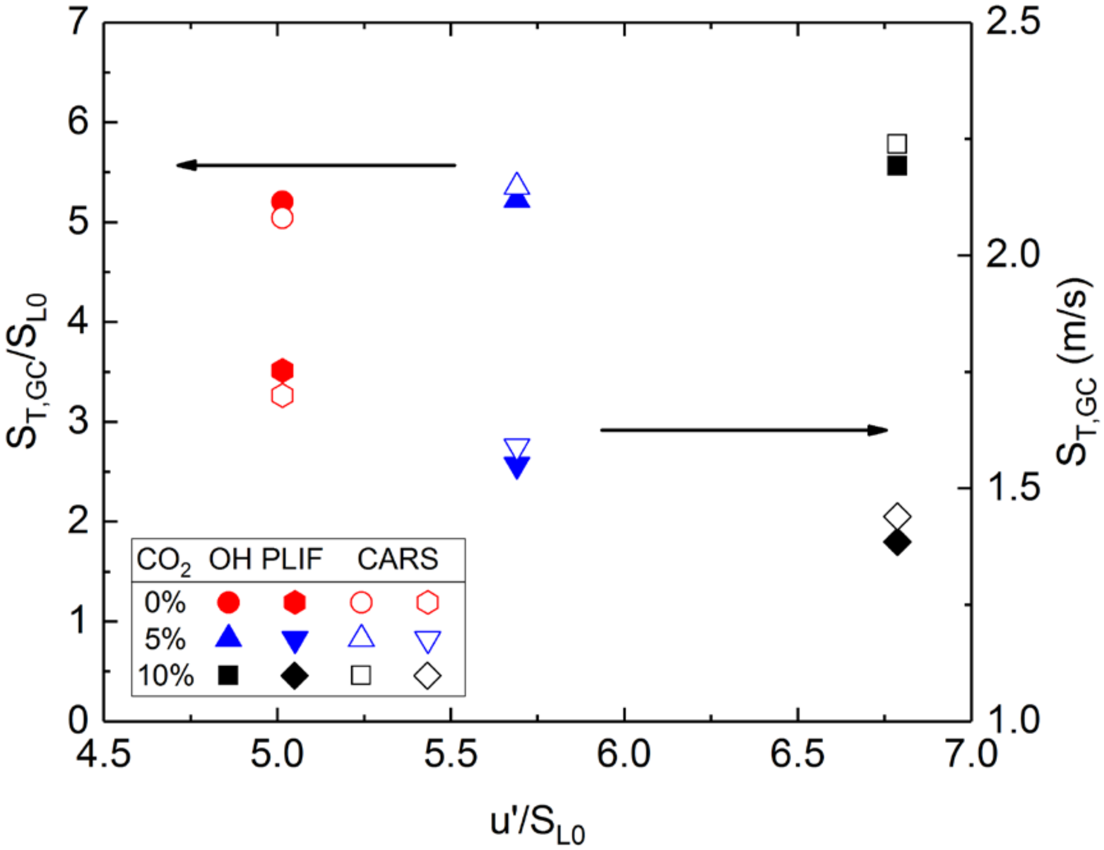
Mean flame surface density

$$\overline{\Sigma} = \frac{1}{n}\sum_{i=1}^{n}\frac{L_i(c)}{A_i(c)}$$

Global Consumption Speed

$$S_{T,GC} = \sqrt{\frac{U^2}{1+\left[2x(\overline{c}=0.2)/D\right]^2}}$$





Local Consumption Speed

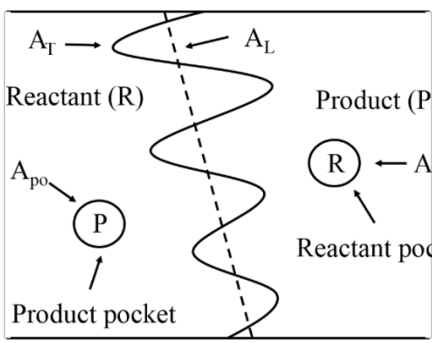
- **w/o pockets**

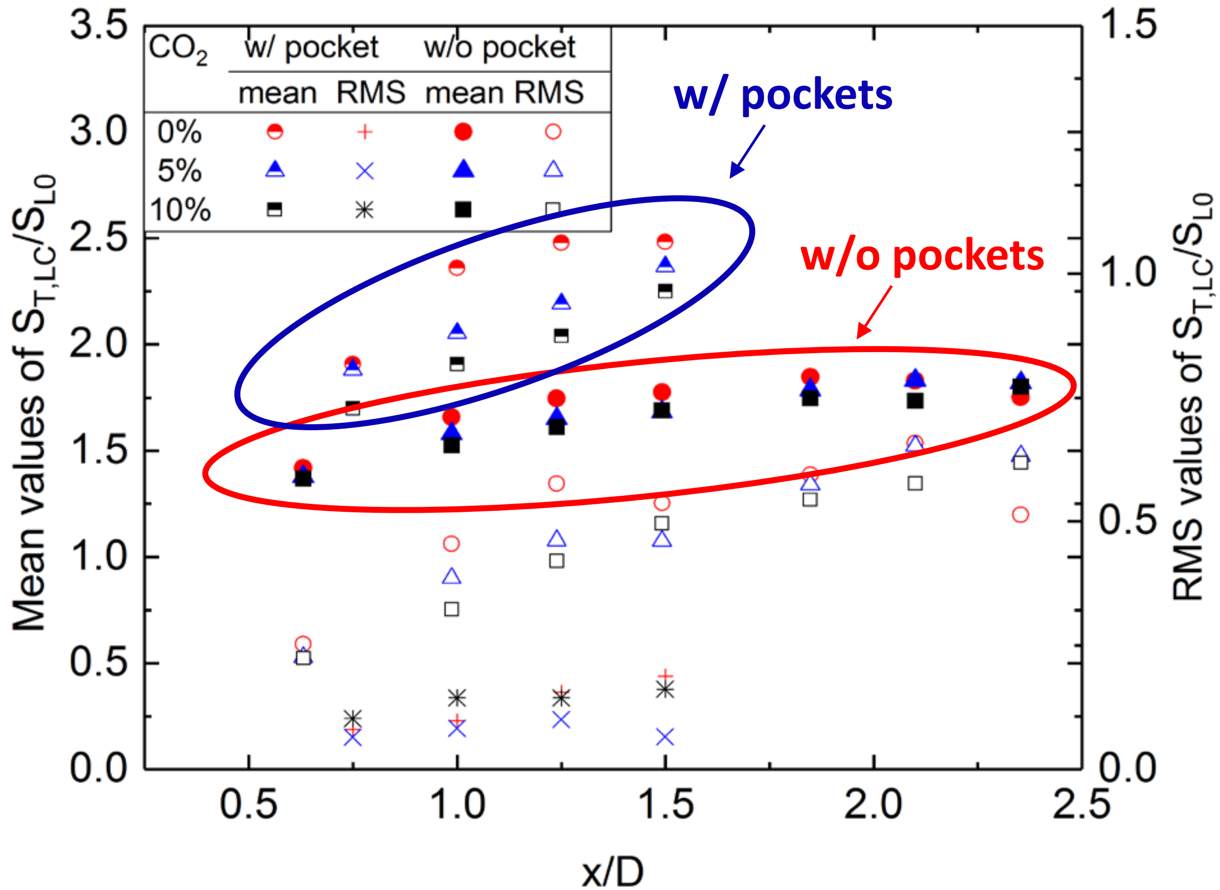
$$S_{T,LC} = S_{L0} I_0 \frac{A_T}{A_L}$$

- **w/ pockets**

$$S_{T,LC} = S_{L0} I_0 \Sigma_{max} \delta_T$$

- **pockets**





Fine-scale Unburned Pocket Consumption

Fine-scale pocket size

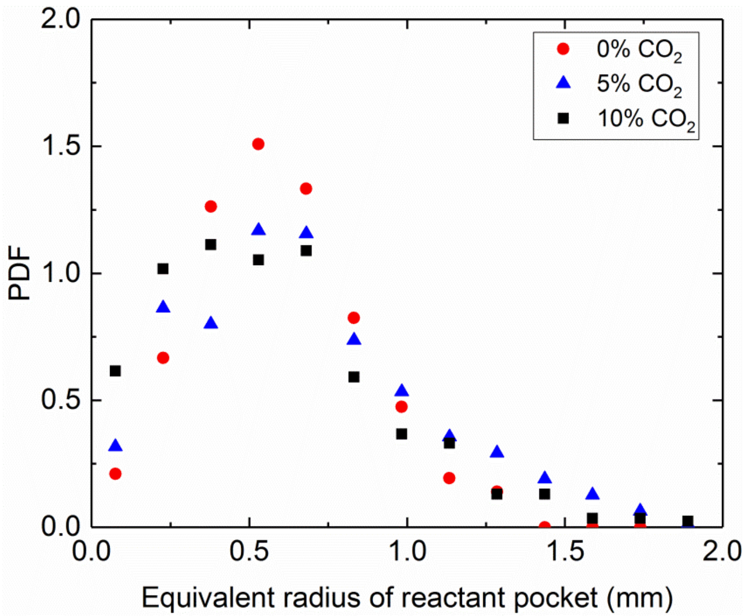
$$R_e = \sqrt{\frac{A_{up}}{\pi}}$$

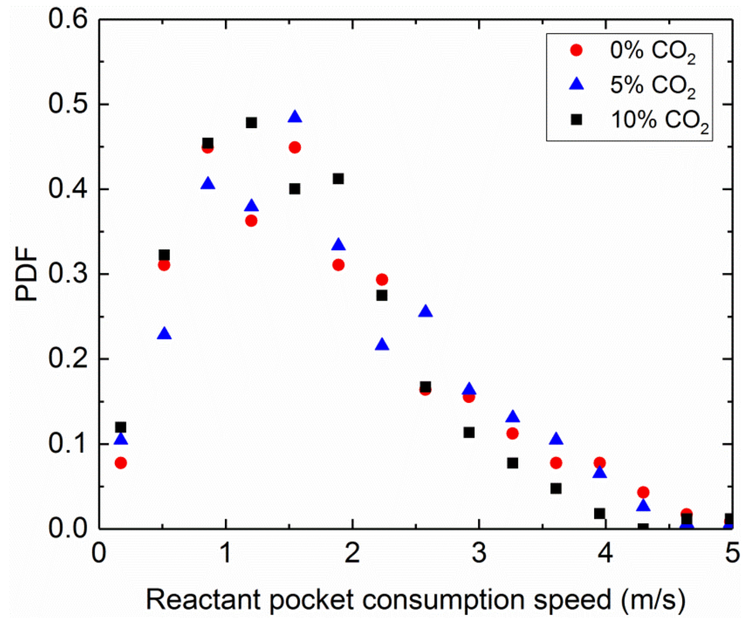
A_{up} Unburned pocket area

Δt Time step

Consumption speed

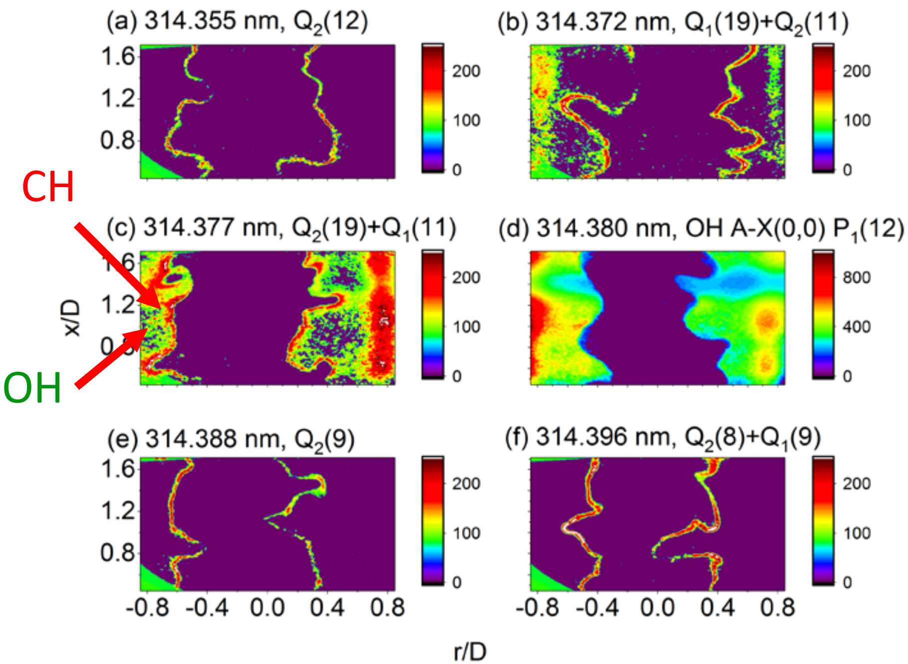
$$S_{T,LCP} = \frac{\Delta A_{up}}{2\pi R_e \Delta t}$$

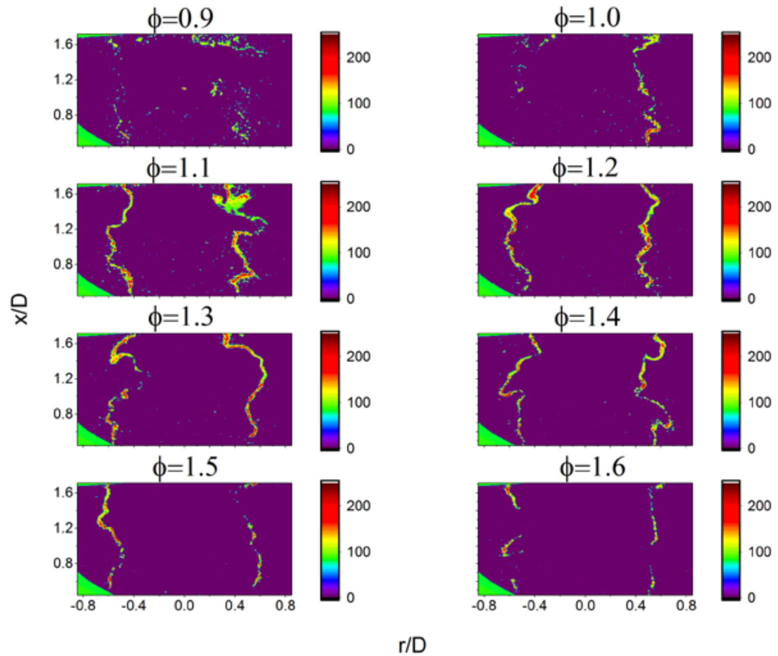


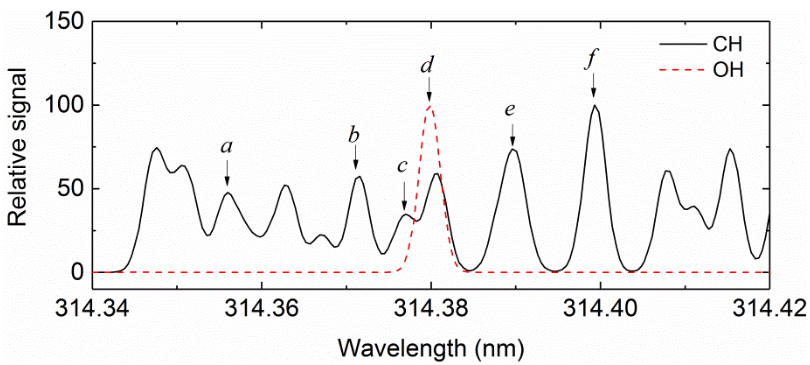


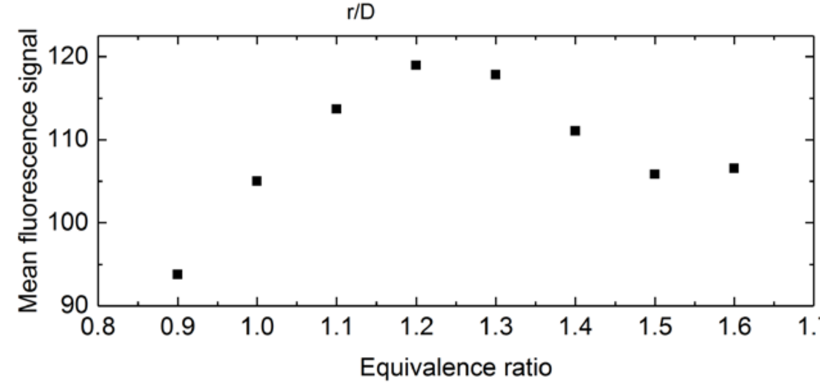
Fine-scale pocket: a pocket does not break up into smaller ones with flame-flame interaction

CH PLIF: Wavelength & Signal Strength





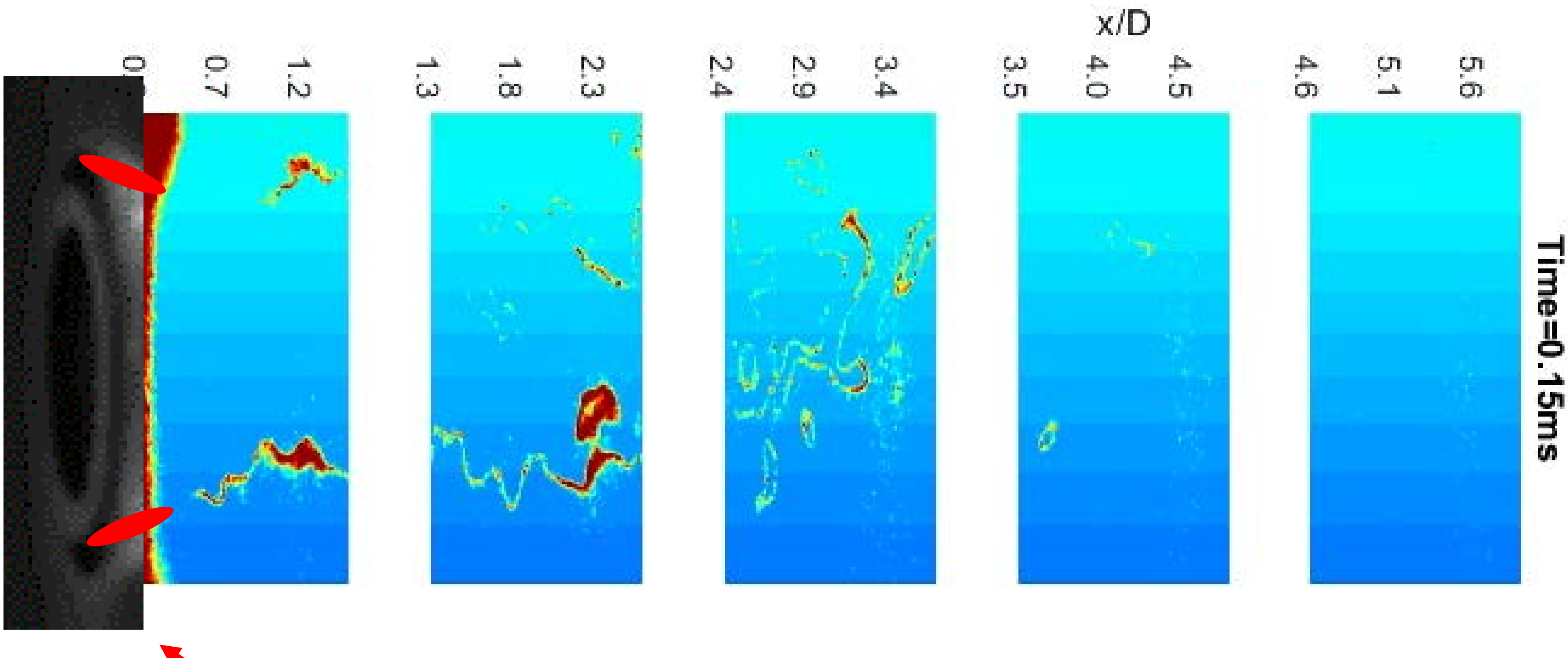




Simulation using LIFBASE

CH PLIF video for flame with 0% CO_2 addition

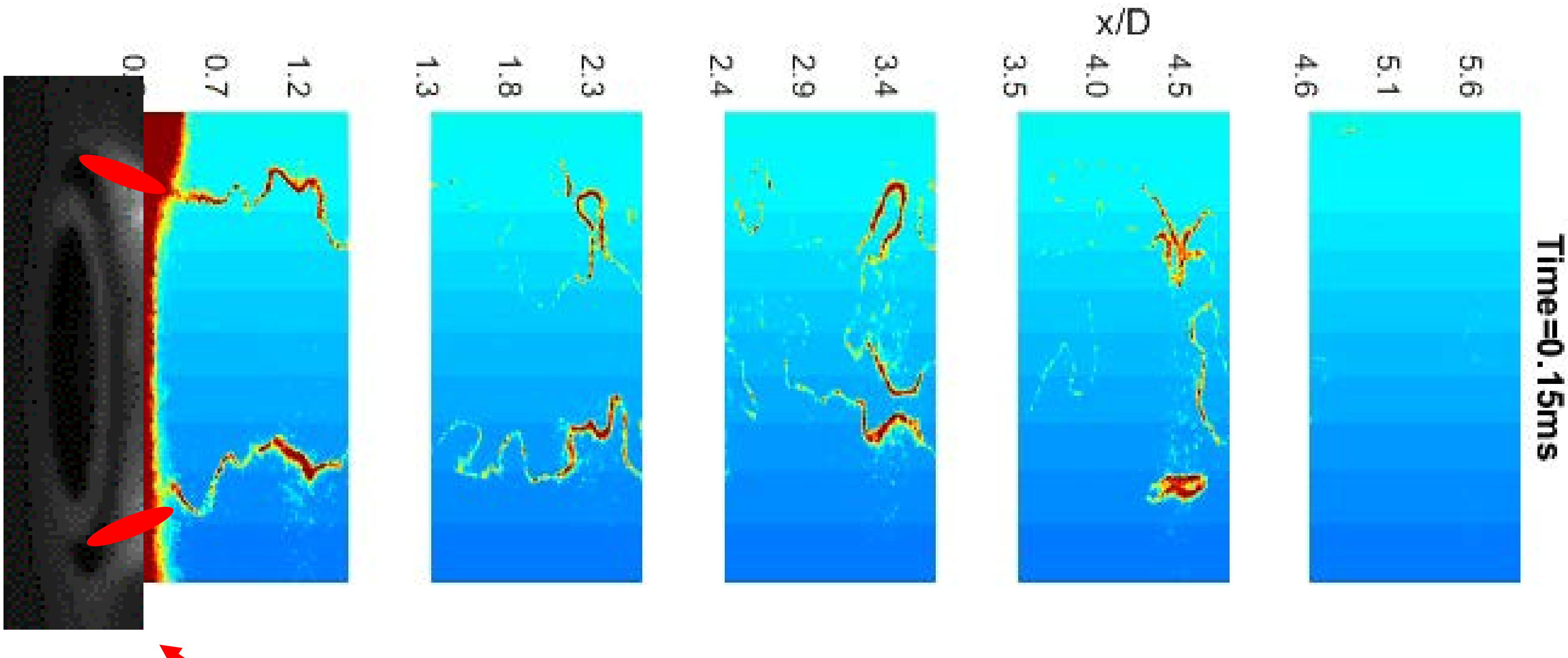
Φ=1, Re=10000



Hydrogen pilot flame

CH PLIF video for flame with 5% CO_2 addition

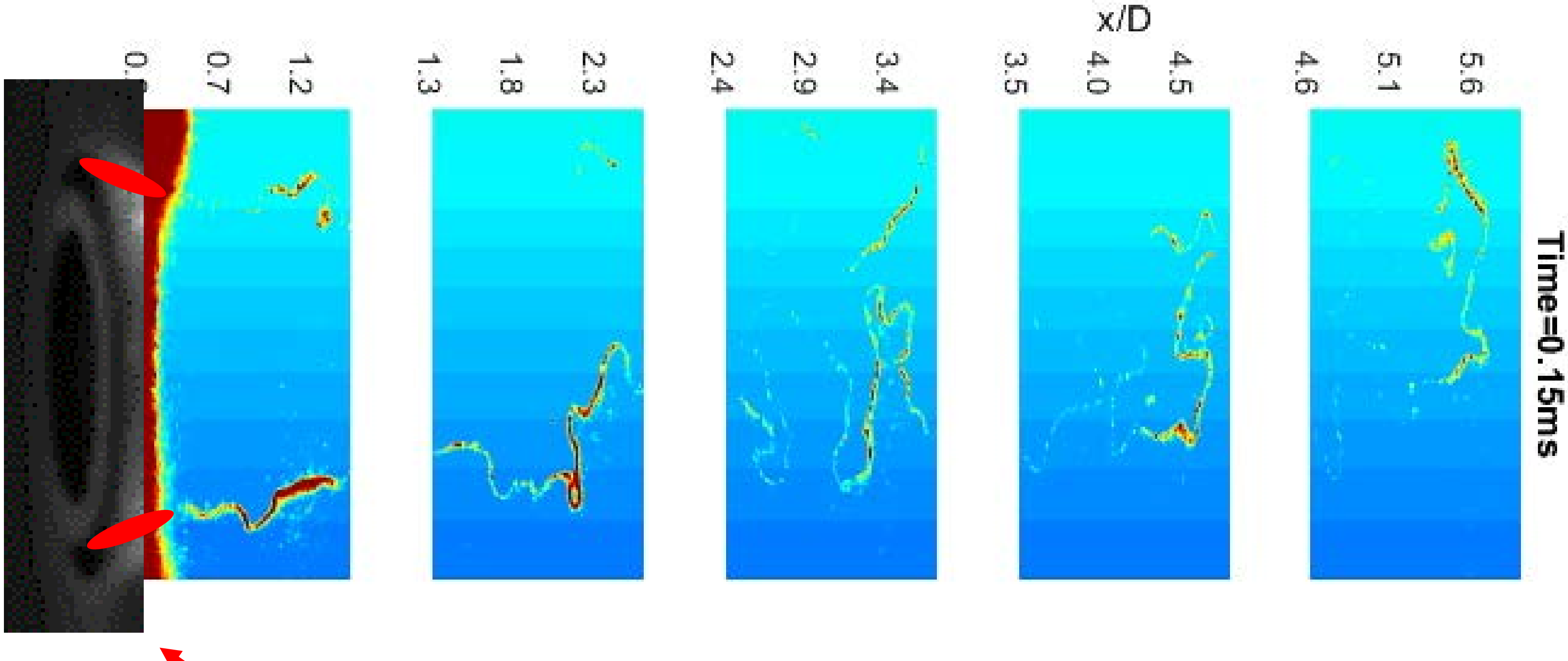
Φ=1, Re=10000



Hydrogen pilot flame

CH PLIF video for flame with 10% CO_2 addition

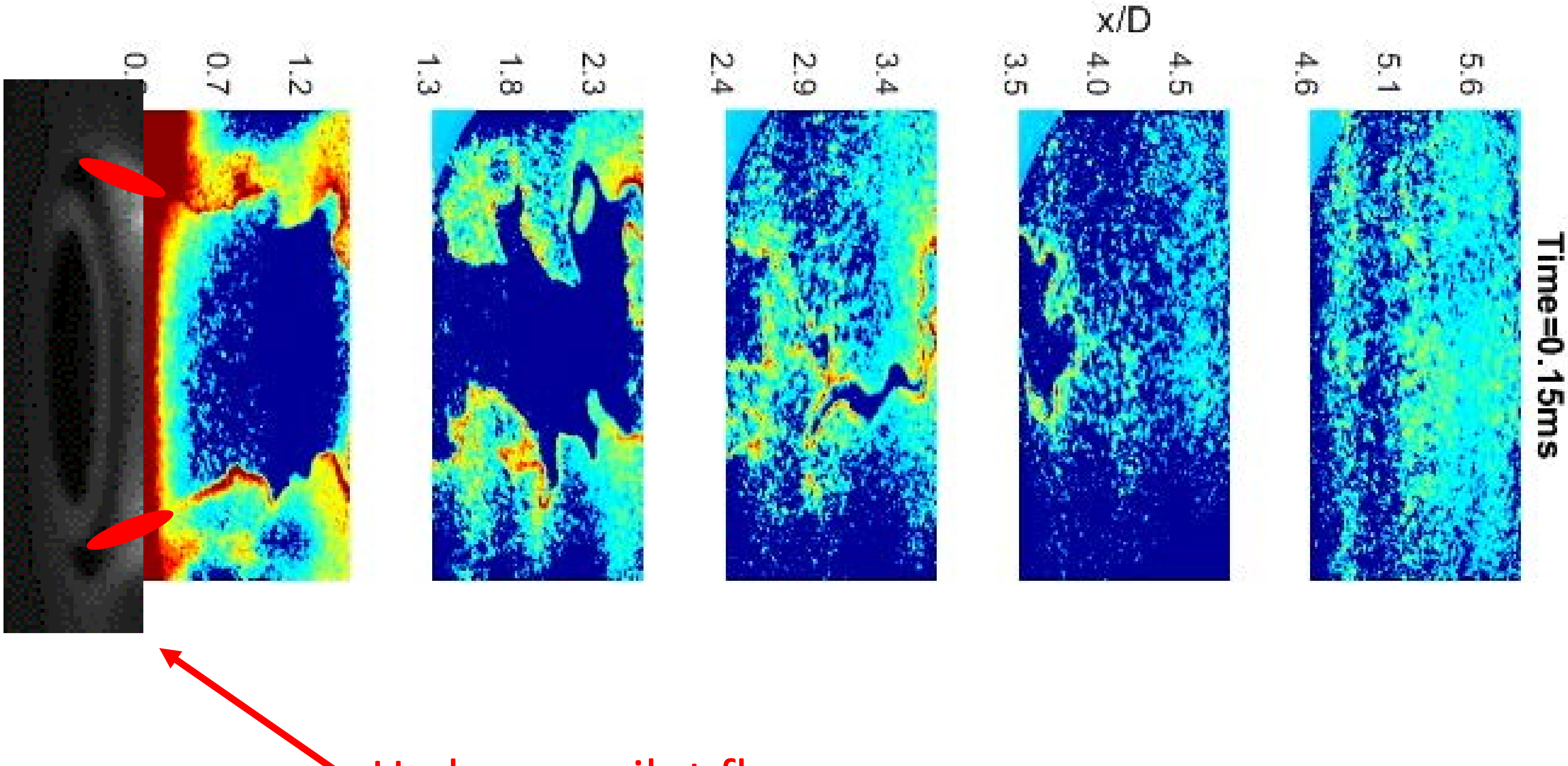
Φ=1, Re=10000



Hydrogen pilot flame

CH-OH PLIF video for flame with 0% CO_2 addition

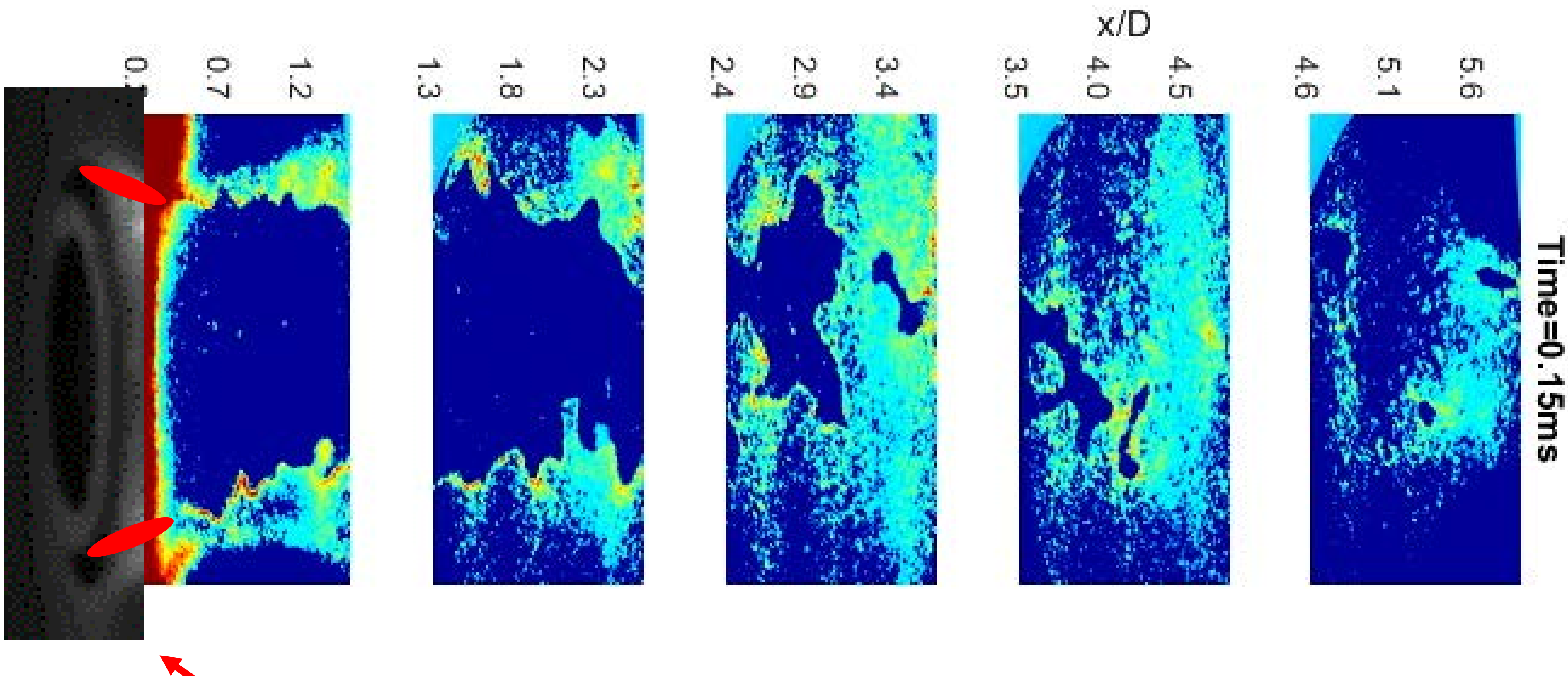
Φ=1, Re=10000



Hydrogen pilot flame

CH-OH PLIF video for flame with 5% CO_2 addition

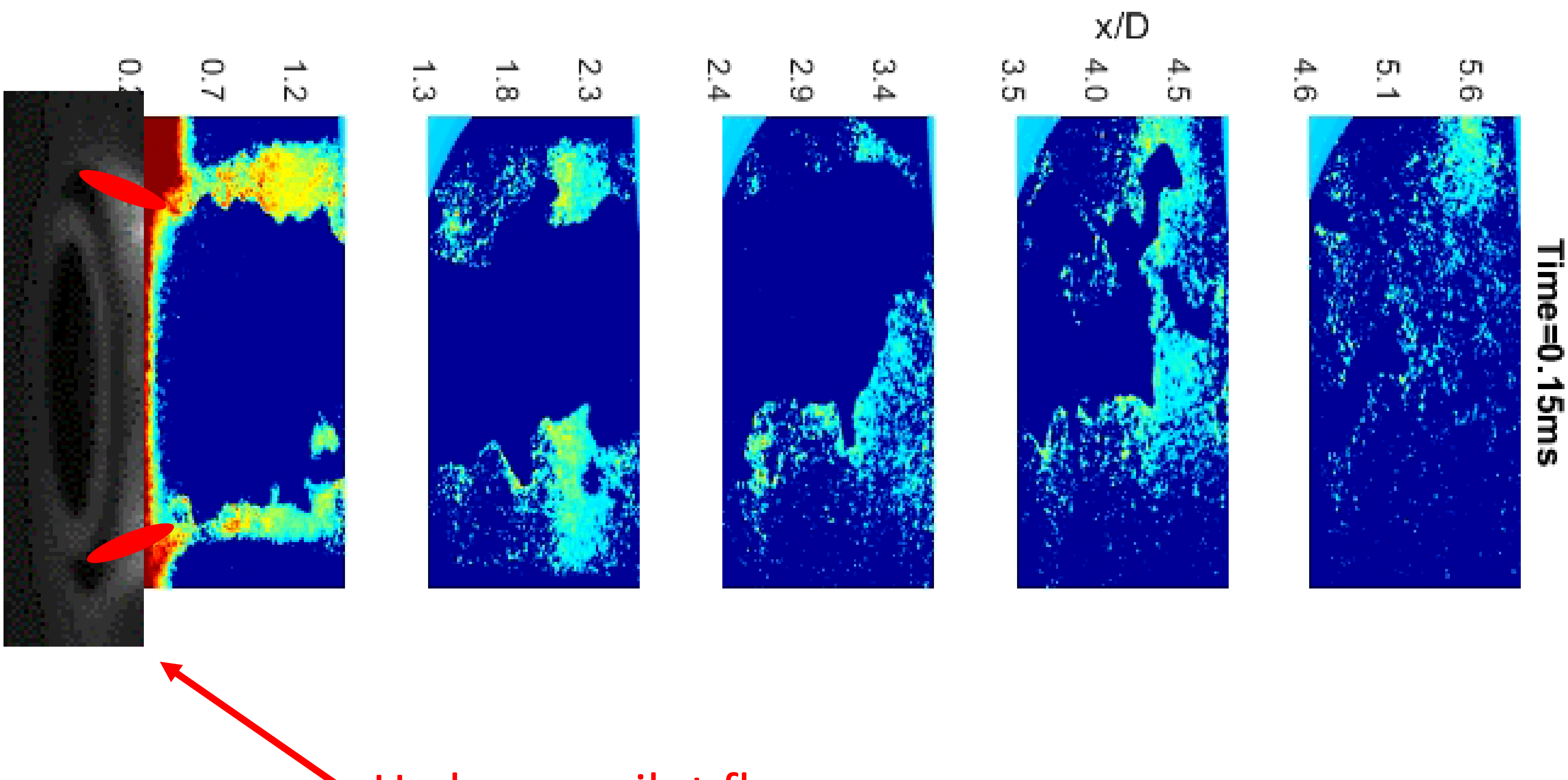
Φ=1, Re=10000



Hydrogen pilot flame

CH-OH PLIF video for flame with 10% CO_2 addition

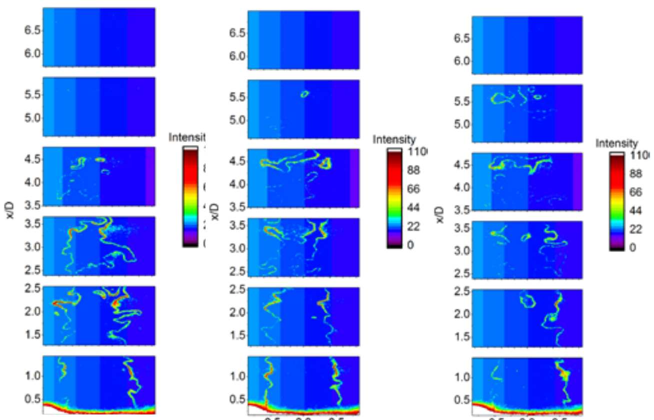
Φ=1, Re=10000



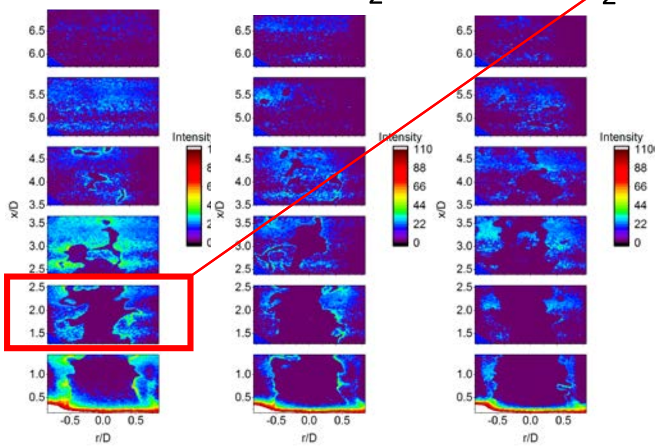
Hydrogen pilot flame

CH PLIF & Simultaneous CH and OH PLIF

Φ=1, Re=10000

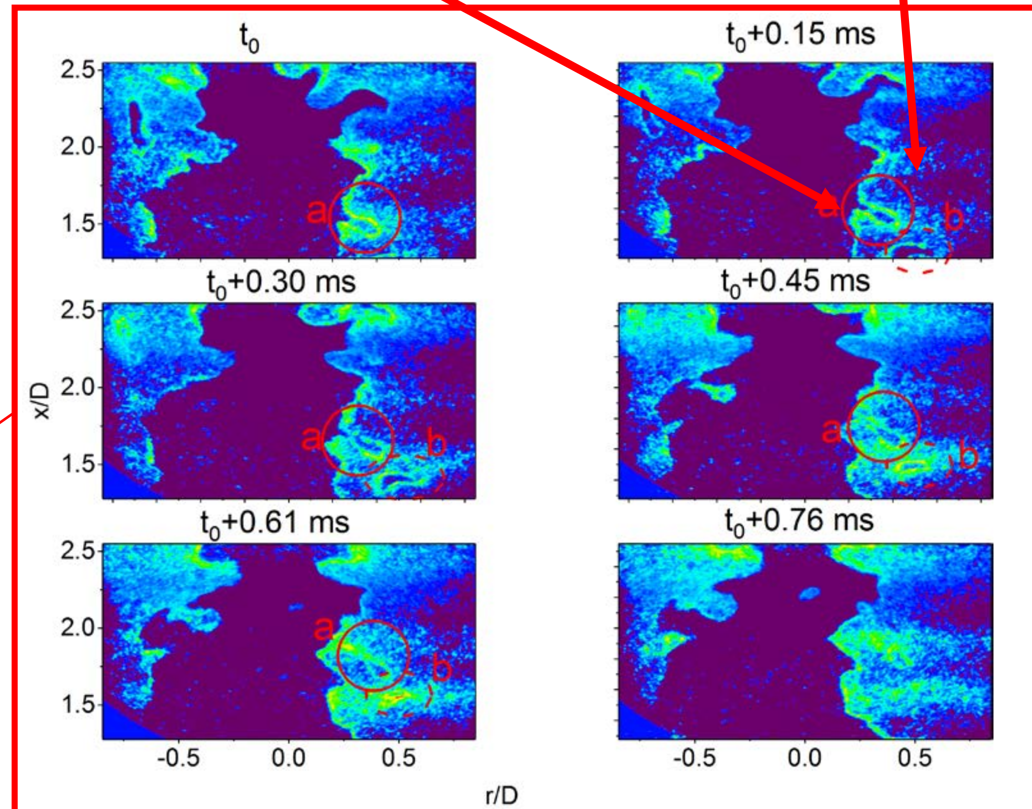


0% CO_2 5% CO_2 10% CO_2



Green: CH Layer

Blue: OH Zone

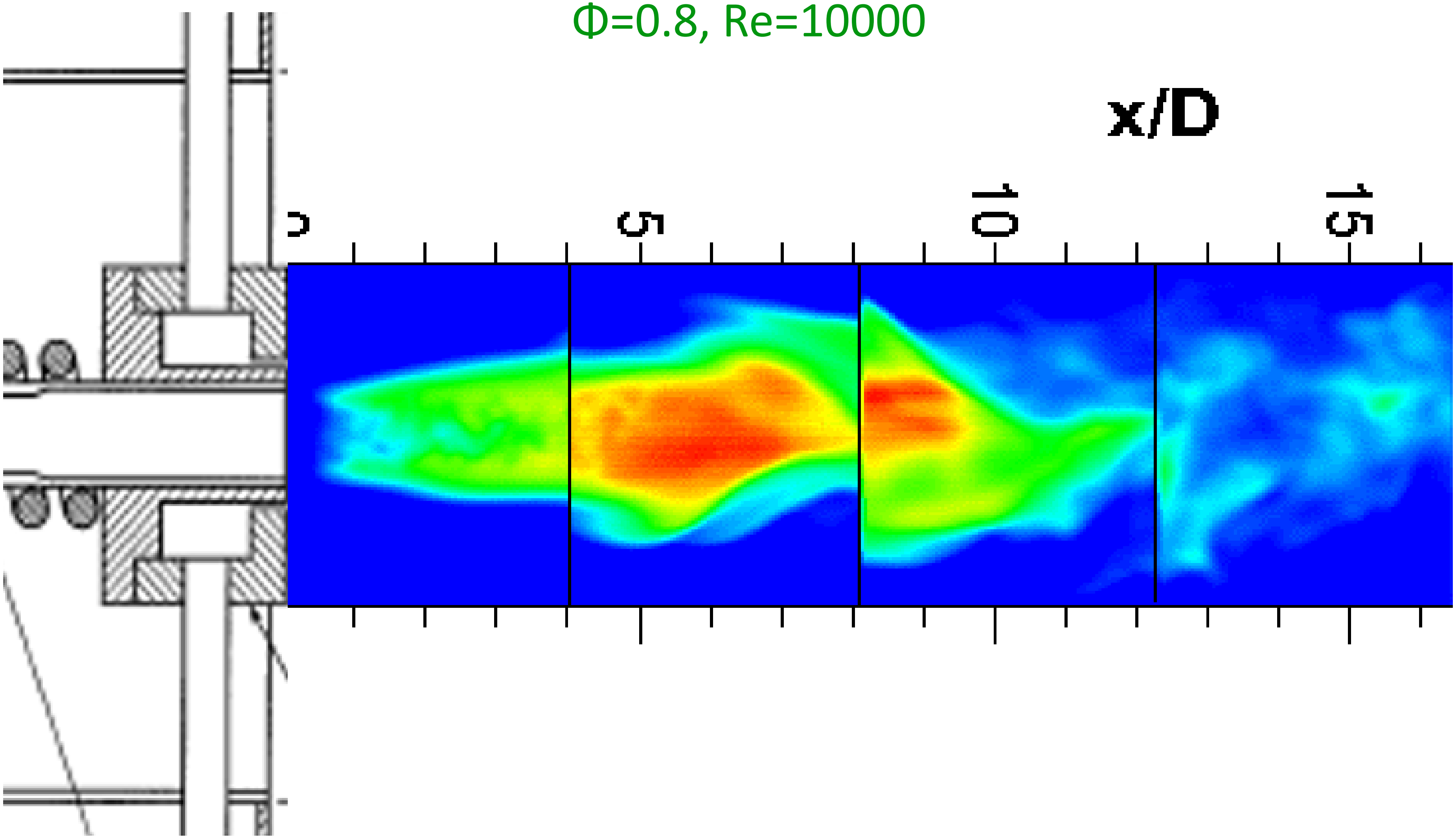


(a) wrinkled flame front, (b) unburned reactant pocket.

Challenging for lean premixed flames with CO_2 dilution due to low CH signal

IR imaging video for CH_4/air flame

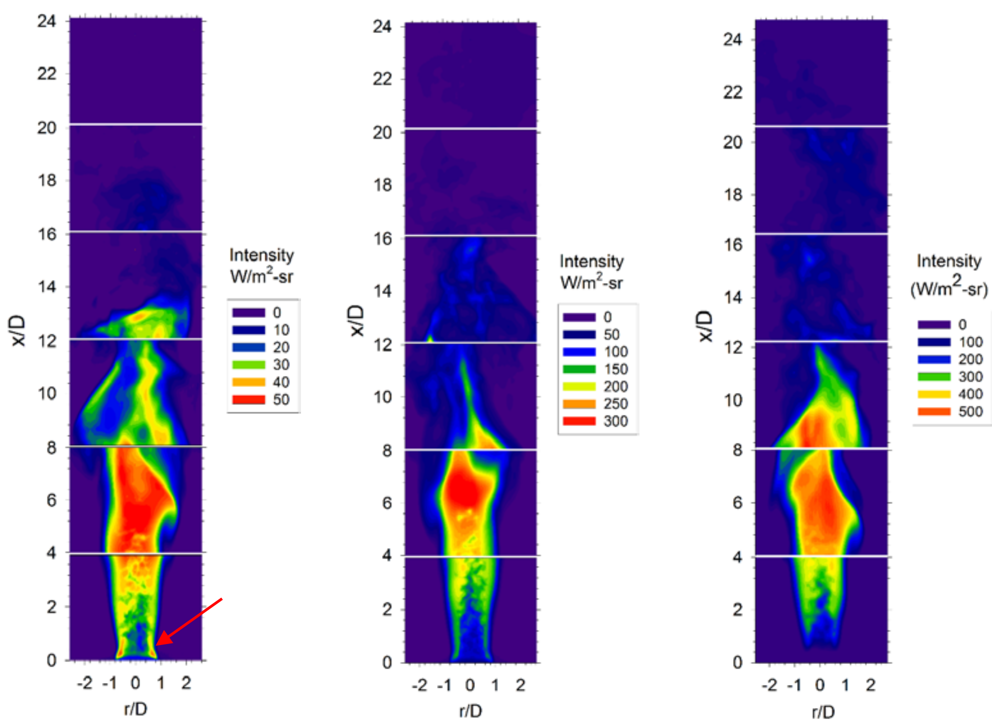
Φ=0.8, Re=10000



Instantaneous IR images

Multiple bandpass filters with KC burner

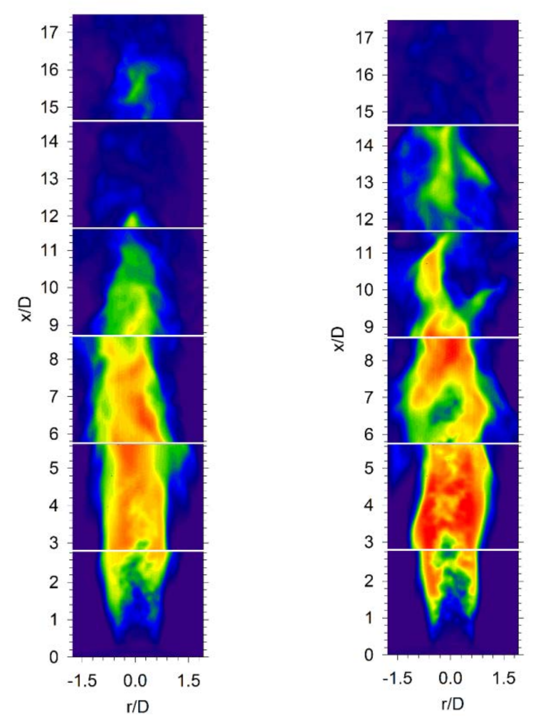
2.58±0.03 µm H_2O | **2.77 ± 0.1 µm H_2O+CO_2** | **4.38 ± 0.08 µm CO_2**



CH_4/air Φ=0.80 Re=10000

Varying CO_2 with PARAT burner

0% CO_2 | 10% CO_2



Φ=0.80 | Φ=0.89

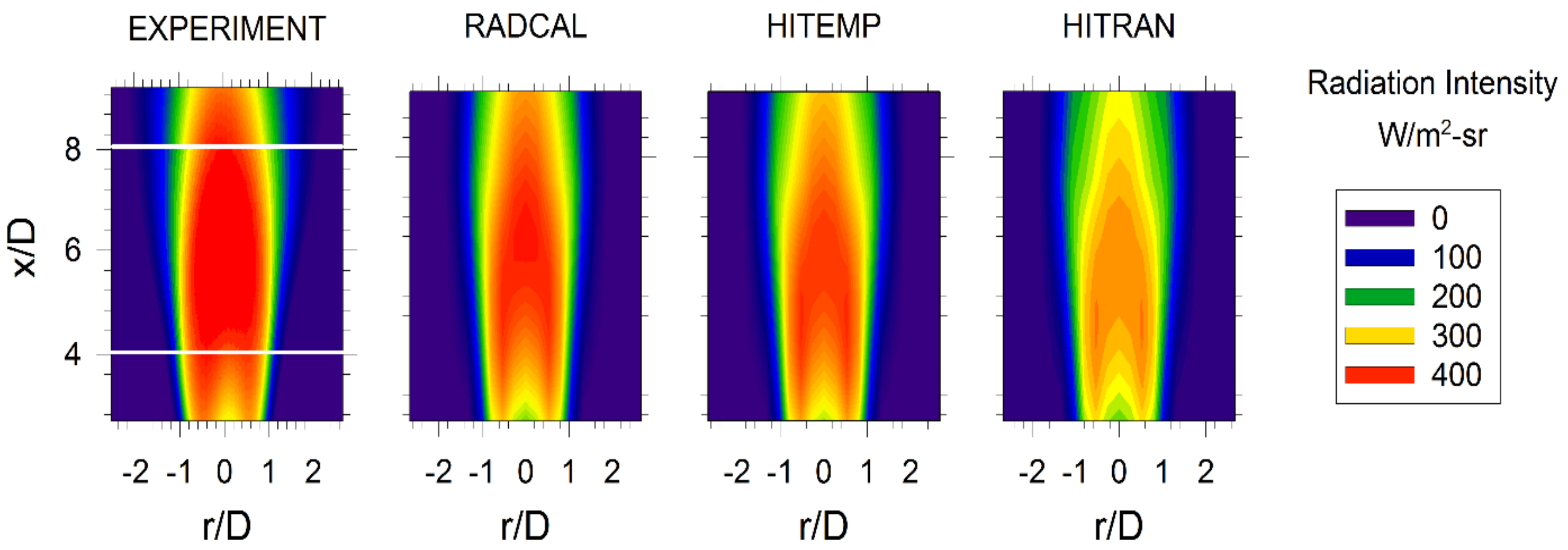
Re=10000

Time Averaged Radiation Model Validation

Turbulence radiation interaction (TRI) modeling:

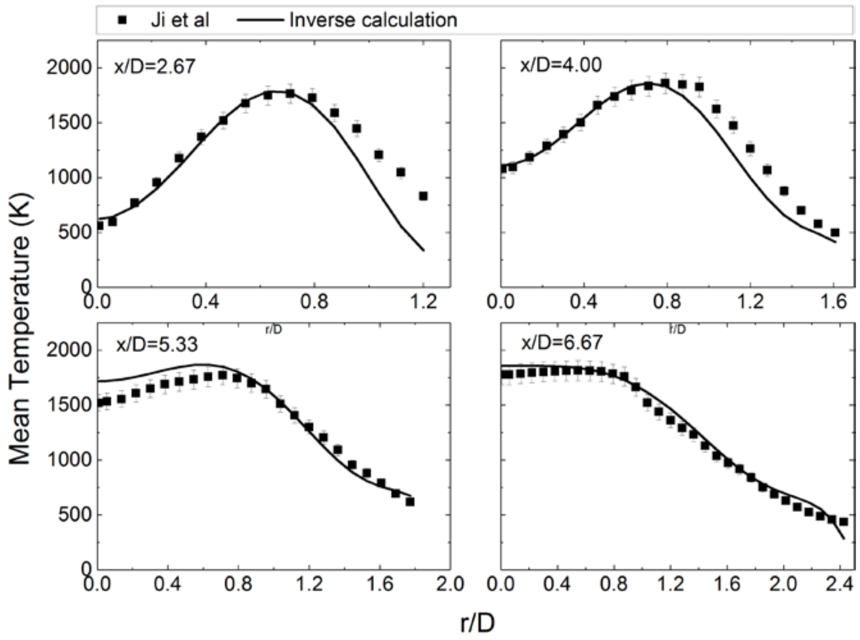
Stochastic time and space series analysis (STASS)

$$I = \int_{\lambda_1}^{\lambda_2} \alpha_\lambda I_\lambda(0) e^{-\tau_\lambda} d\lambda + \int_{\lambda_1}^{\lambda_2} \int_0^{\tau_\lambda} \alpha_\lambda I_{b\lambda}(\tau_\lambda^*) e^{-(\tau_\lambda - \tau_\lambda^*)} d\tau_\lambda^* d\lambda$$

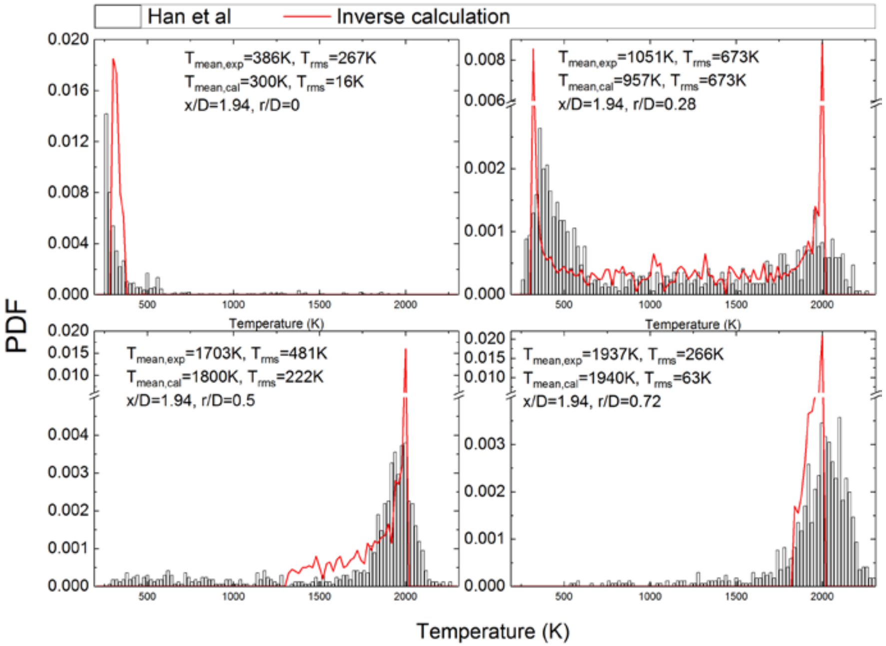


Temperature Deconvolution

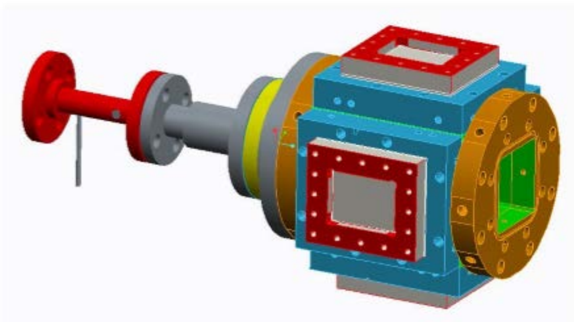
Computed temperature vs thin filament thermometry

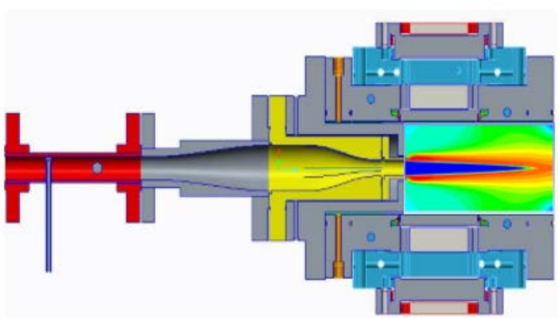


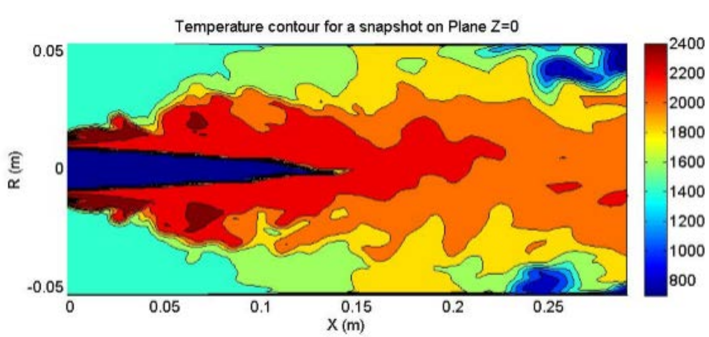
Computed temperature vs CARS thermometry

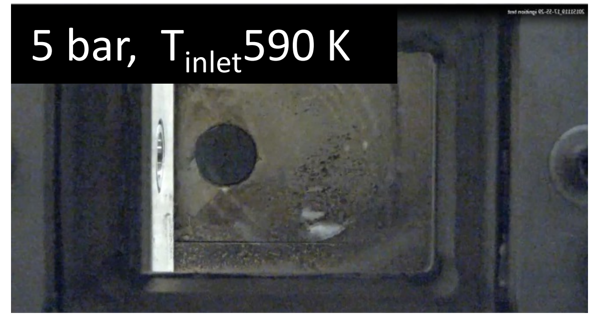


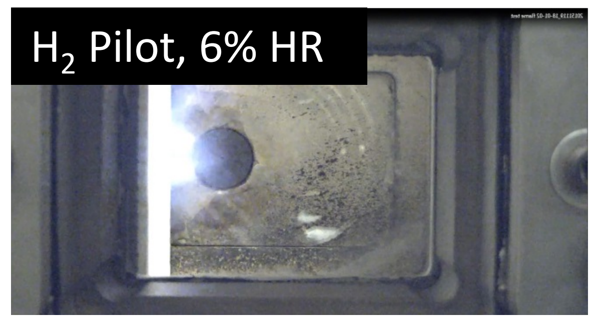
High Pressure PARAT Experiments and LES

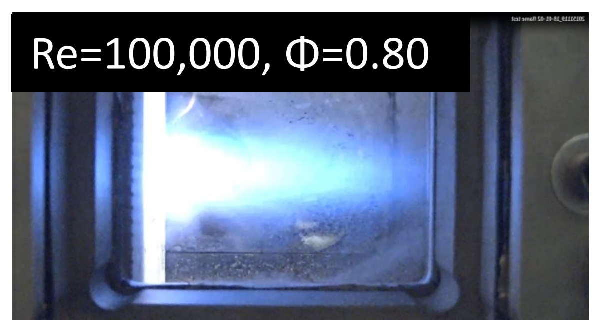












Summary & Conclusions

1. Developed a PARAT burner and demonstrated multiple diagnostic methods including PIV, CARS, OH/CH PLIF and IR imaging for turbulent premixed combustion applications.

2. Performed a comprehensive investigation of the non-thermal effects of CO_2 addition on turbulent premixed combustion for the first time.

3. CO_2 addition extends flame length, Modifies flame brush to be longer and thinner, alters local flame surface area, reduces burning velocities, and enhances pocket formation with negligible effects on pocket consumption speed

4. Developed LES simulation tool for CH_4/air/CO_2 flames and validated using temperature and velocity measurements

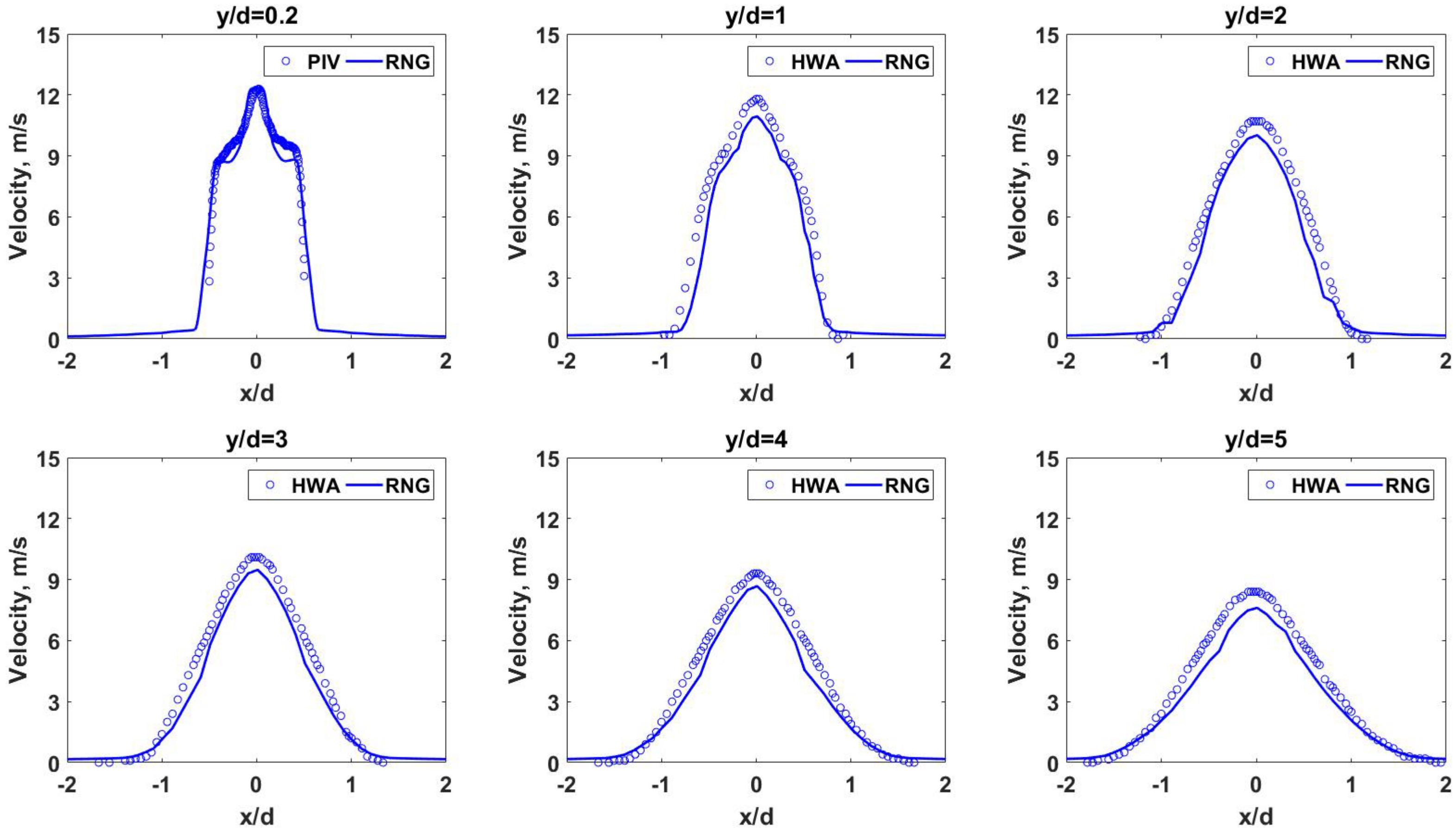
Appendix

Flame operating conditions

Flame #	1	2	3
Reynolds number (± 50)	10000		
Adiabatic Temperature (± 50 K)	2030		
Equivalence ratio (± 0.02)	0.80	0.84	0.89
CO_2 % by total mass (± 0.1)	0.0	5.0	10.0
CH_4 mass flow rate (± 2 mg/s)	111	110	109
Air mass flow rate (± 20 mg/s)	2440	2300	2150
CO_2 mass flow rate (± 4 mg/s)	0.00	124	246
Pilot H_2 mass flow rate (± 0.03 mg/s)	2.7		
Pilot H_2 heat release percent of total (%)	6		
Lewis number	1		
Laminar flame speed (cm/s)	34	30	25
Laminar flame thermal thickness (μm)	70	80	90
RMS turbulence fluctuation (m/s)	1.7		
Integral length scale (mm)	1		

Appendix

Cold flow Results with RANS based RNG k-Ɛ model

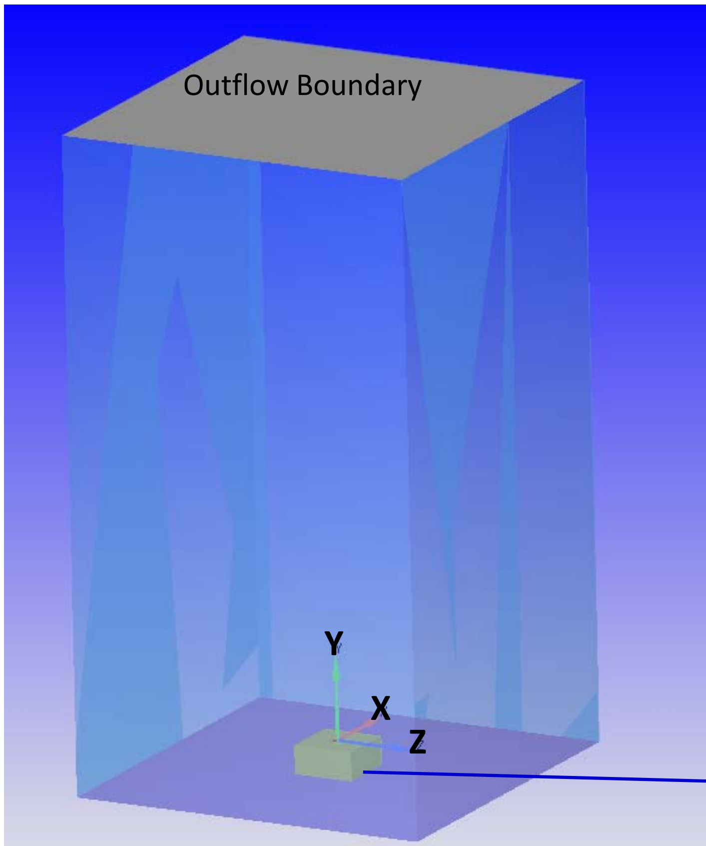


Good Agreement with Hot wire anemometer measurements

Appendix

CFD Domain and BCs - Reacting

36D x 64D x 36D, D= 18 mm



$$u_i = u_{i,set} + u_i'$$

$$u_i'(x_j) = 2\sum_{n=1}^{N} \hat{u}^n \cos(\kappa_j^n x_j + \psi^n)\sigma_i^n$$

Nozzle Exit: Specified mean velocity profile.
Turbulent Fluctuations: Random Fourier Approach

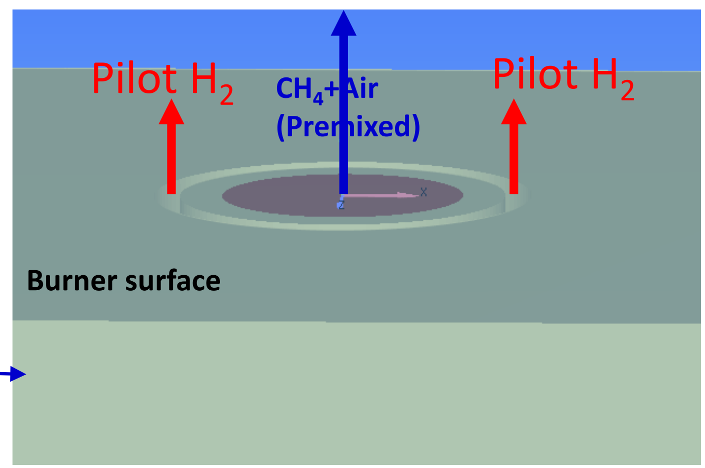
Davidson et.al, IJHF, 27, 2006

$\hat{u}^n$ Amplitude of the nth Fourier mode based on the modeled turbulent spectrum

ψ^n Phase of the nth Fourier mode

σ_i^n Direction of the nth Fourier mode

κ_j^n Wavenumber of the nth Fourier mode in the j direction



Premixing Tube Excluded to Reduce Computational Time