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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National Energy Technology Laboratory
University Turbine Systems Research Program

Thanks: Chris Reuter, Prof. Sang Hee Won

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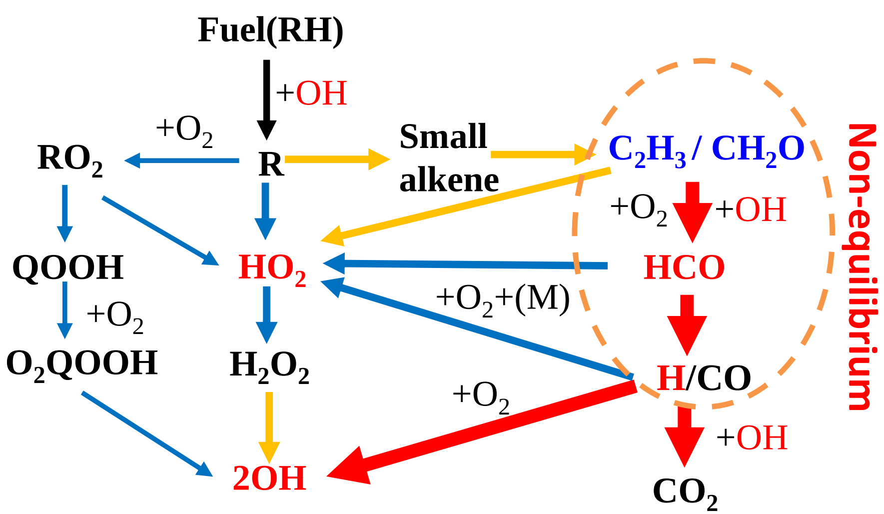
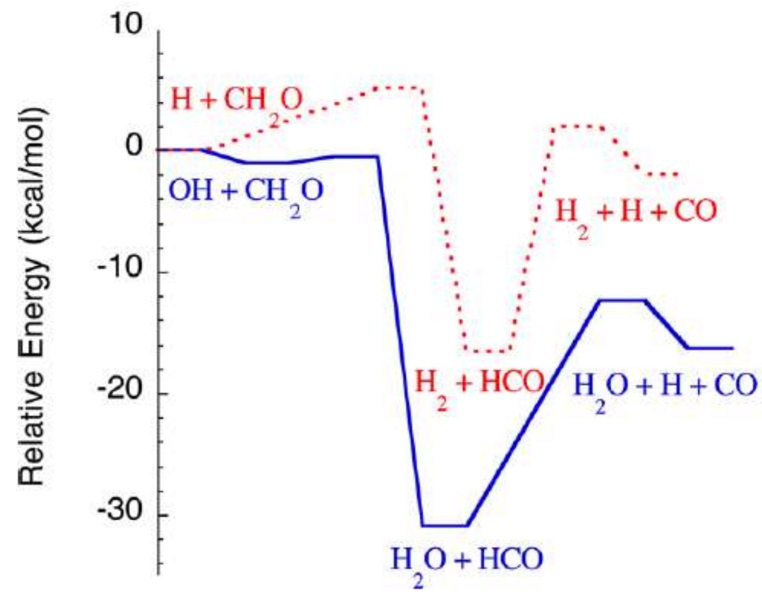
- **New design of Axisymmetric Reactor-Assisted Turbulent (ARAT) Burner for High Turbulence with EGR.**

1. Kinetic study of non-equilibrium prompt dissociation of HCO at elevated pressures with CO_2

Major oxidation pathway of HHC fuels

C_2H_6, CH_4 → CH_2O→HCO→H+CO →CO_2,H_2O





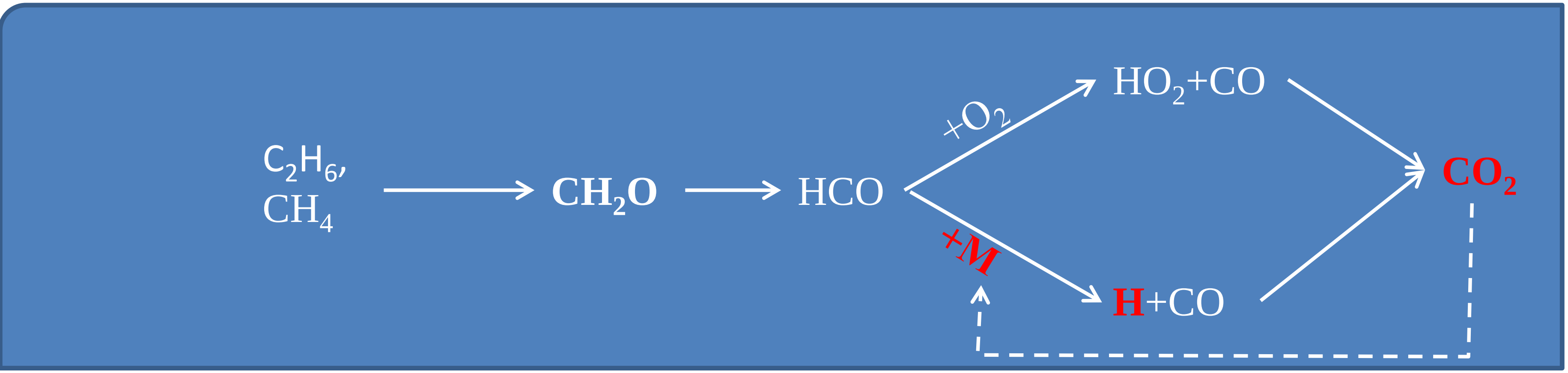
X+CH_2O= HCO+XH (equilibrium) (R_{1a})

X+CH_2O= H+CO+XH (non-equilibrium, Prompt) (R_{1b})

Why CO_2?

$HCO+M=H+CO$ R2a

$HCO+O_2=HO_2+CO$ R2b



CO_2 affects the competition between the two key reactions

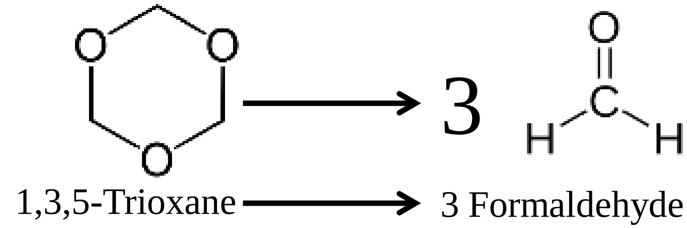
- **Formaldehyde (CH_2O)/CO_2** flames are excellent targets to study HCO prompt reactions and CO_2 effect, but have not been reported in the literature
  - Formaldehyde flame sampling has been done at very low pressure (~30 torr)[1-4]
  - Formaldehyde has been studied in shock tubes[5-9] and flow reactors[10,11]
- We reports the *first flame speed measurements* at high pressure and with CO_2.

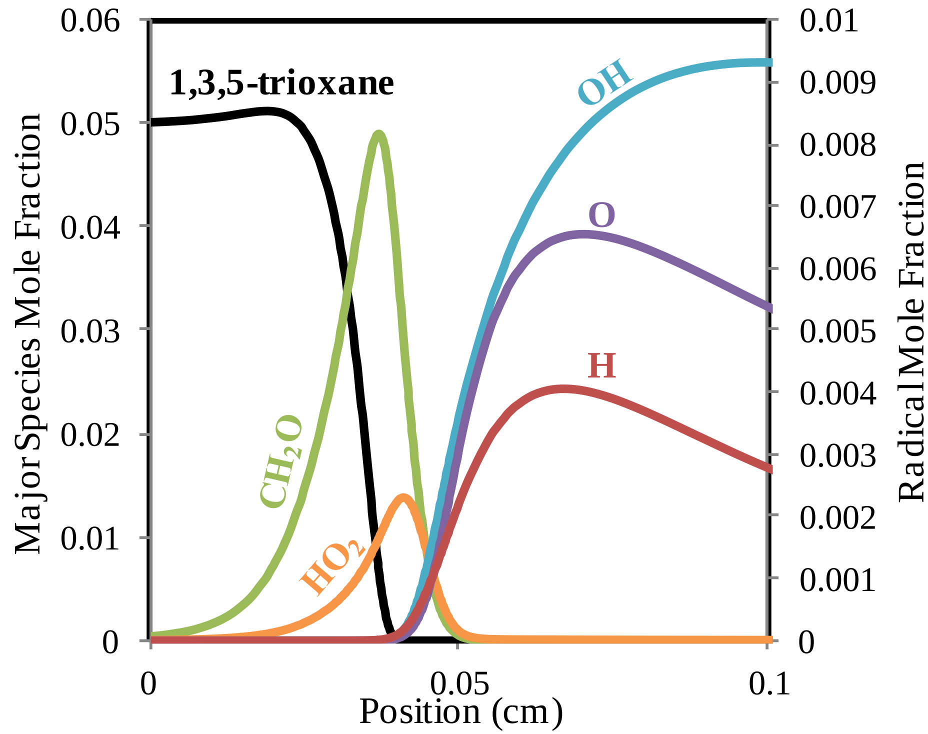
1. J. Vandooren et al. (1986)
2. M.C. Branch et al. (1991)
3. A.R. Hall et al. (1957)
4. V. Dias et al. (2012)
5. Y. Hidaka et al. (1993)
6. V. Vasudevan et al. (2005)
7. G. Friedrichs et al. (2004)
8. G. Friedrichs et al. (2002)
9. S. Wang et al. (2013)
10. P. Glarborg et al. (2003)
11. S. Hochgreb et al. (1992)
12. J. Santner et al. (2015)

J. Santner, F.L. Dryer, Y. Ju, Proc. Combust. Inst. 34 (2013) 719–726.

How do we create CH_2O and HCO?

- Formaldehyde is toxic and difficult to generate in its pure form due to polymerization
- **Use trioxane to generate formaldehyde *in situ***
- Formaldehyde (CH_2O) forms before radical pool
  - > 99% of trioxane is consumed through thermal decomposition
- **These flames are governed by the same chemistry as formaldehyde flames**



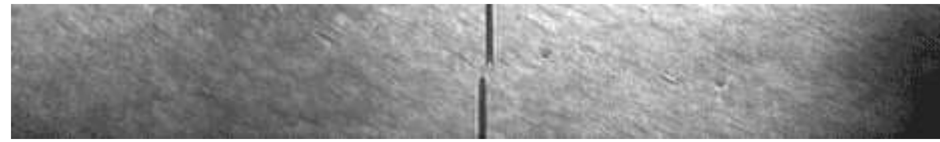


1,3,5-trioxane/O_2/N_2 = 5/25/70
1 atm, T_u = 373 K

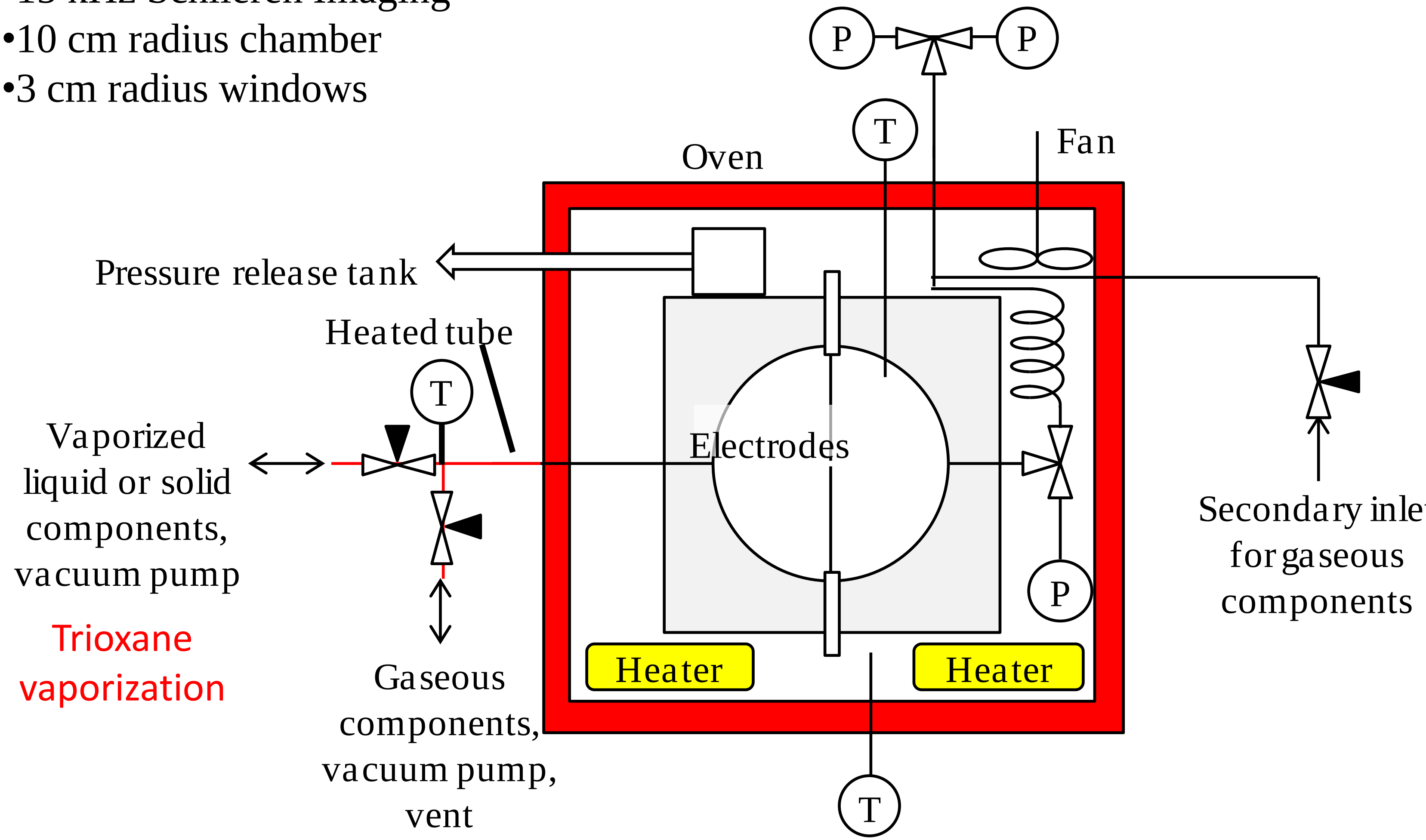
J. Santner, F.L. Dryer, Y. Ju, Proc. Combust. Inst. 34 (2013) 719–726.

High Pressure Flame Experiments

- Pressures up to 10 atm
- Temperature up to 450 K
- 15 kHz Schlieren Imaging
- 10 cm radius chamber
- 3 cm radius windows



6 atm, $H_2/CO/O_2/He$, $\phi = 0.85$, $T_f = 1600K$



Experimental conditions of pressurized trioxane flame speed measurements with/without CO_2

Case	Equivalence ratio	Trioxane	O_2	CO_2	N_2	He	T_f (K)
Lean	0.7	0.0454	0.1946	0.0000	0.5846	0.1754	1900
Ultra-lean	0.34	0.0454	0.4000	0.0000	0.3792	0.1754	1882
Rich	1.4	0.0889	0.1904	0.0000	0.5544	0.1663	2000
Lean with CO2	0.7	0.0491	0.2103	0.2000	0.2201	0.3206	1900
Rich without CO2	1.4	0.0943	0.2021	0.2000	0.1266	0.3770	2000

$X + CH_2O = HCO + XH$ (equilibrium) (**R_{1a}**)

$X + CH_2O = H + CO + XH$ (non-equilibrium, Prompt) (**R_{1b}**)

Why Lean?

$HCO + M = H + CO$ R_{2a}

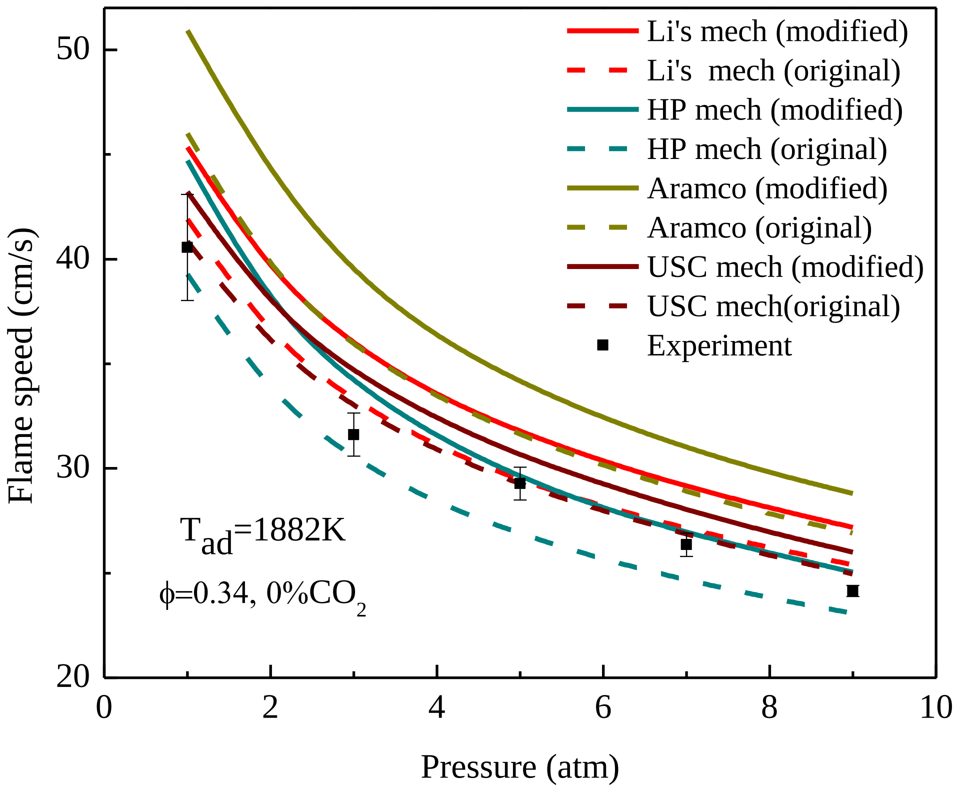
$HCO + O_2 = HO_2 + CO$ R_{2b}

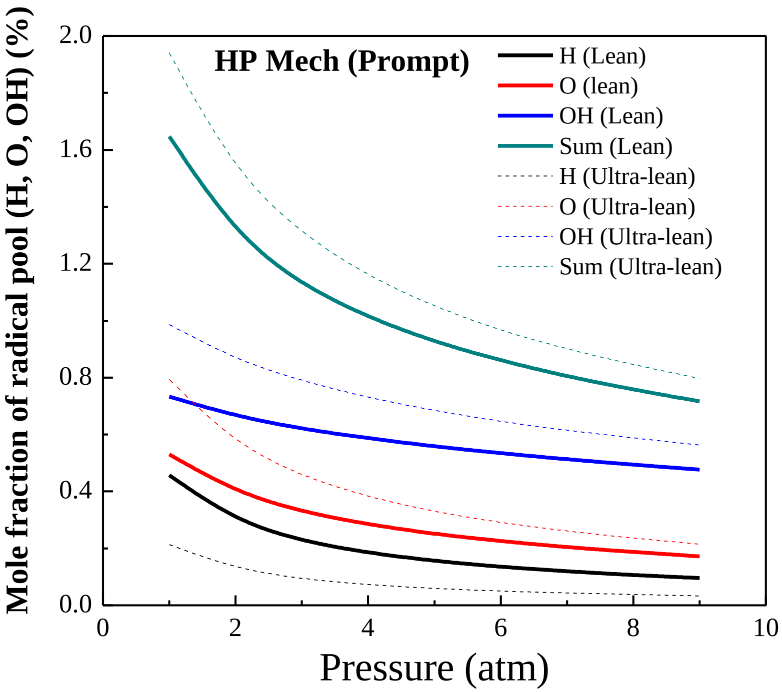
Flame speeds and radical pool

H+O2=O+OH
H+O2+M=HO2+M

HCO+M=H+CO+M (R2a)
HCO+O2=CO+HO2 (R2b)

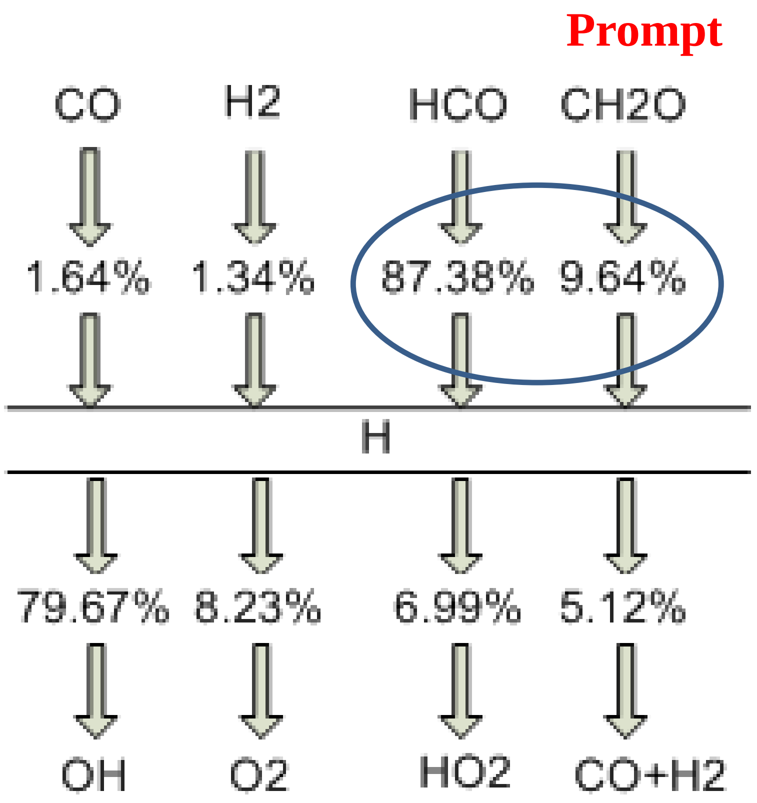
Ultra-lean: Φ=0.34



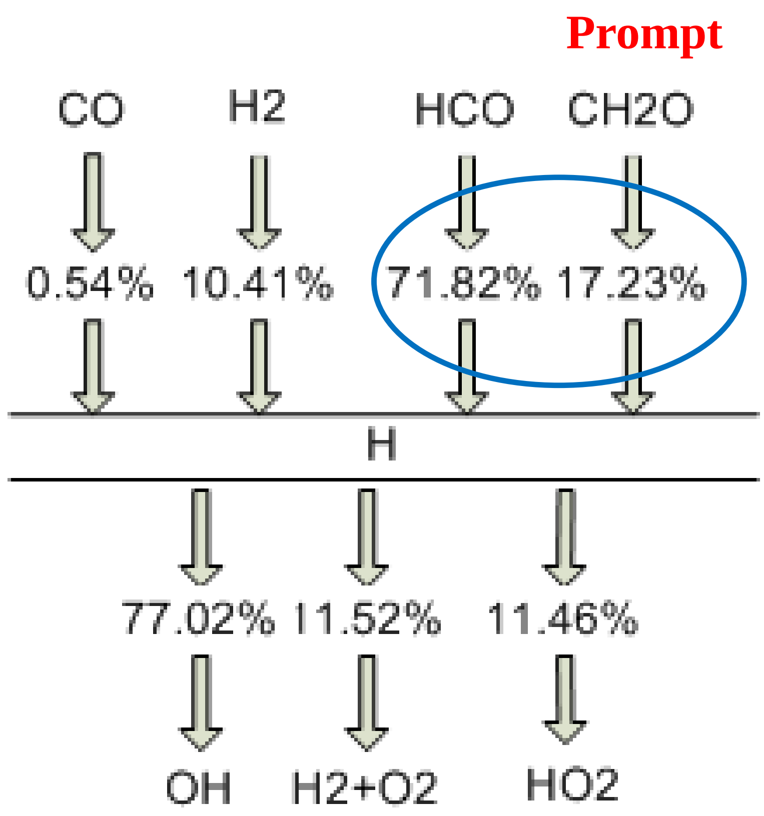


- Mole fractions of O, OH, and total radical pool in the ultra-lean cases is larger than that in the lean case, because of increase of H+O2=O+OH,
- While H radical's mole fraction is lower than that in the lean case, causing a decrease of system reactivity directly, because of the increase of R2a/R2b branching ratio.

HCO prompt dissociation on H production at 4 atm (HP Mech-Prompt)



Lean Φ=0.7



Ultra-lean Φ=0.34

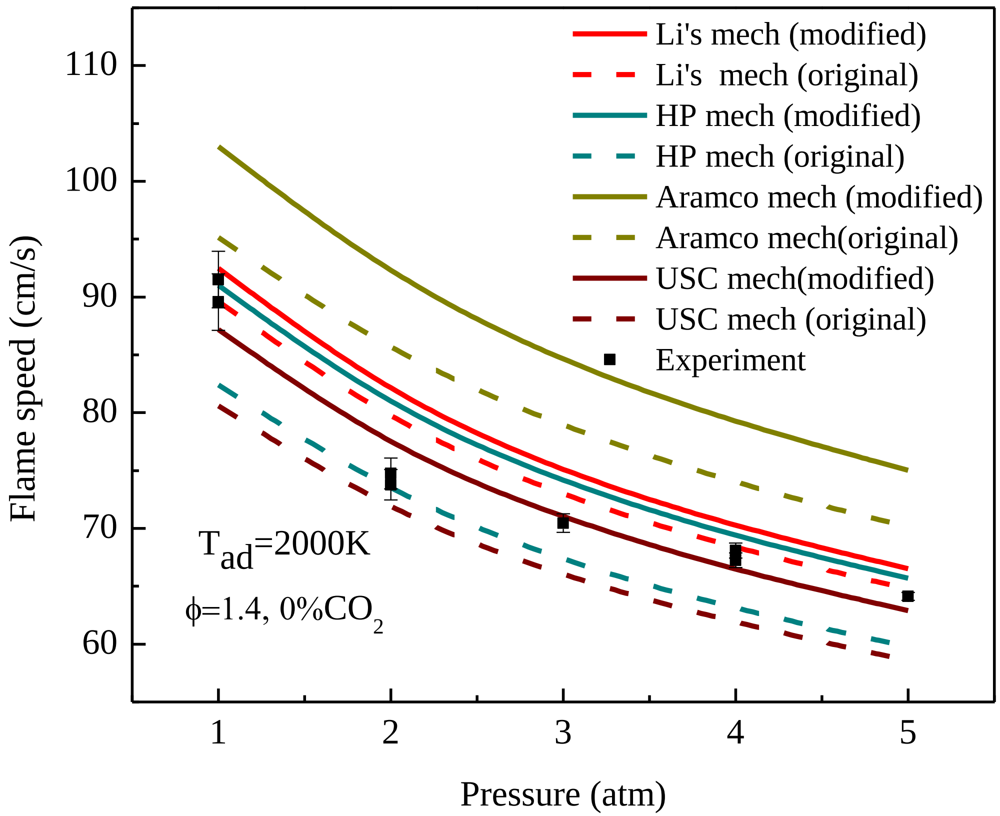
HCO Prompt dissociation effect increases with increasing O2 mole fractions.

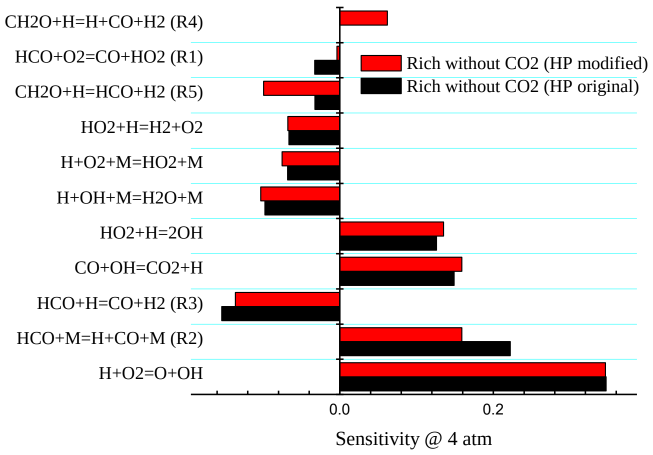
Flame speeds and reaction sensitivity

•HCO+M=H+CO+M (R2a)
•HCO+O2=HO2+CO (R2b)

•CH2O+X=H+CO+HX (R1)

Fuel Rich Φ=1.4

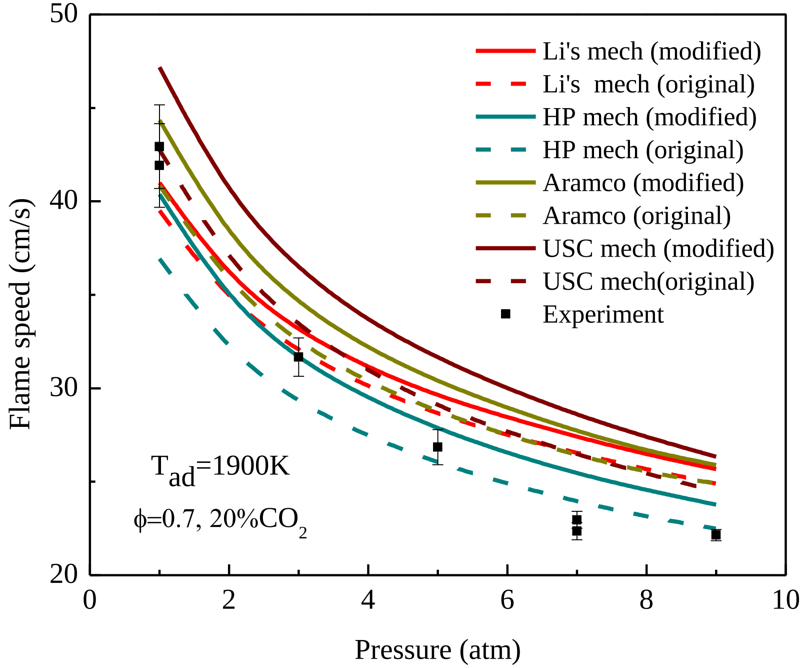




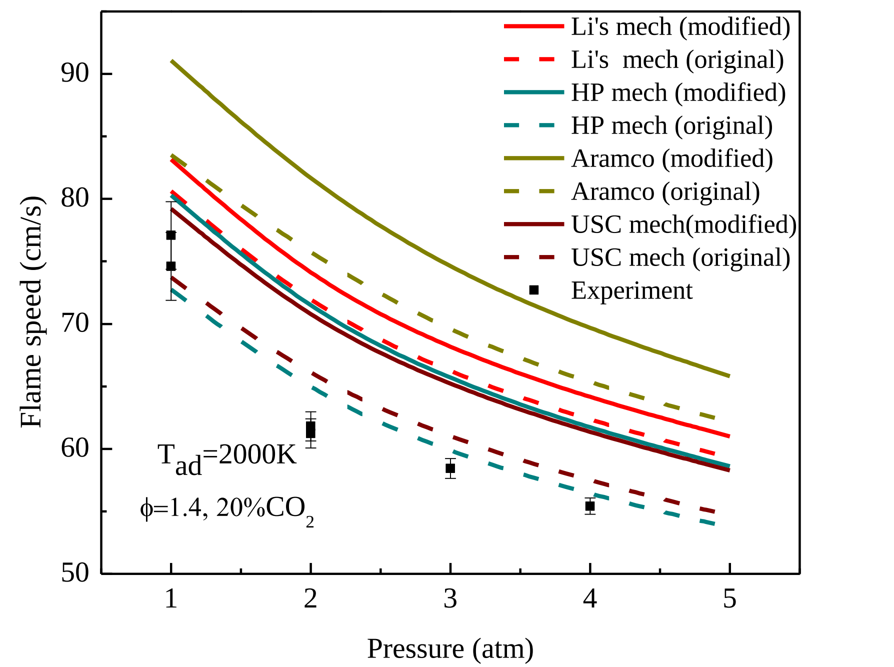
HP-Mech with prompt HCO reactions has better predicted flame speeds.

Effect of CO_2 dilution on HCO prompt reactions

Fuel lean   Φ=0.7, 20% CO_2



Fuel Rich   Φ=1.4, 20% CO_2



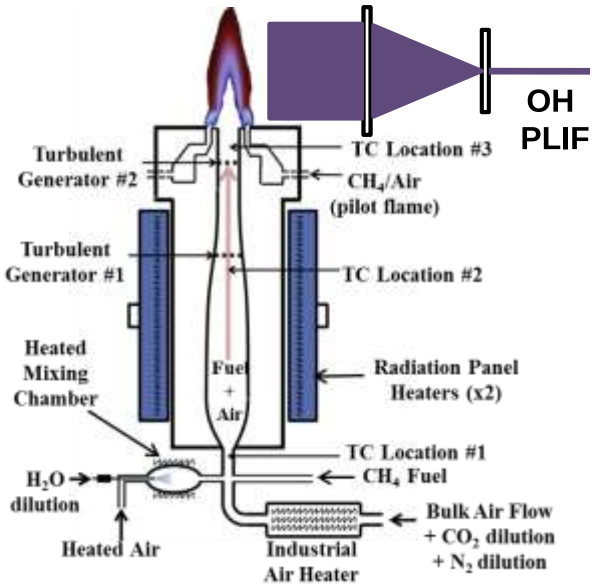
HCO+M=CO+H+M

- HP Mech with HCO prompt reactions has a good prediction of flame speed on fuel lean conditions but over-predict considerably at fuel rich conditions with CO_2.

2. Turbulent flame speeds/structure with H_2O/CO_2 dilutions

Reactor-assisted turbulent slot (RATS) burner

- 10 cm by 1 cm rectangular slot
- Methane/air pilot flame
- OH PLIF for flame imaging



Experimental study:

- CH_4/Air flames with CO_2 and H_2O dilution
- Moderately intense turbulence (up to $Re_T \sim 170$)
- Dilution at either variable T_{ad} or constant T_{ad}

$$Dilution = \frac{X_{Diluent}}{X_{Fuel} + X_{Air} + X_{Diluent}}$$

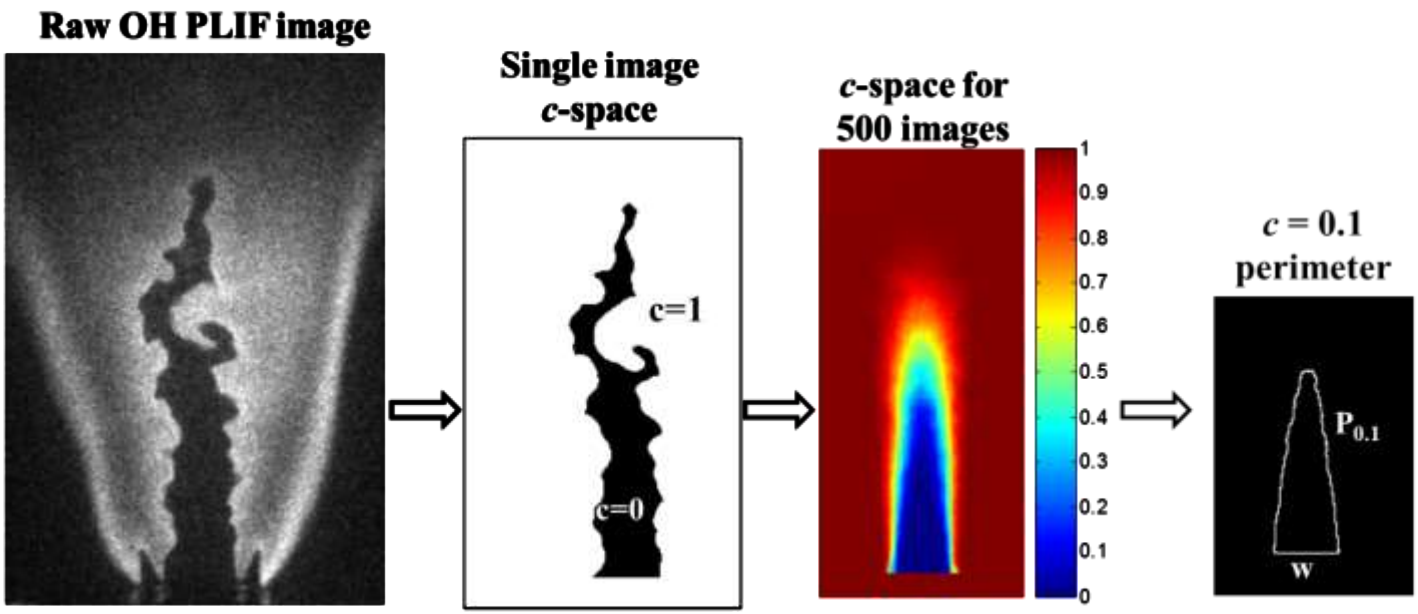
"Variable flame temperature dilution": first three rows (φ = 1.0).

"Constant flame temperature dilution": rows with φ = 0.9.

Add N_2 for each case until T_{ad} is matched

CH_4/Air, T_0 = 450 K, p = 1 atm, U = 15 m/s			
ϕ	Dilution	T_{ad} (K)	S_L (cm/s)
1.0	None	2304	70.6
1.0	20% H_2O	1992	28.4
1.0	15% CO_2	2014	25.9
0.9	(N_2 only)	2025	40.9
0.9	10% H_2O	2025	40.0
0.9	10% CO_2	2025	34.6
0.9	20% H_2O	1822	20.5
0.9	20% CO_2	1822	16.8

Determination of S_T



$$S_T = \frac{Uw}{P_{0.1}}$$

(1) Find inner flame surface, set unburned region to c = 0 and burned to c = 1
(2) Create average of progress variable for entire run (500 images)
(3) Trace c = 0.1 contour to find perimeter
(4) Evaluate turbulent flame speed (S_T) through mass conservation

- More consistent than previous method of using PDF of flame perimeters

H. Kobayashi et al., *Proc. Combust. Sci.* 30 (2005) 827-834
O.L. Gulder et al., *Combust. Sci. Tech.* 179 (2007) 191-206

Scaling of Dilution Effects

- Damkohler's original scaling: $S_T/S_L = (u'/S_L)^{0.5}(l/l_F)^{0.5}$
- Modify using $Sc = 1$ and $l_F = \alpha/S_L$
- Modified Damköhler scaling :

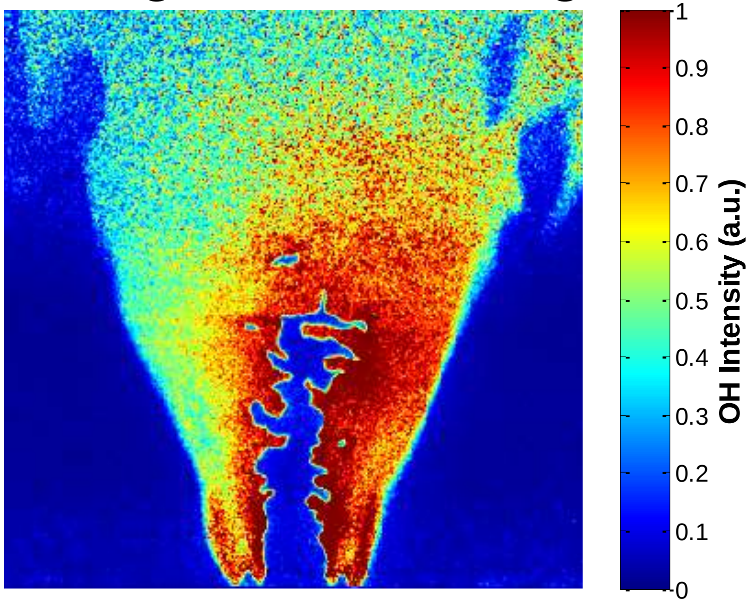
$$\boldsymbol{S_{T,diluted} = S_{T,standard}\left(\frac{S_{L,dil}}{S_{L,std}}\right)\left(\frac{Re_{T,dil}}{Re_{T,std}}\right)^{0.5}\left(\frac{Le_{dil}}{Le_{std}}\right)^{-0.5}}$$

Flame speed /chemistry contribution — Turbulence contribution — Thermo-diffusivity contribution

B. Windom et al., *Combust. Flame* 169 (2016) 19-29.

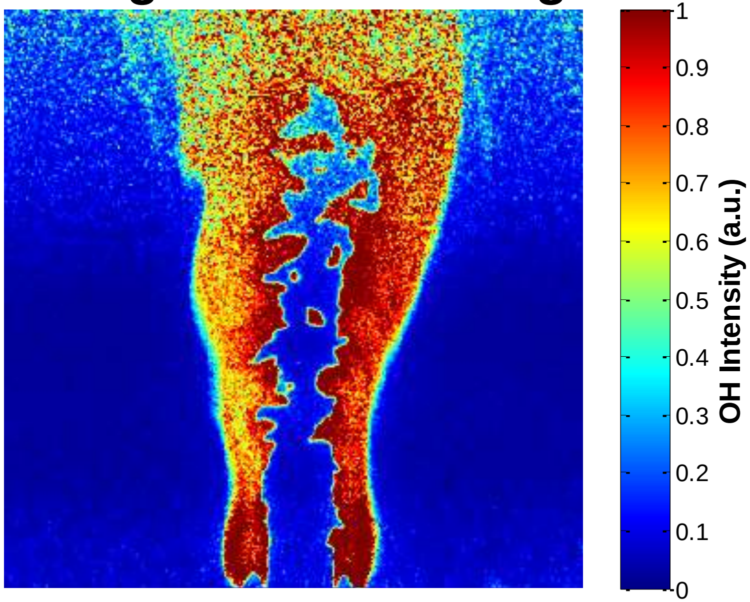
Variable flame temperature with Dilution

Single OH PLIF Image



0% Dilution
T_{ad} = 2304 K

Single OH PLIF Image

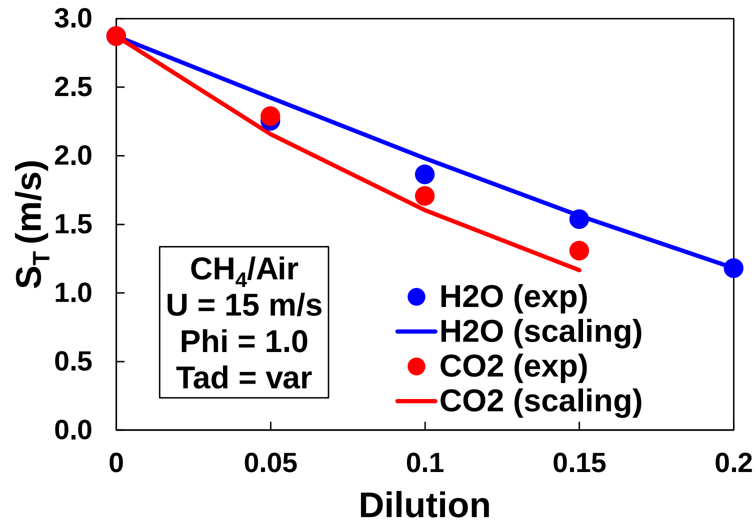


10% CO_2 Dilution
T_{ad} = 2110 K

- Effects of increased dilution are apparent even at a glance
- Clear lengthening of the flame can be seen at higher dilution levels

Variable T_{ad} Dilution

CH$_4$/Air, T_0 = 450 K, p = 1 atm, U = 15 m/s			
ϕ	Dilution	T_{ad} (K)	S_L (cm/s)
1.0	None	2304	70.6
1.0	20% H_2O	1992	28.4
1.0	15% CO_2	2014	25.9



Variable T_{ad}

- Large reduction in S_T for both CO_2 and H_2O
- CO_2 dilution is noticeably stronger

- Modified Damköhler scaling analysis:

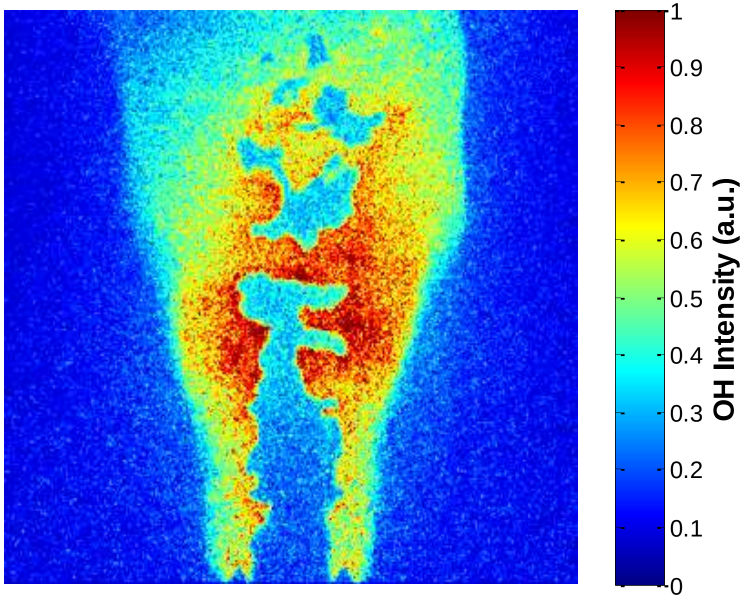
$$S_{T,diluted} = S_{T,standard}\left(\frac{S_{L,dil}}{S_{L,std}}\right)\left(\frac{Re_{T,dil}}{Re_{T,std}}\right)^{0.5}\left(\frac{Le_{dil}}{Le_{std}}\right)^{-0.5}$$

					Scaling	**Measured**
20% H_2O	↓60%	↑0.2%	↑2.1%	→	↓59%	↓~59%
15% CO_2	↓63%	↑6.0%	↑4.0%	→	↓59%	↓~55%

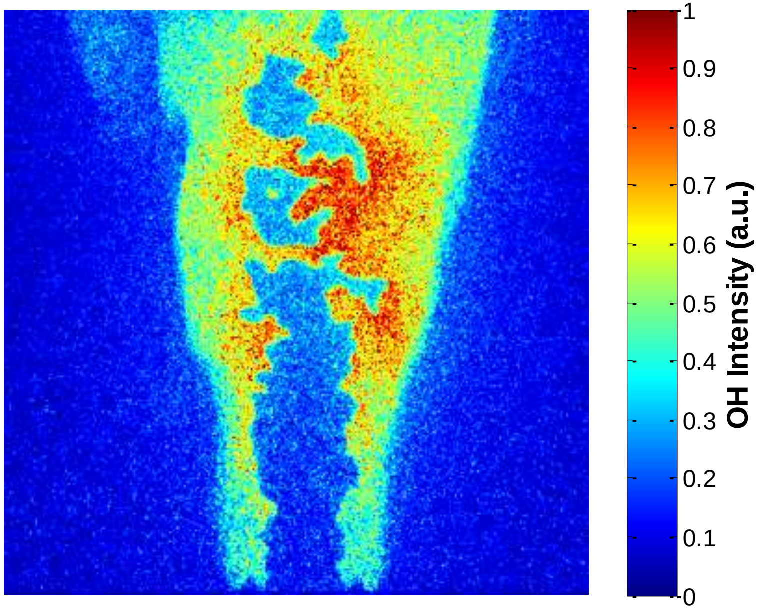
↑S_T/S_L

Thermal effect is the largest contribution with diultions.

Constant Flame temperature with Dilution: T_{ad} = 2025 K



0% Dilution
***T_{ad}* = 2025 K**

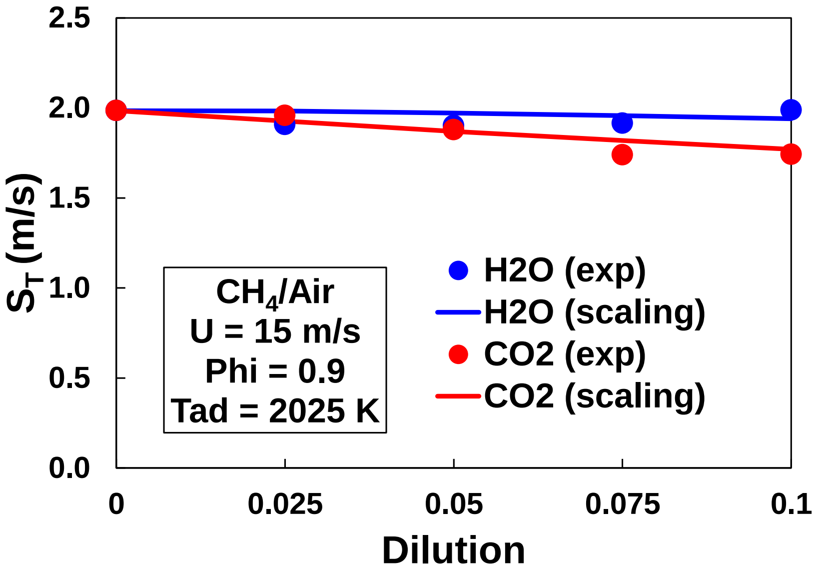


10% CO_2 Dilution
***T_{ad}* = 2025 K**

- Effects of increased dilution are much more nuanced at fixed T_{ad}

Constant T_{ad} =2025 K with Dilution

CH_4/Air, T_0 = 450 K, p = 1 atm, U = 15 m/s			
ϕ	Dilution	T_{ad} (K)	S_L (cm/s)
0.9	(N_2 only)	2025	40.9
0.9	10% H_2O	2025	40.0
0.9	10% CO_2	2025	34.6



Constant T_{ad}

- Water has almost no discernible effect
- Slight (~12%) drop in S_T for 10% CO_2

- Scaling analysis:

$$S_{T,diluted} = S_{T,standard}\left(\frac{S_{L,dil}}{S_{L,std}}\right)\left(\frac{Re_{T,dil}}{Re_{T,std}}\right)^{0.5}\left(\frac{Le_{dil}}{Le_{std}}\right)^{-0.5}$$

	Chemistry	turbulence	diffusion		Scaling	Measured
10% H_2O	↓2.1%	↑0.0%	↓0.3%	→	↓2.3%	↓~0%
10% CO_2	↓15%	↑3.9%	↑1.3%	→	↓11%	↓~12%

At the same flame temperature, chemistry plays a dominant role

Flame Surface Density

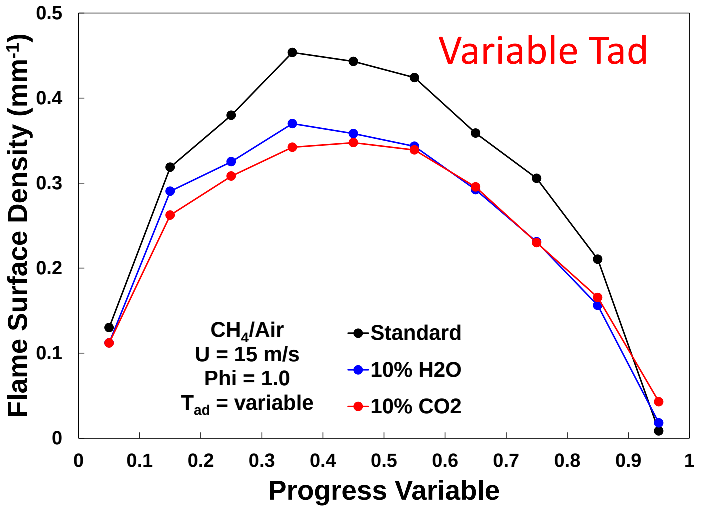
- We can also examine the turbulent flame brush as a whole through the flame surface density:

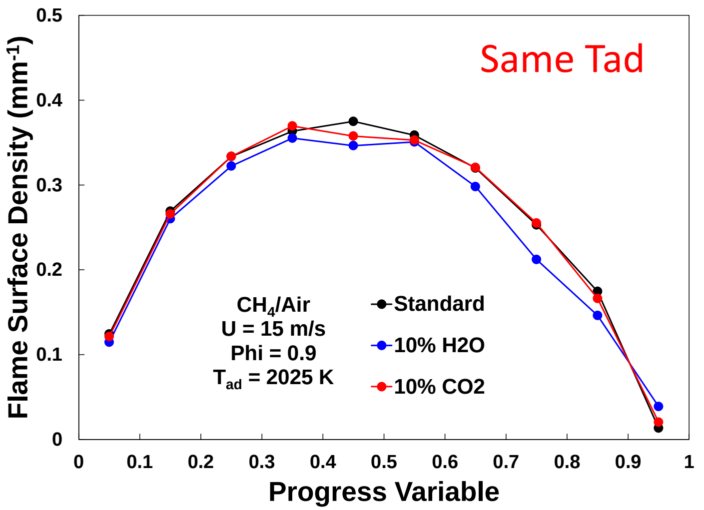
$$\Sigma(c) = \frac{1}{n}\sum_{i=1}^{n}\frac{L_i(c)}{A_i(c)}, \text{ n: num. of images}$$

- As an example, $\Sigma(c = 0.45)$ is the combined length of all the flame edges in the region between $c = 0.4$ and $c = 0.5$, divided by the area of the region and the number of images

- $\Sigma(c)$ decreases by 15-25% for variable flame temperature dilution

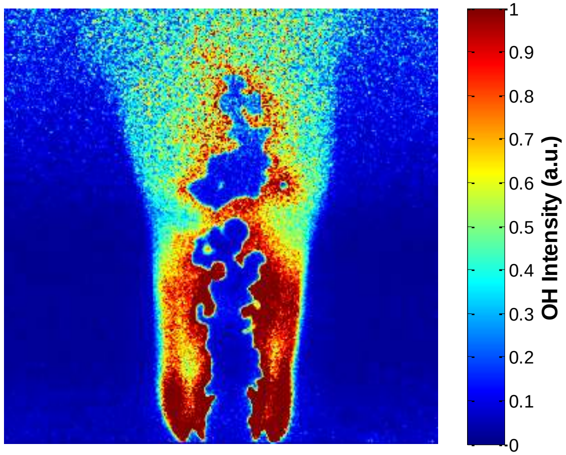
- At constant T_{ad}:
  - $\Sigma(c)$ nearly collapses for CO_2 addition due to opposing increases in flame brush size and flame wrinkling
  - Water slightly reduces $\Sigma(c)$ in the upper region of the brush ($c > 0.6$)



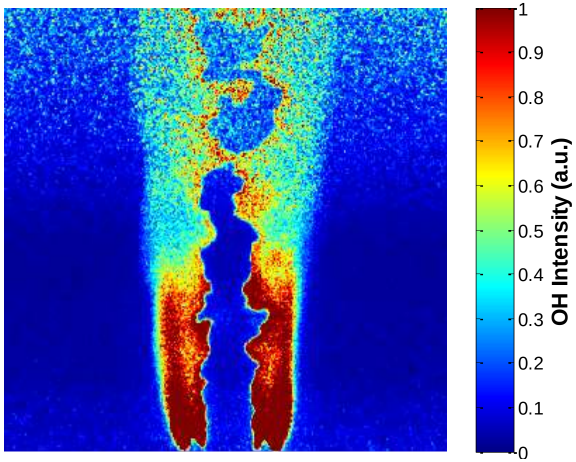


C. Cohé et al., *Proc. Combust. Inst.* 32 (2009) 1803-1810

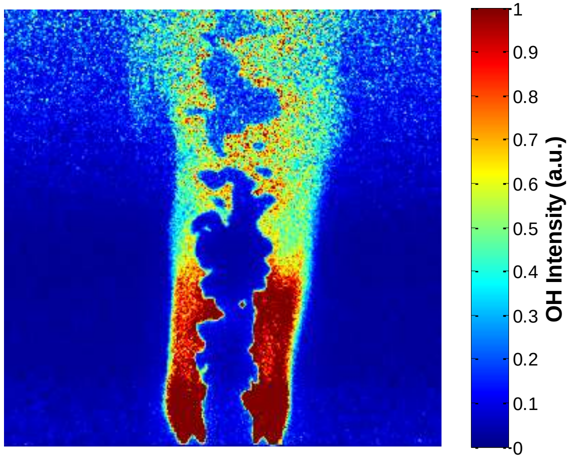
Constant Flame temperature with Dilution:
T_{ad} = 1822 K



0% Dilution
T_{ad} = 1822 K



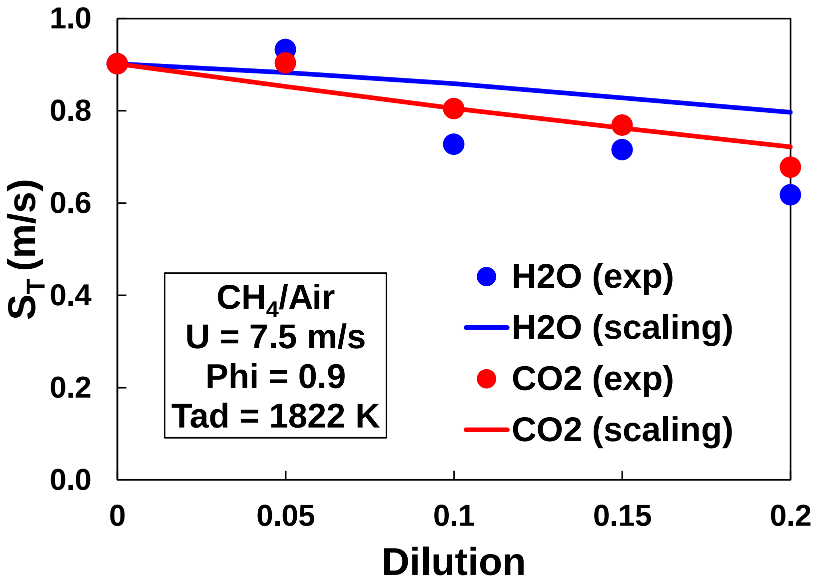
20% H_2O Dilution
T_{ad} = 1822 K



20% CO_2 Dilution
T_{ad} = 1822 K

T_{ad} = 1822 K Dilution

CH_4/Air, T_0 = 450 K, p = 1 atm			
ϕ	Dilution	T_{ad} (K)	S_L (cm/s)
0.9	(N_2 only)	1822	23.2
0.9	20% H_2O	1822	20.5
0.9	20% CO_2	1822	16.8



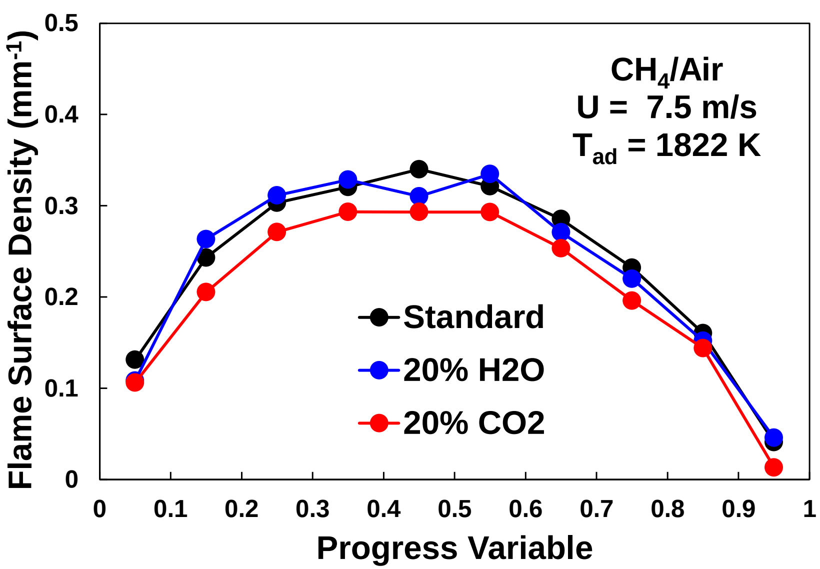
- Water dilution is impactful beyond what the scaling predicts
- Is this an actual trend caused by turbulence-chemistry interactions?

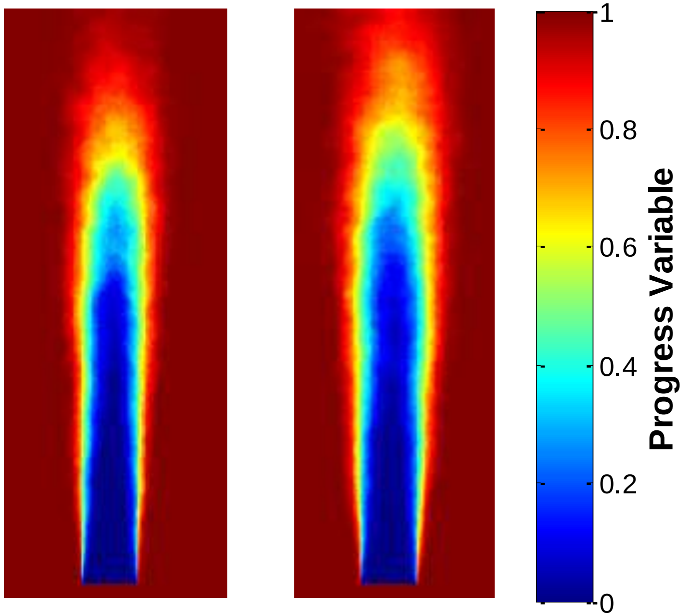
$$S_{T,diluted} = S_{T,standard}\left(\frac{S_{L,dil}}{S_{L,std}}\right)\left(\frac{Re_{T,dil}}{Re_{T,std}}\right)^{0.5}\left(\frac{Le_{dil}}{Le_{std}}\right)^{-0.5}$$

	S_L	Re_T	Le		Scaling	Measured
20% H_2O	↓12%	↑0.1%	↓0.2%	→	↓12%	↓~29%
20% CO_2	↓27%	↑7.2%	↑2.7%	→	↓20%	↓~25%

T_{ad} = 1822 K Dilution

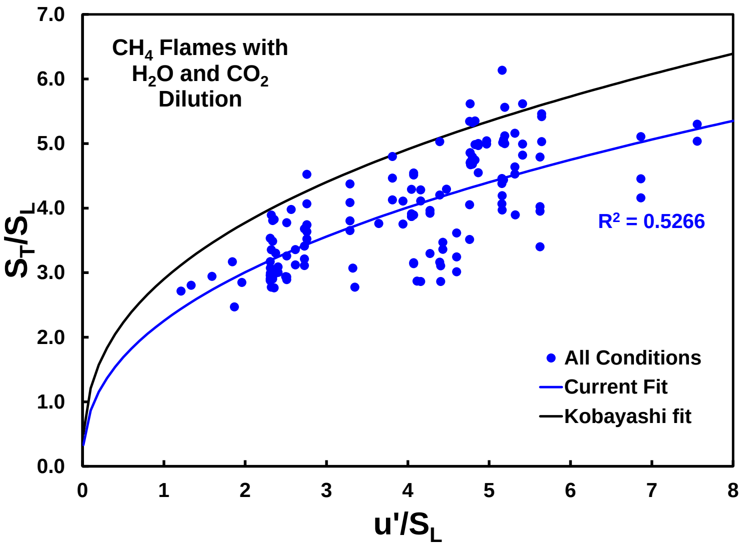
- At 20% dilution, CO_2 and H_2O produced similar S_T values (approximately 25% lower than the undiluted case)
- However, the CO_2 flame surface density is noticeably less
- This is primarily due to differences in the area between *c* contours (larger for CO_2) rather than differences in flame wrinkling





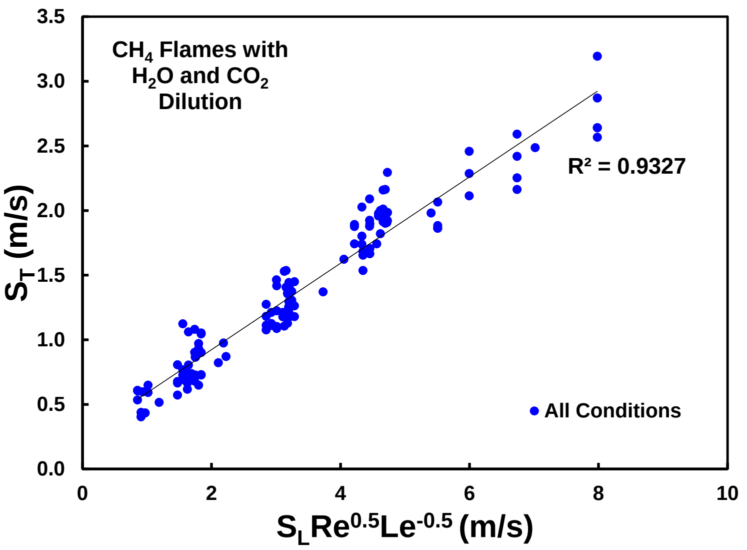
20% H_2O 20% CO_2

Scaling of S_T for All Conditions



- Power fit to current data: $S_T/S_L = 2.3(u'/S_L)^{0.42}$
- Kobayashi fit for CH_4: $S_T/S_L = 2.9(u'/S_L)^{0.38}$

H. Kobayashi, *Exp. Therm. Fluid Sci.* 26 (2002) 375-387

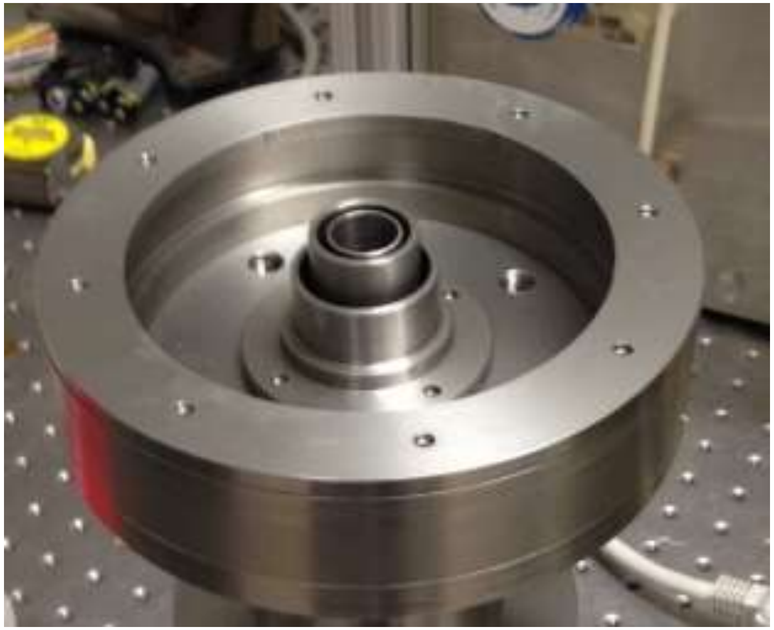


$$S_{T,diluted} = S_{T,standard}\left(\frac{S_{L,dil}}{S_{L,std}}\right)\left(\frac{Re_{T,dil}}{Re_{T,std}}\right)^{0.5}\left(\frac{Le_{dil}}{Le_{std}}\right)^{-0.5}$$

3. A new design of Axisymmetric Reactor-Assisted Turbulent (ARAT) Burner for Turbulent Flame Studies at Higher Reynolds Numbers and with EGR Effects

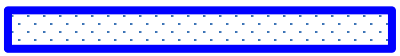
Co-flow Axisymmetric Reactor-Assisted Turbulent (CARAT) Burner

- 15 mm central jet diameter (CH_4/Air)
- Inner pilot flame (have tested CH_4/Air)
- Outer vitiated co-flow (15cm in diameter, tested for CH_4/Air and H_2/Air)



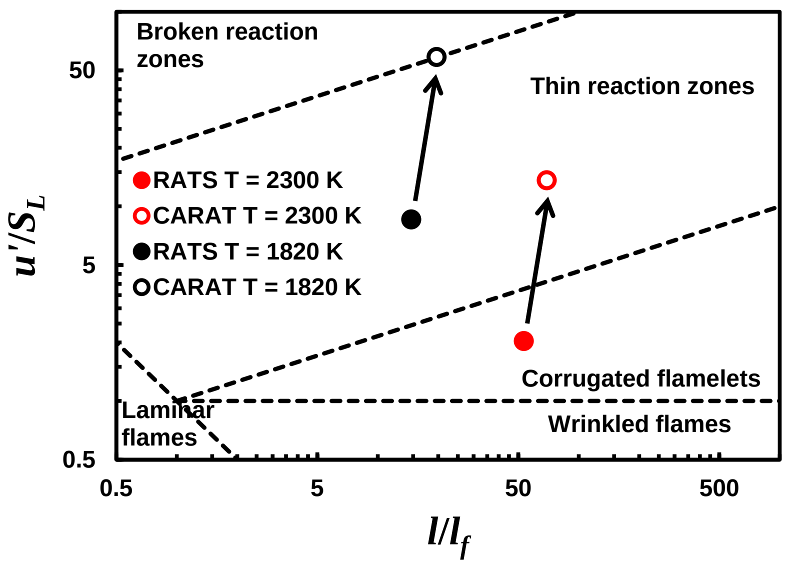
ARAT vs RATS

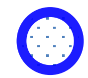
For same flow rates (450 LPM air, 47 LPM CH_4, $\phi = 1.0$, $T_{exit} = 300$ K)



RATS (100 mm by 10 mm)

- $U = 8.3$ m/s
- $Re_{bulk} = 9500$
- $Re_T = 172$
- $T_{env.}$=300 K





ARAT (15 mm diameter)

- $U = 47.0$ m/s
- $Re_{bulk} = 44000$
- $Re_T \approx 1758$
- T_{coflow}=up to1900 K

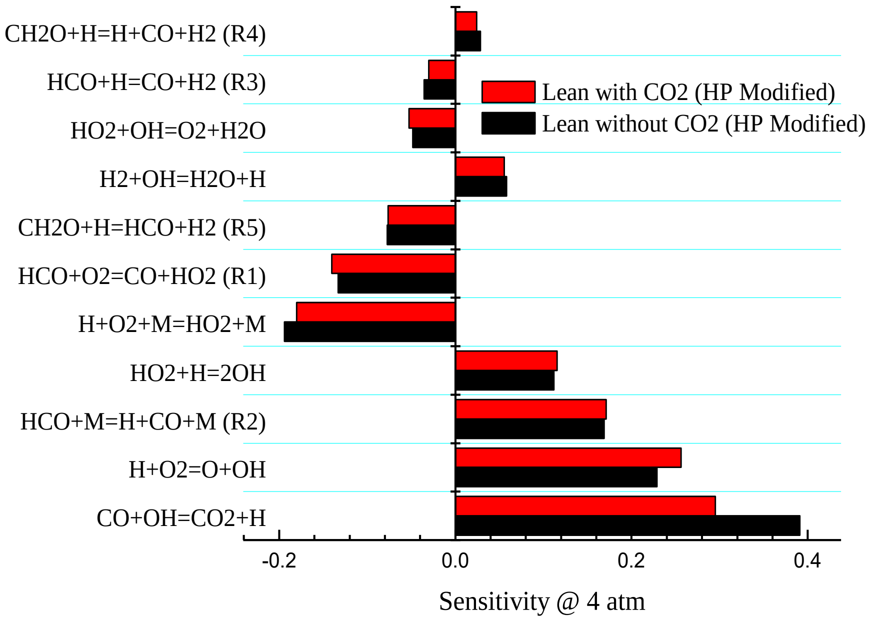
- High higher turbulent intensity
- More turbulent flame regimes accessib
- Capable of more extreme conditions w EGR effects due to vitiated co-flow

Conclusions

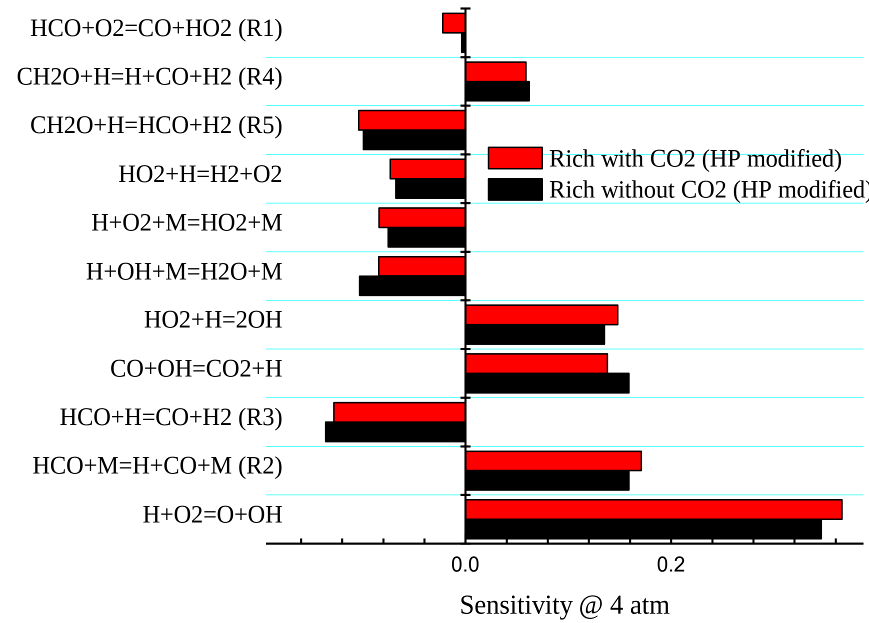
- The high pressure flame speeds of CH_2O flames are measured for the first time.
- HCO prompt reaction affects the burning velocity and radical pool of flames. The updated HP-Mech improved the flame speed prediction.
- CO_2 dilution strongly affects the radical production via HCO(+M) =H+CO(+M) reaction. Existing models are not able to predict the high pressure flame speeds on CH_2O flames with CO_2 dilution.
- In addition to the thermal effect of H_2O/CO_2 dilution, the chemistry effects also significantly reduce the turbulent flame speeds of CH_4/air flames.
- The lower the flame temperature, the higher the kinetic effects of H_2O/CO_2 dilution on flame speeds.
- At lower flame temperature, the kinetic effect H_2O is increased and comparable to that of CO_2.

Reaction sensitivities with CO_2 dilution

Fuel lean Φ=0.7, 20% CO_2

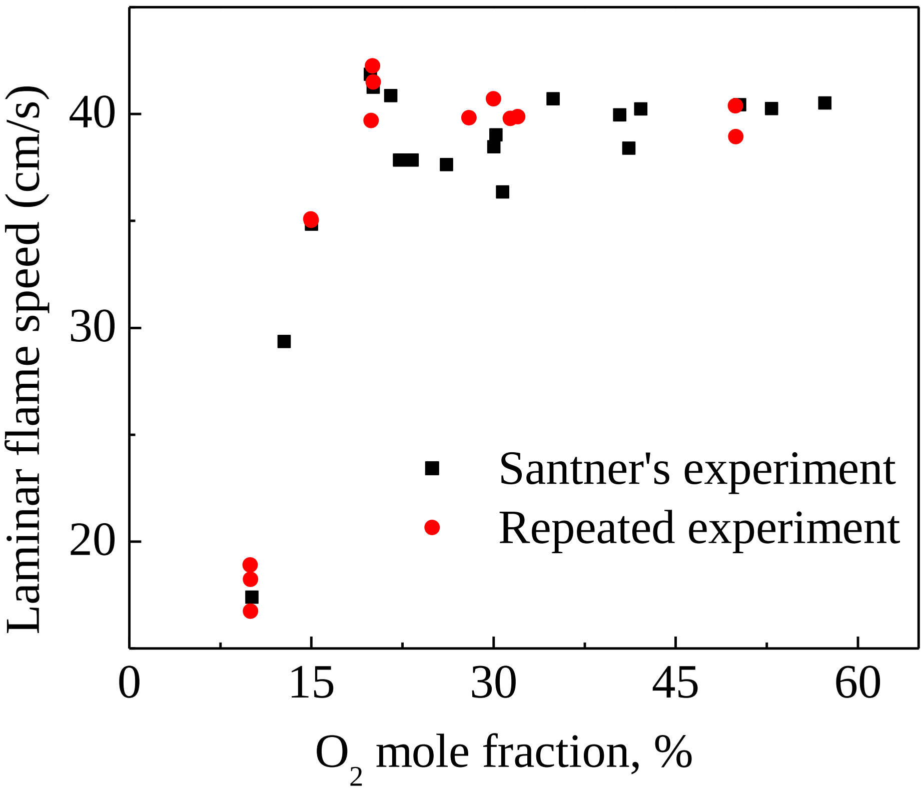


Fuel Rich Φ=1.4, 20% CO_2



- Sensitivity of HCO+M=CO+H+M increases in fuel rich conditions with CO_2
- Sensitivity of $H+O_2+M=HO_2+M$ and $CO+OH=CO_2+H$ decrease in fuel rich conditions with CO_2
- Suggesting that collisional energy transfer in HCO+M=CO+H+M may not be well characterized for CO_2

Validation of previous experiments at 1atm



- **The new experiments have reduced uncertainty due to high speed imaging improvement**

J. Santner, F.L. Dryer, Y. Ju, Proc. Combust. Inst. 34 (2013) 719–726.

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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Aerospace Engineering
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DOE Award No. DE-FE0011822

National Energy Technology Laboratory
University Turbine Systems Research Program

2016 UTSR Workshop, Blacksburg, VA November 1-3, 2016

Outline of the Presentation

- Yiguang Ju - Chemical kinetics with EGR effects, Reactor Assisted Turbulent Slot (RATS) burner studies at atmospheric pressure
- Bob Lucht and Jay Gore: Premixed Axisymmetric Reactor Assisted Turbulent (PARAT) burner, CARS, OH PLIF, and PIV Measurements
- Michael Mueller – Advanced numerical modeling of the RATS and PARAT burners

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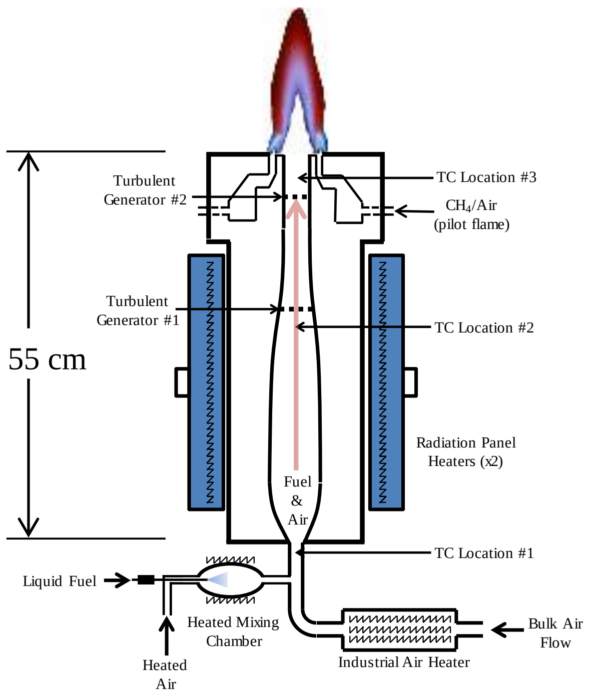
- **PhD student Dong Han, postdoctoral research associate Aman Satija**
- **Jupyoung Kim for help with PIV measurements, Hasti Veeraraghava Ragu for help with PARAT burner development**
- **DOE Program Manager Mark Freeman**

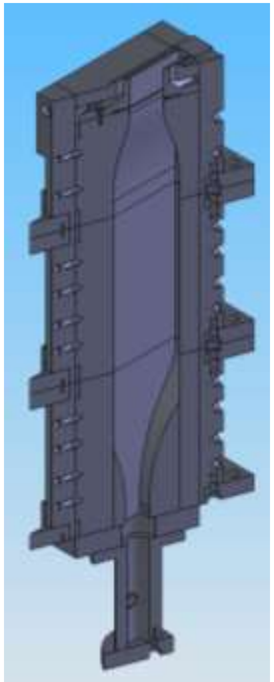
Atmospheric Pressure PARAT Burner Studies

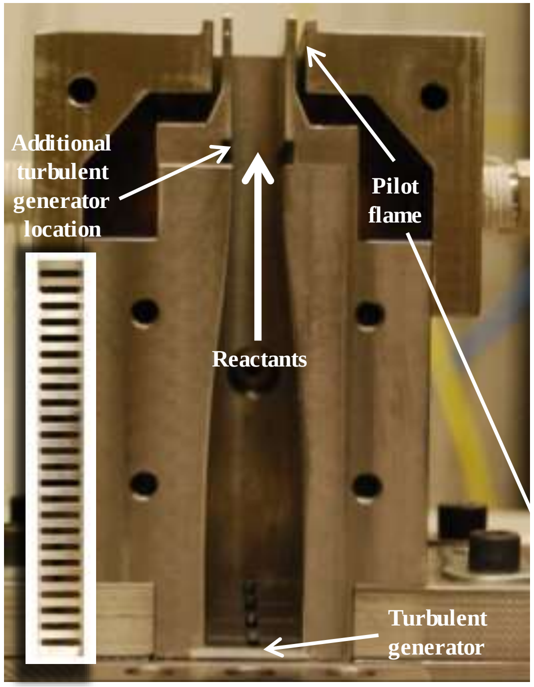
- Measurements performed in CH_4/air/CO_2 flames with same adiabatic flame temperature and Re=10,000, but different levels of CO_2 addition, flames 1, 2, and 3 had 0%, 5%, and 10% CO_2 addition
- Equivalence ratio adjusted to maintain same adiabatic flame temperature
- Dual-pump CARS measurements of temperature, O_2, and CO_2 performed to characterize flame structure
- High-speed (4 kHz) OH PLIF was performed to characterize the flame structure
- Stereo PIV was performed to characterize boundary conditions for advanced numerical simulations

Experiment, RATS Burner

- **Reactor Assisted Turbulent Slot burner (RATS burner)[1]**
  - Heat large flow rates (1000 LPM) up to 700 K with $CO_2/H_2O/N_2$ dilutions
  - ~ 55 cm heated length, 100 × 10 mm exit cross-section ($D_H \approx 18$ mm)
  - Two turbulence generators[2,3], homogeneous isotropic turbulence confirmed by hot-wire anemometry
  - High Reynolds number ($Re_{bulk} > 10{,}000$)





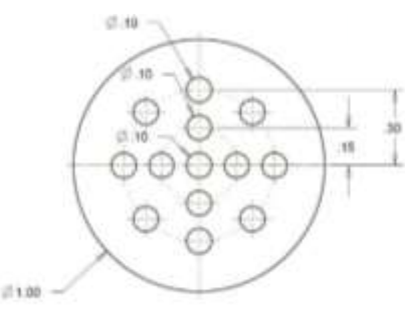


[1] S. H. Won, B. Windom et al, Combust. Flame 161 (2014) 475-483.
[2] Coppola, G., and Gomez, A., *Experimental Thermal and Fluid Science*, Vol. 33, 2009, pp. 1037-1048.
[3] Venkateswaran, P. *et. al., Combustion and Flame., 158, 2011, 1602-1614*

PARAT Burner

Piloted axisymmetric reactor assisted turbulent (PARAT) burner

- High pressure <20 bar
- High temperature < 800 K
- Mixing with bluff body
- Reduced boundary layer
- D=18mm



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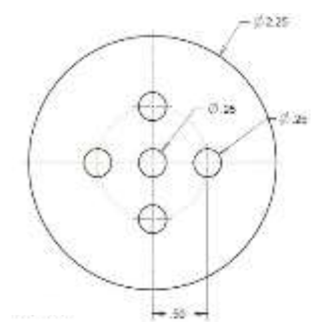

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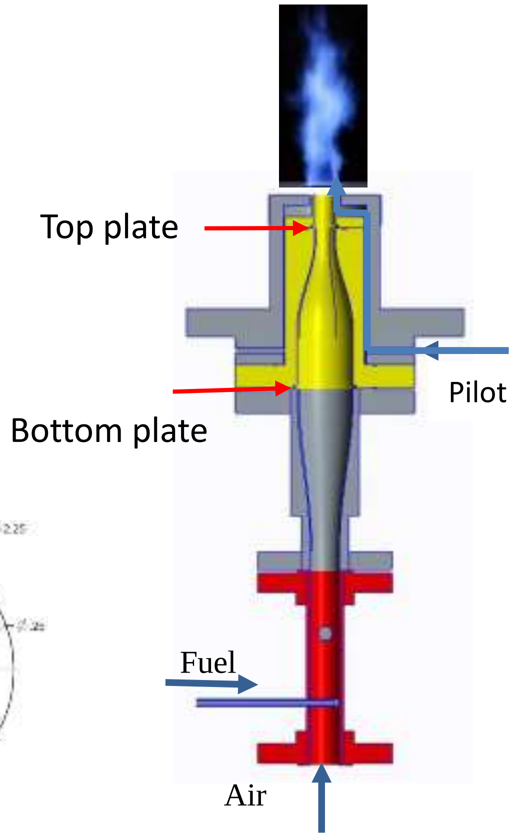


PARAT Burner

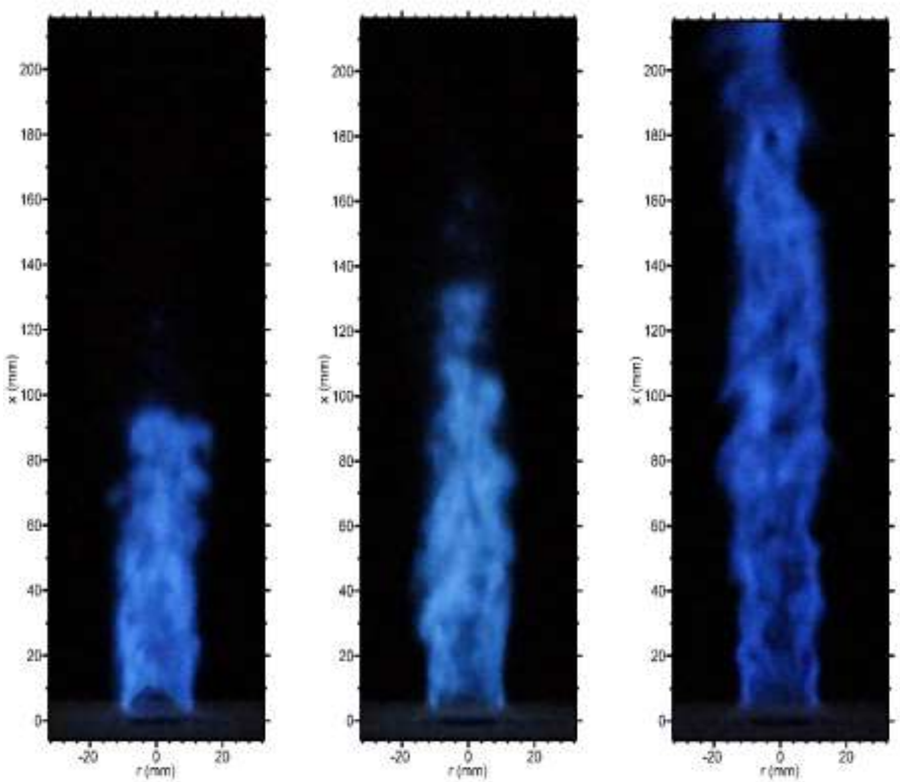
H_2 piloted CH_4/air flame specification

Flame #	1	2	3
Reynolds number	10000 ± 50		
Equivalence ratio	0.80 ± 0.02	0.84 ± 0.02	0.89 ± 0.02
CO_2 % by total mass	0.0	10.0 ± 0.1	20.0 ± 0.1

- **CO_2 addition increases the visible flame length**
- **More local extinctions are observed with increasing of CO_2 additions**

Visible Images at 0.5 ms exposure time

CO_2: 0% 10% 20%



PARAT Burner

H_2 piloted CH_4/air Flame specification

Flame #	1	2	3
Reynolds number		10000 ± 50	
Adiabatic Temperature(K)		2030 ± 50	
Equivalence ratio	0.80 ± 0.02	0.84 ± 0.02	0.89 ± 0.02
CO_2 % by total mass	0.0	5.0 ± 0.1	10.0 ± 0.1
Lewis number	0.99	0.98	0.97
Laminar flame speed (cm/s)	33.7	29.7	24.9

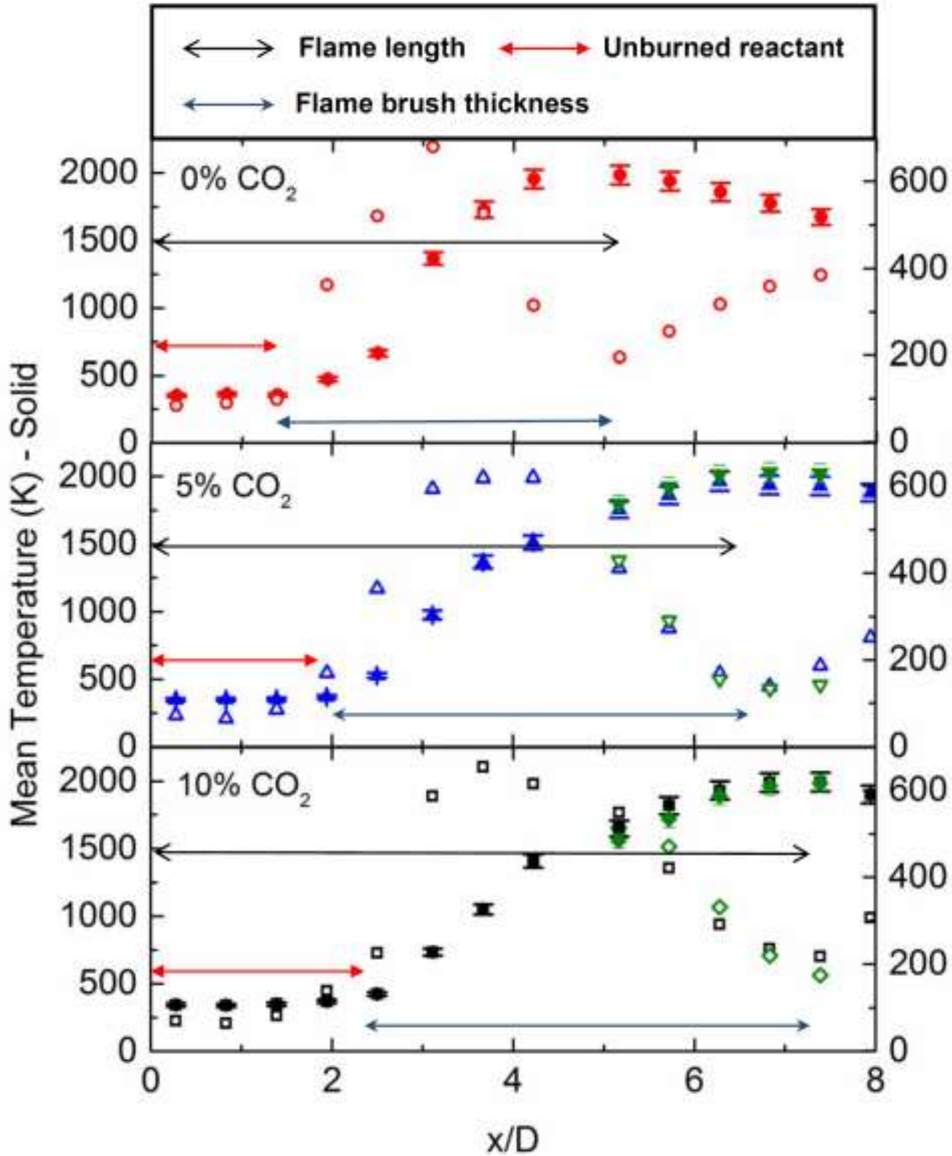
Flames are designed to minimize thermal and transport effects on NO formation

PARAT Burner: Centerline Temperature Profiles

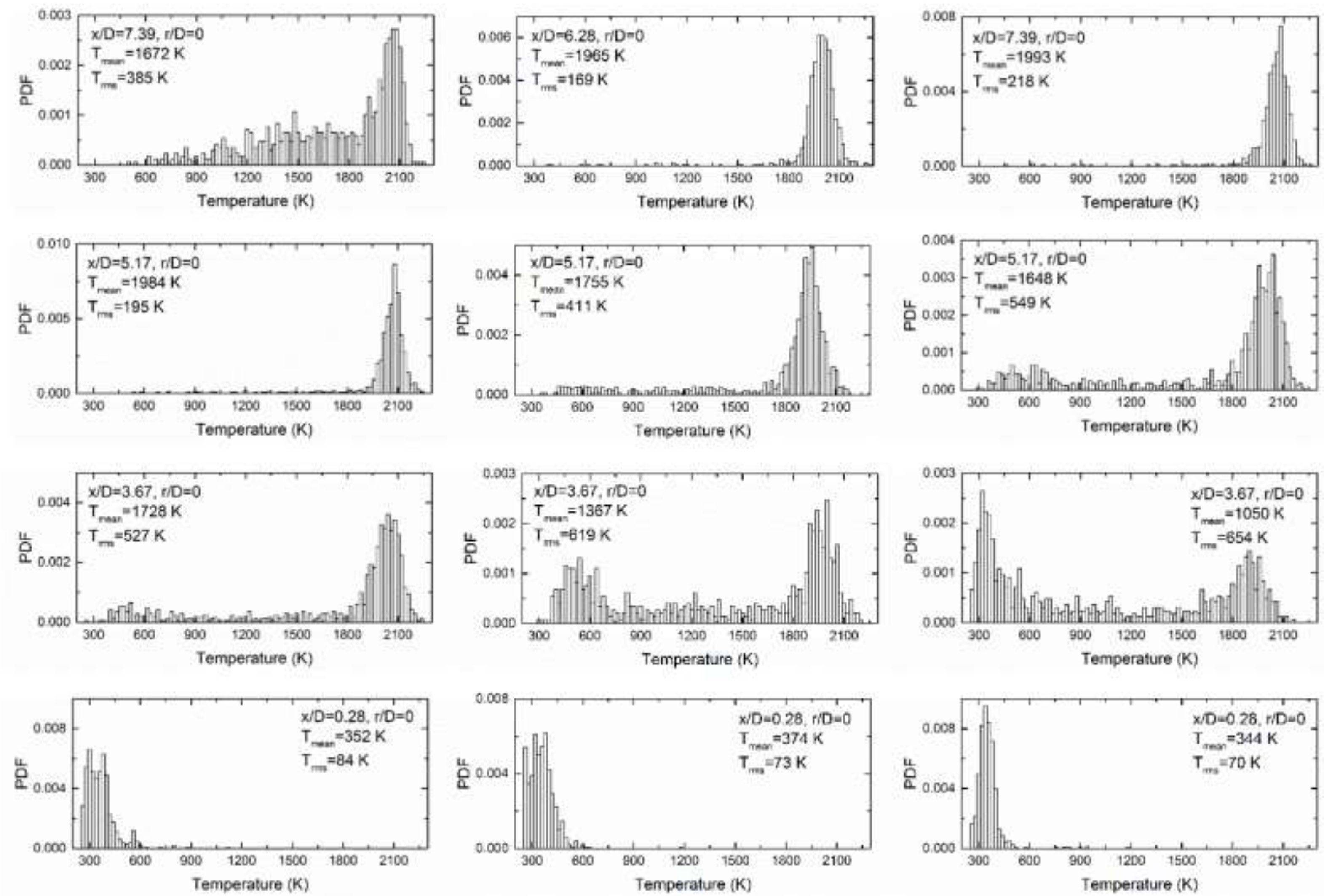
Flame #	Flame length x/D*	Unburned reactant length x/D	Flame brush thickness Δx/D**
1	5.17	1.39	3.78
2	6.28	1.39	4.89
3	7.39	1.39	6

*Flame length is defined as the distance from burner exit to the location $\bar{C} = 0.99$
$\bar{C}$ is the mean progress variable

**Flame brush thickness is defined as the width from leading edge $\bar{C} = 0.01$ to trailing edge $\bar{C} = 0.99$



PARAT Burner: Centerline Temperature Histograms



x/D=7.39

x/=5.17

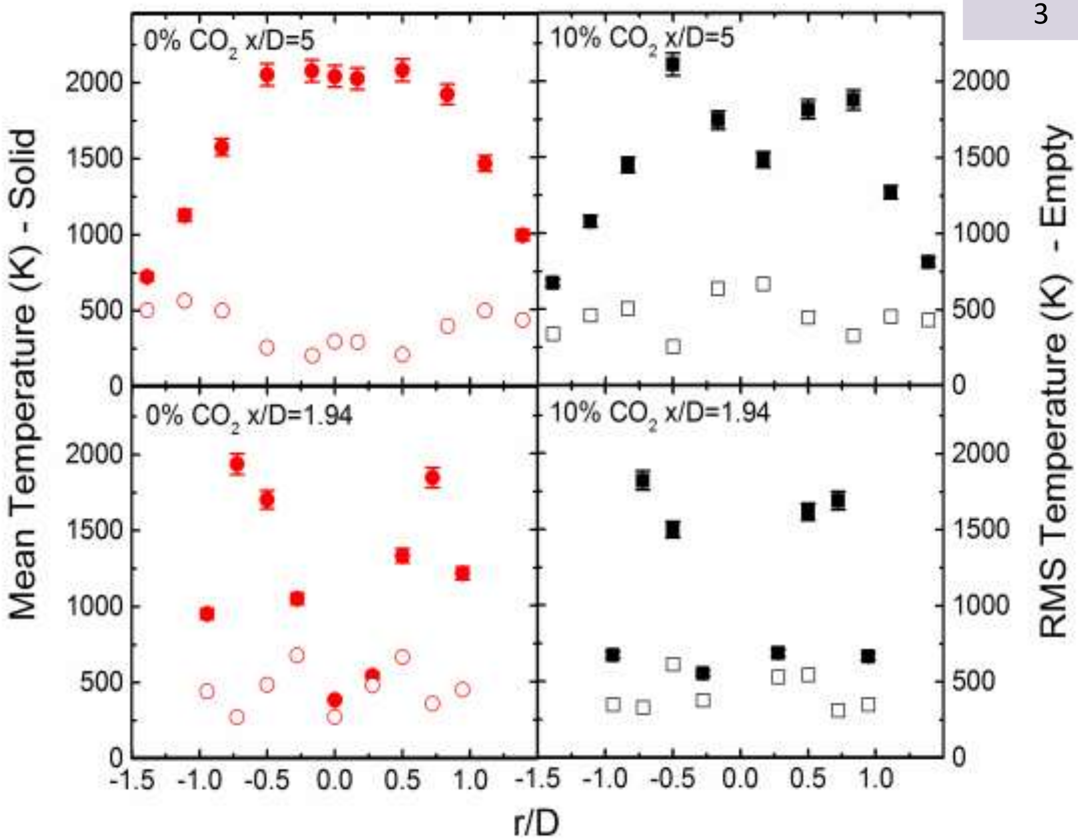
x/D=3.67

x/D=0.28

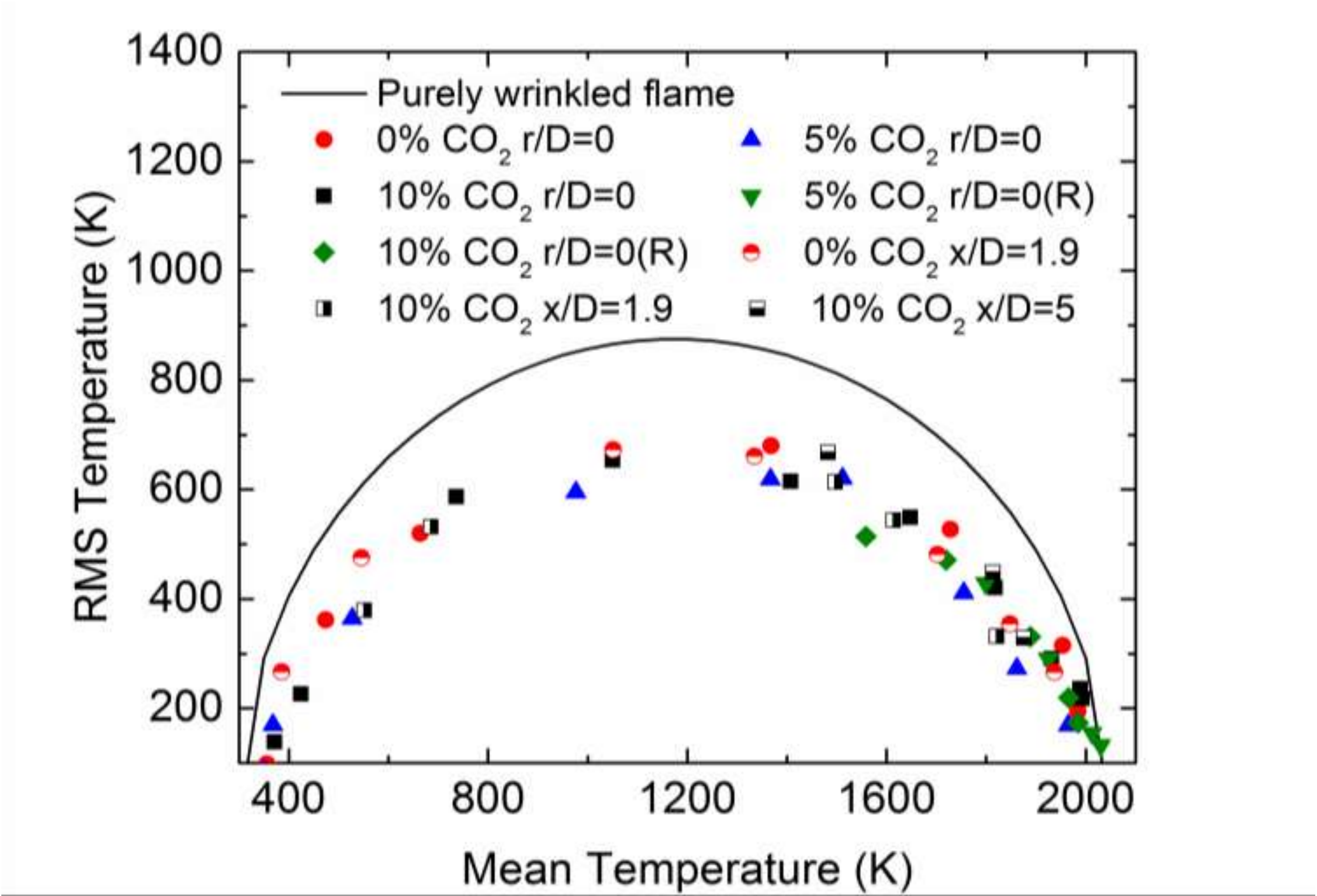
Flame 1 (0% CO_2) Flame 2 (5% CO_2) Flame 3 (10% CO_2)

PARAT Burner: Radial Temperature Profiles

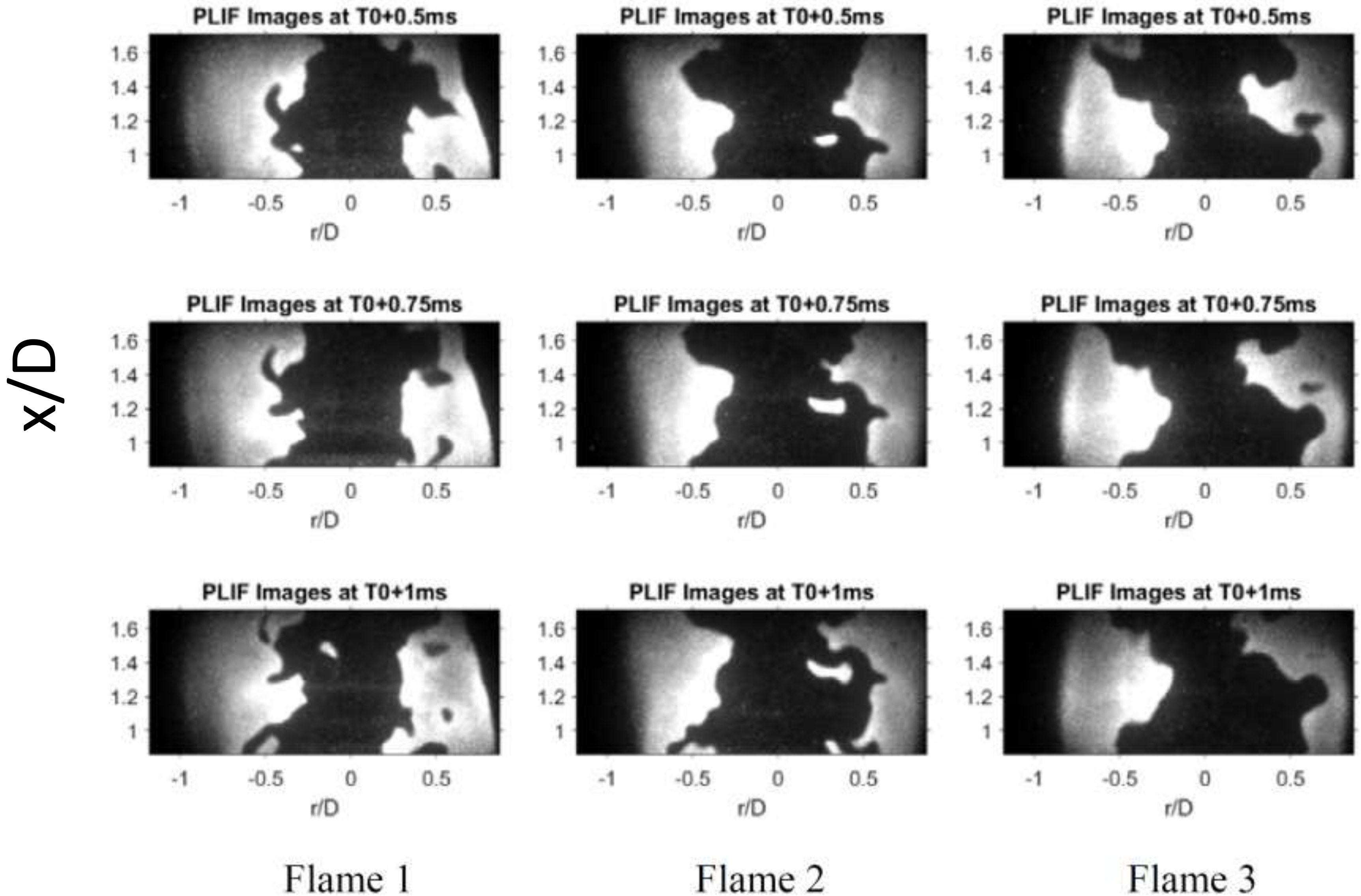
Flame #	Flame length x/D*	Unburned reactant length x/D	Flame brush thickness Δx/D**
1	5.17	1.39	3.78
2	6.28	1.39	4.89
3	7.39	1.39	6



PARAT Burner: Comparison with Wrinkled Flame Theory

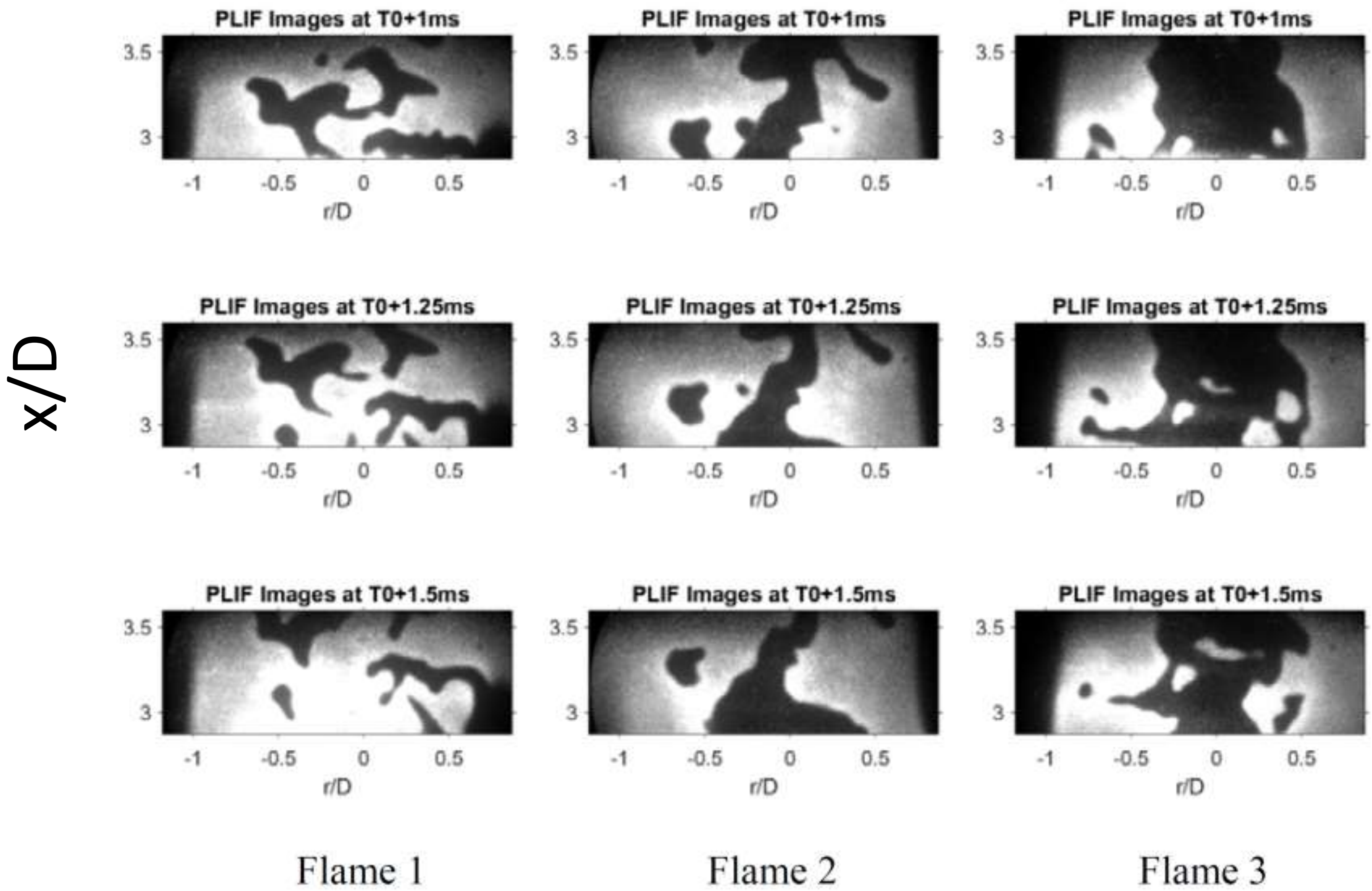


PARAT Burner: 4 kHz OH PLIF Measurements



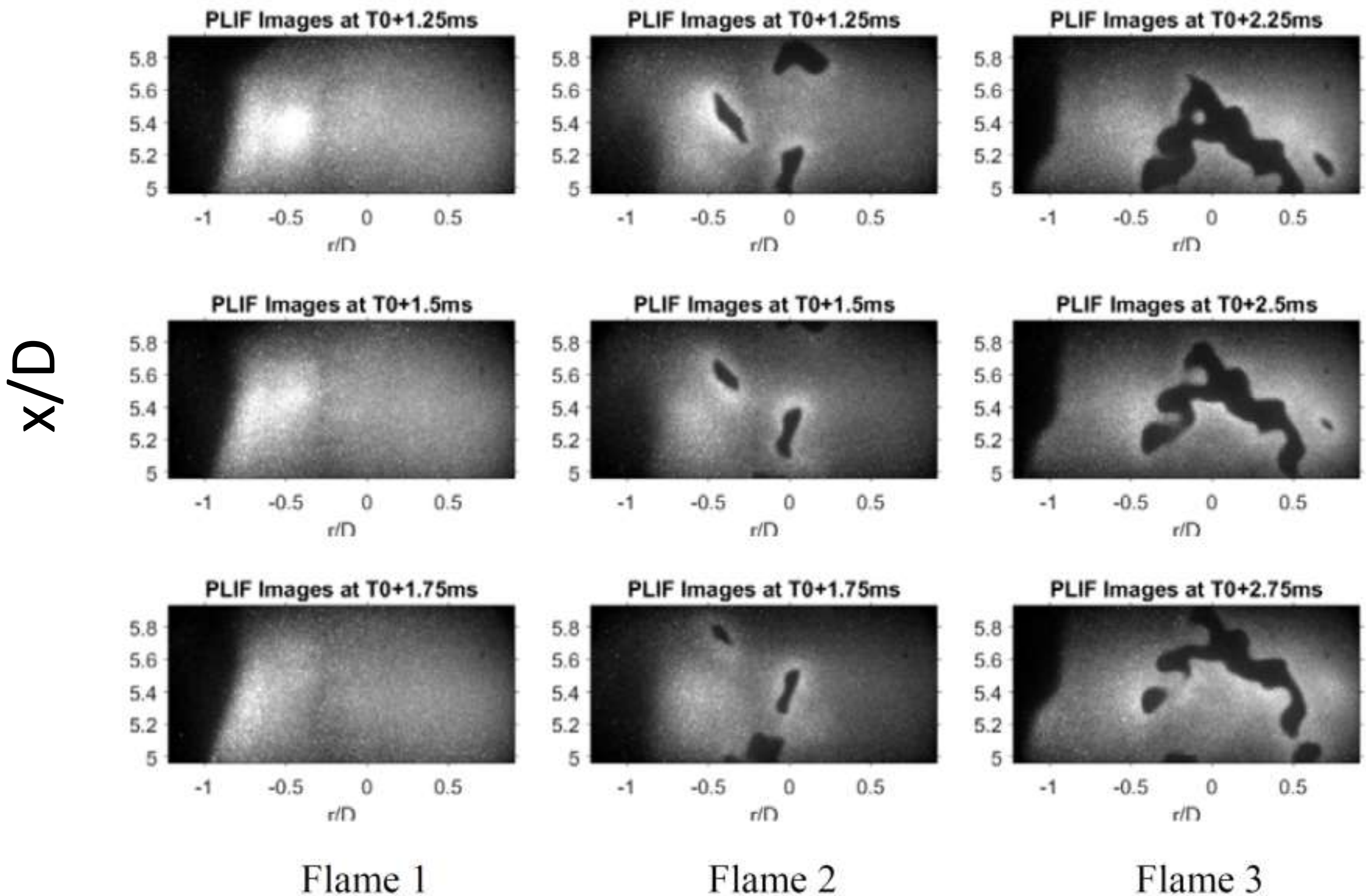
x/D = 0.8 to 1.7

PARAT Burner: 4 kHz OH PLIF Measurements



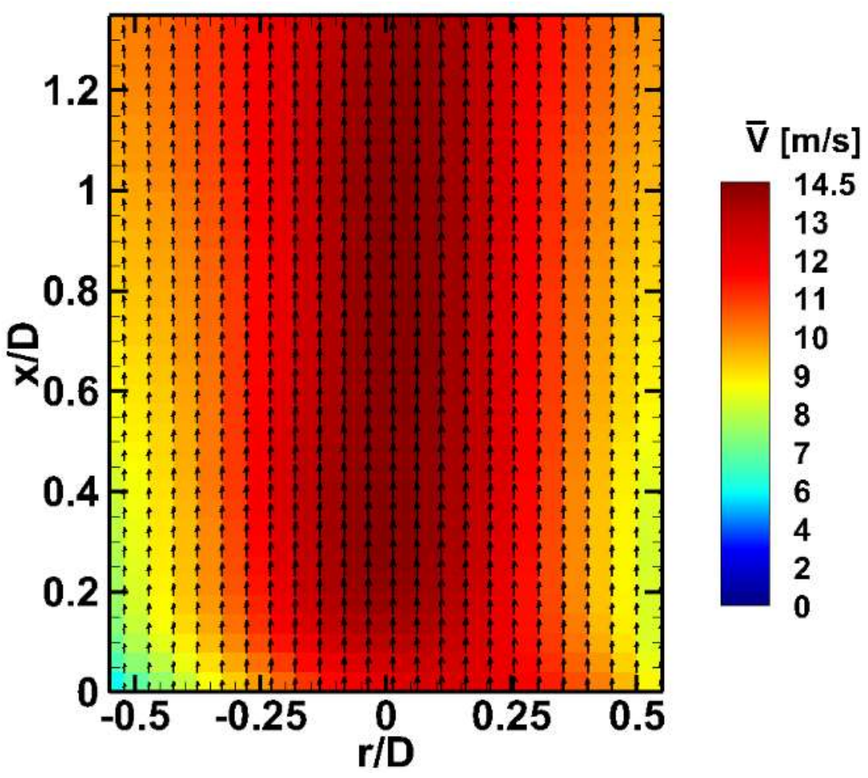
x/D = 2.9 to 3.6

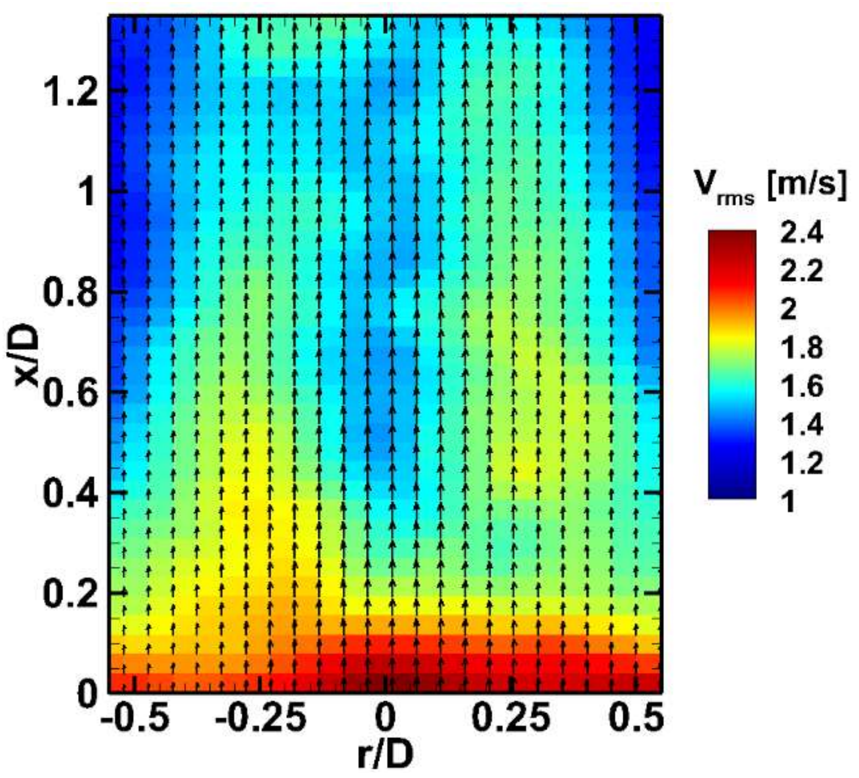
PARAT Burner: 4 kHz OH PLIF Measurements



x/D = 4.9 to 5.9

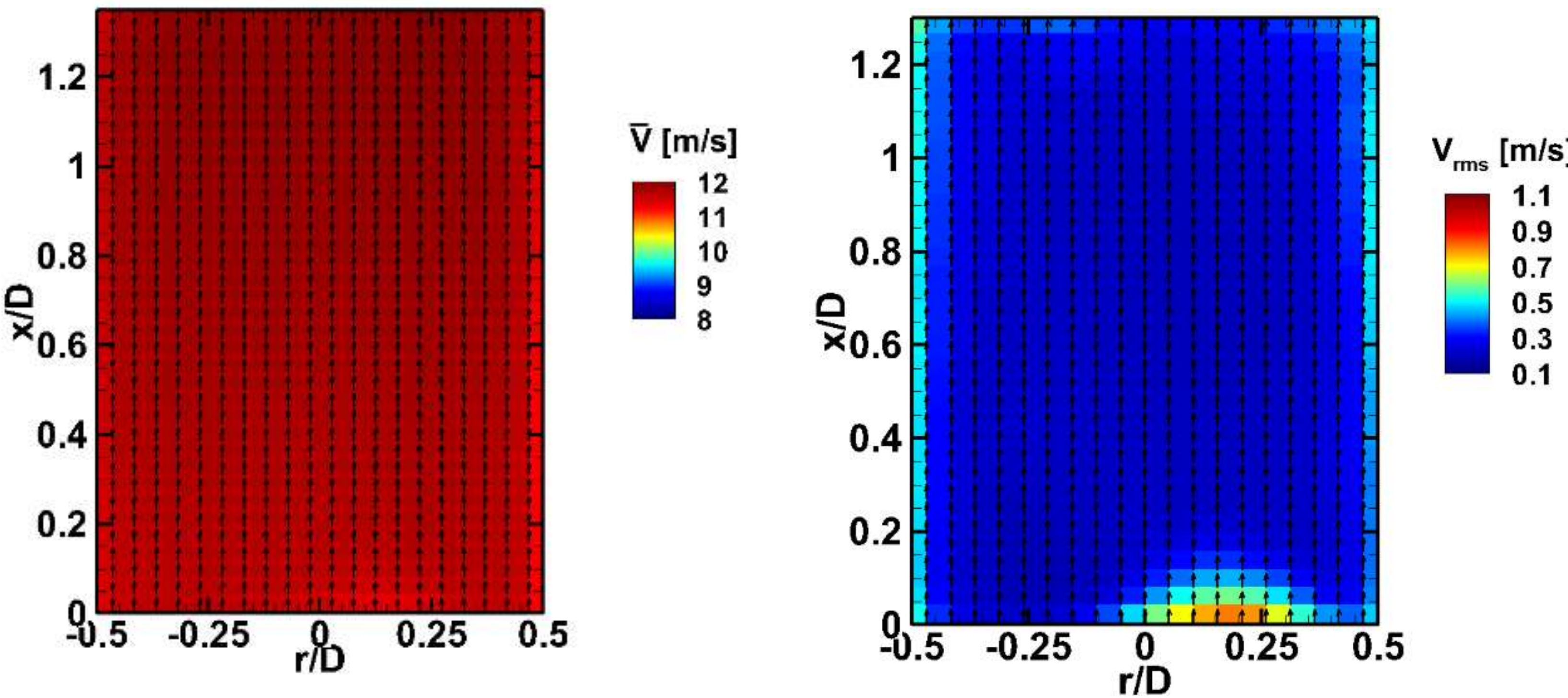
PARAT Burner: PIV Measurements, Flame 1





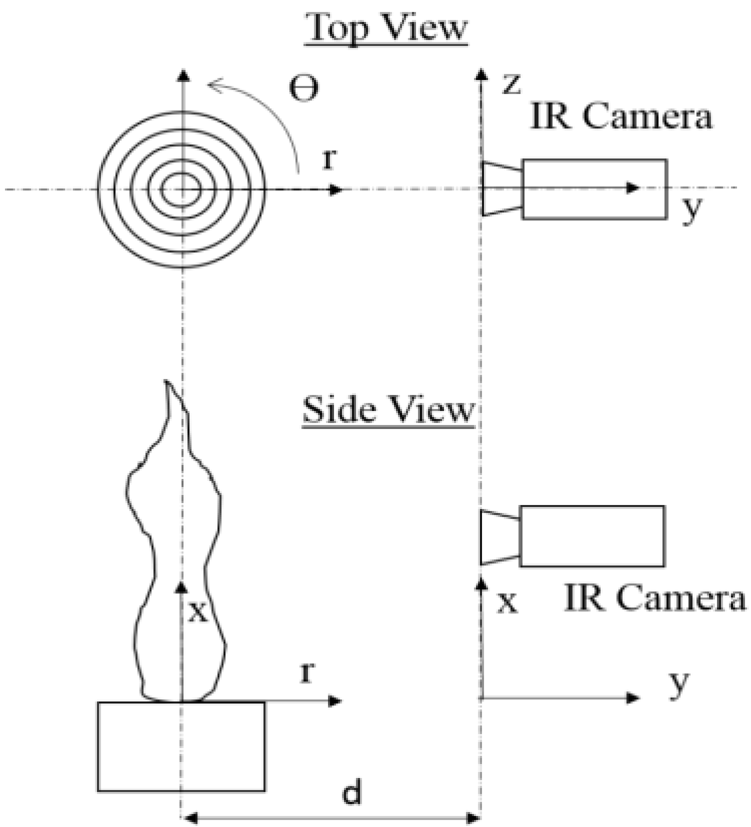
With upper turbulence generator plate

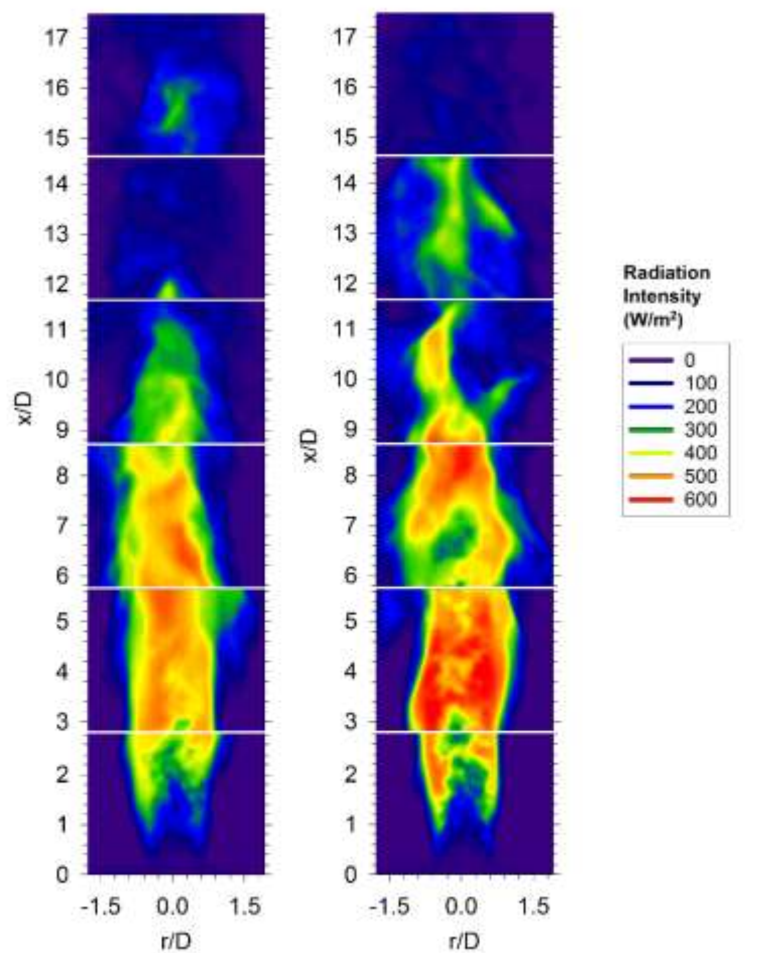
PARAT Burner: PIV Measurements, Flame 1



Without upper turbulence generator plate

PARAT Burner: IR Imaging Measurements

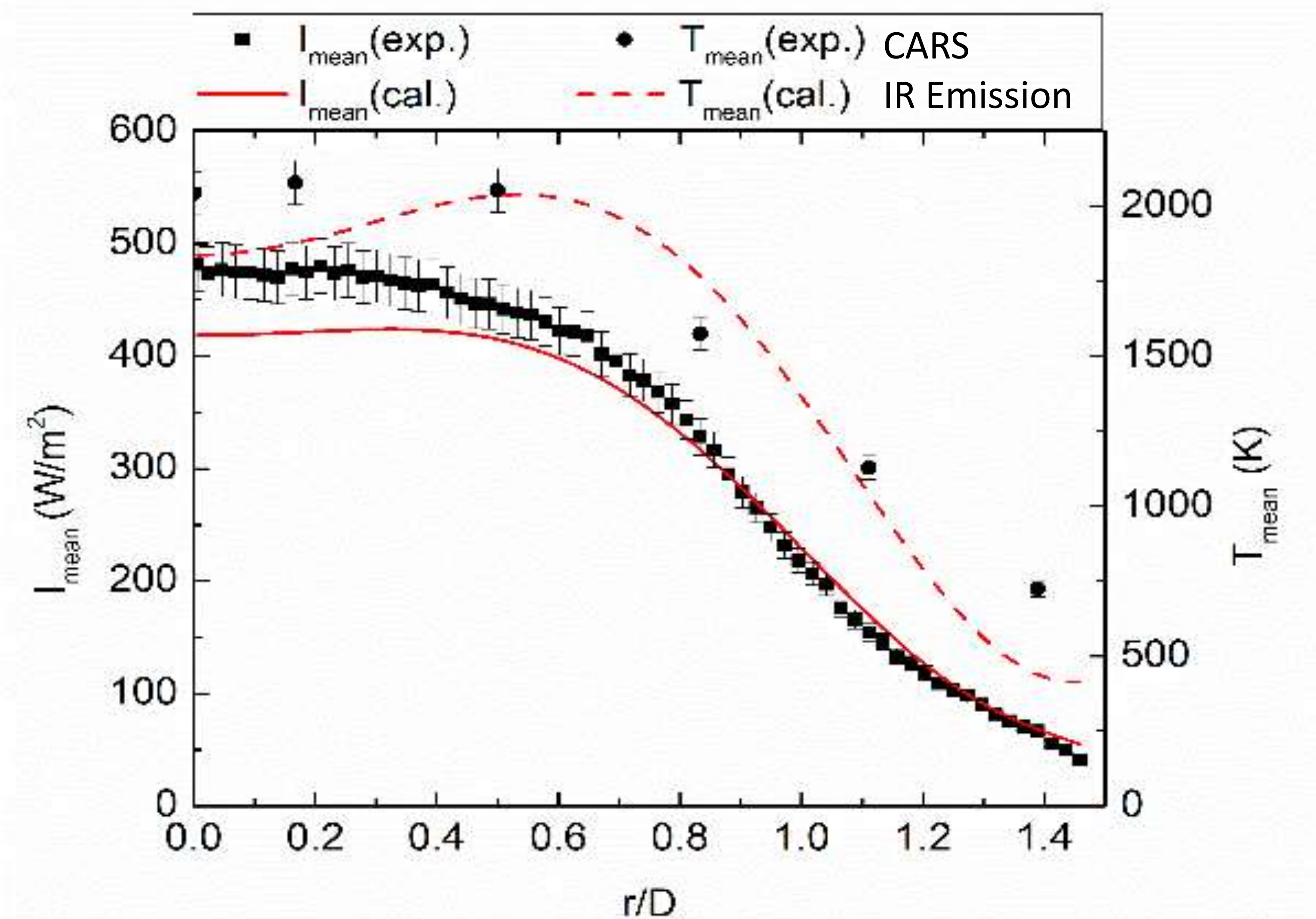




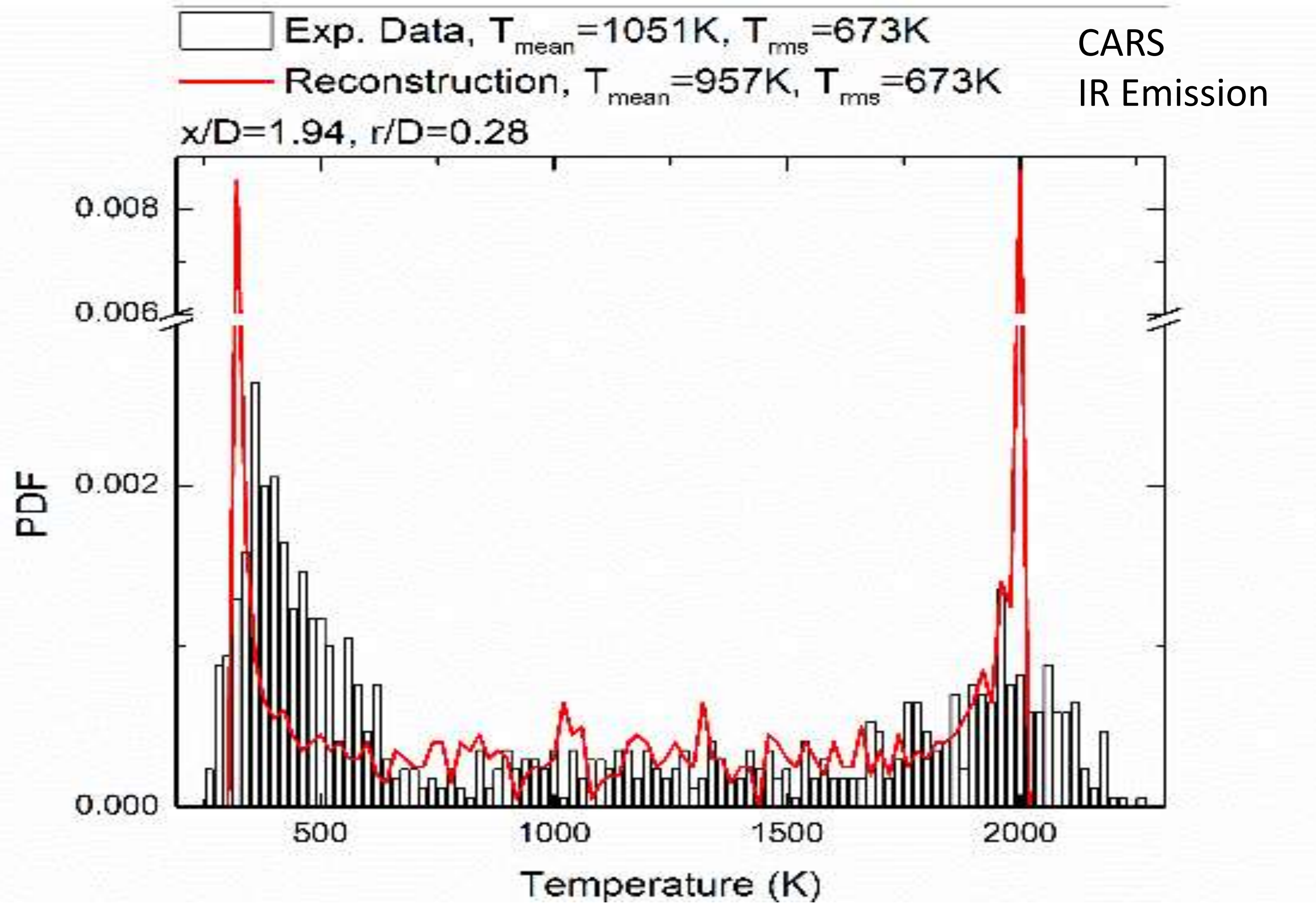
0% CO2 10% CO2

4.38 ± 0.08 µm spectral region

PARAT Burner: Comparison of Temperature Profiles from CARS and IR Emission Measurements



PARAT Burner: Comparison of Temperature Profiles from CARS and IR Emission Measurements



PARAT Burner Studies: Conclusions

- Dual-pump CARS temperature measurements reveal significant differences in structure for flames 1, 2, and 3 ,even though the measured peak mean temperatures are virtually the same for all three flames. Bimodal structure of histograms clearly evident in the inner flame.

- OH PLIF imaging reveals major differences in flame structure for flames 1, 2, and 3. As the percentage of added CO_2 increases, the occurrence of isolated pockets of unreacted premixed gas in the flame brush increases, as does the apparent size of these gas pockets.

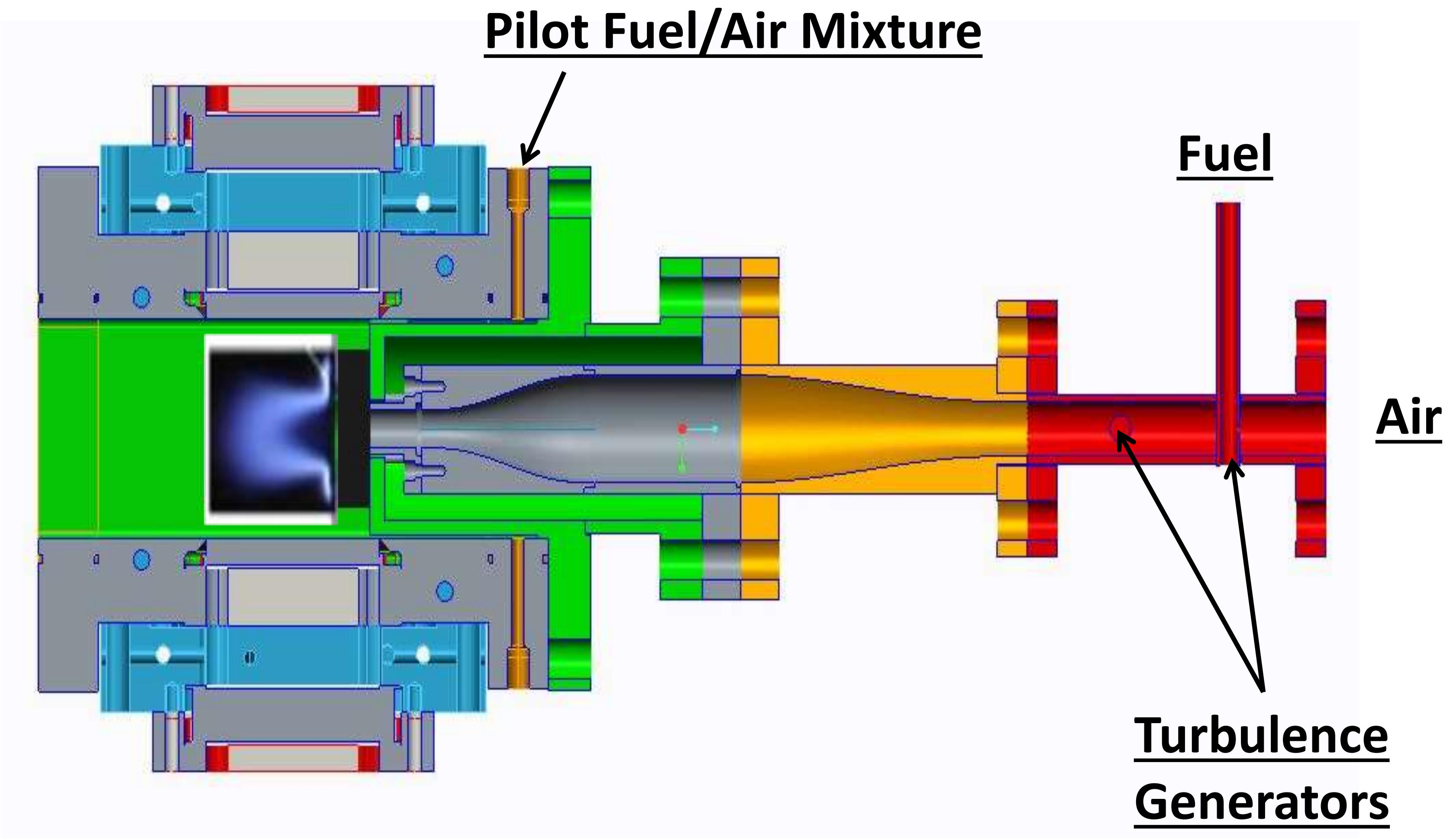
- Stereo PIV was performed to characterize boundary conditions for advanced numerical simulations, analysis still in progress.

- Comparison of CARS and IR imaging show consistent temperatures for all three flames.

PARAT Burner Studies
Future Work

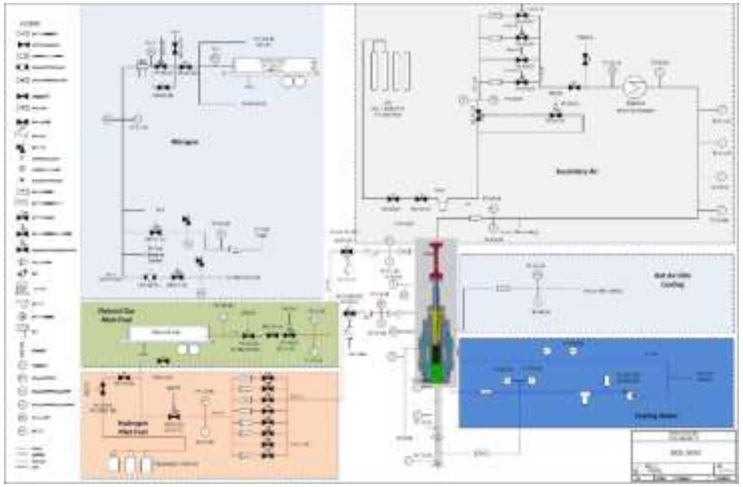
- High speed CH PLIF, simultaneous OH and CH PLIF
- Continued interaction with Princeton on numerical modeling of the PARAT burner
- Operation of the PARAT burner at high pressure, initial experiments were performed at high pressure last year
- NOx, CO emission measurements from the high-pressure for comparison with numerical modeling

Cross-sectional View of PARAT Burner into the Windowed High-Pressure Test Rig

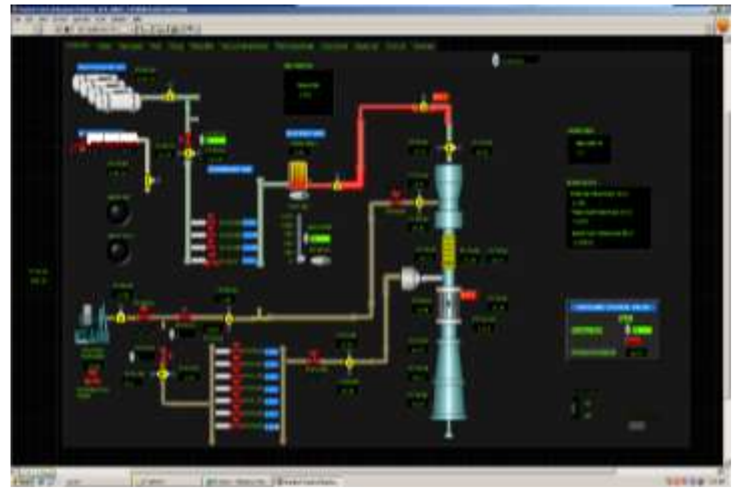


PARAT Burner Operation in HP Test Rig

P & ID



Control panel



H_2 pilot flame

Natural gas flame, Re=100,000, ψ=0.9