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

Robert P. Lucht, Jay. P Gore, Yiguang Ju and Michael Mueller

Maurice J. Zucrow Laboratories
School of Mechanical Engineering
Purdue University
West Lafayette, IN

Dept. of Mechanical and
Aerospace Engineering
Princeton University
Princeton, NJ

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Contents of the Proposal

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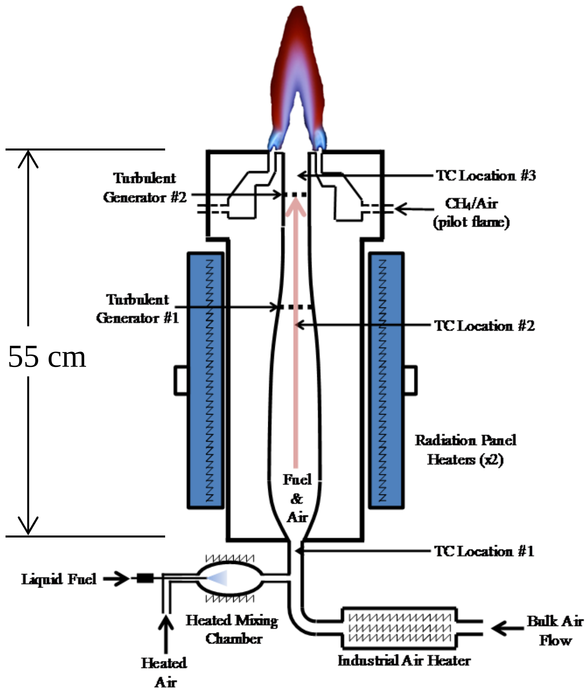
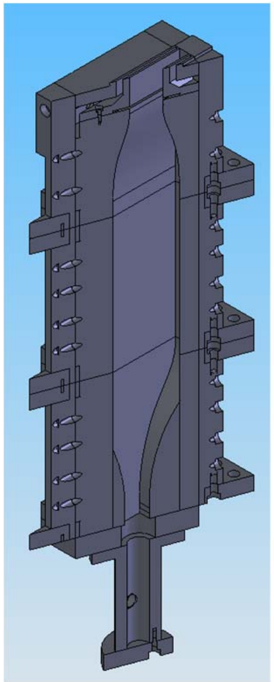
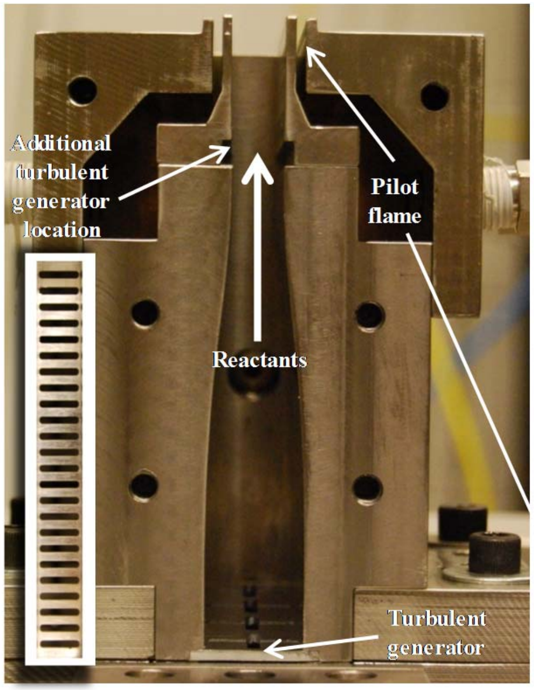
EGR Effects on Turbulent Flame Structure in RATS Burner

- **Reactor Assisted Turbulent Slot burner (RATS burner)[1]**
  - Heat air flows up to 1000 LPM up to 700 K
  - ~ 55 cm heated length, 100 × 10 mm exit cross-section ($D_H \approx 18$ mm)
  - Two adjacent channels on either side of burner exit for pilot flame
  - Two turbulence generators[2, 3], homogeneous isotropic turbulence confirmed by hot-wire anemometry



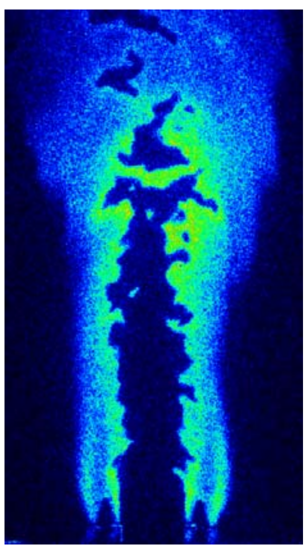




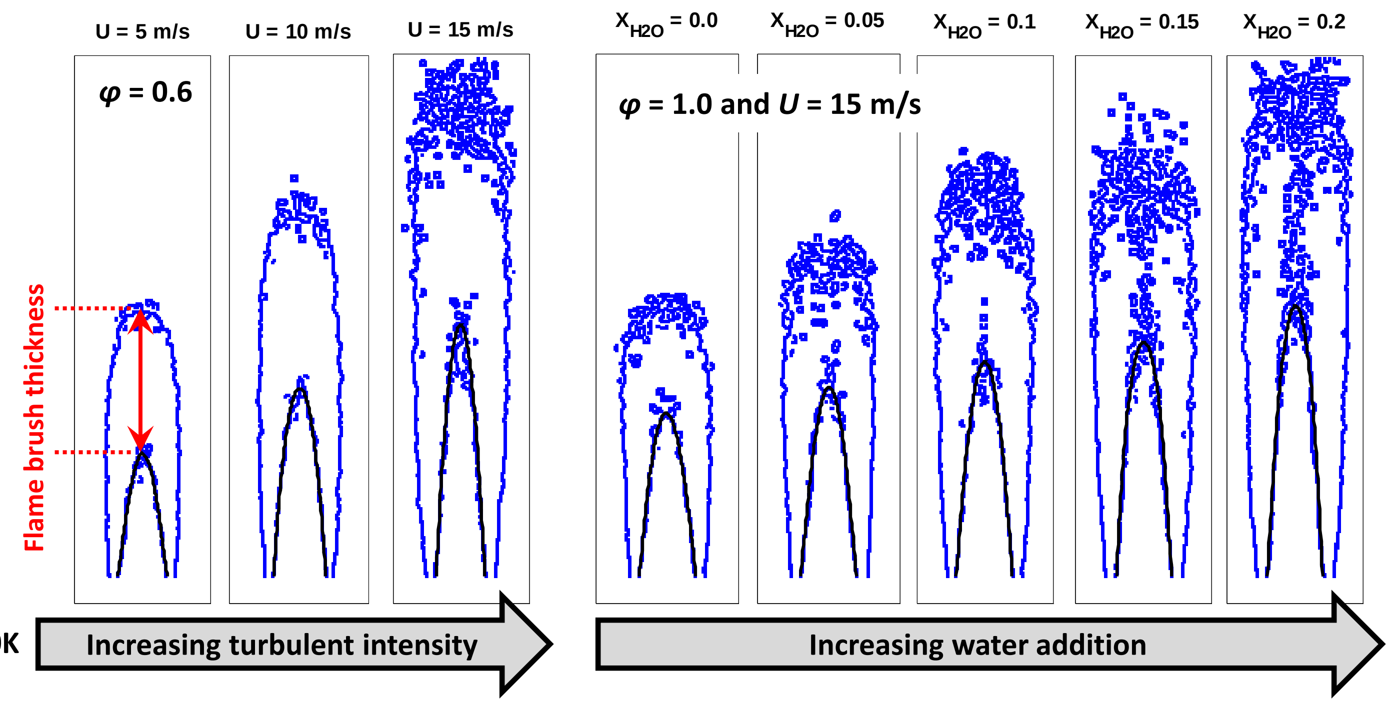
[1] S. H. Won, B. Windom et al, Combust. Flame 161 (2014) 475-483.
[2] Coppola, G., and Gomez, A., *Experimental Thermal and Fluid Science*, Vol. 33, 2009, pp. 1037-1048.
[3] Venkateswaran, P. *et. al., Combustion and Flame., 158, 2011, 1602-1614*

Determination of S_T

- Turbulent burning velocities (S_T) are determined by measuring flame perimeters using OH PLIF imaging. (Individual analysis of 500 instant OH PLIF images)
  - Trace flame fronts, defined by the local maximum gradient of OH signals
  - S_T can be defined by the ratio of nozzle width to average flame perimeter multiplied by mean jet velocity.
  - S_T by Inner perimeters are found to produce consistent results from progress variable approach.[1,2]
  - This approach provides not only average flame perimeters, but also local flame structures, such as PDFs of flame brush thickness and radius of curvature of flame front.



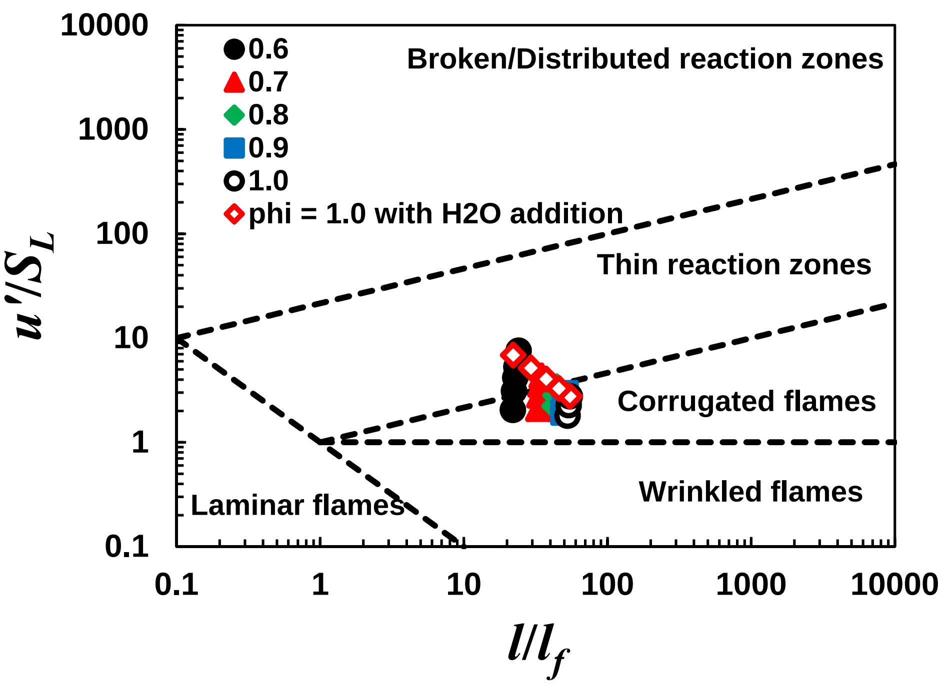
Methane/air
φ = 0.6 and U = 17.5 m/s at 450K



[1] H. Kobayashi et al., Proc. Combust. Inst. 30 (2005) 827-834.
[2] P. Tamadonfar, Ő. L. Gűlder, Combust. Flame (2014) in press.

Experimental Conditions

- At 450 K in RATS burner
- Tested conditions on the premixed combustion regime diagram[1]
  - CH_4/air/H_2O premixed flames have been tested
  - To be tested; CH_4/air/CO_2, H_2/air/H_2O, and H_2/air/CO_2



Without H_2O addition

CH_4/air	U [m/s]	u' [m/s]	l [mm]	Re_l	φ	S_L [m/s]
Min	5	0.62	2.3	45	0.6	0.3
Max	17.5	2.30	2.5	182	1.0	0.71

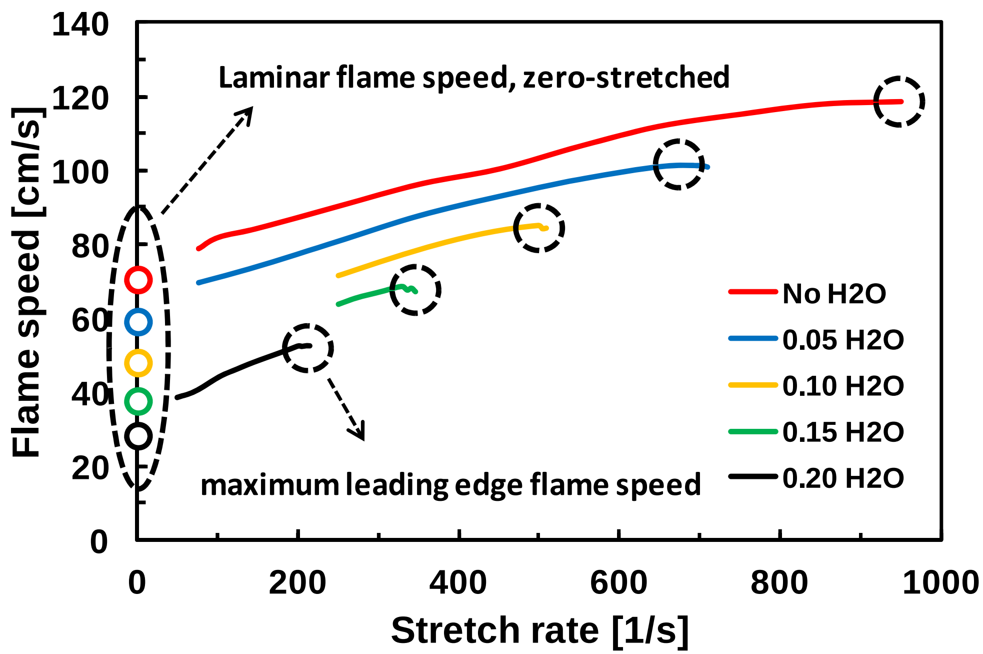
With H_2O addition

CH_4/air/H_2O	U [m/s]	u' [m/s]	l [mm]	Re_l	φ	X_{H2O}	S_L [m/s]
Min	15	1.95	2.5	152	1.0	0 ~ 0.2	0.3

[1] R. Borghi, in: C. Casci, C. Bruno (Eds.), Recent Advances in Aerospace Sciences, Plenum Press, New York, 1985, pp. 117-138.

Turbulent Burning Velocities

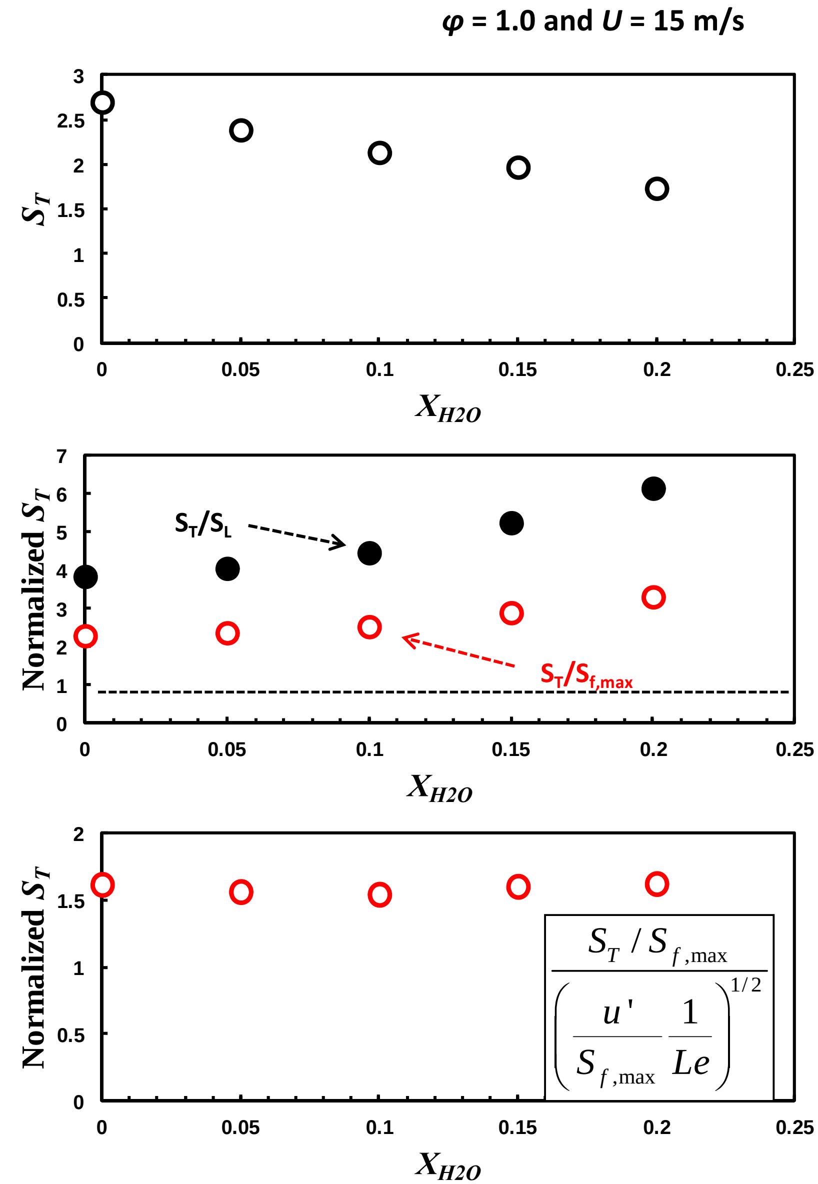
- What is a proper parameter for laminar flame speed?
  - Zero-stretched laminar flame speed or maximum leading edge flame speed?[1-3]
  - Integral time scale is about ~ 1 ms (~ 1000 1/s stretch rate)
- How to evaluate transport variation?
  - Depending on diluents, Lewis number[4] (Le) varies



[1] C. K. Law, Combustion Physics, Cambridge University Press, New York, 2006.
[2] A. N. Lipatnikov, j. Chomiak, Prog. Energy Combust. Sci. 31 (2005) 1-73.
[3] P. Venkaeswaran, A. Marshall, J. Seitzman, T. Lieuwen, Combust. Flame (2014) in press.
4 R. Abdel-Gayed, D. Bradley, M. Hamid, M. Lawes, Proc. Combust. Inst. 20 (1984) 505-512.

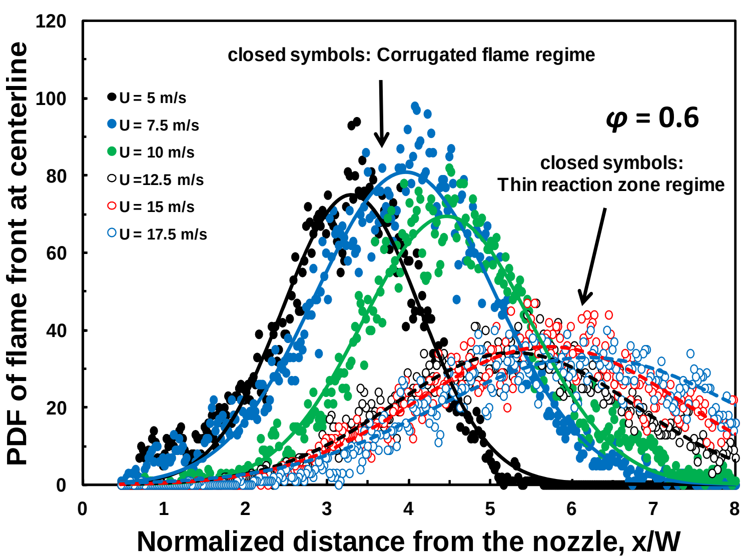
Impact of H_2O Addition

- S_T decreases with increasing H_2O addition.
- Scaling analysis based on Damkőhler suggests
  - $S_T/S_L \sim (u'/S_L)^{1/2} x (1/Le)^{1/2}$
  - Here, $S_{f,max}$ is used instead of S_L to represent laminar flame burning rate at highly stretched condition.
- Slight contribution of diffusive transport at higher H_2O dilution
  - Le increases from 0.82 (0 mole % H_2O) to 0.89 (20 mole % H_2O)

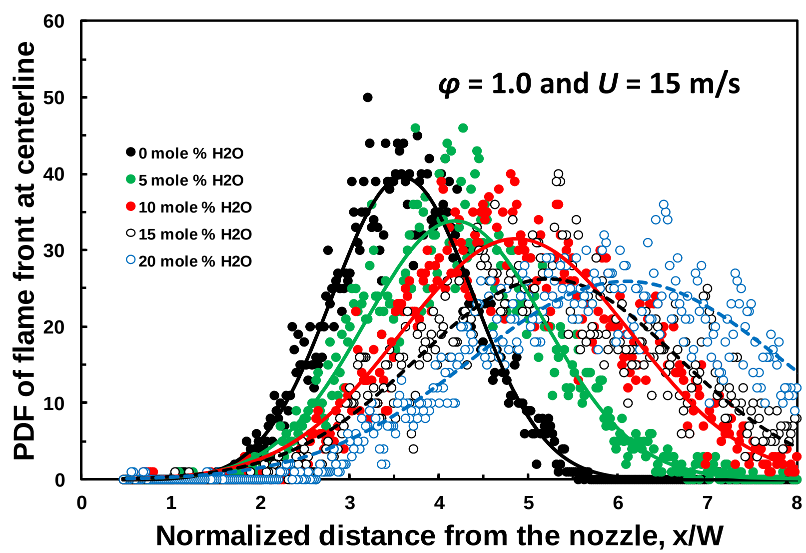


Local Flame Structures

- **PDFs of flame front at the centerline are analyzed.**
- **With increasing turbulent intensity or H_2O dilution,**
  - **PDF results indicate the transition of turbulent flame regimes from corrugated flame to thin reaction zone.**
  - **Increase flame brush thickness substantially**



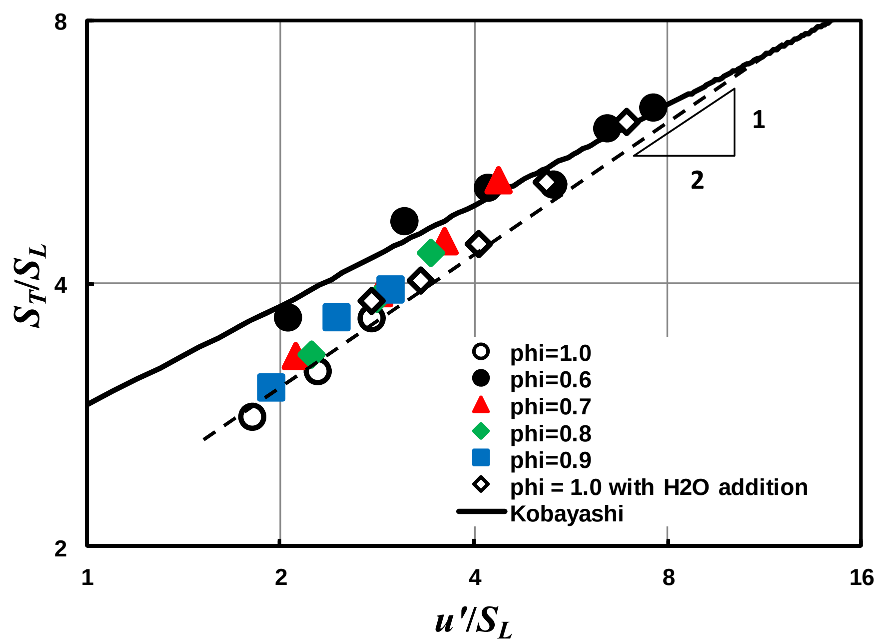
With increasing turbulent intensity



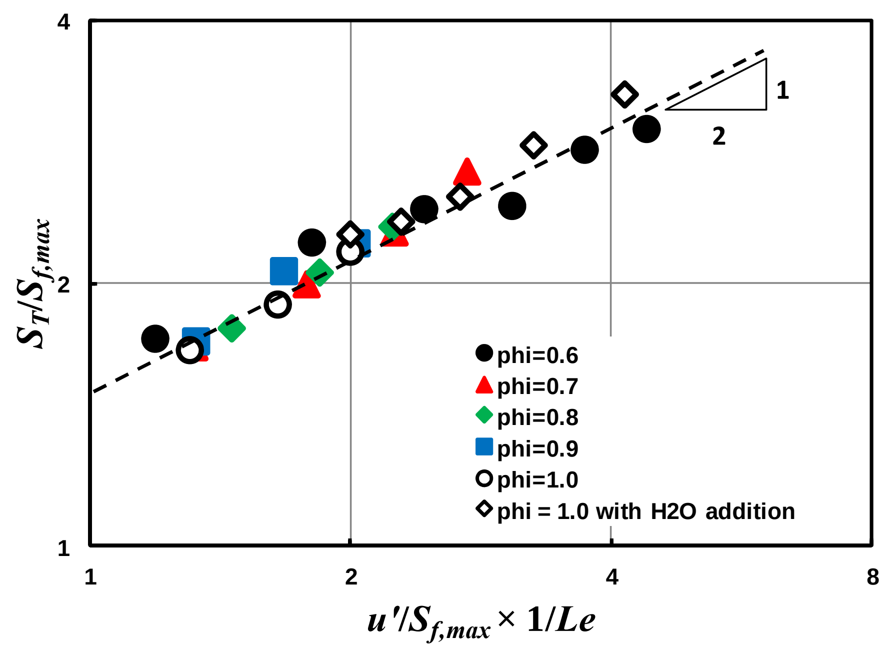
With increasing H_2O dilution

Turbulent Burning Velocities

- Use of normalization by $S_{f,max}$ exhibits improved S_T correlation from Damkőhler's analysis.
  - Particularly for large turbulent intensity, $u'/S_{f,max}$ (or u'/S_L)
  - It is clearly seen for φ = 0.6 case corresponding to the slowest laminar burning rate.



Normalization by Zero-stretched laminar flame speed



Normalization by Maximum leading edge flame speed

Summary

1. High pressure flame speeds of HHC fuels with H_2O/CO_2 addition were measured. Significant kinetic effect from H_2O/CO_2 was observed.
2. About 10% uncertainty in flame speed measurements/computation is identified for HHC fuels with the effect of radiation from EGR.
3. A new High pressure kinetic mechanism (HP-Mech) is developed for HHC fuel combustion with EGR. Preliminary tests show much better predictability.
4. Sensitive HO_2/OH diagnostics is succeed by using Faraday rotational spectroscopy.
5. **Water effect on turbulent flame speed and structure were measured. Water addition significantly change the flame speed and flame brush structure.**

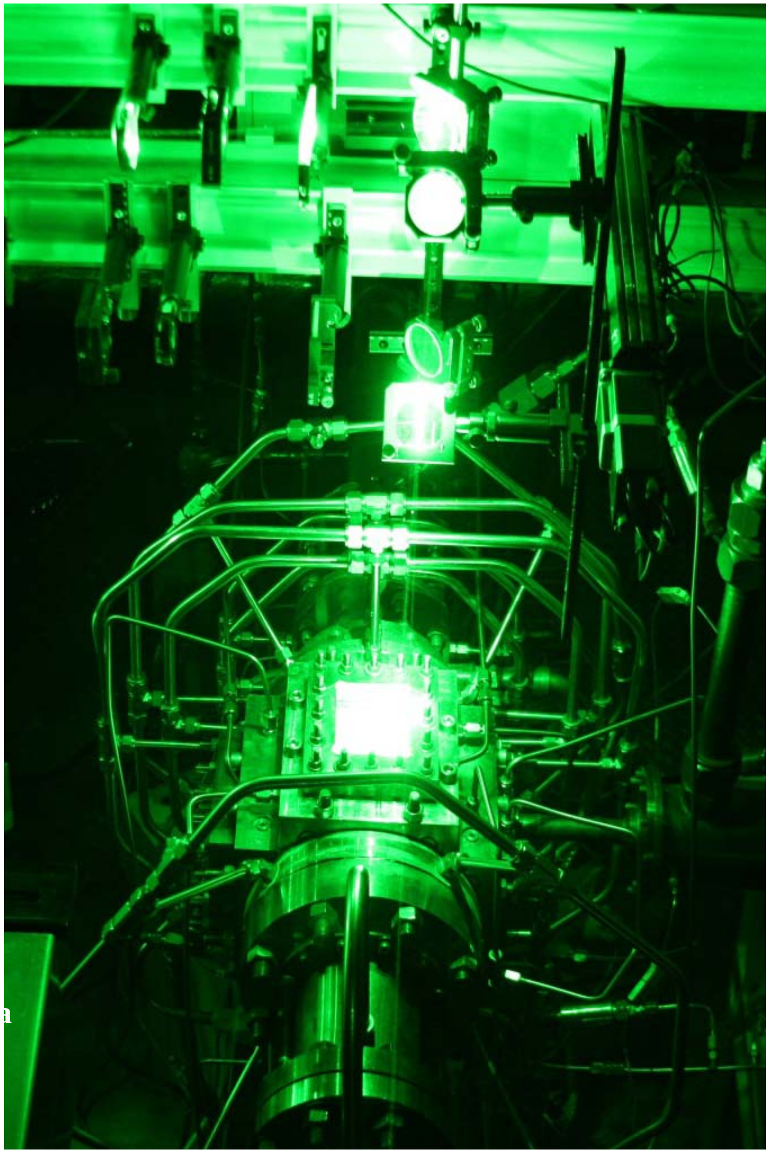
TASK 5.0 Investigation of EGR Effects in Purdue Staged Combustion Test Rig

- Assembly of ARATS Burner into the Windowed High-Pressure Test Rig

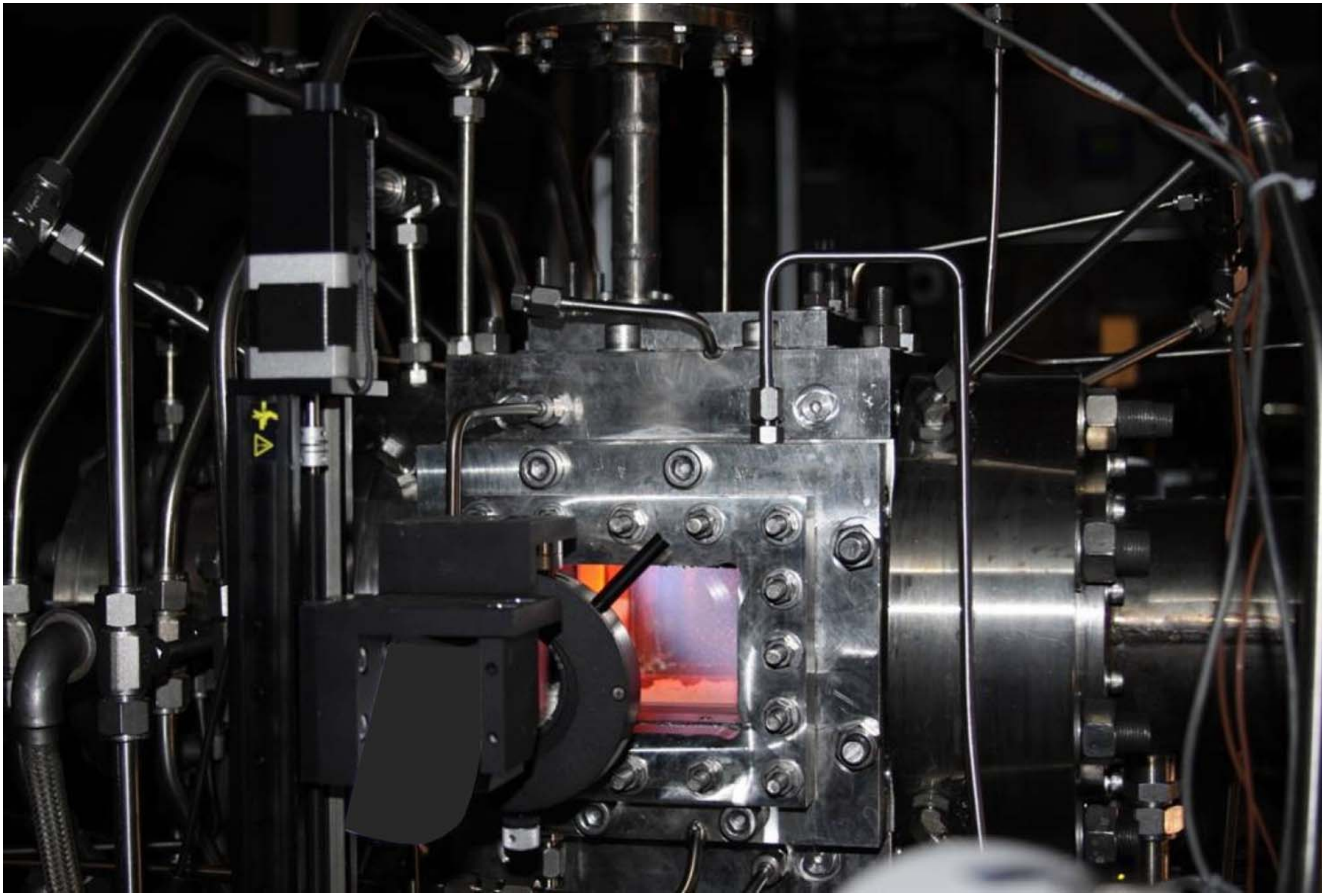
- IR Imaging of Axisymmetric Reactor Assisted Turbulent Slot (ARATS) Burner Flames

Purdue Gas Turbine Combustion Facility (GTCF)

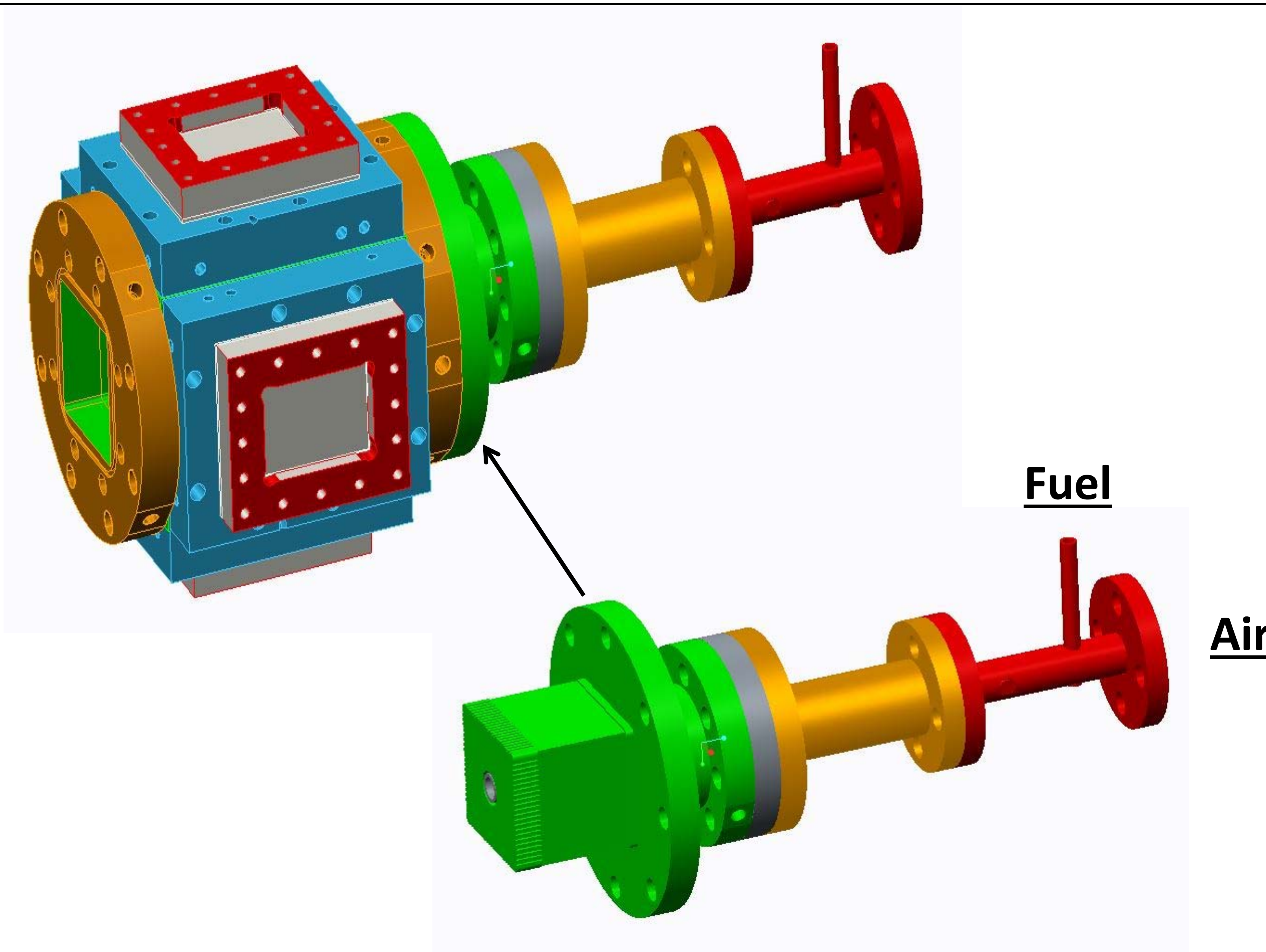
High Pressure Lab System	Maximum Flow Capacity	Max Operating Condition
Natural Gas Heated High Pressure Air	9 lbm/s 4 kg/s	700 psi / 1000 F 1400 F in 2015
Electric Heated Air or Nitrogen	1 lbm/s 0.5 kg/s	600 psi / 1000 F
Nitrogen	5 lbm/s 2 kg/s	1,500 psi
Liquid Aviation Fuel (Kerosene)	1 lbm/s 0.5 kg/s	1,500 psi
Natural Gas	1 lbm/sec 0.5 kg/s	3500 psi



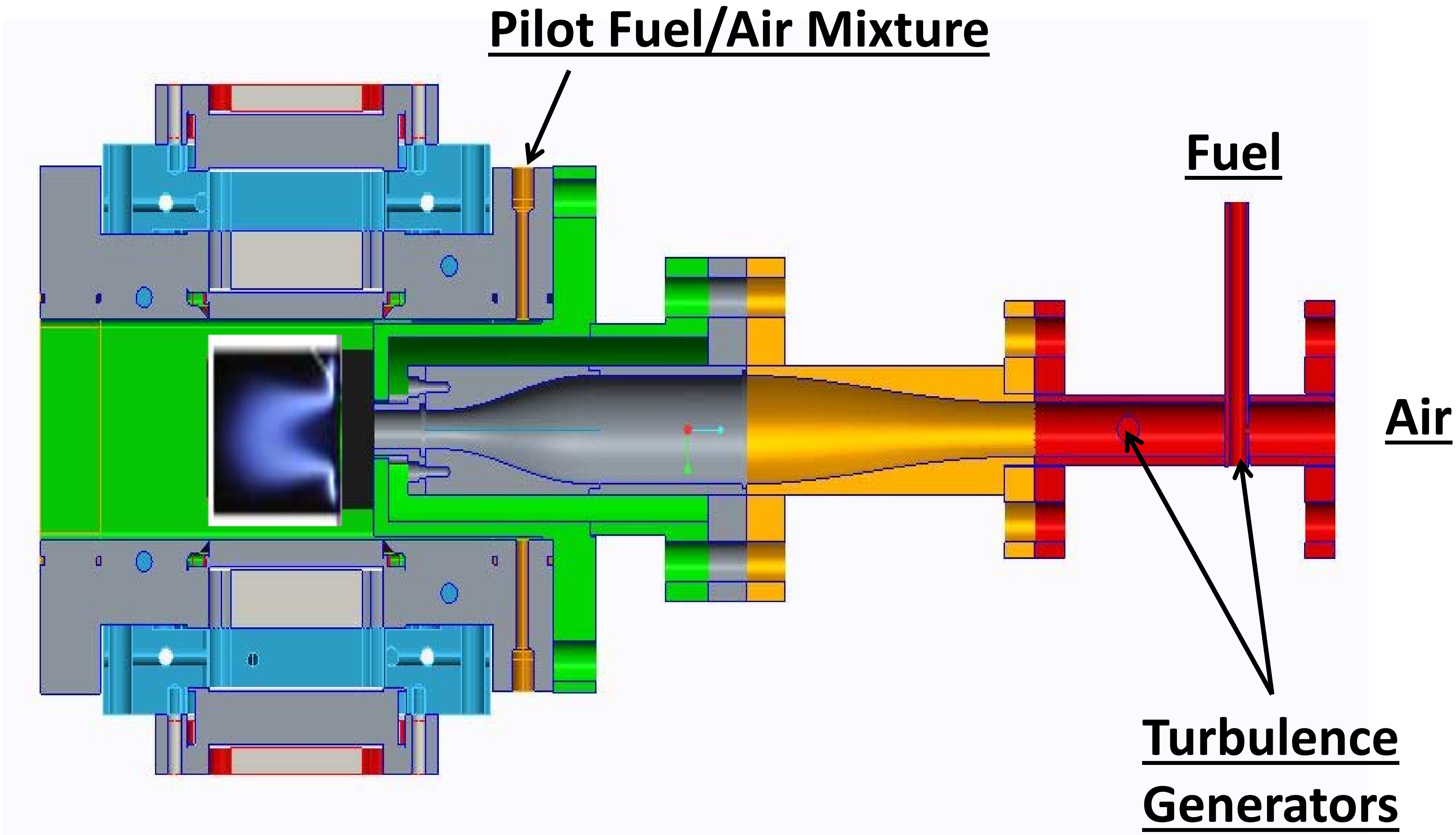
High-Pressure Test Rig



Assembly of ARATS Burner into the Windowed High-Pressure Test Rig



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



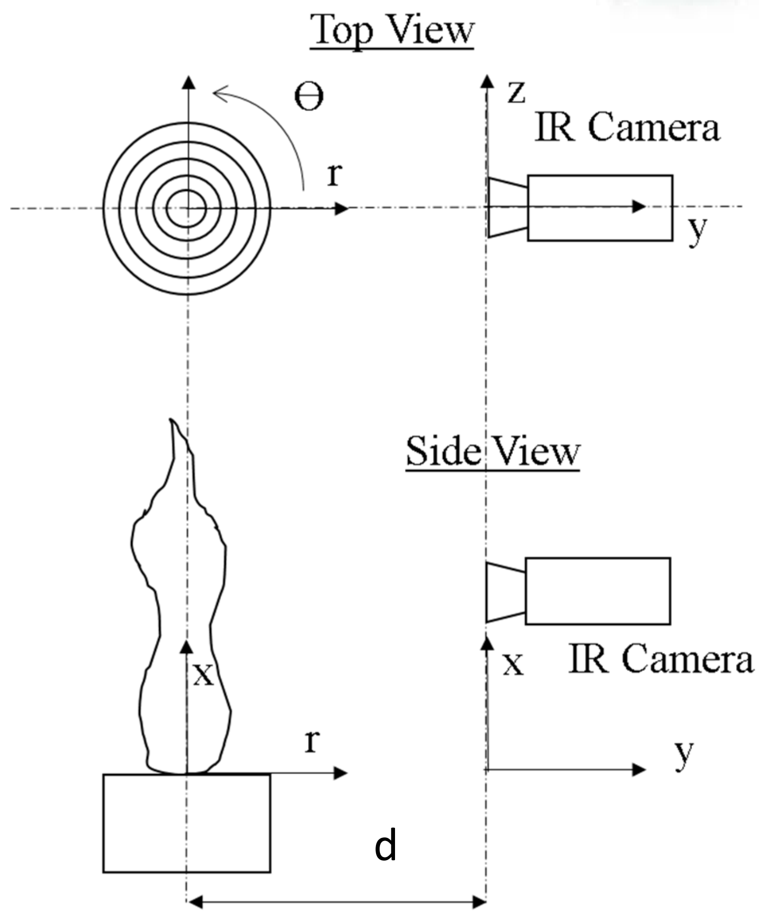
IR Imaging of Axisymmetric Reactor Assisted Turbulent Slot (ARATS) Burner Flames

- **Turbulent lean premixed methane flame**
  - Re = 8950
  - Burner diameter (D) = 15 mm

- **FLIR Infrared Camera**
  w/ band pass filters
  - H_2O: 2.58 ± 0.03 µm
  - H_2O and CO_2 2.77 ± 0.1 µm
  - CO_2 4.38 ± 0.08 µm

- **Distance between camera and flame**
  d = 0.5 m

- **Sampling frequency=430 Hz**



Infrared Image Generation

IR camera measures spectrally integrated radiation intensity through approximate lines of sight through the flame. Described by solution to radiation transfer equation

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

$$I_{Camera} = \alpha_\lambda I$$

$I_{\mathrm{b}\lambda}$ = blackbody spectral intensity (Strong function of temperature)

κ_λ = linear absorption coefficient (Strong function of emitting & absorbing species concentrations)

λ_1, λ_2 = spectral limits of the filter

α_λ = spectral absorption coefficient

τ_λ = optical thickness $= \int_0^S \kappa_\lambda ds$; s = path length

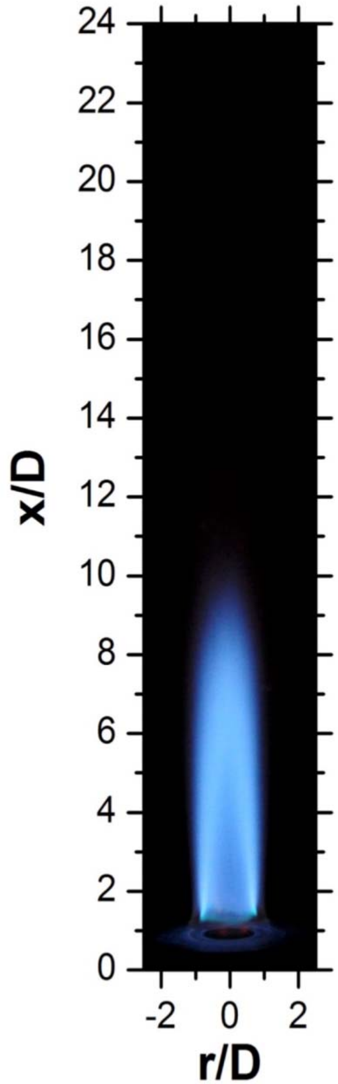
Computational Methods

- Time and space series (TASS) analysis is applied to obtain radiation intensity from temperature measurements.

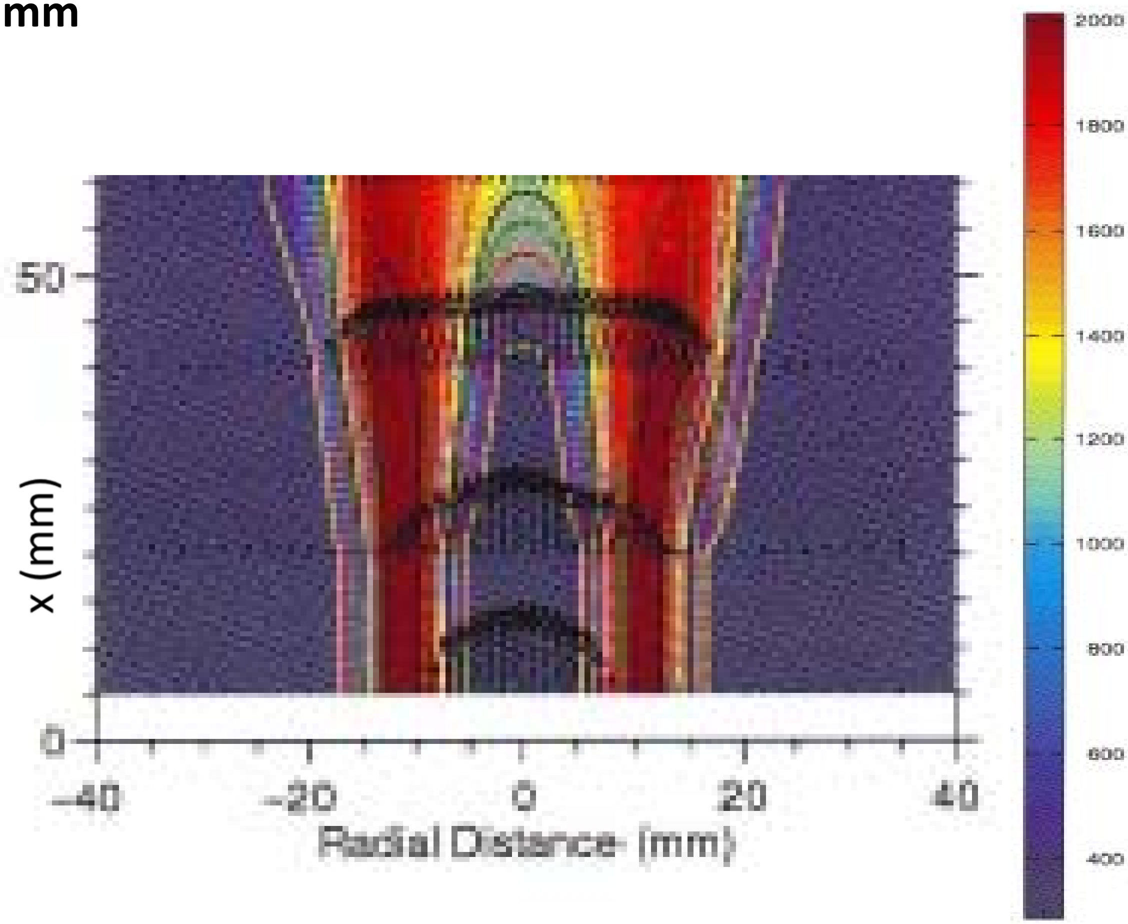
- Scalar properties are calculated using state relationship simulated by CHEMKIN.

- Narrow band model with RADCAL , and line by line calculation based on HITRAN and HITEMP database are adopted to compute spectral radiance for CO_2 and H_2O.

Temperature and Velocity Distributions



D=15 mm



T and Velocity Data from past USDOE supported work at Purdue (Kelkar and Chakka)

Temperature Probability Density Functions (PDFs)

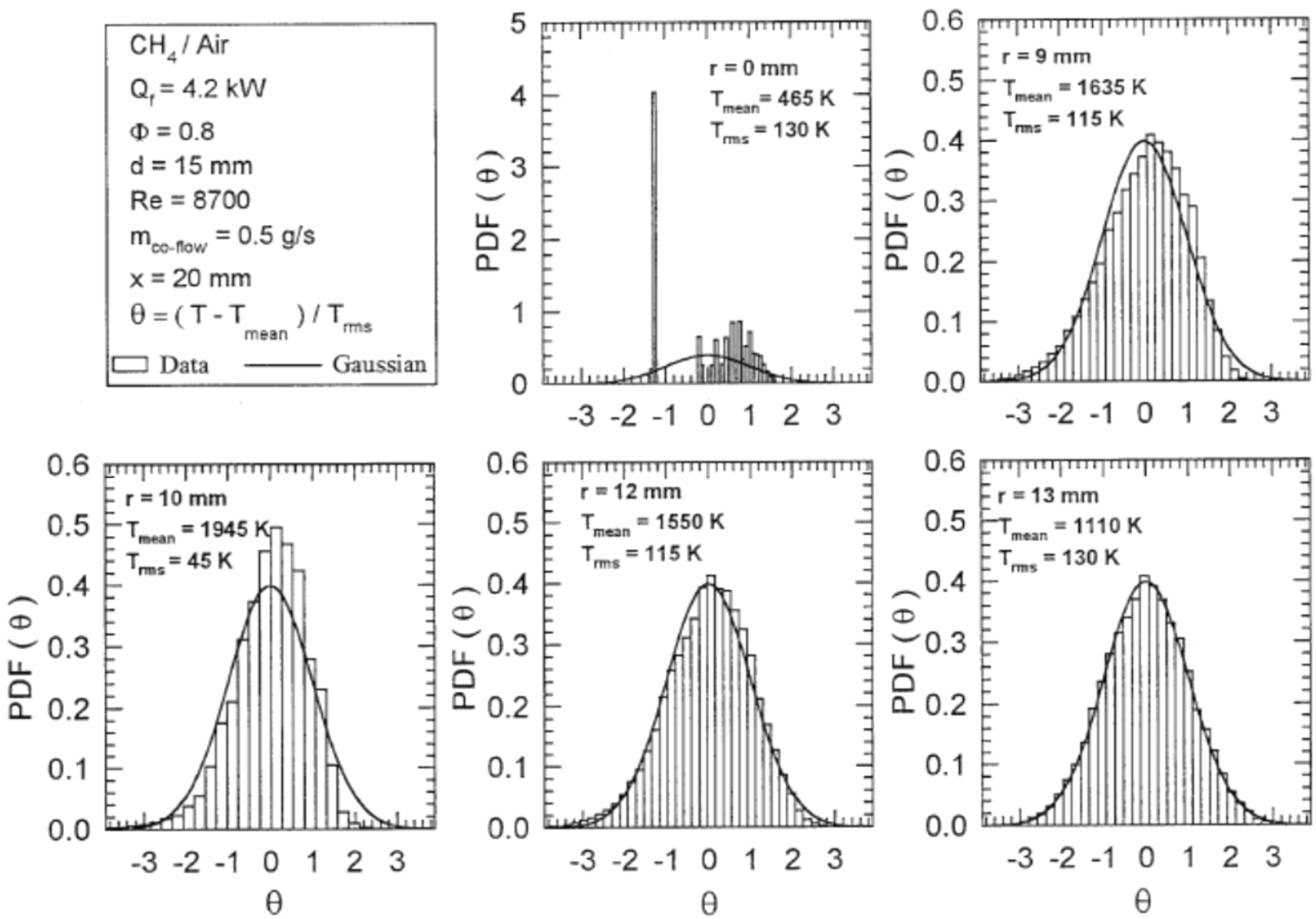
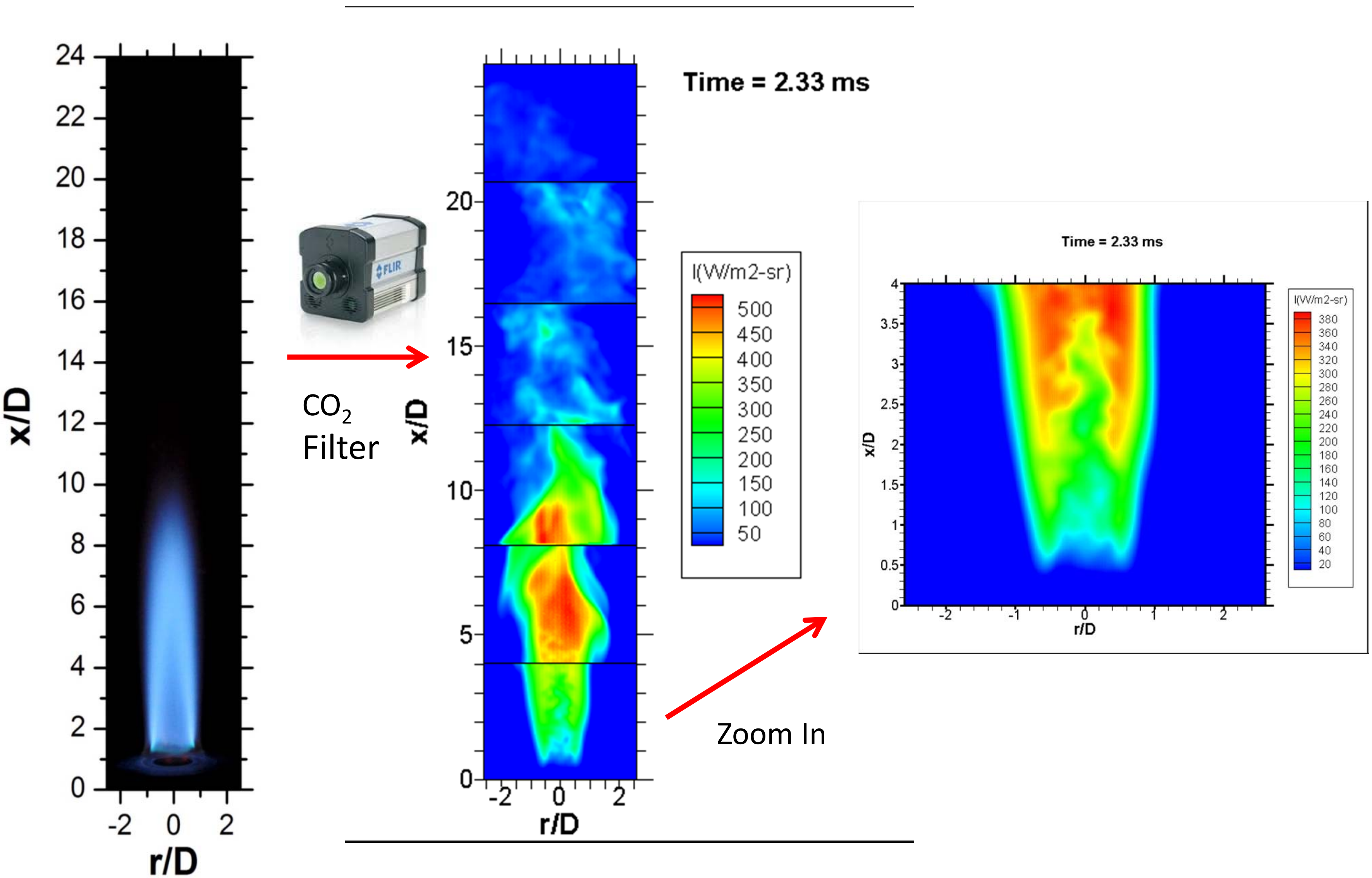
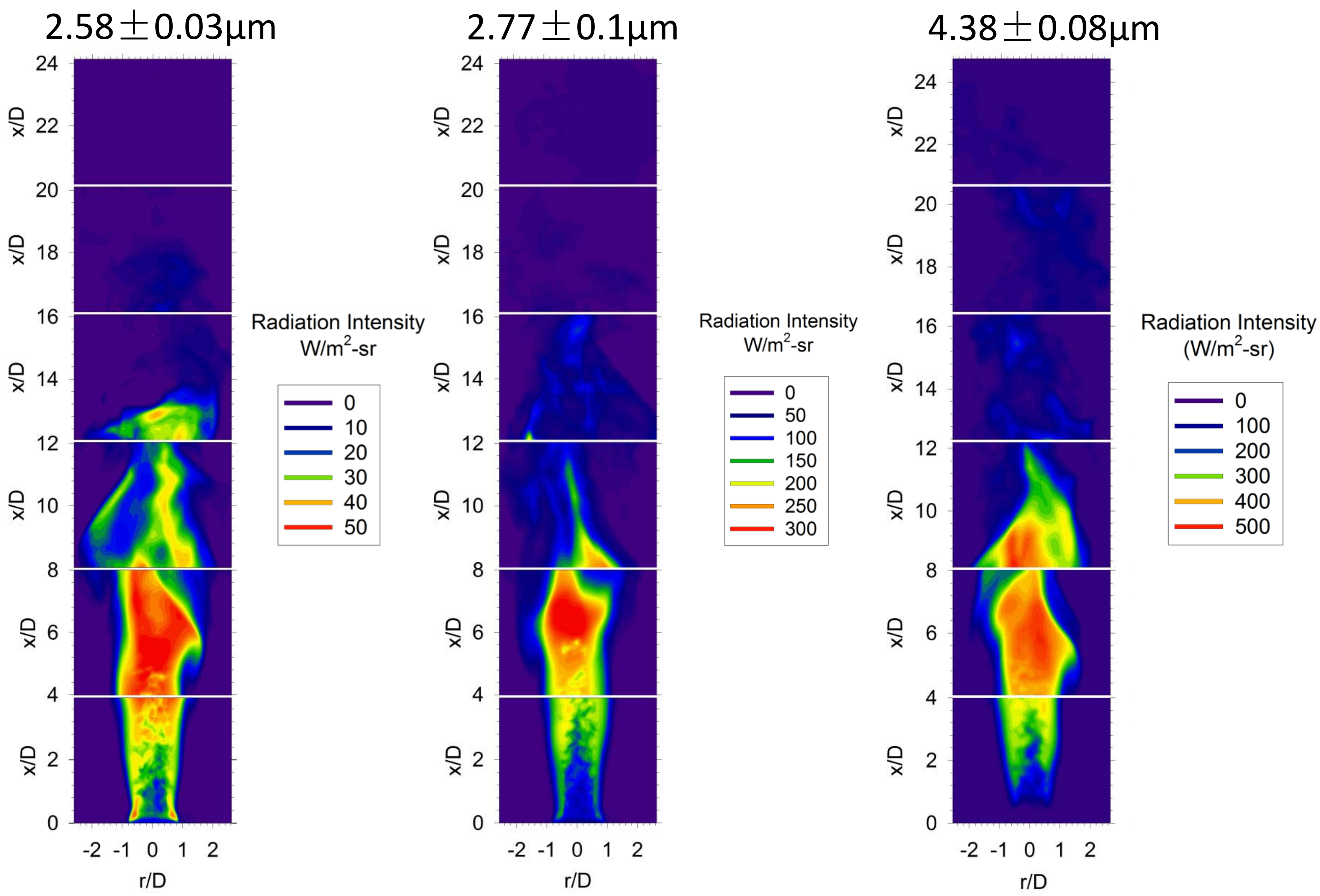


Figure 6.1 Normalized PDFs of temperature in $\Phi = 0.8$, $Q_f = 4.2$ kW flame at x = 20 mm

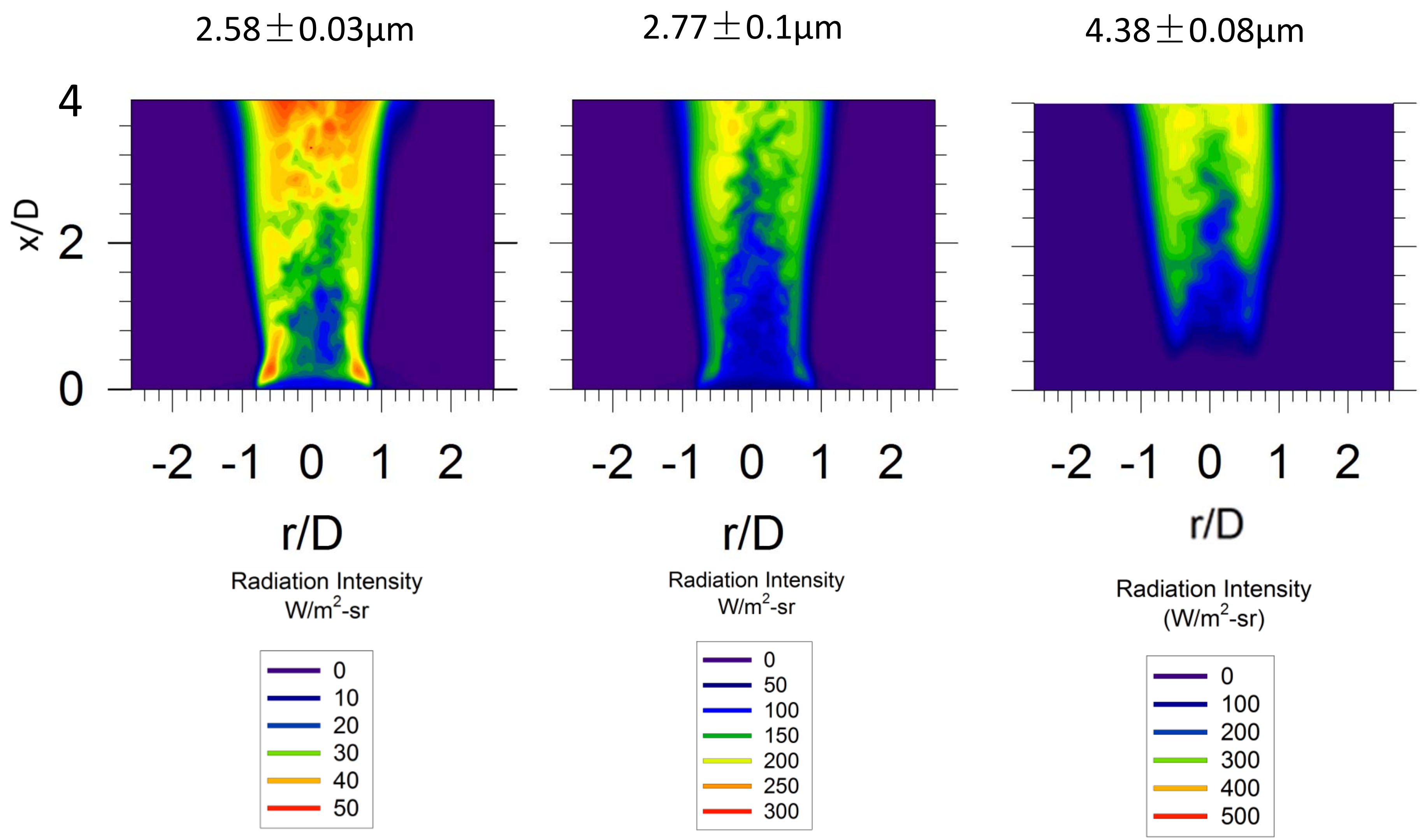
Infrared Images with Emission from the 4.3 micron CO_2 Band



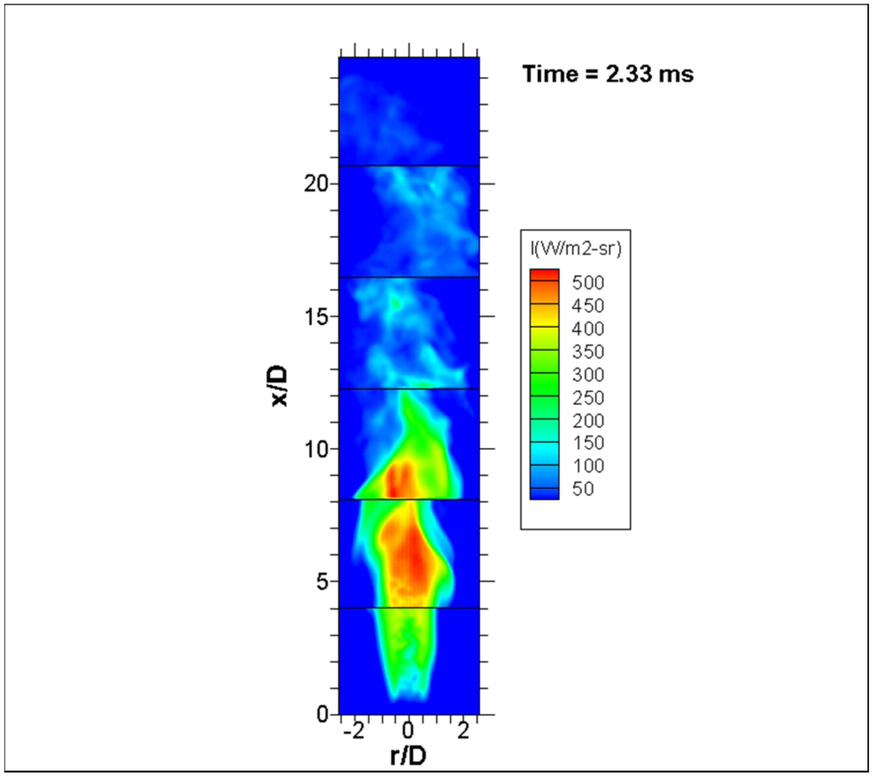
Time-dependent IR Radiation Intensity

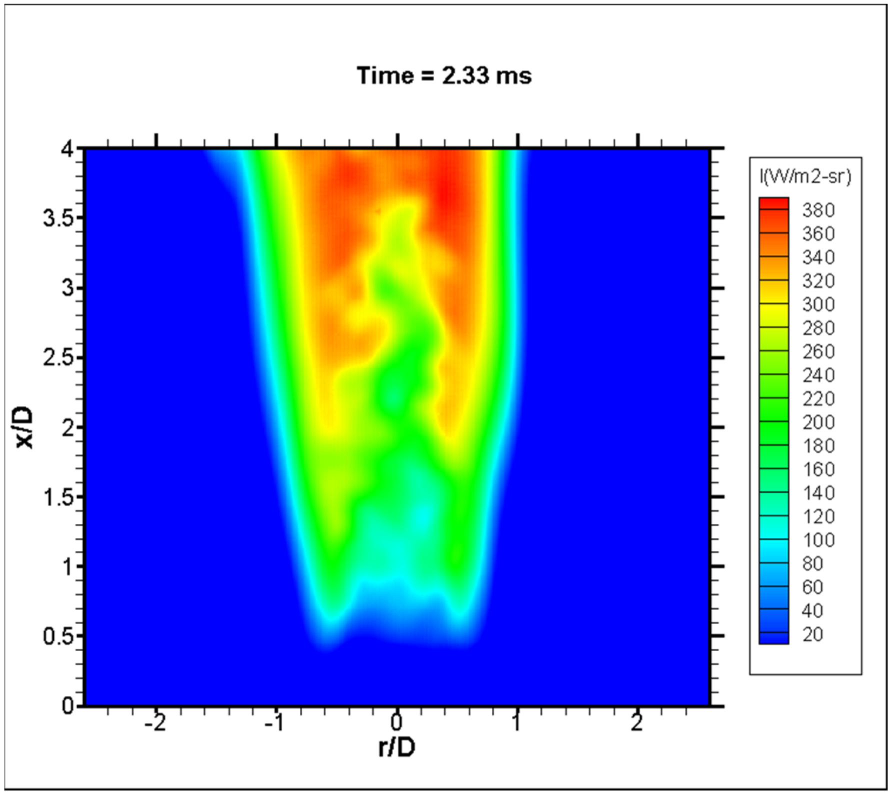


Time-dependent Radiation Intensity



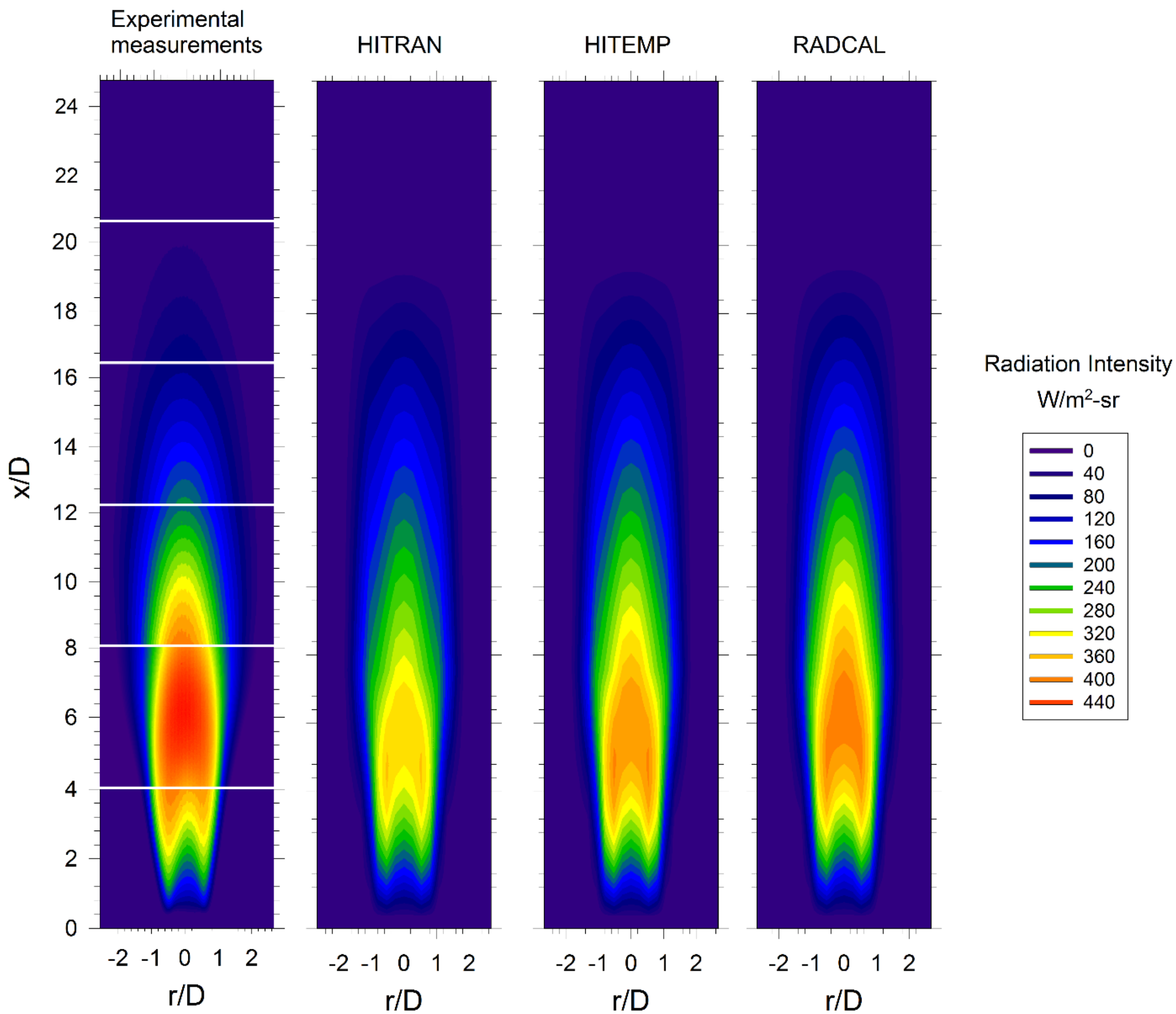
Quantitative Imaging of Time-dependent Radiation Intensity





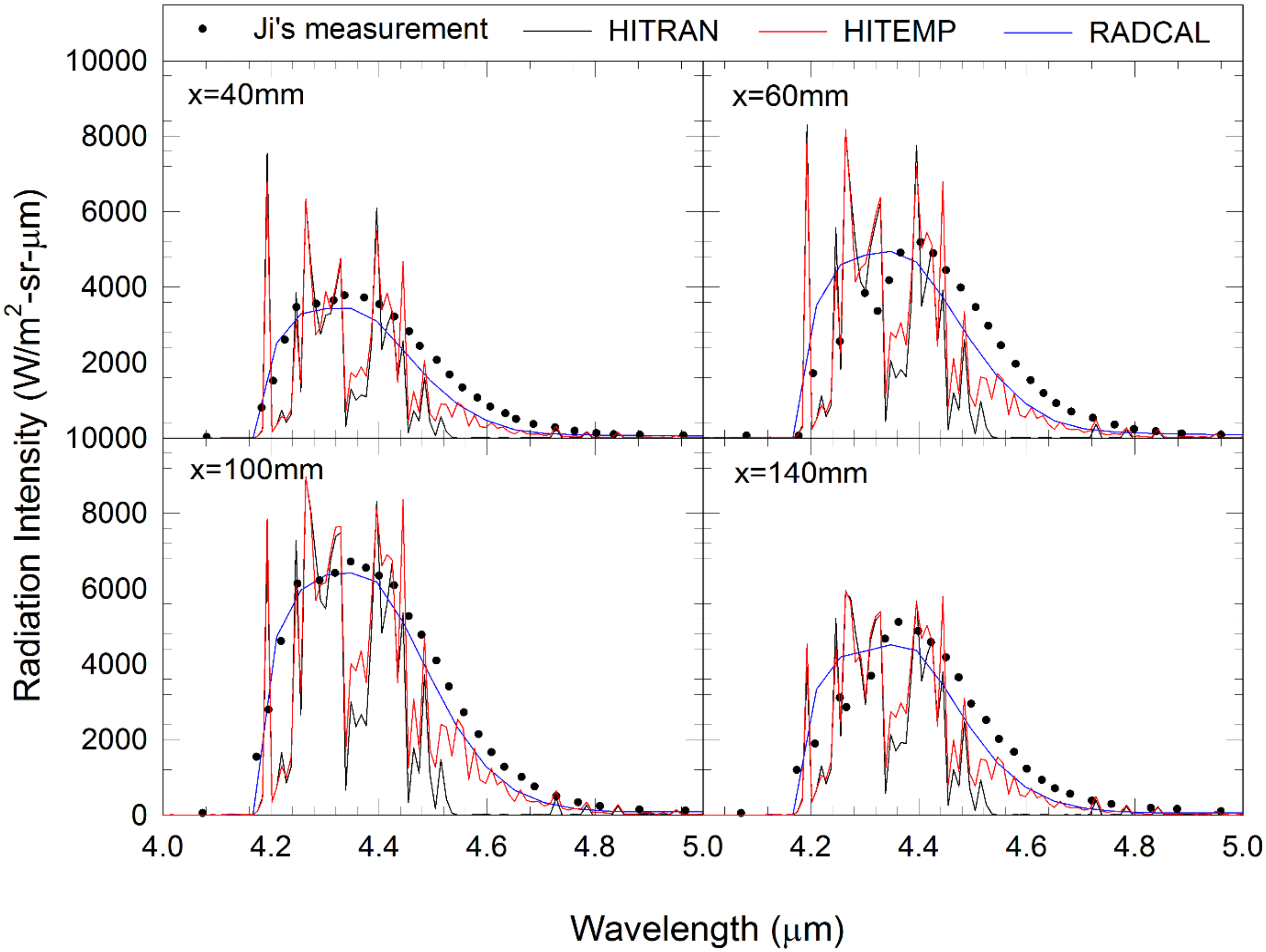
Comparison of Computational & Experimental Results

Integrated Radiation intensity from 4.38 ± 0.08 μm band



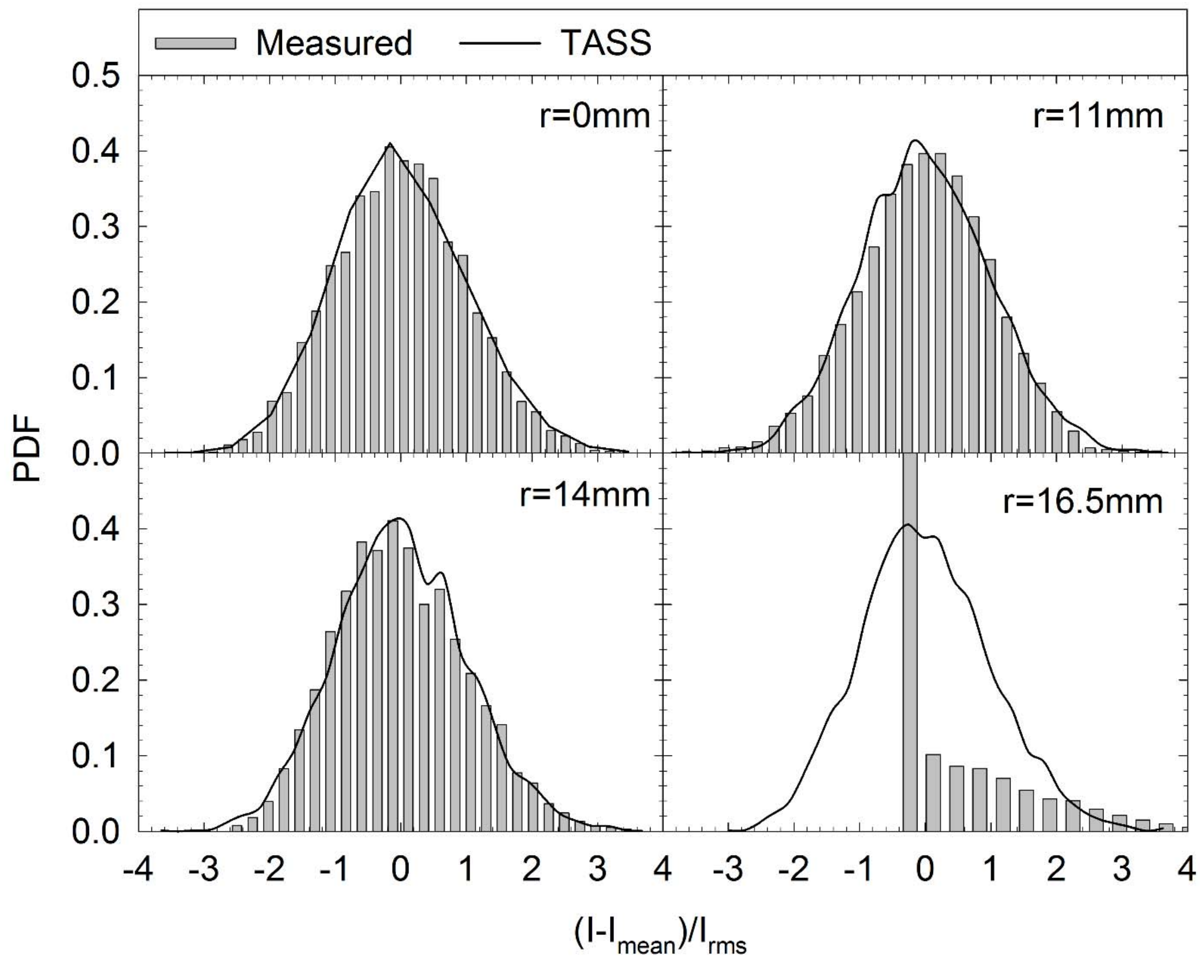
Comparison of Computational & Experimental Results

Spectral Radiation intensity at the centerline of the flame



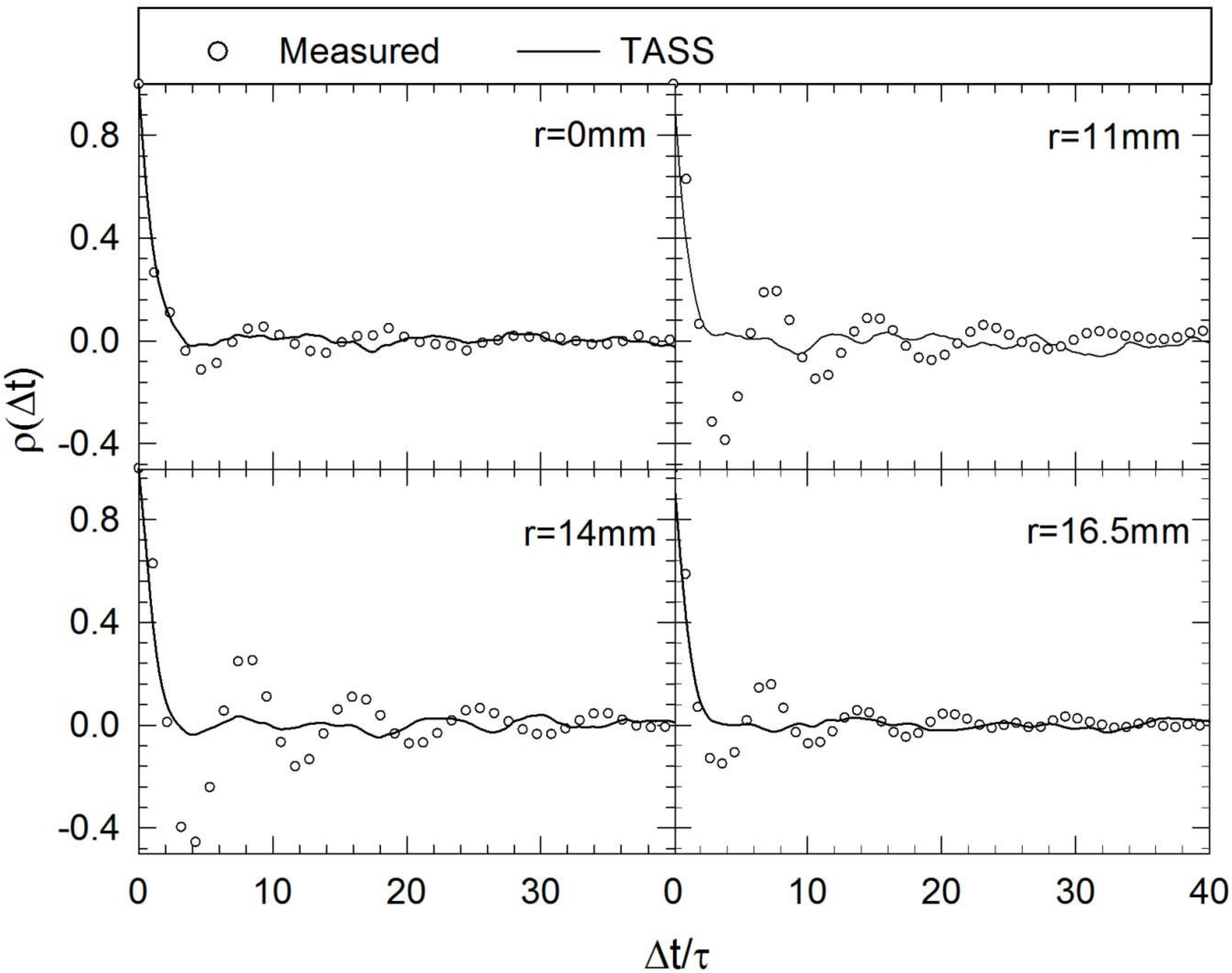
Statistics of Infrared Radiation Intensity at 4.38±0.08μm

Probability Density Function at x=40 mm



Statistics of Infrared Radiation Intensity at 4.38±0.08μm

Temporal Correlation at x=40 mm



Summary and conclusions

- Quantitative infrared radiation images of a representative lean turbulent premixed methane-air flame are presented.
- Computed radiation intensities from both narrow band model and line by line model are compared with experimental measurements
- Quantitative imaging of infrared radiation intensity can be applied as a non-intrusive diagnostic technique for studying lean turbulent premixed flames.
- Stochastic time and space series analysis provides a technique for studying turbulence-radiation interaction for a lean premixed flame.
- This work will be applied to study EGR effects on HHC turbulent premixed flames

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Large Eddy Simulations (LES) Modeling

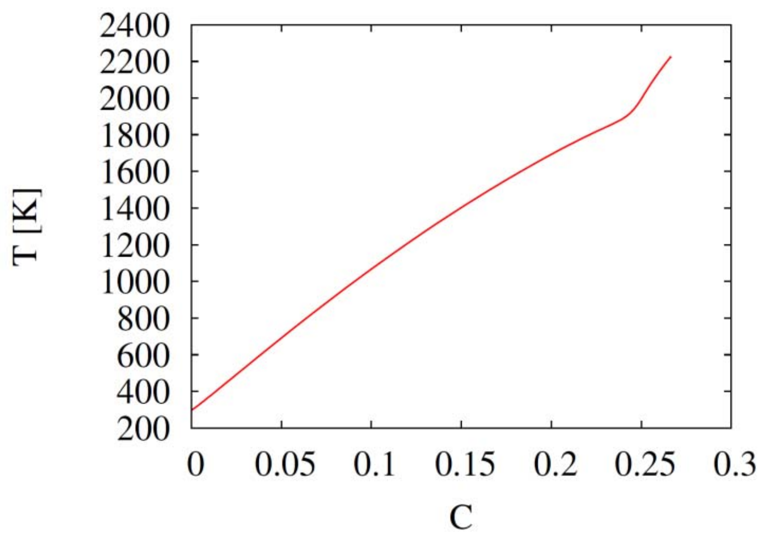
- Model Development
  - Premixed Flamelet Model
  - Heat Losses
- RATS Burner Simulations
  - Computational Details
  - Preliminary Results
- Future Work

Model Development

- Premixed Flamelet Model
  - Use one-dimensional premixed flamelet solutions to map thermochemical state onto a progress variable
    - $\rho_u S_L \frac{dY_k}{dx} = -\frac{d}{dx}(\rho Y_k V_k) + \dot{m}_k$
    - Consider multiple equivalence ratios (mixture fractions) to account for mixing of fuel/air mixture with air coflow
    - $\dot{m}_k(Y_k, T) \rightarrow \dot{m}_k(Z, C)$
  - Solve for progress variable in LES
    - $\frac{\partial \bar{\rho}\tilde{C}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{C}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{D}\frac{\partial \tilde{C}}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\bar{\rho}\widetilde{u_j C} - \bar{\rho}\tilde{u}_j\tilde{C}\right) + \bar{\dot{m}}_C$
    - Retrieve local thermochemical state from flamelet solutions

Model Development

- Premixed Flamelet Model
  - Progress variable subfilter PDF
    - Delta distribution
    - Currently evaluating beta distribution to account for subfilter fluctuations in progress variable



Stoichiometric Methane/ Air with GRI3.0

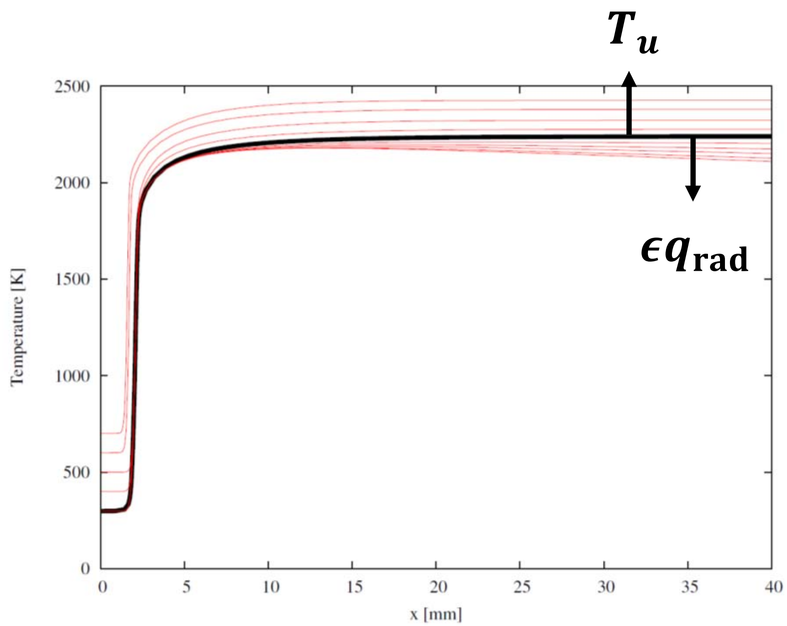
Model Development

- Heat Losses
  - One long-term project goal is to assess the effects of diluents on radiation and NO_x emissions
  - Extend adiabatic flamelet model to account heat loss/gain
    - $Y_k(Y_k, T, H) \rightarrow Y_k(Z, C, H)$
  - To generate flamelets with elevated enthalpies, the unburned gas temperature is increased
  - To generate flamelets with reduced enthalpies, common approach is to reduce temperature then dilute fuel/air mixture with H_2O and CO_2[1]
    - Dilution would change radiative properties of gas mixture

[1]J.A. van Oijen, L.P.H. de Goey, Combust. Sci. Tech. 161 (2000) 113-137

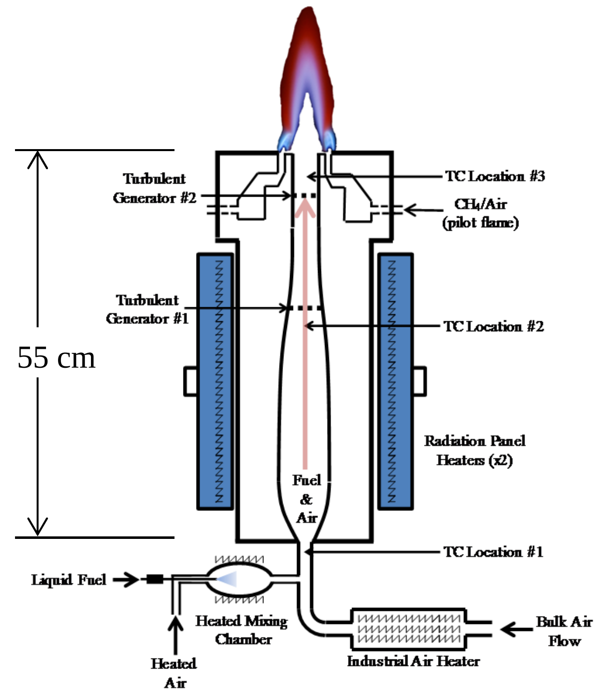
Model Development

- Heat Losses
  - New approach for generating flamelets with reduced enthalpies
    - Solve flamelets with optically thin radiation (local effect) source term with coefficient ranging from zero to one
    - Eliminates unphysically low temperatures and modification of optical properties by H2O and CO2 dilution



RATS Burner

- Configuration: RATS Burner
  - Stoichiometric methane/air
  - $\mathrm{Re} = 12{,}400$
- Code: NGA[1]
  - 0.8M grid points $(128 \times 192 \times 32)$
  - Domain length: $20H$
  - Dynamic Smagorinsky(-like) models for turbulent transport

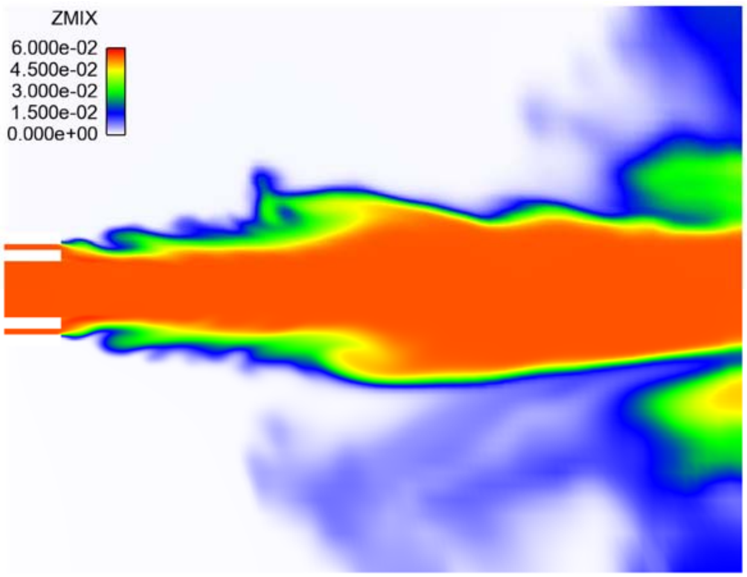


[1]O. Dejsardins, G. Blanquart, G. Balarac, H. Pitsch, J. Comp. Phys. 227 (2008) 7125-7159

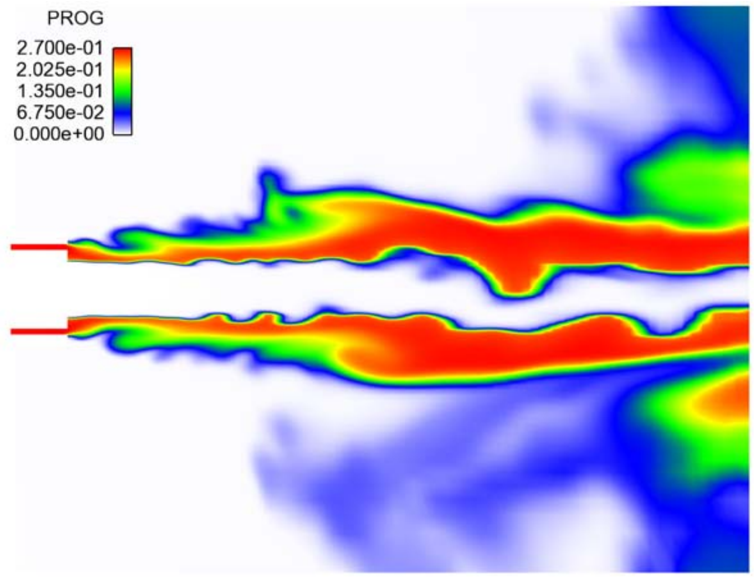
Simulation of the RATS Burner Flame

- Preliminary Results

Mixture Fraction ($Z_{st} = 0.055$)



Progress Variable



Simulation of the RATS Burner Flame

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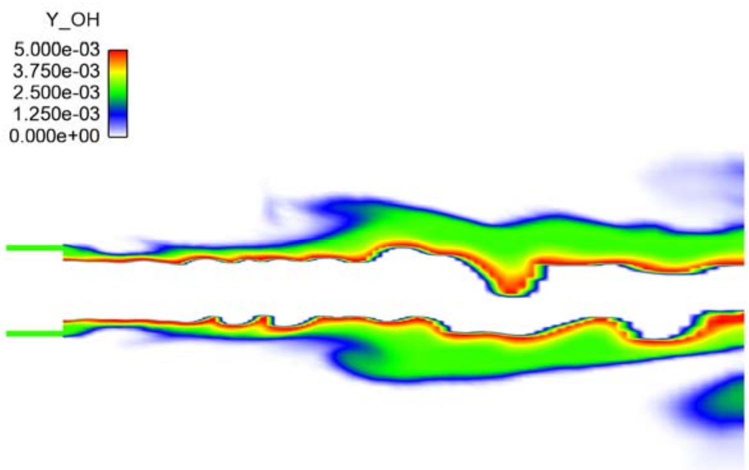

  - Flame length apparently longer than experiment (pending)
    - Boundary conditions?
    - Progress variable subfilter variance?
    - Heat losses?

Future Work

- Model Development
  - Premixed flamelet model with variable enthalpy
  - Full RTE implementation
    - Discrete ordinates method
    - Optical property evaluation
- RATS Burner Simulations
  - Effects of boundary conditions on flame length
  - Effects of heat losses on flame length
  - Longer term: Effects of diluents on radiation and emissions

Summary

1. **Significant effects of water addition on turbulent flame speed and flame brush structure were experimentally observed.**
2. **A new normalization flame speed $S_{F.max}$ representing the speed at the maximally stretched flame tip was found to provide improved collapse normalized flame speed data for flames with a broad range of equivalence ratios and for the stoichiometric flames with water addition.**
3. **Experimental (High Fidelity and Frequency IR Imaging) and Computational (based on Time Series of Scalar Data) Quantitative Infrared Imaging compare well.**
4. **Design of Axisymmetric Reactor Assisted Turbulent Slot (ARATS) burner is ready for safety review.**

Summary

(Work by Ju et al. that I did not have time to present today)

1. High pressure flame speeds of HHC fuels with H_2O/CO_2 addition were measured. Significant kinetic effect from H_2O/CO_2 was observed.
2. About 10% uncertainty in flame speed measurements/computation is identified for HHC fuels because of the effect of radiation from EGR.
3. A new High pressure kinetic mechanism (HP-Mech) is developed for HHC fuel combustion with EGR. Preliminary tests show much better predictability.
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Thank you

Questions?