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INVESTIGATION OF TURBULENT OXY-FUEL JET FLAMES USING RAMAN/RAYLEIGH LASER DIAGNOSTICS

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SINTEF BIGCO2 Sandia National Laboratories

a. Oxy-fuel combustion

BIGCO2 project considers it as a great potential among the CCS technologies

CO_2 capture achieved through simple water removal from flue gas

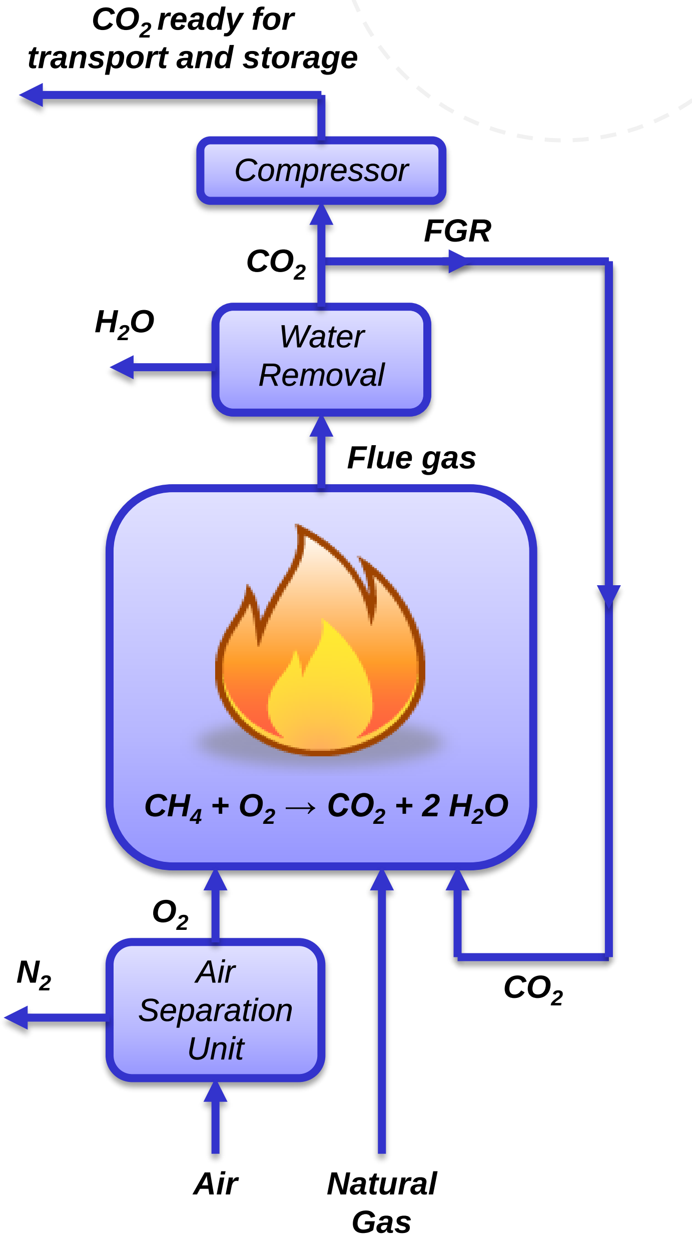
High flame temperature reduced by using flue gas recirculation

Great potential for retro-fitting current gas-fired plants

Main limit: O_2 supply is energy-consuming

Literature:

- Well documented for system and processes
- Not well documented about fundamentals on CO_2-diluted oxy-fuel flames



I. Background and motivations

b. Research topic

Aims of the research:

- Look at turbulent oxy-fuel flame structure
- Create data library eventually used for validation of turbulent combustion codes

Specific objective:

- Investigate turbulent non-premixed CO_2-diluted oxy-fuel jet flame from a coflow burner

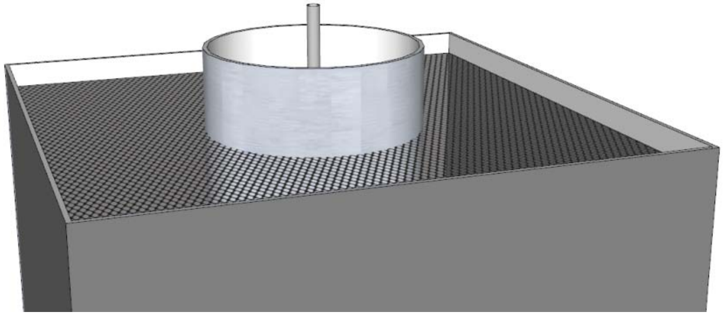
Flame properties:

- 32 % O_2 in oxidizer
- Overall equivalence ratio: 1.25

Flame	%H_2 in fuel	Re_{Fuel}	Jet speed (m/s)	Coflow speed (m/s)
A-1	**55**	15,000	98.2	0.778
A-2	**45**	15,000	84.4	0.755
A-3	**37**	15,000	75.8	0.739
B-1	55	**12,000**	78.6	0.622
B-2	55	**15,000**	98.2	0.778
B-3	55	**18,000**	117.8	0.933

Coflow burner

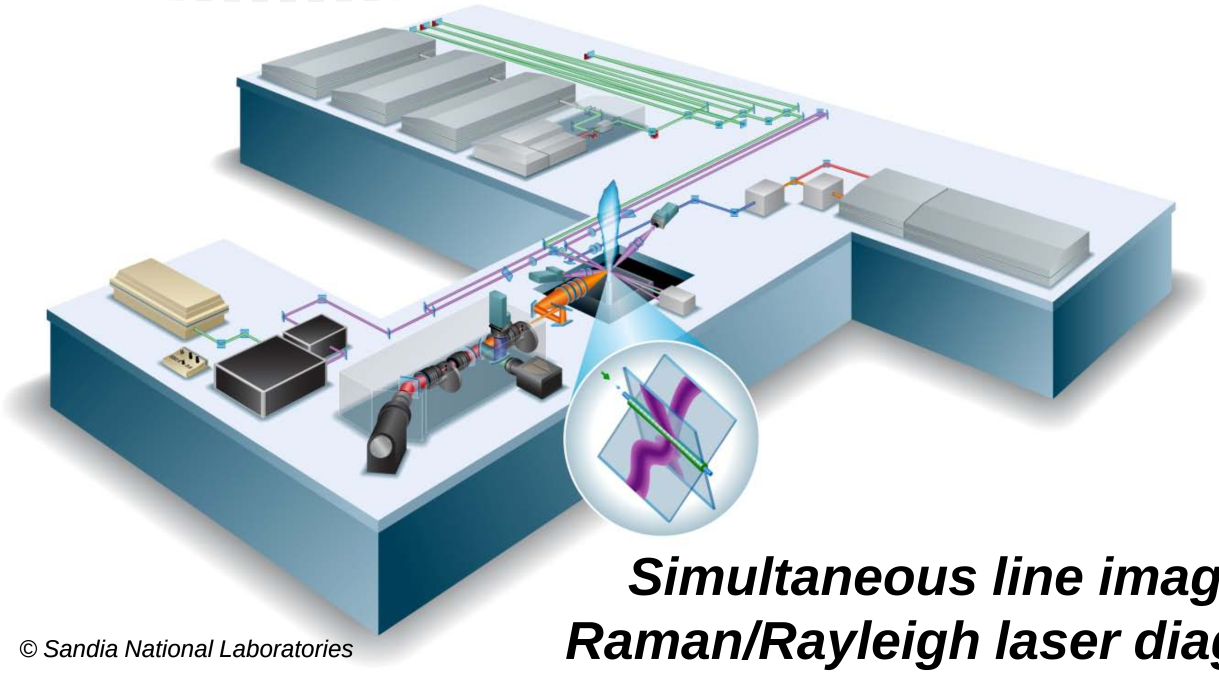
- Fuel nozzle:
  - Fuel: CH_4/H_2
  - 5mm ID
  - Wall thickness 0.5 mm
  - Squared-off end
- Coflow tube:
  - Oxidizer: O_2/CO_2
  - 96.5 mm ID
- Air coflowing at 0.5 m/s



a. Experimental setup

Laser system:
- 3 frequency-doubled Nd:YAG
- Pulse strecher
- 1 J/pulse at 532 nm for 400 ns

Spatial resolution:
- 0.104 mm along 6-mm section of focused beam



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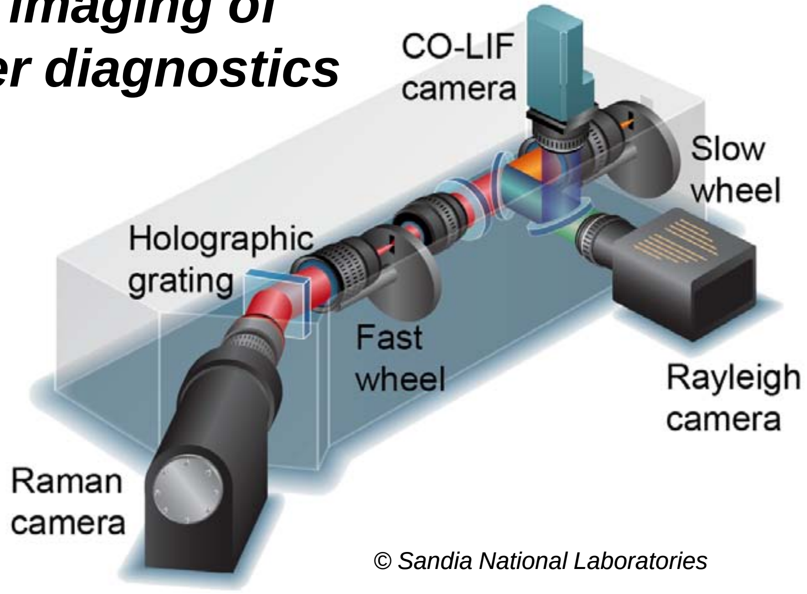
Simultaneous line imaging of Raman/Rayleigh laser diagnostics

Capture on a single-shot basis:
- Local flame temperatures
- Local Concentrations of CO_2, O_2, CO, N_2, CH_4, H_2O and H_2.

Note: CO-LIF and OH-PLIF not used here.



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b. Data processing technique

Hybrid method (Fuest, 2011):

- Based on RAMSES spectra simulation code (Geyer, 2005)

-> Generates Raman spectra libraries for most species over large temperature range (290 K to 2500 K) relatively to optical setup

-> Short series of calibration measurements (one per species) are sufficient to provide most Raman and cross-talk coefficients

- CH_4 and some cross-talk coefficients are not available through RAMSES and are found with calibration measurements over the temperature range

Corrections:

- Signals corrected for CCD background, flat-field, total Nd:YAG laser energy, interferences from laser induced fluorescence, broadband flame luminosity, beam steering through flames and bowing effect through Raman optics

c. Limits and uncertainties

Limits:

- Soot formation at the flame tip leading to interferences on spectra
- OH-PLIF and CO-LIF could not be applied
- Jet Reynolds number limited by CO_2 supply

Uncertainties:

Scalar	Precision σ (%)	Accuracy (flat flames, %)	Accuracy (turbulent flames, %)
T	0.6	2	2
N_2	0.7	2	3
CO_2	3.0	4	6
H_2O	2.2	3	6
F_B	2.1	5	8
CO	5	10	10
H_2	7.5	10	10

(Barlow, 2009)

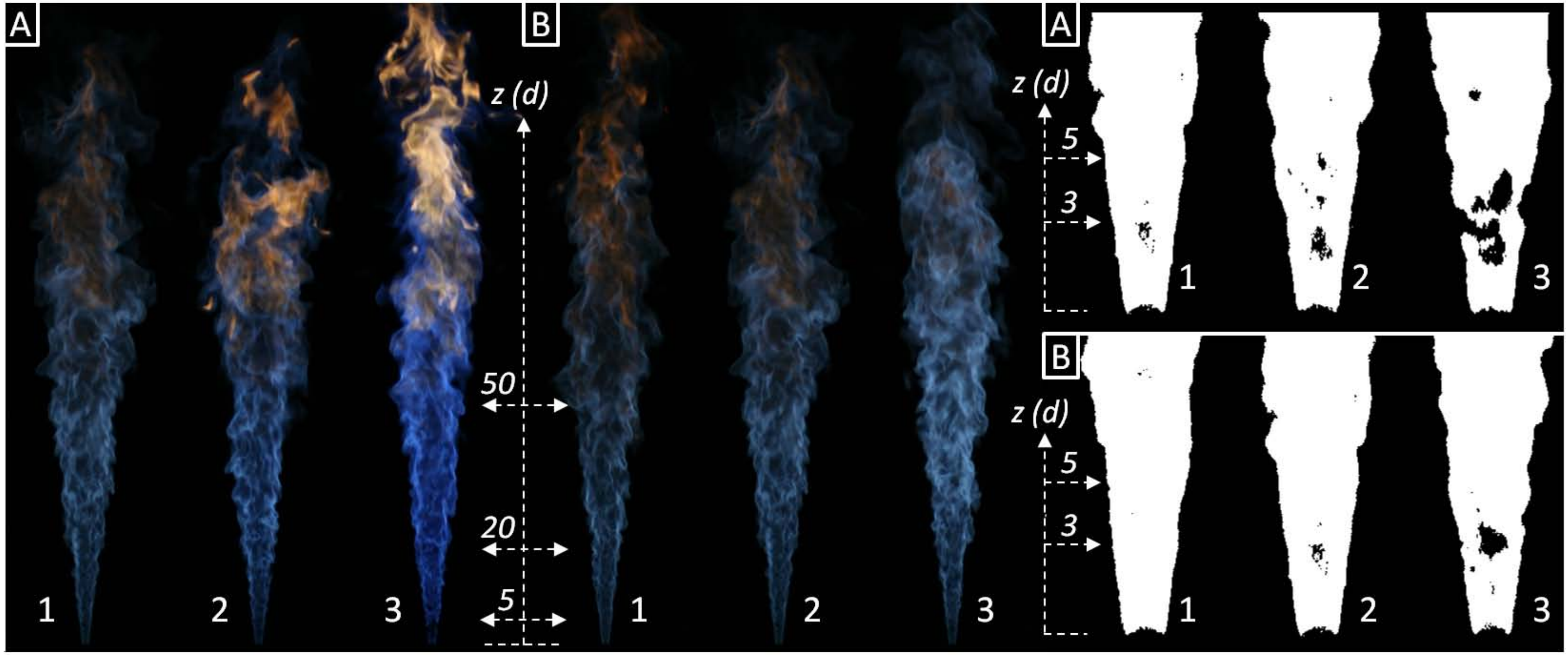
a. Localized extinction (1/3)

Localized extinction:

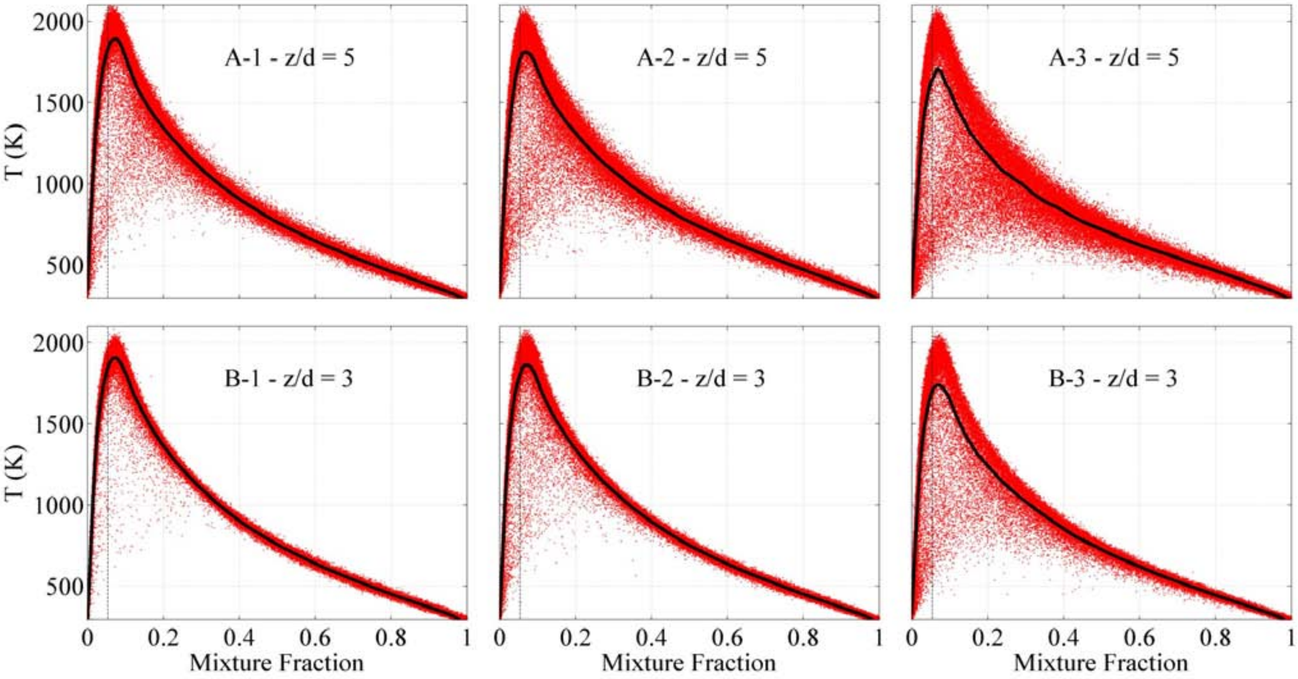
- Occurs when turbulent mixing rates between fuel and oxidizer become competitive with critical rates of chemical reactions

- Takes place in the near-field

- Probability of localized extinction increases with decreasing H_2 content in fuel and increasing jet Reynolds number.



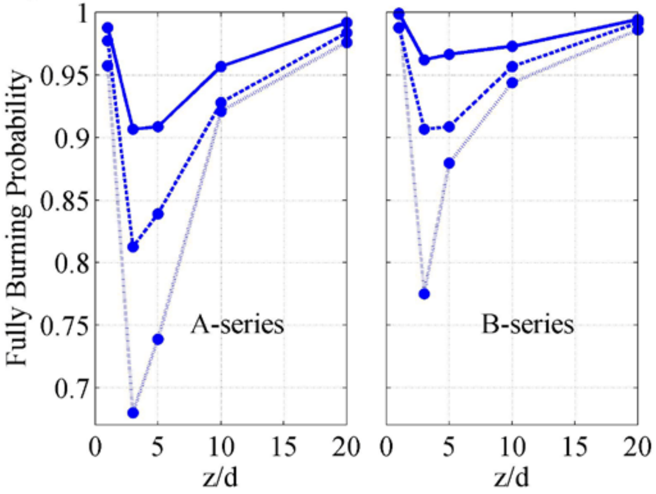
a. Localized extinction (2/3)



Leads to local temperatures drops due to increasing heat removal rates from convection and diffusion along with decreasing chemical reaction rates.

Fully burning probability:

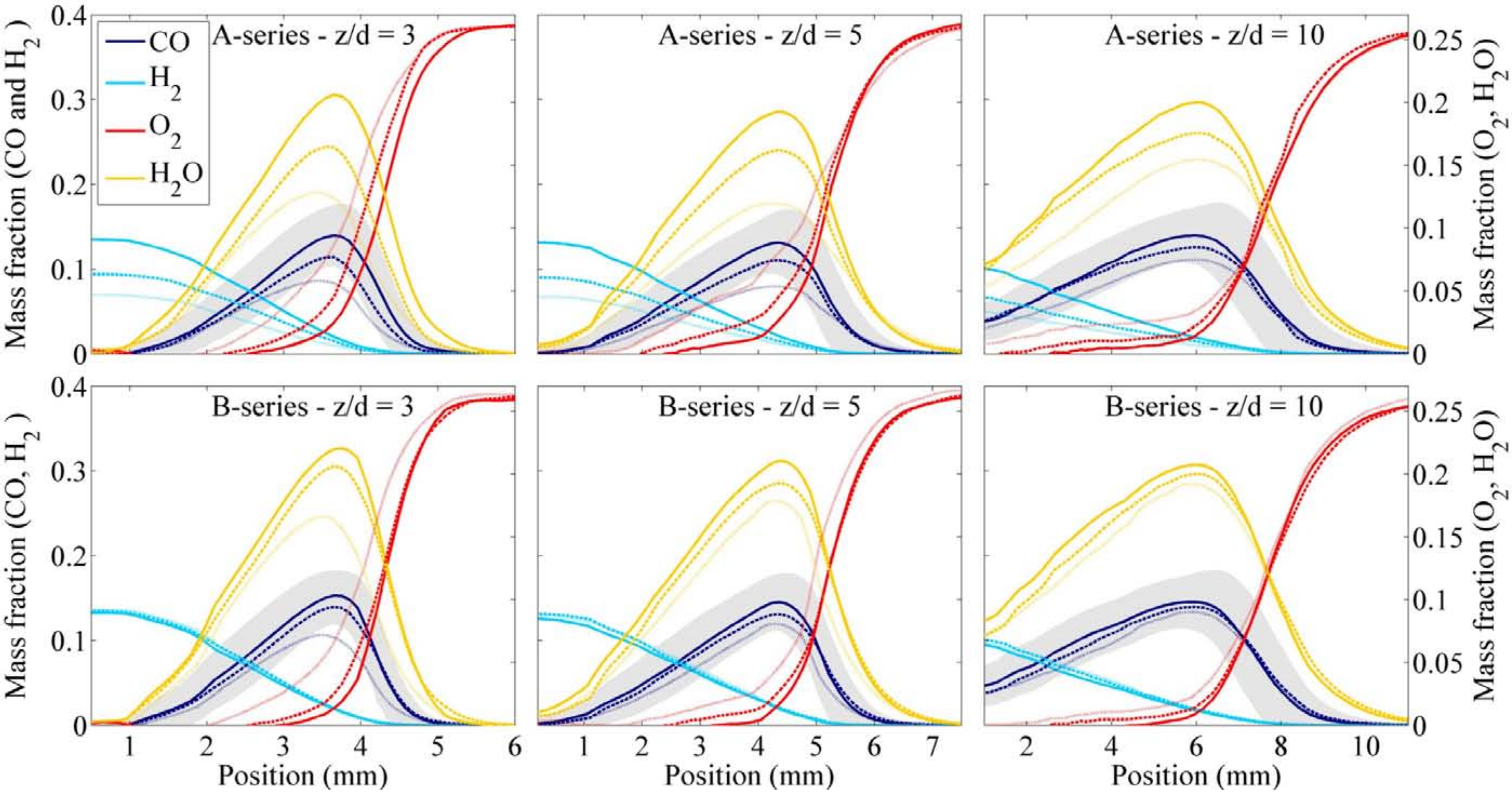
- Enables to quantify the degree of extinction
- Based on pdf of temperatures above T_b in the mixture fraction region $F_{B\text{-}St} \pm \sigma$
- Here, with $T_b = 1700\ K$ and $\sigma = 0.02$



a. Localized extinction (3/3)

Flame structure:

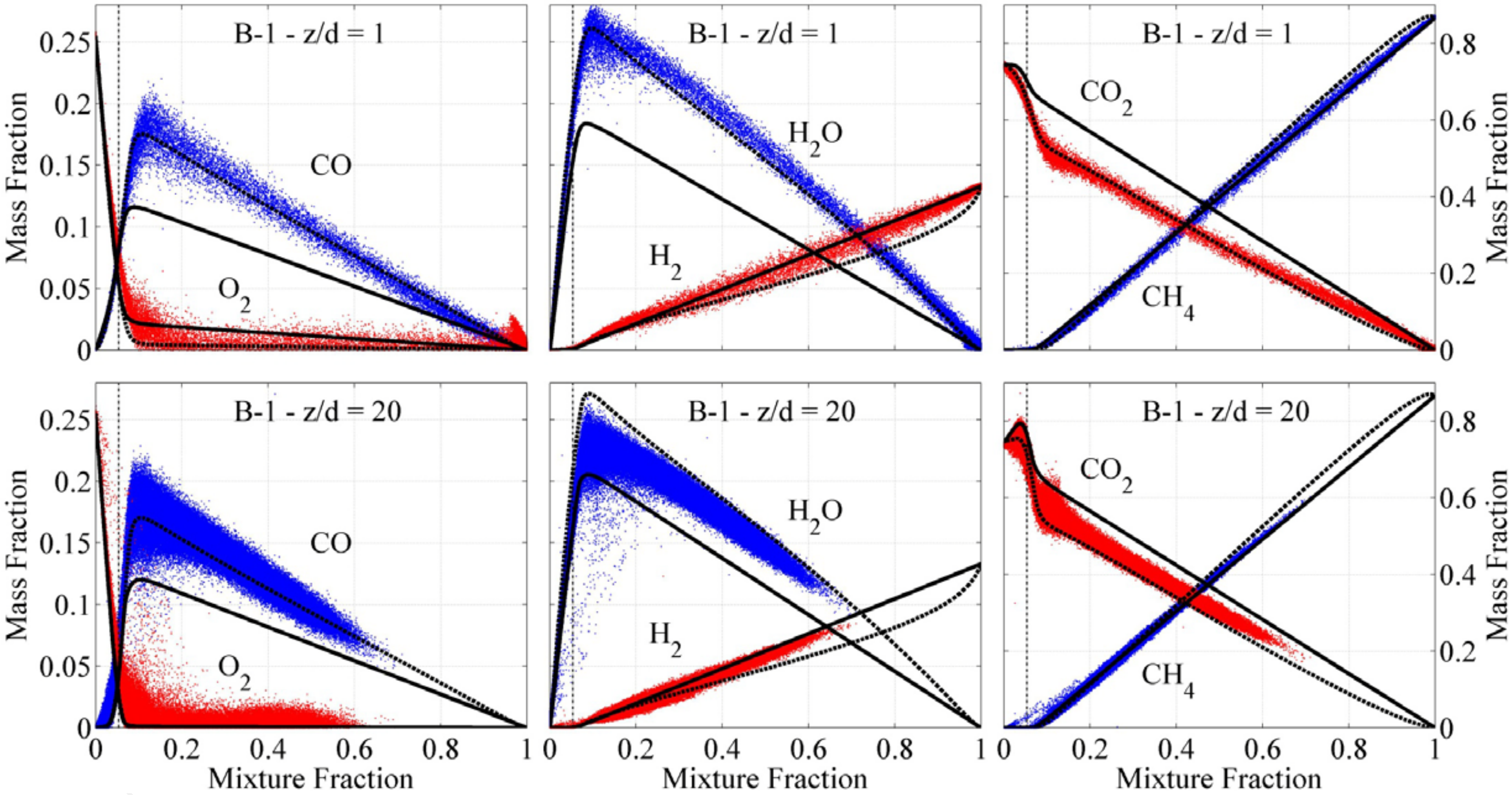
- Unburnt oxidizer shows up in the fuel-rich region (cf. O_2 mass fraction)



b. Differential diffusion (1/3)

Comparison with laminar diffusion flame calculations:

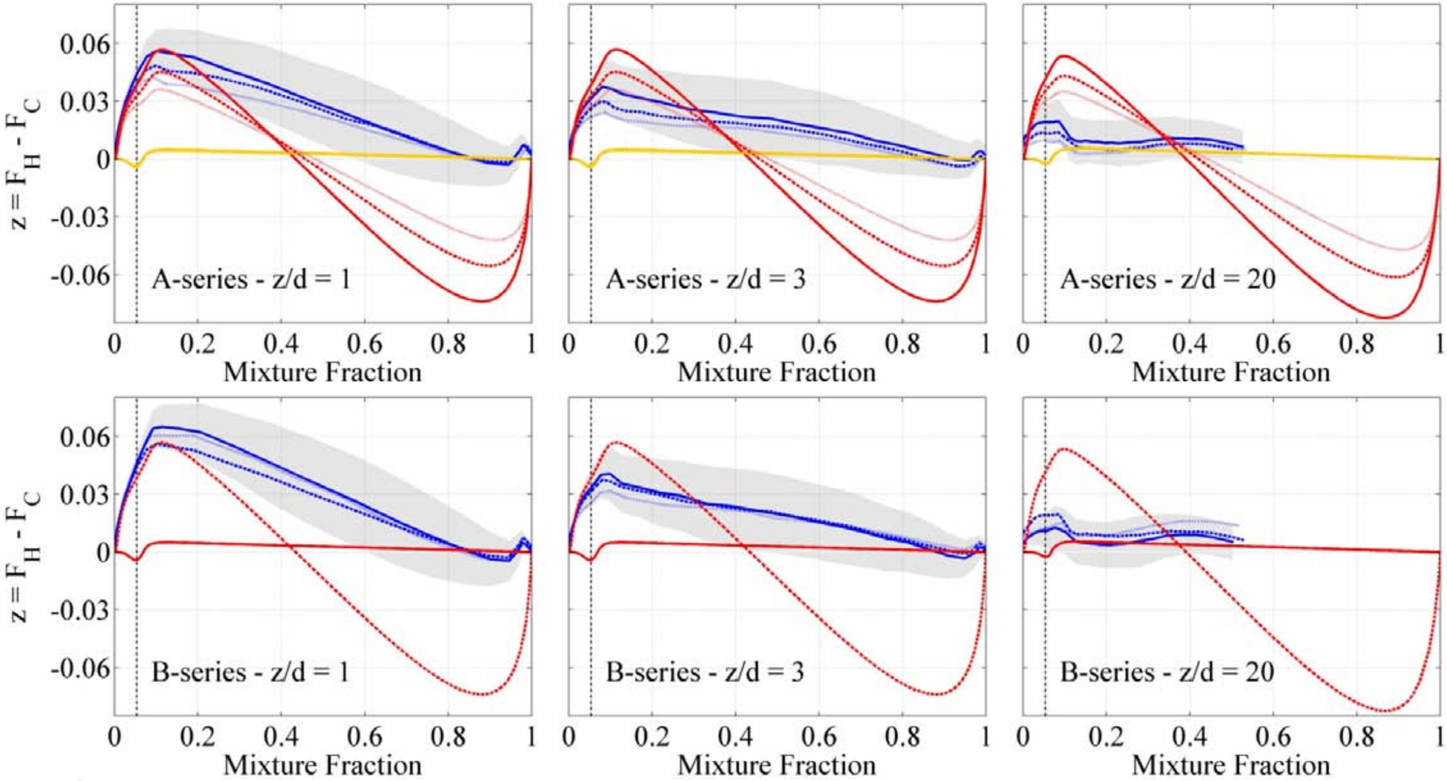
- Match made with CO mass fraction
- Near-field: strong influence of differential diffusion
- Downstream: shift towards equal diffusivities transport regime



b. Differential diffusion (2/3)

Differential diffusion parameter: $z = F_H - F_C$

- Strong influence in near-field but plays minor role farther downstream
- Rich-side less affected by differential diffusion
- Calculations show that influence of differential diffusion is reduced with lower H_2 content in fuel.



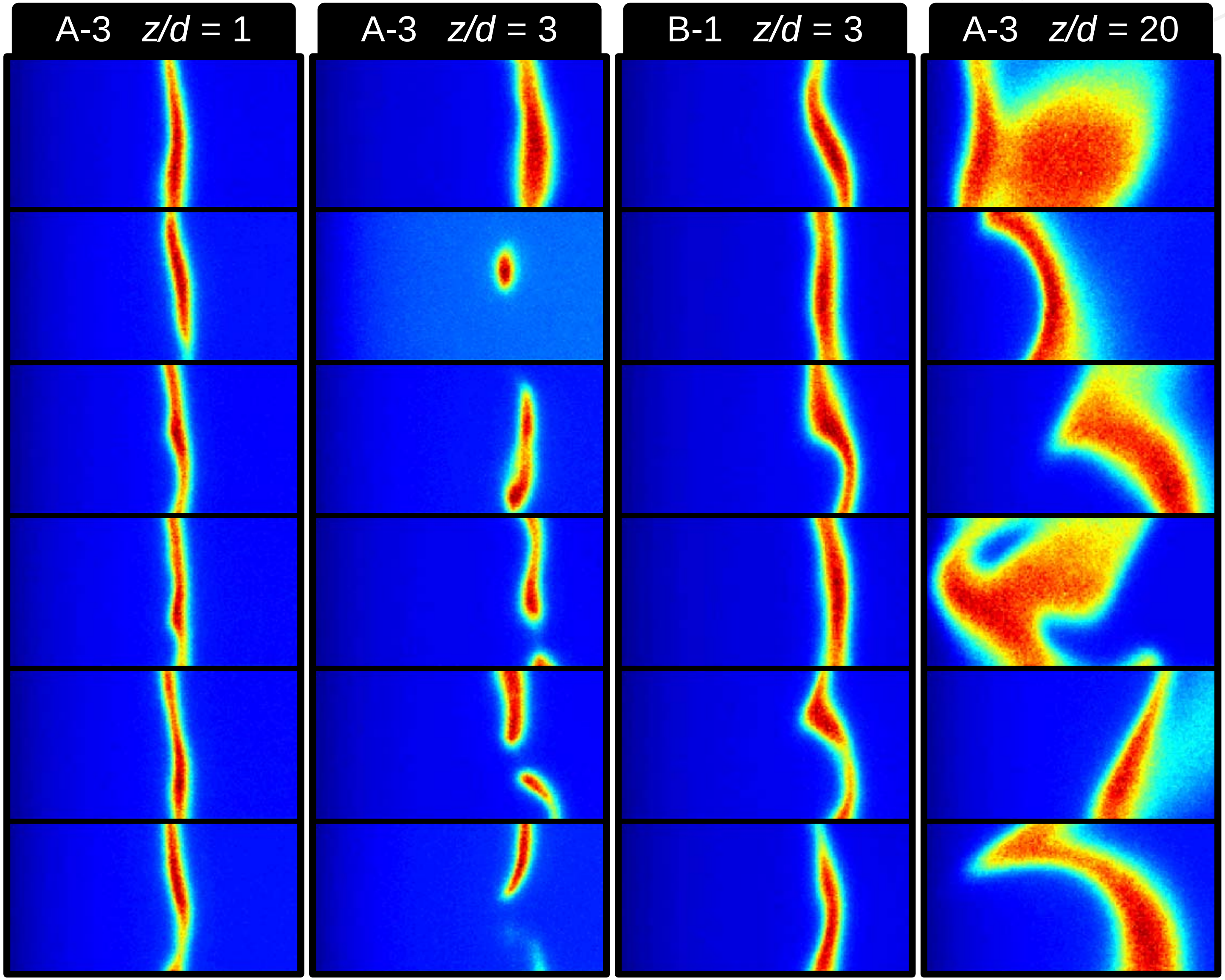
b. Differential diffusion (3/3)

Reaction zone:

Stronger influence when the reaction zone is very thin compared to molecular diffusivity length scales.

-> Helps diffusion of small molecules such as H_2 through the reaction zone.

-> Less influence farther downstream as the reaction zone thickens

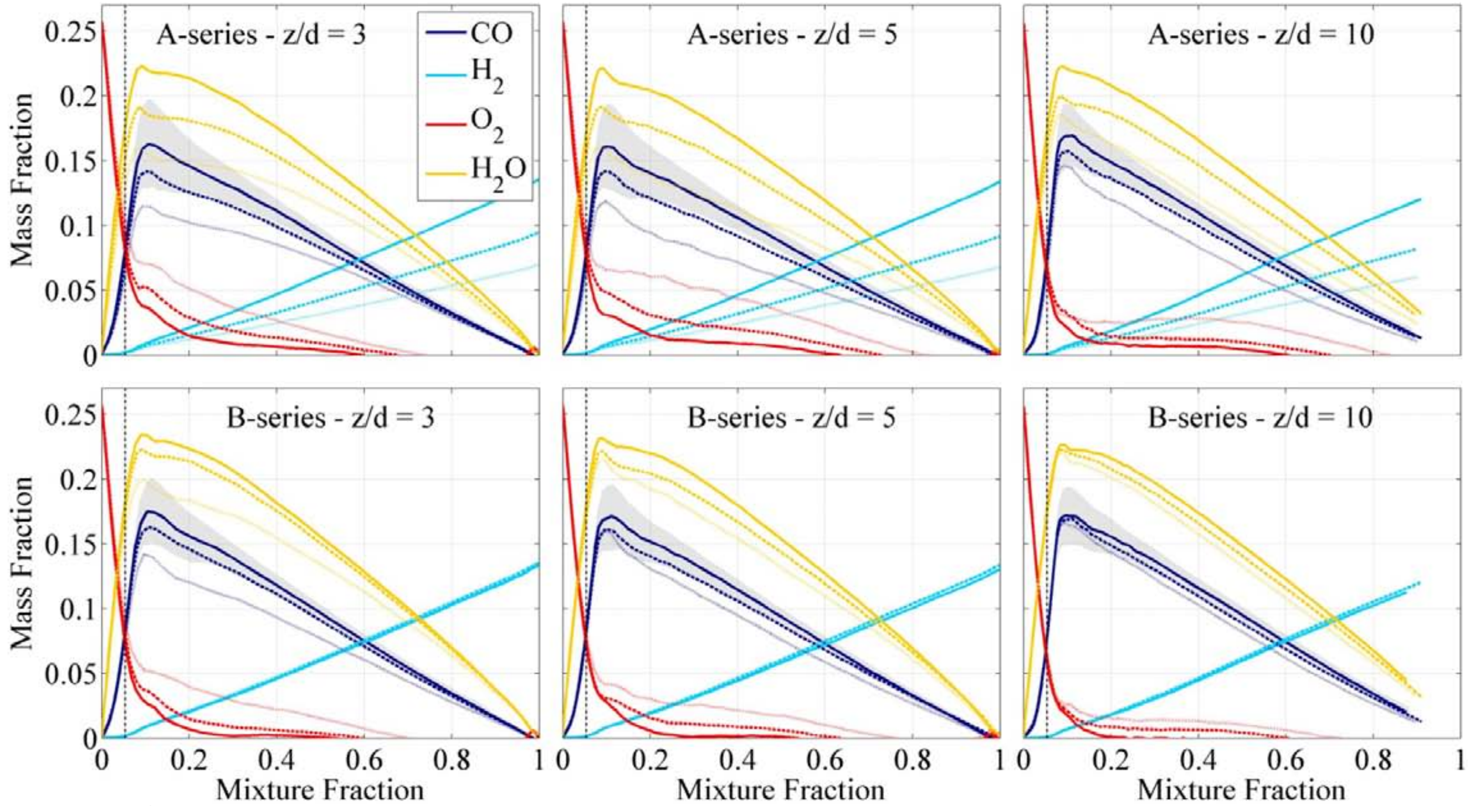


c. High CO levels

Conditional mean of CO mass fraction locally reached up to 0.18

Due to high CO_2-dilution levels:

- CO_2 was not inert but competed primarily with O_2 for atomic hydrogen and lead to formation of CO through the reaction $\boldsymbol{CO_2 + H \rightarrow CO + OH}$



IV. Conclusions and remarks

The objective was to investigate the influence of H_2 content in fuel and jet Reynolds number on localized extinction and flame structure

Localized extinction:

- Higher contents of O_2 on the rich side of the flame
- Fully burning probability was calculated

Differential diffusion:

- Significant level of differential diffusion in the near-field
- Farther downstream, minimized influence as reaction zone thickens

CO levels:

- Enhanced $CO_2 + H \rightarrow CO + OH$ reaction leading to high CO levels

Next steps:

- Make the whole set of results available
- Investigation of influence of O_2 content in oxidizer

Thank you for your attention!

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References:

- **F. Fuest**; R. S. Barlow; D. Geyer; F. Seffrin; A. Dreizler, Proceedings of the Combustion Institute 33 (1) (2011) 815-822.
- **D. Geyer**, 1D-Raman/Rayleigh Experiments in a Turbulent Opposed-Jet, PhD Thesis, TU Darmstadt, VDI-Verlag, Düsseldorf (2005) ISBN 3-18-353306-5.
- **R. S. Barlow**; H. C. Ozarovsky; A. N. Karpetis; R. P. Lindstedt, Combustion and Flame 156 (11) (2009) 2117-2128 DOI 10.1016/j.combustflame.2009.04.005.