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Emission Sensitivity to Non-homogenous Fuel Decomposition

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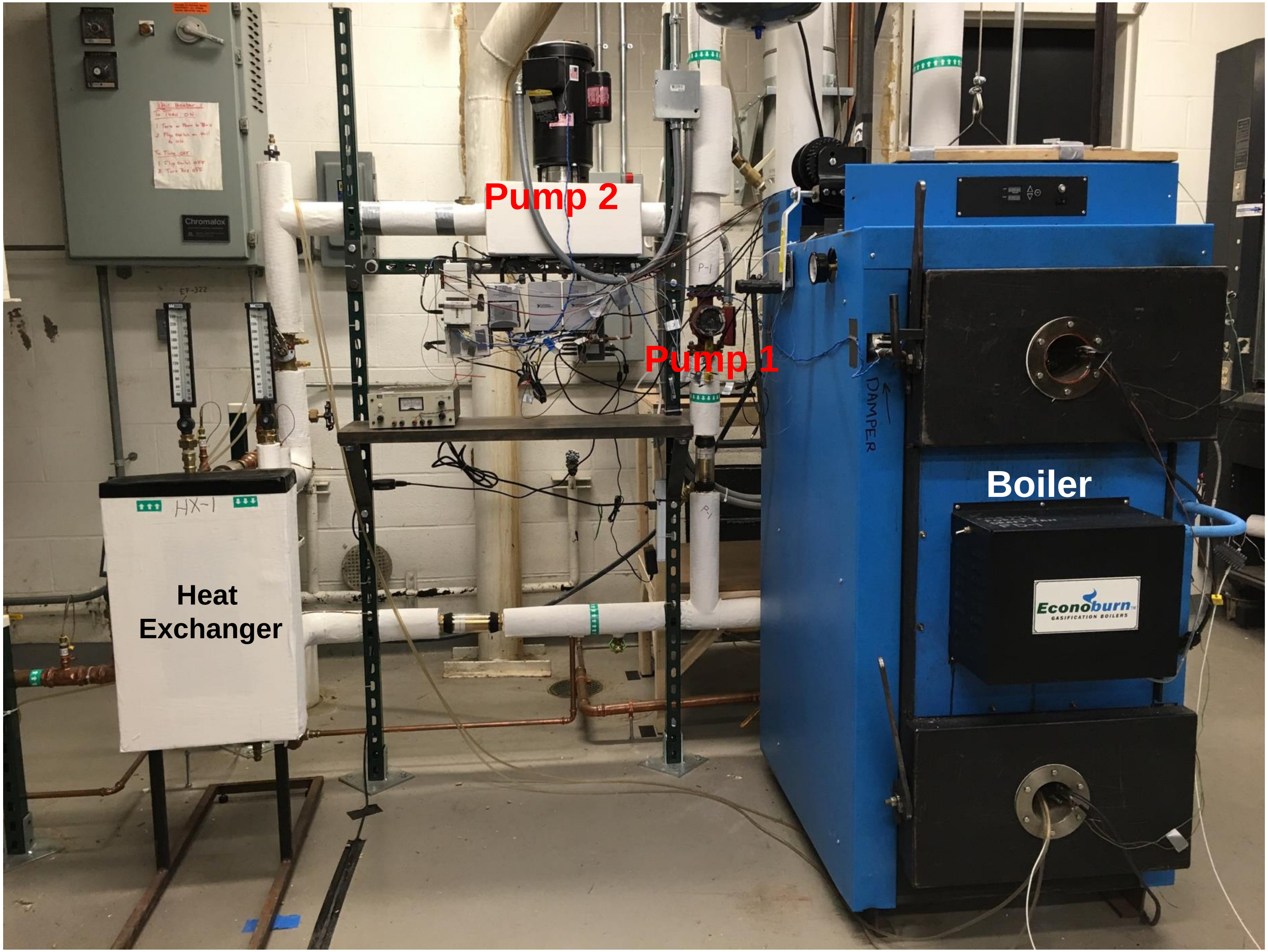
Motivation

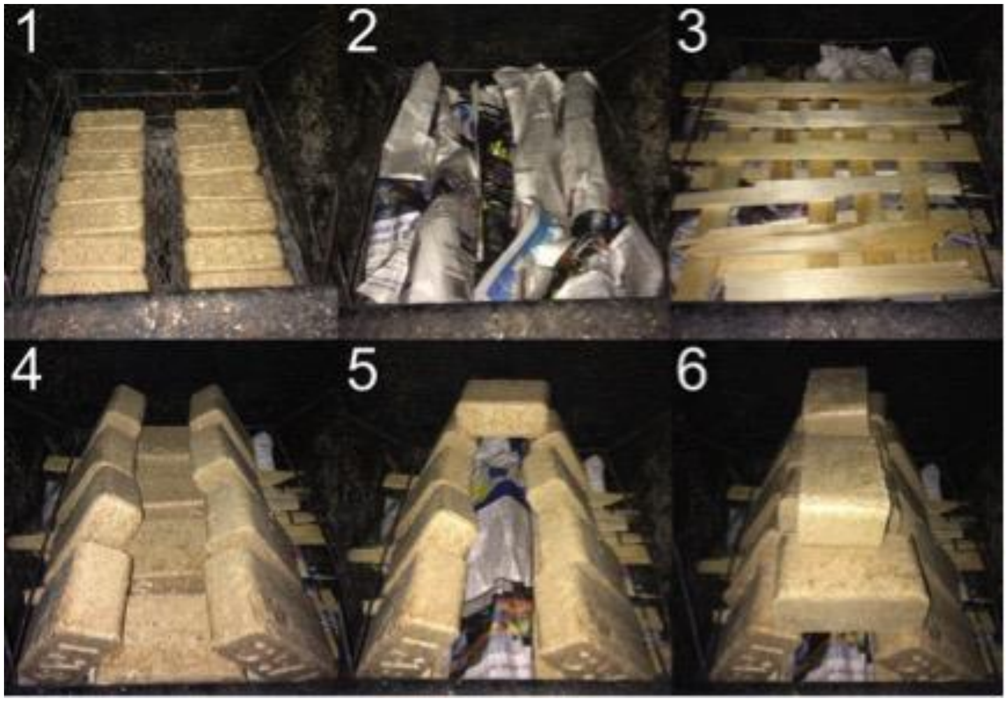
- Biomass stoves and boilers are a significant source of pollution in rural wood burning areas of NY, NH, VT and ME
  - Release of PMs, CO, NO, etc.
- Testing standards
  - Method 28 wood-fired hydronic heaters
  - BNL partial thermal storage (PTS) method
- Fuel does not burn uniformly; simultaneous drying, pyrolysis, charcoal formation/oxidation, at varied rates
- To accurately characterize efficiency and emissions it is important to know the time dependent composition of the fuel
- **Goal**: Understand source of emissions and define reduction strategies

Experimental Setup: Boiler



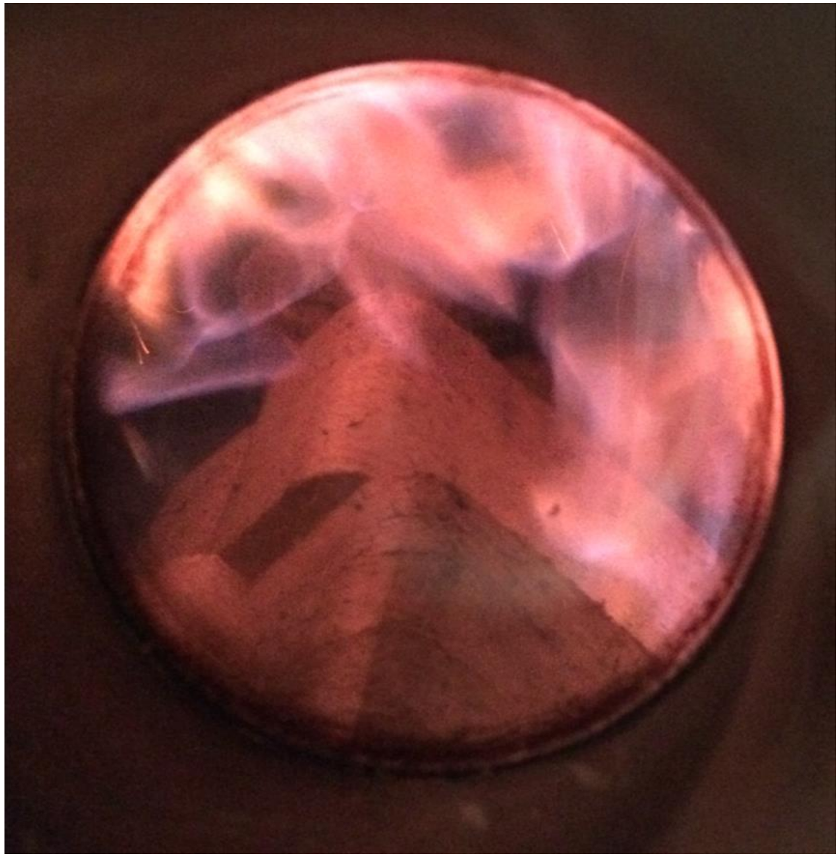
Experimental Setup: Fuel

- BIOBLOCK® fuel source to reduce run-to-run variability
- 100% hardwood – red oak ($CH_{1.7}O_{0.72}N_{0.001}$)
- Consistent shape, size, moisture content ~ 8.3%
- Repeatable loading configuration



Flame Visualization

Upper Chamber



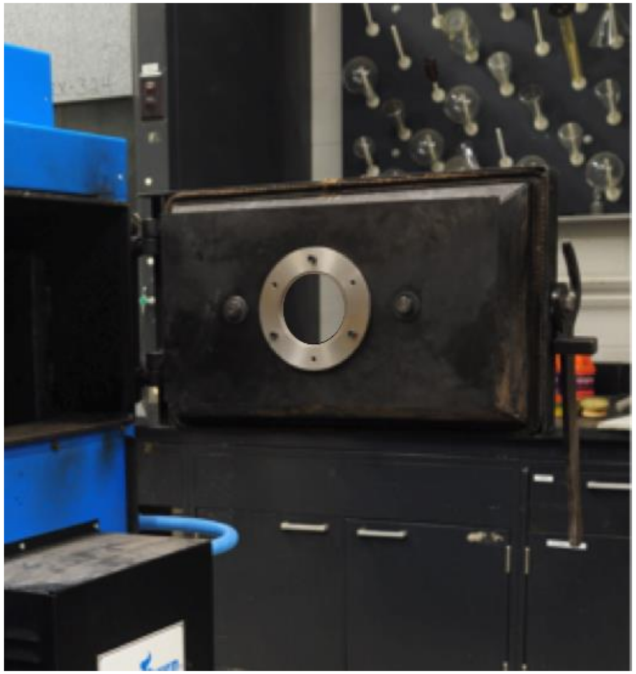
Lower Chamber
High Speed Video

- Slowed down 300 times
- Approximate flow velocity (10 m/s)

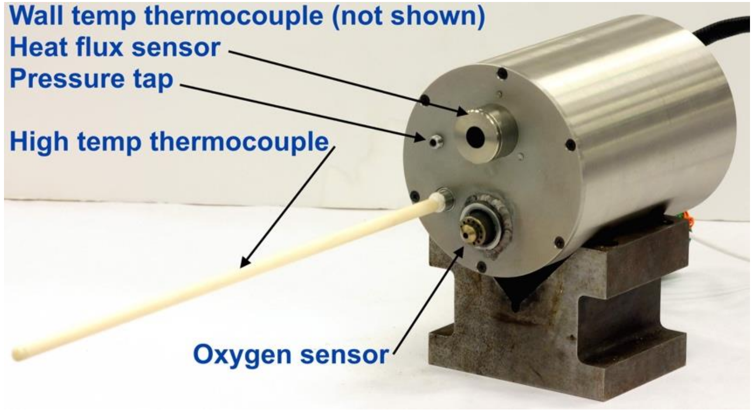
Baseline Emission Diagnostics

Testo model 330-2LL
(CO, NO and O_2)

Instrument Cluster tube



Bosch O_2 Sensor
(correct for water condensation)



Testo Measurement Interpretation

- Testo measures O_2,CO & NO – all other species are <u>inferred</u>
- CO_2 and H_2O are important major species of combustion and are primary indicators of combustion efficiency
- CO_2, H_2O are inferred using a chemical balance:

fuel + air → products

- **Note:** most (all?) current inference methods (incorrectly) assume constant fuel composition

Inferring CO_2 and H_2O

<u>Constant</u> Fuel Formulation (CFF)

$$C_wH_xO_yN_z + a(O_2 + 3.76N_2 + \gamma H_2O) + bH_2O \succ cH_2O + dCO + eNO + fCO_2 + gN_2 + hO_2$$

Fuel **+Air** **+Wood Moisture** **➢ Exhaust Species**

- <u>Constant w, x, y, z</u>
- γ defined by humidity gauge at blower inlet
- b defined by fuel moisture measurement (~8%)

7 unknowns for a, c, d, e, f, g and h

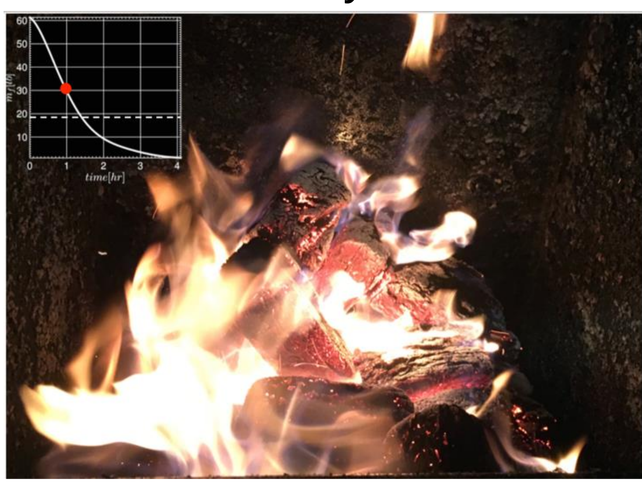
- 4 atom balances (C,H,O,N)

- 3 measurements of CO, NO, O_2

Non-homogenous Fuel Decomposition

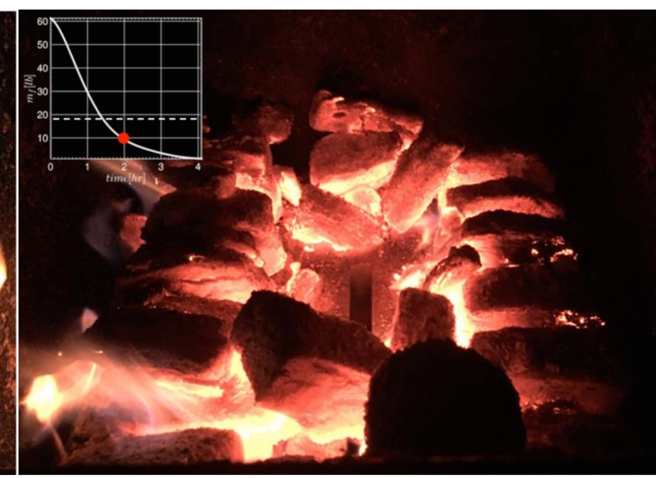
- Three modes of burning
  - **Early** = fuel pyrolysis with large flames (first CO peak)
  - **Intermediate** = pyrolysis and char formation
  - **Late** = charcoal oxidation (second CO peak)

Early



Intermediate

Late



Non-homogenous Decomp. - Lit. Review

Author	Title	Year
Bamford, C.H. et al.	The combustion of wood. Part I	1946
Kanury, A. et al.	Thermal decomposition kinetics of wood pyrolysis	1972
Saastamoinen, J.J. et al.	Drying, pyrolysis and combustion of biomass particles	1988
Ragland, K.W. et al.	Properties of wood combustion analysis	1991
DiBlasi, C.	Processes of flames spreading over the surface of charring fuels: effects of the solid thickness	1994
Jenkins, B.M. et al.	Combustion properties of biomass	1998
Ouedraogo, A. et al.	A quasi-steady shrinking core analysis of wood combustion	1998
Saastamoinen, J.J. et al.	Propagation of the ignition front in beds of wood particles	2000
DiBlasi, C. et al.	Pyrolytic behavior and products of some wood varieties	2001
Glarborg, P. et al.	Fuel nitrogen conversion in solid fuel fired systems	2002
Galgano, A. et al.	Modeling the propagation of drying and decomposition fronts in wood	2004
Fang, M.X. et al.	Kinetic study on pyrolysis and combustion of wood under different oxygen concentrations by using TG-FTIR analysis	2006
Liu, Q. et al.	Mechanism study of wood lignin pyrolysis by using TG-FTIR analysis	2008

Inferring CO_2 and H_2O

<u>Variable</u> Fuel Formulation (VFF) – x, y, z are unknowns

$$C_1H_xO_yN_z + a(O_2 + 3.76N_2 + \gamma H_2O) \succ cH_2O + dCO + eNO + fCO_2 + gN_2 + hO_2$$

Effective Fuel **+Air** **➢ Exhaust Species**

Advantages:

– fuel composition is NOT specified

– fuel moisture content is NOT specified

10 unknowns for a, c, d, e, f, g, h <u>plus</u> x, y, z,

- 4 atom balances (C,H,O,N)

<u>- 3 measurements of CO, NO, O_2 .</u>

= 3 more constraints (or measurements) required

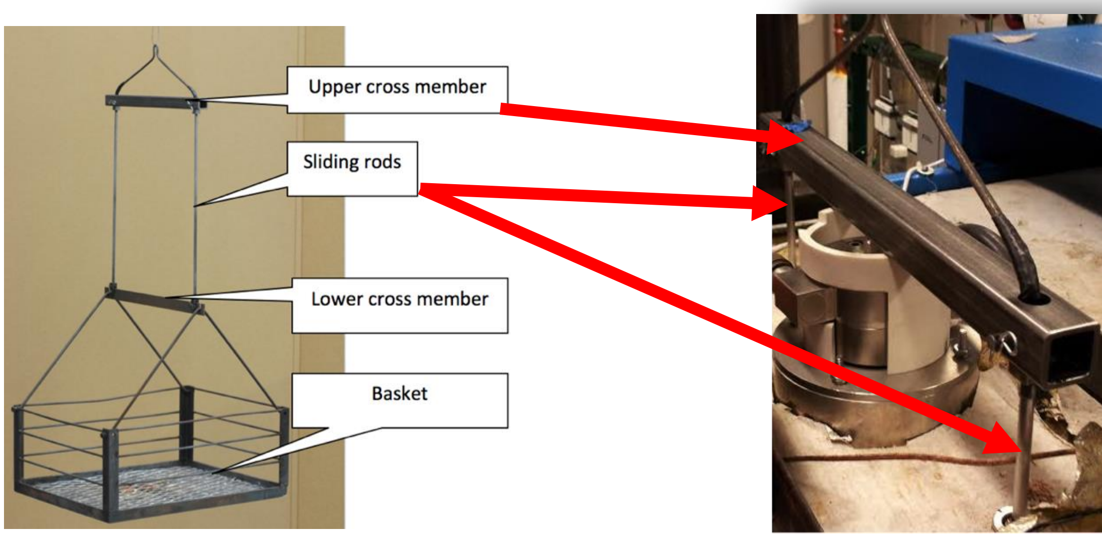
<u>- assume NO comes from fuel (e=z and g=3.76a)</u>

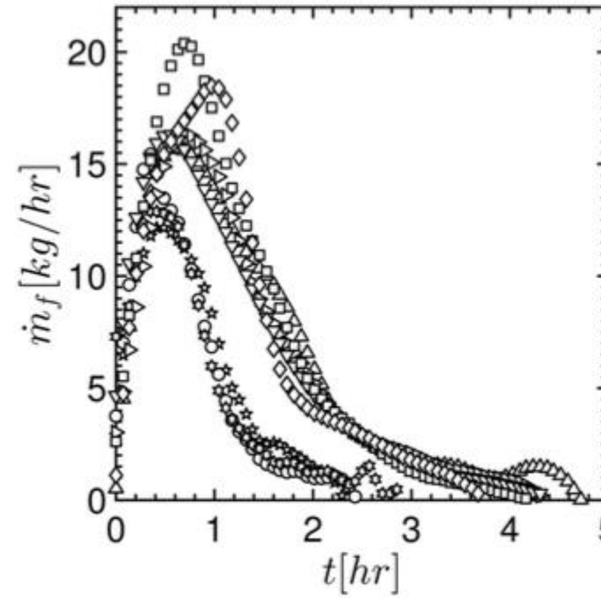
= 2 more constraints (or measurements) required

1) H/O ratio = 2 in the fuel
2) Measurements of fuel mass loss and air flow rates

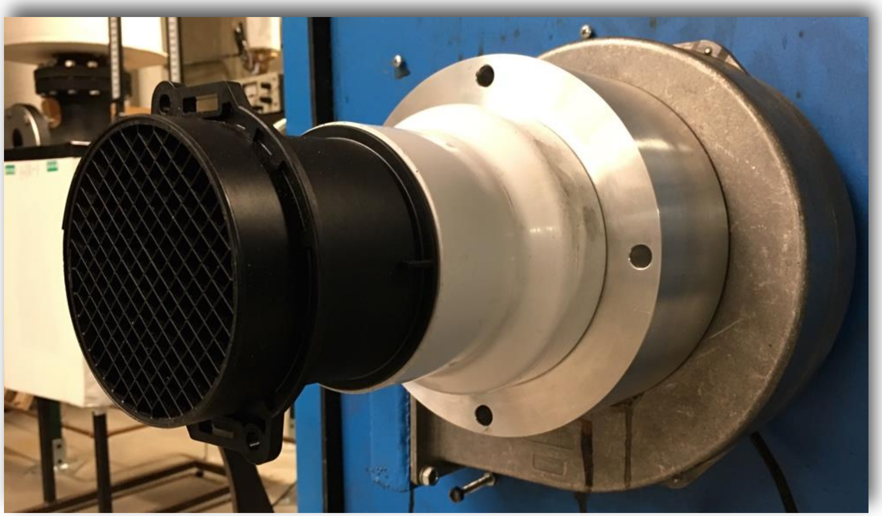
Measuring Fuel Mass Loss and Air Flow Rates

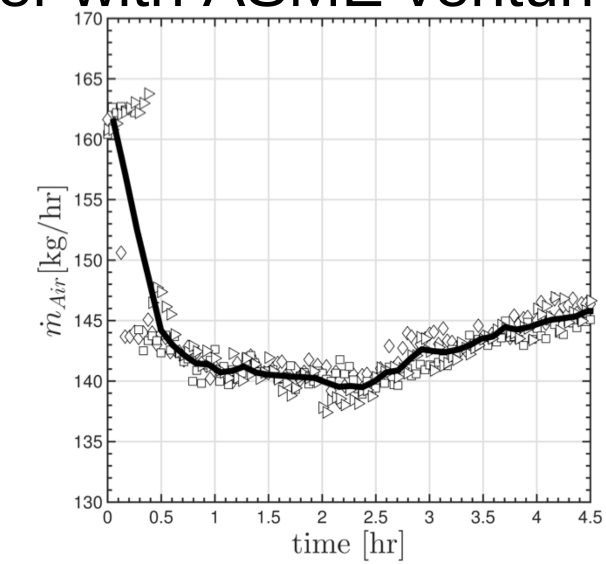
Real-Time Fuel Burn Rate Monitor





Airflow measured using calibrated Bosch meter with ASME venturi

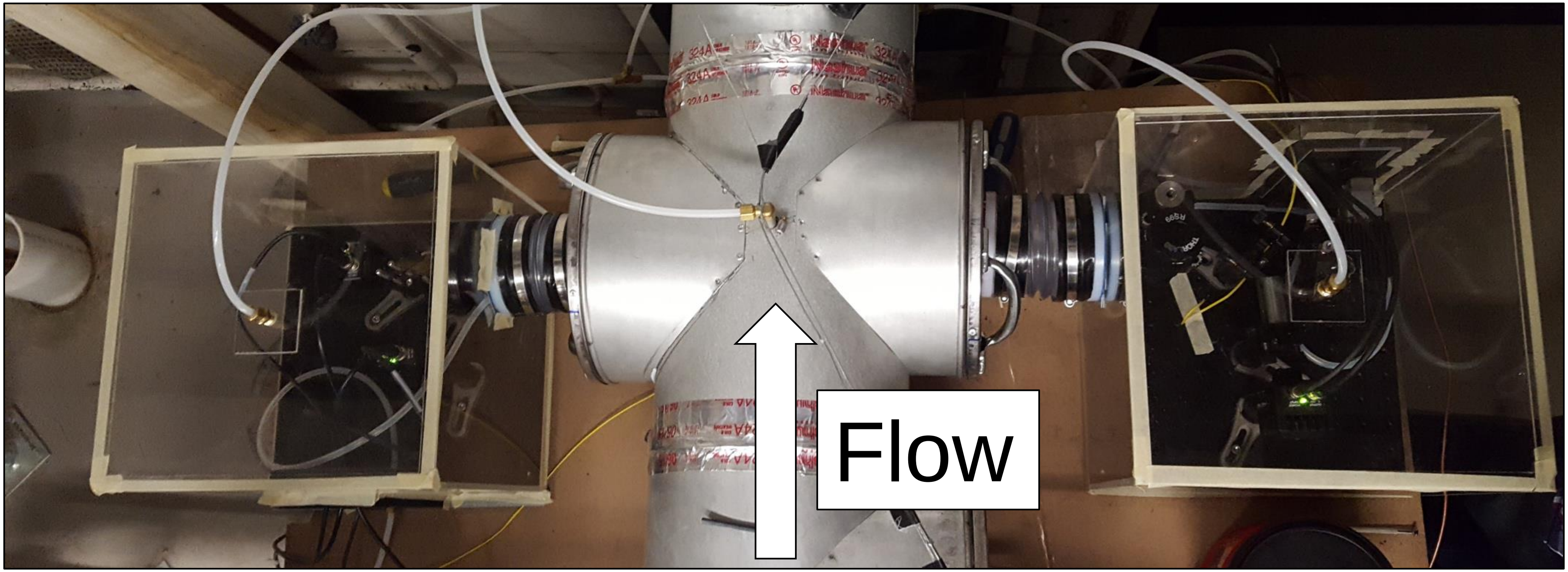




Validation using TDLAS

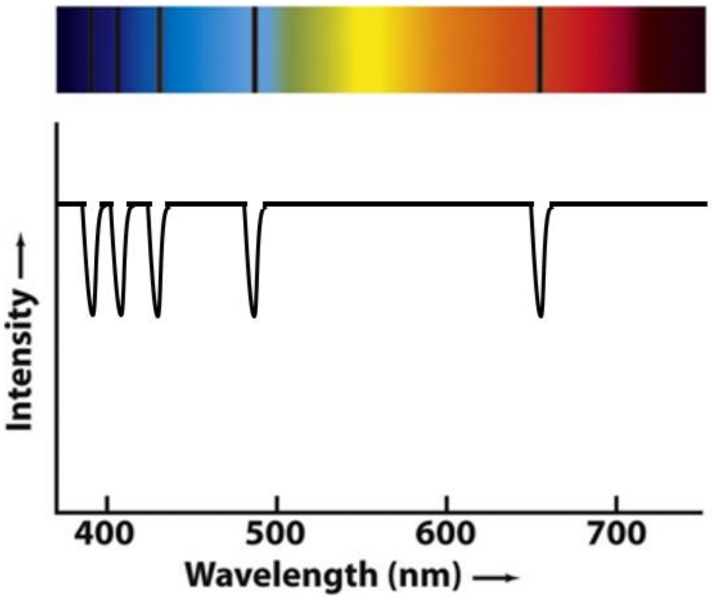
TDLAS = Tunable Diode Laser Absorption Spectroscopy

Top-Down View



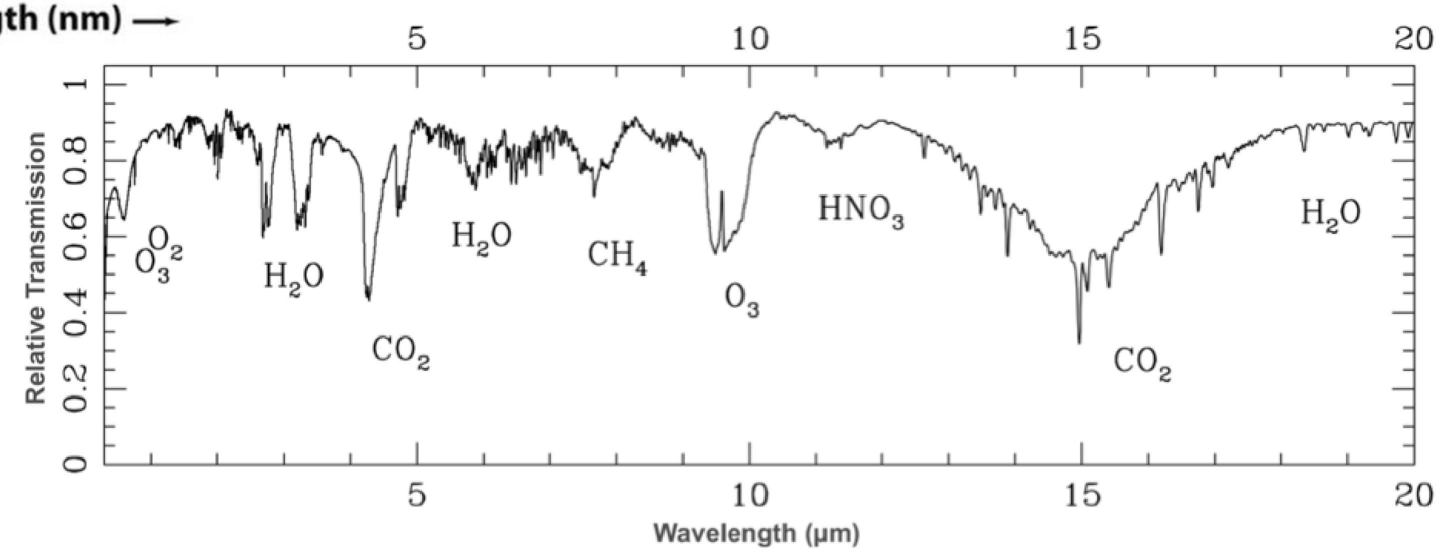
Catch Flue Pitch

TDLAS Primer

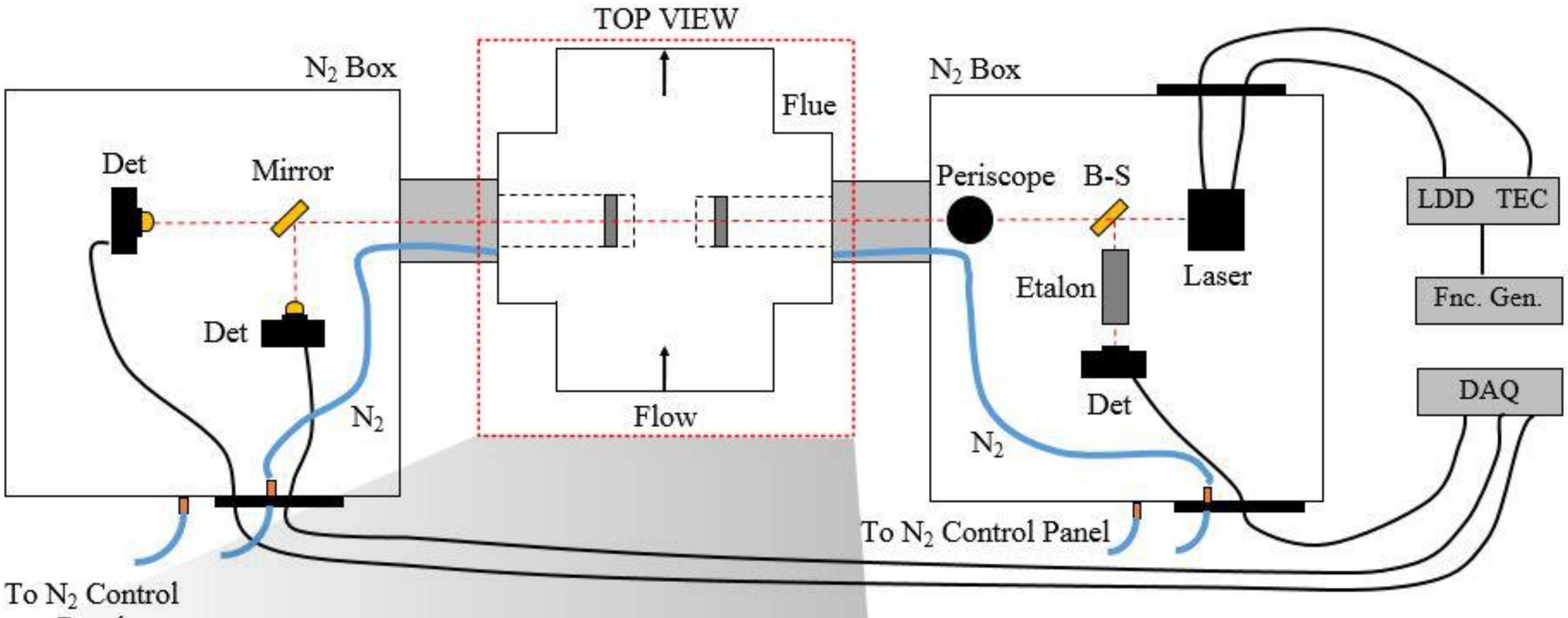


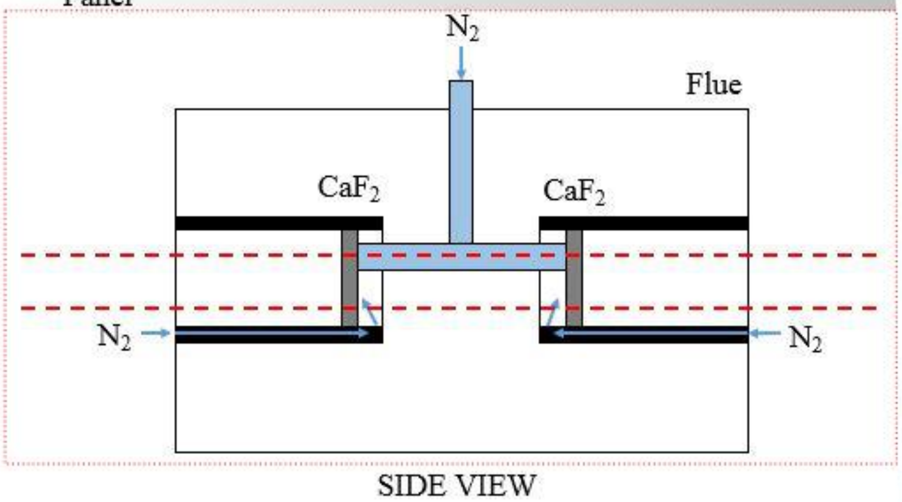
Gases absorb light at different wavelengths

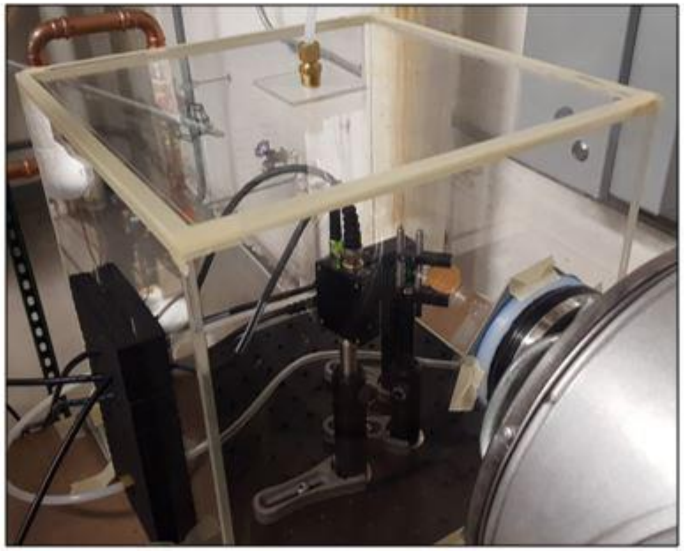
Calculate properties of gas from shape of absorption features



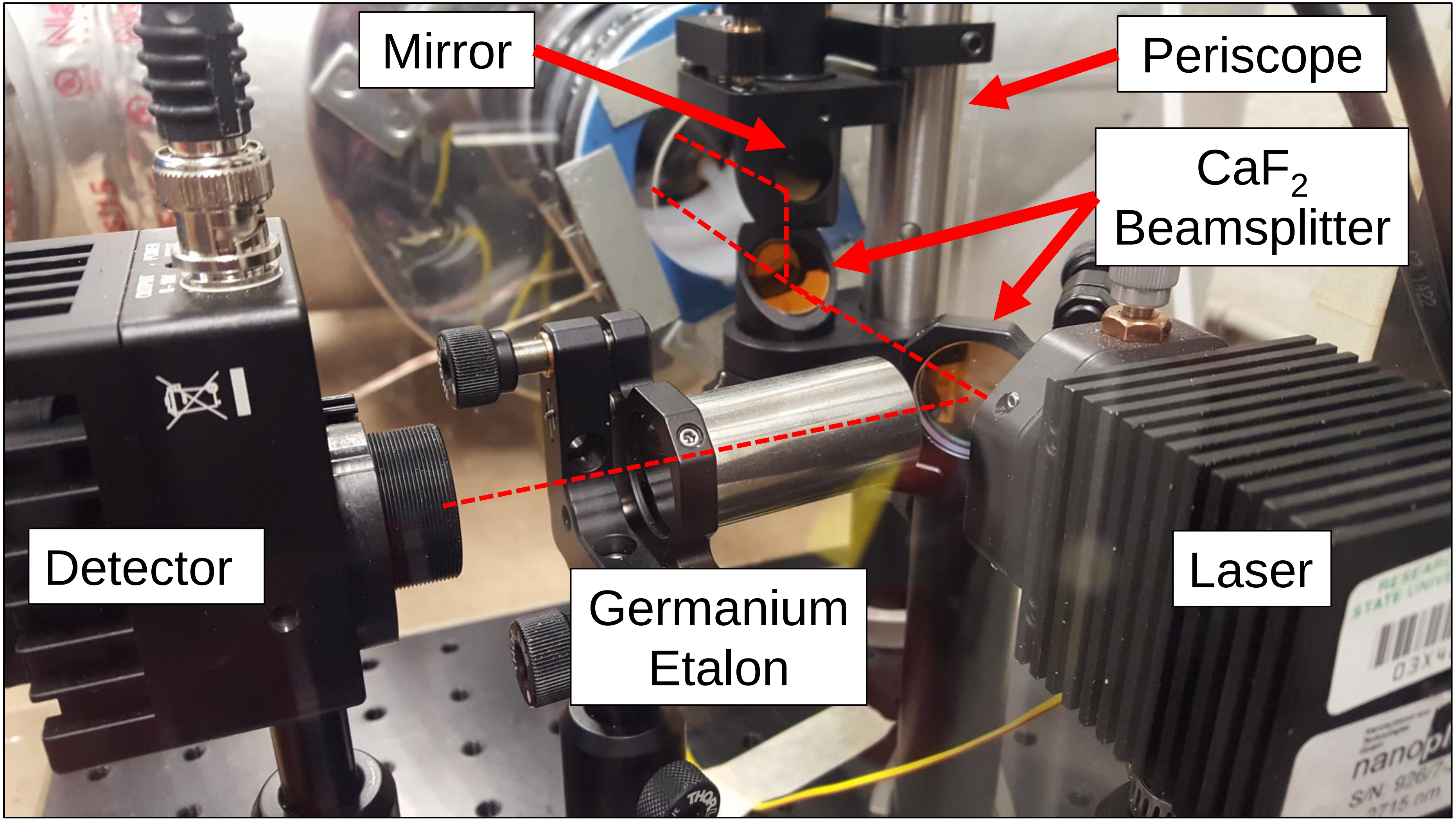
TDLAS Experimental Setup





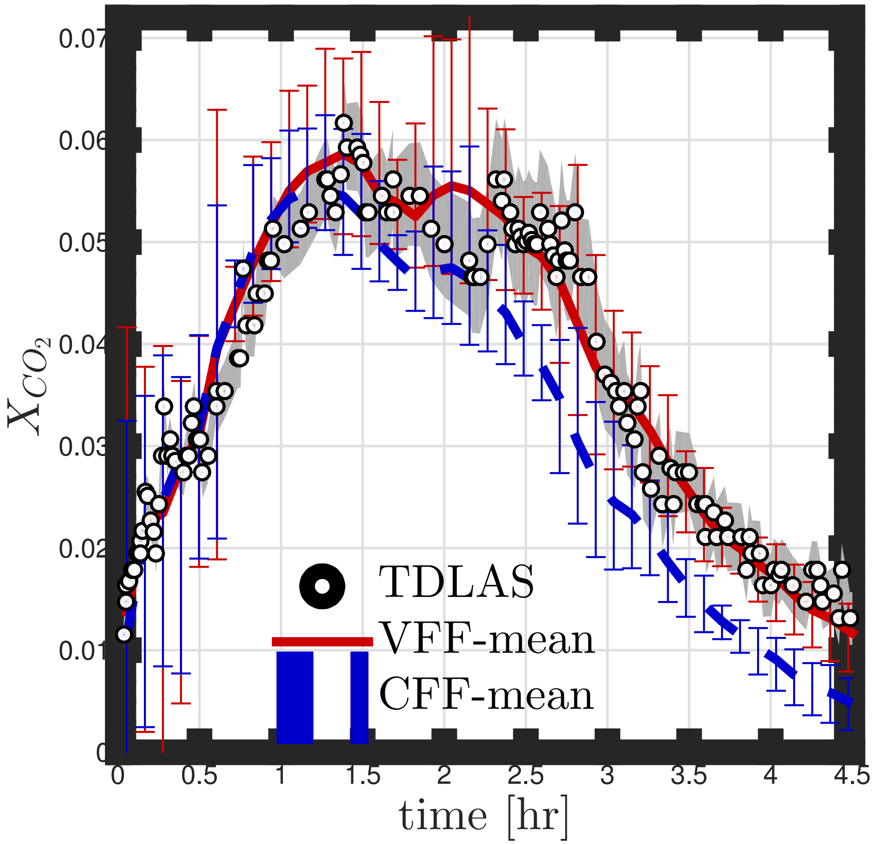


TDLAS Experimental Setup – Pitch Side

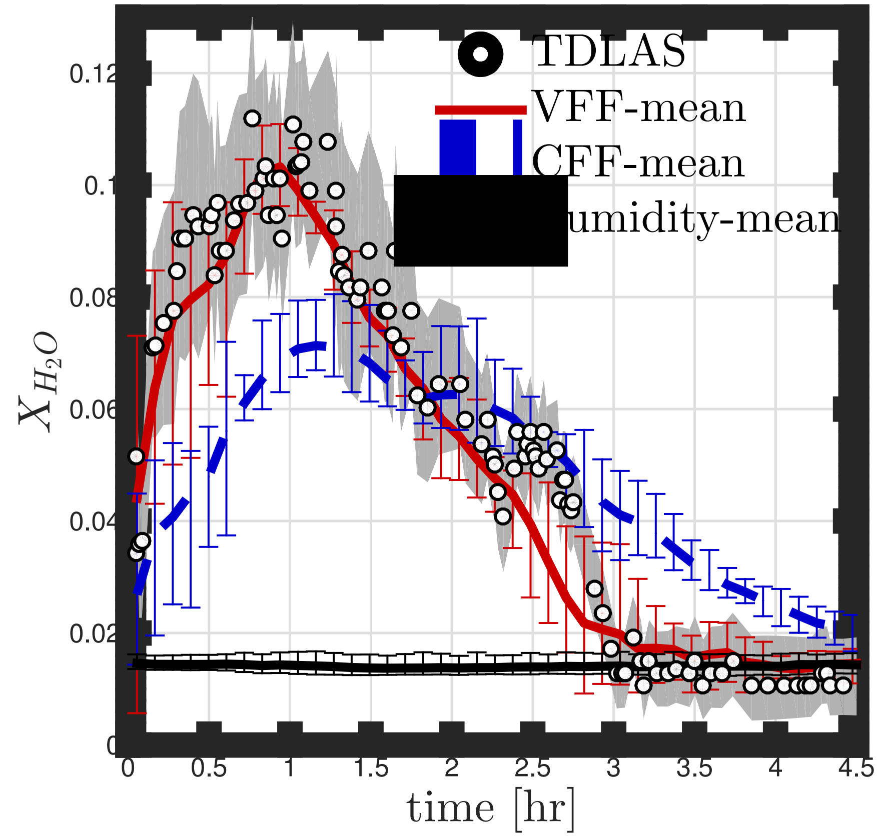


Results: Flue CO_2 and H_2O emissions

X_{CO2} vs. time

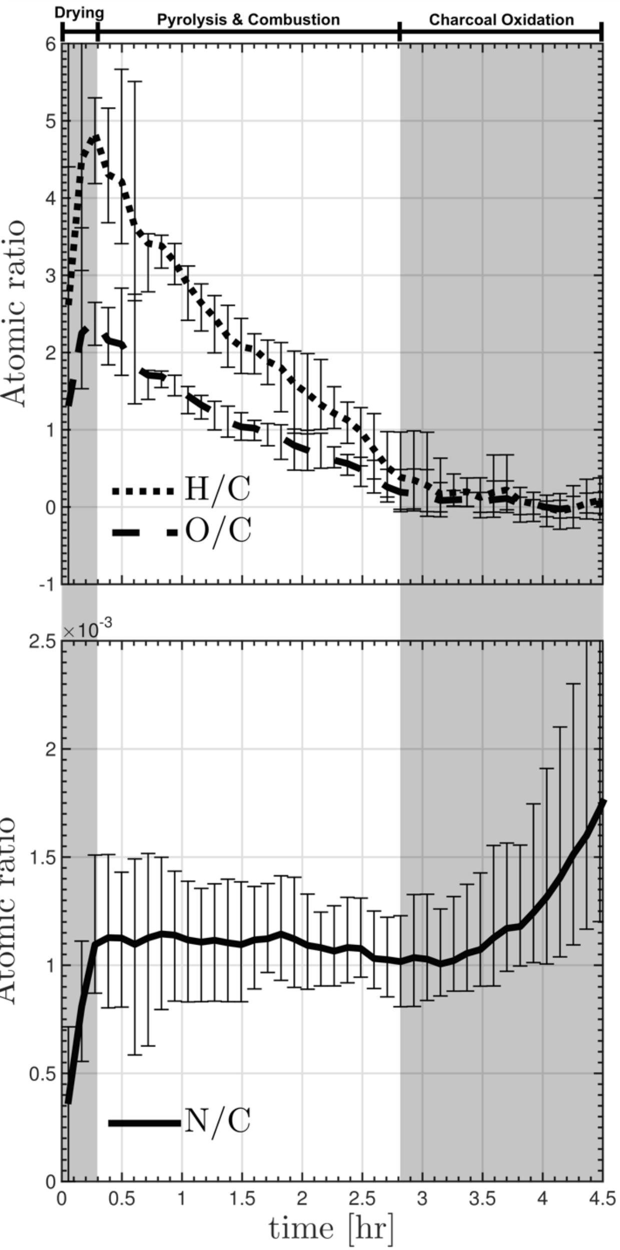


X_{H2O} vs. time



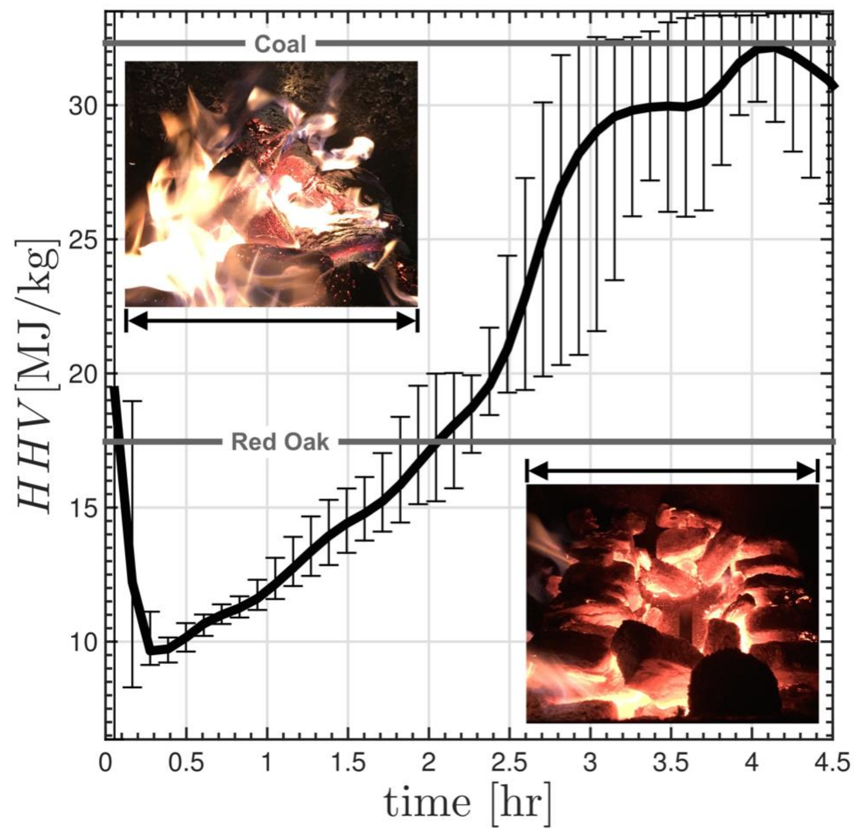
- VFF and TDLAS match !!!

Consequences: Time Dependent Fuel Comp. & HHV



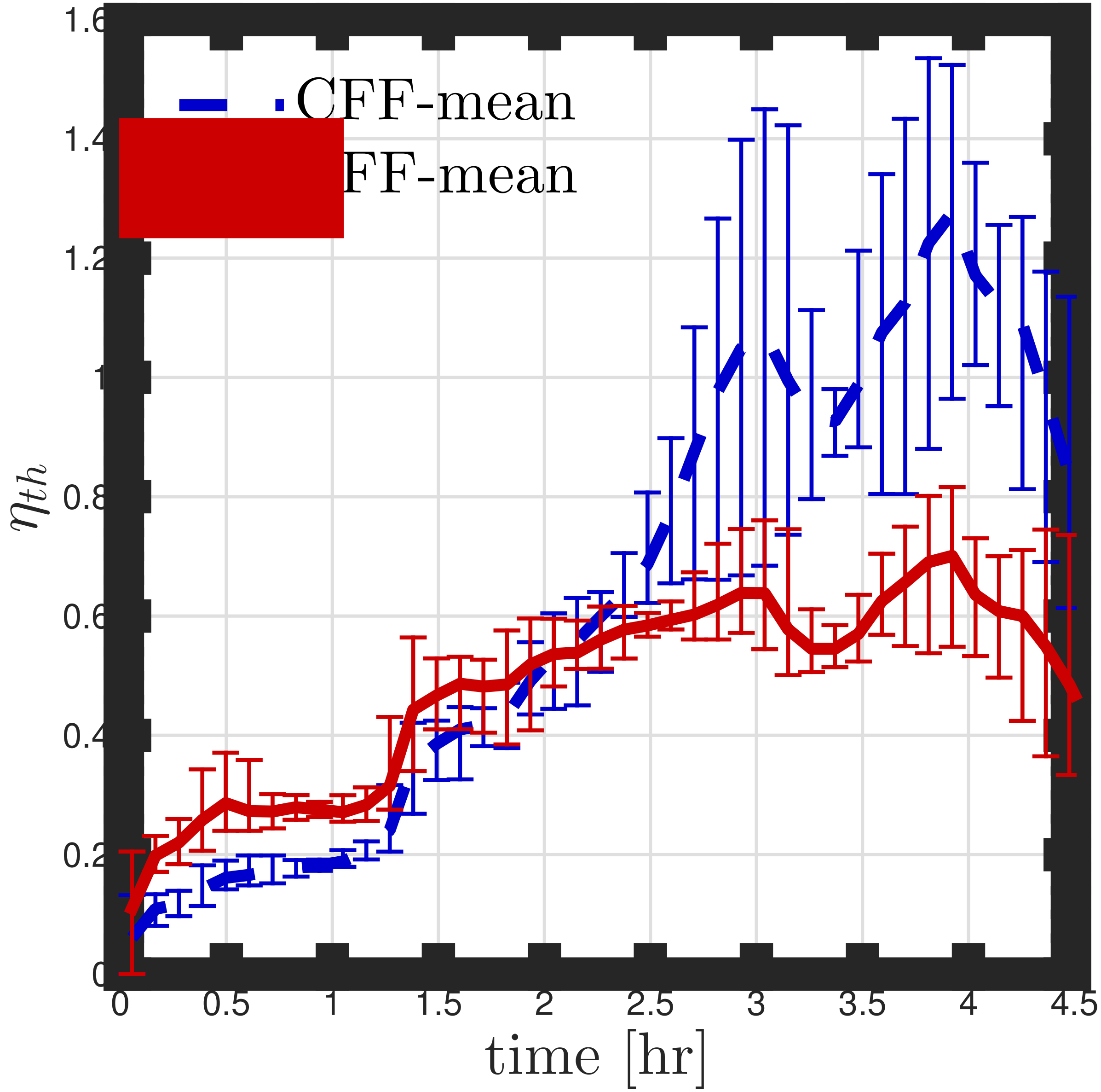
- New inference allows for the <u>prediction</u> of the time dependent fuel composition and instantaneous heating value

* HHV=(33.5[C%] + 142.3[H%] - 15.4[O%] - 14.5[N%]) x 10^{-2}



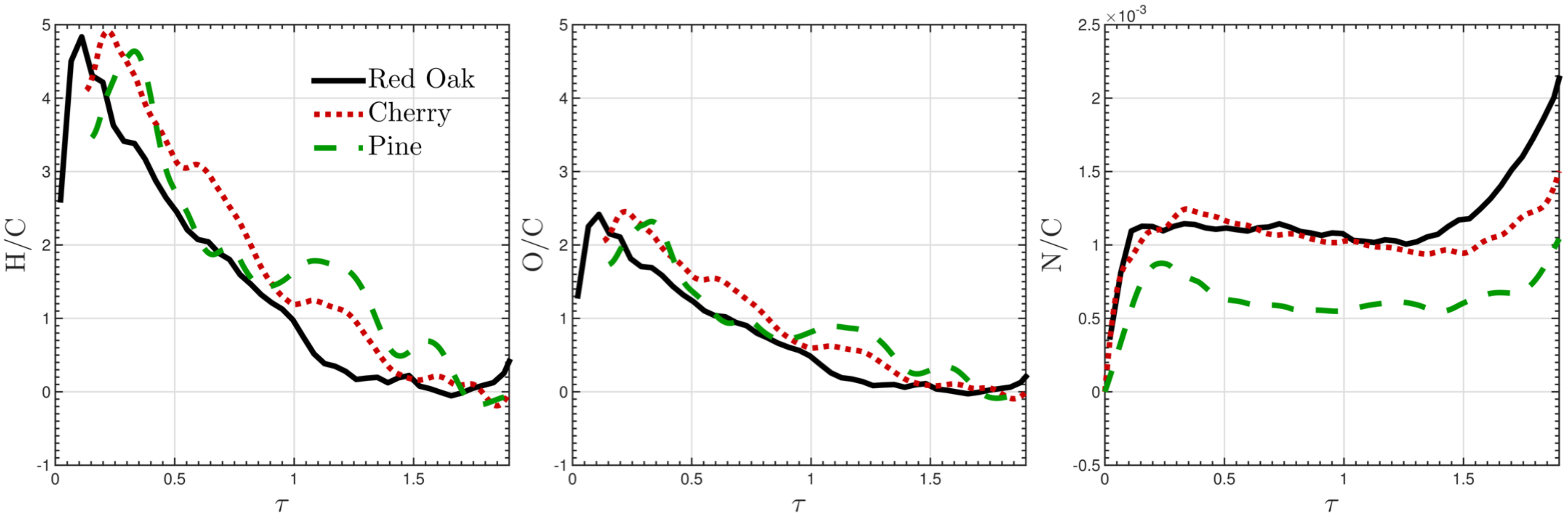
* Demirbas, Combustion characteristics of different biomass fuels, Prog. in Energy & Comb. Sci. 30 (2) (2004) 219–230.

Consequences: Instantaneous Thermal Efficiency

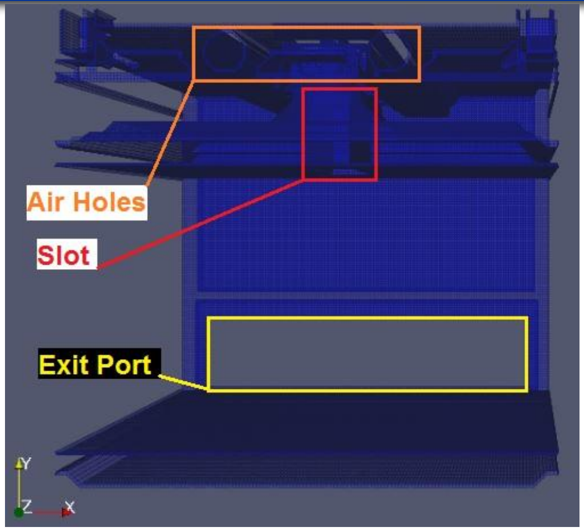


Consequences: Fuel Sensitivity Interpretation

- Fuel:
  - Red Oak (BIOBLOCKS®)........... $C_1H_{1.7}O_{0.72}N_{0.001}$
  - Cherry cord-wood……………….... Comparable to oak
  - Pine 2x4 (no bark) ………………. $C_1H_{1.7}O_{0.83}$
- Comparable H/C and O/C ratios among various wood species
- Lower N/C ratio observed with pine due to absence of nitrogen rich bark

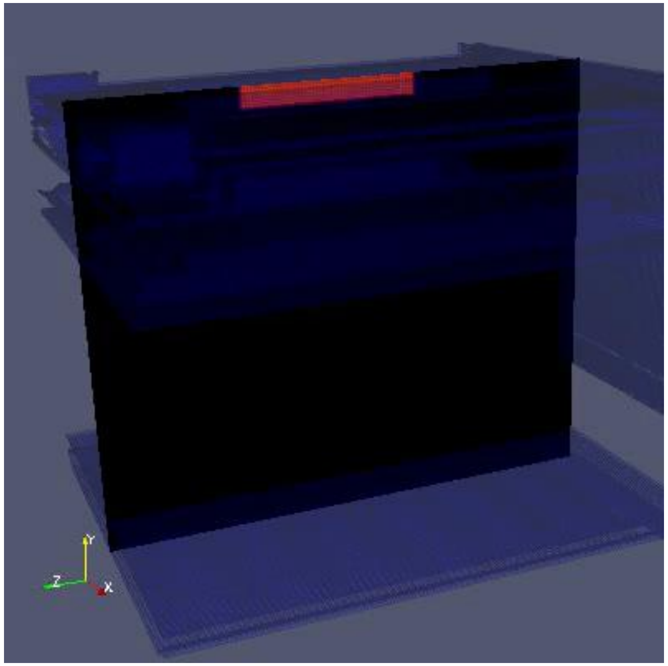


Consequences: CFD Modeling

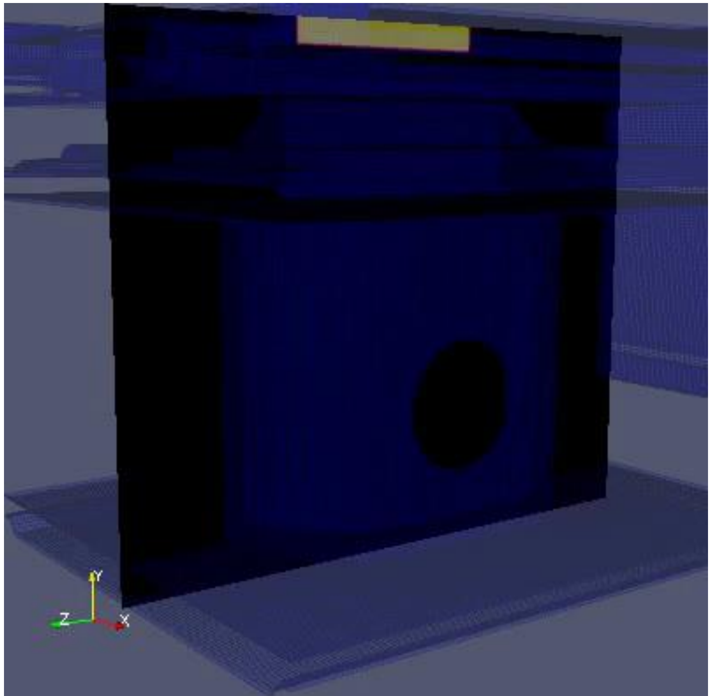


- Time varying fuel for CFD combustion models
  - Prediction of spatial and time dependent temperature and species fields
- Explore CO reduction methods for lower chamber

<u>Baseline</u>



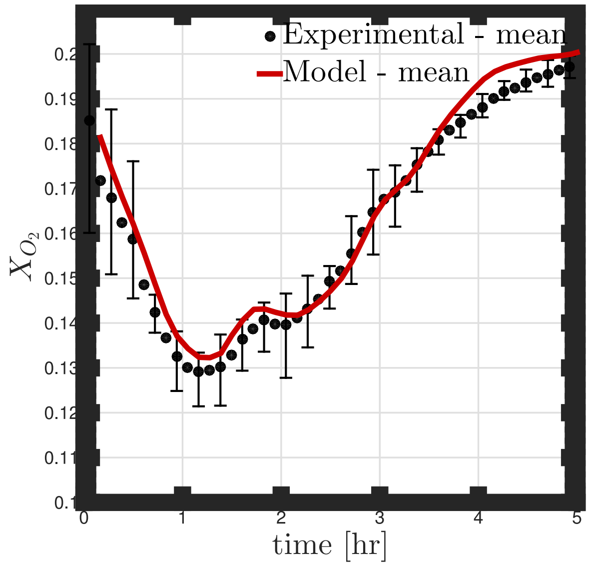
<u>Mixing Pot</u>



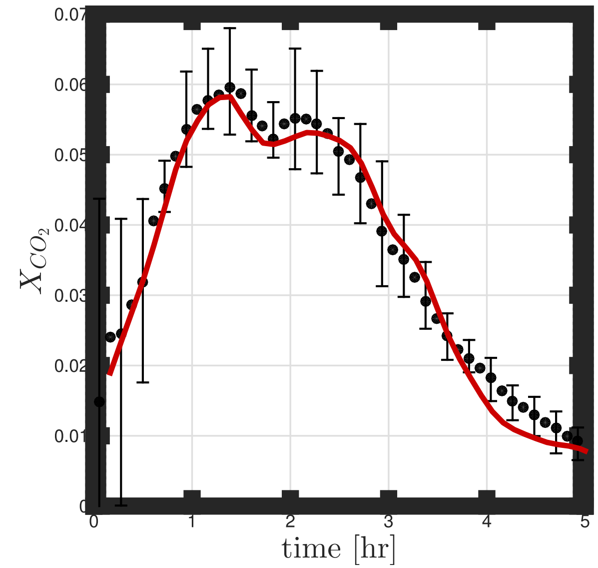
Consequences: Modeling

- Agrees fairly well with experimental data

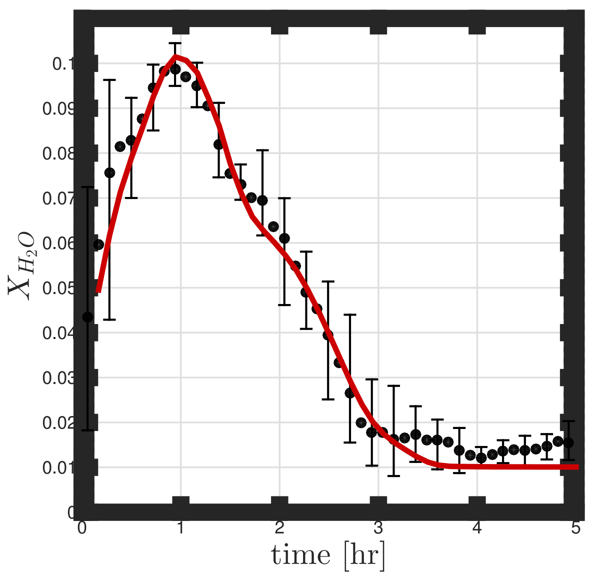
O_2



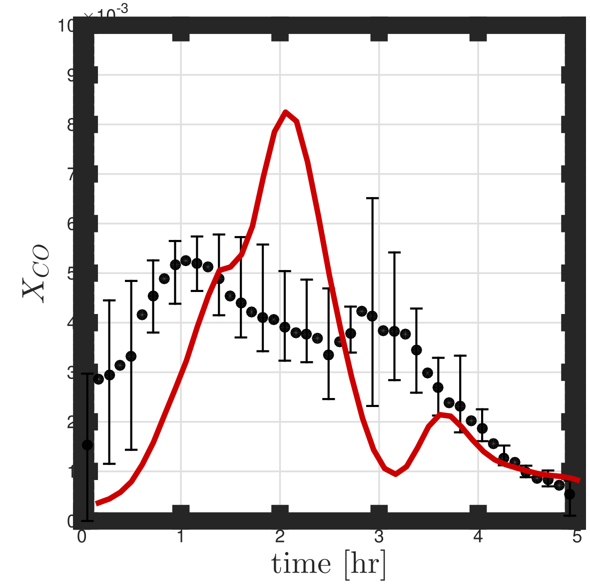
CO_2



H_2O



CO



Summary and Future Directions

- Gas emissions are strongly dependent on non-homogeneous fuel decomposition
- New emission inference method developed
  - Utilizes fuel mass loss rate and air flow measurements
  - Assumes H/O molar ratio = 2 in fuel
- Validated new method using TDLAS
- New insight on the operation of two-stage boilers
  - Instantaneous caloric value and elemental composition of the fuel
  - Instantaneous thermal efficiency
  - Meaningful time dependent fuel input to CFD models

- Potential Future Directions
  - Relax H/O = 2 assumption & directly measure H_2O and CO_2 via miniaturization of TDLAS or some other inexpensive off-the-shelf instrument
  - Optimize boiler operation using improved control logic using instantaneous thermal efficiency
  - Real time monitoring

More Details…

Experiments / Diagnostics

- Richter, JP., Bojko, BT., Mollendorf, JC., DesJardin, PE., Measurement of Fuel Burn Rate, Emissions and Thermal Efficiency from Domestic Two-Stage Wood-Fired Hydronic Heater. Renewable Energy, v. 96, pp. 400-409, 2016.
- Richter JP., Mollendorf, JC., DesJardin, PE., Absolute and Relative Emissions Analysis in Practical Combustion Systems – Effect of Water Vapor Condensation, Measurement Science and Technology, v. 27, 2016.
- Richter, JP., Weisberger, J., Mollendorf, JC., DesJardin, PE., Emissions from a domestic two-stage wood-fired hydronic heater: effects of non-homogeneous fuel decomposition, in review at Renewable Energy, 2016.
- Richter, J.P., Bojko, B.T., Mollendorf, J.C., DesJardin, P.E., “Fuel Burn Rate, Emissions and Gas Temperature from a Domestic Two-Stage Wood-Fired Hydronic Heater”, presented at Eastern States Section of the Combustion Institute, 2016.
- Weisberger, J.M., DesJardin, P.E., “Tunable Diode Laser Absorption Spectroscopy for CO_2 and H_2O Concentration Measurements in Biomass Combustion Systems”, presented at Eastern States Section of the Combustion Institute, 2016.

Modeling

- Bojko, B.T., DesJardin, P.E., “Formulation and Assessment of Flamelet-Generated Manifolds for Biomass Combustion”, Comb. & Flame, v. 172 ,pp. 296-306, 2016.
- Richter, JP., Bojko, BT., Mollendorf, JC., DesJardin, PE., Effect of Variable Fuel Composition in Flamelet Generated Manifold for system level model of a two stage wood fired hydronic heater, to be submitted to Renewable Energy, 2016.
- Bojko, B.T., DesJardin, P.E., “Flamelet Generated Manifold Modeling for Biomass Combustion”, presented at Eastern States Section of the Combustion Institute, 2016.

Thank you!   …   Questions?