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 measures O\textsubscript{2}, CO & NO – all other species are inferred
• CO\textsubscript{2} and H\textsubscript{2}O are important major species of combustion and are primary indicators of combustion efficiency
• CO\textsubscript{2}, H\textsubscript{2}O are inferred using a chemical balance:

  \[
  \text{fuel} + \text{air} \rightarrow \text{products}
  \]

• **Note:** most (all?) current inference methods (incorrectly) assume constant fuel composition
Inferring CO$_2$ and H$_2$O

Constant Fuel Formulation (CFF)

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

Fuel + Air + Wood Moisture → Exhaust Species

- Constant $w$, $x$, $y$, $z$
- $\gamma$ 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$_2$
Three modes of burning

- **Early** = fuel pyrolysis with large flames (first CO peak)
- **Intermediate** = pyrolysis and char formation
- **Late** = charcoal oxidation (second CO peak)
<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
<th>Year</th>
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Inferring CO$_2$ and H$_2$O

**Variable Fuel Formulation (VFF) –** x, y, z are unknowns

\[ C_1H_xO_yN_z + a(O_2 + 3.76N_2 + \gamma H_2O) \Rightarrow cH_2O + dCO + eNO + fCO_2 + gN_2 + hO_2 \]

**Effective Fuel** + **Air** \(\Rightarrow\) **Exhaust Species**

**Advantages:**
- fuel composition is NOT specified
- fuel moisture content is NOT specified
10 unknowns for a, c, d, e, f, g, h plus x, y, z,
- 4 atom balances (C,H,O,N)
- 3 measurements of CO, NO, O$_2$

= 3 more constraints (or measurements) required
- assume NO comes from fuel (e=z and g=3.76a)
= 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
Gases absorb light at different wavelengths

Calculate properties of gas from shape of absorption features
TDLAS Experimental Setup
TDLAS Experimental Setup – Pitch Side

- Mirror
- Periscope
- CaF$_2$ Beamsplitter
- Detector
- Germanium Etalon
- Laser
Results: Flue CO$_2$ and H$_2$O emissions

- VFF and TDLAS match !!!

$X_{CO_2}$ vs. time

$X_{H_2O}$ vs. time

TDLAS
VFF-mean
CFF-mean
Consequences: Time Dependent Fuel Comp. & HHV

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

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

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
Consequences: Modeling

- Agrees fairly well with experimental data

O₂

CO₂

H₂O

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 H₂O and CO₂ 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
Experiments / Diagnostics


Modeling

Thank you! … Questions?