An Improved Methodology for Real-time Emission and Thermal Performance Evaluation of Combustion Systems

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Background

- Methods/protocols for thermal performance and emission evaluation of combustion systems were developed for industrial scale units such as furnaces and boilers.
- Methodologies with the same underlying principle are now being used for residential scale systems (cooking and heating stoves).

### Industrial Scale Systems

- Designed and built to operate steadily on desired output levels.
- No or limited variability in fuel properties.
- Combustion characteristics demonstrate low variability during operation.

### Residential Scale Systems

- Designed with multiple constraints such as cost and affordability.
- Fuel type and properties change drastically.
- Highly variable combustion characteristics due to design, fuel and operating conditions.
Current status of real-time performance evaluation

It is important to capture performance variables in real-time for a better evaluation of any stove, and thus providing more insights leading to design improvement.

Real time performance evaluation has been tried by applying the carbon balance method by:

- dividing the combustion sequence into small intervals
- dividing the combustion sequence into different phases
A fundamental flaw in evaluation real-time performance of a stove using the carbon balance method is the assumption that the fuel composition doesn’t change during the combustion sequence leading to incorrect estimation of real-time thermal performance and emission factors.

Fang et al. (2014), *Fuel;* 116:350
To propose a methodology based on simple mass balance, and considering global chemical reactions involved in combustion capable of

(1) providing real-time composition (C, H, O, N, S, and moisture) of the fuel left in the stove

(2) source apportion water in the flue gas to fuel moisture and product of combustion reactions
Requirements

• Ultimate analysis and proximate analysis data for the fuel
• Real-time concentrations of the various components of the flue gas at the system outlet
  • The major components of the flue gas which must be monitored are O₂, CO, CO₂, H₂, and H₂O
  • Other components such as NOₓ, SO₂, and CH₄ are optional depending on the instrument availability to monitor these gases and N & S content of the fuel
• Either of the following two measurement
  • real-time mass loss of the stove + fuel system (can be the acquired with a weighing scale)
  • real-time flow rate, temperature and pressure of the flue gas (can be acquired with a flow meter, thermocouple, and pressure gauge)
Underlying Principle

Pathway 1: When flowrate of the flue gas is being measured

- Calculate mass flow rate of each component of interest in the flue gas using the recorded data

- Apply mass balance on C, N, and S coming from dry fuel, and mass balance on O & H atoms from dry fuel and fuel moisture, leading to seven variables to be solved for
Mass Balance Equations

- C, N and S in all of the species in the flue gas comes from the fuel

\[ M_{Fuel}^C = M_{CO_2}^C + M_{CO}^C + M_{CH_4}^C \]  \hspace{1cm} (1)

\[ M_{Fuel}^N = M_{NO}^N + M_{NO_2}^N \]  \hspace{1cm} (2)

\[ M_{Fuel}^S = M_{SO_2}^S \]  \hspace{1cm} (3)

- The mass balance for H and O can be written as the following

\[ M_{Fuel}^H + M_{Moisture}^H = M_{H_2O}^H + M_{Gas}^H + M_{CH_4}^H \]  \hspace{1cm} (4)

\[ M_{Fuel}^O + M_{Moisture}^O = \sum M_{Gas}^O - M_{Air}^O \]  \hspace{1cm} (5)

where \[ \sum M_{Gas}^O = M_{CO_2}^O + M_{CO}^O + M_{NO}^O + M_{NO_2}^O + M_{SO_2}^O + M_{H_2O}^O + M_{Gas}^O \]
For O and H coming from fuel moisture, the following relation holds

\[
\frac{M^O_{\text{Moisture}}}{M^H_{\text{Moisture}}} = 8 \quad (6)
\]

The last equation required to solve for the seven variables requires either an assumption or relationship based on experimental observations

\[
\frac{M^O_{\text{Fuel}}}{M^H_{\text{Fuel}}} = \frac{w^O_{\text{Fuel}}}{w^H_{\text{Fuel}}} \quad (7)
\]

Solving this system of equations will provide the real-time changes in fuel composition
Real-time thermal and Emission Indicators

Real-time thermal efficiency

\[
\text{Thermal efficiency} = \frac{\text{The useful heat}}{LHV \times M_{\text{Fuel losses}}}
\]

Real-time emission factors

\[
EF_i = \frac{M_i}{\text{The useful heat}} \quad \text{or} \quad \frac{M_i}{LHV \times M_{\text{Fuel losses}}}
\]

\[
HHV \left( \frac{kJ}{kg} \right) = 339 \ w_{\text{fuel}}^c + 144.3 \ (w_{\text{fuel}}^H - 0.125w_{\text{fuel}}^Q) - 22.4 \ (9 \ w_{\text{fuel}}^H) + 9.3 \ w_{\text{fuel}}^S + 1.464 \ w_{\text{fuel}}^N
\]

Limitations

- Though the proposed methodology is a significant improvement over the current methodology, an additional assumption or experiment based relationship between the release rate of O and H content of the fuel is required.

- Reliance on empirical relationships such as the Dulong formula and Steuer formula, to adjust for the calorific value of the fuel with changing composition.

- Non-methane hydrocarbons and particulate matter are not included in the mass balance.
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