Pilot-scale Investigation of Heat Flux and Radiation from an Oxy-coal Flame

Part 1: Development of Instrument Models

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Presentation Road Map

• Program objective, hierarchy and task objective
• Review of experimental quantities of interest
• New measurement devices with instrument models
  – Heat transfer surfaces
  – Wall thermocouples
  – Radiometers
• Example data set
• Summary & conclusions
Project Objective

Implementation of exascale computing with V&V/UQ to more rapidly deploy a new technology for providing low cost, low emission electric power generation

V&V/UQ – Verification & Validation with Uncertainty Quantification

Ultimate goal to design a next-generation 350 MWe oxy-coal boiler
Program Hierarchy

1.5 MW pulverized coal furnace (L1500)
Task Objectives

• Rework furnace measurement devices to accomplish the following:
  – Reduce the impact of measurement on the quantity of interest
  – Evaluate the relationship between the measured value and the quantity of interest

• Simplify
• Quantify through mathematical relationships (Instrument Model)

– Assign value and uncertainty to the quantity of interest
Quantities of Greatest Interest

• Heat removal through cooling surfaces
• Refractory temperatures at the flue gas interface
• Heat flux through the refractory walls
• Radiative intensity
Measuring Heat Removal Through Cooling Surfaces
Cooling Coils and Panels

- Cooling surfaces are necessary to provide steady state temperature profile
- Heat removal is determined by measuring the mass flow of water and the temperature of the water in and out

\[ Q = \dot{m}_w \cdot c_p (T_O - T_I) \]

- Measurement is very sensitive to particle deposition

Change Burner Swirl 0% → 100%
Cooling Coils and Panels

Flat plate cooling panels

Soot Blower

Multiple depth thermocouples placed in the hot-side plate for heat flux measurements

2 thermocouple sets / heat exchanger

8 total heat flux measurements
Cooling Coils and Panels

Cooling panel cross section

- Outside plate, 304 SS
- Baffled water channel
- Inside plate, 304 SS
- Water flow

Thermocouple cross section

- Thermocouple wires
- Thermocouple bead
- MgO Insulator
- Inconel sheath
- Drill gap (filled with silver paste)
Cooling Coils and Panels Instrument Model

Multi-depth thermocouple mathematical description:

Temperature profile to the thermocouple sheath

\[ q = k_{ref} \left( \frac{T_1 - T_2}{X_1 - X_2} \right) \]

\[ T_s = T_1 + q \left( \frac{X_1}{K_{ref}} \right) \]

Assumption: The 1/16” thermocouple does not impact heat flux

Temperature profile within the thermocouple to bead

\[ T5 = T1 - q \left[ \left( \frac{X_{Sil}}{K_{Sil}} \right) + \left( \frac{X_{inc}}{K_{inc}} \right) + \left( \frac{X_{MgO}}{K_{MgO}} \right) \right] \]

Assumption: Flux through plate = flux through thermocouple

Energy balance mathematical description:

\[ Q = \dot{m}_w \cdot c_p(T_O - T_l) \]

Quantifiable sources of error:

- Standard error in type-k thermocouple bead
- Variability in thermocouple set depth measurement
- Variability in material thermal properties
- Error in flow rate measurement
Measuring Wall Temperatures and Wall Refractory Heat Flux
Wall Thermocouples

Installed in the center of the top wall of each section

Permanently installed indicator of temperature profile
(continuous data)
Old Wall Thermocouple Device

Measured temp is not of the wall

- Heat transfer characteristics of measurement device are dissimilar to surroundings
- Ceramic, wire and air gaps vs. refractory
- Placement of bead is uncertain
- Interpretation of the data requires a complicated model which includes the surrounding environment
New Wall Thermocouple Device

Advantages:
- Environment closely approximates the natural furnace wall
- Simple mathematical description of temperature profile
- Both surface temperature and heat flux can be acquired

Disadvantages:
- Expensive
- Difficult to install
New Wall Thermocouple Instrument Model

Mathematical Description:

\[ q = \frac{k_{ref} (T_1 - T_2)}{(X_1 - X_2)} \]

\[ T_s = T_1 + q \left( \frac{X_1}{K_{ref}} \right) \]

Assumption: The wire and double bore ceramic do not impact the temperature profile

Quantifiable sources of error:

- Standard error in type-B thermocouple bead
- Variability in thermocouple set depth measurement
- Variability in material thermal properties

Expected Behavior:

\[ \Delta T = 748 \text{ to } 894 \pm 5 \text{ (°C)} \]

\[ q = 1651 \text{ to } 1971 \pm 171 \text{ (W/m}^2) \]

Range is from section 1 through 10 device distributions
Measuring Radiative Heat Flux
Radiometer Configuration

- Installed on the center port in the first three sections of the furnace
- Open 4” cavity (optically dark) on the opposite side of the furnace
  - Minimize the wall effects and measure only flame properties
Physical Processes of the Radiometer

- Wheatstone bridge to 5V power supply
- Energy balance around irradiated thermistor wire
- Lens optics and radiation onto thermistor

Black body radiator

object $2r_o$

d_o

$f$ (focal point)

d_i

$2r_i$
Radiometer Instrument Model

Mathematical Description:

\[ d_i = \frac{1}{\frac{1}{d_o} + \frac{1}{f}} \]

\[ r_i = \frac{d_i r_o}{d_o} \quad \text{Lens optics} \]

\[ I_i = I_o \left( \frac{r_{\text{lens}}}{r_i} \right) (1 - \rho) \quad \text{Thermistor irradiation} \]

\[ q_{\text{rad}} = \pi r_i^2 I_i \]

\[ q_{\text{rad}} + q_{\text{rad3}} + q_{\text{rad4}} = q_{\text{cond}} + q_{\text{conv}} + q_{\text{rad2}} \]

\[ R_t = R_{\text{ref}} \exp \left( A + \frac{B}{T_t} + \frac{C}{T_t^2} + \frac{D}{T_t^3} \right) \quad \text{Energy balance} \]

\[ V_{\text{meas}} = V_{\text{app}} \left( \frac{R_{\text{non}}}{R_{\text{non}} + R_1} - \frac{R_{\text{irr}}}{R_{\text{irr}} + R_2} \right) \quad \text{Wheatstone bridge} \]
L1500 Heat Balance
L1500 Heat Balance (High Temp Oxy-coal)

Targeted Conditions

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<td>Outer Secondary Temp</td>
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Skyline Coal Composition

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* all values in mass % unless otherwise specified

- Primary Gas / Coal
- Secondary Gas (O₂)
L1500 Heat Balance

Example Data Set

* Air-fired flame at the end of the high temperature oxygen test
L1500 Heat Balance
Example Data Set

Methods:

- Furnace heat removal can be assessed in two ways
  - Enthalpy of the reactants minus the enthalpy of the flue gas at the furnace exit
  - Direct measurement of active heat removal through water cooled surfaces plus heat loss through the refractory wall
L1500 Heat Balance
Example Data Set

Assumptions:

- Heat loss through the refractory wall is significant
  - Can be estimated using the measured heat flux in the roof of each section.
  - Heat loss is assessed by applying the measured heat flux uniformly across each furnace section.
  - Heat flux through the burner plate is assumed to be the same as in section 1.
  - Heat flux through section 11 and 12 is assumed to be the same as section 10.
  - Heat removal through both radiation heat exchangers is assumed to be the same.
L1500 Heat Balance
Example Data Set

- **Coal**: 3.00 MMBtu/hr
- **Preheated Gas**: 0.01 MMBtu/hr
- **Flue Gas**: 0.33 MMBtu/hr
- **Cooling Panels**: 0.59 MMBtu/hr
- **Cooling Coils**: 0.94 MMBtu/hr
- **Cooling Jackets**: 0.31 MMBtu/hr
- **Wall Heat Loss**: 0.80 MMBtu/hr

**Heat Loss From Furnace**: 2.69 MMBtu/hr
**Measured Heat Removal**: 2.64 MMBtu/hr
**1.3 % Difference**
Summary & Conclusions

• Weaknesses of year 1 measurements performed in the 1.5 MW oxy-coal unit have been identified
• Measurement devices have been upgraded to quantify:
  – Heat transfer through cooling surfaces
  – Wall temperatures
  – Radiation intensity
• Instrument models have been developed
• Pathway for uncertainty quantification has been developed
Questions