Acquisition and Analysis of Data in a Pressurized Entrained-Flow Coal Gasifier for the Purposes of Simulation Validation

Kevin J. Whitty

Department of Chemical Engineering
Institute for Clean and Secure Energy
The University of Utah
Salt Lake City, Utah, USA
Outline

• Introduction
• Background – coal gasification research
• U. Utah pilot-scale coal gasifier
• Types of data available for validation
• Performance issues
• Uncertainty considerations
• Conclusions
Introduction

• Industrial-scale coal gasifiers are primarily pressurized, O2-blown, entrained-flow variety

• Cost of gasification systems provides strong incentive to optimize using computational simulation

• Access to gasifiers for acquisition of validation data is challenging
Pressurized O₂-Blown Entrained-Flow Gasifiers

<table>
<thead>
<tr>
<th>Downflow</th>
<th>Upflow</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Refractory-Lined</strong></td>
<td><strong>Membrane Wall</strong></td>
</tr>
<tr>
<td>GE Energy</td>
<td>SIEMENS</td>
</tr>
</tbody>
</table>

### Downflow:
- Oxygen from Air Separation Plant
- Feed Water
- Burned Slag
- Hot Pressure Steam
- “Black Water” Recycled
- Fly Ash Recovery

### Upflow:
- E-Gas™ Entrained-Flow Gasifier
- Second Stage
- First Stage
- Oxygen (Steam Air Separation Plant)
- Slag/Water Quench
- Slag/Water Quench

### Membrane Wall:
- Shell Global Solutions
Challenges of Validation Data Acquisition

- High temperature
  - 1300-1500°C at reactor exit
  - In excess of 2000°C within oxy-coal flame

- High pressure
  - IGCC application typically 25-30 atm (400 psi)
  - Chemicals / fuel production 70+ atm (1000+ psi)

- Corrosive environment
  - Reducing environment
  - Gaseous sulfur species (H₂S, COS)
  - Molten coal slag

- Consequences
  - Crossing pressure boundary for gas sampling creates safety concerns
  - Thermocouples typically last only a few days
Fundamental Coal Gasification Studies

Coal particle

Drying

Dry particle

Devolatilization (pyrolysis)

Volatile, tars (CH₄, CO₂, CO, H₂)

H₂O

Char

H₂, CO, CO₂

O₂, H₂O, CO₂

Heterogeneous reactions

Slag formation

Slag

THE INSTITUTE FOR CLEAN AND SECURE ENERGY
Experimental Evaluation of Coal Conversion

- Drop tube (entrained-flow) furnaces
  - Pyrolysis yields
  - Char gasification kinetics
  - Physical transformations of coal particles

- Wire mesh heaters
  - Pyrolysis yields

- Thermogravimetric analyzers (TGAs)
  - Heterogeneous char gasification kinetics

- Mini-gasifiers
  - Electrically heated
  - Gases (CO₂, O₂) supplied from laboratory cylinders
“Small” versus “Big”

• Fundamental Studies ("small")
  – Up to perhaps 2 kg/day in entrained-flow reactors
  – Bottled gases
  – Electrically heated

• Commercial-Scale Systems ("big")
  – Hundreds of tons of coal (petcoke) per day
  – Oxygen-blown, with all associated mess
  – Difficult to access

• Need “medium” scale system to bridge this gap of 5 orders of magnitude
Outline

• Introduction
• Background – coal gasification research
• U. Utah pilot-scale coal gasifier
• Types of data available for validation
• Performance issues
• Uncertainty considerations
• Conclusions
Bridging the Gap: UofU Gasifier

• Designed to operate like a “large” system
  – No electrical heating
  – Only inputs are oxygen and coal (slurry)
  – Similar in design to a GE gasifier

• Accessible like a “small” system
  – Reactor “stretched out” to decrease diameter and allow sampling at multiple residence times
  – Several (six) sampling ports down length of reactor
  – Six thermocouples for temperature measurement
Gasifier System Schematic
Gasification Research Laboratory

Pressurized Fluidized Bed Gasifier

Hot Gas Filter

Biomass Feeder

Pressurized Entrained Flow Gasifier

Syngas Cleaning
Entrained-Flow Gasifier
Oxygen Supply System

• On-site oxygen tank
  – 6,000 gallons / 20 tons
  – Serves gasification and oxy-fuel systems

• “Trifecta” system to boost pressure
  – 325 psi
  – Limits standard operation pressure to ca. 260 psi
  – Higher pressures require auxiliary high pressure supply

• Flow control system to gasifier
  – Pressure regulator
  – Control valve
  – Coriolis flowmeter
## Gasifier Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (bar)</td>
<td>18</td>
<td>31</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>1425</td>
<td>1700</td>
</tr>
<tr>
<td>Slurry feed rate (lit/h)</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Coal feed rate (kg/h dry)</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Thermal input (kW&lt;sub&gt;th&lt;/sub&gt;)</td>
<td>220</td>
<td>600</td>
</tr>
<tr>
<td>Slurry concentration (wt%)</td>
<td>59</td>
<td>65</td>
</tr>
<tr>
<td>Oxygen feed rate (kg/h)</td>
<td>35</td>
<td>150</td>
</tr>
<tr>
<td>Syngas production (m&lt;sup&gt;3&lt;/sup&gt;/h dry)</td>
<td>50</td>
<td>150</td>
</tr>
</tbody>
</table>
Reactor Details

- **Reactor dimensions**
  - 30 inch (0.75 m) pressure vessel
  - 8.5 inch (0.22 m) reactor ID
  - 60 inch (1.5 m) reactor length
  - Designed to identify development of gas and condensed phases as coal undergoes conversion

- **Sample ports**
  - Twelve opposing 2 inch (5 cm) ports at six levels for sampling, optical diagnostics
  - Two additional 2 inch (5 cm) ports at burner level
  - Six 1 inch (2.5 cm) ports for temperature/pressure measurement
Outline

- Introduction
- Background – coal gasification research
- U. Utah pilot-scale coal gasifier
- Types of data available for validation
- Performance issues
- Uncertainty considerations
- Conclusions
The Easy Stuff

• Inputs
  – Slurry flow rate and concentration
  – Coal composition
  – Oxygen feed rate
  – Purge flow rates

• Temperatures
  – Five B-type thermocouples along length of reactor
  – Additional thermocouples in quench, on shell, etc.

• Syngas composition
  – Analysis after gas has been quenched, cooled, depressurized

• Solids composition
  – Char caught in filters, slag caught in slag trap
  – Analyzed only after system is depressurized
Extractive Sampling

- Cooled probe for gas sampling within reactor chamber
- Moveable piston will allow quick positioning from wall to centerline of reactor
- Safety systems integrated with gasifier control system
- Can be installed at any of five locations down length of reactor
- Modification of system will allow deposition of condensed-phase material onto probe
Measurement Locations
for Stanford TDL Sensor Project
Absorption Fundamentals:
Wavelength-Multiplexed Tunable Diode Laser Sensing

- Absorption of laser light by molecular transitions in the combustion gases
  - Beer’s law: Transmission = I/I₀ = e⁻ᵏᴸ
  - Absorption coefficient k = f(temperature, pressure, gas composition)
- Ratio of absorbance on two molecular transitions yields gas temperature
- Multiplex additional lasers for more combustion species

Ratio of peak height yields gas temperature
Absorption Fundamentals: Scanned Direct Absorption and Wavelength Modulation Spectroscopy

- Direct absorption: Simpler, if absorption is strong enough
- WMS: More sensitive especially for small signals (near zero baseline)
  - Ratio of two WMS-2f signals provides T (same as direct absorption)
  - WMS with TDLs has improved noise rejection (especially for non-absorption losses)
  - WMS also produces intensity modulation @1f
- *Since both 2f and 1f signals are proportional to I; 2f/1f independent of optical losses*
Absorption Fundamentals: Demonstration that Normalization of WMS Improves Signal-to-Noise Ratio

- Demonstrate normalized WMS-$2f/1f$
  - No loss of signal when beam attenuated (e.g., scattering losses)
  - No loss of signal when optical alignment is spoiled by vibration
  - Normalized WMS-$2f/1f$ signals free from window fouling and particulate loading
TDL Sensor Results at Position 3

Laser Transmission vs. Pressure

- Laser Transmission [%]
- Pressure [psig]

- Location 3 Data

Measured Temperature at 160 psi

- Laser sensor measurements
- Upstream thermocouple
- Downstream thermocouple

P = 160psig

Location 3: Product syngas stream
Run with coal, time resolution = 0.15s
TDL Sensing at Position 2

- High SNR, time-resolved measurements of T
- Normalized WMS accounts for varying transmission
- Measured T at reactor pressures of 90, 120 and 160 psig stable
- Measured T at 200 psig identifies potential spray splashback instabilities
TDL-Based Measurements within Reactor “Core” (Position 1)
**Conditions**

- To 500 kWth
  - 1.5 ton/day coal
- 440 psia (30 atm) pressure
  - Typically operate at psia
- Temp to 3100°F (1700°C)
  - Typically 2400-2600°F
- Various fuels
  - Pittsburgh #8
  - Illinois #6
  - Utah Sufco
  - Texas Lignite
  - Petcoke

**Measurements**

- Wall temperature
  - 5 positions
- Syngas composition
  - Post-quench
  - Pre-quench
- Reactor temperature
  - Integrated TDL-based
- Internal gas composition
  - Extractive sampling
  - Integrated TDL-based
- Internal condensed-phase
  - Extractive sampling
Outline

• Introduction
• Background – coal gasification research
• U. Utah pilot-scale coal gasifier
• Types of data available for validation
• Performance issues
• Uncertainty considerations
• Conclusions
Injector Cold Flow Test System

- Identification of injector performance
  - Uniformity
  - Spray angle
  - Droplet size
- Full scale model
  - Uses same injector as actual reactor
  - Air instead of oxygen
  - Water instead of slurry
- Pressurized system (to 5 bar) under development
- Analytical methods under development
Flow rates of air and water adjusted simultaneously to maintain air/water ratio
Air pressure drop 2.8 bar
45 degree nozzle

7.5 LPH H₂O
4.25 Nm³/h air

30 LPH H₂O
17.0 Nm³/h air
Both cases have 30 LPH water feed, 17 Nm$^3$/h air feed
65 degree nozzle

$\Delta P = 0.7 \text{ bar}$

$\Delta P = 3.5 \text{ bar}$
Adjustable Injector Tip

Coal Slurry

Oxygen

Oxygen
Performance vs. Injector Gap

- Oxygen annulus gap, mm
- $\Delta T$ (Top – Bottom), °C
- $O_2$ Injector $\Delta P$, bar

<table>
<thead>
<tr>
<th>Oxygen annulus gap, mm</th>
<th>2.0</th>
<th>1.5</th>
<th>1.0</th>
<th>0.6</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$ (Top – Bottom), °C</td>
<td>-50</td>
<td>-25</td>
<td>0</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>$O_2$ Injector $\Delta P$, bar</td>
<td>-50</td>
<td>-25</td>
<td>0</td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>
Temperature Profile

45° nozzle angle (Day 1)

65° nozzle angle (Day 2)
Syngas Composition

45° nozzle angle (Day 1) 65° nozzle angle (Day 2)
Outline

• Introduction
• Background – coal gasification research
• U. Utah pilot-scale coal gasifier
• Types of data available for validation
• Performance issues
• Uncertainty considerations
• Conclusions
Uncertainty Considerations

- **Temperatures:** Thermocouple junction located within wall, approx. 0.5 inch from refractory face, to extend thermocouple life

- **Gas composition:** Cooling within extractive probe may affect gas composition due to:
  - Changes in gas equilibrium composition at lower temperatures
  - Absorption of minor constituents (sulfur compounds, ammonia) by condensed water
  - Condensation of e.g., polyaromatic hydrocarbons as gas is cooled
Uncertainty Considerations (2)

- **Condensed-Phase Material**: Difficult to obtain instantaneous compositions. Must be aggregate over time.

- **All Data**: Fluctuations on various time scales need to be quantified
  - 2 seconds
  - 20 minutes
  - Day-to-day
Conclusions

• Acquisition of data within reaction zone of pressurized gasifier very challenging

• Gasifier performance strongly tied to injector design and efficiency of fuel distribution

• Optical techniques offer unique opportunity for real-time non-invasive sampling

• Quantification of data variation and associated uncertainty is important if data is to be used for validation of simulations
Acknowledgements

• U.S. Department of Energy
  —Award DE-NT0005015
  —Award DE-FE0001180

• Electric Power Research Institute

• Stanford University

• Eastman Chemical Co.

• Hard working crew of Dave Wagner, David Ray Wagner, Travis Waind, Randy Pummill, Jessica Earl, Mike Burton, Ray King and Eric Berg