Linking Laboratory Scale Gasification Measurements with Coal Performance in a Pilot Scale Gasifier

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CCT 2009, Dresden
18 May, 2009

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Outline

• Pilot and laboratory testing of a reference suite of four well-characterised coals
• Coal gasification performance issues
  • Laboratory characterisation of coal gasification behaviour
    • Volatile yield, char structure, char reactivity
    • Slag viscosity and flow behaviour
  • Application of fundamentals through ‘simple’ conversion models
• Pilot scale gasification test program
  • Validating and applying the fundamentals
  • Identifying the key coal selection and operating criteria
  • Impact of coal properties on plant operation and performance
  • Guidance for future coal gasification and syngas R&D program
Gasification Research Program

Improve the understanding of coal performance in gasification technologies, supporting:

- Use of Australian coals in new technologies
- Implementation of low emissions coal technologies in Australia.

- High pressure, high temperature coal conversion measurements
  - Effects of reaction conditions and coal type
  - Development of coal test procedures

- Fundamental investigations of coal gasification reactions
  - Reaction mechanisms and kinetics, model development.

- Slag formation and flow for entrained-flow gasification
- Syngas cleaning & processing
- Gas separation (H\textsubscript{2}/CO\textsubscript{2})
- Technology performance models
Interrogating the Gasification Process

- PEFR: Investigating gasification behaviour under controlled and measurable conditions.
- Laboratory-scale investigations to understand the important processes that combine to gasify coal under practical conditions.
- Larger-scale testing to ‘recombine’ process steps under process conditions to investigate interactions.
- Predictive capability of gasification behaviour.
- Assess coals for specific gasification technologies.
- Develop operating strategies.
- Troubleshooting gasification processes.
- Char gasification kinetics: high pressure TGA and fixed-bed reactors.
- Support technology development.
- Slag viscosity measurements.
- Predictive capability of gasification behaviour.
- Assess coals for specific gasification technologies.
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- Char gasification kinetics: high pressure TGA and fixed-bed reactors.
- Support technology development.
- Slag viscosity measurements.
Evaluation of Coal Gasification Behaviour

- Optimum range of stoichiometries for ‘gasification efficiency’. Trade-off to achieve maximum conversion.
- Higher volatile coals (generally) achieve greater conversion than lower volatile coals
  - Exception is CRC299 – indicates that char reactivity is also significant (agrees with TGA testing of coal suite)
- Higher temperature differentiates coals on the basis of different char reactivities
- Effect of coal type also reflects extent of conversion
- Conversion drives syngas composition (via gas phase equilibria)
CO₂/char reaction rate at ‘high’ temperature

20 bar total pressure, 5 bar CO₂ partial pressure

- PEFR operated with controlled gas atmospheres (fix PCO₂, P_{total}, T)
- Char produced in-situ
- Conversion measured along length of reactor (t ≤ 3s)
- Char samples taken for thorough analysis
  - Morphology, structure, surface area, pore size distribution…
  - ‘Intrinsic’ reactivity
  - Density and particle size
Char/CO$_2$ reaction rates: understanding chemical and physical factors

- First of a kind data for high pressure char/CO$_2$ and char/steam reactions (PEFR)
- Thiele modulus and effectiveness factor based on observed particle morphology
  - ‘effective’ diffusion length
- Low T ‘intrinsic’ and high T ‘practical’ rate data can be reconciled when a detailed understanding of char structure is available
- Still difficult to resolve burnoff effects
- Challenge to extend to multiple reactants

• Model needed for interrogation and application of measurements
• Integration of fundamentals with system and technology models
  • relationships with international programs, pilot and demo plant operators
• Australia has no pilot or commercial scale gasification plant
  • Collaboration is essential to apply knowledge and to ‘validate’ outcomes
  • First pilot scale test program conducted August 2007 (Siemens, Germany)
Pilot Scale Gasification Testing of Australian Coals

- Sponsored by
  - ACARP, Xstrata Coal, WA Coal Futures Group, Verve Energy, Delta Electricity, CCSD, CSIRO
- Siemens gasification test facility, Freiberg, Germany
Siemens Gasification Test Facility

- 5MWth gasification facility
- Dry or slurry feed
- Cooling screen walls
- Includes syngas quench, gas analysis and sampling points
- Slag, solids and process water sampling
- Gas treatment, S removal systems
- Expert operations team!
Test Program

• **Four Australian Coals**
  - Selected to cover a wide range of coal properties
    - Rank, petrography, volatile yield, char structure
      - Semi-anthracite, high vol bituminous, high vol sub-bit, high moisture ‘lignitic’
    - Well characterised through laboratory gasification research program
    - Attempted to keep ash fusion/flow temperatures low

• **Five Gasification Tests**
  - One ‘pre-test’
  - One test program on each coal
  - Each test consisted of 2-3 ‘balance phases’, where the coal and $O_2$ feeds were steady and measurements and samples could be taken
  - Two sets of conditions:
    - ‘optimal’ gasification conditions for each specific coal, and
    - comparison of coals under common ‘reference’ conditions
# Coal Sample Analyses

<table>
<thead>
<tr>
<th></th>
<th>CRC701</th>
<th>CRC702</th>
<th>CRC703</th>
<th>CRC703 (fluxed)</th>
<th>CRC704</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (% ar)</td>
<td>6.4*</td>
<td>1.3</td>
<td>0.9</td>
<td>0.9</td>
<td>2.3**</td>
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<tr>
<td>Ash (% ar)</td>
<td>5.6</td>
<td>8.7</td>
<td>9.6</td>
<td>10.9</td>
<td>11.7</td>
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<tr>
<td>VM (% ar)</td>
<td>36.2</td>
<td>34.4</td>
<td>7.2</td>
<td>8.7</td>
<td>44.1</td>
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<tr>
<td>FC (% ar)</td>
<td>51.8</td>
<td>55.6</td>
<td>82.3</td>
<td>79.5</td>
<td>41.9</td>
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<td>C (% daf)</td>
<td>76.1</td>
<td>86.3</td>
<td>92.8</td>
<td>93.5</td>
<td>79.0</td>
</tr>
<tr>
<td>H (% daf)</td>
<td>4.5</td>
<td>5.2</td>
<td>3.7</td>
<td>4.0</td>
<td>5.8</td>
</tr>
<tr>
<td>N (% daf)</td>
<td>1.5</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>S (% daf)</td>
<td>1.1</td>
<td>1.2</td>
<td>0.7</td>
<td>0.7</td>
<td>0.3</td>
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<tr>
<td>O (% daf)</td>
<td>16.8</td>
<td>5.3</td>
<td>0.9</td>
<td>0.0</td>
<td>14.1</td>
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<tr>
<td>AFT flow (reducing) °C</td>
<td>1290</td>
<td>1310</td>
<td>1540</td>
<td>1430</td>
<td>1440</td>
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<tr>
<td>Specific Energy (HHV), MJ/kg as rec</td>
<td>25.7</td>
<td>30.6</td>
<td>32.1</td>
<td>31.1</td>
<td>28.2</td>
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</tbody>
</table>

* CRC701 dried prior to tests (initially 25%), **CRC704 dried from 13.4%
Estimated slag viscosity for test coals

- Viscosity calculated prior to tests from models based on experimental database for a wide range of Australian coals.
- CRC704 ash composition indicated slag flow T and viscosity in upper end of desired range.
- CRC703 required fluxing – supplied sample indicated excessively high viscosity.
- Viscosity of gasifier and lab slags examined after pilot test program.
Typical Data: Reactor Parameters (single run)

- Decreasing O:C ratio decreases temperature (indicated by decreased heat loss)
  - Affects conversion, gas quality, slag formation and flow
Typical Data: Gas Composition (major species)

- Decreasing O:C ratio increases CO and H₂ production (decreases CO₂ production)
• Consistent with pilot scale data, decreasing O:C ratio decreases CO₂ and increases CO and H₂.
## Initial Results – Runs Summary

<table>
<thead>
<tr>
<th>Test and Balance Phase</th>
<th>Coal</th>
<th>Temp. Ave (°C)</th>
<th>X (%)</th>
<th>O:C (mol:mol)</th>
<th>CGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NKV100 BP1</td>
<td>CRC701</td>
<td>1616</td>
<td>98.5</td>
<td>1.27</td>
<td>67.5</td>
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<td>96.5</td>
<td>1.37</td>
<td>66.7</td>
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<td>NKV102 BP2</td>
<td>CRC702</td>
<td>1620</td>
<td>100.6</td>
<td>1.38</td>
<td>73.4</td>
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<tr>
<td>NKV102 BP3</td>
<td>CRC702</td>
<td>1240</td>
<td>99.8</td>
<td>1.32</td>
<td>73.0</td>
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<td>1453</td>
<td>93.8</td>
<td>1.26</td>
<td>67.8</td>
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<tr>
<td>NKV103 BP2</td>
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<td>1.33</td>
<td>71.5</td>
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<tr>
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<td>CRC703</td>
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<td>94.8</td>
<td>1.20</td>
<td>74.3</td>
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<td>NKV104 BP1</td>
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<td>93.3</td>
<td>1.47</td>
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<td>NKV104 BP2</td>
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<td>1.42</td>
<td>63.3</td>
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<tr>
<td>NKV104 BP3</td>
<td>CRC704</td>
<td>1679</td>
<td>96.0</td>
<td>1.37</td>
<td>66.6</td>
</tr>
</tbody>
</table>
PEEFR and Pilot data

- Effects of stoichiometry on gasification performance demonstrated using PEFR experiments
  - ‘Peak’ at just under 1:1 stoich then decrease with increasing O:C (for HV coals).
- Results of pilot scale tests consistent
  - Decrease in GE as O:C increases above 1:1
  - Smaller differences between coals because gasifier is ‘optimised’ for maximum conversion (PEFR data includes effects of reactivity differences)
• Attempt to decouple operating conditions and coal gasification behaviour
  • Pilot tests require higher O:C stoichiometry
  • ‘normalise’ for additional CO₂
• Relative ranking consistent between PEFR and Pilot tests
  • PEFR results indicative of need for more or less aggressive gasification conditions
• Slag requirements may over-ride gasification reaction requirements (eg CRC704)
Slag analysis – composition, leaching, viscosity…

* Semi-anthracite, fluxed
Measured Slag Viscosity

CRC701
- laboratory slag
- trial slag

CRC702
- predicted
- laboratory slag
- trial slag

CRC703 fluxed
- predicted
- laboratory slag
- trial slag

CRC704
- predicted
- laboratory slag 1
- laboratory slag 2
- trial slag
Summary

• First comparative pilot scale performance data for Australian coals
• Laboratory scale measurements provide ‘transportable’ performance data for different coal types
  • Volatile yield, reaction kinetics, char structure, conversion…
  • Slag viscosity and flow behaviour
  • Data and knowledge applicable through reactor and flow models
• Entrained flow reactor (PEFR) demonstrates differences in coal behaviour
  • indicates strategies and operating parameters to achieve satisfactory conversion in practical systems.
• Pilot tests demonstrate clear relevance of lab/PEFR measurements
• Design and operating strategies for ‘difficult’ coals identified and tested at lab and pilot scale
• Clear linkage of results and data between lab and pilot scale essential for application and validation of research program (eg coal testing, syngas quality etc)
  • Detailed evaluation of coal, char, slag, water samples from pilot tests is providing unique and valuable insights for reference coal suite
Thank You

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Gasification based low emissions energy

Source: US DoE Oak Ridge Laboratories

Gasification R&D focus

Coal
Other Fuels
Oxygen Membrane
Gasification
Gas Stream Cleanup
CO₂ - H₂ Shift
H₂ / CO₂ Separation
CO₂ Sequestration
FUELS
Liquids Conversion
Electricity
Fuels/Chemicals
Power Fuel Cell
High Efficiency Turbine
Process Heat/Steam

Source: US DoE Oak Ridge Laboratories
High Pressure Entrained Flow Reactor (PEFR)

- Entrained-flow reactor
- 20 bar pressure, 1500°C wall temperature
- Coal feed rate of 1-5 kg/hr
- Gas mixtures of O₂, CO₂, H₂O and N₂
- Adjustable sampling probe - char and gas samples collected at different residence times (0.5-3s)
Gasification conversion drives gas phase composition

**Equilibrium Gas Composition (mol%)**

- **CRC274 – 1300°C, 5%O₂**
  - VM (daf) = 32.6%
  - Points = measured
  - Lines = eqbm

**Carbon Conversion (%)**

- CO
- CO₂
- H₂
- Steam
- O₂
Reconciliation of ‘low’ and ‘high’ T rate data

- Consistent trends observed in rate, activation energy
  - Low and high T data measured independently
- Apparent discontinuity remains between high and low T data sets
  - High rank coal most affected
  - Greater variation in char types, pore structure, surface area
High pressure char gasification rates

CRC252

CRC272

1/temperature (1/K)

0.0004 0.0005 0.0006 0.0007 0.0008 0.0009

ln (gasification rate (g g\(^{-1}\) s\(^{-1}\)))

-12

-10

-8

-6

-4

-2

0

low temp specific rate

intrinsic rate

combined morphology

Group I

Group II

Group III

1673 K

1573 K

1473 K

1373 K

1273 K

low temp specific rate

CRC272

CRC252

1/temperature (1/K)

0.0005 0.0006 0.0007 0.0008 0.0009

ln (gasification rate (g m\(^{-2}\) s\(^{-1}\)))

-18

-16

-14

-12

-10

-8

-6

-4

-2

0

low temp intrinsic rate

intrinsic rate

combined

Group I

Group II

Group III

CRC2009, Dresden
Slag Viscosity Testing

- Slag Viscosity
  - 25 Pa s is the accepted maximum viscosity at the slag tap for successful operation
  - Flux addition required if viscosity is too high

- Temperature of Critical Viscosity
  - Slag becomes heterogeneous
  - Trouble-free tapping of slag not possible
Why Pilot Testing?

• Goals of the Laboratory and Technical Scale work to date have been specific:
  • Fundamental understanding of gasification process
  • Flexible and transportable data applicable to a range of gasification technologies
  • Identification of ‘indices’ for coal assessment and gasifier optimisation & design

• This leaves some unanswered questions:
  • Are the scientific issues identified and understood to date significant at pilot scale (and full scale) coal gasification?
  • Can the models under development be used to target specific gasification technologies?
  • Do the tools and techniques developed accurately reflect variations in coal performance under ‘real’ gasification conditions?