Abstract

Existing ex-situ techniques for measuring the gas content and permeability of coals require collection and laboratory analysis of core samples. In some cases, those samples do not reflect the complex, distributed characteristics of the coal seam being evaluated. In other cases, the analyses are complicated by changes to the samples that may occur during collection.

Gas content measurements

Gas content of coals is typically measured using the Direct Method Analysis (DMA) on freshly cut cores. The problem with the DMA technique is that overall results can be greatly influenced by artifacts of the test apparatus and procedures used by core sample type, sample collection methodology, and analysis conditions. Even if all these factors are precisely controlled, the accuracy of in situ gas content values obtained using the DMA technique can still be greatly compromised through large errors in Q1 values, which can only be predicted, not measured. Compounding this inherent error of the technique is the fact that core desorption is a destructive testing method that cannot be completed twice on the same sample. This means it is not possible to assign error bars on core desorption data, or on the major safety implications of decisions made by using them.

Permeability measurements

It is possible to quantify permeability from tests on whole cores under precisely controlled laboratory conditions. The accuracy of such tests, however, can be impacted by a number of factors including: the method used to capture the cores; the extent of filtrate invasion; damage to cores during retrieval; poor core preservation at the surface; improper re-stressing of cores in the laboratory; re-stress hysteresis of cores; and, scaling effects (core diameter relative to primary, secondary, and tertiary fracture network spacing).
Combined in-situ measurements

A new capability has been developed for simultaneously determining both parameters in-situ. This new combined method provides some advantages; it can be performed more quickly and at a greater density than typical off-situ methods. Its in-situ methodology is, furthermore, well suited to challenging downhole environments such as those containing friable coals, and mixed carbon dioxide and methane gases. Additionally, it can be performed in remote locations without local laboratory support. This new capability has involved the integration of two very different technology platforms that, nevertheless, use reservoir fluid as a key component of their measurement modes. Drill Stem Testing (DST) technology is used to determine flow capacity based on monitoring of fluid behaviour as it is drawn from the coal cleat system. Reservoir Raman Spectroscopy (RRS) logging technology is used to derive gas content based on measurement of various properties of the extracted fluid.

A description of both enabling technologies, operating principles, and the innovative surface system developed to facilitate concurrent operation of both has been documented in a recent publication by Pope and Morgan (‘A new in-situ method for measuring simultaneously coal seam gas content and permeability’, Proceedings of 13th Underground Coal Operators Conference, Wollongong, February 12-14, pp 284-290). In it, the authors show that of the many DST technology platforms, both tubing deployed and wireline deployed, only one - involving the use of tubing pressure to set packers and vertical movement of the work string to manipulate a tester valve - is suited for facilitating simultaneous production and logging of formation fluids. A wireless surface readout formation pressure monitoring system is incorporated between the straddle packers, which use a low-frequency Electromagnetic (EM) signal to propagate formation pressures through the surrounding overburden to the surface. To facilitate concurrent wireline operations and manipulation of the DST system tester valve, a unique load-bearing Wireline Entry Guide (WEG) system was developed, along with a load- bearing quick-union connection system.

The publication by Pope and Morgan also detail a generic test program to highlight the ability to examine produced fluids located in either the wellbore or displaced to the surface under pressure, while simultaneously monitoring the behaviour of fluids still residing in the cleat system. The publication also provides insight into data validation techniques that have been developed to prove self-consistency. Not disclosed, however, are the methods developed to enable the appropriate generation of the adsorption isotherms that are required to accurately calculate gas content from the measured fluid properties. This will be addressed in this paper as part of the case studies review.

This case studies review will also reveal mitigation measures and procedures developed to address the challenges of the new technique. These include the need to manage fluids wisely to ensure representative data and minimise test duration, and the need to use a pragmatic approach in identifying a coal sorptivity that represents a well’s drainage area (versus a single core sample) for each coal intersected.
Session 4
Concurrent *In-situ* Measurement of Flow Capacity and Gas Content
by
Quentin Morgan

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Introduction

- *Ex-situ* techniques for measuring gas content $G_c$ and permeability $k$ of coals require collection and laboratory analysis of core samples.
- In some cases those samples do not reflect the complex, distributed characteristics of the coal seam being evaluated.
- Experimental results can however potentially be influenced by artefacts of the test apparatus, test procedures and sample collection method.
- Drill stem testing (DST) is an established method for *in-situ* analysis of coal permeability.
- Reservoir Raman Spectroscopy (RRS) is an established method for *in-situ* analysis of coal gases.
Introduction

• Combination of both fluid-based techniques enables concurrent determination of both parameters
• A development project was commissioned in 2011 to integrate both testing platforms
• Field trials have also been conducted to demonstrate system performance, evaluate results speed and accuracy, and assess efficiency gains
• All key deliverables established for the field trial were met, with computed gas contents found to closely match measured values from desorption tests
Overview of presentation

- DST technology for coal permeability
- RRS technology for gas content in coal
- Combined DST/RRS technology
- Field trial terms of reference
- Field trial summary
- Field trial results
- Key learnings
- Conclusions
Technologies - DST

- A variety of technology platforms are available to test coal seam flow capacity:
  - Tubing deployed systems referred to as DST systems
  - Wireline deployed systems referred to as pump-out systems
- Both categories are further classified according to:
  - Type of packer setting method (compression vs. inflate)
  - Control systems used to actuate the tester valve
A variety of DST system types are available

<table>
<thead>
<tr>
<th>System Actuation Type</th>
<th>Conveyance Method</th>
<th>Application Types</th>
<th>Internal Wireline Access</th>
<th>Multi-Cycle Circulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wireline</td>
<td>Tubing</td>
<td>Off Bottom</td>
<td>Single Trip MZ</td>
</tr>
<tr>
<td>Annulus Pressure</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Compression Set</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Internal Control Line</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>External Control Line</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Positive Pressure Pump-Out</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hydraulic Amplifier Pump-Out</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Tubing Rotation Actuated (TRA)</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Tubing Pressure Actuated (TPA)</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Tubing pressure actuated systems are most appropriate for ready integration with RRS systems

Other systems are attractive for other situations
Technologies – TPA DST

- Straddle packers are used to isolate the test interval.
- Inflatable packer elements are used which are actuated through pressure applied from surface.
- Embedded sensors monitor all relevant pressures:
  - Hydrostatic (annulus) pressure
  - Formation pressure
  - Cushion (tubing) pressure
  - Packer inflation pressure
- System design allows integration of real time surface read out of coal seam pressure using wire-less E-M telemetry.
- Raman spectroscopy used to detect and measure trace gases dissolved in coal seam fluids.
Technologies - RRS

- Result are quantitatively related to gas content in coal seam, when equilibrium conditions are met.
  - Gas concentration $\rightarrow$ gas partial pressure $=$ critical desorption pressure (CDP) $\rightarrow$ gas content $G_c$
- For example:
  - $[\text{CH}_4]$ \xrightarrow{P(\text{CH}_4)=\text{CDP}} \Gamma(\text{CH}_4)$

- Accurate transformations require accurate correlations
  - Solubility constant and adsorption isotherm
- Representative transformations require representative samples.
Technologies - RRS

- Advantages
  - Measured P(CH4), and consequently CDP, is not impacted by geological heterogeneity.
  - Measurement validity therefore extends some distance away from the wellbore.
  - With flow induced spanning the entire coal seam thickness, a bulk averaged value is obtained that is applicable to the entire region of constant CDP.
  - In an optimised dewatering or pre-drainage strategy, this region would represent the accessible drainage volume for each well.
Objectives

• Confirm ability to effectively and safely integrate wireline logging operations with DST operations.
• Evaluate robustness of fluid management guidelines, set thresholds and establish decision criteria.
• Assess operational efficiencies achieved in a multi-seam open hole environment.
• Benchmark analyses of acquired data with results from traditional core desorption studies and DSTs using alternative DST systems and testing techniques.
Field Trial Summary

- Two wells were selected with three seams targeted in each for testing.
- Due to hole instability problems only one seam was ultimately tested in the first borehole.
- Gas data from the second borehole has been withheld to respect client confidentiality, with scaling applied to other data revealed for this borehole.
- Key deliverables were met on all four seams tested across the two boreholes.
- Computed gas contents were found to closely match those derived from fast desorption tests on cores.
- Permeability data was found to be self-consistent, but differed with values obtained from earlier DSTs in neighbouring boreholes.
### Borehole 1

#### DST Data

<table>
<thead>
<tr>
<th>Interval name</th>
<th>Interval (m BS)</th>
<th>Flow capacity (mD-ft)</th>
<th>Skin</th>
<th>Pressure (psia)</th>
<th>CDP (psia)</th>
<th>Std. Dev (%) spectra (no.)</th>
<th>$V_L$ (m³/ton) / $L_D$ (psia)</th>
<th>$G_C$ (m³/ton)</th>
<th>$G_S$ (m³/ton)</th>
<th>$G_C/G_S$ (%)</th>
<th>Drainage dP (psi)</th>
<th>$P_{abandon}$ (psia)</th>
<th>Recovery (m³/ton)</th>
<th>R.F. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seam 1</td>
<td>114.6–118.2</td>
<td>960</td>
<td>3.8</td>
<td>90</td>
<td>20</td>
<td>12.5/25</td>
<td>23.11/289.0</td>
<td>1.5</td>
<td>5.49</td>
<td>27</td>
<td>70</td>
<td>10</td>
<td>0.72</td>
<td>48</td>
</tr>
</tbody>
</table>
RRS vs Core Gas Content Data

Gas content [RRS, m3/t] vs Gas content (Fast Desorption, m3/t)
Derivation of Gas Content

- **Process**
  - Evaluate available isotherm data for variation in sorptivity.
    - Similarity to tested coals (depth, temperature, rank, etc.)
  - Investigate outliers individually and identify a representative P(L) with a statistical measure of deviation.
  - Identify dry ash free adsorption isotherm values.
    - Correct V(L) to DAF
    - Check consistency of similar coals
  - Establish density to ash correlation.
  - Evaluate coal density data
    - Density log data compared to in-situ data (isotherm)
  - Customize V(L) for coals based on average ash content.
    - Representative of entire coal seam
  - Correct for temperature effects to derive new P(L) and V(L).
Derivation of Gas Content

- **Graphs:**
  - Graph 1: Comparison of V(L) as received and V(L) dry ash free across different seams.
  - Graph 2: Scatter plot showing the relationship between ash content and relative density.

- **Equation:**
  \[ y = 0.0122x + 1.2124 \]
  \[ R^2 = 0.9908 \]

- **Table:」
<table>
<thead>
<tr>
<th>Seam no.</th>
<th>Average density (g/cc)</th>
<th>Average ash (%)</th>
<th>V(L)—DAF (psi)</th>
<th>Synthetic V(L)—AR (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seam 1</td>
<td>1.57</td>
<td>29</td>
<td>27.06</td>
<td>19.21</td>
</tr>
<tr>
<td>Seam 2</td>
<td>1.63</td>
<td>34</td>
<td>29.74</td>
<td>19.65</td>
</tr>
<tr>
<td>Seam 3</td>
<td>1.50</td>
<td>23</td>
<td>32.87</td>
<td>25.17</td>
</tr>
<tr>
<td>Seam 4</td>
<td>1.62</td>
<td>33</td>
<td>29.84</td>
<td>19.93</td>
</tr>
</tbody>
</table>
Data Validation

• Cross-referencing data sets
  – Primary vs Backup Formation Gauges (P&T)
  – Primary Formation Gauge vs Fluid Gauge (P&T)
  – RRS Logging Tool vs Fluid Gauge (P&T)
  – RRS Logging Tool vs Surface Meter (Conductivity)
• Comparison with absolute references
  – Atmospheric pressure readings
  – Cuvettes of known salinity
• Independent verification
  – RRS and gauge calibrations
• Self-consistency
## Gauge Comparison

<table>
<thead>
<tr>
<th>Client</th>
<th>Test No.</th>
<th>Well No.</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>19931</td>
<td>19932</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>19931</th>
<th>19932</th>
<th>19933</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge Type</td>
<td>Piezo-resistive</td>
<td>Piezo-resistive</td>
<td>Piezo-resistive</td>
</tr>
<tr>
<td>Depth (m BS)</td>
<td>xxx.xx</td>
<td>xxx.xx</td>
<td>xxx.xx</td>
</tr>
<tr>
<td>Gauge Location</td>
<td>Workstring</td>
<td>Formation</td>
<td>Formation</td>
</tr>
<tr>
<td>Maximum Temperature (C)</td>
<td>34.8</td>
<td>35.2</td>
<td>35.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time/Date</th>
<th>Event / End of</th>
<th>Pressure (PSIA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:00</td>
<td>At surface</td>
<td>14.58</td>
</tr>
<tr>
<td>12:00</td>
<td>Initial hydrostatic</td>
<td>19.54</td>
</tr>
<tr>
<td>13:48</td>
<td>Start of 2nd flow period</td>
<td>64.41</td>
</tr>
<tr>
<td>12:38</td>
<td>End of 2nd build-up period</td>
<td>50.8</td>
</tr>
</tbody>
</table>
## Data Validation

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Temperature</th>
<th>Conductivity</th>
<th>TDS</th>
<th>Solution gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>psia</td>
<td>°C</td>
<td>uS</td>
<td>ppt</td>
<td>[CH₄], mM</td>
</tr>
</tbody>
</table>

**Pressure log** indicates fluid height and density.

**Conductivity log** is shown in micro Siemens.

**Total dissolved solids log** is derived from conductivity log, and is temperature corrected.

**Blue line** shows saturation concentration at each depth.
PTA Validation

Borehole 2 Seam 1 Workstring Fill Time

- CDP = 20.0 psig
- CDP = 48.3 psig
- CDP = 76.5 psig
- CDP = 104.8 psig
- CDP = 133.0 psig

kh = 962 md.ft
Actual = 43 mins
Theoretical = 39 mins
Key Learnings

• Standard well design and completion techniques do not conflict with RRS and DST testing methods.
• It is possible to quickly retrieve reservoir fluids from coal seams isolated in open holes, with lowest flow capacity tested to date being 39 mD.ft.
• The RRS logging technique can readily distinguish reservoir & non-reservoir fluids.
• The design of surface pressure and flow control system can safely manage CH4-laden fluids at the rig floor.
• The RRS system has a wide dynamic range, with tested to date having $1.5 < G_c < 13.3$ m3/t.
• The limit of detection (LOD) of new high sensitivity RRS instrument is +/- 0.1 m3/t.
Key Learnings

• It is possible to obtain data needed to quantify $G_c$ & $k$ for a target coal seam in less than 24 hours.
• The field trial proved ability of the DST system to facilitate multiple tests in separate seams in a single trip, saving test time.
• Testing time can be compressed significantly via certain equipment refinements, which have been verified on subsequent wells.
Conclusions

- A new core-less technique has been developed to yield concurrent *in situ* measurements of $k$ & $G_c$.
- The new capability integrates DST and proprietary RRS technologies, with both using reservoir fluid as part of their measurement modes.
- Effective fluid management is therefore crucial to achieving accurate representative results.
- Analyses of fluid behaviour and properties yield *bulk* averaged values of $k$ and $G_c$.
- Operation of this integrated service has been successfully demonstrated in a 2-well field trial.
- All key deliverables established for the field trial were met, with computed $G_c$ values matching those derived from fast desorption tests on cores.