Novel data interpretation and active monitoring methods for intelligent wells

Khafiz Muradov, Heriot-Watt U

Acknowledgments: D. Davies, R. Malakooti, F. Silva

Aberdeen, 22 Oct 2013
Outline

- Introduction
- I-well Monitoring Systems Review
- Novel P and T Analysis in I-wells
- Novel Active Monitoring Concept for I-wells
Value of Information

Remarks:
- Value of Information comes from zonal, phase flow rate values as:
  - Improved recovery: Well and field control basis
  - Regulations met: Zonal flow rate values
  - Reservoir model/understanding update
  - Reduced risk
  - Reduced number of interventions
  - Value of information

Also:
- All (worldwide) case studies demonstrating the added value from I-wells presume zonal, phase flow rates are known
Wellbore measurements can provide a wide range of information. Few examples:

- **Temperature**
  - DTS, FBG, ATS, PDG
- **Pressure**
  - PDG, FBG
- **Acoustic signal**
  - Seismic Array, FBG, DAS
- **Density**
  - Density-meter, FBG
- **Flow rate**
  - Venturi, Spinner
- **Tracers**
  - DTS, Multi-point T gauges
- **Etc. Etc.**

Applicable measurement system greatly depends on the installation and operational capabilities.
Monitoring Objectives for I-wells

- Condition Monitoring
- Well Performance
- Well Stimulation
- Flow Assurance
- Advanced Completions Monitoring
- Reservoir Characterization and Optimisation

Specific information is needed in each application case!
Outline

- Introduction
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## Sensor Combinations: P & T are Key Elements


<table>
<thead>
<tr>
<th>Type</th>
<th>Application</th>
<th>Distributed</th>
<th>Quasi-distributed/Discrete (limitations might be applied due to spatial resolution)</th>
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<td>T A V ε T P A S Q ε EM</td>
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<td>Condition Monitoring</td>
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<td>Influx identification</td>
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<td>ICV position</td>
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<tr>
<td>Reservoir Characterization</td>
<td>Structural features (faults, folds, etc)</td>
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<td>Boundaries</td>
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<td>Well test</td>
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- Quantitative P&T interpretation methods are not available for many scenarios
- This reduces the sensor value; slows their development, installation and usage
Metrology, System’s Response, Interpretation Uncertainty

Sensor’s Performance

Well/Reservoir Performance: Spatial, Temporal (Alberts, Belfroid et al. 2007) + Signal’s Value

Robustness of Interpretation Methods

![Graph showing gas rate vs time](image-url)
Outline

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- Novel Active Monitoring Concept for I-wells
Common P&T Interpretation Practices

Discrete P sensors:
- Well Testing
- Production Analysis
- Cross-correlation in flow meters etc.

Distributed T sensors:
- **Continuous Testing**: Flowing temperature profile matched or Temperature gradient analysis used
- **Periodic Testing**: Warm- or cool- back temperature profile on shut-in

- Little software available for conventional temperature analysis
- No software or analytical methodology available for transient T or T & P testing
- P & T data are used separately
Other Temperature Interpretation Methods

Temperature Analysis has Many Applications

- **Qualitative:**
  - Temperature change
    - Gas or Water breakthrough identification
    - Operating GLV or casing leak
    - Fracture height, scale deposition, other features
  - Shut-in temperature change
    - Cross-flow

- **Quantitative**
  - Thermal slug tracing
  - Rate allocation:
    - Temperature of mixed inflows
    - Inverse modelling using wellbore temperature models
Real-Time, Zonal Flow Rate Soft-Sensor

Measured values of Pressure, Temperature & total flow rate can be **used** for real-time, zonal rate allocation **if the model is properly calibrated**. The soft-sensor uses the advanced wellbore T-model developed by *Muradov and Davies, 2008*

<table>
<thead>
<tr>
<th>Zonal phase flow rates</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
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<tbody>
<tr>
<td><strong>Oil rate, in situ bopd</strong></td>
<td>0</td>
<td>3,900</td>
<td>9,700</td>
<td>14,400</td>
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<tr>
<td><strong>Gas rate, in situ bgpd</strong></td>
<td>0</td>
<td>7,800</td>
<td>2,200</td>
<td>0</td>
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<tr>
<td><strong>Water rate, bwpd</strong></td>
<td>0</td>
<td>0</td>
<td>11,200</td>
<td>8,800</td>
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</tbody>
</table>

Advantages: Transient Temperature Analysis

Discrete or distributed, temperature transient analysis is attractive:

- A new generation of down hole sensors has become available: e.g. ATS, FBG
- Layer-by-layer testing is not required
- Tolerant of gauge drift & accuracy problems
- Differentiates zones

![Graphs showing zonal temperatures and pressures](image)

VS.
Interpretation of temperature transient allows estimating:
1. Thermal properties if rates and PIs are known (calibration mode) OR
2. Rates and PIs if thermal properties are known (soft-sensing mode)

Temperature Transient Analysis: Example Application

A PDG, installed across a toe zone of a multi-zone, intelligent well, measures pressure and temperature:

The measurements at the toe zone are analysed first, with the analysis further extended to the other sensors.

**Temperature Transient Analysis:**

Example Application

Zonal pressures

Zonal temperatures
Diagnostic Plot:
Both Pressure & Temperature Data required

1. Diagnostic, log-log plot of T recognises early-time regimes better than P,
2. P is more robust at later times

Pressure and Temperature Transient Analysis: Zonal Contribution to Total Well Flow Rate

Initial P & T decrease

Later T increase

Liquid rate is allocated:

\[
\frac{Q_{\text{toe}}}{Q_{\text{well liq}}} \approx \sqrt{2 \frac{\partial T}{\partial t} \frac{1}{JT_{\text{coef}}}} \sqrt{\frac{\partial P}{\partial \sqrt{t}} \sqrt{C_{\text{compressibility}}} \pi} \frac{L_{\text{enthalpy toe}}}{L_{\text{enthalpy well}}} = 0.78
\]

Multi-zone Interpretation Workflow

- Sandface T reconstructed using sensors installed downstream
- Interpretation started from the most upstream sensor

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Multi-phase Soft-sensing

Previous Works (Passive Soft Sensing)

Well → Measurement → Model → Estimate → Match Measurement & Estimation

Noise

This work (Active soft sensing)

Control ICV setting

Manipulate ICVs to estimate reservoir properties: Reservoir Pressure, Well Productivity Index, Water-Cut & Gas Liquid Ratio

Model

Dynamic Multi-phase Flow Model

• IPR Equation
• CPR Equation
• TPR Equation
• Welltest Equation

Match Measurement & Estimation

• Downhole Pressure (steady-state or transient measurements)
• Downhole Temperature
• Surface Flow Rates

Measurement & Estimation
Active Soft Sensing
(Flow rate allocation in an n-zone I-Well)

Change ICV’s Setting

Measured Data from n+1 ICV Settings
P_{annulus}, P_{tubing}, ΔP, T & Q_{surface}

Data Estimation
Q_{surface}, ΔP_{ICV}, ΔP_{Drawdown}

Minimize Mismatch

Reservoir parameters assumed constant during test period.

Predefined Accuracy

Estimate Reservoir Parameters & Flow Rates
Case Study: A Three-Zone, Intelligent Oil Producer

Integrated wellbore-reservoir transient simulation model

This study is on a triple zone I-well with two-phase (Oil & Water) flow

- Rectangular reservoir with constant pressure boundaries
- I-Well model (Annulus, ICV, Tubing) in OLGA connected to reservoir
- Used a PVT file instead of a Black oil model
- Zero skin

Coupled Rocx Simulator with Wellbore Model in OLGA
Design Multi-Rate Tests

- Only pressure transient data from build up tests analysed to avoid the complexity generated by multi-layer reservoir well testing.

<table>
<thead>
<tr>
<th>No. of Experiment</th>
<th>ICV$_1$ (Open Area Fraction)</th>
<th>ICV$_2$ (Open Area Fraction)</th>
<th>ICV$_3$ (Open Area Fraction)</th>
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<th>ICV2</th>
<th>ICV3</th>
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<th>Qw</th>
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<th>Pan$_2$</th>
<th>Pan$_3$</th>
<th>Ptub$_1$</th>
<th>Ptub$_2$</th>
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</table>
Optimization of ICV Positioning
(USS Pressure, SS Pressure & Flow Rate)

- DC (simplex) technique selects ICV settings for new experiment
- Experiment with least mismatch (white rows) removed as new experiment updates the reservoir properties

<table>
<thead>
<tr>
<th>NO. of EXP.</th>
<th>ICV1</th>
<th>ICV2</th>
<th>ICV3</th>
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Workflow gradually approaches the unknown reservoir parameters via a further multi-rate experiment
Two-Phase Flow Rates Allocation
(USS & SS Pressure & Flow Rate)

- Zonal Productivity Index (Comparison between active soft-sensing method & OLGA)

![Graphs showing Zonal Productivity Index for different zones.](image-url)
Two-Phase Flow Rates Allocation (USS & SS Pressure & Flow Rate)

Zonal Water Cut (Comparison between active soft-sensing method & OLGA)

- Zone 1
  - Estimated Value
  - True Value

- Zone 2
  - Estimated Value
  - True Value

- Zone 3
  - Estimated Value
  - True Value
Two-Phase Flow Rates Allocation (USS & SS Pressure & Flow Rate)

- Zonal Reservoir Pressure (Comparison between active soft-sensing method & OLGA)

Problem possibly caused due to initial guess in Excel Solver
Summary

- Value of information in intelligent wells was explained.
- Downhole sensors have been discussed.
- Transient P&T analysis has been shown to be advantageous.
- Active soft-sensing, utilising i-well abilities to both control and monitor separate production zones, has been explained and its potential emphasized.
Contact Details

“Added Value from Intelligent Well and Field Systems Technology” JIP

http://www.pet.hw.ac.uk/research/iwfst/

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