Online Water-Injection Optimization and Prevention of Reservoir Damage
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Abstract
Waterflood injection on the Shell Bonga field offshore Nigeria is accomplished via a network of subsea flowlines and 15 subsea injection wells. Maximizing water injection volume is an important economic objective for Bonga. Water injection is used for maintaining the reservoir pressure and thereby maximize oil production. The water injection flowrate to each well is limited by the fracture pressure of the overlying shale layer. Fracture of overlying shale could significantly reduce oil recovery from the damaged reservoir.

Hence, it is important to accurately control the reservoir injection pressure such that volume of injected water is maximized without excessive risk of damaging the overlying shales. Since there are no downhole pressure gauges in the injection wells, the downhole injection pressure must be estimated from other measured variables.

For this, we developed a novel technology, WRIPS (Waterflood Reservoir Injection Pressure System). The WRIPS algorithm is used to:
- Estimate downhole injection pressure based on the model and available measurements
- Estimate injection pressure uncertainty as a function of available measurements
- Calculate an injection pressure target as a function of system conditions
- Calculate injection rates for wells where the venturi has failed
- Data reconciliation: calculate the most probable pressures and flowrates based on model, measurements, and sensor accuracies
- Set conditioned alarm flags

The paper gives a brief description and the experience gained with WRIPS applied to water injection wells. The main contribution from the paper is to demonstrate the benefits with such a system and that the WRIPS is an attractive solution compared to expensive downhole pressure gauges.

Introduction
WRIPS is an operational support system for online or offline monitoring of water reservoir injection pressure, water injection rate calculation, control and optimization. It has been installed on Bonga since 2005. The knowledge of the water injection pressure and rates to each reservoir is important to achieve better reservoir management and ultimately increased recovery. Generally, this information would have to come from venturies and downhole pressure sensors installed on each well.

The basis of WRIPS is the Well Monitoring System (WMS) module, which is a software based multiphase metering system for production wells described in reference 1. For water injection networks, WRIPS uses the topside pressure and flow sensors together with available sensors throughout the network and from each well. A typical sensor layout is given in Figure 1.

The main objective with WRIPS is to calculate the most probable bottomhole pressure on basis of online sensor data. The problem is how to distribute the rates, pressures and temperatures throughout the network.
This paper consists of three parts: In the first part, we explain the theory behind the WRIPS and the definitions used. The second part tells how the system was used and an evaluation of the system and its application. In the third part, we present data and results.

Theory and Definitions
The problem of estimating the most probable water injection rates, pressures and temperatures throughout the network is solved on basis of a statistical approach which is built on top of the pipeline network solver. It ensures continuity in mass, energy and pressure and the most probable distribution of the uncertainties of individual component pressure and temperature drops throughout the complete network. The uncertainty in each component’s pressure and temperature drop is calculated by perturbation of all sensor and model uncertainties to find the uncertainties in pressure and temperature drop for each component. A component can be a pipe, a choke, a venturi etc.

WRIP calculates the injection flowrates, pressures and temperatures for all wells and flowlines at all locations in the injection network, based on online measured sensor values. Because it neither distributes the uncertainties nor provides continuous pressures and temperatures throughout the injection network, it is necessary to post process the results. This post processing is performed automatically by the new developed statistical approach.

It is mathematically proven that the new developed statistical approach, gives the most probable pressures temperatures and water rates based on the sensor and model accuracies. The following assumptions are made:

- The change in pressure and temperature drop is a linear function of the uncertainty variables within the confidence interval of the uncertainty variables.
- All pressure and temperature drops and measurements are independent and random variables that follow a normal Gauss probability distribution.
- All uncertainty parameters are specified with the same confidence interval, e.g. a 90% confidence interval.

The sensor uncertainty is normally defined in sensor datasheets as the sum of non-linearity, hysteresis, and non-repeatability. In addition – for pressure sensors, the “thermal error” should be included. This type of error is caused by thermal expansion, change in diaphragm elasticity with temperature etc. Normally this is automatically compensated for, but if the temperature is measured incorrectly the compensation becomes wrong.

Pressure Uncertainty.

The injection pressure uncertainty is available as an individual simulation running at a specified frequency. The principle of how WRIPS estimates the pressure uncertainty related to the measurements, model parameters and model accuracy is described by the following:

\[ f(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2} \]

where \( x \) is the pressure value of a stochastic variable \( X \), and \( \mu \) and \( \sigma \) are its expected value and standard deviation. The combined probability density function for all the pressures (stochastic variables), is equal to the product of all probability density functions for each pressure. This derivative of this product is set equal to zero to find the most likely pressure distribution and injection pressures.

Estimation.
The uncertainty estimate consists of a model estimate and a verification of the linear assumptions made in the estimate.

- Select the confidence level to be used (e.g. 90%) and define the corresponding uncertainty (= standard deviation times a factor corresponding to the confidence interval) for each uncertain variable (sensor and model parameter)
- Each variable is in turn set to the limit of the corresponding confidence interval. A new value for the injectivity pressure is then calculated for each variable with the added uncertainty.
- The perturbations performed for each variable are used to build a linearization of the injection pressure model. The linearized model is only used within the confidence intervals defined by the uncertainties.
- All estimated sensor pressures in the network are assumed random variables distributed according to normal distributions, i.e. their probability density functions are assumed to be of the following form, the uncertainty is specified, either as relative accuracy (± x%) or as absolute accuracy (± x bar).
- The uncertainties entered by the operator are used as basis for the standard deviation of the corresponding sensors, parameters, and models.

Input.
- Uncertainty for all sensors (pressures, temperatures, flowrates, choke positions and differential pressure sensors), and model parameters (e.g. fluid density and viscosity, pipe diameter, pipe roughness, etc.).
- The uncertainty is specified, either as relative accuracy (± x%) or as absolute accuracy (± x bar).
- The uncertainties entered by the operator are used as basis for the standard deviation of the corresponding sensors, parameters, and models.

Verify Model
- The highest and lowest possible injection pressures are calculated by setting all variables simultaneously to the “worst case” value inside the confidence interval for each variable.
- Finally the linearized model is compared with the “worst case” simulation to verify that the linearized
model predicts the “worst case” simulation with reasonable accuracy.

- If the difference between the conservative "worst case" value and the estimated value is too large, a warning is given. If this occurs, the assumption of linearity and/or independency is not correct. It is then required to adjust the configuration w.r.t to weight on the various sensors and/or increase the safety margins. However, the risk of this is low, proven by the fact that it has yet not occurred on Bonga.

Target Pressure.

The target pressure of the injection pressure is calculated based on the following parameters: shale layer fraction pressure and safety range for pressure (e.g. 500 psia). The target pressure is calculated each time a new model uncertainty is calculated.

The target pressure is set equal to the:

\[ P_{\text{target}} = P_{\text{fracture}} - P_{\text{safety range}} \]  \hspace{1cm} (1)

Alarm Limits.

WRIPS will report an uncertainty (Punc) equal to 2 times the standard deviation (sigma) of the injection pressure,

\[ P_{\text{unc}} = 2 \times \sigma \]  \hspace{1cm} (2)

Operating at a calculated injection pressure two sigmas below the estimated fracture pressure, will give us a 95% confidence that we operate below the estimated fracture pressure. This uncertainty level was chosen as a compromise between flow assurance and maximized injection rates.

This is implemented into WRIPS alarm for HH, H, L and LL as follows:

\[ P_{\text{HH}} = P_{\text{fracture}} \]  \hspace{1cm} (3)

\[ P_{\text{H}} = P_{\text{target}} + \sigma \]  \hspace{1cm} (4)

\[ P_{\text{L}} = P_{\text{target}} - 2 \times \sigma \]  \hspace{1cm} (5)

\[ P_{\text{LL}} = P_{\text{target}} - 3 \times \sigma \]  \hspace{1cm} (6)

Description and Application of System on Bonga

The WRIPS is set up as a redundant system with two servers. Although both WRIPS servers read all inputs and perform all the calculations in parallel, only one of them are designated Master. The other is designated Slave. Only the Master transfers the calculation results to the control system. If the Master fails, the Slave will be designated Master and continue its operation and communication until the problem with the first server is solved.

The reason for having two WRIPS servers on Bonga was the necessity of knowing the injection pressure at the point of injection to avoid fracturing the above shale layer and risking water breakthrough. Should there be only one WRIPS server and this server crashed, the client would have to shut down the water injection to the wells.

Verifying that the calculated water injection pressure is correct is impossible, as there are no measurements downhole to compare the results to. WRIPS was therefore tested by checking that the calculated water injection rate matched each venturi rate and that the total mass balance was correct. Seeing that these rates were correct, gave the client confidence that the calculated water injection pressures throughout the water injection network were correct.

Presentation of Data and Results

The WRIPS system has been running on Bonga since November 2005. The Bonga field consists of production and water injection flowlines as seen in Figure 2, where the brown circles represent the production and the green circles the water injection flowlines. The flowlines, designated East and West are independent subsea network feeding multiple subsea injection wells.

The East and West flowline are each supplied with one water injection pump. In the case that one of the pumps should fail, a crossover valve lets the remaining pump distribute injection water to both flowlines.
For the water injection flowline going West, WFL-01 and its subflowline, WFL-02, there are four water injection wells:
- 690w4
- 702w1
- 702w2
- 710w3

For the water injection flowline going East, WFL-03, there are three water injection wells:
- 702w4
- 702w5
- 702w6

**WFL-01.**

Figures 3 – 7 show the results for WRIPS on Bonga for WFL-01, with each figure showing the comparison between the calculated water injection flow rates using the WRIPS module and the measured venturi rates. The sum of all the calculated WRIPS rates is also compared to the topside flow rate measured downstream the water injection pump for this flowline.

As can be seen from the results, the calculated WRIPS rates follow the measured venturi rates. For well 702w2, the venturi is not functioning, as can be seen from the erratic reading. WRIPS provides the injection rate for this well based on a mass balance and the pressure drop over the choke.

The erratic trend around December 14th – 19th 2005 is due to the water injection pump not functioning properly.
Figures 8 – 10 show the results for WRIPS on Bonga for WFL-03, with each figure showing the comparison between the calculated water injection pressures using the WRIPS module and the measured venturi rates. The sum of all the calculated WRIPS rates is also compared to the topside measured water injection pump rate for this flowline.

As can be seen from the results, the calculated WRIPS rates follow the measured venturi rates. Well 702w5 was not started as this point and only results for 702w4 and 702w6 are shown here.

The erratic trend around December 14th – 19th 2005 is due to the water injection pump not functioning properly.

Benefits

The main benefits with WRIPS are:

- **Avoid damage to the shale layer:** Monitoring of the injection pressure and its uncertainty ensures that shale fracture pressure is never exceeded. No injection is allowed into the Bonga reservoir without WRIPS in operation, due to the expected major economic loss if the maximum allowable bottom hole injection pressure is exceeded.

- **Optimize water injection:** WRIP calculates a target pressure for each well. The operator can optimize the production by keeping the injection pressure at the target pressure. Operating at maximum allowable injection pressure has been given large focus on Bonga and WRIPS has been used a lot for this.
- **Reliability:** Significantly improved reliability compared to conventional downhole sensors. Downhole sensors often fail and are too expensive to replace.
- **Cost saving:** The cost of software, hardware, commissioning, and maintenance for WRIPS is negligible compared to the cost of bottom hole sensors in all injection wells.
- **High accuracy of the downhole pressure:** WRIPS uses all available sensor data and a model to calculate the pressure. A downhole sensor would have higher accuracy, but it might fail or drift. In a big field like Bonga some downhole sensors would most likely fail and a system like WRIPS would have been beneficial anyway.
- **High accuracy in the estimated injection rates:** This enables higher accuracy for volume balance calculations (i.e. better reservoir model).
- **Redundancy:** WRIPS uses all available sensors for its estimates and will proceed undisturbed of failing sensors as long as the system is solvable.
- **Hardware and software redundancy:** WRIPS is set up as a redundant system with two servers. If one server fails, the other continues the estimations.
- **Alarm system:** The alarm system keeps the operators aware of unsafe or non-optimal water injection.

**Conclusions**
This paper demonstrates the ability of a software based water injection module to calculate: downhole injection pressure, injection rates, injection pressure uncertainty, injection pressure target and injection pressure alarms. The methodology used is based on the Well Monitoring System software that can cover both multiphase production and water or gas injection networks. The results show that WRIPS is a reliable and trusting tool that can be used to calculate, control and optimize the water injection on the Bonga field.

**Acknowledgements**
The authors would like to thank Shell and ABB for permission to publish this paper.

**Nomenclature**
\( P_{\text{target}} \) Target pressure  
\( P_{\text{fracture}} \) Shale layer fraction Pressure  
\( P_{\text{safety range}} \) Safety range for pressure  
\( P_{\text{model uncertainty}} \) Model uncertainty  
\( P_{\text{minimum model uncertainty}} \) Minimum model uncertainty

**References**