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Analytics-Driven Method for Injectivity Analysis in Tight and Heterogeneous Waterflooded Reservoir

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Abstract

Waterflood is one of the most reliable methods to enhance oil recovery. Among many factors governing waterflood performance, injectors' injectivity is considered as the key factor. Throughout the life of a waterflooded reservoir, injectivity impairment occurs which can have a negative impact on pressure maintenance and sweep efficiency provided by the waterflood, which both have a direct impact on production. This study aims to establish an integrated, analytics-driven method that will be leveraged to analyze injectors' performance in a tight and heterogeneous reservoir and monitor the evolution of their injectivity over time. An injectivity diagnostic methodology was developed by incorporating daily injection data and integrating various analytical techniques including instantaneous injectivity index, Hearn plot, Hall plot, derivative Hall plot, and falloff test and analysis. The resulting analytics performed well in assessing the performance of all injectors in the studied reservoir and identifying which injectors were experiencing formation damage and need stimulation. Instantaneous injectivity index quantifies the injectivity of each well. Hearn plot presents the change of the reciprocal injectivity index throughout the injection period. Hall plot provides qualitative indicators of formation damage and stimulation in each injector. Derivative Hall plot was able to capture subtle changes in injectivity that cannot be detected by conventional Hall plot, making it a powerful tool for real-time injectivity monitoring. Falloff analysis provides well and reservoir characterization in a particular injector, proving the low permeability and fractured characteristics in the injector. Each technique has its advantages and limitations and the best practice was implemented by combining all the techniques to obtain a clearer and bigger picture of the performance of all injectors. This paper describes the integrated data analysis for injectivity analysis in a tight and heterogeneous reservoir. The workflow presented is practically applicable and highly recommended for monitoring and evaluating injectors' performance in any reservoir, including the most complex ones.

Introduction

Field Overview

The reservoir of interest in this study is the TK reservoir, which is currently operated by PT. Medco E&P Indonesia. This reservoir is located onshore Sumatra, approximately 70 km northwest of Palembang City. TK is a saturated, low permeability, shaly, and heterogeneous sandstone reservoir. The key properties of this reservoir is summarized in Table 1. Due to the relatively low reservoir permeability, all TK wells are hydraulically fractured to enable production. The production started in 2002. After fast production build up in the early stage of the production life, the reservoir pressure dropped significantly.

Considering the weak pressure support provided by the solution-gas drive, water injection was then established in 2009 as a means of pressure maintenance. The required injectors are put in place by conducting convert-to-injector (CTI) jobs to convert producers that were inactive or had low oil reserve to be water injection wells. This strategy is beneficial, not only because it is significantly more economical than drilling new injectors, but also because the conversion process will maintain the existing fractures thereby allowing the injectors to have high injectivity.

Table 1. TK reservoir properties summary

Parameters	**Value**
Lithology	Sandstone
Depth (ft-TVD)	2,000 – 3,000
Initial Pressure (psia)	1,230
Current Pressure (psia)	500 – 1,230
Initial Temperature (°F)	175
Porosity (%)	10 – 20
Permeability (mD)	5 – 50
Average Net Pay (ft)	29
Initial Water Saturation (%)	40 – 65
Drive Mechanism	Solution-gas Drive
Production Commencement	Year 2002
Production Commencement	Year 2009

Since the beginning of its operation, water injection has been the main energy source supporting TK. Therefore, the performance of the water injection will strongly influence the production performance, and hence, the ultimate recovery factor of the reservoir. Among many factors affecting the performance of water injection, it is considered that injectors' injectivity plays the key role (Palsson, 2003). It is thus very important to monitor, diagnose, and thoroughly evaluate the injectivity of all injectors on the field; necessary actions to maintain or to improve the injectivity can then be formulated based on the evaluation. This study aims to analyze the performance of the water injection wells in the TK field and evaluate the evolution of their injectivity over time.

Data and Method

Five analytical techniques, incorporating injection flowrate and pressure data, were leveraged to evaluate the evolution of injectivity of the water injectors in TK reservoir: (i) instantaneous injectivity index, (ii) Hearn plot or reciprocal injectivity index plot, (iii) Hall plot, (iv) derivative Hall plot, and (v) falloff test and analysis.

Instantaneous Injectivity Index

The instantaneous injectivity index (II) combines all of the factors affecting the injection performance, which include effective permeability to water (k_w), effective injection zone thickness (h), water viscosity (μ_w), reservoir radius (r_e), wellbore radius (r_w), and skin factor (s). In oilfield units, assuming that the injection establishes a radial flow regime, the injectivity index can be calculated using Eq. 1.

$$II = \frac{k_w h}{141.2\,\mu_w B_w \left(\ln\left(\frac{r_e}{r_w}\right) + s\right)} = \frac{i_w}{P_{bhi} - \bar{P}_r} \qquad \text{Eq. 1}$$

The advantage of this method is that the injectivity can be directly expressed quantitatively without the need of further interpretations. Also, the injection rate and the wellhead injection pressure are normally available in timely basis. The main disadvantage of this method is that fluctuations in the measured rates and injection pressure, which normally occur during injection either due to inaccurate measurement or because of transient effects caused by reservoir or operational changes, will also result in fluctuating injectivity index. This fluctuations can sometimes be so significant such that the real instantaneous injectivity index value cannot be identified. Other drawbacks of this technique are the uncertainty in both the reservoir pressure and the bottomhole injection pressure predictions. Obtaining the actual reservoir pressure requires shutting in well(s) which is not always desirable. Bottomhole injection pressure can be predicted by calculating the friction loss across the tubing as well as the hydrostatic pressure, as expressed by Eq. 2-4.

$$P_{bhi} = P_{whi} - h_f + P_{hyd} \qquad \text{Eq. 2}$$

$$h_f = 2.083\,x\,\left(\frac{100}{C}\right)^{1.85} x\,\left(\frac{\left[\frac{i_w}{34.3}\right]^{1.85}}{ID^{4.8655}}\right) \qquad \text{Eq. 3}$$

$$P_{hyd} = fluid\ gradient\ \text{x}\ midperf\ depth \qquad \text{Eq. 4}$$

Hearn Plot

Hearn plot (Hearn, 1983) is also called reciprocal injectivity index plot. This method presents the reciprocal of the injectivity index plotted against cumulative water injection volume. In cases where the injection rate and/or injection pressure fluctuates significantly due to operational or subsurface reasons, which will result in fluctuating injectivity, this plot is often more applicable as it is less sensitive to fluctuations.

Hall Plot

Hall plot (Hall, 1963) is arguably the most popular method for injectivity monitoring and analysis. This technique incorporates the following data to generate the plot:

- Average monthly bottomhole injection pressures obtained either from direct measurement with downhole pressure gauges or predicted from wellhead injection pressures using flow correlations
- Average reservoir pressure in the injection zone
- Water injection rates and/or volumes (daily or monthly)
- Injection elapsed time

This method assumes that the steady-state water injection has been achieved and can be described by Darcy's equation as shown in Eq. 5.

$$i_w = \frac{0.00708\,k_w\,h\,(P_{bhi} - \bar{P}_r)}{\mu_w B_w \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]} \qquad \text{Eq. 5}$$

The plot is generated by plotting the cumulative pressure-time product (*i.e.* $\int_0^t (P_{bhi} - \bar{P}_r)dt$) against the cumulative volume of water injected (*i.e.* $\int_0^t i_w\,dt$). Hall plot provides a visual indication of the injection behavior where a change in injectivity, which is primarily caused by the change in skin factor, appears as a change in the slope of this plot as mathematically expressed by Eq. 6.

$$slope = \frac{141.2\mu_w B_w \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]}{k_w\,h} \qquad \text{Eq. 6}$$

This cumulative summing reduces fluctuations in the injectivity index which makes this tool more useful compared to injectivity index plot and Hearn plot.

Derivative Hall Plot

The advantage of the Hall plot, *i.e.* not susceptible to fluctuations, in many cases becomes the major drawback of this technique. It should be noticed that the changes in the slope of Hall Plot usually occurs gradually as it involves cumulative summation. A slight or sudden change of injectivity can easily be masked making it difficult for engineers to notice it. Due to this limitation, Hall plot is incapable of performing real-time monitoring and diagnostics.

To overcome this, Izgec and Kabir (2009) developed an extension to the Hall plot which involves plotting the derivative (DHI) of the Hall integral (HI) on the same axis. This will visually signify the injectivity changes thereby improving its diagnostic capability to capture small and sudden injectivity changes and making it applicable for real-time observation.

The derivative of the Hall integral can be calculated using Eq. 7:

$$DHI = \frac{d(HI)}{d(\ln(W_{inj}))} \approx \frac{(HI)_{t+1} - (HI)_t}{\left[\ln(W_{inj})_{t+1} - \ln(W_{inj})_t\right]} \qquad \text{Eq. 7}$$

Plotting the HI and DHI on the same Cartesian scale would reveal the following behaviors:

- If both plots trace the same path, then neither wellbore stimulation (e.g., fracturing or acidizing) nor formation damage (e.g., plugging or scaling) occurs
- If DHI plot falls below HI plot, then wellbore stimulation is indicated
- If DHI falls above HI plot, then wellbore plugging is indicated

Falloff Test

A falloff test is actually the pressure build-up version for injectors. It is a pressure transient test that is done by injecting water into the reservoir for a certain period of time and then shutting in the injector while measuring the pressure falloff. As this test requires the injector under investigation to be shut-in, this test is not routinely done in many operations.

This test provides useful information regarding the injector and the reservoir including the average reservoir pressure, effective permeability-thickness product, skin factor, and fracture characteristics (e.g., conductivity, dimensionless conductivity, and half-length). From this analysis, reservoir permeability can be determined by incorporating injection zone thickness obtained from log analysis or production/injection logging analysis.

Result and Discussion

Instantaneous Injectivity Index

Instantaneous injectivity index plots are generated for all the injectors. Injectivity index plot of one of the injector is shown in Figure 1.

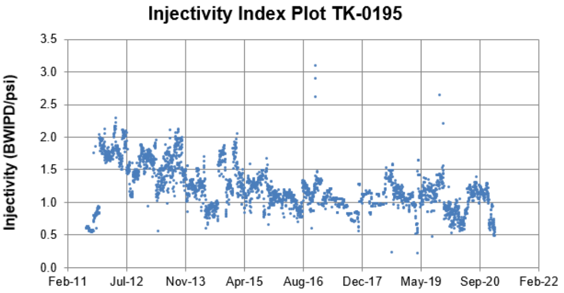

Figure 1: Injectivity index plot of injector TK-0195

As can be seen from Figure 1, there was a continuous decline of injectivity from approximately 2.0 BWIPD/psi in 2011 to about 1.0 BWIPD/psi in end of 2013. Since then, the average injectivity tends to be stabilized though the instantaneous injectivity keeps fluctuating. The latest trend of injectivity profile however shows a sharp injectivity impairment. This observation was important as an input for further investigation before the best remedial action to improve the injectivity can be formulated and conducted.

Hearn Plot

Hearn plots were also constructed for all injectors along with the injectivity index plot. This technique plots the reciprocal injectivity index against the cumulative water injection volume to measure the injection performance of the injector for every available data point. It has the same weakness as the instantaneous injectivity index plot although it is slightly less reactive to fluctuations in injection rate and pressure. Hearn plot of TK-0195 is presented in Figure 2.

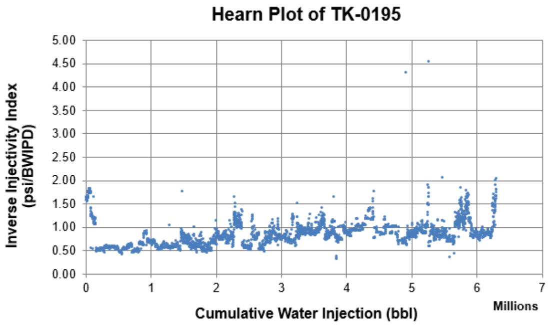

Figure 2: Hearn plot of injector TK-0195

As can be inferred from Figure 2, in average, there was a continuous increase of inverse injectivity index in the early operation of this injector. After the injection volume of 3 MMbbls was reached, the average reciprocal injectivity was relatively constant although instantaneously it keeps fluctuating. The latest reciprocal injectivity trend however shows a significant increase which indicates wellbore plugging that needs further study and action.

Hall Plot

As a best practice, Hall plots were generated for all injectors as illustrated in Figure 3. Based on the Hall plots, some injectors maintained their initial injectivity even after years of injection operation, while several others showed injectivity impairment. The main cause of injectivity decline was the accumulation of oil and suspended solids carried by the injection water. The other sources of injectivity impairment were sand and proppant build-ups covering the perforation or the choked fracture caused by the loss of proppant bed conductivity at sandface as the proppant were pushed by the injection water towards the reservoir.

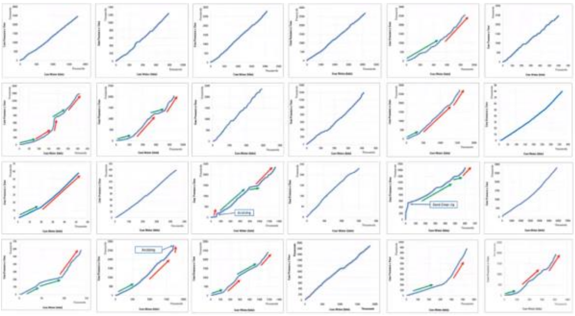

Figure 3: Hall plots of several TK injectors (Arnold & Asrul, 2020)

Using this analytical tool, injection performance of each injector can be monitored and analyzed. For comparative analysis, all Hall plots were plotted on a same graph, and based on the slope of each plot, each injector was then categorized into one of the two groups, as shown in Figure 4. The two groups are separated by the unit-slope line. Steep slope of the Hall plot or slope higher than unity indicates low injectivity or high resistance to flow, which can be caused by low reservoir permeability, formation damage, or local over-pressurization that minimizes the injection driving force. On the other hand, gentle Hall slope or slope lower than unity suggests high injectivity or low resistance to flow, which can be due to high reservoir permeability, connection with high permeability layer, or low reservoir pressure which maximizes the injection driving force.

Based on the comparative Hall plots, it was found that most of the injectors exhibited high resistance to injection. There was one injector that outperformed other injectors, both in terms of injectivity and injection sustainability. There are several possible reasons for this, including waterflood-induced fracturing that improved and sustained the injectivity, connection to high permeability streaks or to other zone, or wellbore leakage. Comprehensive investigation including reservoir, geomechanics, and wellbore integrity studies is required to identify the root cause of this anomaly.

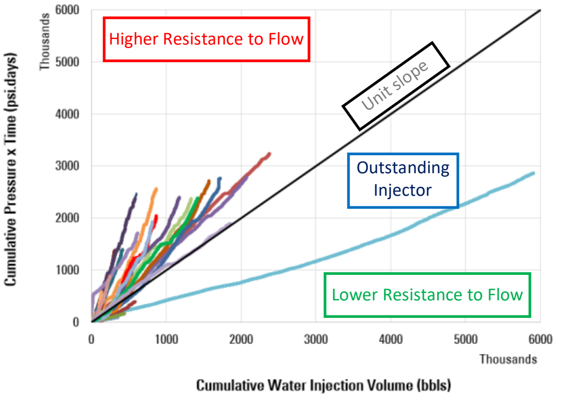

Figure 4: Comparative analysis with Hall plot (Arnold & Asrul, 2020)

Derivative Hall Plot

Derivative Hall plots were constructed for all injectors along with the construction of Hall plots. Hall plot and derivative Hall plot of TK-0195 is depicted in Figure 5.

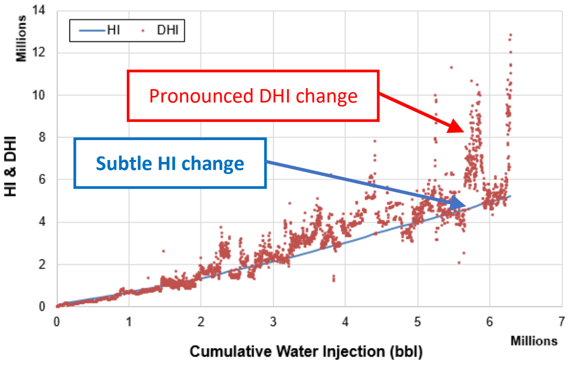

Figure 5: Hall plot and derivative Hall plot of TK-0195

As evidenced in Figure 5, the changes in slope of the Hall plot was subtle, making it difficult to identify the injectivity change. However, the derivative nature of the DHI plot is able to magnify these changes, making it easy to detect whether the injector experienced well stimulation or wellbore plugging.

In addition, the instantaneous injectivity, Hall plot, and derivative plot can be combined on the same graph to create a more comprehensive injectivity monitoring tool (Onwuchekwa, 2019) as demonstrated in Figure 6.

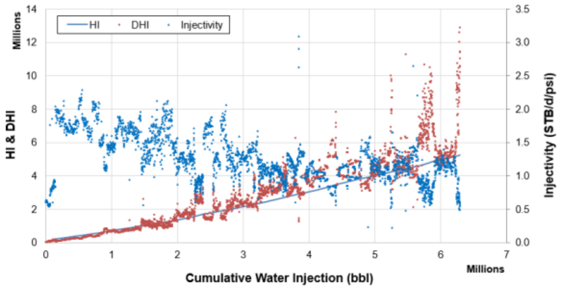

Figure 6: Combination of injectivity plot, Hall plot, and derivative Hall plot of TK-0195

Falloff Test

Due to the requirement of shutting in the injector of interest, falloff test was rarely executed. This test is only performed when there is a strong need of reservoir or well data, for example reservoir pressure to validate the reservoir simulation, fracture conductivity to validate the fracture simulation results following hydraulic fracturing execution, or permeability-thickness product to greatly enhance the quality of the injection analysis.

The latest falloff test conducted in TK field was performed in TK-0257. The log-log plot result of this test is shown in Figure 7. This analysis highlighted three important things, which are:

- Very high reservoir pressure exceeding the original reservoir pressure, which can be caused by continuous water injection within the reservoir zone that has low continuity to the far field area resulting in localized pressurization
- Low reservoir permeability of 7 mD, which confirmed the tight characteristic of TK reservoir
- Fracture half-length of about 300 ft, which validated the fracture analysis.

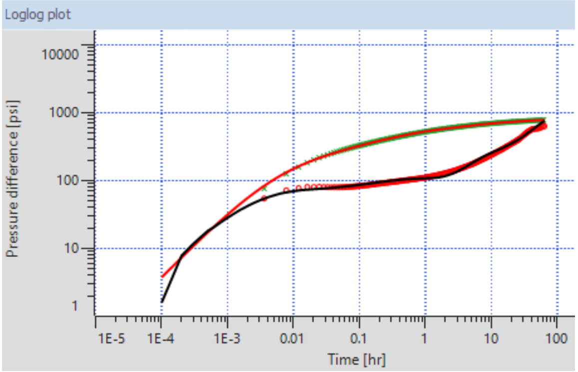

Figure 7: Log-log plot of falloff analysis in TK-0257

Conclusions

In this study, an integrated injectivity analysis methodology was developed by incorporating daily injection data and various analytical techniques including instantaneous injectivity index, Hearn plot, Hall plot, derivative Hall plot, and falloff test and analysis. Each technique has its advantages and drawbacks and the best practice was leveraged by combining all the techniques to obtain a clearer and bigger picture of the performance of all injectors in TK reservoir. The resulting analytical methodology performed well in assessing the injectivity of all injectors and identifying which injectors were experiencing formation damage and in need of wellbore stimulation. This method is very useful as it provides more accurate well performance assessment and faster opportunities identifier to improve injectors' performance.

Nomenclature:

B_w = water formation volume factor (RB/STB)
h_f = pressure drop due to friction (psia)
ID = tubing internal diameter (inch)
k_w = effective permeability to water, mD
h = effective injection zone thickness, ft
II = injectivity index (BWIPD/psi)
i_w = water injection rate (BWIPD)

μ_w = water viscosity, cp
P_{bhi} = bottomhole injection pressure (psia)
P_h = hydrostatic pressure (psia)
$\bar{P}_r$ = average reservoir pressure (psia)
P_{whi} = wellhead injection pressure (psia)
r_e = reservoir radius, ft
r_w = wellbore radius, ft
s = skin factor

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