Waterflooding surveillance: real time injector performance analysis using Hall plot method & derivative

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Abstract. In waterflooding operation, it's important to do performance surveillance of injection well so the oil recovery can be optimum as well as planned. Loss in injectivity can cause several problems and will give a bad impact on both surface and subsurface facilities. So this paper will discuss injector performance evaluation in order to minimize those problems. The methods that is presented in this paper is Hall Plot (1963) and Derivative Hall Plot (2009). Hall proposed a qualitative method to analyze injector well performance based on plot between cumulative drawdown pressure against cumulative water injected. In 2009, Izgec & Kabir proposed a new method to monitor injector well performance that can be more discriminate in any subtle slope changes.This paper presents the advantages using Hall Plot and its derivative compared than other methods. Also analyzingthe cause of problems that happened and also give recommendation to overcome the problems.

1. Introduction
Nowadays,when exploration activity is diminished due to low oil price condition, development and optimization of the field is come as the solution. Waterflooding has proven to be the most successful and most widely used methods to improve oil recovery since it is efficient to displace oil, the water availability is easy to find, more effective to inject water into formation, and last but not least, cost friendly compared to other injection fluids. Whenever water injection is implemented, it is essential to monitor the injection capacity of injection wells throughout the field. This is the case because ultimately any injectivity changes in injection wells can lead an effect on the reservoir pressure and the sweep efficiency and therefore the oil production rate. Loss in injectivity can also lead to a need of higher pump capacity, increased workover or even drilling a new injection wells. There are several methods commonly used in waterflooding surveillance, such as Reciprocal Injectivity Index (RII) or Hearn Plot, Fall Off Analysis, Step Rate Test and Hall Plot. Each method has its own advantages and disadvantages. Researches reveal that Hall Plot is become the most effective methods to analyze injector well performance since it is a steady state analysis method and the data acquisition is inexpensive because only the recording of daily wellhead pressure and injection rate is required.

2. Waterflooding for Recovery Improvement
Waterflooding is the most common IOR technology used to recover oil. The concept is to inject a large amount of water to sweep the oil into the producer so it will gain more oil recovery after the primary

recovery done. Some advantages from waterflooding are water is available in a large amount, has a good sweep efficiency, also cheaper compared than other IOR methods.

In waterflooding, it's important to maintain the quality of water injection to prevent any problems that may occur in waterflooding operation. As stated by Bennion, D.B et all (1994) and Charles (1990), almost all problems associated with impairment injectivity can ultimately be related back to problems associated with water quality. Ideally, injection water should enter the reservoir free of suspended solid or oil. It should also be compatible with reservoir rock and fluids and would be sterile and non-scaling. The objective of any water injection is to inject water into reservoir rock without causing any problem, such as plugging, permeability reduction from particulates, dispersed oil, scale formation, bacterial growth, or clay swelling. A good water monitoring system is required to maintain the quality of water. it can be useful for early detection of water quality problems so the prevention can be prepared earlier.

3. Hall Plot

The Hall plot was originally proposed to analyze the performance of waterflood injection wells. Hall (1963) simply used Darcy's law for single phase, steady-state, Newtonian flow of a well centered in circular reservoir:

$$qi = \frac{K_w h \left(P_{wf} - P_e \right)}{141.2 \mu_w B_w \left(\ln \dfrac{r_e}{r_w} + S \right)} \dots (1)$$

Hall Integrated both sides with respect to time to obtain:

$$\int q_i . dt = Wi = \frac{K_w h}{141.2 \mu_w B_w \left(\ln \dfrac{r_e}{r_w} + S \right)} . \int (P_{wf} - P_e) . dt \dots (2)$$

Where,

$$P_{wf} = P_{wh} - \Delta P_f + (\rho g x TVD)$$

Thus, re-arranging the equation, becomes:

$$\sum_t \left(P_{wf} - P_e \right) . dt = \frac{141.2 \mu_w B_w \left(\ln \dfrac{r_e}{r_w} + S \right)}{K_w h} Wi$$

This is a linear equation. A plot of cumulative volume water injected (Wi) versus the pressure summation (the left-hand side) gives what is known as Hall Plot.

The data that is required in hall plot are record of daily wellhead pressure and injection rate. It is a plot between cumulative water injection versus cumulative pressure drawdown in days. Hall observed that if an injection well was stimulated or fractured, the slope decreased while if a well is damaged, the slope is increased.
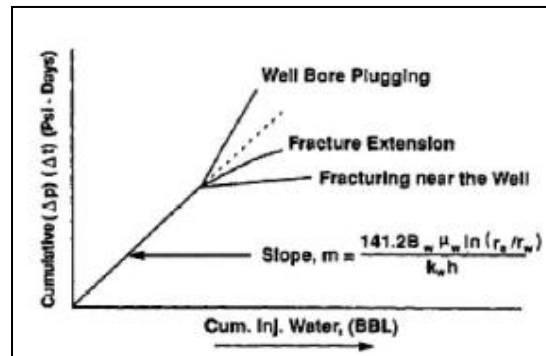
Figure 1. Hall Plot[1]

Analysis of an injector performances can be done when there is changes in slope inhall plot. But sometimes, it can't be seen by only using hall plot. Because hall plot only can identify a significant change in slope while a subtle change can't.In 2009, Izgec and Kabir(SPE 109876) presented a new formula called Derivative Hall Plot (Appendix A). It's simply using hall plot derivative both analytical and numerical so it can see a subtle change that is unseen by using hall plot conventional. Derivative Hall Method can be used for the real-time injection performance analysis. It's relatively simple diagnostician tool and can distinguish between formation plugging or fracturing.
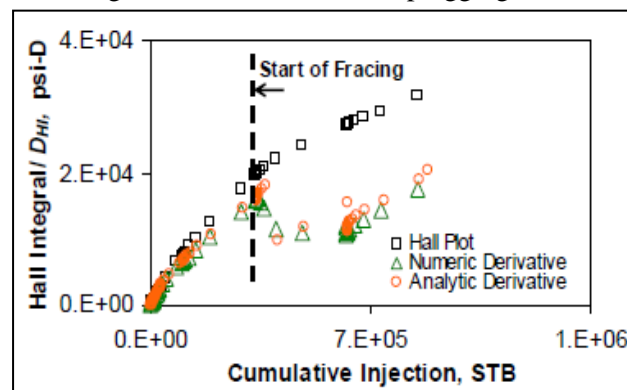

Figure 2. Derivative Hall Plot[2]

As stated by J. Amedu and C. Nwokolo (2013), there are some possible interpretation that could result from changes in the slope of hall plot.Mostly, the slope changing in hall plot is caused by impairment if the slope is increasing or fracturing if the slope is decreasing. But there are also factors controlling non- impairment related to slope increases, such as nearby producershut in, tubing size reduction and reservoir re-pressurization. While factors controlling non-fracturerelated to slope decreases are increased offtake from nearby producer, change in tubing size to a higher tubing, stimulation and declining reservoir pressure.
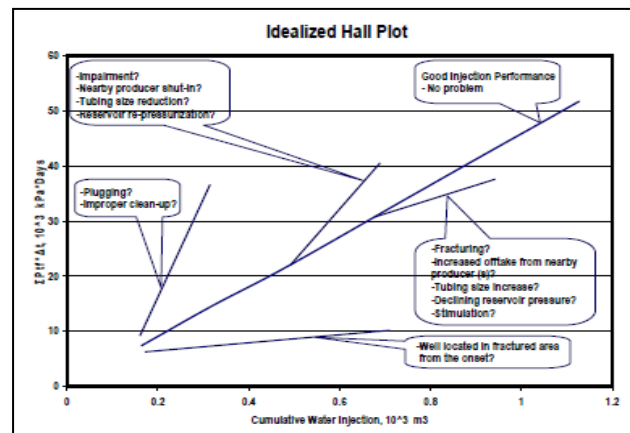
Figure 3. Idealized Hall Plot[4]

4. Field Results and Analysis

In this paper, author will give three cases from Perkutut Field in analyzing injector wells performance using Hall Plot method. They are Well X-1, X-2 and X-3.

4.1 Well X-1

Well X-1 has been operated since 2015. It's a converted well from previously producer well. Currently, X-1 injector is operatinginjection rate at 982 bwpd and wellhead pressure 310 Psi.Figure 4 shows daily data monitoring from injector X-1. From the plot,around October 2015, when injection rate is decreased, wellhead pressure doesn't follow the same, indicated plugging happens in injector.From figure 5, we can see there are no changes in slope. But after we add its derivative (Figure 6), we can see there is an increasing in slope after 1 months. The problem that may concur in X-1 Injector is plugging. Calculation of plugging estimation in Perkutut Field reveals that plugging can happen in Perkutut Field after 6.6 months of injection (Appendix B). But in fact, plugging has happened 1 month after injection started. So, there must be another source of plugging. The suspect is, because X-1 injector is a new converted well, plugging could come from debris that didn't cleared perfectly. The debris then come flowing into the perforation and thus clog the perforation. The prevention from this problem is to do and review pipeline cleaning according to SOP, so the debris couldn't clog the perforation. And to overcome this problem, acidizing or breakdown can be the solution.
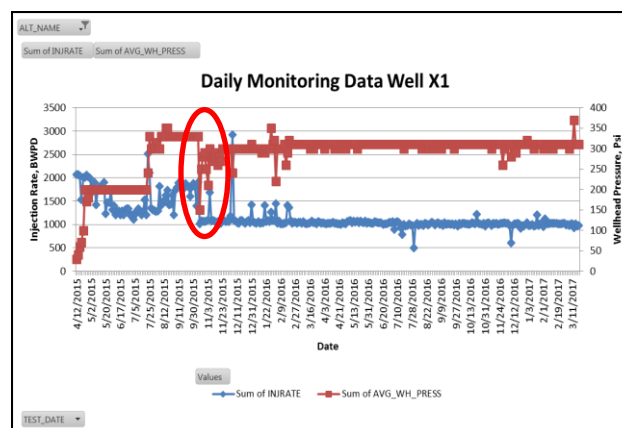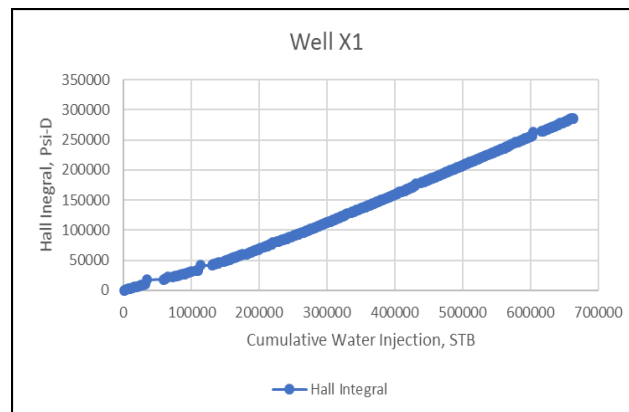

Figure 4. Daily Monitoring Data Well X-1
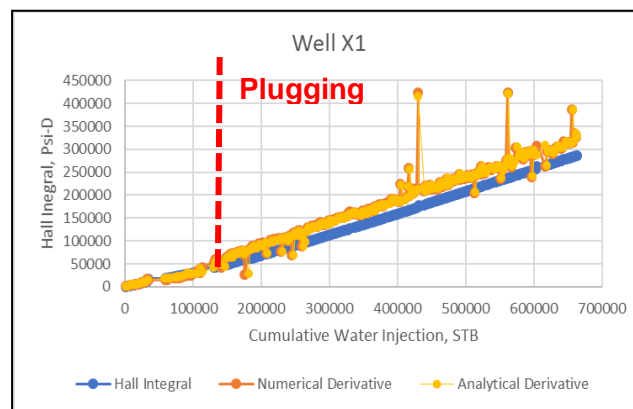
Figure 5. Hall Integral Well X-1

Figure 6. Hall Integral Well X-1 and Derivative

4.2 Well X-2

Well X-2 Injector has been operated since late 2016. This well is a converted well from previously producer well. Currently, X-2 injector is operating injection rate at 1466 Bwpd and wellhead pressure 275 Psi. Figure 7shows daily data monitoring well X-2. From Figure 7, when the injection rate is decreased, wellhead pressure is increasing instead. It indicates plugging happened in injector. From Figure 8, the hall integral shows an increasing in slope. Also from figure 9, the derivative also shows the same. The causes of this plugging problem in X-2 injector is same with X-1 injector, which is early plugging happens after 1 month of injection. The causes of this early plugging is coming from debris that didn't cleared clearly. The prevention and overcome this problem is also same with X-1 injector.
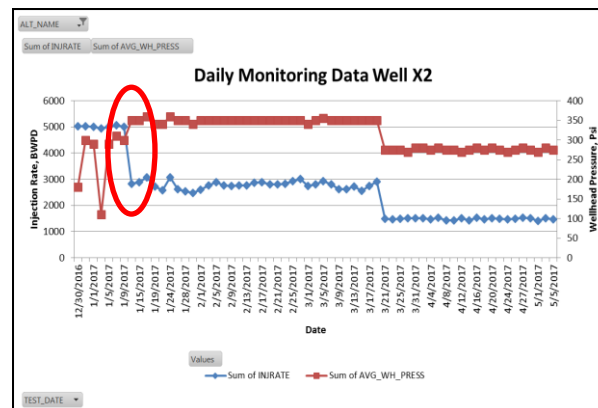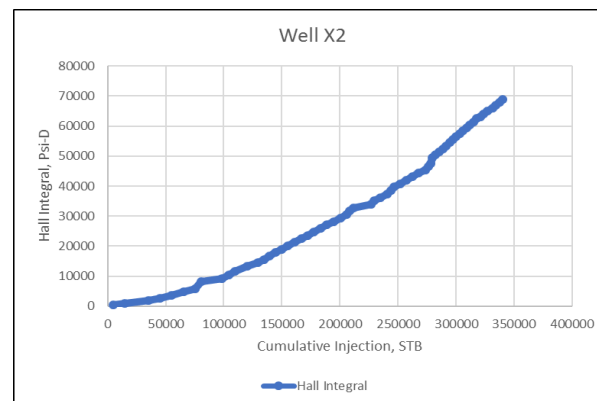
Figure 7. Daily Monitoring Data Well X2

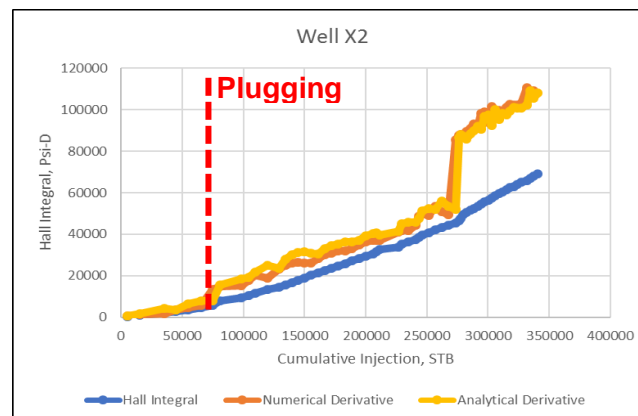**Figure 8.** Hall Integral Well X-2

Figure 9. Hall Integral Well X-2 and Derivative

4.3 Well X-3

Well X-3 injector has been operated since late 2016. This well is a converted well from previously producer well. Currently, X-3 injector is operating injection rate at 10172 Bwpd and wellhead pressure 275 Psi.

As shown from Figure 10, daily data monitoring shows around medio March 2017,when injection rate is increased, wellhead pressure is also increased exceed maximum sand fracture pressure. It indicates fracturing happened in injector. From figure 11, the hall integral doesn't show any changes in

slope, indicating a normal injection. But after we add its derivative (Figure 12), it shows a decreasing in slope, indicating fracture happened. From injectivity test (Appendix C), it shows that maximum wellhead pressure in injection sand is 250 Psi. Meanwhile current wellhead pressure is at 275 Psi. So, it's confirmed that fracture happen in injection well.

Fracturing in injection well is not a serious problem.Butone thing to remember is the pressure must be maintained below maximum seal fracture pressure, so the water injection doesn't flow into the upper layer or into surface. Also, when fracturing happens, the adjacent producer need to be maintained to prevent water coning/channeling problem (due to higher water supply from injector) and also make a water shut off candidate for producer that already breakthrough and doesn't meet the economic value anymore.
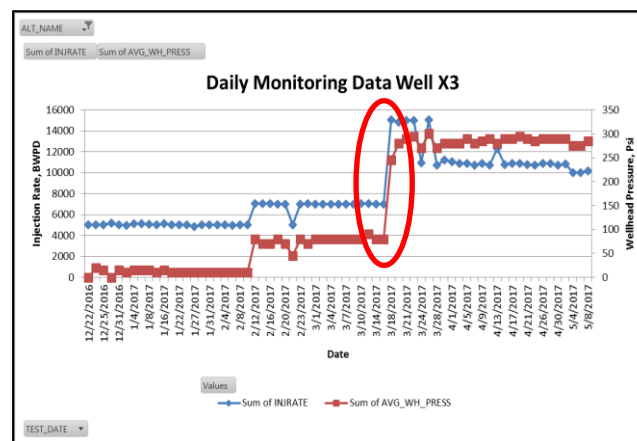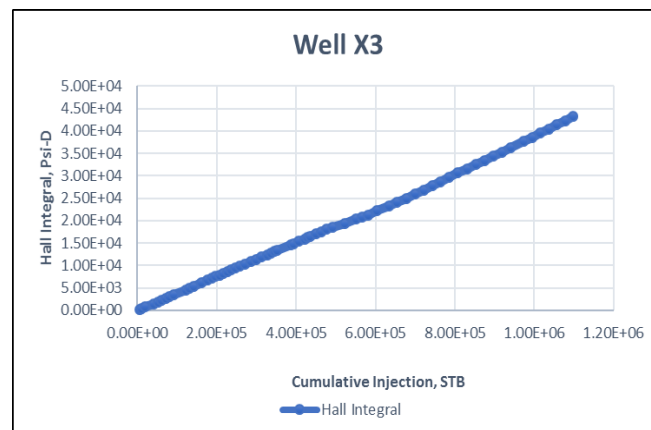

Figure 10. Daily Monitoring Data Well X3

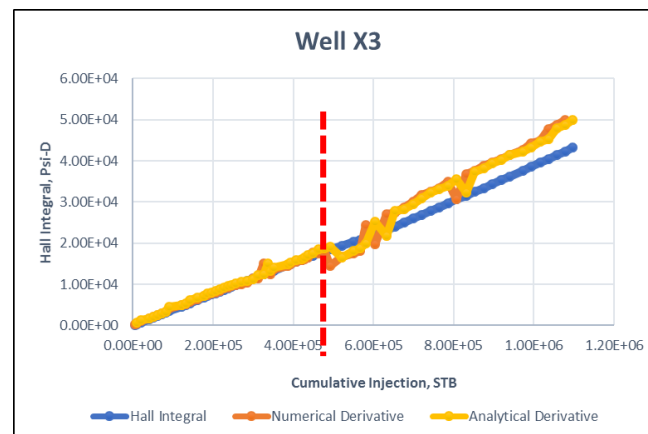**Figure 11.** Hall Integral Well X-3

Figure 12. Hall Integral Well X-3 and Derivative

5. Discussion

Hall Plot is basically a plot between cumulative water injection versus cumulative drawdown pressure in days. It's the most effective and simplest method for monitoring real time injector performance since only daily wellhead pressure and injection rate data are required. Through hall plot, it can be seen whether a problem occur in injector or not. If the slope is increasing, impairment occurred. And if the slope decreasing, fracturing/stimulation occurred. Hall plot sometimes hard to see any subtle changes in hall plot slope, so we can add its derivative. By using derivative, it's clearer and more discriminate to see any subtle changes in slope. One thing to remember is, hall plot is only a tool to make it easier to evaluate the injector performance. But in the end, it's still need to being validated again with another supporting data to ensure what problem has happened in the injector.

X-1 and X-2 injector have a plugging problem. Meanwhile X-3 injector has a fracturing problem. It's indicated from changes of hall plot slope. X-1 and X-2 injector show an increasing slope which indicates plugging. It's also strengthen by daily monitoring data when the injection rate is lowered, the wellhead pressure remains stable. X-3 injector shows a decreasing slope which indicates fracturing. It's strengthen by daily monitoring data where wellhead pressure already exceed the sand fracture pressure so the fracture happens.

Early plugging problem mainly caused by debris that is cleared uncleanly. Debris then flow into wellbore and clog the perforation. It makes plugging happen faster than before. Prevention act can be done for this problem. Review the pipeline cleaning SOP. When plugging has happened, breakdown or acidizing can be the solution to overcome the problem. Fracturing problem basically doesn't make a serious problem as long as the injection pressure doesn't exceed the maximum seal fracture pressure. When fracturing problem happen, maintain rate at producer to prevent production problem such as water coning/channeling problem andalso make a water shut off (WSO) job candidate for a well that isnot productive anymore (WC 100%).

6. Conclusion

Hall Plot is the simplest and cheaper method compared to another method. It is useful to evaluate injector performance qualitatively because it only needs a daily record of wellhead pressure and injection rate which include in daily data monitoring. Derivative hall plot is very useful to discriminate any subtle changes that can't be seen by only using hall plot.

Basedon the injector performance analysis in Perkutut Field, Well X-1 and X-2 injector have a plugging problem. Well X-3 has a fracturing problem. Hall plot analysis can be useful to evaluate the injector well performance based on daily monitoring data. But in the end, it still needs to be validated again with daily monitoring data and another supporting data to make sure what problem has happened in the injector. A preventive action can be done when plugging happened in Perkutut Field is to do the

SOP of pipeline cleaning clearly. It's because based on the plugging estimation calculation in Perkutut Field, plugging normally can happen in 6.6 since the first injection started. But in fact, plugging happened only about 1 month after the injection started. The cause of this early plugging is suspected from debris that didn't clearly cleared after the well conversion. A preventive action can be done when fracturing happen in Perkutut Field is not to operate wellhead pressure exceed the maximum seal fracture pressure to prevent bubbling problem.

Nomenclature

B_w = FVF water (BBL/STB)
G = Gravitation, m/s^2
h = Formation thickness (ft)
K_w = Water relative permeability
m = Slope
P_e = Extended pressure (psia)
P_{wf} = Wellfloor pressure (psia)
Pwh = Wellhead pressure (psia)
q_i = Injection rate (BWPD)
r_e = Encroachment radius (ft)
r_w = Well radius (ft)
S = Skin factor
TVD = True vertical depth, ft
Wi = Cumulative water injected (STB)
ρ = Fluid density, ppg
ΔPf = Frictional pressure loss
$μ_w$ = Water viscosity (cp)

References

[1] Hall, H. N. *How to Analyze Waterflood Injection Well Performance*, World Oil, October1963, pp. 128-130
[2] Izgec, B., Kabir, C.S. 2007 *Real-Time Performance Analysis of Water-Injection Wells*, paper SPE 109876
[3] Silin, D.B., Holtzman, R. et all 2005 *Waterflood Surveillance and Control: Incorporating Hall Plot and Slope Analysis*, Paper SPE 95685
[4] Amedu, Jonah.,Nwokolo, Christopher 2013 *Improved Well and Reservoir Production Performance in WaterfloodReservoirs-Revolutionalizing the Hall Plot*, Paper SPE 167602
[5] Bennion, D.B, et all 1994 *Injection Water Quality – A Key Factor to Successful Waterflooding*, Paper Petroleum Society of CIM & AOSTRA no 94-60
[6] Smith, James., Cobb, William M. 1997 *Waterflooding*

Appendix A. Analytic Derivative of Hall Integral

Starting from *pseudosteady-state* equation:

$$P_{wf} - P_e = \frac{141.2\mu qB}{kh}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.5 + S\right] \cdots (1)$$

Integrating both sides with respect to time,

$$\int\left(P_{wf} - P_e\right)dt = \frac{141.2\mu WiB}{kh}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.5 + S\right] \cdots (2)$$

The Hall Plot is generated by plotting the integral term against cumulative injection. *Wi*. The derivative term can be obtained by differentiating the integral with respect to natural logarithm of cumulative injection. Designating the derivative as D_{HI}, we have

$$DHI = \frac{d\int\left(P_{wf} - P_e\right)dt}{d\ln(Wi)} \cdots (3)$$

Replacing the term in the parenthesis with the right-hand side and defining parameters:

$$\alpha_1 = \frac{141.2\mu B}{kh} \cdots (4)$$

$$r_e = \left(\frac{5.615WiB}{\pi\phi h(1-s_{or})}\right)^{\frac{1}{2}} \cdots (5)$$

$$\alpha_2 = \left(\frac{5.615B}{\pi\phi h(1-s_{or})}\right)^{\frac{1}{2}}\frac{1}{r_w} \cdots (6)$$

Combining Eqs 3-6, one obtains:

$$DHI = \frac{d\left[Wi\alpha_1\left(\ln\left(Wi^{\frac{1}{2}}\alpha_2\right) - 0.5 + S*\right)\right]}{d\ln(Wi)} \cdots (7)$$

Expanding the terms, Eq 7 becomes:

$$DHI = \frac{d\left[0.5Wi\alpha_1\ln(Wi) + Wi\alpha_1\ln(\alpha_2) - 0.5Wi\alpha_1 + S*Wi\alpha_1\right]}{d\ln(Wi)} \cdots (8)$$

Using the following relation,

$$\frac{d(x)}{d(\ln x)} = e^{\ln x} \cdots (9)$$

We have the final form of analytic derivative as:

$$DHI = \frac{Wi\alpha_1}{2} + e^{\ln(Wi)}\left(\frac{\alpha_1\ln(Wi)}{2} + \alpha_1\ln(\alpha_2) - \frac{\alpha_1}{2} + S*\alpha_1\right) \cdots (10)$$

Upon manipulation, one obtains,

$$DHI = \frac{Wi\alpha_1}{2} + \alpha_1 Wi\left(\frac{\ln(Wi)}{2} + \ln(\alpha_2) - \frac{1}{2} + S*\right) \cdots (11)$$

Finally we can write:

$$DHI = \alpha_1 Wi\left(\ln\left(\frac{r_e}{r_w}\right) + S*\right) \cdots (12)$$

And steps for calculating pseudoskin:

$$S^* = \frac{1}{0.868}\left[\frac{b}{m} - \log\left(\frac{k}{\phi\mu CtRw^2}\right) + 3.23\right]$$

Where,   m = slope $= \dfrac{162.6B\mu}{kh}$

$\Delta t_{sup}=$ Time Superposition $= \sum_{j=1}^{N}\dfrac{(q_j - q_{j-1})}{q_N}\log(t_N - t_{j-1})$

b = Intercept $= \dfrac{P_i - P_w}{q_n} - m\Delta t_{sup}$

Appendix B. Plugging Estimation in Perkutut Field
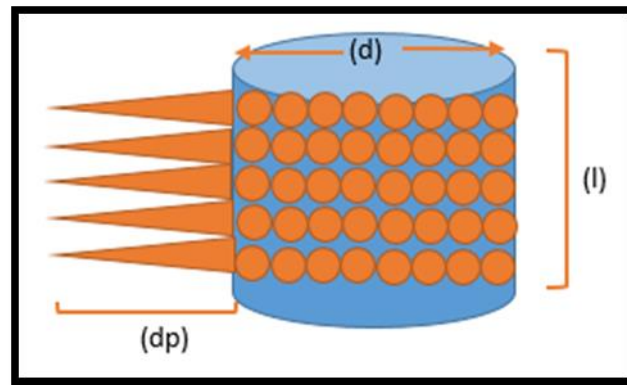

Illustration of Perforation in Injector Well Tubing

If known:
Perforation Length (L)   = 30 ft   = 914.4 cm
Casing Diameter (D)   = 7"   = 17.8 cm
Perforation Diameter (dp)   = 2"   = 5.1 cm
Perforation Penetration (pl) = 1 ft   = 30.48 cm
Total Injector   = 114
TDS Value   = 3002 mg/bbl
So,
1. CalculatingCasing Cover (s)
   a. $s = \pi D$ = 3.14 x 17.8
             = 55.9 cm
2. Calculating Casing Area
   s x L = 55.9 x 914.4
           = 51096.7 cm^2
3. Calculating Perforation Area
   = π x dp
   = 3.14 x 5.1
   = 20.3 cm^2
4. Calculating Perforation Holes
   N = Casing Area / Perforation Area
     = 51096.7 / 20.3
     = 2520 holes
5. Calculating Perforation Cone Volume
   a.   Cone Volume = 1/3 π r^2 (pl)

   = 1/3x 3.14 x (5.1/2) x 30.48
   = 206 cm^3

6. Calculating Total Perforation Volume in 1 Well
   = Total perforation holes x perforation cone volume
   = 2520 x 206
   = 519142.2 cm^3

7. Calculating Total Volume of Field
   = Total Injector x Total Perforation Volume in 1 Well
   = 144 x 519142.2
   = 59.182.209,4 cm^3
   If 1 cc is equivalent with 2.41 grams in concrete mass, so:

8. Calculating Total Solid of Field
   = 59.182.209,4 cm^3 x 2.41
   = 142.629.124,6 gram

9. Calculating Total Solid in 1 Well
   = Total Solid of Field / Total Injector
   = 142.629.124,6 / 114
   = 1.251.132,7 gram

10. TDS Value = 3002 mg/bbl
                = 3.002 g/bbl

11. Calculating Total Injection in 1 day
           = 240.000 bbl
           = 240.000 x 3.002
           = 720.480 gram

12. Calculating Total Solid Injection in 1 Well
           = Total Injection in 1 Day / Total Injector
           = 720.480 / 114
           = 6.320 gram
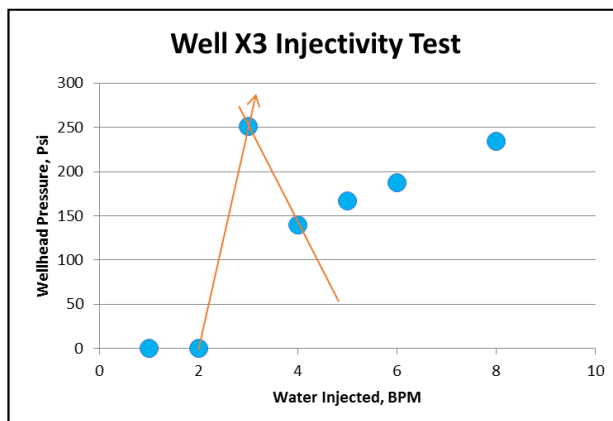
13. Calculating Estimation of Plugging in Field
           = Total Solid in 1 Well / Total Injection in 1 Well
           = 1.251.132,7 / 6.320
           = 197.964 days
           = 6.6 months

Appendix C. Injectivity Test Well X-3

BPM	Wellhead Pressure	Bottom Hole Pressure
1	0	463
2	0	463
3	251	714
4	140	603
5	167	630
6	187	650
8	234	697

X-3 Injectivity Test