Petroleum and Coal

Article **Open Access**

INSTANTANEOUS DETERMINATION OF BASIC RESERVOIR PROPERTIES IN NEAR WELLBORE WATER INJECTION USING ROUTINE INJECTION DATA

Mohammad Shadadeh, Mahdi Zeinali Hasanvand, Hassan Shokrollahzadeh Behbahani

Research Institute of Petroleum Industry, Tehran, Iran

Received February 6, 2018; Accepted April 27, 2018

Abstract

Planning for injection operation and determination of optimum time for acidizing an injection well require knowing the reservoir properties in the near wellbore. Conventional method to determine these properties is using two observation and one injection well, which is require ceasing the injection operation and spending more money and time. Based on performed studies, using daily production and injection data could be a proper solution to reduce expenses.

In this paper, it has been tried to determine essential near wellbore properties such as formation skin, radius of damage and permeability of damage area using daily injection data including: pressure, injection rate and injection time.

A new method to determine reservoir properties around the wellbore was devised by the application of injection process modeling. Finally, the developed method was applied to a real data of a water injection well in one of southern Iranian oil fields. In addition, the estimated data were validated comparing the real injection well conditions.

***Keywords**: Water Injection; Wellbore skin; Injection Rate; Injection Pressure; Hall plot; Hearn Plot; Injectivity.*

1. Introduction

Water injection in different geological layers is aimed to pressure maintenance, EOR or associated produced water disposal [1]. Because of different dissolved solids in injecting water, injection usually encounter challenges. Some challenges include reservoir permeability reduction due to incompatibility between injection water and formation water, formation fracture due to a higher injection pressure than layer fracture pressure, determining maximum injection volumes in a specific formation and determining the injection depth to ensure not blending the injecting water with freshwater resources [2-7]. Due to the high salinity of associated produced water and the presence of radioactive elements in their solutions, environmentally, it is forbidden to release water on ground or to dispose it in rivers [8-9].

In order to timely dispose of producing water from an operation unit and determine the water movement in the injecting formation, it is necessary to know the compatibility of injecting and formation water, the amount and type of salt, and the exact determination of rock formation properties, such as permeability and porosity. In common ways of reservoir properties determination around the wellbore, two injection and monitoring wells are used, additionally it needs to stop injection process, then this takes time and causes extra costs. In addition, determine reservoir and well properties in this method requires bottom hole pressure gauges. Although this method has a great accuracy, it is defective due to the discontinuation of injection and high time consuming and expenses.

Different researchers have provided models and auxiliary diagrams for avoiding the problems of the falloff test by modeling the injecting fluid flow into well, which by their means, without having to discontinue the injection, only by using the basic variables such as the injected fluid volume, the injection time, and the wellhead pressure. These models have the ability to obtain adequate information about the reservoir condition, skin effect, well injectivity and the presence of fracture around the well. These methods include Hall [10] and Hearn [11-12]

In this paper, it has been tried to investigate essential reservoir properties alongside the accuracy of proposed models by using the injection data and injecting and formation water compatibility, the geological characteristics of the injection well and the data related to injection operation in a real disposal water well, the main reservoir characteristics and skin effect, along with the performance of the proposed models. The defect of the Hearn and Hall methods is the simultaneously being unknown of the reservoir pressure, the damage radius of the well and the permeability around the well, which is resolved in the inventive method.

2. Modeling

2.1. Determination of reservoir properties by Hall method:

In the injection process, determination of the injectivity of the well is essential for determining the flow rate and injection pressure and the injection schedule. In case of reduction of the injectivity of well, determination of the amount of well damage is done through two falloff tests or direct method. The falloff test method compared to the direct method is time-consuming and costly and requires stopping of injection in both wells. In the direct method, the amount and the nature of injectivity drop is determined only by using the injection data of the well, without the need for an observation well.

Hall [10] presented a graph for analyzing the injectivity of wells. This graph, which is to be made on a monthly basis, includes the pressure at the time of injection versus the total injected volume in the same period of time. The analysis of the Hall graph before and after the well stimulation shows the amount of success of this operation. Generally, increasing the gradient of the curve shows a decrease in the injectivity. According to the Darcy relationship, in the cylindrical coordinates, the slope of pressure- versus rate will be equal to:

$$m = \frac{\mu_w B_w \ln(r_e / r_w)}{0.00707 k_w h} \quad (1)$$

The most important assumptions of this relationship are the constant pressure of the reservoir and the radius of injection. The concept of transmissibility is used to determine the amount of change in the injectivity and the effect of the skin. According to the definition of transmissibility:

$$Tm = \frac{k_w h}{\mu_w} \propto \frac{1}{m} \quad (2)$$

Based on this relation, with respect to the unit change from psi-month per barrel (P/Q) to mili Darcy-foot per centipoise (Kh/μ), the coefficient 29.2 is added to the relationship and the relation converted into the following equation:

$$Tm = \frac{4.884 B_w \ln(r_e / r_w)}{m} \quad (3)$$

Therefore, if the slope increases in the Hall diagram, there has indeed been a decrease in permeability in the porous medium. By having two different transmissibility values, mathematical analysis of relationships can be used to calculate the amount of the skin around the wellbore. Assume that the well has a skin and its permeability has decreased, in this case the average permeability will be equal to:

$$k_{avg} = \frac{k_a k_e \ln(r_e / r_w)}{k_a \ln(r_e / r_a) + k_e \ln(r_a / r_w)} \quad (4)$$

By using the definition of transmissibility in the above relation, and assuming that the reservoir thickness and viscosity of the fluid are constant over the radius of injection, we will have:

$$Tm_{avg} = Tm_2 = \frac{Tm_a Tm_1 \ln(r_e / r_w)}{Tm_a \ln(r_e / r_a) + Tm_1 \ln(r_a / r_w)} \qquad (5)$$

From the above relation, assuming to have the value of damage radius, which is often about 3 feet [14]), the amount of Tm_a in the damage area is obtained. By having the value of Tm_a, the important variables for the injectivity, such as skin value, pressure drop in the skin region, damage ratio, Flow Efficiency, Damage Factor and minimum increase in the injection, are obtained from the following relationships:

$$S = \frac{(k_e - k_a)}{k_a}\ln(r_a / r_w) = \frac{(Tm_1 - Tm_a)}{Tm_a}\ln(r_a / r_w) \qquad (6a)$$

$$\Delta P_a = \frac{q_{sc2} B_w S}{0.00707 Tm_1} \qquad (6b)$$

$$P_e = P_{w1} - \frac{q_{sc2} B_w S}{0.00707 Tm_1} \qquad (6c)$$

$$DR = \frac{P_e - P_w}{P_e - P_w - \Delta P_a} \qquad (6d)$$

$$FE = 1/DR \qquad (6e)$$

$$DF = 1 - FE \qquad (6f)$$

$$I_{sr} = DR(q_{sc2}) \qquad (6g)$$

Daniel Hawe [13] showed that the results obtained from the Hall diagram were more reliable than the results of the falloff test. The Hall plot is originally presented for the single-phase mode (water) under constant conditions and cylindrical flow of Newtonian fluid. This method is used assuming that the condition is stable, and since the data are investigated at weekly and monthly period, it is possible to determine the variation of the injection variables over time. Data acquisition is simple in the Hall method, and the only data that are used include the total injected volume and the injection pressure, which should eventually be converted to the bottom hole pressure. The dependence of the slope of the graph on both the skin factor (S) and transmissibility ($k_w h/\mu_w$) is the most important drawback of the Hall diagram method, which, to overcome the obstacle, the value of the skin radius is determined using estimate and error. (Radius ranging from 1 to 3 feet) [14].

2.2. Determination of reservoir properties by Hearn method:

This method is presented to estimate the permeability of the reservoir in the process of water injection into an oil layer. In this method, it is assumed that there is no gas phase in the porous medium, and the front between oil and water is piston-like. The Hearn method is actually a Muscat [15] corrected method for calculating a constant pressure well. Accordingly, the fluid flow relation around the wellhead is as follows:

$$q_w = \frac{0.00707 k_w h (P_w - P_e)}{\mu_w B_w (\ln(r_o / r_a) + M \ln(r_e / r_o))} \qquad (7)$$

In which, $M = (k_w \mu_o / k_o \mu_w)$

The above equation is slightly changed to the following relation where the values of ro and re are obtained using a mass balance.

$$q_w = \frac{0.01414 k_w h (P_w - P_e)}{\mu_w B_w (\ln(r_o^2 / r_a^2) + M \ln(r_e^2 / r_o^2))} \qquad (8)$$

In which, $r_o^2 = FW_i$, $r_e^2 = CW_i$, $F = (5.615/\pi h) \times \phi(\bar{S}_{wBt} - S_{wc})$ and $C = (5.615/\pi h) \times \phi(1 - S_g - S_{wc})$

By manipulating the above relations we get the following relation

$$\frac{\Delta P}{q_w} = a \ln W_i + a\left(\ln \frac{F}{r_a^2} + M \ln \frac{C}{F}\right) \quad a = \frac{\mu_w B_w}{0.01414 k_w h} \tag{9}$$

By plotting the reverse of injectivity versus logarithm of total injected fluid, we expect the straight line with slope of a and intercept of $\left(\ln \frac{F}{r_a^2} + M \ln \frac{C}{F}\right)$, which is the same as the Hearn graph. Since, in the above-mentioned relation, mobility and saturation percentages are only present in the intercept part, the actual permeability of the reservoir can be calculated using the slope value.

In related industrial reports, four graphs are presented: 1) Flow rate and injection pressure versus time; 2) Hall diagrams; 3) Hearn diagrams; and 4) Injection rate and injectivity versus time. By analyzing the obtained diagrams, near wellbore reservoir properties and the existence of fracture are detrermined [12].

2.3. Innovative method

The problems of the Hall and Hearn method is that the number of unknown variables is greater than the equations. For this reason, in order to solve the relations and obtain the necessary values, some preset values should be considered using the initial guesses.

For example, in Hall's relation, the radius of damage is considered to be between 1 and 3 feet, and by assuming the value of this parameter, the value of the other variables (such as permeability, damage factor, etc.) are determined by solving the equations. In these methods, the amount of damage (S), the radius of damage (r_a), the pressure of the formation at the boundary (P_e) and the permeability of the reservoir (k_w) is unknown. Having three equations of skin (6a), slope of Hall plot (5), slope of Hearn plot (9) one more equation is needed to obtain all parameter without need to guess a value for damage radius. The missing equation is introduced in this innovative method.

As shown in Equation 9, the intercept of Hearn plot is a function of the dynamic and static properties of the reservoir around the well opening. This value is equal to:

$$a\left(\ln \frac{F}{r_a^2} + M \ln \frac{C}{F}\right) = a\left(\ln \frac{(5.615/\pi h) \times \phi(\bar{S}_{wBt} - S_{wc})}{r_a^2} + (k_w \mu_o / k_o \mu_w) \ln \frac{(1 - S_g - S_{wc})}{(\bar{S}_{wBt} - S_{wc})}\right) \tag{10}$$

Therefore, if we sure that no fracture has been created in the formation during the injection and acidizing process (the near wellbore static properties of the formation remain unchanged), the fourth equation can be calculated by subtracting the intercept of Hearn diagram before and after operation. Real data analysis shows that the slope of the Hearn graph is the same before and after the operation. Equation 10 is, in fact, the additional equation that can equate the multiplicity of equations and the unknown variables. Therefore, there is no need for the initial guess to calculate other variables. The method will be explained more in the follow.

3. Water injection case study

In this case study, associated producing water from Fahliyan Formation in one of Iranian southern oilfields is injected into Asmari Formation of the oilfield. The results of the pressure test in this formation indicate that in depth of 1443-1490 meters, the formation pressure changes from 2164 psi to 2241 psi, and this pressure gradient this layer confirms the presence of formation water.

Investigation of the chemical properties of injecting water and formation water as well as chemical equilibrium calculations show that Asmari Formation water has a high dissolved solid content (240 g/L) which is mainly made up from sodium and calcium chloride. The water produced from the Fahlian reservoir is less salty than the Asmari Formation water. The solids content of this formation in the two sub-layers is 75 and 150 g/L, which is mainly made up from sodium chloride and calcium chloride, respectively.

The compatibility analysis has been performed by SOLMINEQ88 PC / Shell software. In this analysis different ratios of Fahlyan member 2 and 3 formation water and Karun River as injecting water and Asmari formation water as target for injection has been considered. The results of the analysis show that two salt precipitation of barium sulfate and carbonate calcium has a chance to be formed in all water combination. Calcium carbonate (aragonite and calcite) is the most considerable salt precipitation in all water combinations. Fahlyan member 2 formation water at surface facilities and downhole will precipitate moderate amount of barium sulfate and calcium carbonate and Fahlyan member 3 formation water will precipitate large amount of calcium carbonate.

The formation of calcite deposition depends on the amount of alkaline ions in the water. By reducing the amount of these ions, the amount of carbonate deposits decreases. To this end, the continuous addition of alkali-reducing chemicals to surface facilities and downhole wells can reduce the sedimentation process.

Table 1. The highest amount of salt formed due to the incompatibility of injection and formation water (g/m^3)

	Water blend in surface facilities at 25^{0}C and 73 Psi		Water blend in wellbore at 63^{0}C and 2140 Psi		
Chemical deposition	Karun River + Layer 2 Fahliyan	Karun River + Layer 3 Fahliyan	Asmari + Layer 2 Fahliyan	Asmari + Layer 3 Fahliyan	Asmari + Karun river
Barium sulfate (barite)	34	0	30	0	0
Calcium carbonate (aragonite and calcite)	26	700	20	900	443
Calcium sulfate (Anhydrite)	0	0	0	0	0
Strontium sulfate (Celestine)	0	0	0	0	0

To reduce damage around the wellbore during water disposal due to sedimentation, the process of water treatment is used before injection of water. The greater the amount of salt removal during this process, the lower the deposit in the reservoir conditions. However, due to the incompatibility of injected water and the formation water, damage in the injection wellbore is inevitable. During two years of water injection in Asmari formation four operation of acid treatment has been performed. To determine the properties of the formation during the water injection process and the success of acidizing operations, Hall and Hearn chart along with the history of water injections over two years has been plotted. In Figures 1 to 3, these operations are marked with a black, green, red and blue arrow line.

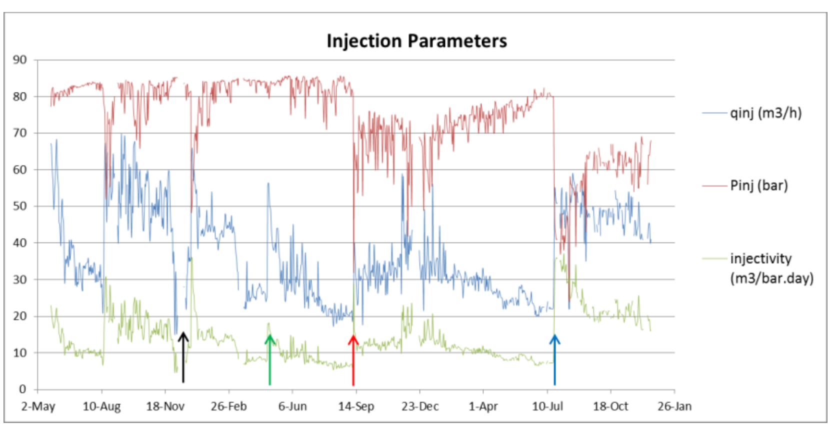

Figure 1. Water injection rate, injection pressure, and well injectivity over time

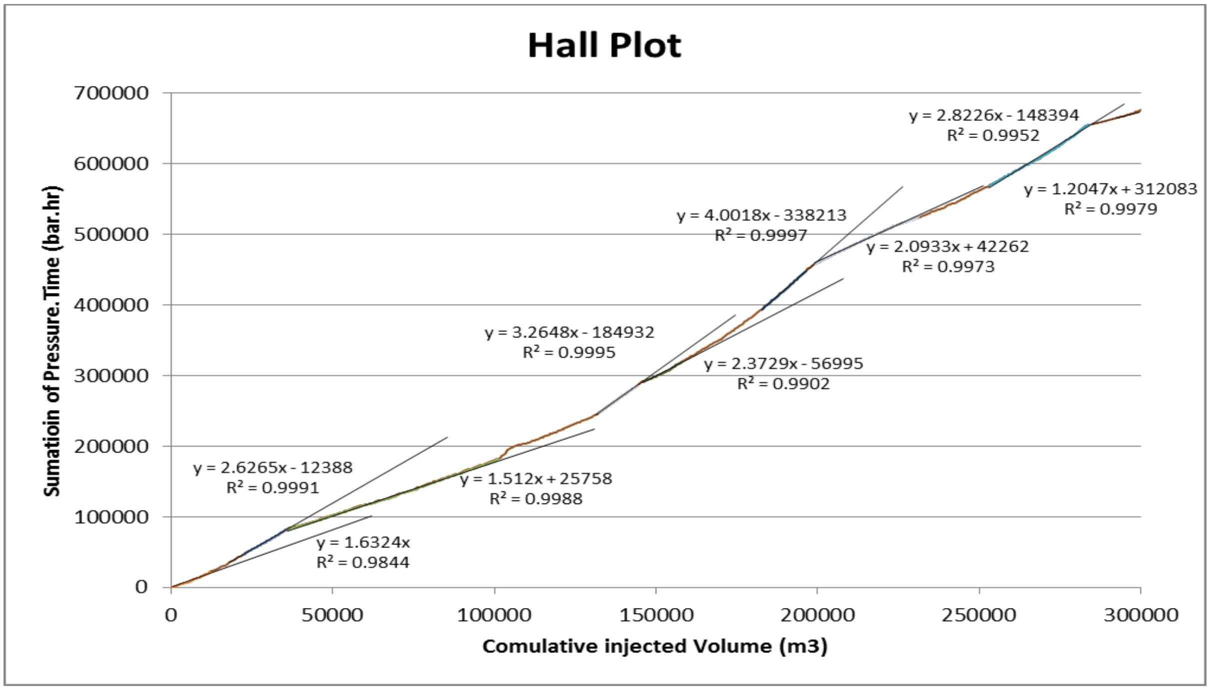

Figure 2. Hall plot for two years of injectable data

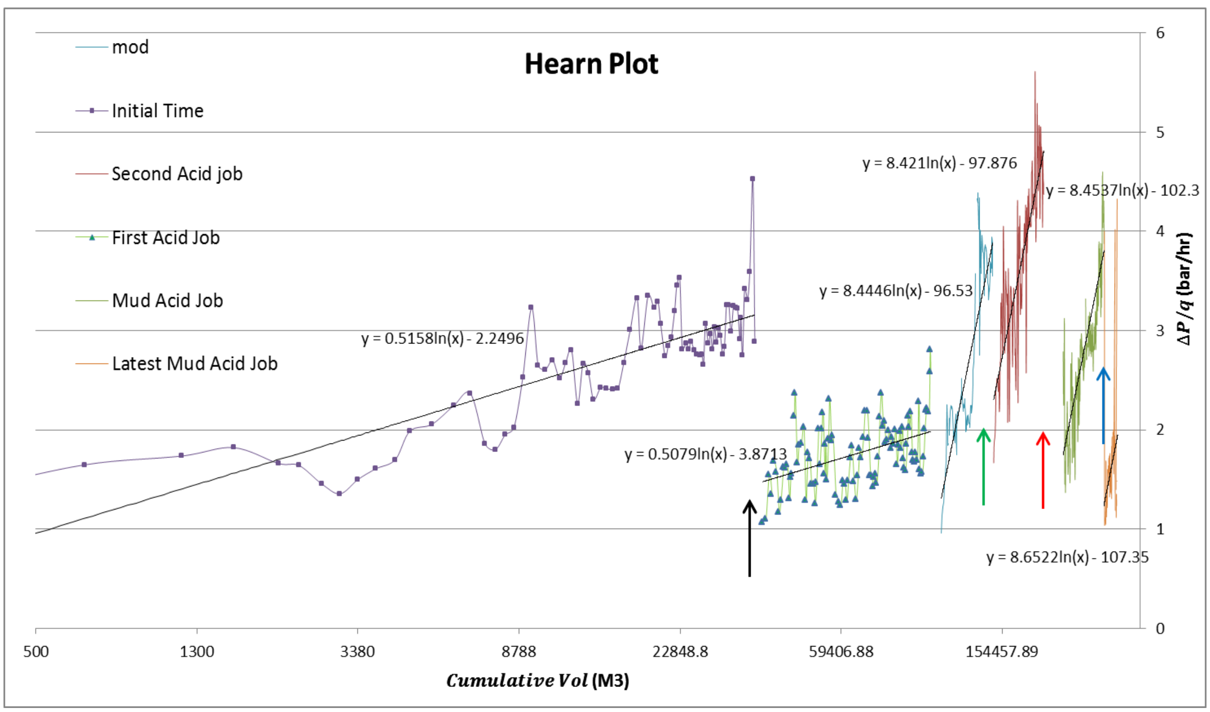

Figure 3. Hearn plot for two years of injectable data

According to the lines obtained from Hall and Hearn plots, the following table is presented to analyze the success of acidizing and determining the permeability of the reservoir.

Table 2. The results obtained from Hall and Hearn charts, include slope and intercepts

Acidizing operation #	Hall plot		Hearn plot		
	Slope before operation	Slope after operation	Slope before operation	Slope after operation	Interception difference
1	2.6	1.5	0.5	0.5	1.6-
2	3.2	2.3	8.4	8.4	1.3-
3	4	2	8.4	8.4	5.5-
4	2.8	1.2	8.4	8.6	5-

Regarding lower injection pressure compared to fracture pressure, the intercept change in Hearn plot after acidizing would be due to Skin removal in near wellbore which has a similar effect as fracture.

To determine precisely the amount of equivalent radius r_a and permeability near wellbore, the Hearn and Hall equations simultaneously is used. For this purpose, we obtain the value of the difference in intercept of the two graphs.

Using the equation 10 in water disposal wells, since both of the initial and injecting fluid are water, then mobility ratio M could be considered equal to one. In this case, given the fact that the coefficients *F* and *C* are constant before and after the acidizing operation (assuming complete removal of damage during the acid treatment operation), the difference in intercept will be equal to:

$$Difference\ in\ intercept = a\ ln\frac{r_w^2}{r_a^2} = 2\ a\ ln\frac{r_w}{r_a} \qquad (11)$$

The amount of viscosity and formation volume factor at the reservoir conditions are 0.48 cP and 1.01, in the studied well, the thickness of the formation is 36 ft. Using the equation 9 and having the slope 8.4 for Hearn plot, the mean permeability of the reservoir is equal to 882 md. Now, having the unknown value of the Hall relationship, i.e. the damage radius, we can calculate the skin coefficient and the permeability of the reservoir using equations 6a and 9. Based on this, properties around the wells, including permeability, skin, and damage radius during different operations are presented in Table 3.

The important point in this approach is that since the number of variables and the number of equations are equal, the obtained values are definite, and in fact, they can be considered as actual results of well testing. In Hall and Hearn methods, due to the assumption of some variables, the results should be verified using other methods, but in the new method, since none of the fundamental variables are assumed, the results are reliable. However, to verify this claim, well tests are helpful and can confirm the results.

Table 3. Near wellbore properties during different acidizing operations in the studied injection well

Acidizing operation#	$Ln(r_w/r_a)$	S	Ka (md)
1	0.8324	0.3522	682.06
2	0.6763	0.1902	781.46
3	2.8613	1.4307	173.15
4	2.6012	1.4864	181.23

4. Conclusion

In this paper, a direct method to determine reservoir properties such as reservoir pressure and reservoir permeability and near wellbore properties such as skin, damage radius and permeability of damage area has been presented. These properties were determined using only daily injection data such as pressure, flow rate and time. As a case study, daily injection data of one of the water disposal wells was investigated. The results show the success of operation of acidizing in removing salt deposition and treatment of near wellbore damage. The study and analysis of daily injection data by this method can show the behavior of sediments in injected water in damaging the wells. The information obtained from the direct method has a high accuracy, and requires minimum time and cost, so this method is preferred to the traditional falloff test method.

In this method, there is no need to stop the injection for well testing, and only using the injection data the dynamic properties of the reservoir and near wellbore could be calculated. Unlike previous methods, which use guessing and error method to determining the dynamic properties near wellbore, because of providing an additional equation in the presented method none of the variables is previously assumed.

This results in precision and the conversion of this method into a permanent well test method. Another result from this study is the use of gas injection data in hydrocarbon reservoirs to determine the Instantaneous properties of the reservoir. Implementing this method for gas injection wells requires a more detailed study of well testing in gas injection wells, that will be tried to be investigated in the in a separate paper in near future.

References

[1] Paige RW and Murray LR. Re-injection of produced water - Field experience and current understanding. Presented at the Rock Mechanics in Petroleum Engineering, Delft, Netherlands, 29-31 August 1994. SPE-28121-MS.

[2] Barkman JH, Davidson DH. Measuring water quality and predicting well impairment. Journal of Petroleum Technology, 1972; 24(07): 865-873.

[3] Eylander JGR. (1988). Suspended Solids Specifications for Water Injection from Core flood Tests. SPE Res Eng., 1988; 3 (4): 1287–1294. SPE-16256-PA.

[4] Sharma MM, Pang S, Wennberg KE, Morgenthaler LN. Injectivity decline in water-injection wells: an offshore Gulf of Mexico case study. SPE Production & Facilities, 2000; 15(01): 6-13.

[5] van Oort E, van Velzen JFG, Leerlooijer K. Impairment by suspended solids invasion: testing and prediction. SPE Production & Facilities, 1993; 8(03): 178-184.

[6] Wennberg KE, Sharma MM. Determination of the filtration coefficient and the transition time for water injection wells. In SPE European Formation Damage Conference. Society of Petroleum Engineers, 1997, January.

[7] Shutong P, Sharma MM. A model for predicting injectivity decline in water-injection wells. SPE Formation Evaluation, 1997; 12(03): 194-201.

[8] Christie C. Disposal of produced water from oil & gas exploration. Masters project. Duke University Durham 2012, NC

[9] Pichtel J. (2016). Oil and gas production wastewater: Soil contamination and pollution prevenion. Applied and Environmental Soil Science, 2016.

[10] Hall HN. How to analyze waterflood injection well performance. World Oil, 1963; 157(5): 128-33.

[11] Moffitt PD, Menzie DE. Well injection tests of non-newtonian fluids. In SPE rocky mountain regional meeting 1978, January. Society of Petroleum Engineers.

[12] Jarrell PM, Stein MH. Maximizing Injection Rates in Wells Recently Converted to Injection Using Hearn and Hall Plots. In SPE Production Operations Symposium. Society of Petroleum Engineers 1991, January.

[13] Hawe DE. Direct Approach Through Hall Plot Evaluation Improves The Accuracy Of Formation Damage Calculations And Eliminates Pressure Fall-Off Testing (1976).

[14] Buell RS, Kazemi H, Poettmann FH. Analyzing injectivity of polymer solutions with the Hall plot. SPE Reservoir Engineering, 1990; 5(01): 41-46.

[15] Muskat M. Physical Principals of Oil Production. McGraw-Hill Book Co. Inc., New York, 1949, pp.682-686.

To whom correspondence should be addressed: Dr. Mahdi Zeinali Hasanvand, Research Institute of Petroleum Industry, Tehran, Iran, hasanvand@put.ac.ir