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Water Injection Performance in the Abu-Attifel Oil Field Using the Hall Plot

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A B S T R A C T

Waterflooding is the most common improved oil recovery (IOR) technology used to improve oil recovery. The water flooding project should be launched at an optimal time to increase the recovery and maximize profits. It is important to have tools available to monitor and assess the wells that are additionally cost-effective. Not only the monitoring of the whole flooding project but also the monitoring of each individual well is important to guarantee a successful oil recovery. In this paper, the Hall plot analysis was applied to evaluate the injection performance of M20 and M21 injection wells in the Abu-Attifel oil field. The Abu-Attifel oil field was discovered in 1967 and began production in 1972 with a weak water drive and an ongoing injection process. Hall's method is a simple and cheap tool used to evaluate the performance of water injection, and it is based on the assumption of steady-state radial flow. It is concluded that the hall plots showed a change in slope after an initial period of fill-up for both injectors, which indicates the occurrence of skin due to the near-wellbore plugging.

1 Introduction

The terms primary oil recovery, secondary oil recovery, and tertiary (enhanced) oil recovery are traditionally used to describe hydrocarbons recovered according to the method of production or the time at which they are obtained. Secondary oil recovery refers to the additional recovery that results from the conventional methods of water injection and immiscible gas injection. The injection of water, on the one hand for secondary recovery reasons and on the other hand to maintain the pressure in the reservoir, is one of the oldest techniques used in the petroleum industry. Before undertaking a secondary recovery project, it should be clearly proven that the natural recovery processes are insufficient; otherwise, there is a risk that the substantial capital investment required for a secondary recovery project may be wasted. [1]. Over the years, enormous progress has been made in the design, development, and monitoring of waterflooding projects. However, it must be said that most of the attention is paid on the design and development phases, although surveillance is indispensable to guarantee a successful waterflooding project.

The quality of injection water is one of the important factors in waterflood success. Nature rarely provides water containing free chemicals and bacteria. The main problem with using water to increase oil production is the reaction between the reservoir and the water, where there could be damage to surface and subsurface equipment by corrosion. Water injection operations aim to inject water into reservoir rocks without blockage or permeability reduction from particulates, oil dispersion, scale formation, bacterial growth, or clay swelling [2].

Monitoring and control of the performance of each individual well is an important component of successful oil recovery operations. The dramatic progress in information technology over the past decade has made it possible to collect and store huge volumes of high-quality production and injection data. These data, if appropriately interpreted, provide new insights into reservoir dynamics across multiple temporal and spatial scales. As a result, efficient processing and interpretation

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of high-frequency field measurements is critical to modern oil and gas recovery project management [3].

Traditional transient well tests have been used to evaluate the average near-wellbore formation transmissivity. Injection tests employed to determine water injectivity and long-term injection efficiency may last as long as several weeks or months. The transient pressure analysis methods, e.g., falloff tests, injection tests, etc., may not be adequate for evaluating the variations in reservoir characteristics and injection efficiency that occur during the long-term test. Inadequacy is inherent to the essence of transient pressure analysis methods that estimate reservoir properties at one point in time, whereas the Hall plot is a continuous monitoring method for that purpose [4, 5, 6]. The Hall plot method, proposed by Howard Hall in the 1960s [4], is a widely used tool for analyzing injectivity. Hall plots are routinely used in industry to identify injection performance from production data. It is a plot of pressure integral versus cumulative injection volume. For non-damaged or stable radial injection into the matrix system, it will produce a unit slope line. An increase in gradient or slope (upward deviation away from the function of the unit slope) is generally an indication of decreasing injection, while a general reduction in slope generally shows an increase or has increased injection as illustrated in Figure 1. The big advantage of the Hall Plot is that only injection rates, which are regularly collected, are needed to create the plot. This slope analysis has already been used to assess well treatments. The Hall plot method has proved to be a simple, inexpensive, and effective way to analyze injectivity [2, 7, 8]. This paper presents the Hall plot analysis that is used to evaluate the injectivity performance for two injectors, M20 and M21, in the Abu-Attifel Oil Field, Libya.

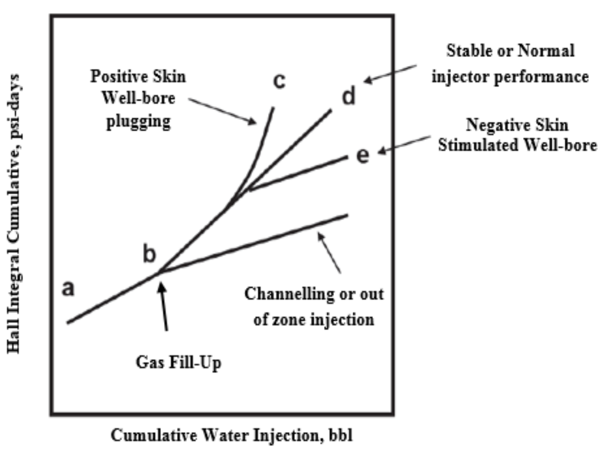

Figure 1. Typical Hall Plot for a water injector [3].

2 Materials and Methods

2.1 Field Overview

Abu-Attifel is located in the Sirte basin, about 300 kilometers southeast of Benghazi, just east of Jalu, as shown in Figure 2. The Abu-Attifel oil field is one of the richest and best-known oil fields in Libya; in fact, it was the first "giant oil field" discovered in Libya by ENI, which is the largest foreign player active in the country. It was discovered in the late 1960s, specifically in 1967 in the Sirte Basin [9]. About 300 km south-east of the major city of Benghazi, just east of Jalu, with an average depth of 13780 ft, the first explorative well was completed in March 1968, and it was put into production in the year 1972. The oil-bearing zone extends for about 60 kilometers. The oil production began with 14 wells, with the reservoir section having an average thickness of 820 ft. at an average depth of 13795 ft. The early-phase production caused by natural reservoir energy depletion confirmed what had been suspected, namely a lack of water drive to the bottom aquifer's limited volume [8]. After a strong depletion phase, water injection was set up and started in the Abu-Attifel field in 1974. A row of wells were drilled along the northern border of the field, which helped increase production considerably [9], [10].

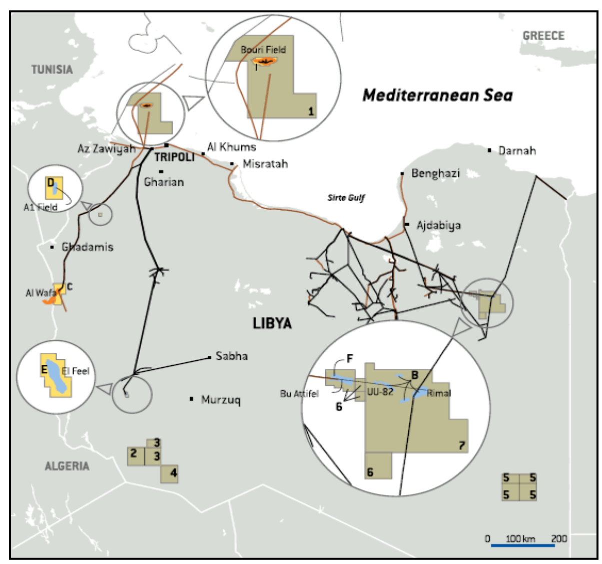

Figure 2. Location of Abu-Attifel oil field in Libya [9].

The Abu-Attifel Field trapping system is formed by a large northerly tilted fault block located in the central part of the Hameimat Trough; a northwest-southeast trending fault borders the field on its southwestern edge. It is limited on alt Bides by faults and with a low dip of 5° to the North. Another significant tectonic feature, an anti-Siberian trending fault, separates the field's main area from the west area. The synrift clastic depositional sequence of the Upper Nubian Sandstone (Lower Cretaceous) represents the reservoir unit; it is at an average depth of 15,000 ft and is one of the deepest commercially oil-producing reservoirs in Libya.

The oil-bearing rock is a fine to coarse-grained sandstone with interbedded shale and shaly-siltstones; fit ranges in net thickness from 246 ft – 820 ft (75 to 250 m). The quality of this reservoir is quite impressive, with porosity ranging from 20 to 28 percent. The horizontal permeability spans from a few mD to more than 1000 mD, and the anisotropy ratio (vertical permeability/horizontal permeability) ranges from 0.48 to 1.23. The initial water saturation, which correlates quite well with the local porosity, averages 16% [8]. Its OOIP is estimated at some 3.9 MMMbbl (620 Mm3). The oil production comes from Upper Nubian sandstones, a formation of a Lower Cretaceous age whose depth goes from 12750 – 14226 ft (3886 to 4336 m) S.S.L (SubSea Level).

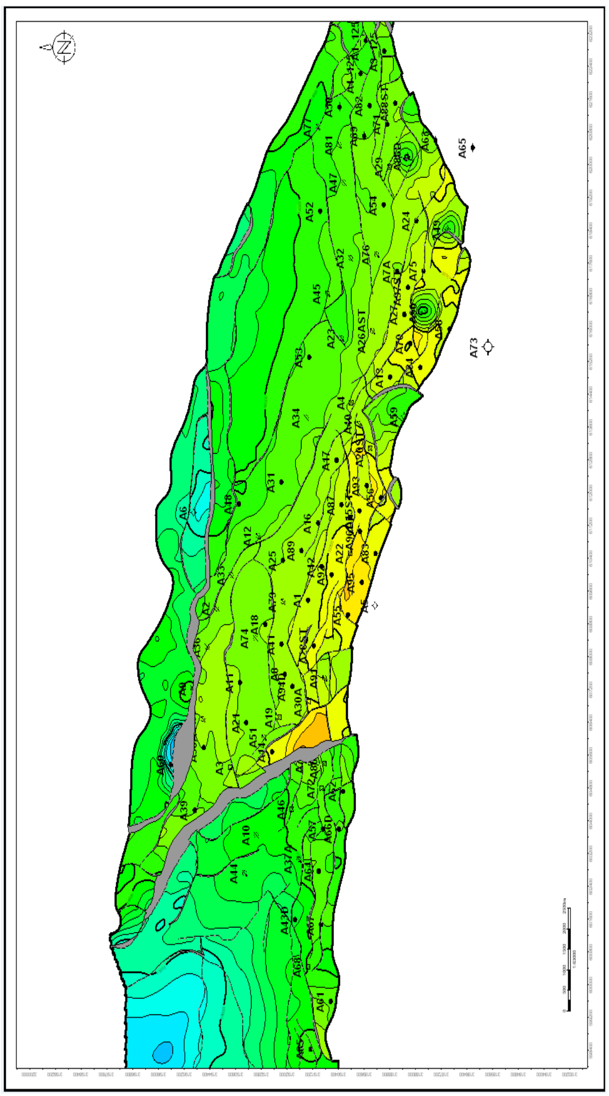

Figure 3. A structural map of the entire field [9].

At discovery, a bubble point variation with the depth was recognized, but the oil resulted under saturated at the initial pressure of 6904 psia (47.6 MPa) through the entire field. The crude has a 41 °API gravity; its base is paraffinic at high wax content (36 .7%) with an upper pour point of 39 °C [8]. Table 1 lists the basic reservoir fluid properties [9], [10].

Table 1. Reservoir fluid properties [9].

Property	Main Area	West Area	Unit
Datum	13800	14150	ft (sub-sea level)
Reservoir Temperature	292.1	305.1	°F
Reservoir Pressure	6899.5	6613.7	psia
Bubble Point Pressure	5946	6605	psia
Solution Gas	2.36	1.76	Mscf/stb
Gas Formation Volume Factor	0.70	0.68	rb/Mscf
Reservoir Oil Viscosity	0.16	0.29	cp
Reservoir Oil Density	52.6	53.6	lb/cf
Oil Formation Volume Factor	2.41	2.06	rb/stb
Stock Tank Oil Gravity	41		°API
CO_2 Content (in reservoir oil)	3.06	4.26	%
H_2S Content (in reservoir oil)	0.00		%
Sulfur Content (in reservoir oil)	0.04		%

2.2 Hall Plot-Theoretical Background

In 1963, Hall provided a straightforward graphical technique for the analysis of long-term injection well performance data [4, 11]. The data required for Hall Plot analysis includes the following:

1. monthly bottom-hole injection pressures (monthly average)
2. average reservoir pressure
3. monthly water injection volumes
4. injection days for the month

This plot makes the following assumptions: piston displacement, steady-state condition, radial single phase flow, and single layer flow with reservoir pressure where the pressure is constant. It is also assumed that there is no residual gas saturation in the water and oil zones. This plot can be used to determine reservoir properties such as transmissivity (kh) and others when changing reservoir conditions. This plot is based on the form of Darcy's law, namely:

$$i_w = \frac{0.00707kh(p_{wi} - p_{avg})}{\mu[\ln\left(\frac{r_e}{r_w}\right) + s]} \tag{1}$$

Where:

i_w = injection rate, bbl/day.
k = reservoir permeability, md.
h = effective formation thickness, ft.
p_{wi} = bottomhole injection pressure, psia.
p_{avg} = average reservoir pressure, psia.
μ = injection water viscosity at bottomhole conditions, cp.
r_e = distance of the equilibrium pressure from the well center, ft.
r_w = wellbore radius , ft.
S = skin factor, dimensionless.

It is assumed at this point that k, h, r_e, r_w, and S are constants. Therefore, Eq. 1 reduces to:

$$i_w = c(p_{wi} - p_{avg}) \tag{2}$$

Where:

$$c = \frac{0.00707kh}{\mu[\ln\left(\frac{r_e}{r_w}\right) + s]}$$

Rearranging Eq. 2 yields the following:

$$(p_{wi} - p_{avg}) = \frac{i_w}{c} \tag{3}$$

Integrating both sides of Eq. 3 with respect to time gives:

$$\int_0^t (p_{wi} - p_{avg})dt = \frac{i}{c}\int_0^t i_w\, dt \tag{4}$$

The integral on the right side of Eq. 4 represents the total amount of water injected. Hence, Eq. 4 can be represented as:

$$\int_0^t (p_{wi} - p_{avg})\, dt = \frac{w_i}{c} \tag{5}$$

Where W_i is the cumulative volume of water injected at time t, bbl.
A closer inspection of Eq. 5 indicates that a coordinate graph of its left side versus the right side should form a straight line with a slope of (1/C). The Hall coefficient, which is defined as the cumulative total of the product of the average monthly injection pressure and the number of days per month the well is on injection, can be plotted versus cumulative water injected to produce a diagnostic plot for monitoring the behavior of injection wells. This type of graph is called the Hall plot. If h, r_e, r_w, and S are constants, then C and slope are constants as well, according to Eq. 3. However, if the parameters change, C will also change, and thus the slope of the Hall plot will change, which is where the diagnostic value of the plot lies. Changes in injection conditions may be noted from the Hall plot. For example, if wellbore plugging or other restrictions to injection are gradually occurring, the net effect is a gradual increase in the skin factor, S. As S increases, C decreases; thus, the slope of the Hall plot increases. Conversely, if S decreases (as would be the case if injecting pressure exceeds fracture pressure, causing fracture growth), then C increases and the slope of the Hall plot decreases. See Figure 4 for various injection well conditions and their Hall plot signatures [4, 11].

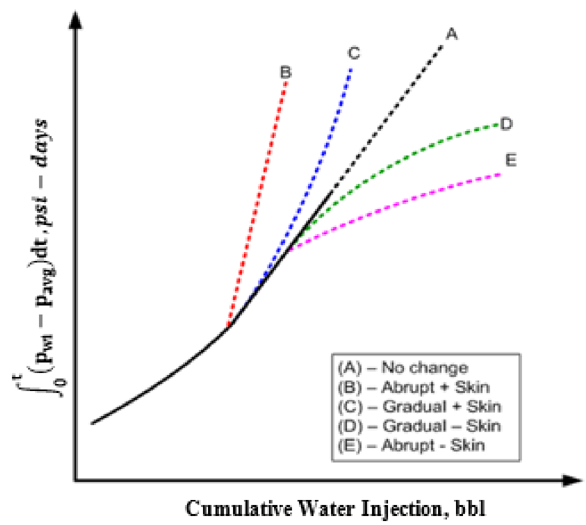

Figure 4. Hall plot for various injection well conditions [12].

3 Results and Discussion

Two injectors, M20 and M21, were selected from the Abu-Attifel Oil Field to evaluate injectivity performance using Hall plot analysis. The data required for a Hall plot analysis were collected and analyzed carefully. M20 is the injector in question; it started as a producer at the beginning of production, in the 1970s, but later on, due to its strategic position and high water production, it was turned into an injector in 1994. The data collected from that date onward was used to draw the Hall plot. Figures 5 and 6 show the Hall plot for two injectors, M20 and M21, by plotting between the cumulative water injection and the Hall cumulative integral. This analysis is compared with the theory of Hall plots as illustrated in

Figures 1 and 4. Both plots showed a change in slope after an initial period of fill-up. It is obvious that the slope moved upwards, indicating that the injection was stable in the beginning. However, over time, there is an increase in slope, which indicates the occurrence of skin due to the possibility of a near-wellbore plugging process taking place. I.e., as skin factor (S) increases, the Hall coefficient (C) decreases; thus, the slope of the Hall plot increases. This could be an indication that the injected water might contain particles that damage the formation or that the injection water is moving grain particles in the formation, which tightens the gaps that allow water to flow. Of course, these are two out of many explanations that might be clearer after further tests. Early plugging problems are mainly caused by debris that is cleared uncleanly. Debris then flows into the wellbore and clogs the perforations. It makes plugging happen faster than before. This problem can be avoided by taking preventative measures. When plugging has occurred, breakdown or acidizing can be the solution to overcome the problem.

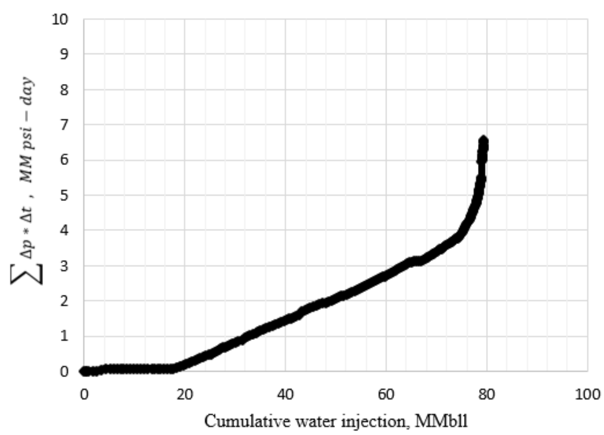

Figure 5. M20 Hall plot

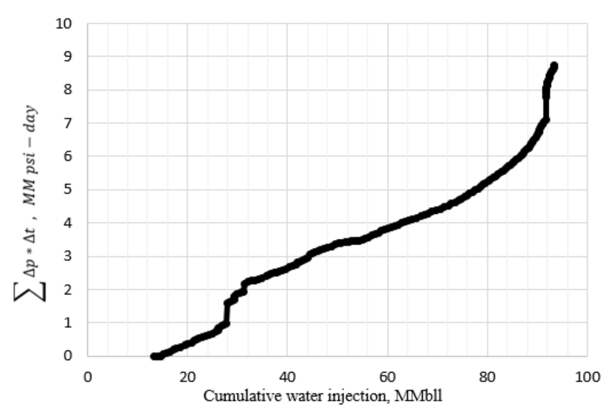

Figure 6. M21 Hall plot

To determine whether average reservoir pressure is changing, it is necessary to conduct regular pressure buildup/falloff tests and to monitor monthly voidage replacement ratio (VRR) plots. The objective of the Hall plot is to detect changes in the injection well skin factor. It is not a perfect tool but can, under certain conditions, provide reasonable insight on skin changes. The best tool for quantifying injection wellbore skin damage is a properly designed, well executed, and fully analyzed transient pressure analysis (falloff) test.

4 Conclusions

The following conclusions are drawn from the dataset examined in this study:

[1] The Abu-Attifel oil field has been supported by water injection since the early period of the field and produces large amounts of produced water daily.

[2] Hall plot is the most effective and simplest method for monitoring real-time injector performance since only daily wellhead pressure and injection rate data are required.

[3] Hall plots for M20 and M21 injectors show an increasing slope, which indicates that near-well bore plugging is taking place. Further investigation is required to validate the plot results using well test analysis.

[4] A fine grid scale reservoir model should be built from the case study to conduct a history match of the production and injection data to improve the diagnostic procedure.

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