ABSTRACT

A sandstone reservoir (SA) is the main producer reservoir in offshore Khafji oil field. This field has been producing since 1959. However, for time being, some wells suffer from excessive water production especially in old vertical wells. In addition, early water breakthrough in vertical wells is mainly due to high permeability streaks and unfavorable mobility ratio. Therefore, controlling water production is a challenge for reservoir management team work in Khafji Joint Operations (KJO) because there are several different explanations for the water sources in SA sandstone reservoir. These sources could be one or combination of edge water movement and flow behind casing. This phenomena can occur due to high permeability streaks, and conductive channels or/and faults.

To sustain the company required target rate, reservoir management in KJO should apply optimum development scenarios for reducing the water production utilizing several and effective water shut-off techniques due to production facility bottlenecks. Converting the old and high water production vertical wells to horizontal and lateral wells which have shown a high rate of success in terms of conducting better technique and scenario to retrieve and bring these wells into production with low water cut. The approaches included also reducing the choke size, cement jobs to shut-in watered out intervals and adding new perforations or re-perforating oil productive intervals. Several successful field cases have been applied in SA reservoir which resulted to high oil production with low water cut. This paper discussed more details of lessons learned and applied techniques to control excessive water production from oil wells and comparison in selecting them for applying optimum applicable techniques.

The results of water management techniques and scenarios to retrieve the wells are analyzed and discussed in this study. Reasons for conversion, directions, diagnosis, selected intervals, simulation results analysis, lessons learned, challenges and conclusions were addressed in this paper.

Keywords: Petroleum engineering, reservoir management, vertical wells, water conning, water shut-off

1. INTRODUCTION

Reservoir management has now matured to the point where great emphasis is placed on working as a cross-functional team, involving all technical areas, management, economics, legal, and environmental groups [1-10]. This type of reservoir-management model has proved to be quite successful. Reservoir management practice relies on use of financial, technological, and human resources, while minimizing capital investments and operating expenses to maximize economic recovery of oil and gas from a reservoir. The purpose of reservoir management in Khafji reservoirs is to control present and future operations on the basis of information, facts, and knowledge which become crucial. This is because Khafji reservoirs are producing for more than 50 years, and become mature oil reservoirs. Such work needs better understanding of the reservoir drive mechanics, reservoir heterogeneity, shale continuity, vertical and horizontal permeabilities. However other reservoir and production issues should be considered such as types of suitable artificial lift systems and future prediction scenarios involving secondary and/or tertiary recovery techniques.

Main key elements of reservoir managements are various including better sweep efficiency aiming high oil recovery factor through reservoir monitoring, based on optimum well placement and control of water production by all new different techniques. In fact, reservoir management are and will be considered in the next future as a vital key for KJO reservoirs, that is because KJO reservoirs are subject to excessive water production because of its long production history. The major reasons of water production from oil wells in this reservoir are mainly due to the underlying active strong aquifer below the lower sandstone reservoir (SB) which acting as Edge water drive for SA. Therefore the excess of water production from oil wells in several areas of Khafji field is a subject of concern for reservoir management.

Increasing water production from high permeability sandstone reservoirs during oilfield operations causes major reservoir development problems such as non-efficient sweeping factor leading to non-producible oil, in addition to economic, operational and environmental difficulties. Water production can affect production operations, such as oil reduction, low-flowing wellhead pressure, and the necessity to expand the capacity of water separation and handling facilities for disposing large volumes of waste water [1-9].

Furthermore, water production can also cause secondary problems such as sand production, corrosion, emulsion and scale formation. Therefore, a conformance technology is required to reduce water production and to improve an operation’s profitability through increased well life, reduced lifting, and lower well maintenance costs. In addition, a reservoir management board desires improved enhanced recovery efficiency in the reservoir as...
well as reduced environmental concerns [1-12]. Therefore such high potential reservoirs should require reservoir-management practice relies on use of financial, technological, and human resources, while minimizing capital investments and operating expenses to maximize economic recovery of oil and gas from KJO reservoir.

2. FORCES CONTROL FLUID FLOW IN SA RESERVOIR

Fluid flow and fluid distribution around the wellbores are usually affected by a combination of viscous, gravity and capillary forces. Capillary forces could be neglected for water conning specially in high permeable reservoirs such as SA reservoir, while the gravity forces that come from fluid density differences tend to keep the water out of the oil zone. Therefore, at any given time there is a balance between the gravitational forces and viscous forces where depends on the location from the completion interval. When the viscous forces at the wellbore exceed the gravitational forces, a cone of water will appear into the well to produce water along with the oil. The effect of reservoir forces can be analyzed using the gravity number. The gravity number is defined as the ratio of gravity to viscous forces [2-3]:

\[
\Delta P_{\text{viscous}} = P_i - P_{wf}
\]

\[
\Delta P_{\text{gravity}} = \left(\frac{\Delta \rho}{144}\right)h_{bp}
\]

\[
N_{\text{Grav}} = \left(\frac{\Delta P_{\text{gravity}}}{\Delta P_{\text{viscous}}}\right)
\]

When the gravity number \(N_{\text{Grav}}\) is low due to viscous forces \(\Delta P_{\text{viscous}}\) are greater compared to gravity forces \(\Delta P_{\text{gravity}}\), the tendency for water conning becomes high. Coning occurs when the gravity number is less than one as shown for SA in all cases to be less than one. It is also important to note that the gravity number changes as reservoir and fluid properties changes.

3. CRITICAL RATE FOR WATER CONING

Water coning happens on the vicinity of the well when water moves up from the free water level in a vertical direction. Production from a well causes a pressure sink at the completion. When the wellbore pressure is higher than the gravitational forces, this phenomenon is resulted from the density difference between oil and water which leads to water coning occurrence.

Critical rate is defined as the maximum rate at which oil/gas is produced without production of water. The critical rate for oil-water systems has been discussed in several publications on developed different correlations to calculate the oil critical rates \(^{2,12}\).

Joshi [12], explained in details an excellent discussion about critical rate in oil wells including analytical and empirical correlations to calculate critical rates. The correlations include: Craft and Hawking method (1959), Meyer, and Grader method (1954), Chaperon method (1986), Schols method (1972), and Hoyland, Papatzacos and Skjaeveland method (1986). Joshy [12] explained equations and example calculation for each method, concluding that the critical rate calculated for each method is different. He stated that, there is no right or wrong critical correlation; and each one should make decision about which correlation could be used for specific field applications. Meyer, and Grader correlation (1954), and Schols correlation (1972) are shown here as examples of critical rate equations for oil-water system:

\[
q_c = \left(0.001535\left(\rho_o - \rho_w\right)k\left(h^2 - D^2\right)\right)/\left(\mu_w \beta_o \ln\left(r_c / r_w\right)\right)
\]

More investigation on the suitable critical oil rates in Khafji wells by both simulation and analytical solutions are also discussed in future work.

4. WATER SOURCES IN RESERVOIR SANDSTONE SA

Although the production in the studied sandstone reservoir SA has started since more than fifty years, there are different explanations of water sources which cause water production. Many different concepts and scenarios are considered to be the main causes of water production such as high permeability streaks from edge water to the crest, channeling behind casing, highly conductive faults and channeling through high permeability zones.

4.1 Streaks of High Permeability

High permeability streaks are natural flow units which have higher permeability and much lower resistance to flow formation fluids than other layers of low permeabilities. Because of these characteristics and high water mobility related to oil, an acceleration of the water production always arises. The studied sandstone reservoir, SA consists of three sand units, the upper, the middle and lower sand. The lower flow unit, (Lower Sand) has permeability approximately 2 to 13 Darcies, contained the bulk of the oil. In addition inter-bedded zones have high permeability in each sand of the three sands. The upper layer (Upper Sand) permeability is in the range of 200 milli-Darcy and contains approximately low percentage of the total oil in place. This paper is an example to analyze water sources through the high permeability streaks creating local water conning in lower sand after water flooding with water even through the work-over and re-perforation the upper sand due to potential of high permeability.

4.2 Edge Water Inducing Local Bottom Water and Coning Effect

Although there is no direct bottom water aquifer under the sand stone reservoir SA, the main water source is coming as edge water from the aquifer under the second bottom reservoir (SB) through high permeability streaks and/or faults or fractures occurrences. Oil production was started from the crest of SA which encourages the water to breakthrough through the mentioned high permeability
streaks. After water reached the wells in the crest and because of the high reservoir thickness, about 400 ft., bottom water has induced causing local aquifer in lower sand. As continuing production and changing the perforations water coning has been occurred in many existing vertical wells.

Water coning is a term used to describe the mechanism underlying the upward movement of water into the perforations of a producing well. Petroleum reservoirs often have a gas cap and/or an aquifer. In these situations they are subjected to rapid gas or water movement towards the well as a result of a sharp pressure drop in the direction of the well. Prior to production, these reservoirs have defined fluid contacts: Water-Oil Contacts (WOC) and Gas-Oil Contacts (GOC). Once production commences, the previously defined contacts (WOC or GOC) now become deformed from its plane shape to form a cone or a crest. If a field is developed by vertical wells, the deformation would be referred to as a cone. For horizontal wells, it is known as crest, as shown in Fig.1. For the purpose of quantitative discussion, either the term “crested” or “coning” may be used. Even in horizontal well cases, most engineers adapt the term “coning” to describe the simultaneous production of water.

Water coning is a serious problem for (SA) sandstone reservoir in Khafji field while the bottom water is the main problem in the second bottom reservoir (SB) in Khafji field. Several wells, especially the vertical ones, are examples for suffering from water conning problem because of the high permeability streaks. Therefore, the wells were shut in due to bottom water coning because the oil rate was subsequently reduced and water rates are increased to a level which is not permitted by the company strategy. In such a case, if the bottom water can be controlled, the revenue would be significant.

4.3 Flow behind Casing and Near Wellbore Problems

Poor cement bonding could be the cause of water channeling behind casing which is one of the most serious problems to increase water production. Poor cement, wrong and improper perforation intervals, and unsuitable completion practices are some of many wellbore challenges and difficulties. In addition, wrong and improper perforation intervals near the bottom water, or the above gas or adjacent to a conductive fault or high permeability streaks in both vertical and/or horizontal well can dramatically accelerate the water production which leads to poor conformance. In such case, unless a blocking agent by cement or chemicals can be applied, the well’s potential is seriously impacted.

In conclusions, the sandstone reservoir (SA) has different reasons for water production which represented from water movement behind casing, water movement through high permeability streaks and/ or water movement through high conductive faults. This paper provides a quick clarification for such types of paths of least resistance which can be presented in Khafji reservoirs and which resulted in poor sweep and recovery performance. In such case, unless a blocking agent by cement or chemicals can be applied, the well’s potential is seriously impacted.

5. APPLICABLE MANAGEMENT TOOL METHODS

Currently, worldwide there are several methods and techniques that are in use to provide solutions including:

- Packers and bridge plugs
- Cement squeeze
- Re-entry and horizontal wells
- Polymer and gel placement.

5.1 Application of Water Control Techniques in SA Reservoir:

- Reservoir monitoring by well logging (PLTs) and pressure surveys.
- Reservoir simulation for current and prediction scenarios.
- Production monitoring by reviewing and controlling water cut for each well, and closing high water cut wells for work-over operations.
- Cement squeeze.
- Mechanical through Tubing Bridge Plugs (MTTBP).
- Inflow Control Devices (ICD).
- Re-entry by converting vertical wells to Horizontal wells in upper zones.
- Controlling the chock size on the wells.

This paper, which is for water management techniques and scenarios to retrieve the oil wells, mainly concerns with the last two techniques which are the re-entry of some vertical wells with conning problems to successful horizontal wells and choking down to reduce water production. Mechanical Through Tubing Bridge Plugs (MTTBP) and Inflow Control Devices (ICD) have been deeply discussed and published in references 1 and 10 respectively.

5.1.1 Re-entry Technique

Well-A: This well was completed in May, 1963 as a vertical producer with average net oil rate of 2,500 BOPD with no water cut. The water production has started in 2000 and has sharply increased with water cut of 62% in 2003. Many work overs had been carried out in Jan, 2001 and May 2007 to shut off the water out perforation interval utilizing the squeezed cement and re-perforate the remaining oil bearing intervals based on RST (Reservoir Saturation Tool) logging data but failed because the water was coming quickly from the bottom as conning through the high vertical permeability. Water conning was also shown in the simulation work at this time as shown in Fig. 2.
Fig 1: Water coning in vertical wells and water creasing in horizontal wells.

Fig 2: Simulation results of water sources from edge water and inducing bottom aquifer and water conning (Time step: Jan, 2002).
The latest ability test conducted on Sep, 2007 showed an oil production rate of 850 BOPD (Unstable flow with tight emulsion) with 60 % water cut with gas lift supply. After converting the well into re-entry on October 2008, the well has been revived with net oil of 3,000 BOPD and zero water cut as illustrated in Fig. 3. The well has been reentered in the top of the same sand layer but far away from the original vertical location with about 1,400 ft. in order to avoid the conning problem. The new well location at the top of the sand layer has thick remaining oil intervals observed from the cross section in simulation model results in different time steps as examined in Figs. 4-6.

![Fig 3: Well-A Performance before and after the Re-entry work over in Oct. 2008.](image)

![Fig 4: Simulation results for water conning in well-A under work over Time step (Time step: Jan, 1970).](image)
Fig 5: Simulation results for water conning in well-A under work over (Time step: Jan, 2006).

Fig 6: Simulation results for well-A after work over (Time step: Jan, 2009).
Currently the well is producing with net oil of 2,500 BOPD and water cut of 20% as shown in Fig. 3. This 20% water cut is stable since 2010 because of the large horizontal well contacted area with the reservoir which leads to low draw down reducing the conning phenomena.

As a conclusion, the oil rate has increased three times while the water rate reduced to half. The cumulative oil gain from this job is about 3.8 MMSTB, and reduced the cumulative water production with about 1 MMSTB, see Table 1.

Table 1: Summary of Re-entry Wells

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Oil rate (BOPD)</th>
<th>Date of Re-entry</th>
<th>Cum. Oil gain (MMSTB)</th>
<th>Water rate (BOPD)</th>
<th>Cum. water (Reduced) (MMSTB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Re-entry</td>
<td>After Re-entry</td>
<td></td>
<td>Before Re-entry</td>
<td>After Re-entry</td>
</tr>
<tr>
<td>A</td>
<td>700</td>
<td>3000</td>
<td>April, 2009</td>
<td>2.23</td>
<td>1300</td>
</tr>
<tr>
<td>B</td>
<td>600</td>
<td>2500</td>
<td>July, 2010</td>
<td>4.30</td>
<td>900</td>
</tr>
<tr>
<td>C</td>
<td>600</td>
<td>3200</td>
<td>May, 2009</td>
<td>3.50</td>
<td>1100</td>
</tr>
<tr>
<td>D</td>
<td>400</td>
<td>3350</td>
<td>May, 2010</td>
<td>3.23</td>
<td>940</td>
</tr>
</tbody>
</table>

The same conning problems have been encountered in some other vertical wells in the same reservoir; work-overs were conducted for each case to control the water conning but failed soon or later after short periods. The problems have been treated with the same process. These wells have been mentioned in this paper such as wells B, C and D as illustrated in Figs. 7-21 and Table 1. Also, Figs. 15 and 16 illustrate an example to show well logs for well-C. The original watered out zone before reentry is shown by Resistivity Saturation Tool (RST) log in Fig 15, while the new location at the top of the sand layer which has thick interval remaining oil columns as observed from the Resistivity log is shown in Fig. 16.

![Well-B Performance Before & After Work over Re-entry](image)

**Fig 7:** Well-B Performance before and after the Re-entry work over in Feb. 2009.
**Fig 8:** Simulation results for water coning in well-B under work over (Time step: Jan, 1970).

**Fig 9:** Simulation results for water conning in well-B under work over (Time step: Oct, 2002).
Fig 10: Simulation results for water conning in well-B under work over (Time step: Oct, 2009).

Fig 11: Well-C Performance before and after the Re-entry work over in May. 2009.
**Fig 12:** Simulation results for water conning in well-C under work over (Time step: Jan, 1960).

**Fig 13:** Simulation results for water conning in well-C under work over (Time step: Jan, 2004).
Fig 14: Simulation results for water conning in well-C under work over (Time step: Oct.2006).
Fig 15: Reservoir Saturation Log (RST) for well C, shows the watered-out original location.

Fig 16: Open hole Resistivity log for well C, shows the re-entry location.
Fig 17: Well-D Performance before and after the Re-entry work over in May, 2010.

Fig 18: Simulation results for water conning in well-D under work over (Time step: Jan, 2002).
Fig 19: Simulation results for water conning in well-D under work over in (Time step: Jan, 2009).

Fig 20: Well-E Performance before and after choking up.
5.1.2 Choking Down High Production Wells

Due to the high permeability with high mobility ratio and initial potential, usually the production wells of khafji sandstone reservoir SA have been started with high flow rate particularly in the early life of khafji sandstone reservoir SA. This phenomenon can be explained to water conning specially in the vertical wells. Therefore some wells have been controlled by choking down to control and delay the water production. Two examples are discussed here to explain this techniques. The first case is the well-E which explains that the main cause of water production is the choking up the well, while the second case is the well-F which shows applying lesson on well-E with a successful to control water by this technique:

Well-E: After the work over as the water shut-off, the well has started to produce with small choke size (48/64”). The results initially showed no water production and about 2,000 BOPD which is considered as a successful water shut-off job. The obtained results for this well continued for two months as shown in Fig. 20. After that the well was choking up (fully open) which has accelerated the water cut to 50 % within less than one month which reduced the oil production rate to about 1,000 BOPD as illustrated in Table 2.

Table 2: Summary of Chocking up Wells

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Oil Rate (BOPD)</th>
<th>Water Cut %</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Before Choking up on (48/64”)</td>
<td>After Choking up on (96/64”)</td>
</tr>
<tr>
<td>E</td>
<td>2500</td>
<td>1300</td>
</tr>
</tbody>
</table>

Well-F: This well is an excellent example for controlling the water conning by choking down. The well was worked over in 2010 for water shut-off job. The well has started to produce with small choke size (48/64”). The results initially showed no water production and about 1,800 BOPD. These obtained results for this well are continuing up to date on the same choke size. The results confirmed that the main reason of accelerating the water in well-E was choking up as shown in Table 3 and Fig. 21.
6. CONCLUSIONS
a. The subject reservoir is a good example for water coning tendency because of the viscous forces related to gravity forces, therefore low production rates are recommended to avoid water conning.
b. The sandstone reservoir (SA) has different reasons for water production which represented from water movement behind casing, water movement through high permeability streaks and/or water movement through high conductive faults.
c. Successful re-entry wells have been planned and achieved to reduce the water production and increased the oil production.
d. Khafji wells should be controlled by proper choke size.
e. Producing the wells with fully open choke size leads to acceleration of water production.
f. More study for the critical rate should be done to control water production by applying critical rates.

NOMENCLATURE
\[ \Delta P_{\text{viscous}} \]: viscous forces (psia)
\[ P_i \]: initial pressure (psia)
\[ P_{wf} \]: bottom hole flowing pressures
\[ \Delta P_{\text{gravity}} \]: gravity forces (psia)
\[ N_{\text{Grav}} \]: gravity number
\[ \Delta \rho \]: density difference (gm/cc)
\[ h_{bp} \]: thickness interval below perforation to WOC (ft)
\[ q_c \]: critical oil rate (STB/D),
\[ \rho_w \]: water density (gm/cc),
\[ \rho_o \]: oil density (gm/cc)
\[ k \]: formation permeability (md)
\[ h \]: oil zone thickness (ft)
\[ D \]: completion interval thickness (ft)
\[ \mu_o \]: oil viscosity (cp),
\[ B_o \]: oil formation volume factor (bbl/STB),
\[ r_e \]: external drainage radius (ft),
\[ r_w \]: wellbore radius (ft).

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REFERENCES
[10] Mahmoud A. F. et. al. “The Application of Nozzle Based Inflow Control Devices (ICD) in Al-Khafji Field” This paper was prepared for presentation at the International Petroleum Technology Conference held in Beijing, China, 26–28 March 2013.

