International Journal of Petroleum and Petrochemical Engineering
Volume 6, Issue 2, 2020, PP 17-22
ISSN No.: 2454-7980
DOI: http://dx.doi.org/10.20431/2454-7980.0602003
www.arcjournals.org

Waterflood Pattern Size Reduction in Faulted Anticlinal Reservoirs

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Abstract: *Waterflooding is a secondary recovery method applied in reservoirs when the natural energy drives are depleted (Asadollahi et al, 2009). Reduction in the sizes of waterflood patterns have an impact on waterflood efficiency and ultimate oil recovery. As such, this study was geared towards investigating the impact of waterflood pattern size reduction in faulted anticlinal reservoirs. ECLIPSE 100 was used to build a reservoir model on which pattern size reduction of a normal 5-spot pattern was carried out. The production period of the reservoir spun for 20 years. Results obtained showed that the oil production rate and total oil production of the field increased as the waterflood pattern size was being reduced. It was concluded that pattern size reduction through infill drilling and producer-to-injector conversions increases well density and reduces well spacing, which contributes to an increase in ultimate oil recovery.*

Keywords: *Waterflooding, Pattern size reduction, 5-spot patterns, Oil recovery*

1. INTRODUCTION

Crude oil is among the most profitable natural resources that any country can have. This is as a result of its high profitability on the international market and its myriad purposes. One can say oil is the lifeblood of the industrialized nations; underpinning modern society. Every reservoir possesses some natural driving mechanisms that help it produce oil on its own. However, this energy is usually not sufficient to produce the hydrocarbons for certain extended periods (Ahmed, 2010). The insufficiency of the natural drives demands the implementation of artificial methods to assist the reservoir in producing hydrocarbons to surface. These artificial methods are traditionally known as secondary recovery methods. Other methods include tertiary methods and improved methods. Waterflooding is the most common method of secondary recovery (Ahmed, 2010).

Over the years, waterflooding has gained popularity as a result of the general availability of water, relative ease of injecting water and the ability of water to spread easily through an oil bearing formation (Ogbeiwi, 2016). The process of waterflooding basically involves the pumping of water through injection wells into the reservoir. The water then pushes the oil towards production wells thus causing an increment in the total oil production from the reservoir.

Injection and production wells used in a waterflood can be configured according to different patterns. The common patterns include the peripheral pattern, five-spot, four-spot, seven-spot, nine-spot, staggered line drive, direct line drive among others. According to Ahmed (2010), the efficiency of a waterflood depends on certain factors such as the formation lithology, fluid properties, reservoir depth, reservoir geometry, pattern arrangement and well spacing involved in the flood operation.

In recent times, reservoir engineers have employed the use of waterflood pattern size reduction as a means of optimising waterflood operations. Suttles and Kwan (1993) argued that oil recovery from waterflooding is primarily improved by increasing the rate of injection throughput and ultimate throughput volume, improving pattern geometry and by creating smaller patterns.

This study seeks to assess the performance of waterflood pattern size reduction in faulted anticlinal reservoirs.

2. METHODOLOGY

This section describes the geologic and dynamic models created and the procedure used in simulating the reservoir to carry out the pattern size reduction.

2.1. Geologic Model

The geologic model used for the project was built using a corner point geometry option of the ECLIPSE software. The model is made up of 24 cells in the X direction, 25 cells in the Y direction and 12 cells in the Z direction. Each cell measures 200×200×50 ft. The reservoir is an anticline with two partial sealing faults. These faults have divided the reservoir into three fluid-in-place regions; the left, right and top regions. Since the faults are not fully sealing, the various regions are expected to have fluid and pressure communications.

The average horizontal permeability of the reservoir is 253.67 mD. The average vertical permeability is 10% of the horizontal permeability. The average porosity is 15.67%. The reservoir is initially saturated and characterised with heavy oil. The oil-initially-in-place is 1.13 MMMSTB.

2.2. Dynamic Model

The dynamic model consists of a fluid model and a rock saturation model. These models contain pressure dependent functions and saturation dependent functions respectively. The rock model consists of the relative permeability curve and the capillary pressure curve. Figure 1 shows the relative permeability curve of the rock model.

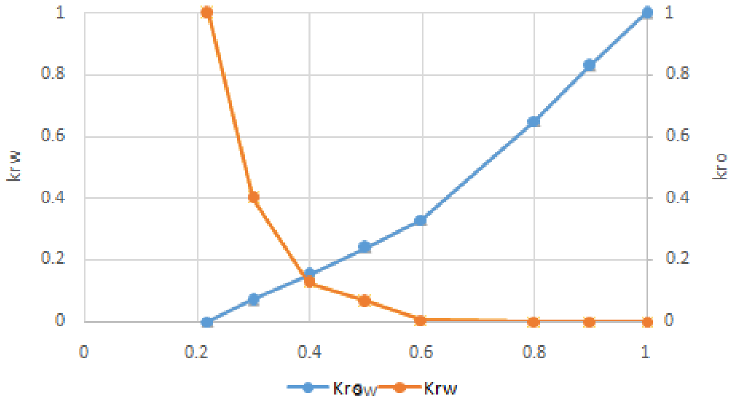

Figure1. *Relative Permeability Curve of the Rock Model*

The initial oil saturation is 0.78; residual oil saturation is 0.2; initial water saturation and critical water saturation are both 0.22; and the residual water saturation is 0.8. Figure 2 illustrates the capillary pressure curve of the rock model which shows no transition zone.

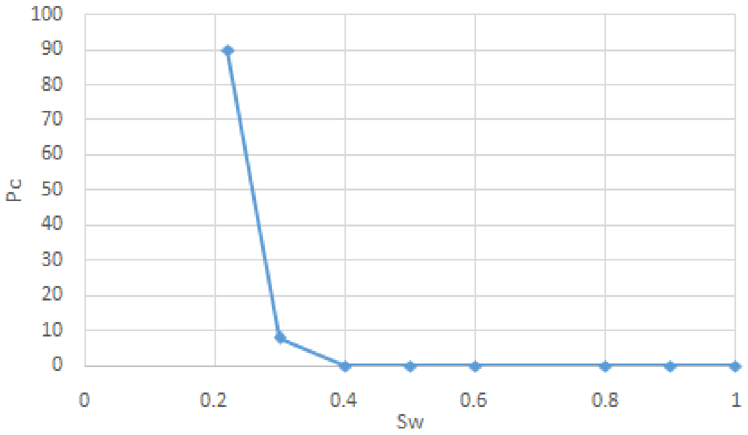

Figure2. *Capillary Pressure Curve of the Rock Model*

The reservoir fluid is a dead oil with a solution gas oil ratio of 0.4 scf/stb and an initial reservoir pressure of 3407.52 psi. The reservoir has a rock compressibility of 3.0×10^{-6} at 14.7 psi. The densities of oil, gas and water are 49.1 lb/ft^3, 0.06054 lb/ft^3 and 64 lb/ft^3 respectively.

2.3. Reservoir Simulation

The reservoir model was initialised by drilling a single producing well at the centre of the reservoir and flowed for four years. At the second stage, four additional producers were drilled at the corners of the reservoir and flowed for two and a half years. This was followed by a third stage, where all producers drilled at the second stage were converted into injectors and four infill wells were drilled in between the new injectors to form a five-spot pattern. Production was allowed for five years.

At the fourth stage of the project, a workover was performed to convert producers drilled at the third stage into injectors. Twelve infill wells were drilled to reduce the size of the five-spot pattern. Production at this stage lasted for 5 years.

At stage 5, all producers drilled at the fourth stage were converted into injectors and four infill wells were added. Production lasted for three and a half years. Five sets of reduced five-spot patterns were obtained at the end of the project.

3. RESULTS AND DISCUSSION

3.1. Field Oil Producing Rate (FOPR)

The FOPR represents the producing rate of the entire field over the 20 years it was produced. The results for this are shown in Figure 3 with all 5 stages of production marked out.

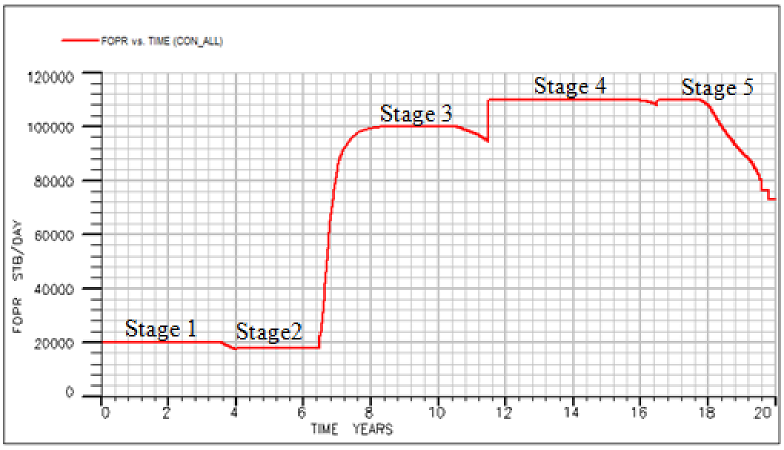

Figure3. *A Plot of Field Oil Producing Rate Versus Years*

3.1.1. *Stage 1*

At this first stage of the simulation, the centre well was set to produce oil at a rate of 20 000 STB/day for four years. The producing rate started to decline after 3.5 years till the 4th year. The reservoir model at this stage of production is shown in Figure 4. From the oil saturation scale in the Figure 4, a high initial oil saturation is observed. This is because the reservoir was at its initial years of production and as such, had not been depleted much.

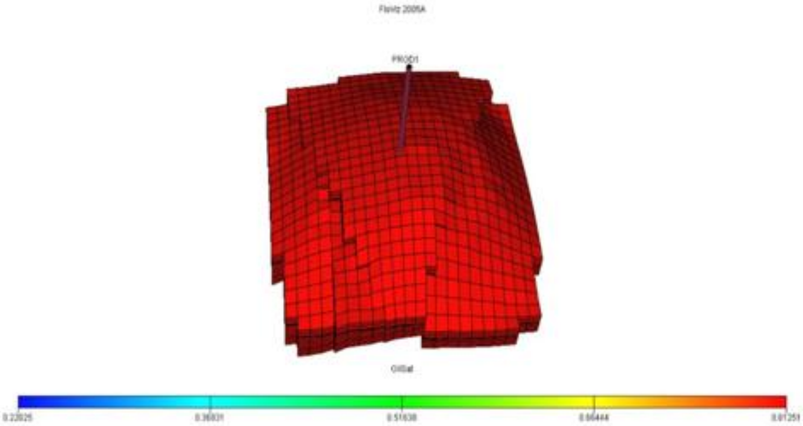

Figure4. *Stage 1 (1 Producer)*

3.1.2. Stage 2

At this stage, the four additional wells drilled at the corners of the reservoir (in a five-spot pattern) produced at a group production rate of 18 000 STB/day for 2.5 years. These wells did not produce at a rate higher than the centre producer in Figure 4 because the goal was to deplete the reservoir gradually. Figure 5 shows the reservoir at the second stage of the project.

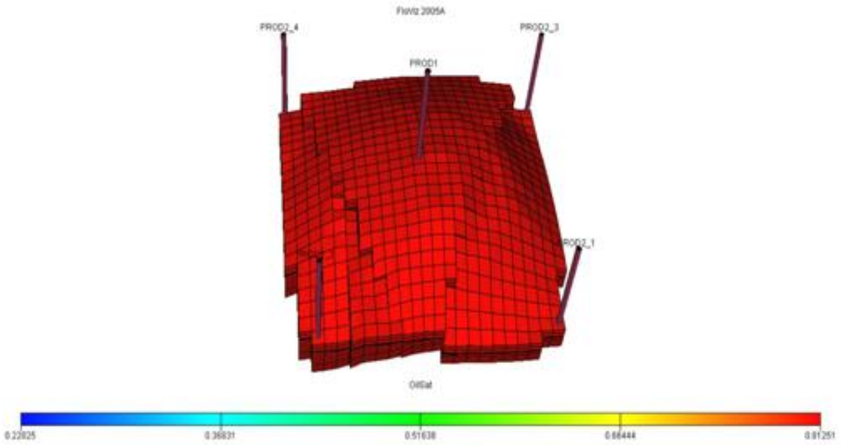

Figure5. *Stage 2 (5 Producers)*

3.1.3. Stage 3

As shown in Figure 3, the oil production rate shot up to 100 000 STB/day at Stage 3 when four producers were converted into injectors, and four new producers were drilled in a reduced five-spot pattern. Figure 6 shows the reservoir at this stage of the project.

The sharp rise in FOPR from Stage 2 to Stage 3 can be attributed to the fact that waterflooding was initiated. The wells were able to produce at higher rates because of the extra energy from the injected water. The production plateau was sustained until 10.5 years, where it began to decline till the 11.5th year.

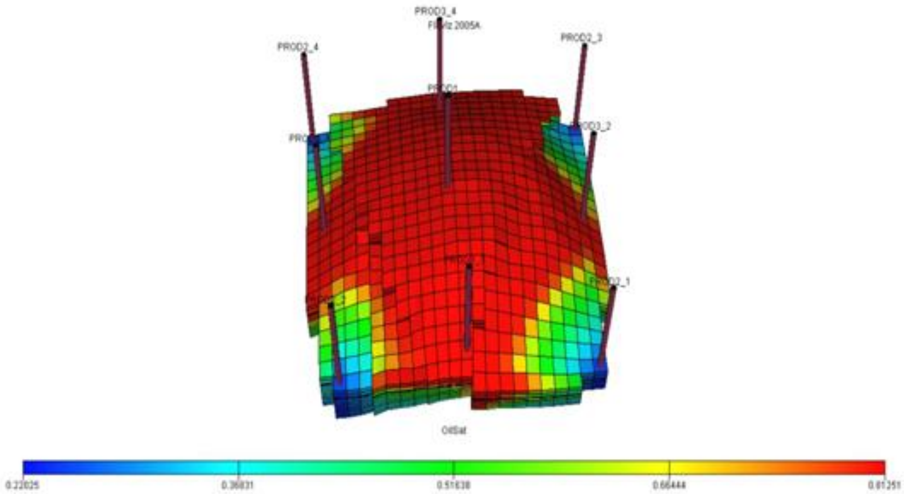

Figure6. *Stage 3 (5 Producers, 4 Injectors)*

3.1.4. Stage 4

As seen in Figure 3, the production rate at Stage 4 (Figure 7) increased to 110 000 STB/day when the producers at Stage 3 were converted to injectors and twelve infill wells were drilled to further reduce the pattern size. A production plateau was maintained at this rate for 4.3 years, after which it declined slightly till the 16.5th year.

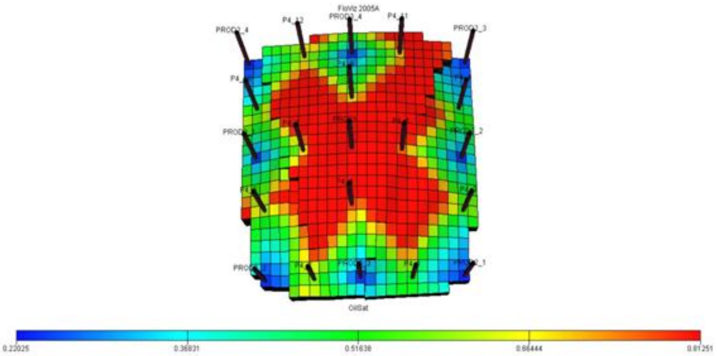

Figure7. *Stage 4 (13 Producers, 8 Injectors)*

3.1.5. Stage 5

At Stage 5 of the waterflood project, all producers drilled at Stage 4 were converted into injectors and four infill wells were drilled. From Figure3, the production rate plateaued at 110 000 STB/day for 1.2 years after which it declined to a rate of 73 000 STB/day in the 20th year.

As shown in Figure 8, there were five sets of reduced five-spot patterns by the end of the waterflood pattern size reduction project.

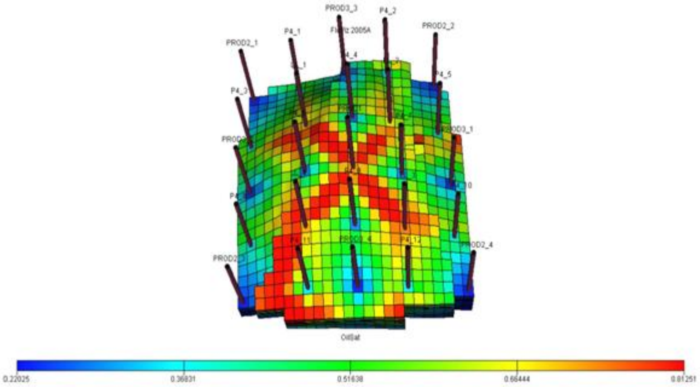

Figure8. *Stage 5 (5 Producers, 20 Injectors)*

3.2. Field Oil Production Total (FOPT)

The plot in Figure9 shows the cumulative field oil production for the twenty years the project was undertaken. From Year 1 to Year 6, a gentle rise in production is observed. However, production rises sharply after Year 6.5 till Year 20. This can be attributed to the fact that waterflooding was initiated after Year 6.5 and the pattern size was reduced at subsequent stages. By reducing the pattern size through the use of infill wells, well density was increased and smaller well spacings were attained. This contributed to an increase in oil production by increasing reservoir continuity between injectors and producers. More fluid extraction points were also created in parts of the reservoir with unswept oil. A total amount of 54.3 MMSTB of oil was produced at the end of the project.

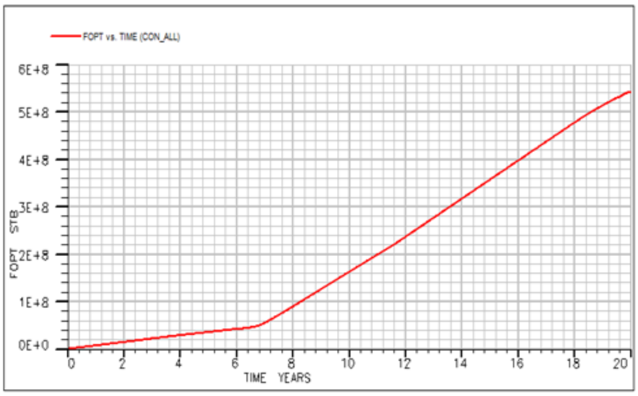

Figure9. *A Plot of Field Oil Production Total Versus Years*

3.3. Field Water Cut (FWCT)

This represents the ratio of water produced compared to the total volume of liquids produced. As shown in Figure 10, there was no water production for the first ten years of the project. The highest FWCT was about 73%. This could be as a result of the increase in number of injectors at the latter stages of the project.

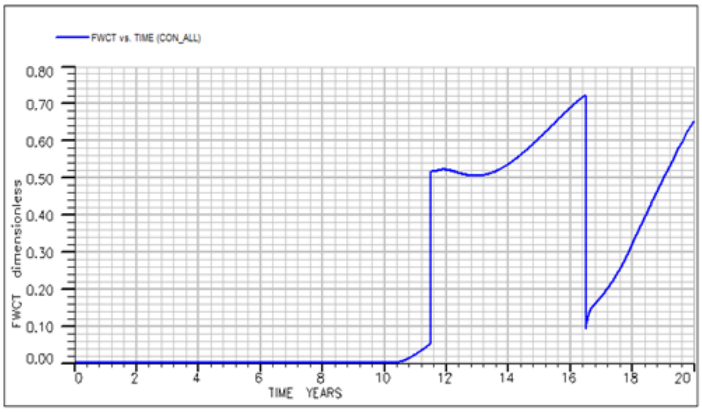

Figure10. *A Plot of Field Water Cut Versus Years*

4. CONCLUSION

From the results of the study the following conclusions were made;

- Reducing the pattern size of a normal 5-spot through infill drilling and producer-to-injector conversions yields higher oil recovery;
- Infill drilling improves recovery of unswept oil by increasing reservoir continuity; and
- Pattern size reduction leads to an increase in well density and a reduction in well spacing that improve oil recovery.

ACKNOWLEDGEMENT

The authors wish extend their appreciation to the support from the Petroleum Engineering Department of the University of Mines and Technology, Tarkwa, Ghana.

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Citation: *E. M. Amarfio, R. N. A. Akoto, B. Bediako, “Waterflood Pattern Size Reduction in Faulted Anticlinal Reservoirs”, International Journal of Forestry and Horticulture, 6(2), pp. 17-22. DOI: http://dx.doi.org/10.20431/2454-7980.0602003*