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Research Article

Unveiling Heterogeneity's Reservoar Impact: A Reservoir Simulation Odyssey Into Cyclic Waterflooding Dynamics

Ratna Widyaningsih[1]*, Edgie Yuda Kaesti[1], Dhika Permana Jati[1], Fahrur Rozi[1], Suwardi[1], Adam Raka Ekasara[2]

[1] Petroleum Engineering Department, UPN "Veteran" Yogyakarta, Sleman 55283, Indonesia; email: ratna.widyaningsih@upnyk.ac.id
[2] Geological Engineering Department, UPN "Veteran" Yogyakarta, Sleman 55283, Indonesia; email: adam.raka@upnyk.ac.id
* Corresponding Author : Ratna Widyaningsih

Abstract: Reservoir heterogeneity has long been recognized as a critical factor influencing the efficiency of enhanced oil recovery (EOR) methods. Among the techniques applied, cyclic waterflooding is considered one of the promising approaches due to its relatively simple operational design and potential to improve sweep efficiency. This method involves alternating water injection in specific cycles to mobilize trapped oil and redistribute reservoir pressure. However, the variation in geological properties such as porosity, permeability, and fluid saturation creates challenges in achieving uniform displacement, especially in reservoirs with high heterogeneity. Understanding the role of heterogeneity is therefore crucial for optimizing cyclic waterflooding applications. This study applies a literature review approach by synthesizing findings from previous experimental and field studies that evaluated cyclic waterflooding under different reservoir conditions. The analysis compares the performance of cyclic water injection periods across reservoirs characterized by varying levels of heterogeneity. Parameters such as injection rate, water breakthrough time, and oil recovery factor were considered in evaluating the effectiveness of this method. The results highlight that reservoirs with high heterogeneity often experience uneven fluid distribution, leading to early water breakthrough and reduced oil recovery. In contrast, reservoirs with relatively low heterogeneity tend to respond better to cyclic waterflooding, resulting in improved sweep efficiency and higher incremental recovery. Moreover, the optimization of cycle timing and water injection intervals appears to significantly mitigate the negative effects of heterogeneity. In conclusion, the study emphasizes that reservoir heterogeneity plays a decisive role in determining the success of cyclic waterflooding. Tailoring injection strategies based on geological variability is essential to maximize recovery efficiency. Future research should focus on integrating advanced reservoir characterization techniques with adaptive cyclic flooding models to further enhance oil production outcomes.

Keywords: Cyclic Waterflooding; Oil Recovery; Porosity; Reservoir Heterogeneity; Water Injection

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1. Introduction

The extraction of oil from mature reservoirs has become a significant challenge for the petroleum industry, especially as easily recoverable reserves are rapidly depleting [1]. Among the various exploitation techniques, cyclic waterflooding has garnered considerable attention due to its ability to mobilize residual oil trapped in the reservoir [2]. Cyclic waterflooding, often referred to as periodic or alternate water injection, involves alternating between injection and production phases [3]. This process helps to manage reservoir pressure, improve sweep efficiency, and enhance overall oil recovery [4].

During the injection phase, water is injected into the reservoir to maintain pressure and displace oil, while during the production phase, the pressure is allowed to drop, encouraging the oil to flow towards the production wells [5]. The fundamental advantage of cyclic waterflooding over continuous waterflooding lies in its ability to re-distribute reservoir fluids dynamically, thereby enhancing oil sweep efficiency, especially in complex reservoirs [6]. The cyclic waterflooding method can be applied by periodically altering the injection volume, which creates an unstable pressure field within the formation, leading to continuous redistribution of fluid throughout the reservoir [8].

One of the most critical factors influencing the performance of cyclic waterflooding is reservoir heterogeneity, which refers to the variation in rock and fluid properties throughout the reservoir [9]. These properties include porosity, permeability, saturation, and pore throat size, among others [10]. Heterogeneous reservoirs, characterized by non-uniform distribution of these properties, present a significant challenge to any waterflooding operation [10]; [11]. Water tends to follow the path of least resistance, which means that in a highly heterogeneous reservoir, the injected water may preferentially move through high-permeability zones, bypassing oil-rich low-permeability areas. Permeability increases during advanced stages of high air cut development, using techniques like core analysis, log evaluation, physical modeling, and numerical simulation to assess this effect [12]. This results in poor sweep efficiency and suboptimal oil recovery [13]. Enhancing oil recovery in such fractured, low-permeability reservoirs is challenging [14]. Understanding and managing the impact of heterogeneity on the cyclic waterflooding process is crucial to maximizing the recovery factor and economic viability of the operation [15].

Reservoir heterogeneity can occur at various scales and may be influenced by several geological factors. Stratification, fracturing, and faulting are common geological features that can introduce significant heterogeneity within a reservoir. These variations create challenges in fluid flow, often leading to uneven distribution and making reservoir management and optimization more complex [16]. Stratification, where the reservoir rock is layered with varying permeability and porosity, can lead to vertical heterogeneity, making it difficult for injected water to uniformly displace oil across the different layers [17]. Similarly, fracturing and faulting create horizontal heterogeneity, compartmentalizing the reservoir and restricting fluid flow across certain barriers [18]. These variations can dramatically alter the behavior of fluid flow within the reservoir, posing significant challenges to waterflooding operations [19]. This compartmentalization often leads to uneven sweep efficiency, impacting overall recovery rates [10].

To overcome these difficulties, reservoir modeling and simulation serve as essential techniques for evaluating heterogeneity and enhancing recovery methods. Reservoir modeling develops a digital representation of the subsurface by combining geological, geophysical, and engineering information, whereas simulation applies numerical calculations to forecast fluid flow within these models. When integrated, these methods allow engineers to optimize production strategies, improve reserve estimation, and guide decisions in field development planning [20]. Consequently, reservoir modeling and simulation play a vital role in forecasting reservoir behavior, reducing uncertainties, and increasing overall recovery efficiency [21]. The effectiveness of these methods depends on accurate reservoir characterization, which delivers comprehensive knowledge of geological, petrophysical, and fluid properties. By defining the dimensions, distribution, and connectivity of hydrocarbon-bearing formations, characterization ensures the development of robust models capable of simulating production scenarios and predicting challenges such as water intrusion or gas breakthrough. This knowledge further assists engineers in optimizing well placement and completion, improving recovery performance, and adjusting strategies throughout the reservoir's lifecycle as rock and fluid properties change [22]; [23].

2. Literature Review

Cyclic waterflooding presents a viable solution to some of the challenges posed by reservoir heterogeneity [24]. With conventional oil production declining rapidly and energy demand increasing, tight oil reservoirs are becoming crucial in oil and gas field development due to their substantial geological reserves [25]. Waterflooding is the primary technique used to enhance ultimate oil recovery in many oilfields. As a secondary recovery method, it involves injecting water into the reservoir to push out the oil [26]. By alternating between injection and production cycles, the cyclic process allows for periodic pressure buildups and releases within the reservoir [27]. This variation in pressure can help mitigate some of the negative impacts of heterogeneity, as it encourages fluid redistribution and reduces the risk of channeling, where water bypasses oil-rich zones entirely [28]. Research has shown that cyclic waterflooding can lead to improved oil recovery in heterogeneous reservoirs by enhancing the sweep efficiency in areas that are otherwise difficult to access with continuous water injection [29]. However, the effectiveness of cyclic waterflooding is highly dependent on several factors, including the nature of the heterogeneity, the design of the cyclic injection and production periods, and the overall reservoir management strategy [30]; [31].

Recent studies have emphasized the importance of tailoring cyclic waterflooding strategies to the specific characteristics of the reservoir [32]. This approach ensures more efficient fluid distribution and maximizes recovery by adapting to reservoir heterogeneity [33]. For instance, the timing of the injection and production cycles is a critical factor that can influence the success of the process [10]. If the production phase is initiated too early, before sufficient pressure buildup occurs, the injected water may not have enough time to effectively displace the oil, leading to premature water breakthrough [34]. Conversely, if the production phase is delayed too long, the reservoir pressure may become excessively high, causing operational difficulties and reducing the effectiveness of oil displacement. Therefore, optimizing the timing of these cycles is essential for maximizing oil recovery, particularly in reservoirs with high levels of heterogeneity [17].

In addition to cycle timing, the value of reservoir heterogeneity itself plays a fundamental role in determining the effectiveness of cyclic waterflooding [7]. Higher heterogeneity can lead to uneven fluid distribution, reducing sweep efficiency and overall recovery [35]. High-heterogeneity reservoirs, where there is significant variation in permeability and porosity across the reservoir, tend to exhibit more unpredictable and uneven fluid flow patterns [36]; [37]. In such reservoirs, cyclic waterflooding may help to even out the distribution of injected water, reducing the risk of channeling and improving overall sweep efficiency [19]. On the other hand, in low-heterogeneity reservoirs, where the properties are more uniform, cyclic waterflooding may have a less pronounced effect, as continuous water injection might already achieve relatively high recovery rates [38]; [39].

One of the key challenges in implementing cyclic waterflooding in heterogeneous reservoirs is the complexity of reservoir modeling and the need for advanced simulation techniques [40]. This complexity demands precise data integration and advanced computational modeling approaches [33]. Accurate predictions require high-resolution models to capture flow dynamics precisely [40]. Reservoir simulation has become an indispensable tool for predicting the performance of cyclic waterflooding under various geological and operational conditions [14]; [41]. It allows for optimizing injection strategies, enhancing oil recovery, and minimizing operational uncertainties in reservoir management [42]. These simulations allow engineers to test different cyclic waterflooding scenarios and optimize the design of the process based on the specific characteristics of the reservoir [36]. By modeling the effects of heterogeneity on fluid flow and pressure distribution, simulations provide valuable insights into how to mitigate the negative impacts of heterogeneity and maximize oil recovery [43]. These simulations help optimize injection strategies, improve sweep efficiency, and reduce the risk of premature water breakthrough, enhancing overall recovery [44].

However, it is important to note that cyclic waterflooding is not a one-size-fits-all solution [42]. Reservoir characteristics, such as permeability and fracture distribution, must be carefully evaluated to determine its effectiveness and optimize outcomes [46]. The success of this method depends not only on the geological characteristics of the reservoir [47]. But, it is also on the careful management of operational factors such as injection rates, water quality, and well placement [33]. Studies have shown that improper management of these factors can lead to suboptimal results [48]. Even in reservoirs where cyclic waterflooding is theoretically advantageous, this can still happen [28]. Therefore, a comprehensive approach to reservoir management is necessary to ensure the successful implementation of cyclic waterflooding in heterogeneous reservoirs [49].

In conclusion, this study aims to further investigate the impact of reservoir heterogeneity on the performance of cyclic waterflooding. By focusing on the interaction between cyclic injection periods and reservoir heterogeneity, the research seeks to provide valuable insights into how these factors can be optimized to enhance oil recovery [50]. Given the increasing importance of EOR methods in extending the life of mature oilfields, understanding the role of heterogeneity in cyclic waterflooding is critical for the future success of oil recovery operations.

3. Proposed Method

There are some stages which are needed to complete this research. It begins from variable of Dykstra-Parson (VDP) calculation to design the heterogeneity of reservoir. Then the model was built up based on its design. In the created 1D model, there are two wells (an injector and a producer well) which have distance is 660ft. Subsequently, it is divided by 33 grids, which has dimension 33*1*1. There-fore, each grid has dimension 20ft*20ft*20ft.

The simulation method used Black oil modelling by TNavigator simulator. Reservoir fluid (PVT analysis) and SCAL data are inputted before arranging the scenario of cyclic waterflooding. The detail of each step is described below.

3.1. Dykstra-parson variable analysis

It begins from variable of Dykstra-Parson (VDP) calcula-tion to design the heterogeneity of reservoir. 1D model was chosen to concentrate on linier flow which is built based on VDP calculation design. Basically, the VDP method is used for heterogeneity of reservoir analysis by processing routine core analysis which were taken at certain depth. That means that method results the vertical heterogeneity. Since the aim of the research is focusing upon the heter-ogeneity effect on cyclic waterflooding performance, so this method will be the approach to calculate the distribu-tion of permeability on the model.

Determining heterogeneity of reservoir by VDP value are 0 (represent homogeneous reservoir); 0.2; 0.5; 0.8 (rep-resent extremely heterogeny reservoir). Dykstra-Parson equation is shown below.

$$V_{DP} = \frac{k_{50} - k_{84.1}}{k_{50}} \tag{1}$$

Each grid's permeability values are tabulated to deter-mine VDP design calculation which is provided in results section.

3.2. Fluid Properties

Fluid properties represent the light oil with the API 42.1. Table 1 is provided the used fluid properties in the model.

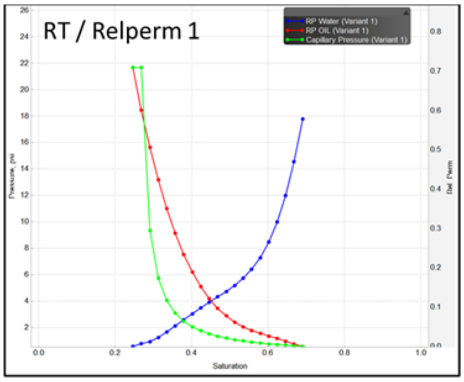
Table 1. Fluid Properties

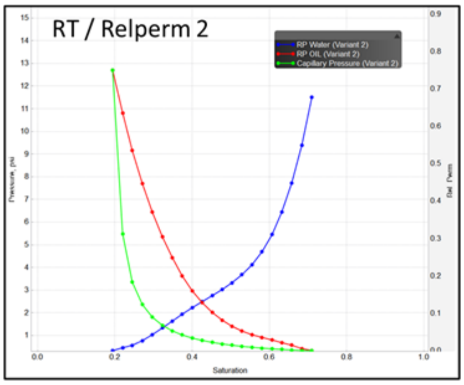
Black Oil Model				
Oil Density (lb/cuft)	Pb (psi)	Boi (bbl/stb)	Rs (Mscf/stb)	m_o (cp)
50.863	2166	1.417	0.7314	0.32373

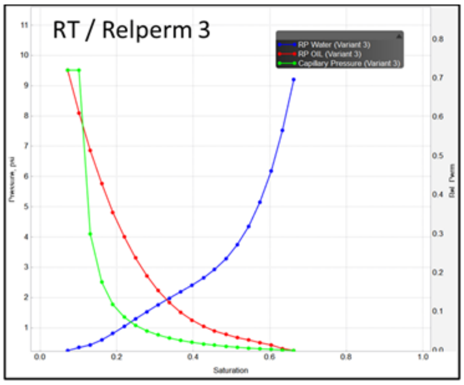
3.3. Special Core Analysis Data

Considers that fluid flow's behavior is different in the different size of rock's pore, therefore the rock types in this model are defined into 3 types. These curves, de-scribed that the reservoir rock is water-wet. The used Special Core Analysis data (SCAL) are illustrated in Figure 1.

Fig. 1. Capillary pressure and relative permeability curve





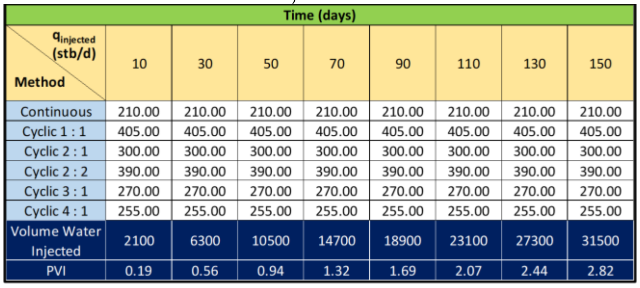


3.4. Scenarios

Some scenarios are arranged after all data were in-putted. Its preparation considers the aim of the sensitivity parameter such as injection rate and period of cyclic wa-terflooding. The injection rate sensitivity range is 10; 30; 50; 70; 90; 110; 130; 150 stb/day and the injection period sensitivities are continuous injection, 1:1; 2:1; 2:2; 3:1; 4:1. The explanation of injection method of 2:1 period is 2 period for injection and 1 period for shut-in, while 1 peri-od is equal to 15 days. The production well is always open.

For each rate scenario, the PV injection is maintained equal amount. Therefore, the injection time in cyclic method is longer than continuous method. However, the continuous injection methods with different rate are lim-ited in 210 days. This technique intended to observe the response of each rate to a certain time. Furthermore, the pore volume injected is also investigated. After that, by those scenarios are applied to those 4 different models. The resume of applied scenarios is shown in Table 2.

Table 2. Injection Scenarios



	Time (days)							
$q_{injected}$ (stb/d) Method	10	30	50	70	90	110	130	150
Continuous	210.00	210.00	210.00	210.00	210.00	210.00	210.00	210.00
Cyclic 1 : 1	405.00	405.00	405.00	405.00	405.00	405.00	405.00	405.00
Cyclic 2 : 1	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Cyclic 2 : 2	390.00	390.00	390.00	390.00	390.00	390.00	390.00	390.00
Cyclic 3 : 1	270.00	270.00	270.00	270.00	270.00	270.00	270.00	270.00
Cyclic 4 : 1	255.00	255.00	255.00	255.00	255.00	255.00	255.00	255.00
Volume Water Injected	2100	6300	10500	14700	18900	23100	27300	31500
PVI	0.19	0.56	0.94	1.32	1.69	2.07	2.44	2.82

3.5. Results Analyzing

The sensitivities aim to observe the effect of injection rate and injection method/period toward oil recovery in the different heterogeneity level.

4. Results and Discussion

4.1. 1D Build-up Model

Five simulation models were constructed to analyze the sensitivity of varying VDP values (Figures 2 to 6). According to the Dykstra-Parsons calculation and classification, a VDP of 0 represents a homogeneous reservoir, a VDP of 0.2 in-dicates a slightly heterogeneous reservoir, a VDP of 0.5 represents a very heterogeneous reservoir, and a VDP of 0.8 reflects an extremely heterogeneous reservoir.

The cyclic waterflooding simulation run in black oil model.

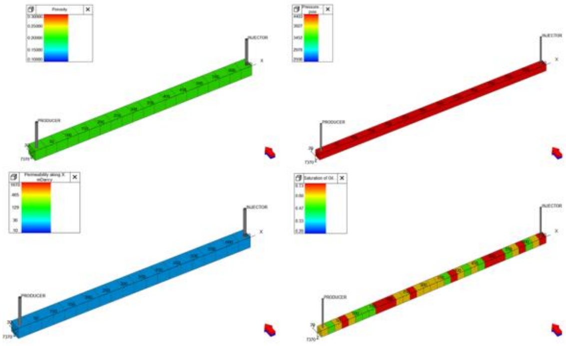


Fig 2. Reservoir model with V_{DP}=0

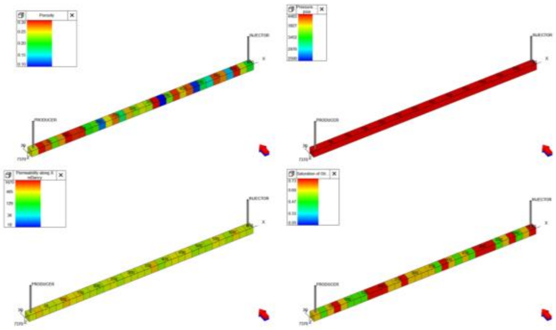


Fig 3. Reservoir model with V_{DP}=0.2

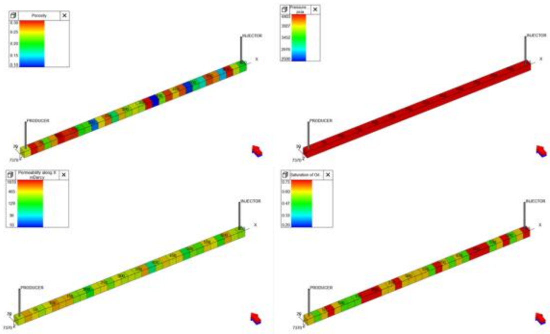


Fig 4. Reservoir model with V_{DP}=0.5

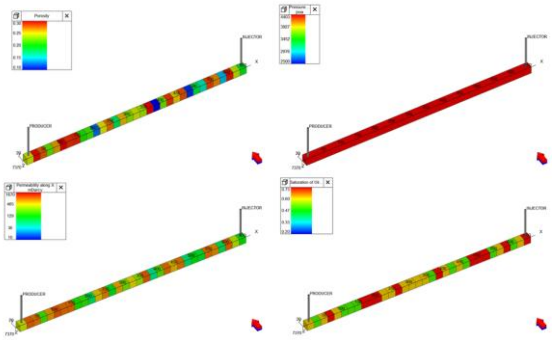


Fig. 5. Reservoir model with V_{DP}=0.8

4.2. Waterflooding Scenarios

Scenarios involves 6 injection methods and 8 injection rate variants. Arranged scenarios are run by the reservoir simulation. The bar chart on Fig.7 to Fig. 11 are compre-hensively shown the results from each scenario. The rig-orous discussion will be depicted in every sub chapter.

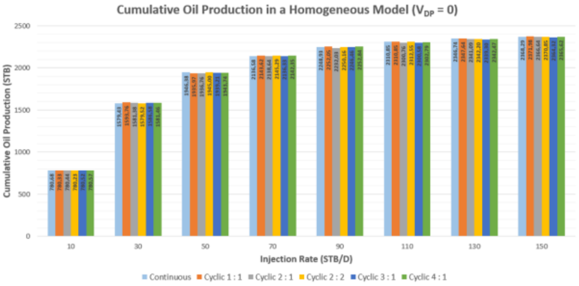


Fig. 6. Results of rate and method/period waterflooding sensitivity on model @V_{DP}=0

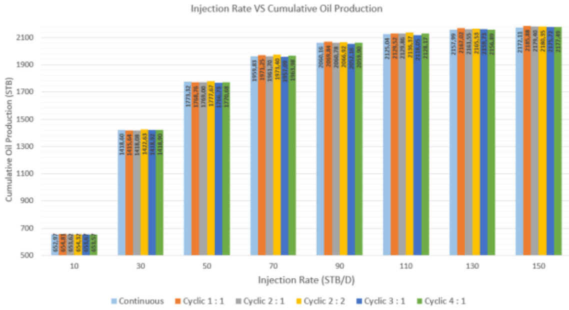


Fig. 7. Results of rate and method/period waterflooding sensitivity on model @V_{DP}=0.2

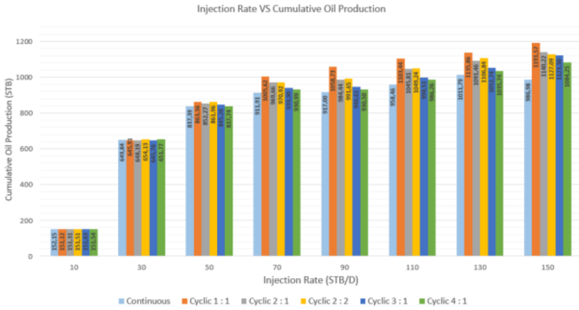


Fig. 8. Results of rate and method/period waterflooding sensitivity on model @V_{DP}=0.5

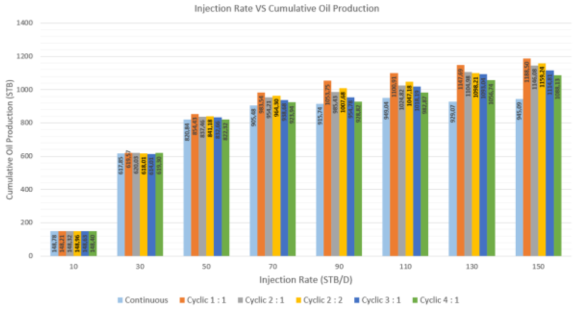


Fig. 9. Results of rate and method/period waterflooding sensitivity on model @V_{DP}=0.8

The 5 models have the same dimension (□ x,□ □ y,□ z) but they have different properties especially permeability which are supposed to express the heterogeneity sensitiv-ity. The VDP's model are differentiated into 0; 0.2; 0.5; 0.8.

4.3. Model @V_{DP} = 0

The buildup model @VDP=0 performs the homogeneous reservoir. It has a permeability of 410mD (Fig. 2). The in-jection rates and injection methods sensitivity have been implemented as mentioned in the method section. Figure 7 shows the simulation results for which both sensitivity combinations were performed. Through this figure, the optimum injection rate and method could be determined.

At the first sight, all injection periods for each injection rate scenario produce similar cumulative oil production results, with minimal differences observed across the scenarios. For example, at an injection rate of 10 STB/day, the injected volume reaches 0.19 pore volume (PV) by the end of the simulation. This relatively low injection volume appears insufficient to significantly impact the total pore volume of the reservoir, potentially explaining the lack of substantial recovery increase at this rate. When comparing results from higher injection rates, the cumulative oil production trends remain largely indistinguishable, indi-cating that in a homogeneous reservoir, the choice of cy-clic injection method has minimal effect on overall oil re-covery.

It means that the cyclic injection method does not sig-nificantly affect oil recovery in this homogeneous reser-voir. On the other hand, injection rate and injected pore volume do have an impact on oil recovery. However, the scenario yielding the highest cumulative oil production is not always the most optimal. Analyzing the incremental recovery across different rate scenarios indicates that an injection rate of 90 STB/day, or an injected volume of ap-proximately 1.69 PV, provides optimal recovery

4.4. Model @V_{DP} = 0.2

The second model (Figure 3) represents a slightly het-erogeneous reservoir with a Dykstra-Parsons coefficient (VDP) of 0.2. When observing the bar chart in Figure 8, the results are comparable to those of the homogeneous res-ervoir model, showing minimal differences in cumulative oil recovery across the various injection methods when tested at the same rate. This similarity indicates that, at this level of heterogeneity, the choice of injection method alone does not significantly impact oil recovery outcomes.

However, the data suggest that both injection rate and the volume of injected water do influence oil recovery for this slightly heterogeneous model. Additionally, the cumulative oil recovered is lower than that achieved in the ho-mogeneous reservoir model. This observation under-scores a general trend: as reservoir heterogeneity in-creases, the efficiency of oil recovery tends to decrease. Consequently, this finding highlights the need to consider reservoir heterogeneity when optimizing injection strate-gies, as even slight heterogeneity can reduce overall oil recovery potential.

4.5. Model @V_{DP} = 0.5

The buildup model with a Dykstra-Parson coefficient (VDP) of 0.5 represents a very heterogeneous reservoir, with permeability values ranging from 70 to 700 mD. The simulation results, as shown in Figure 9, differ significantly from the previous model. At each injection rate, the cyclic in-jection method generally achieves better oil recovery than the continuous injection method, except at lower rates of 10 and 30 STB/day. At an injection rate of 50 STB/day, the benefits of the cyclic injection method over the continu-ous method begin to emerge clearly. This suggests that to achieve greater oil recovery, a higher injected pore vol-ume is necessary.

The large variation in permeability within the reservoir affects how pressure and fluid distribution occur during water injection. High permeability contrasts can cause reservoir pressure to become unevenly distributed, lead-ing to areas where injected water does not effectively displace trapped oil. A potential solution to this issue is the application of a depressurization cycle, where the injec-tion well is temporarily shut off. When injection stops, high-pressure fluids within the reservoir can redistribute, allowing the fluid trapped in smaller pores to migrate to-ward regions of lower pressure.

Moreover, during depressurization, oil viscosity de-creases if the pressure is above the bubble point pressure, while the viscosity of water remains constant. This viscosity reduction enables oil to flow more easily from the smaller reservoir pores than water, which improves overall oil recovery. Thus, the combination of cyclic injection and depressurization cycles offers an effective strategy for enhancing oil displacement in a highly heterogeneous reservoir.

4.6. Model @V_{DP} = 0.8

The buildup model @VDP=0.8 represents the extremely heterogeneous reservoir. The simulation results in Figure 9 outcomes differently. In each rate variables, the cyclic method 1:1 gives the highest recovered oil except at the rate 10 and 30 stb/day. At the 10 stb/day and 30 stb/day, there are no significant recovery that distinguished for each method because at that rate, the pore volume in-jected is insufficient and far from 1 PV. Therefore, the ef-fect of water injection rate or cyclic period was not visible.

The sensitivity of cyclic period has noticeable effects on oil gain when the rate is above 50stb/day and injected volume 0.59PV. At CWF method, higher pore volume in-jected performs higher oil recovery in cyclic waterflood-ing.

It can be seen that in a higher-level heterogeneity of reservoir condition, a higher rate and pore volume in-jected will not always increase the oil cumulative as in more homogeneous reservoir. In this VDP model, contin-uous injection scenario gained the smallest cumulative oil. That's because water movement is not uniform to displace oil in every grid, especially in low permeability cells. The difference of fluid movement affects to pressure changes distribution. In the lower permeability grid, may occur higher pressure. It seems like a "bottle-neck" effect. The oil flow is a function of relative permeability and pressure each region.

By comparing each VDP value, it is clearly seen that higher level of reservoir heterogeneity are increasingly affected by cyclic waterflooding method. It is because af-ter pressurized period, there is a shut-in period when it is time to distribute pressure uniformly. Increasing pressure in the higher permeability leads lower viscosity which means easier to flow. Those mechanism able to explain why the more injection period performed the lower oil production such as 1:1 period compares to 2:1, 3:1 and 4:1.

Adding shut-in period by 2:2 gives a better response than 2:1, 3:1 and 4:1 but still lower than 1:1. It is because the shut-in period must be able to compensate the in-creased pressure which will be distributed to other cells.

6. Conclusions

Through did sensitivity of injection rate, continuous waterflood method, period of cyclic waterflooding, there are some important points can be found through this re-search. Homogeneous reservoir responses almost equal on oil recovery for each method (the same rate and the same amount of PV injection). It may due to the pressure distribution on the grid model are almost uniform related to permeability. Higher of Dykstra-Parson variables lowered oil recovery in every water injection method. Oil displacement seems like a bottle-neck when the permeability be more heterogeneous between cells. Cyclic waterflooding performs better gain on oil recovery than continuous water injection in heterogeneous reservoir. This is due to the shut-in time when the reservoir pressure decreases. Decreasing pressure in the system induces trapped oil saturation in lower permeability which higher pressure comes out. Then the pressure profile seems almost uniform during shut-in period. Decreased pressure during shut-in period leads lowered oil viscosity which means oil flow is easier. This condition is happened to under saturated oil reservoir. In cyclic water injection, the longer injection period does not imply on improving oil recovery. The method of 1:1 period was observed to be the best scenario in heterogeneous reservoir model (VDP > 0.5). The period of 1:1 method efficiently allows for the mechanism of oil recovery that has been described earlier.

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