Waterflooding Management: Challenges and Solutions During the Injection Process to Obtain Effectively and Environmentally Based Oil Recovery in Oil and Gas Industry

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Abstract. Water is an important element for every creature in the earth. Almost 70% of earth surface is covered by water. Since 1974, not only contribute to life, water also can be used in oil and gas industry, to improve the oil recovery through waterflooding. Waterflood now became one of oil enhancement methods that often applied in oil field because it’s proved effective can enhance the oil recovery with minimum impacts to ecology and environment. However, the use of water in oil and gas industry requires comprehensive understanding about the technical problem and environmental impact during waterflooding process. Hence, in this study a review is carried out on several problems that occur in the waterflooding injection process and provides solutions so as to be able to manage projects effectively and efficiently also considering the environmental aspects.

1. Introduction
In general, the oil and gas field development project have an orientation to obtain the maximum benefit with the existing reservoir conditions. In order to obtain the maximum profit, many problems can happen. Therefore, it is necessary to do management in carrying out an oil and gas field development project to get a significant profit that can be observed from the higher oil acquisition. No exception is also in the process of Enhanced Oil Recovery (EOR).

Currently, waterflooding became one of the common techniques in EOR, as well as pressure maintenance for the reservoir. Waterflooding is an important method in the oil field development in order to increase the economic value of the field. The successful waterflooding project can be done by a comprehensive management strategy to make sure the reservoir pressure stayed above the fluid's level, which leads to maximizing oil recovery also to gain more profitable income.

In the waterflooding injection process, several problems can happen to make the economy of oil field development keep decreasing. Most of it caused by technical issues such as early breakthrough, leak of cement in a casing, or maybe while setting the injection constraints [1]. However, at this time in addition to technical issues, it is also necessary to conduct a study of the impact on the environment such as pay attention to the level of safety and environmental impact or can be called "zero waste management.”. Hence, this study will discuss solutions to several problems in the waterflooding process as an effort to maximize the economy of an oil field development.

2. Theory and Definitions
2.1. Definition and Review of Waterflooding

Improvement oil recovery is the methods used to improve oil production by injecting something into the reservoir. The injected fluid or chemical or thermal could act as displacement fluid and could cause physical, chemical, compositional and thermal changes in the reservoir rock and fluids. By so, the oil in the reservoir can flow easier. When the injected fluid act as displacement fluid, displacement process that could happen is miscible displacement or immiscible displacement.

Immiscible displacement is done to produce remaining oil in the reservoir that still remain after primary recovery by inject the fluids into reservoir. When the injection fluid is water, then the displacement process is called waterflooding. In Schlumberger Oilfield Glossary [2], waterflooding is a method of secondary oil recovery where water is injected into the reservoir formation to displace the residual oil. According to Colomberra, L et al [3] and Medici, G. et al [4], the geological properties of reservoirs are very heterogeneous, and hence permeability significantly spatially vary; could cause some potential problems associated with waterflood techniques. The potential problems include inefficient recovery (due to variable permeability) and early water breakthrough that may cause production and surface processing problems. In Table 1, Kristanto, Dedy et al [5] has summarized the description, limitation, and challenges in waterflooding process to help us understanding the work principal of waterflooding easily.

Table 1. Summary of waterflooding [5].

| Description                  | Most widely used post-primary recovery method |
|------------------------------|----------------------------------------------|
| Mechanisms That Improve      | Water injected in patterns or along periphery of reservoir |
| Recovery Efficiency          | Water-drive mechanism                         |
| Limitations                  | High oil viscosities                         |
|                              | Higher (more adverse) mobility ratios         |
|                              | Reservoir heterogeneity such as stratification, permeability contrast, and fracturing will reduce sweep efficiency |
| Challenges                   | Poor compatibility between injected water and reservoir (it may cause formation damage) |
|                              | Subsurface fluid control to divert injected water and shut off undesirable produced fluids |

2.2. Displacement Concept of Waterflooding

Displacement concept of waterflooding was presented by Wilhite, 1983 [6]. Currently, there are two known of oil displacement concept, piston like displacement and leak piston like displacement. Piston like displacement consider that before the front point, only displacement fluid (water) flows; while after the front point, only displaced fluid (oil) flows. In other words, all of oil zone will be displaced by water. This is an ideal condition where you won’t find in any real case.

![Figure 1. Leak piston like displacement process [6].](image-url)
In the other hand, leak piston like displacement considering before the front point, both displacement fluid (water) and displaced fluid (oil) flows; while after the front point, only displaced fluid (oil) flows. In this mechanism, transition zone will be occurred in form of saturation distribution. The transition zone will move to production well. When the transition zone reach production well, the phenomena called breakthrough. The both displacement concept are illustrated in Figure 1.

2.3. Factors Affect the Waterflood Process

Waterflooding management represents a routine of underperforming injection identification and executing remedial actions to press the interval among technical potential and field actual performance. An analytical estimation and actual performance are observed to ensure the highest increment upon optimization of the injection process. In planning waterflooding, it is necessary to pay attention to appropriate reservoir characteristics so that the waterflooding project can be implemented, among others (Tarek, Ahmed. 1946) [7] as shown in Table 2:

### Table 2. Factors that affect the waterflooding process [5].

| Influencing Factors on Injection | Effect on Injection Process |
|---------------------------------|----------------------------|
| Reservoir Geometry              | This parameter will affect the location of the well |
| Reservoir Fluid Characteristic  | Oil viscosity is an important parameter of fluid properties that influences the mobility ratio of waterflooding |
| Reservoir Depth                 | This parameter affects both technically and economically. The deeper a reservoir, the higher the injection pressure |
| Reservoir Heterogeneity &       | Reservoir heterogeneity & continuity is an important parameter in the location planning and injection well pattern - production. |
| Reservoir Continuity            |                                          |
| Fluid's Saturation              | Large oil saturation will result in large oil recovery which lead the greater the oil saturation at the start of waterflooding |
| Lithology and Rock Characteristic| The physical properties of rocks that influence the success of waterflooding include porosity, permeability, and reservoir net thickness |
| Reservoir Drive Mechanism       | Driving mechanism is related recovery factor and sweep efficiency of waterflooding injection |

3. Methodology

This paper is submitted with reference to the theme of this ISWEE 2020 Session, ‘Challenges on water, ecology, and environment,’ this paper discussed the challenges that happen during the waterflooding injection not just from technical but also from ecology and environmental point of view. This study focuses more on explaining some of the challenges that can occur during the injection process at each stage of operational systems. Method used in this study can be define as follows: First, the challenges are stated, then the background on each of the waterfloods is given, after it we describe how the different waterflood systems approached the challenges, and which is the outcome of these different approaches.

4. Result and Discussion

4.1. Technical Problem of Waterflooding & Solution

Bibars [8] and Hussein [9] has explained challenges in every stage of waterflooding such as unpredicted high-water production followed by a significant reduction of oil production, sand fill, scale deposition, lateral water intrusion, high operating cost, and new technologies are the challenge in waterflooding stages. The study carried out by Dadang Rukmana [10] has summarized lesson learnt for a successful waterflooding implementation in Indonesian oil field. The solution is by optimizing the planning and the monitoring phase of waterflooding. Technical problems and the solutions were summarized in Table 3 and Table 4. There are two key parameters of successful waterflooding in monitoring phase of waterflooding. They are Voidage Replacement Ratio (VRR) and gross up of production wells. The suggested VRR is 1:1, where the injected water volume is equal to liquid production of production wells.
Gross up of liquid production can improve the oil recovery. The question is, when will we do gross up. Dadang Rukmana [10] suggested to do gross up in these conditions:

- Current water cut is at the declivous phase of fractional flow curve
- Moveable oil saturation > 5%
- Reservoir pressure still high (> Pb)
- GOR is low

Table 3. (a) Summary of technical problem and solutions in planning phase of waterflooding [5,6,10].

| Technical Problem | Caused by | Remarks | Solution(s) |
|------------------|-----------|---------|-------------|
| Early Breakthrough (High Water Production) | Reservoir Heterogeneity | Zone with fracture or contrast permeability will reduce waterflooding efficiency | Choose area with low heterogeneity reservoir |
| | High Permeability Zone | High permeability zone will allow water to flow faster | Choose area with low permeability |
| | Poor Cement Bonding | Poor cement bond cause near wellbore channeling, which allows water from aquifer flows into production well | Chan Diagnostic Analysis shows no channeling |
| | Unfavourable Mobility Ratio | Oil with high viscosity will cause fingering | Oil viscosity < 20 cp |
| Late Peak Production | Waterflooding was Done in the 3rd Phase | In third phase, displacement process no longer occurs and oil recovery of the phase is low | Waterflooding Must be Done in the 1st - 2nd Phase |
| | Pressure Reservoir < Pb | If the injection done when the reservoir pressure is less than the bubble point pressure, the gas will be produced first and then the water displaced the remaining moveable oil | Injection at Reservoir Pressure > Pb |
| Pore Plugging | Incompatible Water Injection | Solid content, oil content, and microbial content are the main factor that cause pore plugging | Water Compatibility Test (Table 4.) |
| | Low Permeability Zone | Low permeability zone can cause pore plugging | k > 100 mD with population > 50% |

Table 3. (b).
recovery of the phase is low

| Poor Pattern Connectivity | Poor connectivity means no breakthrough and no oil recovery | Choose area with good reservoir connectivity |
|---------------------------|-------------------------------------------------------------|--------------------------------------------|
| Strong Water Drive Mechanism | Strong Water Drive can cause injected water dilute to the aquifer | Weak Water Drive/Depletion Drive/Gas Cap Drive |
| Poor Cement Bonding | Poor cement bond cause near wellbore channeling, which allows the injected water flow into aquifer | Chan Diagnostic Analysis shows no channeling |

| Table 4. Water compatibility requirements for waterflooding [9,10]. |
|---------------------------------------------------------------|
| **Parameter** | **Limitation** |
| Hard Grain Concentration | < 1 ppm |
| Iron Concentration | < 0.1 ppm |
| Oxygen | 0 – 0.01 ppm (0 ppm is more recommended) |
| Oil content | < 1 ppm |
| Solid Content | < 1 ppm (recommended) |
| | < 5 ppm (allowable) |
| Alkalinity | < 2,000 ppm |
| Silicates | 1/3 times Alkalinity |
| RPI (Relative Plugging Index) | < 3 |
| Microbial Content | < 10³ cell/mL |
| pH | 7 - 12 |
| Turbidity | < 10 NTU |
| Scaling Index | 0 |
| Corrosion Rates | < 2 mpy |

4.2. Environment Aspect of Waterflood

4.2.1. Environment aspect

The waterflood process involve the injection of water into the well. Water used from injection wells commonly from organic and inorganic materials that formed naturally in reservoirs. This is an advantage to maximize oil production and limit any invasion of barrier material into the pay zone. Water produced from a reservoir to be used for the injection will generally be in the form of recycling for use in subsequent injections, this is aimed at reducing costs incurred by the operator. Therefore, Geraci M et.al [11], Corden C et al [12], Love, T et al [13], and Bennion D.B. et al [14] has explained that the environment should be considered because the water used to inject is not always compatible with the ecological and environmental levels of the surrounding area.

From an environmental perspective, waterflood still has a minimal impact on the environment. This happens because the fact is that the waterflood process has done a pretty good process considering this technique is an old technique and of course various developments have been made in its operation to maximize injection performance with minimal risk. Based on the research carried out in “The Environmental Risks and Oversight of Enhanced Oil Recovery in the United States”, the primary environmental impacts of waterflooding (beyond corrosion and leakage risks that are present in all EOR techniques) are related to the large amounts of produced water used and generated by the process, which requires treatment and management. This quantity of water presents increased opportunities for contamination, especially at the surface [15].
Meanwhile, Dadang Rukmana [10], in his book written regarding the classification of injection water quality based on the API spec which can be seen in the Table 4. The quality of injection water is an important component that can affect the success of the injection operation, but it is also an important consideration related to the environmental impact around the well.

4.2.2. Challenges and Development of Waterflood Technology

Although waterflooding now is one of the methods to maximize the production rate, but due to the limitations and drawbacks of waterflood in some cases, there should be an advanced technique to overcome the limitations. Below (Table 5) would be a brief summarize for several advanced technologies in waterflooding injection, as follows:

| Development Technology in Waterflooding | Remarks |
|----------------------------------------|---------|
| Gas Cap Water injection                | This injection process is by injecting water through a gas cap along with a gas injection well to build a wall of water which will separate the gas cap from the oil column |
| Heavy Oil Waterflooding                | On this study, it's proven that by control the injection rates, it can make waterflooding injection be as viable non-thermal EOR, even it can be applied in fields with high oil viscosity |
| Coiled Pipeline                        | Using of coiled pipeline to minimize the cost, easy installation, and promising pipe capabilities to inject water into produced well |
| Satellite Waterflood                   | Satellite waterflooding is unique methods which it can inject water into small reservoirs to minimize the risk in the marginal field nor be used as a pilot project prior to full scales in the field |
| Smart Waterflooding/ Low Salinity WF (LSWF) | Advanced, or smart waterflooding is a term denoting directed alteration of the ionic composition of the injected brine in order to achieve a better oil recovery, in particular, the low salinity flooding |
| Water Alternating Gas (WAG) injection  | WAG injection is a method that combines the effect of the advantages of water and gas flooding. Both microscopic oil displacement and sweep efficiency can be improved by WAG implementation (Surguchev et al. 1992) |

Besides, the challenges of waterflooding can also come from surface treatment, here are some advanced techniques to solve the problems that are related to surface treatment, following examples as shown in Table 6:

| Innovative Solution in Injection Planning | Remarks |
|------------------------------------------|---------|
| Injection Source and Vertical Transfer Well | Transfer the water from the source water zone to the oil zone which has been already depleted by modifying the completion of the existing water injection into a vertical shape or can be called "vertical transfer well" |
| Gel Conformance                          | Using of the crosslinked polymers into the injection water to be more viable workover toll for the enhancement of reservoir performance during injection |
| Reservoir souring                        | Injection water treatment technique to reduce the H2S contains to prevent corrosion |
| Environment Protection from Oily Waste Water | An advanced method to reduce the oily waste water to achieve more environmental based enhanced oil recovery by waterflood |
5. Conclusion
Waterflooding project must consider the three essential factors: engineering, experience, and economics. These factors must go through a comprehensive engineering study and evaluation before the project is undertaken. Waterflooding management represents a routine of underperforming injection identification and executing remedial actions to close the gap between technical potential and actual performance. An analytical estimation and actual performance are observed to ensure the highest increment upon optimization of the injection process.
Successful waterflood management can efficiently lead to maximize the overall sweep efficiency also gain more production by maintaining the reservoir pressure above the fluid's level, which allows for more production rate levels. This paper suggests the application of a predictive means of waterflooding management as a possible means of evaluating and controlling the problems during injection looked from the technical, economic, and environmental aspect

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