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Full Length Article

Numerical simulation study of factors affecting relative permeability modification for water-shutoff treatments

Dheiaa K. Alfarge [a], Mingzhen Wei [b,*], Baojun Bai [b]

[a] Iraqi Ministry of Oil, Missouri University of Science and Technology, United States
[b] Missouri University of Science and Technology, United States

HIGHLIGHTS

- Identified eight parameters influencing RPM treatment performance.
- Provided the guidelines to select the best candidate well for RPM treatments.

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ABSTRACT

Polymer solutions and gels are frequently used to control excessive water production in oil and gas wells by reducing the permeability to water flow to a greater extent than to oil or gas flow (Relative Permeability Modifiers, RPM, or disproportionate permeability reduction, DPR). RPM and DPR can be used as synonymous in this study; however, specialists use RPM term for the cases in which permeability reduction is less compare to DPR. The significance of RPM agents, chemicals using in water-shutoff treatments, is that their placement does not require mechanical isolation. However, the performance of RPM treatment is still poor in field applications. This study applied numerical simulation methods to investigate the factors impacting RPM treatments on reservoir (Macroscopic) level. Furthermore, Design of Experiments (DOE) was used to rank these factors based on their influence on RPM performance (water cut reduction and oil recovery improvement).

The results indicated that there are nine parameters which can enhance or downgrade the success of DPR treatments, treatments at oil/gas wells when use of DPR polymer or gel results in Disproportionate Permeability Reduction of treated formation. The performance of DPR treatment was more pronounced at low oil density, low oil viscosity, high gel penetration depth, and at high permeability heterogeneity among layers (linear flow is more dominated). However, the performance of DPR treatments was downgraded if the treatments were applied at high production flowrate, low ratio of residual resistance factor for water (Frrw) to residual resistance factor for oil (Frro), and high G-shape (crossflow indicator) values. Moreover, when the capillary forces dominate the flow (capillary-viscous number > 10), RPM results were not largely encouraging due to water blocking effect. On the other side, in the viscous dominated flow, RPM performance was more pronounced. These factors which were studied in this work can promote a short-term successful remedy, a long-term successful treatment, or even a failed treatment. Some of these factors can be controlled; the operator can choose the optimum level of the parameter, like production flowrate. However, other factors cannot be controlled, but the value of this study is still increase probability of success the treatment prior to field application.

1. Introduction

Excessive water production makes reservoir life shorter and worse economically due to corrosion of tubulars, fines migration, environmental damage, low oil recovery, and hydrostatic loading. Hill et al. [56] estimated the total cost associated with separation, treatment and disposal of produced water at $50 billion annually which urges most specialists to find appropriate solutions for excessive water production. Generally, different solutions for water production control in oil and gas reservoirs were suggested according to the source and reason of produced water in hydrocarbon reservoirs [30]. The reasons causing excessive water

* Corresponding author.
E-mail address: weim@mst.edu (M. Wei).

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Nomenclature

ADMAX	Maximum Adsorption Capacity, lbmole/ft3
DOE	Design of Experiments
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DPR	Disproportionate Permeability Reduction
Frro	Residual Resistance Factor for Oil Phase
Frrw	Residual Resistance Factor for Water Phase
Gshape	Cross flow indicator
K	Permeability
K1/K2	Ratio of High-Permeability Zone to Low-Permeability Zone
KH	Horizontal Permeability
kV	Vertical permeability
Perm-k	Vertical Permeability
Qo	Oil Flowrate (STB/day)
RPM	Relative Permeability Modifiers
RRFT	Residual Resistance Factor for the Adsorbing Component in Rock Type
SCTR	Sector
VE	Vertical Equilibrium

production are commonly due to mobility issues, fractures, high-permeability channels, or heterogeneous features which provide preferential paths with least resistance to the fluid being injected to sweep hydrocarbons, and lead to an early breakthrough for displacing phase. The usual solution for these problems and to maximize the swept areas is to place sealants or blocking agents in the least resistance paths. Polymer, gels and other types of conformance materials are common examples of permeability-reducing agents that can fill fractures and high-permeability channels through injectors or producers to generate flow diversion and increase sweep efficiency [54].

It is known that the gel treatments can be conducted in three locations of hydrocarbon reservoirs: a) injection wells which is called injection profile control, b) production wells which is called water-shutoff, and c) in depth of reservoir which is called in-depth diversion process. Each method has its advantages and disadvantages. However, the main advantage of water-shutoff treatments is the immediate response, while its disadvantages are low success rate and the risk to damage oil zone [55].

One of the critical methods used in production wells as a water-shutoff treatment is called Disproportionate Permeability Reduction (DPR) or Relative Permeability Modifier (RPM). This terminology came from noticing the ability of polymers and some gels to reduce the permeability to water flow (Krw) to a greater extent than to oil or gas flow (Kro or Krg). The DPR property of gels and polymer has a significant role in many of hydrocarbon reservoir cases especially when mechanical isolation process is difficult to be performed during gel placement process [41]. However, there is a clear disagreement among the investigators about the main mechanism beyond DPR behavior. This disagreement led to the lack of understanding for this property and resulted in absence of a standardized method to predict DPR performance in field applications. A brief description about these mechanisms would be introduced since the discussion of the DPR mechanisms details are out of this study scope. The objective from this study is to form a prediction methodology for DPR success or failure depending on reservoir and well candidate conditions. In addition, this study would give details about the factors which impact DPR performance on reservoir level (macroscopic level) and how to select the best candidate well.

2. Disproportionate permeability reduction

DPR is the property which some polymers and weak gels crucially have for reducing the permeability to water to a greater extent than to oil or gas flow [9,10,60,44,65,28,11,41]. Water-shutoff treatment by using DPR fluid is interestingly effective for reducing water production in production wells which cannot be generally treated with conventional methods like mechanical isolation [21]. Although Seright [28] reported different types of gels which produce DPR property, the performance of DPR treatments in field applications have a high ambiguity. However, [44] reported significant successful jobs in field applications which used DPR fluids in Mid-Continent Region for water-shutoff purposes. Therefore, it is clear that there is a lack in understanding the behavior of DPR treatments on macroscopic level. This study indicated that carefully selected-candidates, wells and reservoirs, are the critical point to give a successful DPR treatment.

3. A critical review about DPR mechanisms

The ability of polymers and some gels to reduce the permeability to water to a greater extent than to oil or gas flow urges different researchers to investigate why these chemical agents produce this behavior. Many previous investigators tried to explain different mechanisms for DPR agents. However, our literature review came with ten proposed mechanisms by different investigators, but no agreement among the previous investigators on a unique mechanism. Although some researchers think DPR resulted from a combination of two or more from these ten mechanisms; another opinion said that DPR property could be caused by hysteresis effect because types of fluids are changing in the reservoir formation before and during gel injection. However, [20] concluded that hysteresis has not effect to produce DPR behavior. The goal beyond focusing on identifying the correct DPR mechanism is to help in understanding and predicting the behavior of this treatment in production wells. Also, if the correct mechanism has been known, this would help to improve this treatment more by improving its mechanisms. Table 1 summarized the proposed mechanisms with their investigators, proposal of each mechanism, the opinions which conflict with, and the weak points in each one. These results regarding DPR mechanisms are solely based on the review and analysis for different resources from lab works and field applications which have been reported by different investigators. It is clear that the conditions which had been used by the investigators are different from each other, but we tried to explain the strength of each mechanism depending on their weak points and the physically-based strength. Depending on the critical review conducted, the segregated pathway mechanism is the most acceptable one; therefore, this mechanism would be simulated in this study.

4. Numerical simulation methodology

STARS simulator ([53]), one of the CMG packages, was used to simulate creating a DPR chemical agent. Since the most common mechanism for DPR is segregated pathways mechanism [44,19,39], this mechanism was represented in this work by penetrating the gels to the water zone deeper as compared to the oil zone. The cases which were modeled in this work are heteroge-