IMPACT OF INJECTION WELL FRACTURES ON WELL INJECTIVITY AND RESERVOIR SWEEP IN WATERFLOODING AND ENHANCED OIL RECOVERY

by

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REPORT

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ABSTRACT

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Water injection is widely used to maintain reservoir pressure and to displace bypassed oil from unswept zones. During the water injection process, deposition of suspended solids and oil droplets at the wellbore zone leads to a decline in well injectivity. Hence, an increased injection pressure is required to maintain a given injection rate. If the increase in the injection pressure is such that it exceeds the minimum horizontal stress within the formation rock around the wellbore, fractures are initiated in the adjacent formation. If the temperature of the injected fluid is different from that of the formation, a thermal front propagates from the injection
well. This change in temperature causes the rock to contract or expand, thereby altering the stresses both in the region of changed temperature and in the surrounding rock. For example, injection of cold water into a high temperature reservoir can induce thermal stresses in the near wellbore region, which facilitates fracturing. The above two processes, pore plugging and changes in the temperature of the rock, are the main mechanisms that drive injection well fractures.

To maximize the oil recovery the consideration of fracture growth rate and fracture orientation is essential. The extent of fracture growth and the fracture orientation significantly affects the sweep efficiency for given well pattern. Therefore, in the reservoir with complicated well patterns, the optimum fracture growth rate and fracture orientation is essential in maximizing the oil recovery. The appropriate selection of injection rate and the knowledge of particle concentration of the water and the temperature of the water are key factors necessary to determine the optimum fracture growth rate.

Therefore, the accurate oil recovery simulation should include the detailed description of the fracture growth during the water injection. However, there is no reservoir simulator which explicitly considers fracture growth during the simulation so far. The usual simulator considers just the fixed fracture in the reservoir. However, because the fracture grows continuously as the injection of water progresses, a proper consideration of the fracture growth is necessary in the process of reservoir simulation.
To add the explicit accounting of the fracture growth to the reservoir simulator will be the initial focus of my thesis research, as I describe it in the method for conducting research. After completing the combination of two simulators (single-well fracture growth simulator and reservoir simulator), the optimum fracture growth rate, optimum fracture orientation and optimum properties of injected water can be obtained by a sensitivity study.
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1. Research Objective

The primary objective of this research is to determine the impact of fractures and complex wells on oil recovery achieved by water flooding and Enhanced Oil Recovery (EOR).

This research objective will be met by simulating the growth of fractures in water injection wells as well as polymer injection wells. The approach that we intend to follow is to develop analytical and numerical models for fracture growth in injectors. We then proposed to combine single well models (UTWID) with reservoir simulator (UTCHEM or GEM) so that the physics of fracture growth can be modeled accurately in the single well models while the reservoir architecture can be incorporated in the reservoir simulator. Models will also be developed for deviated and horizontal wells. These models will incorporate the effects of complex fluid rheology (shear thinning and viscoelastic effects) as well as thermal stresses induced by fluid injection and particle plugging effects due to solids and oil droplets in the injected fluids.

The results of this research will provide clear understanding of the impact of both hydraulic fractures and dynamically growing injection well fractures in both producers and injectors. Simulations will also help to identify conditions under which
complex wells and fractures may be used to accelerate oil production in water
flooding and EOR processes.
2. Review of Relevant Literature

The effect of hydraulic fractures of constant length on oil recovery and injectivity has been investigated in detail in the past. Improvements in injectivity of a factor of 2 to 5 are computed and observed in the field. Wang et al. (1970) showed that the creation of fractures in injectors can accelerate oil production but can also lead to early water breakthrough in water flooding applications.

In 2001, Gadde et al. combined single injection well simulator with reservoir simulator and for the first time simulated oil displacement efficiency in systems where the fracture length was increasing with time. The physics of fracture growth was modeled consistently by taking into account thermal stresses as well as particle plugging effects. Single well injection model (UTWID) was combined with a three dimensional chemical flooding simulator (UTCHEM) to capture the effects of fracture growth rate, fracture orientation and reservoir properties on oil recovery. This study was designed to investigate the impact of growing injection well fractures on water flood performance and reservoir sweep. Deviated or horizontal wells were not considered. The injection of reologically complex fluids such as polymers was also not included in this investigation. In addition, the study was limited to water flooding applications.
Pang et al. (1997) investigated the modeling of the injectivity decline in water injection wells. The reason for fracture generation is the injectivity decline due to the particle and oil droplet in the water. The fracture growth rate and its relation with injection rate and the concentration of the injected water are shown in this paper. Also, the concept of the transition time was proposed in this paper at first. The transition time means the time at which no more particles invade the rock, the time at which the initial layer of external filter cake is completely formed. The concept of transition time makes the filtration models suggest both internal and external filter cakes for the first time.

Barkman et al. (1972) proposed the water quality ratio which is the concentration of suspended solids to the permeability of the filter cake formed by those solids. It can be used to calculate the rate of formation impairment.

Perkins and Gonzalez (1985) investigated the mechanism behind how the temperature difference between injected water and reservoir should affect the thermoelastic properties in the reservoir and how it affects the fracture growth as water is injected. For typical water flooding of a moderately deep reservoir, horizontal earth stresses may be reduced by several hundred psi.

Peaceman (1983) investigated the interpretation of well-block pressures in numerical reservoir simulation with anisotropic permeability. The interpretation of
well-block pressures could be progressed even though the grid blocks were not square and the permeability distribution was not isotropic.

Stenebraten *et al.* (2002) investigated experimentally the growth of the injection well fractures using large block tests. They showed clearly that the growth of the fracture was closely related to particle plugging of the fracture face. The injection of plugging particles significantly increases the fracture growth rate. In periods of clean water injection, the fracture does not grow. Most of the injected particles were found to be trapped within a very short distance from the face of the fracture and near the tip of the fracture. Despite of plugging of the fracture face by particles, the injectivity remains constant over long periods of time.

Wang *et al.* (2007) established the optimum polymer formulations, injection rates, and individual well production allocations, and time-dependent variation of the molecular weight of the polymer used in the injection slugs. Because of the economic problem, the optimal time to change frac-fluid from polymer to water or low molecular weight polymer should be determined.

In summary, particles in the water injection can plug in the fracture face during water injection. Hence, an increased bottom hole injection pressure is required to maintain a given injection rate. Due to the increased bottomhole pressure, a fracture can be generated in the formation.
Also, the temperature of the injected water affects the hydraulic fracturing. Usually, the temperature of the injected water is lower than the temperature of the formation. Due to the temperature difference between the injected water and the formation, the horizontal earth stresses may be reduced by several hundred psi. With injecting water and particles in the water, hydraulic fracturing generates easily as a result of reducing horizontal earth stresses. This is termed ‘thermally induced fracturing’.

Fracture orientation and fracture growth rate play important roles in determining the maximum production rate and ultimate oil recovery. Growing fractures from the injection well in the direction of the producer results in premature water breakthrough. On the other hand, the fracture toward the space between two producers makes the sweep efficiency higher. In other words, the orientation of the fracture growth may result in different sweep efficiency depending upon the orientation of the fracture relative to the position of the injection wells.

To show the effect of the orientation of injection well fractures, two different well positions can be considered. The first case is when the injection well fractures are growing directly towards the producers. The second case is when the orientation of the injection well fracture lies between the producers. The second case in which the orientation of the injection well fracture lies between the producers is better because the first case results in poor sweep and premature water breakthrough. This
means that the water could not sweep the oil in the reservoir and there is a substantial amount of remaining oil in the reservoir after water flooding.

Whether fracture growth rate increases the oil recovery or not depends on the fracture orientation. In the case of favorable fracture orientation, which means the fracture lies between the producers, the poor sweep area by the flood front results in lower oil recovery due to slow fracture growth. As fracture growth rate increases, the ultimate oil recovery is increased. On the other hand, there is unfavorable fracture orientation case, which means the fractures are growing directly towards the producers. In the case of really slow fracture growth, the situation is the same as the favorable fracture orientation case. However, too high fracture growth results in premature water breakthrough, the worst case.

To date, no fracture simulator has considered dynamically growing fractures in EOR processes. This research proposal aims to develop a simulator for fracture growth and injection wells and combine it with the reservoir simulator to predict the performance of EOR processes and water floods in reservoirs that contain fracture injectors and producers. The effective important parameters such as water quality, water temperature, reservoir properties, injection and production well patterns, orientation of fractures, and the placement of horizontal or deviated wells will be considered in the simulations. These simulations will help us to devise optimum injection schemes and well placement strategies for water flooding and EOR
processes so that the time to first oil can be reduced and reservoir sweep can be maximized.
3. Method for Conducting the Research

Task 1: Impact of static fractures on reservoir sweep and injectivity

The first set of simulations that we proposed to conduct are in simple reservoir patterns such as a 5 spot, a line drive and an inverted 5 spot with both unfractured and fractured injectors and producers. In these simulations the fracture length will be held constant with time. The oil recovery versus time and the injectivity will be compared for the different cases as a function of fracture orientation, fracture length and reservoir properties.

Task 2: Derivation of analytical and numerical models

Analytical and numerical models will be derived for fracture growth in polymer injection wells. These models will be based on earlier models developed for water injection wells for vertical and horizontal wells. It is expected that the polymer rheology including shear thinning and viscoelastic behavior will play an important role in these models and simulation results. The models will include residual resistance factors for the polymer as well as particle plugging and thermal effects that may be important. The model will be implemented in a numerical single well model, UTWID that currently simulates water injection into vertical and horizontal injectors.
Task 3: Combining a single well model for injectors with reservoir simulator

Single well injector model that accounts for fracture growth will be combined with a reservoir simulator (UTCHEM 9.9 and GEM). The proposed strategy for combining these two models is shown in figure 1. Key variables from the reservoir simulator such as simulation time, average reservoir pressure, and reservoir properties will be transmitted to the single well injector model which will then compute the fracture length based on the physics of fracture growth for both water injection and polymer injection. The computed fracture length will be used to repopulate the transmissibility matrix for the reservoir simulator so that the new fracture length can be incorporated into the pressure profile and sweep calculations. Similar approach was followed by Gadde (2001) for water injection into vertical wells. Incorporating more complex well geometries, such as horizontal wells and polymer injections into this scheme will pose some challenges.
Combining two simulators in this manner can be accomplished not only for homogeneous reservoir, but also for heterogeneous reservoir. A reservoir with heterogeneous permeability and porosity distribution could have different fracture half lengths in different layers or on the opposite sides of the fracture. When the reservoir has the different permeability and porosity from each layer, the degree of sweep and the length of the fracture should be different from each other. As a result, the oil recovery is not as simple as for a homogeneous reservoir. Also, when the reservoir properties are different for each layer, the fracture half length should be different at each layer as well more accurate simulation could be conducted by
combining two simulators. Unlike the static fracture reservoir simulators, the combination of two simulators could show the effect of the growing fracture with different reservoir properties in each layer and direction.

After completing the combination of two simulators, the optimum fracture length and orientation can be obtained. Also, the location of injectors and producers will be considered. The variables that could be changed easily are the injection rate and the concentration of solids in the injected water. The fracture growth rate is a function of the injection rate, the temperature of the injected water and the concentration of solids in the injected water. The fracture orientation will be changed by altering the location of the producers. By changing the location of the producers, the effect of the fracture orientation at each injection rate and concentration of the injected water could be investigated. Similarly, the temperature of the injected water will be changed and a sensitivity study for the temperature of the injected water will be done. Finally, the optimum well pattern, spacing and injection rate will be determined according to the reservoir properties.

A comparison will be made of vertical versus horizontal wells for different reservoir geometries. Fracture growth in both types of wells will be studied to determine when it may be appropriate to fracture these injection wells and when fractures and producing wells would be desirable. The well spacing and well pattern
for maximizing reservoir sweep and injectivity will emerge from these simulation results.

Task 4: Simulation of EOR processes with fractured injectors and producers.

Surfactant and EOR process using surfactants and polymers will be simulated to study the impact of fractures in injectors and producers. Both static and dynamic fractures (fractures growing with time) will be studied. Vertical and horizontal wells will be investigated to see how the time to first oil can be minimized and the reservoir sweep maximized. It is expected that the formation of an oil bank in injection wells and production wells are fractured will yield significantly different results than cases where no fractures are present. The properties of the surfactant as well as polymer will be varied so that the mobility ratio can be changed and the effect of the mobility ratio can be clearly seen. To the best of our knowledge, this will be some of the first systematic simulation of EOR processes using injectors and producers.

Task 5: Comparison of laboratory and field data

The results of the simulation from the combined model will be compared with results obtained in EOR pilots conducted in the past. It is anticipated that these results will primarily be for cases where no fractures are present. However, there have been some recent reports of polymer injection field studies which have resulted in very
high injectivities presumably due to the creation of fractures. An attempt will be made to compare the simulation results with the field results for both unfractured and fractured injection wells. The advantage or disadvantage of using horizontal wells with and without fractures will be studied for specific instances in the field where EOR processes are proposed to be used.
4. Preliminary Results

Before combining the injection well simulator with a reservoir simulator, some simple cases of water injection will run to investigate the role of fracture length on reservoir sweep efficiency. All of these simulations were to investigate the impact of static fractures with constant length on oil recovery.

Two patterns were chosen for the simulations. Figure 2-A. shows a fracture oriented in an unfavorable direction so that the injected water migrated directly towards the producers. Whereas Figure 2-B. shows a 5 spot pattern with a favorable fracture orientation with the fracture propagating away from the producers.

![Figure 2-A: Five spot injection pattern with unfavorable direction of fracture](image)
Figure 2-B: Five spot injection pattern with favorable direction of fracture

Figure 3 shows the cumulative oil recovery normalized with the original oil in place (OOIP) as a function of time for three different injection rates for an unfractured well. The injection rate determines the oil production rate. However, the cumulative oil recovery does not depend on injection rate. Figure 4 shows the same results for three different well spacings for an unfractured well. The cumulative oil recovery normalized with the original oil in place does not depend on the well spacing. The time to reach the maximum production changes only as the well spacing changes.
Figure 3: Effect of injection rate on dimensionless production

Figure 4: Effect of well spacing on dimensionless production
Figure 5 and 6 show the effect of static fracture length and mobility ratio on oil recovery. As the following figures show, the oil recovery is increased as mobility ratio increases and as fracture length is decreased. The mobility ratio shows that the mobility of the displacing material should be higher than that of the displaced material to get the high oil recovery. This concept is used for increasing oil recovery by polymer flooding as polymer flooding is used due to the high viscosity of displacing material. Also, the reasons for lower oil recovery in a longer fracture are early water breakthrough and poor sweep efficiency.

Figure 5: Effect of fracture length and mobility ratio on dimensionless production
Figure 6: Effect of fracture length on dimensionless production
5. References


