On the evaluation of steam assisted gravity drainage in naturally fractured oil reservoirs

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1. Introduction

Enhanced Oil Recovery (EOR) is a promising improvement technique for oil production. Application of EOR methods on oil fields has received a significant attention due to the increase of oil price as well as oil consumption, in recent years \(^{[1,2]}\). Average oil recovery factor for most of oil fields is less than 40\%. This means that a large amount of Original Oil in Place (OOIP) remains entrapped in host reservoir rocks \(^{[3]}\). Based on the type of reservoirs’ rock and fluid type, different EOR methods should be
implemented on oil fields to extract more oil and increase recovery factors [4,5]. Chemical, gas injection, water flooding and thermal methods are the main EOR categories. In general, thermal methods are applied on heavy oil reservoirs to increase the oil mobility ratio and pushing more oil towards producing wells. In spite of huge amount of heavy oil resources, the recovery factor of these reservoirs does not normally exceed 10% implementing primary and secondary recovery; therefore, applying thermal methods on these fields, provides more oil production and recovery factor.

Huge amount of global heavy oil resources exists in carbonate reservoirs which are mostly naturally fractured reservoirs. Global oil consumption in recent years reveals the importance of fractured reservoir development for the future of oil supply. Different thermal methods are being employed in heavy oil production including, Continuous Steam Injection [6,7], Cyclic Steam Injection [8,9], In-situ Combustion and Steam Assisted Gravity Drainage (SAGD) [10–12]. Complexity of fractured reservoirs reduces the efficiency of classic steam injection methods. One of the most efficient thermal methods used in heavy oil recovery and bituminous sands is known as Steam Assisted Gravity Drainage which was invented by Butler in the 1970s [13]. This method which benefits from a pair of injection/production horizontal wells ensures a stable and uniform expansion of steam, resulting in economical oil production rates [11]. During the process, the heated oil moves approximately parallel to the steam-saturated zone interface, called steam chamber [14]. The entrapped oil due to more contact with steam, exchanges heat with the steam more efficiently, leading to a considerable reduction of oil viscosity and better oil displacement in reservoir rock. As it is well-known, viscosity plays a key role in any EOR process [15–18]. Fig. 1 schematically illustrates the SAGD mechanism. In the first stage, the steam chamber rises vertically in the reservoir rock; and oil production increases steadily [19,20]. In the next stage, after the steam chamber touches the top of the reservoir, lateral expansion of steam chamber begins and this expansion starts controlling the oil production. Although SAGD is an assuring method for fractured reservoirs especially for those with heavy oil reservoirs, few studies have been carried out to investigate the applicability of this method in these types of reservoirs.

Study of SAGD method can be conducted in two main approaches including investigation of reservoir parameters and investigation of operational parameters. Reservoir parameters are the main criteria in selection of EOR methods [4]. In naturally fractured reservoirs, fracture characteristics such as fracture orientation, fracture permeability and fracture size and spacing have important roles in selection of SADG method. Therefore, fracture characteristics as well as reservoir parameters need to be investigated. Bagci [21], through an experimental and numerical study on SADG process in conventional and fractured models, found that the shape of steam chamber in fractured models is elongated, while the conventional steam chamber is almost round. Nasr et al. [22] investigated the effect of vertical permeability in CDOR (calendar day oil rate) and SOR (steam oil ration), and found that the reduction of vertical permeability produces a remarkable decrease in CDOR and SOR. Sola and Rashidi [11] studied the effects vertical and horizontal fractures on SAGD performance. They stated that an increase in vertical fracture density causes the steam chamber to inflate more effectively, while the rise of the level of horizontal fractures adversely affects steam chamber expansion. Chen et al. [23] also investigated the effect of heterogeneities including vertical and horizontal fractures. They came up with the conclusion that the case of vertical fracture produces more oil in the first stage of production than any of horizontal fracture and base case. Laguno et al. [24] performed a study on SAGD screening methodologies and found that accumulation parameters (porosity, thickness, oil saturation) have more impact on SAGD performance than fluid parameters (permeability, oil viscosity, reservoir pressure and API). Several other studies have been carried out on the effect of oil pay thickness on SAGD performance; all of the investigators unanimously, stated that the higher the reservoir thickness, the better the SAGD performance [25–27]. Shanqiang and Baker [28] reported that an increase in API results in a decrease in SAGD performance. Very recently, Hashemi-Kiasari et al. [29] showed that reservoir dip adversely affects SAGD performance due to overriding effects.

Several studies have been carried out to identify the effects of operational parameters on SAGD performance. Gates and Chakrabarty [30] observed that the quality of injected steam should be as high as possible due to the fact that any condensate in the injected fluid that drops due to gravity from the injector approaching the producer and through this cause an insignificant quality of heat to be sent to the oil sand. Ong and Butler [31] investigated the effect of well length and found that it does not have significant impact on gravity head in comparison with well size. Very recently, Hashemi-Kiasari et al. [29] reported that in thin reservoirs injector/producer and injector/top of the reservoir spacing, need to be optimized to get the best performance. More details about the effect of operational and reservoirs parameters on SAGD were thoroughly reviewed elsewhere [29].

Unlike clastic reservoirs, very few studies were conducted to identify the performance of SAGD in carbonate reservoirs. Although SAGD is a highly promising technique, many uncertainties and unanswered questions still exist and they should

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**Fig. 1.** Essential feature of the SAGD process [19].

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be clarified for expansion of SAGD methods to world wide applications especially in naturally fractured reservoirs [29]. This study aims to investigate the effect of some operational and reservoir parameters on SAGD processes in naturally fractured reservoirs, which were not yet fully examined. In fact, the purpose of this study is to investigate the role of fracture properties including fracture orientation, fracture spacing and fracture permeability on the SAGD performance in naturally fractured reservoirs. In this study by observation of steam chamber expansion during the process and production profile, these features of fracture are analyzed. Moreover, one operational parameter is also studied; one new well configuration, staggered well pair is evaluated.

2. Reservoir description

The reservoir model in this study is a 3-D rectangular model and the simulator used in this study is Computer Modeling Groups (CMG), Steam and Thermal Advance Reservoir Simulator (STARS). Peng-Robinson78 equation of state (EOS) was used for PVT and thermodynamic modeling. Phase behavior data as well as EOS phase behavior are generated by Winprop module of CMG. The base model is rectangular reservoir with dimension of \(210 \times 100 \times 90\) ft and grid number of \(21 \times 10 \times 10\) cell in X, Y, Z coordinates. Average porosity and permeability, irreducible water saturation and residual oil saturation were set at 0.20, 2000 md, 0.15 and 0.25, respectively. Formation thermal conductivity and rock heat capacity were assigned 24 Btu/ft\(^3\) F and 30 Btu/Day ft\(^3\) F. Oil viscosity at the reservoir temperature, 140 °F, is about 2000 cp. The oil density, gas oil ratio (GOR) and oil volume formation factor \((B_o)\) at reservoir condition (140 °F and 1200 psi) are 61.5 lbm/ft\(^3\), 67 SCF/STB and 1.05 bbl/STB, respectively. Reservoir properties are shown in Table 1.

In this model, one horizontal injector/horizontal well pair with 36 ft vertical spacing is located at the bottom of the model. Fig. 2 illustrates the 3-D view of well locations. The injection scenario is based on a constant total injection rate of 1000 stock-tank barrel per day (STBD) cold water equivalent (CWE) for field during 10 years. The maximum injection pressure is set at 1220 psi (corresponding maximum temperature is set at 600 °F). The minimum pressure of production well is set at 1150 psi (50 psi less than reference pressure at the bottom of model), and steam quality is assumed 0.9. The designed period of preheating by steam circulation is four months to establish better communication between well pairs. We considered heat loss at top and also bottom of the reservoir using convective heat transfer model with the following parameters:

- Heat transfer coefficient: 150,000 Btu/(day. °F)
- Temperature set-point: 600 °F i.e. if temperature of upper or lower blocks exceeded the set-point, the heat loss would be occurred.

To simulate the naturally fractured reservoir, Dual Porosity Model has been used in which the fracture and matrix communicate through a single exchange term. There is no direct communication between interblock matrices, i.e., neighboring blocks are connected only through fracture flow. The heat inside matrix or fluid can be transferred only to fracture. The fracture parameters are summarized in Table 2. Fracture porosity (fracture vol./bulk vol.) is 0.006. Fracture permeability is considered the same in all directions (2000 md) and it is assumed that the fractures is full of oil \((S_o = 1)\). Gilman-Kazemi method is set to calculate matrix–fracture interaction (sigma factor).

3. Results and discussion

3.1. Base case analysis

Gravity drainage is the main mechanism of oil production in SAGD process. Gravity drainage is a result of gravity difference between steams inside the fractures and heated oil inside the matrices. After starting injection, steam immediately flows through the fracture system which has higher permeability than the matrix block. Then, steam rises due to its lower density compared to reservoir oil. By continuing injection, steam rises quickly through fractures to the top of the reservoir. After reaching the impermeable layer, it starts developing laterally toward both sides of upper blocks. As the time passes steam chamber begins to heat up lower blocks. Therefore, blocks close to the producing-well will be heated up at later stages of steam injection. In the SAGD process, heavy oil reaches the producing-well due to gravity drainage. Heavy oil is drained at the early stage of production due to the higher fracture permeability than matrices. Fig. 3 schematically shows the steam chamber development in fracture reservoir at different time stages. It can be observed that after the steam chamber rises and faces the impermeable layer, it expands laterally. In the next section, the effects of various variables of fractured reservoir on production and temperature profile will be discussed.

3.2. Reservoir parameters

3.2.1. Fracture orientation

In order to study the effect of fracture orientation on oil production, three models of horizontal fractures, vertical fractures and networked fracture (base case) were simulated. The fracture distance in all directions (of base case) is considered to be equal to 20 ft. For other horizontal case, the fracture distance in vertical direction is also 20 ft. In the same way, the fracture distance in horizontal direction (both X & Y directions) is considered as 20 ft for vertical case. For all cases, the fracture network is distributed uniformly throughout the reservoir models. Fracture provides a high conductive pathway for steam to flow. Therefore, the direction of fracture offers steam a pathway; hence, determines the form of steam chamber expansion. In vertical fractures, steam chamber rises quickly through vertical fractures and reaches the top blocks in earlier times. In a reservoir where vertical fractures are dominant, steam has more chance to diffuse into matrices and heat them up through more contact area. Lower blocks gradually heat up over the time; therefore, vertical connections between blocks cause an effective chamber expansion. In horizontal fractures, a
traversal direction for steam chamber is provided to be developed; this reduces the steam diffusion into matrices to some extent. Consequently, it declines ultimate oil recovery. Fig. 4 illustrates the comparison between oil production profiles of different cases. It can be observed that oil production rate pulses are significantly higher in vertical fracture case compared to other cases. In fact, good depletion of vertical fractures toward horizontal producer results in more oil production rate. On the other side, the case of horizontal fractures has low pulses of production rate, which is an indicator of weak fracture depletion.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Fracture parameters.</th>
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<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Fracture porosity</td>
<td>0.006</td>
</tr>
<tr>
<td>Fracture permeability in all directions</td>
<td>2000 md</td>
</tr>
<tr>
<td>Fracture spacing in all directions</td>
<td>20 ft</td>
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Fig. 2. Schematic of the reservoir model.

Fig. 3. Reservoir temperature change during SAGD process in naturally fractured reservoir.

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Ultimately, vertical fracture case has the best recovery factor which is near 14% more than horizontal fracture case. Moreover, it has a more acceptable steam oil ratio as an economical viewpoint.

3.2.2. Fracture spacing
Perpendicular distance between two fractures is called fracture spacing. To study the effect of fracture spacing on oil production, three cases of 5 ft, 10 ft (base case) and 20 ft fracture spacing were studied. When fracture spacing decreases, the number of fracture per specified volume of reservoir matrices increases. Therefore, steam will have more pathways to invade into matrices, whereas due to an excess of fractures, the phenomenon of diffusing steam into matrices is insufficient for the entire reservoir. Fig. 5 shows a comparison between cumulative oil productions and steam oil ratio of all three cases. In case of 5 ft, the near-injector region will get heated up rapidly because of more fracture density. But later, high ratio of fractures per specified volume of reservoir matrices prohibits extensive expansion of the steam chamber. Therefore, the injected steam cannot completely cover the reservoir. On the other hand, in 20 ft case steam has less conductive area compared to 5 ft case. In this case, near-injector region will get heated up later, whereas steam extensively diffuse into more matrices and steam expansion phenomenon helps perfect chamber coverage. As a result, more oil bank is surrounded by steam front, and this leads to a higher oil recovery. From an economical point of view, a reservoir with less fracture density is considered better for SAGD method due to its less steam oil ratio.

3.2.3. Fracture permeability
In a reservoir, fractures can offer a high conductive path for steam to pass through rather than through the matrices. By increasing the permeability of fracture, steam can rise more easily into fracture. Decrease in fracture permeability makes the steam rise lower, and consequently, lateral expansion of steam is weakened. But, when permeability increases, steam chamber will expand more easily. To analyze the effect of fracture permeability on SAGD efficiency, three cases of 1000 md, 1500 md, and 2000 md (base case) were considered. Fig. 6 compares the ultimate recovery and cumulative steam oil ratio of these different cases. It is obvious that in the case of higher permeability, the chamber gets developed and covers the reservoir more efficiently; therefore it has the best ultimate recovery and the lowest steam oil ratio.

3.3. Operational parameters
In addition to three reservoir parameters, one operational parameter is studied in this paper. In this part, a numerical parametric study is conducted to determine the best positions for the well pairs in naturally fractured reservoirs.

Fig. 4. Effect of fracture orientation on oil production and steam oil ratio during SAGD process.

Fig. 5. Impact of fracture spacing on cumulative oil production and steam oil ratio during SAGD process.
3.3.1. Well pair placement optimization

In conventional well configuration by increasing the vertical well spacing and changing the location of injector well near the top of the reservoir, the chamber can rise and expand earlier and better, which results in better performance. For optimizing the wall pair placement, our idea was to change the location of injector well diagonally. In order to implement this configuration, one staggered model was developed in which the well pairs were located in a staggered position. The results demonstrated that the staggered model enhanced the efficiency of the process significantly. One of the most important mechanisms contributing to this phenomenon is the pressure-drive mechanism being intensified by offsetting the wells. Therefore, lateral expansion of staggered model is improved and can cover the larger portion of the reservoir. Fig. 7 compares the temperature profiles of conventional and staggered models. By analyzing temperature profile, the differences between chamber expansions in two cases can be observed. In staggered model, due to pressure potential existing between producer and injector, steam chamber instead of rising tends more to expand laterally. Therefore, in earlier times of the process, its oil production is not considerable. But, after conducting a good connectivity between two wells (36 months), oil production rate increases rapidly and staggered model surpasses conventional model. Finally, staggered model improved the ultimate recovery up to 6% compared to the conventional well pair configuration.

4. Conclusion

In this work, the effects of three reservoir parameters as well as one operational parameter on SAGD process in a naturally fractured reservoir were analyzed. Based on the obtained results in this study the following conclusions can be drawn:

- Fracture orientation influences steam expansion and oil production from the horizontal well pairs. Horizontal fractures have unfavorable effects on oil production, while vertical fractures increase the production rate for the horizontal well. Vertical fracture case showed 14% ultimate recovery more than horizontal fractures.
• Increase in fracture spacing results in more oil production, because in higher fracture spacing model, steam will have more time to diffuse into matrices and heat up the entire reservoir.

• An increase in Fracture permeability results in process enhancement and ultimate recovery improvement.

• Diagonal change in the location of injection wells (staggered model) increases the recovery efficiency in long-term production plan.

References