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INVESTIGATION ON EFFECTS OF ROCK-FLUID PROPERTIES ON THE SAGD PRODUCTION PROFILE IN NATURALLY FRACTURED RESERVOIR (NFR)

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Abstract

A few studies were done on the SAGD process in naturally fractured reservoirs (NFR). In this study, the effects of rock-fluid properties on the production profile were investigated using commercial software. The results showed three different periods of oil production in SAGD process in NFR. First, fractures depletion in NWR (Near Well Region) affects mainly the initial oil production rate. Second, due to rising of steam into AWR (Above Well Region), oil rate increases and therefore the first flag of the oil rate pulse occurs. Third, another flag with a reduction trend is observed due to start of oil drainage from matrix blocks. In the water-wet condition, capillary pressure leads to better steam penetration from fractures into matrices, but in oil-wet, capillary pressure acts inversely. Fractures play important role in case of zero capillary pressure of matrix but with increasing the capillary pressure, pulses of production magnified and early production raises. In negative threshold pressures, capillary pressure acts as an obstacle against steam diffusion into matrices initially, however in non-negative cases there is no considerable difference in oil production rate. Steam profile being more distributed with reduction of matrix capillary pressure and also tendency to oil wettability due to less diffusion of steam into matrices and more penetration into upper fractures.

Keywords: EOR, SAGD; Naturally fractured reservoir; Wettability; Capillary pressure.

1. Introduction

Among steam injection methods, the Steam-Assisted Gravity Drainage (SAGD) by using gravity as the driving force and a pair of horizontal wells for injection/production ensures both a stable displacement of steam and economical oil rates and is a promising recovery process for producing heavy oils and bitumen [1]. In the SAGD process the heated oil moves approximately parallel to the interface which forms the boundary of a growing, steam-saturated zone known as the steam chamber. Although in other thermal recovery methods the oil bank remains cold when arrives at production well but in SAGD process the heated reduced viscosity oil is produced since there is no large distance between wellpair [2]. The mechanism of SAGD is illustrated schematically in Fig. 1.

Sedaee Sola *et.al* investigated application of SAGD process to natural fractured heavy oil reservoir in field scale. The results showed that the SAGD process was feasible and also produced more oil than other EOR methods in this reservoir [1]. Bagci made experimental and simulation studies on SAGD process in conventional and fractured model and found that the shape of steam chamber in fractured model is elongated while the conventional steam chamber is almost round [4]. Serhat Akin proposed a mathematical model for gravity drainage process in heavy oil reservoirs and tar sands during steam injection based on experimental observations and found that rather than the change in steam zone height and lateral transfer of the drained fluid to the fixed well, steam distillation and asphaltene effects are more dominant in steam assisted gravity drainage process [5]. Chen *et.al* investigated the effects of heterogeneity including either vertical or horizontal fractures. The case of vertical fractures produced more oil in the first stages of production rather than horizontal fractures [6]. Das *et al.* compared the feasibility of the SAGD process and CSS in fractured carbonate reservoirs [7]. Fatemi investigated both fractured and conventional models numerically and stated that the oil recovery mechanism is different [8].

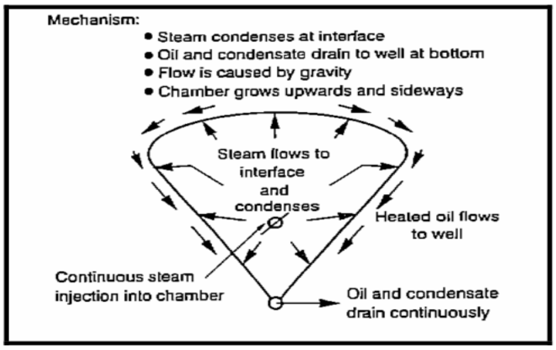

Fig. 1 Essential feature of the SAGD process [1]

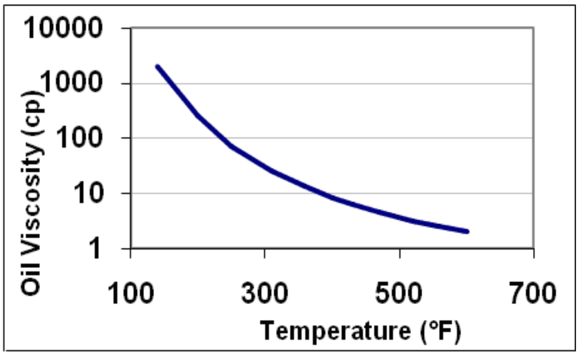

Fig. 2 Oil viscosity versus temperature

Since the various stages of heavy oil production in application of SAGD process in naturally fractured models has not been ever investigated, therefore in this study the sensitivity of the SAGD process to rock-fluid properties at various stages of oil production has been studied and also the production profile were investigated. Despite former studies, the field scale was selected for investigation of the process in macroscopic scale.

2. Simulation study of SAGD: description of the model

In order to study the effect of basic matrix properties on the SAGD performance, a base case should be defined. In this study, the base case was a rectangular reservoir with dimension of 9000 × 9000 × 300 ft. To exclude grid sensitivity of the results, the grid sensitivity analysis was done and 30 × 30 × 10 cell in X, Y, Z coordinate selected as a base case grid number. The simulator used in this study was CMG-STARS. PVT properties were calculated using CMG-Winprop software.

Average porosity and permeability, irreducible water saturation and residual oil saturation of water-wet matrix were set to 10%, 50 md, 40% and 20%, respectively. Formation thermal conductivity and rock heat capacity of matrix were set to 24 Btu/ft^3. °F and 30 Btu/Day .ft. °F. The matrix properties are summarized in Table 1. To simulate NFR, Dual Porosity Model has been used in this study. The fractures with permeability of 2000 md and 30 ft distances in X, Y and Z direction made a networked fracture with porosity (the ratio of fractures volume to bulk volume) of 0.006 that fully saturated by oil. The oil thermal conductivity in the fractures was set to 2 Btu/ft^3. °F. The fracture parameters are shown in Table 2.

One horizontal injector/producer well pair with 4800 ft length and 30 ft vertical spacing was located three blocks above bottom of model. The injection scenario was based on constant injection rate of 1000 STBD CWE for 10 years and maximum injection pressure was set to 1500 psi (corresponding maximum temperature was set to 600 °F). The minimum pressure of production well was set to 1150 psi (50 psi less than reference pressure at bottom of model) and 0.95 was assigned to the steam quality. Four months preheating by steam circulation was designed.

The crude oil composed of three pseudocomponents known as X_2^+ (gaseous phase), C_2^+ (oil phase) and C_7^+ (oil phase). The Peng-Robinson (1978) Equation of State and Modified Pederson Equation were used to model fluid properties. The oil viscosity at reservoir temperature (140 °F) is about 2000 cp and its changes versus temperature are shown in Fig. 2. The reservoir condition oil density and GOR are 61.5 lb$_m$/ft^3 and 67 scf/stb, respectively and also the oil formation volume factor (B_o) is 1.05 at reservoir pressure (1200 psi). The relative permeability of oil-water and capillary pressure curves are illustrated in Fig. 3 and Fig. 4 respectively. Also, the residual oil saturation changes versus temperature are considered into simulation (Table 3). The operational and fluid data are shown in Table 4 and 5, respectively.

Table 1 The matrix properties

Parameters	Value
Porosity (%)	10
Permeability (md)	500
Irreducible water saturation (%)	40
Residual oil saturation (%)	20
Formation thermal conductivity (Btu/Day .ft. °F)	24
Rock heat capacity (Btu/ft3. °F)	30

Table 2 The fracture properties

Parameters	Value
Porosity (%)	0.006
Permeability (md)	2000
Oil saturation (%)	100
Oil thermal conductivity (Btu/Day .ft. °F)	2.0

Table 3 S_{or} versus temperature [3]

Temperature (°F)	S_{or}
300	0.15
600	0.05

Table 5 Mole fraction and molecular weight of the crude oil used in the simulation

Component	MW	Composition (%)
X_2^+	17	0.1124
C_2^+	74	0.1854
C_7^+	411	0.7022

Table 4 The operational properties

Parameters	Value
Maximum injection temperature (°F)	600
Maximum injection pressure (psi)	1500
Steam quality (%)	95
Production pressure (psi)	1150
Initial pressure (psi)	1200
Number of injector/producer well	1
Well pair length (ft)	4800
Vertical well spacing (ft)	30
Maximum injection rate (STBD)	1000
Preheating period (months)	4

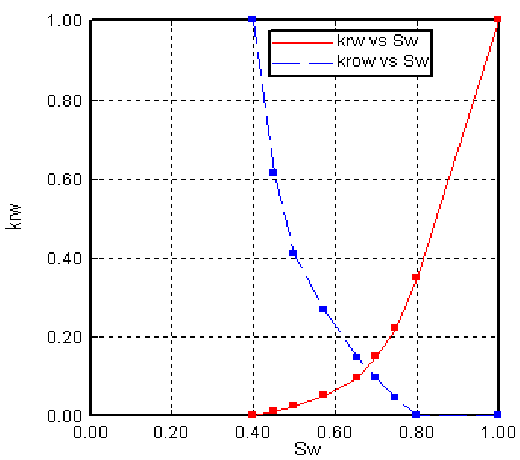

Fig. 3 Oil-water relative permeability

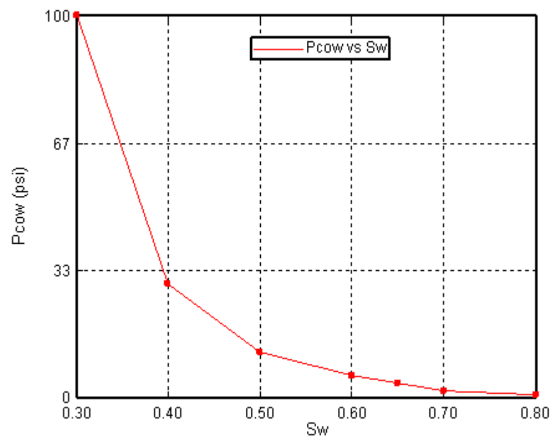

Fig. 4 Matrix capillary pressure curve

2.1. Base case analysis

To investigate the effect of rock-fluid properties on the oil production profile it is needed to discuss fully about base case and describe the mechanisms of production and also steam development in a 2D map. The stages of production can be divided into three periods. At first period due to long preheating period, the oil of NWR is heated enough and becomes movable prior to production. At this stage by depletion of the fractures it seems oil rate decreases but due to steam moving through fractures and heating of matrix, oil rate reduction is delayed. The governing mechanisms of oil production in this period are decreasing oil viscosity, expanding oil and somewhat steam invasion (till point A). After this period, steam penetrates into upper fractures and therefore a pulse in oil production rate occurs (till point B). After depletion of fractures, drainage of this block matrixes begins due to more heating by steam moving through fractures, therefore cannot compensate depletion of fractures and a reduction in oil rate seems (till point C). Next, due to penetration of steam into another block, another pulse occurs in the oil rate trend and consequently as steam raises into one block in AWR, a pulse in oil production trend appears. In Fig. 5 the oil production rate at the various stages of oil production are shown.

3. Results and discussions

3.1. Wettability

Three cases were chosen for investigation; water-wet (base case), oil-wet and intermediate. In the water-wet condition, capillary pressure leads to better steam penetration from fractures into matrices, but in oil-wet, capillary pressure acts as an obstacle and oil drainage stage from matrices to fractures becomes linear (not pulse shape). In water-wet, both matrix and fracture between well pair cooperate in early production, therefore oil production increases severely. On the other hand, in the oil-wet condition only preheated fractures affect early production and preheated oil in matrices drain into fractures limitedly (Fig. 6).

As mentioned above, in the oil-wet rocks, capillary pressure reduces the steam penetration into matrix and steam diffuses more into upper fractures and consequently, number of heated layers increases. On the other side, when the rock is water-wet, capillary pressure has a positive effect on steam penetration and less upper layers warm. Clearly, in this case, temperature of NWR is much more than oil-wet rocks (Fig. 7).

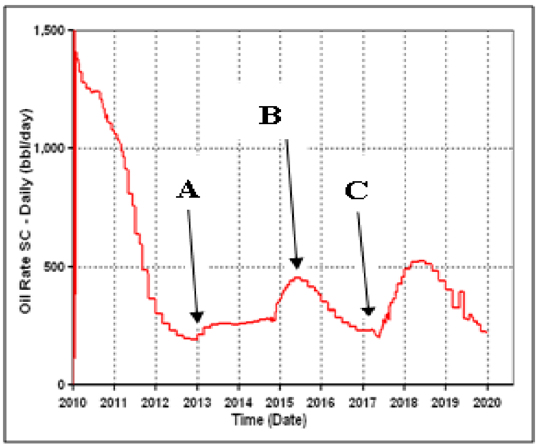

Fig. 5 The various stages of oil production profile in the base case

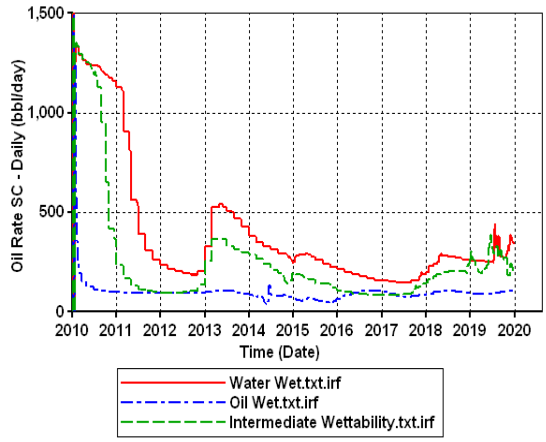

Fig. 6 Effect of matrix wettability on oil production profile in NFR

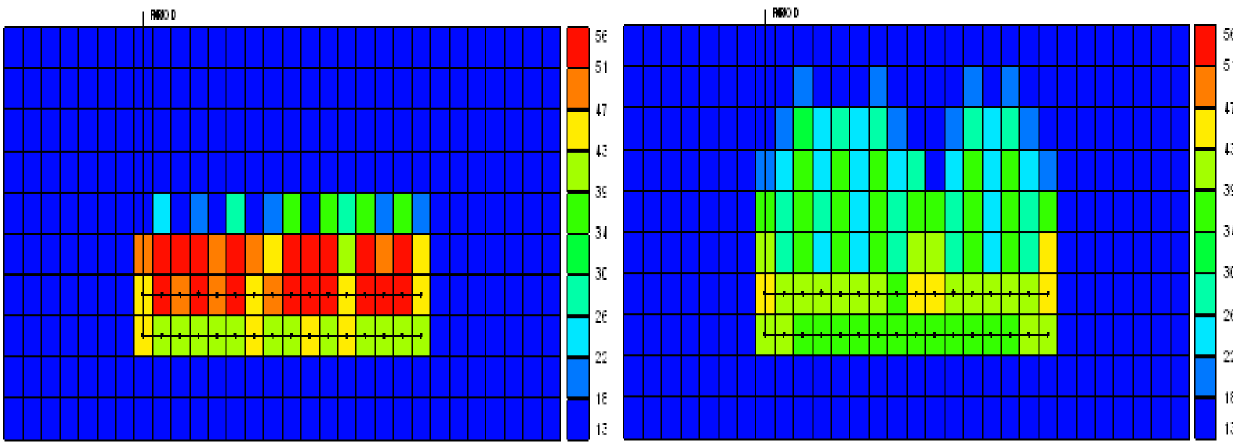

Fig. 7 Temperature profile in base case (left) and oil-wet matrix (right) after 10 years

3.2. Capillary pressure

Three conditions with capillary pressures equal to 10, 100 (base case) and 1000 psi at the Sw_{irr} point and also another case without capillary pressure (Pc=0) are considered. When capillary pressure is zero, fracture plays important role in oil production and less oil drains from matrices into fracture but in other cases (with capillary pressure) matrices have effective role on oil production so that with increasing the capillary pressure, pulses of production magnified and early production raises (Fig. 8). This parameter has no significant effect on temperature profile of reservoir, but, to somewhat its increment leads to better early penetration of steam into matrix and hence more heating of them. Therefore, diffusion of steam into upper layers partially decreases. When capillary pressure is non-zero, with increasing of this parameter, profile temperature slightly increases and less part of upper layers have been affected because of more steam penetration into matrix. When capillary pressure is zero, there is approximately no steam penetration into matrix. In this condition, steam penetrates into upper layer through fractures and majority of oil produces through fractures. (Fig. 9).

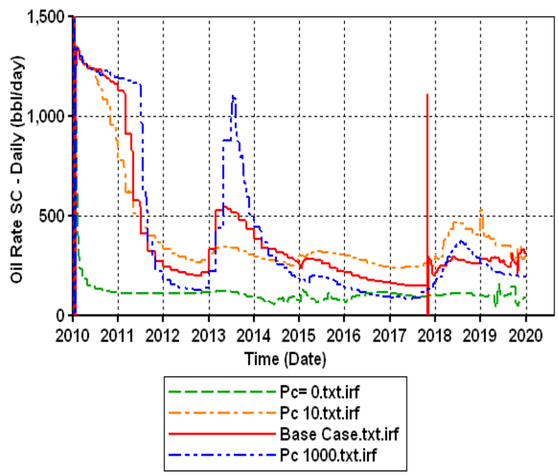

Fig. 8 Effect of matrix capillary pressure on oil production profile in NFR

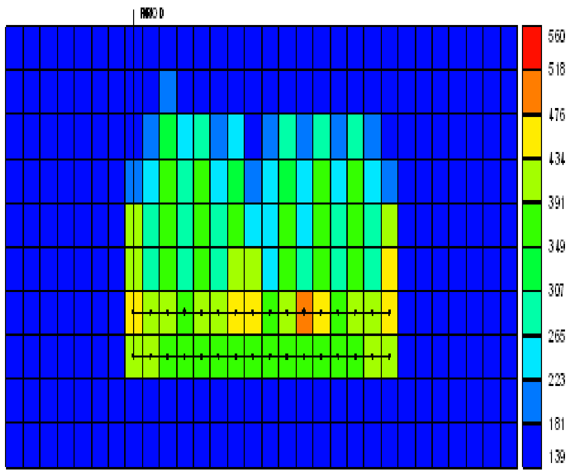

Fig. 9 Temperature profile in case of Pc=0 after 10 years

3.3. Threshold pressure

Three models with threshold pressures of (-10), Zero and (+10) psi were selected. When the threshold pressure is negative (-10 psi) steam has less primitive power to diffuse into matrix, so capillary pressure acts as an obstacle and steam penetration from fracture into matrix decreases. In other cases, when threshold pressures are non-negative, there is no significant increment in oil production with increasing the threshold pressure (Fig. 10). This parameter has no effect on steam profile.

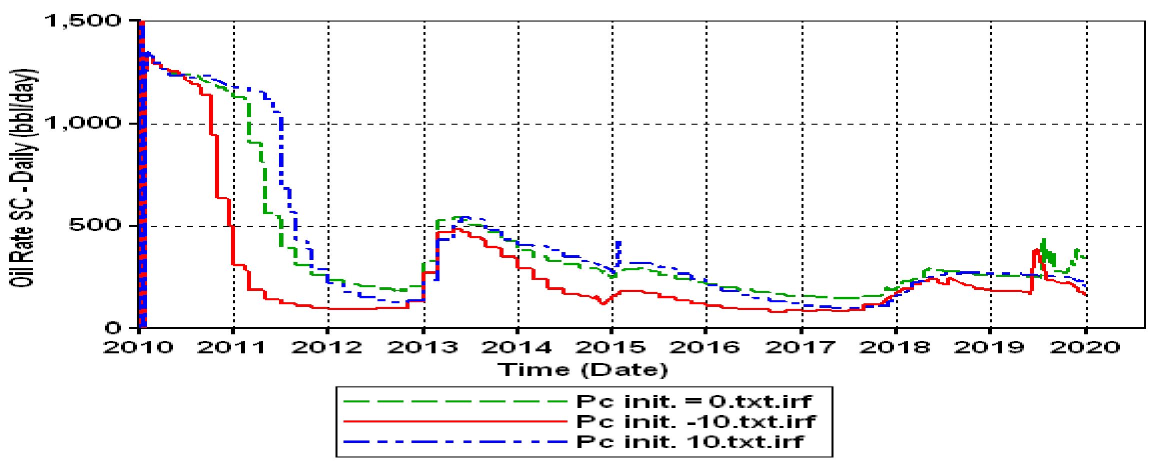

Fig. 10 Effect of threshold pressure on oil production profile in NFR

4. Conclusions

In present study, the effects of rock-fluid properties on SAGD production profile in NFR were investigated numerically and the results showed that:

Three different periods of oil production exist in SAGD process of naturally fractured reservoirs. The pulses of oil production include one increasing flag due to fractures depletion and a decreasing flag due to drainage of matrixes surrounded by these fractures. In the water-wet condition, capillary pressure leads to better steam penetration from fractures into matrices, but in oil-wet, capillary pressure acts as an obstacle against steam diffusion into matrices and oil rate pulses vanish. When capillary pressure is zero, fracture plays important role in oil production and less oil drains from matrices into fracture but in other cases (with capillary pressure) matrices have effective role on oil production so that with increasing the capillary pressure, pulses of production magnified and early production raises. In negative threshold pressures, capillary pressure causes steam to diffuse into upper fractures and not surrounded matrices initially, however in non-negative cases there is no considerable difference in oil production rate. Threshold pressure has no considerable effect on the steam profile. Steam profile being more distributed with reduction of matrix capillary pressure and also tendency to oil wettability due to less diffusion of steam into matrices and more penetration of upper fractures.

Nomenclature

AWR	Above Well Region
BHP	Bottom-Hole Pressure, [psi]
CWE	Cold Water Equivalent, [STB/day]
EOR	Enhanced Oil Recovery
K_h	Horizontal Permeability, [mD]
K_v	Vertical Permeability, [mD]
NFR	Natural Fractured Reservoir
NWR	Near Well Region
PVT	Pressure-Volume-Temperature
STBD	Stock Tank Barrel Per Day

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