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ORIGINAL PAPER - PRODUCTION ENGINEERING

Significant effect of compositional grading on SAGD performance in a fractured carbonate heavy oil reservoir

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Abstract

In reservoir simulation, the fluid composition is usually assumed uniform for the whole reservoir, while in many reservoirs, oil and gas composition changes with depth. This phenomenon which is known as compositional grading could be significant in heavy and super heavy oil reservoirs. In these reservoirs, biodegradation and asphaltene precipitation are considered as the main reasons behind this phenomenon. Compositional grading in heavy oil reservoirs could affect fluid viscosity and vaporizing–condensing mechanism in steam-assisted gravity drainage (SAGD) operations. In this paper, through a simulation study, one of the Iranian heavy oil reservoirs which have a significant compositional grading was selected to investigate the effect of compositional grading on the performance of simulated SAGD method. The reservoir is a fractured carbonate reservoir, and its compositional grading is maintained because of the lack of convection inside the reservoir. To verify the importance of compositional grading, the performance results of the SAGD method for compositional grading case were compared with that of uniform composition case. The result showed that ignoring compositional grading would lead to underestimation of ultimate recovery in the fractured model. The study of SAGD process in a non-fractured reservoir model showed that considering compositional grading has an insignificant effect on SAGD performance.

Keywords Compositional grading · Uniform composition · Steam-assisted gravity drainage (SAGD) · Heavy oil · Fractured carbonate reservoir · Simulation study

Introduction

The compositional grading is a phenomenon that could be observed in many of the world's hydrocarbon reservoirs (Firoozabadi 1999). This phenomenon refers to the molar variations of oil and gas components in reservoirs in the vertical direction with depth and in some cases in the horizontal direction. As depth increases, the heptane plus (C_{7+}) mole fraction and dew point pressure increases, whereas the methane (C_1) mole fraction, gas/oil ratio (GOR), and bubble point pressure decreases (Danesh 1998).

The reservoir fluid data are obtained from both the surface and subsurface samplings and the PVT tests and are usually reported for the whole reservoir. In many reservoirs, however, the oil and gas composition changes with depth. Ignoring compositional grading or its incorrect prediction leads to an erroneous estimation of initial hydrocarbon values and wrong production forecasts in reservoirs (Ghorayeb and Firoozabadi 2000).

The main factors that cause composition variations with depth are as follows (Høier and Whitson 2001):

- Gravity force segregates the heavier components like C_{7+} toward lower parts of reservoir and lighter components like methane toward the upperparts.
- Thermal diffusion in contrast to gravity force drives lighter components toward the lower parts of reservoir in which temperature is higher and heavier components toward the upperparts (toward lower temperatures).
- Asphaltene precipitation in the lower parts of the reservoir because of various thermodynamic factors and during migration causes the different oil types in the reservoir layers.

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- Biodegradation in vertical and horizontal directions causes significant variations in oil viscosity and API gravity.
- In the situation where the migration and equilibrium distribution of hydrocarbons is not yet complete, time is needed for the diffusion and displacement of hydrocarbons to reach a thermodynamic equilibrium.
- Oil migration from various source rocks into reservoir layers.

In some of the heavy and super heavy oil reservoirs in the world, a significant compositional grading occurs often because of biodegradation or asphaltene precipitation. Hirschberg (1988) investigates the role of asphaltenes in compositional grading of a reservoir's fluid column. Their results confirmed that the compositional grading in heavy oil reservoirs is often because of asphaltene precipitation. The asphaltene precipitation causes large variations in oil viscosity and the formation of tar mats. An example is a North African field in which strong grading in stock-tank oil gravity and a related variation in reservoir oil viscosity have been observed (Hirschberg 1988). Biodegradation is another important factor in the formation of the compositional grading in heavy oil reservoirs. For example, this factor causes a strong compositional grading in the Peace River and Athabasca reservoirs in Canada (Larter et al. 2008; Zhou et al. 2008). Another example is the Grosmont reservoir and largest fractured carbonate bitumen reservoir in the world, located in the Alberta state of Canada. Oil viscosity gradient and different API gravity values (5–9) resulted from biodegradation in this reservoir (Head et al. 2003).

SAGD is an efficient recovery process for producing heavy oils and bitumen resources (Ameli and Mohammadi 2018; Kamari et al. 2015). This method was first proposed and developed by Butler et al. (1981). In SAGD method, a pair of horizontal wells is drilled into the reservoir with a vertical spacing of about 5 m (Amirian et al. 2015; Kivi et al. 2013). Steam is injected through the upper well (injection well) and heated oil is produced through lower well (production well). Figure 1 shows a schematic representation of SAGD process. The main mechanisms of oil recovery in SAGD method are reduction in oil viscosity and gravity drainage at edges of the steam–oil interface (Ameli and Mohammadi 2018; Delamaide 2018; Kamari et al. 2015; Khan and Awotunde 2017; Mohammadzadeh and Chatzis 2016). The vaporizing–condensing is another mechanism that improves oil recovery from SAGD process)Ghasemi and Whitson 2015; Golombok and Ineke 2013). The effects of this mechanism increase when the lighter fraction in heavy oil increases)Ghasemi and Whitson 2015). Through a simulation study, Ghasemi and Whitson (2015) investigated the effect of vaporizing–condensing mechanism on SAGD performance for different oil compositions with API gravity of 8, 10, 12, 14, 16, and 18. Their results showed that the effect of this mechanism in heavy oil recovery is considerably increased for higher API because of increase in the amount of lighter fraction.

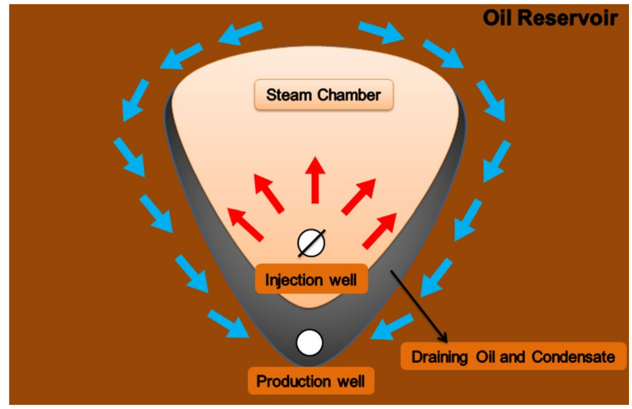

Fig. 1 Schematic representation of the SAGD process

The compositional grading in heavy oil reservoirs could affect fluid viscosity and vaporizing–condensing mechanism in SAGD operations. This phenomenon causes the oil viscosity variations relative to the depth (the oil viscosity increases with depth) in heavy oil reservoirs. In the simulation of heavy oil reservoirs, oil viscosity has been assumed uniform throughout the reservoir. This assumption is not true because of oil viscosity gradient in heavy oil reservoirs is significant (Chen and Ito 2012; Erno et al. 1991).

The effect of oil viscosity gradient on the performance of the SAGD process in heavy oil sand reservoirs has been studied by various researchers but different results obtained. Through simulation studies, McFarlane (2006), Chen and Ito (2012) and Ghasemi and Whitson (2015) compared the performance results of the SAGD method in oil viscosity gradient case with uniform oil viscosity case. The results by McFarlane (2006) and Chen and Ito (2012) showed that the effect of oil viscosity gradient on the cumulative oil production was insignificant. The results by Ghasemi and Whitson (2015) show that the SAGD performance in viscosity gradient case is slightly improved in comparison with uniform viscosity case. Larter et al. (2008) and Gates et al. (2008) reported different results where the performance of SAGD deteriorates with oil viscosity gradient and consequently, lower cumulative oil production is obtained compared to uniform oil viscosity.

Contradictory simulation results reported by different researchers indicate that further investigation is required to evaluate the effect of oil viscosity gradient on SAGD performance in heavy oil sand reservoirs. One purpose of this paper is to evaluate this issue. Moreover, the effect of the compositional grading on the performance of the SAGD method has not been investigated in the heavy oil fractured carbonate reservoir. Therefore, the main purpose of this study is to investigate this issue.

Simulation model

Reservoir parameters

In this work, a massive Iranian heavy oil reservoir which has a significant compositional grading was studied. It is a fractured carbonate reservoir and located in the south of Iran. The reservoir is still not developed; therefore, it is a good candidate for study of enhanced oil recovery (EOR) methods. To evaluate the effect of the compositional grading on the SAGD performance, a sector of this reservoir was selected. The simulation model is a rectangular cube, and its dimensions in *I*, *J*, and *K* directions were 210, 100, and 90 ft, respectively. The grid number was set to $21 \times 10 \times 10$ in *I*, *J*, and *K* directions, respectively. The near well simulation was performed to increase simulation accuracy around the well. The grid length in *J* and *K* directions kept constant and in *I* direction the grids length became finer toward the injection and production wells (Fig. 2). The number and the size of grid blocks were selected after grid sensitivity analysis to eliminate the grid size effect (Luo and Barrufet 2004). The software used for numerical simulations was CMG-STARS. The heterogeneity distribution map of porosity, permeability, and water saturation for the matrix is shown in Fig. 3. The dual porosity model was used for simulation of fractured model. The fracture spacing in *I*, *J*, and *K* directions is 20 ft, and the permeability and porosity of fractures are 2000 md and 0.006, respectively. The fracture network is completely saturated with oil. The heat loss from the steam chamber

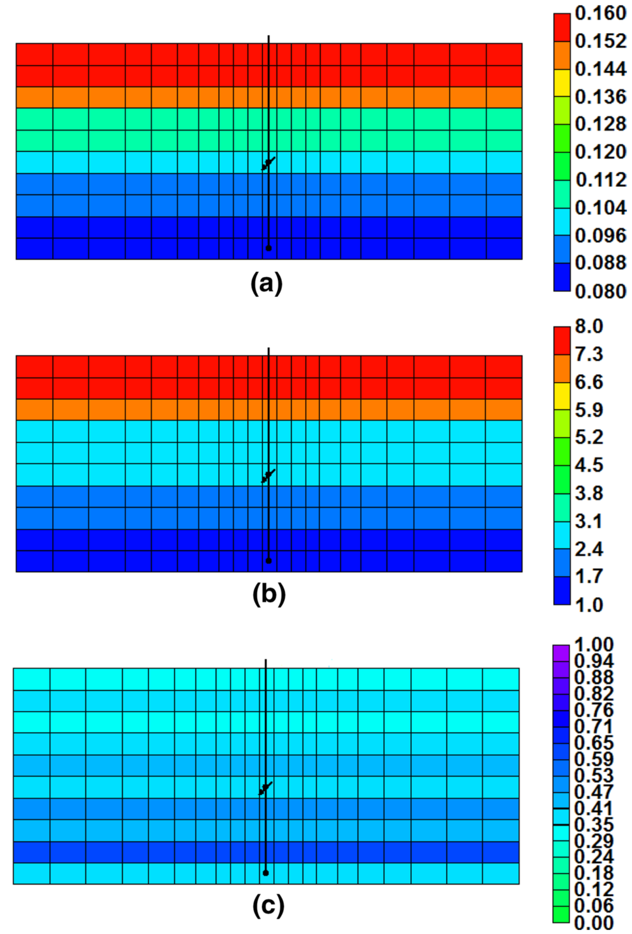

Fig. 3 Heterogeneity distribution map of porosity (**a**), permeability (**b**), and water saturation (**c**)

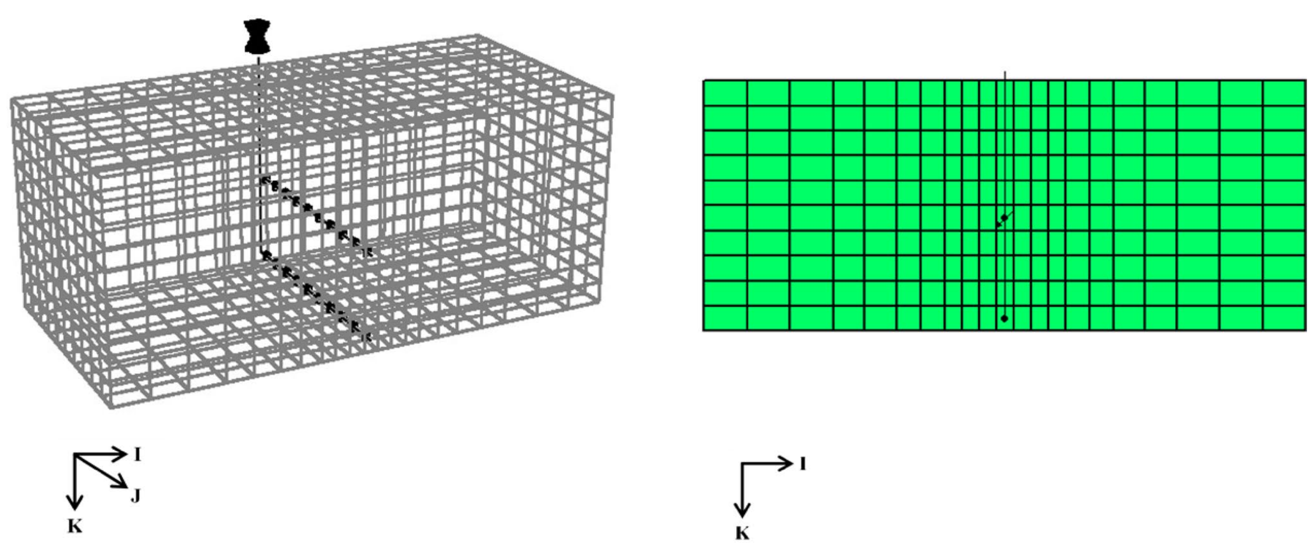

Fig. 2 Schematic representation of the reservoir model showing the wells placement (left) and mesh refinement toward the wells (right)

to the overburden and underburden of the reservoir model was also considered. The reservoir properties and heat loss parameters are presented in Table 1. The producer well and the injector well are placed at the bottom of model with 100 ft length in J direction. The injector well is 36 ft above and parallel to the producer well. Figure 2 shows 3D and 2D views of the model.

Before the steam injection, 120 days preheating was performed by steam circulation. After preheating stage, the wells were switched to become injection and production wells. The steam was injected at a constant rate of 1000 cold water equivalent (CWE) barrels per day with a maximum bottom hole pressure of 1300 psi. The steam temperature was 560 °F and the steam quality was 0.9. The producer well was operated at minimum bottom hole pressure of 1150 psi.

Fluid properties

The CMG Winprop software was used to make the fluid model, and regression was based on experimental data. The PVT properties were predicted by the Peng–Robinson equation of state and fluid viscosity by the Modified Pederson correlation. The gas oil ratio (GOR), oil formation volume factor (Bo), and oil density (for the oil composition of the layers 5 and 6) at reservoir condition (1200 psi

Table 1 Reservoir parameters

Reservoir reference depth	1040 ft
Reservoir reference pressure	1200 psi
Reservoir temperature	142 °F
Residual oil saturation	0.25
Rock heat capacity	30 Btu/ft^3 °F
Rock thermal conductivity	24 Btu/ft h °F
Oil thermal conductivity	2 Btu/ft h °F
Water thermal conductivity	10 Btu/ft h °F
Over/under burden heat capacity	34 Btu/ft^3 °F
Over/under burden thermal conductivity	20 Btu/ft h °F

Table 2 Reservoir fluid composition and viscosity at different layers

Layers	Molar fraction (%) C_1-CO_2	Molar fraction (%) C_2-C_{11}	Molar fraction (%) C_{12+}	Oil viscosity at initial reservoir temperature (cp)
1–2	12.23	33.31	54.46	1765
3–4	11.73	32.11	56.16	1840
5–6	11.23	30.91	57.86	1938
7–8	10.73	29.71	59.56	1996
9–10	10.23	28.51	61.26	2080

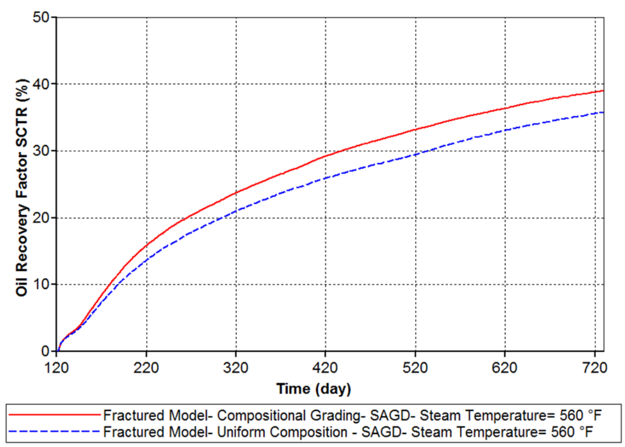

Fig. 5 Oil recovery factor for the compositional grading and uniform composition cases in fractured reservoir model at steam temperature of 560 °F

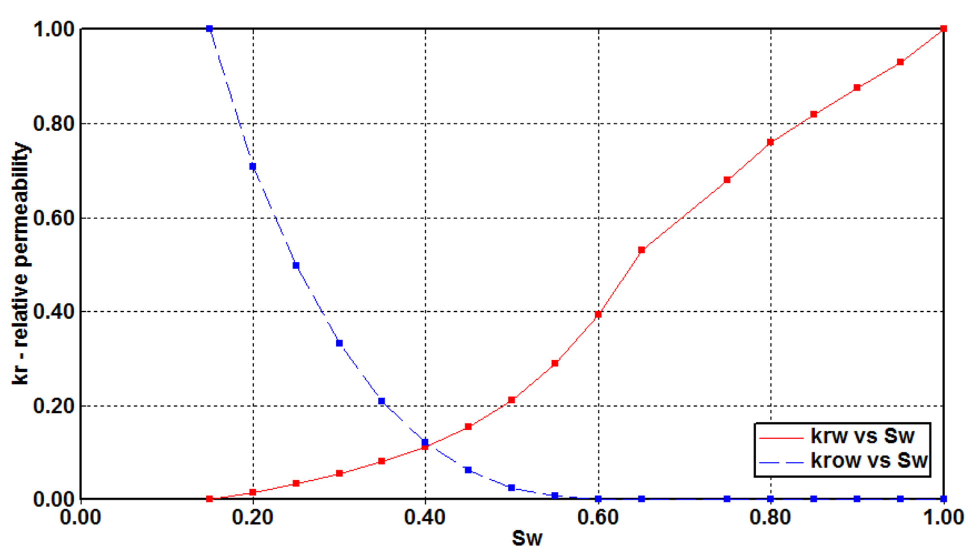

Fig. 4 Oil–water relative permeability

and 142 F) were 68 SCF/STB, 1.048 bbl/STB, and 60.6 lbm/ft^3, respectively. The oil components were grouped as (CO_2-C_1),) C_2-C_{11}), and (C_{12+}). The oil–water relative permeability curve is shown in Fig. 4.

The reservoir compositional grading

The data obtained from reservoir show that the oil API gravity changes from 17 °API in the upperpart of the reservoir to 13 °API in the lower part. The presence of the compositional grading in this fractured reservoir indicates a lack of convection inside the reservoir. Fluid compositions in different layers are shown in Table 2. In the next section, the importance of considering compositional grading in simulation studies of fractured reservoir will be discussed.

Effect of compositional grading on SAGD performance

In this section, the importance of considering compositional grading in reservoir simulation studies was determined by comparing the efficiency of the SAGD method in uniform composition (neglecting compositional grading) with that of compositional grading. The uniform composition case was simulated based on the composition of the layers 5 and 6 because it is the average of the oil composition in the upper and lower layers of the reservoir.

Figure 5 shows the oil recovery factor of two cases (considering or neglecting compositional grading) at steam injection temperature of 560 °F. It can be observed that the difference in ultimate recovery factor between two cases is 3.12% which is significant. Therefore, ignoring compositional

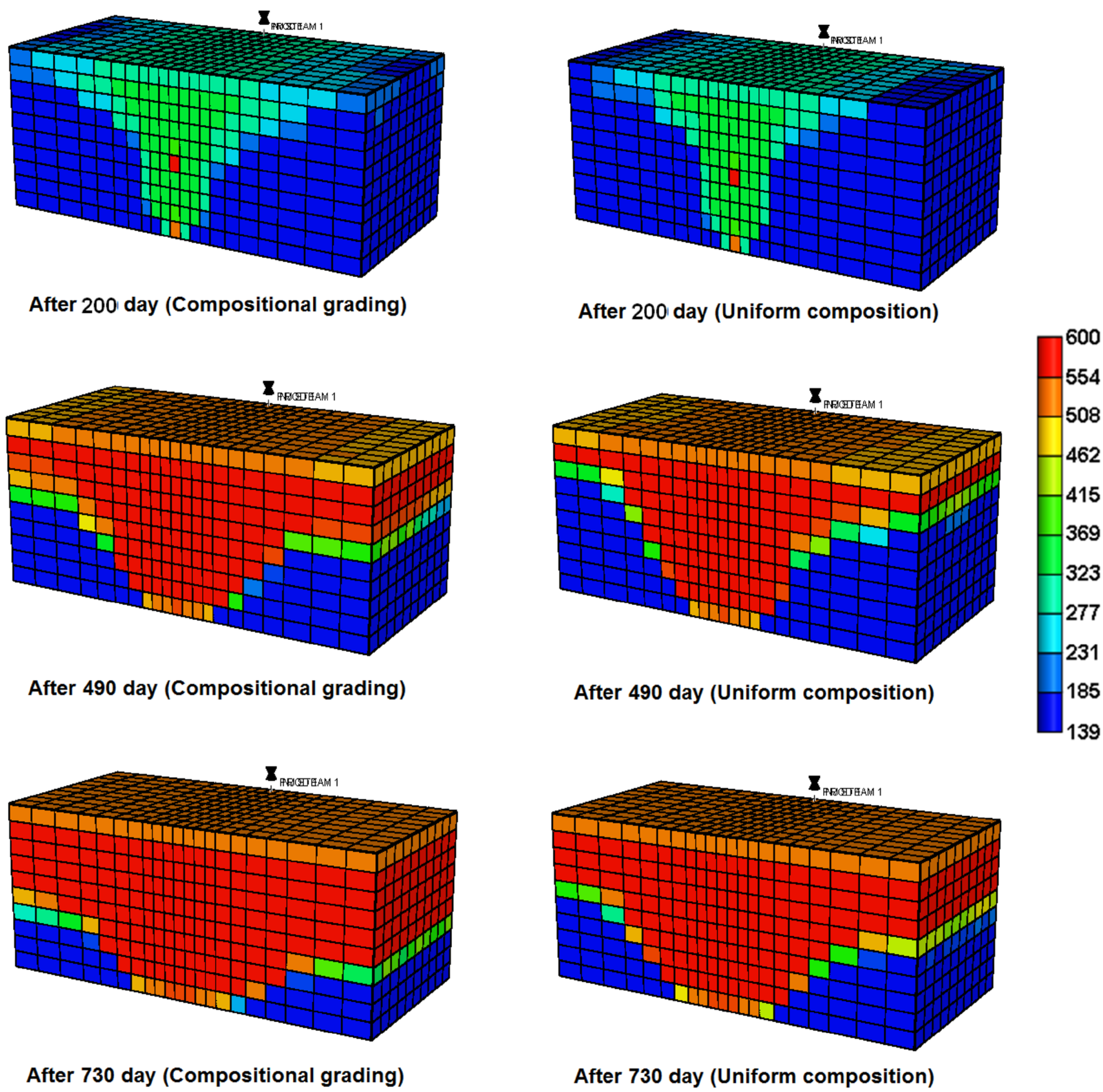

Fig. 6 Reservoir temperature profile for the compositional grading case and the uniform composition case in fractured reservoir model at injected steam temperature of 560 °F

grading would lead to underestimation of ultimate recovery. Figure 6 schematically shows the reservoir temperature profile at different production times for the compositional grading case and the uniform composition case in the fractured reservoir model at steam injection temperature of 560 °F. The reservoir temperature profile somehow expresses how the steam chamber develops in fractured reservoir model. Because of lower density of steam compared to the oil and the presence of fracture network, specially vertical fractures, after starting injection, the steam chamber rises and faces the impermeable layer and then it expands laterally. Therefore, at the beginning of steam injection into the fractured model, the upper layers of the reservoir are most affected by the steam chamber and by continuous injection; the steam chamber gradually covers the lower layers at later time (Fig. 6). In this reservoir, the matrix permeability of upper layers is higher than that of lower layers; therefore, steam tends to expand at upper layers rather than lower parts. After 730 days of steam injection, the water cut reaches to 99%, causing incomplete sweep of lower layers. As can be seen in Fig. 6, the steam chamber in compositional grading case is more developed (higher oil rate) compared to the uniform composition case. Lower oil viscosity at the upper layers of the reservoir for the compositional grading is the main reason for this phenomenon. Also, the effect of the vaporizing–condensing mechanism in compositional grading case is higher compared to uniform composition because of the presence of a large amount of lighter fraction in the upper-part of the reservoir (Ghasemi and Whitson 2015). These make the oil recovery factor for the compositional grading case to be higher than that for the uniform composition case.

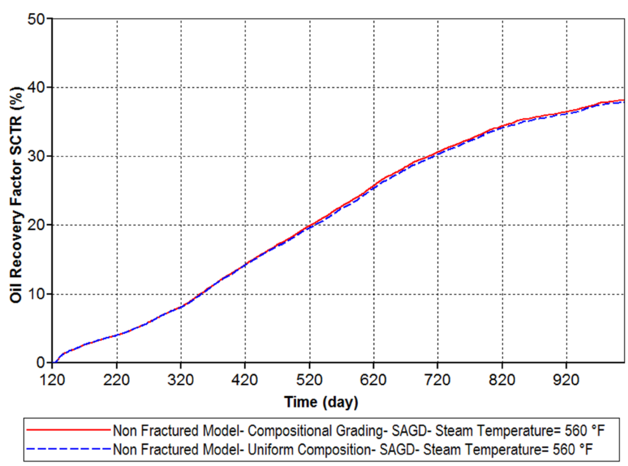

Fig. 7 Oil recovery factor for the compositional grading and uniform composition cases in non-fractured model at steam temperature of 560 °F

Effect of compositional grading on SAGD performance in non-fractured model

Figure 7 shows the oil recovery factor of two cases (considering or neglecting compositional grading) in non-fractured model. The difference in ultimate recovery factor for two cases is insignificant. Figure 8 schematically shows the change in reservoir temperature profile at different time stages, which somehow represents how the steam chamber is developed in non-fractured model. As mentioned in the previous section, at the beginning of steam injection into the fractured model, the upper layers of the reservoir are most affected by the steam chamber and then the lower layers gradually covered by steam. But in non-fractured model, because of the simultaneous vertical and lateral expansion of the steam chamber, oil production at different time steps will be the same for all layers. Therefore, because of oil mixing, the composition of oil produced in the compositional grading case is similar to that in the uniform composition case, making the difference in ultimate recovery factor for two cases insignificant. The results confirm the finding of

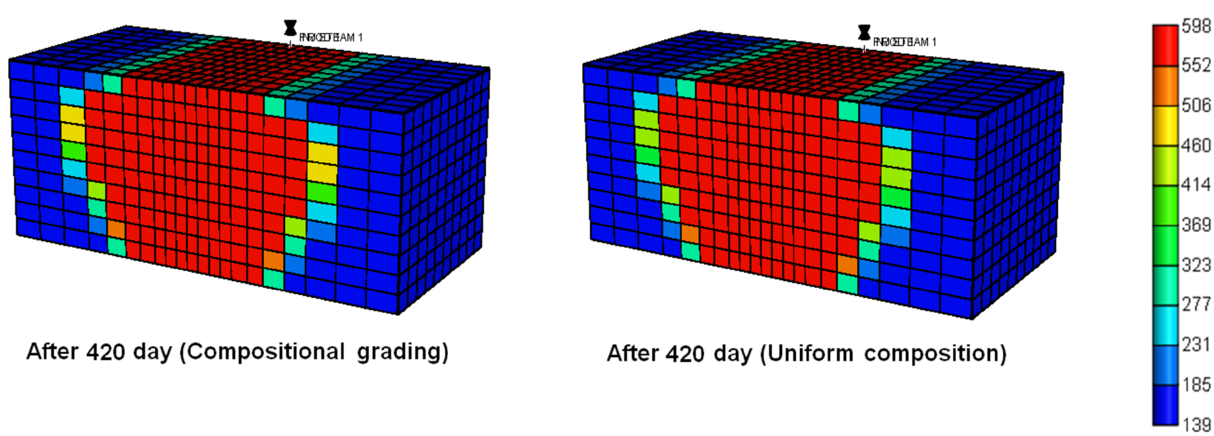

Fig. 8 Reservoir temperature profile for the compositional grading case and the uniform composition case in non-fractured model at injected steam temperature of 560 °F

McFarlane (2006), Chen and Ito (2012), and Ghasemi and Whitson (2015).

Conclusions

In this study, the effect of compositional grading on SAGD performance in fractured and non-fractured models was investigated by comparing the efficiency of the SAGD method for uniform and non-uniform composition. Investigation of the effect of compositional grading on SAGD performance in fractured model showed that ignoring compositional grading would lead to underestimation of the ultimate oil recovery. In the fractured model, the steam initially intends to move upward through vertical fractures and then expands laterally. Therefore, the upper layers of the model are first swept by the steam chamber and then the lower layers are gradually covered by steam. In the models studied here, because of matrix permeability heterogeneity (upper layers are more permeable than lower layers), steam tends to sweep upper layers rather than lower layers. The lower oil viscosity and more effective vaporizing–condensing mechanism in compositional grading case results in higher oil production compared to uniform composition case. For both uniform and compositional grading cases, the matrix permeability heterogeneity causes the incomplete sweep of oil in lower layers.

In non-fractured model, considering the compositional grading has an insignificant effect on SAGD performance. The simultaneous vertical and horizontal expansion of steam chamber from the beginning of injection causes the oil production from all layers at different time steps. Because of oil mixing, the composition of oil produced in the compositional grading case is similar to that in the uniform composition case, making the difference in ultimate recovery factor for two cases insignificant.

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