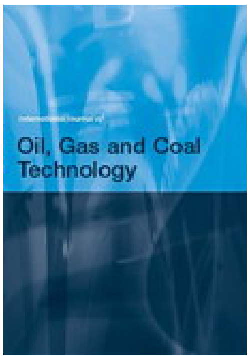

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Numerical simulation of the reservoir and operational parameters to optimise steam flooding performance

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Abstract: A comprehensive sensitivity analysis among various parameters is conducted to understand steam flooding in the oil reservoir. The result obtained for the scenario of crude oil's quality and reservoir wettability indicated that light crude oils (Oil-D, Oil-F, Oil-H) are a better choice than heavy crude oils (Oil-A and Oil-B) for steam flooding in the oil-wet and water-wet reservoirs due to improved oil mobility. In addition, it was also found that a water-wet reservoir offers more oil recovery than an oil-wet reservoir regardless of the crude oil grade due to effective displacement efficiency. Furthermore, the effect of wettability becomes more pronounced for heavy crude oils. The results for the scenario of steam quality and injection rate in the water-wet system indicated that high-quality steam with an intermediate rate of injection or medium quality steam with a high injection rate is the best option to enhance the recovery from light, medium and heavy oils reservoirs. [Received: February 21, 2022; Accepted: May 15, 2022]

Keywords: steam flooding; wettability; oil grade; steam quality; injection rate; numerical simulation; operational parameters.

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Farzain Ud Din Kirmani holds a BSc in Petroleum Engineering and MSc in Energy and Environment from UET Lahore and Punjab University, respectively, Pakistan. His area of research focuses on the application of simulators to quantify the behaviour of unconventional reservoirs.

1 Introduction

Given the low recovery factors often observed during the primary recovery phase of oil reservoirs, secondary recovery (i.e., injection of gas or water) and/or tertiary enhanced oil recovery (EOR) (e.g., injection of miscible/immiscible, chemical or thermal fluids) methods are applied (Bhatti et al., 2018; Coats et al., 1974; Ding et al., 2019; Sandrea, 2007; Terry, 2001). Unlike the secondary recovery methods, in the EOR stage, three basic mechanisms are considered including

1 reduction of oil viscosity

2 extraction of oil with solvents

3 alteration of capillary and viscous forces between oil, injected fluid, and rocks (Bhatti et al., 2018; Mozaffari et al., 2013).

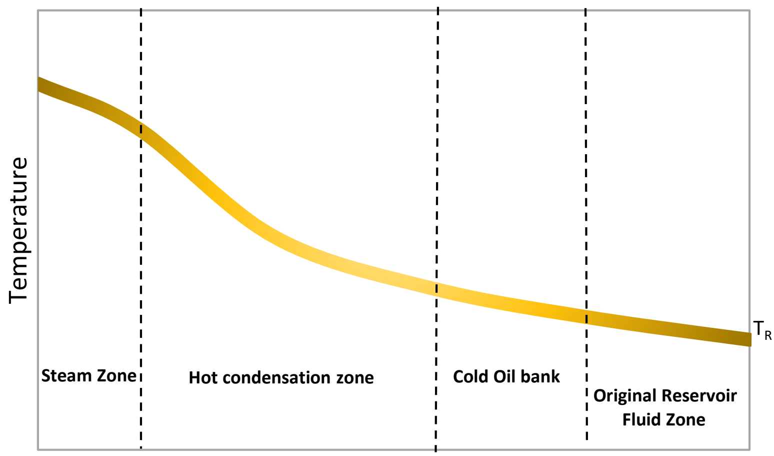
Thermal recovery is one of the highly advantageous EOR methods implemented in heavy oil reservoirs to reduce oil viscosity and increase the mobility of oil (Dong et al., 2020; Huang et al., 2018; Mokheimer et al., 2018; Mozaffari et al., 2013). Steam injection [steam stimulation, steam flooding and steam-assisted gravity drainage (SAGD)] and in-situ combustion are the most popular thermal recovery methods (Mozaffari et al., 2013). Particularly, the steam injection technology has been widely tested on the field scale in the large-scale projects located in Tia Juana, Venezuela and Schoonebeck, Holland (Al-Hinai et al., 2010; Gates and Brewer, 1975; Kovscek, 2012; Olsen et al., 1993; Patzek, 1996). The principle mechanisms involved in this EOR method are fluids thermal expansion, thermal expansion of minerals, oil viscosity reduction and the steam distillation effect under the reservoir conditions (Bagheripour Haghighi et al., 2012; Demiral and Okandan, 1987; Huang et al., 2018; Mozaffari et al., 2013).

However, although, steam flooding is considered a better choice compared to the steam stimulation (huff-n-puff) and the SAGD method when it comes to heavy/highly viscous oil reservoirs, it has a few shortcomings. For instance, gravity segregation or steam override causes the steam to gradually rise towards the top of the reservoir which initiates the early breakthrough of steam in the production well. Moreover, the formation heterogeneity and the viscosity difference between the steam and crude oil can cause steam fingering or steam channelling in permeable formations which poses a poor sweep efficiency and low oil recovery (He et al., 2012; Pang et al., 2018; Yanbin et al., 2012). Thus, it is essential to include the steam override issues, viscosity differences, wettability effects, and crude oil grade and heterogeneity factors in the assessment of oil reservoirs for implementation of the steam flooding. In this study, attempts are made to assess the effects of wettability (the preference of one fluid over another to be in contact with the rock’s surface), crude oil grade (light oil, moderate oil and heavy oil), and steam quality (SQ) and injection rate (IR) on the performance of steam flooding in oil reservoirs.

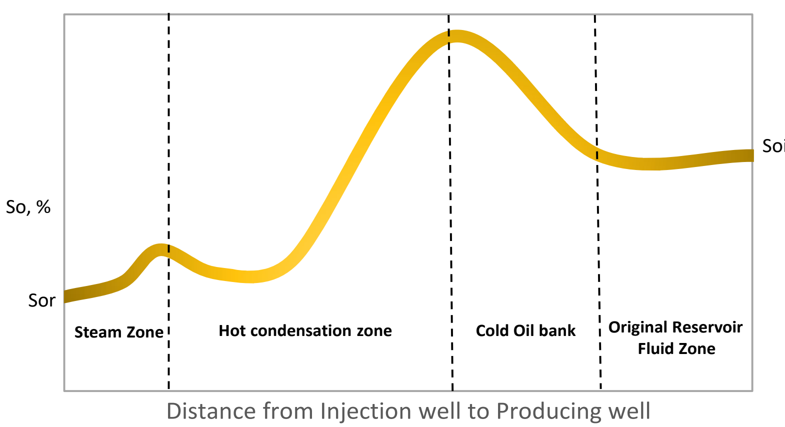
2 Previous work in steam flooding

Steam flooding is the continuous injection of hot steam into the reservoir to enhance the oil recovery in conventional reservoirs (Bagheripour Haghighi et al., 2012). Some typical mechanisms such as viscosity reduction, steam distillation and thermal expansion are involved in this flooding technique (Bagheripour Haghighi et al., 2012; Demiral and Okandan, 1987; Huang et al., 2018; Mozaffari et al., 2013). Figure 1 shows the development of different zones upon steam injection.

Figure 1 Temperature profile (a) and saturation profile (b) versus distance from injection to production wells in the direction of the flood during steam injection (see online version for colours)



(a)



(b)

Notes: S_{oi} is initial oil saturation, S_o is oil saturation and S_{or} is residual oil saturation, where T_R is reservoir temperature.

Source: Based on Abubakar (2016) and Hama et al. (2014)

As shown in this Figure 1, the steam zone is formed near the wellbore with a temperature (T_S) higher than the reservoir temperature (T_R). This zone reduces the oil saturation at the early stages. Ahead of the steam zone, the steam condenses into water and carries heat into the cooler region further away from the injector. The mobilised oil is then pushed by steam and hot waterfronts. When the temperature of the injected steam reduces to the reservoir temperature (in the cold condensation zone), an oil bank with a saturation higher than the initial oil saturation is formed. Finally, saturation and temperature will reach their initial conditions in the reservoir fluid zone as the condensate loses its heat. Variation of saturation from the injection well to the production well, on these occasions, depends on the oil composition and temperature (Abubakar, 2016; Hama et al., 2014). Nitrogen foam is used in steam flooding to increase performance by reducing the mobility of gas and steam block, reducing the residual oil saturation, and improving the displacement efficiency (Lu et al., 2014).

There have been many studies carried out in the past decades indicating the application of steam flooding in oil reservoirs. For instance, Hoffman and Kovscek (2003) numerically studied the thermal recovery in reservoirs with low permeability and natural fractures. They found that the thermal expansion of the hydrocarbon contributes more than 50% in the early recovery while the incremental recovery splits equally among thermal expansion, vapourisation, and oil viscosity reduction when cold water bank breakthrough. The late response to the steam injection is dominated by vapourisation as the distillate bank breaks through to the producer. Unlike water flooding, steam flooding can increase the recovery to 35%. Xiao et al. (2005) examined the impact of formation damage on the performance of the steam flooding using a 3D, 3-phase, compositional thermal simulator called numerical model for steam injection processes (NUMSIP). Their study concluded that the dynamic change in porosity and permeability due to clay swelling, fines migration, sanding and asphaltene precipitation may have a negative effect on heavy oil production through steam injection. Alajmi et al. (2008) experimentally observed the advancement of the steam zone during heavy oil recovery. They reported that the steam zone advancement is dependent on the heat supply and degree of heat loss. Thus, it would be very difficult to drive the steam as a vapour phase from the injection well to the production well. Trigos et al. (2010) considered a reservoir with a high clay content to study the steam flooding in oil reservoirs. It was found that the thermal efficiency decreases by 30% because a huge amount of heat is required for oil recovery in the presence of shale. Zan et al. (2010) conducted a study on shallow and thin reservoirs by the experimental and simulation approaches. The objective covers three different arrangements:

1. a vertical injection well with the production from the vertical well
2. a vertical injection well with the production from the horizontal well
3. a horizontal injection well with the production from the vertical well.

They concluded that the vertical injection well with the production from a vertical well and the vertical injection well with the production from a horizontal well provide the most promising results. According to this research, the horizontal injection well with production from the vertical well is not feasible and the steam override has a negative effect on the oil recovery. The results also revealed that the argillaceous interbed reduces the gravity drainage and decreases the oil recovery. Wu et al. (2010) adopted numerical and physical stimulation processes to assess the efficiency of steam flooding in low-permeability light-oil reservoirs at the pilot scale. They indicated that the injectivity of steam from the injector head was doubled by the temperature increase and the productivity from the production well increase almost three times by vapourisation, thermal expansion and viscosity reduction. Bagheripour Haghighi et al. (2012) worked on light and heavy oil to predict the contributing mechanisms. It was found that viscosity reduction is the main mechanism to improve the recovery in heavy oil. The results also stated that all the mechanisms (viscosity reduction, steam distillation, thermal oil expansion) play important roles in the recovery of the light oil. Mozaffari et al. (2013) provided a numerical method for steam flooding and indicated that steam injection can improve oil recovery by 60%. In addition, it was shown that only 30% of the original oil in place (OOIP) can be recovered by hot water injection. Zhao et al. (2014) provided a guideline for the thermal recovery process in heavy oil reservoirs by the analysis of SAGD, steam flooding, hot water flooding, and alternating steam/hot water flooding. They concluded that SAGD offers a higher recovery with the worse thermal efficiency. Pang et al. (2015) addressed the steam override and steam channelling issues by introducing nitrogen foam as a means to improve the displacement efficiency. They found that nitrogen foams can increase the displacement efficiency of the steam flooding from 43.30% to 81.24%. Wang and Fan (2017) simulated different patterns of horizontal wells (i.e., row pattern, five-spot patterns, and inverted nine-spot pattern) for steam flooding in heavy oil reservoirs. They concluded that the recovery of row pattern (51.85%) is the highest. Wu et al. (2018) introduced an anionic-non-ionic surfactant as a viscosity reducer (VR) during steam flooding and carried out core flooding tests to examine their synergistic effect on oil recovery. They concluded that the surfactant could improve the results by changing the interfacial tension and surface wettability of reservoir rocks. Table 1 summarises the recent studies performed on steam flooding.

Many researchers carried out experimental studies on the wettability alteration of sandstone when temperature increases during the steam injection. They indicated that residual water saturation and oil-water relative permeability increase, and the residual oil saturation decreased upon the increase in temperature due to the decrease in surface tension and contact angle. Thus, reducing adhesion tension (product of the surface tension and the cosine of the contact angle) and changes in the surface roughness could help to have a better wettability alteration (Edmondson, 1965; Escrochi et al., 2008; Habowski, 1966; Kamari et al., 2015; Poston et al., 1970; Punase et al., 2014; Sinnokrot et al., 1971; Weinbrandt et al., 1975). Some of these studies, however, reported an oil-wet surface for quartz at high temperatures (Escrochi et al., 2008; Wang and Gupta, 1995) while carbonate reservoirs were found to be water-wet at high temperatures (Hjelmeland and Larrondo, 1986; Lichaa et al., 1993; Rao, 1996; Wang and Gupta, 1995). Having said that it appears that the efficiency of steam flooding in light and heavy oil reservoirs could be affected by rock and fluid characteristics. As such, more studies are required to have a deeper understanding of the effect of oil grade and wettability on steam flooding.

SQ (mass fraction of the vapour to the liquid phase) and IR are often considered to determine an optimum flooding condition but it may require significant energy consumption (Srochviksit and Maneeintr, 2016) and cost (Hama et al., 2014). There have been several studies on the SQ and IR during the steam flooding but limited attempts were made to evaluate the SQ and IR in different crude oil reservoirs for cost-effective purposes. For instance, Zan et al. (2010) also investigated the SQ (mass fraction of the vapour over the liquid phase) and revealed that the recovery increased with the increase in SQ, however, it is better not to have a very high SQ but must quantify an optimum SQ for cost-effective operation. Similar findings are also reported in other studies e.g., Ashrafi et al. (2011), Hong (1994), Messner (1990) and Srochviksit and Maneeintr (2016). In the context of IR, Ashrafi et al focused on the effect of IR on the performance of steam flooding by doing experimental and numerical studies. They analysed and reported the increase in recovery with IR (Ashrafi et al., 2011). The influence of IR is also reported in other studies (e.g., (Haghighi et al., 2012; Tian et al., 2016) thus this factor is considered as a dominant factor to optimise.

Table 1 Summary of recent studies carried out on the steam flooding

References	*Adopted approach*	*Conditions*	*Viscosity level*	*Conclusions*
Hoffman and Kovscek (2003)	Numerical	API 32° Viscosity of 60 cp Wettability: oil wet	Light oil	Permeability distribution is a key factor in incremental recovery by steam flooding.
Xiao et al. (2005)	Numerical and Experimental	Density 0.92 g/cm^3 Wettability: -	Heavy oil	Oil recovery factor is 2.9% higher without formation damage.
Alajmi et al. (2008).	Experimental (x-ray computerised tomography)	Viscosity 500 cp Wettability: -	Heavy oil	Advancement of steam zone depends on the heat supply and heat loss.
Zan et al. (2010)	Experimental and numerical	Viscosity >100,000 cp at 20°C Wettability: -	Heavy oil	Combination of vertical and horizontal wells does not play a significant role in oil recovery.
Trigos et al. (2010)	Analytical and numerical	°API. 11.5–12.5 Viscosity of 4,031 cp Wettability: -	Heavy oil	Intercalated shale in the steam flooding has an adverse effect on the thermal efficiency.
Wu et al. (2010)	Physical and numerical	Viscosity of 20 cp Wettability: -	Light oil	Increasing the injectivity of the steam increases the production.
Ashrafi et al. (2011)	Experimental and numerical	Viscosity of 500,000 cp Wettability: -	Heavy oil	Permeability of shale and IR have significant effects on recovery.
Bagheripour Haghighi et al. (2012)	Numerical	API 12° Wettability: oil wet	Light and heavy oil	Viscosity reduction and thermal expansion are the major mechanisms of recovery in light oils.
Zhao et al. (2014)	Numerical	Viscosity of 15,212 cp		Steam flooding has a better performance than SAGD in terms of heat utilisation.

Table 1 Summary of recent studies carried out on the steam flooding (continued)

References	*Adopted approach*	*Conditions*	*Viscosity level*	*Conclusions*
Pang et al. (2015)	Experimental	Viscosity of 11,310 cp	Heavy oil	Nitrogen foam effectivity increases the sweep efficiency in steam flooding.
Wang and Fan (2017)	Physical simulation	-	Heavy oil	Row pattern is efficient in horizontal wells.
Wu et al. (2018)	Experimental	Viscosity of 8,000 cp Wettability: oil wet	Heavy oil	An anionic-non-ionic surfactant was proposed as a VR.

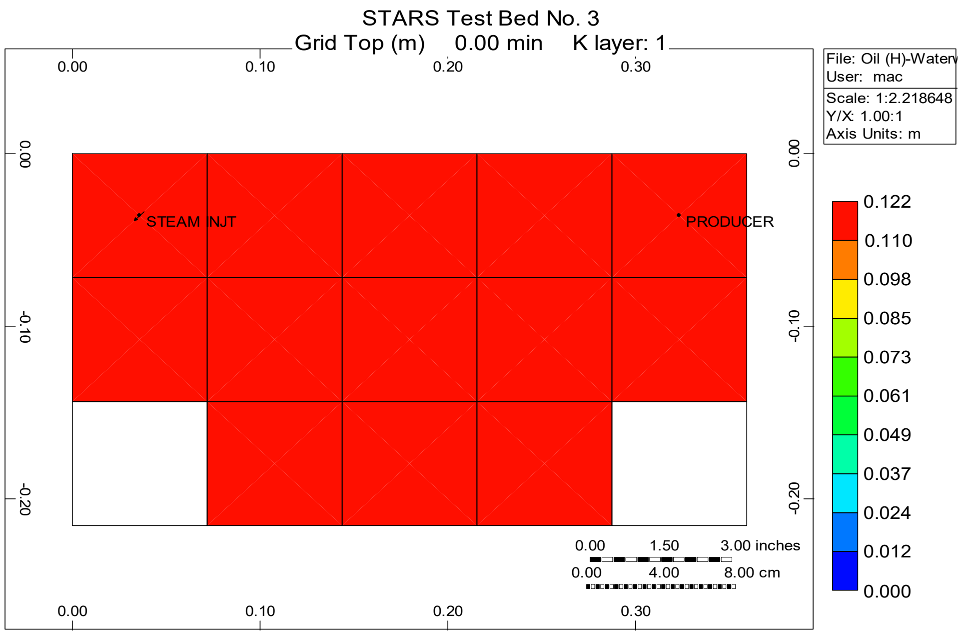
Despite the aforementioned body of literature, there is a significant ambiguity present with the current assessment of steam flooding optimisation. In addition, the degree of wettability, SQ, and IR the most important factor of crude oil quality still needs more investigation. Moreover, and importantly, while crude oil quality is known to influence recovery performance, the effect is typically not considered in the reported studies. Thus, we numerically assessed the performance of steam flooding in different crude oil quality reservoirs as a function of wettability, IR, and SQ. To this end, eight fluid samples data were used. These results may lead to a better understanding of reservoir selection criteria and operational parameters.

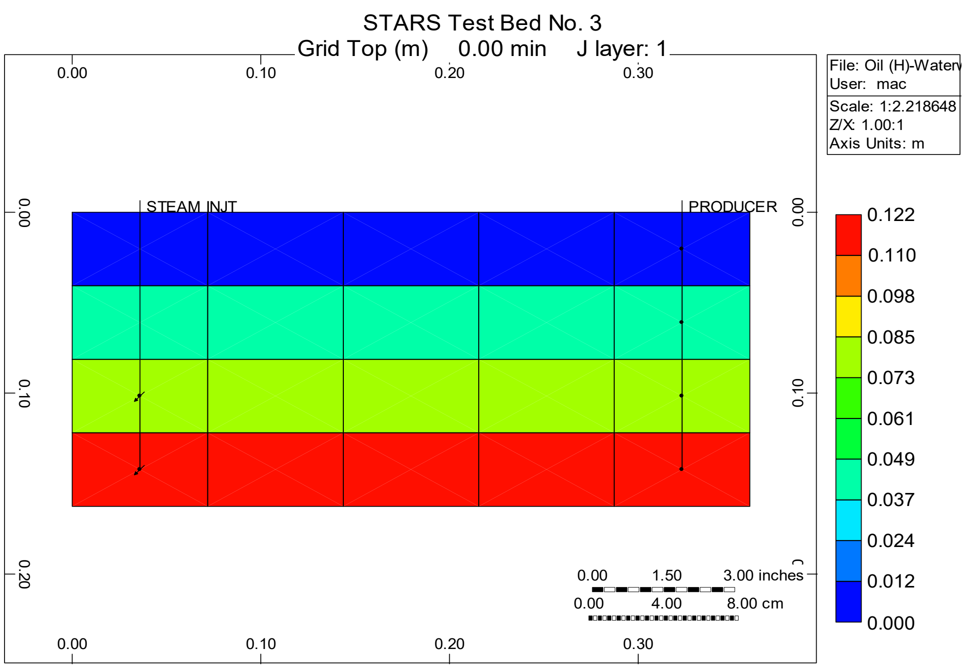
3 Numerical simulation

In this study, a three-phase (oil, water and gas), three-dimensional numerical model was used. The accuracy of this model has already been examined for the steam flooding in dead oil based on the experimental data reported (Coats et al., 1974). This model simulated a laboratory-based heavy oil steam flooding, reporting the steam flood pressure effect on the oil recovery. In this study, this model was used to evaluate steam flooding in the reservoirs with different crude oils and wettability characteristics. A commercial thermal reservoir simulator, CMG STARS™, was used for simulations. This simulator solves three-phase mass balance equations for water, steam and oil by considering the energy balance and the steam-water equilibrium equations simultaneously. Thermodynamic equilibrium in this simulator is solved by the k-values in each time step. In addition, there are thermodynamic properties of a steam system, such as density, viscosity, specific heat capacity, enthalpy, and thermal conductivity coefficient (Hamdy et al., 2020), and these have been calculated using the Redlich-Kwong equation of state (RK EOS).

A total number of 52 grid blocks were used with four layers in the z-direction to build the model as shown in Figure 2. The inter-well distance was 0.431 m (1.414 ft) giving a block size of 0.07184 m. Pay thickness was 0.16256 m while the hypothetical reservoir porosity and permeability were 30% and 207 mD respectively. To achieve the aim of this study, a wide range of crude oil quality (light, moderate, and heavy) ranging from 12.2°API to 40.4°API were considered. Table 2 gives the classification of oil samples considered based on the API gravity grades. Variations of the viscosity due to temperature were obtained from past studies (Ramírez-González, 2016; Shalali and Farahbod, 2018), as shown in Figure 3.

Figure 2 Reservoir model and the position of injection and production wells along with the top depth (see online version for colours)





Notes: Colours are representing grid top depth in K and and J layer: 1.

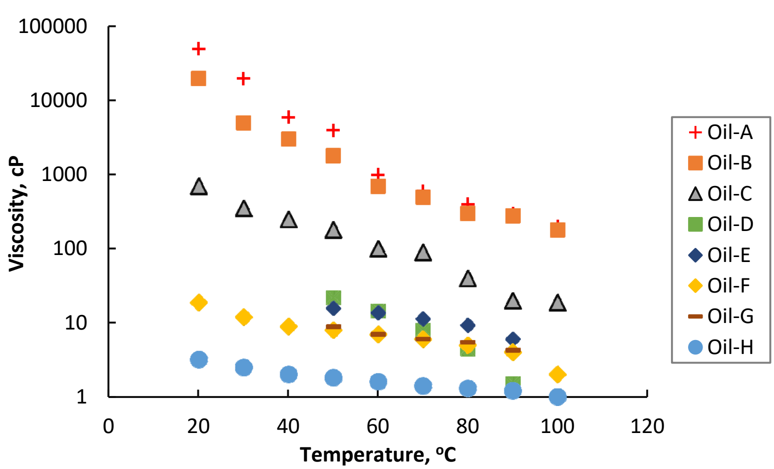
Two scenarios were made among which the first one is to study oil grade and wettability effects in steam flooding considering eight sample viscosity data along with water-wet and oil-wet systems. Further, hot water with a temperature of 195°C was injected for 100 min by maintaining the SQ of 70% at an IR of 0.053 cm^3/min. Steam flooding was done in two layers with production from four layers simultaneously. The second scenario is for SQ and IR considering three sample viscosity data (Oil-A, Oil-F and Oil-H) in a water-wet system in which hot water with a temperature of 195°C was injected for 100 min. The reason to consider a water-wet system is to avoid the wettability alteration posed by the increase in temperature. Further, different SQ between 0.1 (low), 0.5 (medium), and 1 (high) and the IR between 0.01 (low), 0.05 (medium) and 0.1 (high) cm^3/min, as given in Table 3 were considered to develop nine cases in the second scenario (see Table 4), for the steam flooding in two layers with production from four layers simultaneously in the second scenario. Production trends of oil and water, as well as the total oil production, were then assessed in different cases.

Table 2 Oil samples used in this study[a] and their classification based on API grades[b]

Sample no.	*Sample ID*	*API gravity grades (deg)*	*Grade*
1	Oil-A	12.2	Heavy
2	Oil-B	12.6	
3	Oil-C	18.5	
4	Oil-D	21.45	
5	Oil-E	27.9	Moderate
6	Oil-F	29.7	
7	Oil-G	32.95	Light
8	Oil-H	40.4	

Source: [a]Ramírez-González (2016), Shalali and Farahbod (2018) and [b]Suhag et al. (2017)

Figure 3 Viscosity of five samples as a function of temperature[a] showing a decrease in trend with the increase in temperature (see online version for colours)



Source: [a]Ramírez-González (2016) and Shalali and Farahbod (2018)

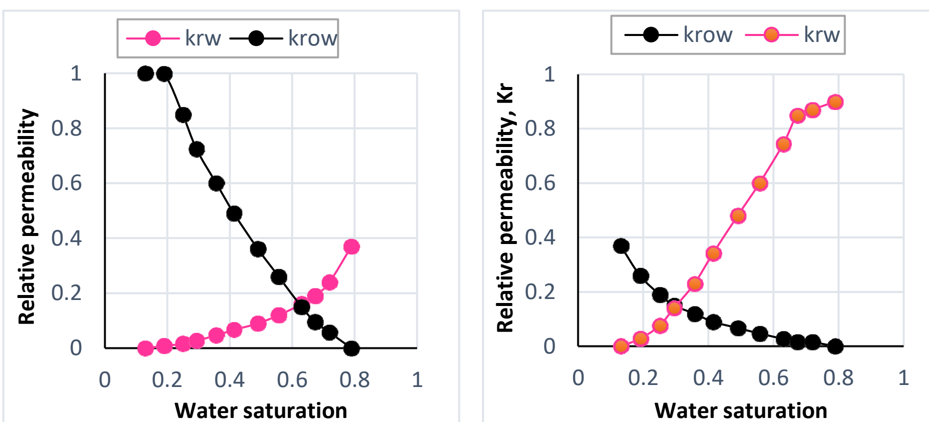
Table 3 Different parameters used in the second scenario

Parameters	*Low*	*Medium*	*High*
Steam quality	0.1	0.5	1.0
Injection rate (cm^3/min)	0.01	0.05	0.1

Table 4 Development of cases for SQ and IR assessment

Case no.	*Steam quality*	*Injection rate (cm^3/min)*
1	0.1	0.01
2	0.5	0.01
3	1	0.01
4	0.1	0.05
5	0.5	0.05
6	1	0.05
7	0.1	0.1
8	0.5	0.1
9	1	0.1

Figure 4 (a) Water-oil relative permeability (krow) for the water-wet system (b) Water-oil for the oil-wet system (see online version for colours)



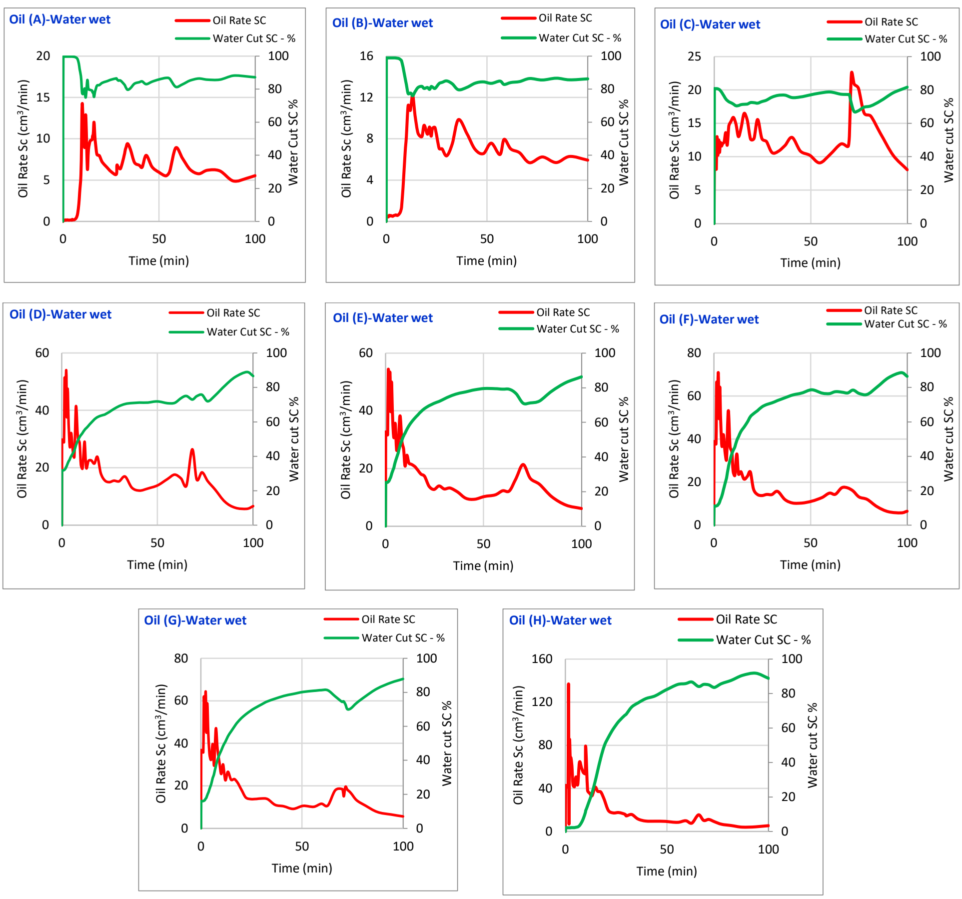
(a) (b)

Relative permeabilities were generated by considering typical trends for the water-oil system to have water-wet and oil-wet reservoirs as shown in Figure 4. Water saturation and oil saturation in the model were 18% and 82%, respectively with zero gas saturation at the initial stage. Initial reservoir pressure and temperature were 483 kPa and 74.5°C. One vertical injection and one production well were placed in the model as shown in Figure 2.

4 Result and discussion

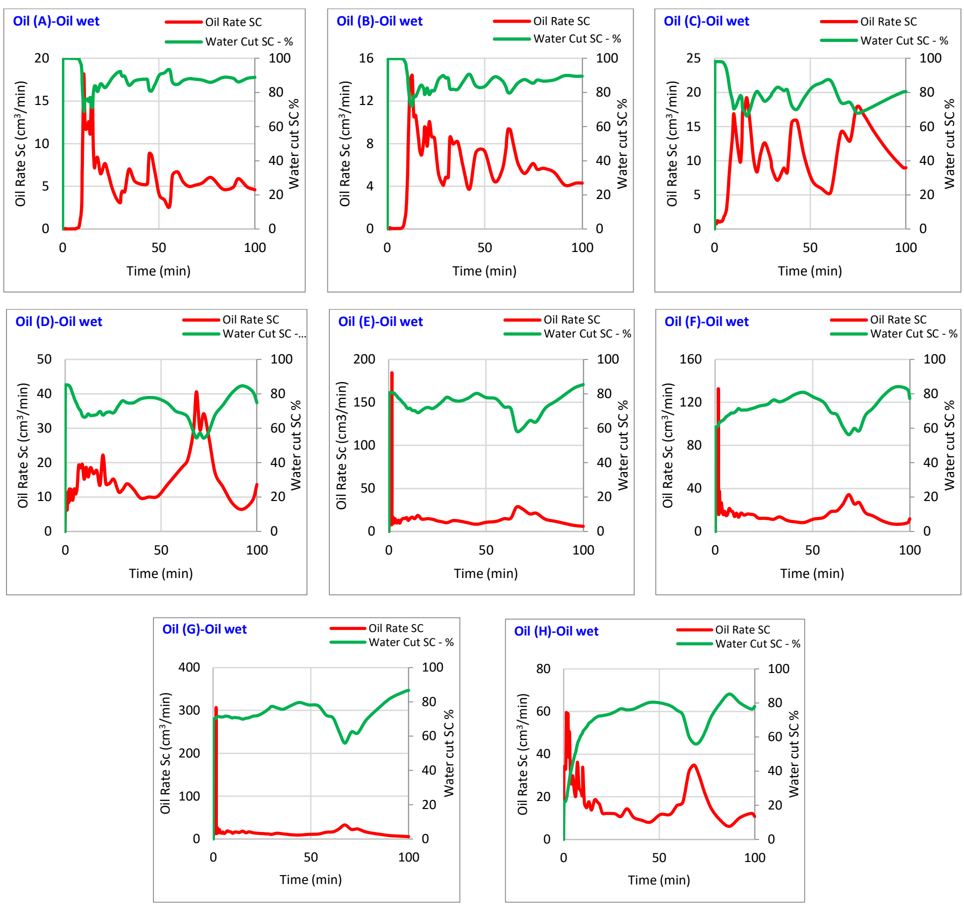
Steam flooding is a suitable approach due to the additional driving mechanism provided by the steam pressure and changes in the hydrocarbon viscosity. The results obtained for oil grade and wettability first scenario considering 8 oil samples (A-H), SQ and IR second scenario for three oil samples (Oil-A, Oil-F and Oil-H) are discussed here.

Figure 5 Oil production rate and water cut of different cases (or viscosity levels) for a water-wet porous medium showing the variation in oil and water rate trends with the time that is attributed to the influence of oil grade on steam flooding performance with subject to particular wettability system (see online version for colours)



Figures 5 and 6 show the production rate and water cut of different cases explained earlier for oil grade and wettability first scenario considering 8 oil samples (A-H). As shown in these figures, the trend of the production rate and water cut is different given the crude oil quality and rock wettability. There is a period of 100% water cut at the early stages for Oil-A and Oil-B reservoirs. Zero production at the initial stage caused a 100% water cut in Oil-A and Oil-B reservoirs under water-wet conditions and for Oil-A, Oil-B and Oil-C reservoirs under oil-wet conditions regardless of the presence of irreducible water saturation. This indicates that there is a slight fraction of irreducible water saturation in the heavy oil reservoir at the initial stage upon steam flooding. While in other cases, the water cut intensity starts to decrease at the initial stage due to the increase in oil mobility posed by the reduction of oil viscosity. Here, the variation of the production rate in the later stages of different reservoirs could be due to the impact of crude oil grade and wettability. It seems that the production rate increases initially for a certain period for all cases except for the samples Oil-A and Oil-B. This suggests that the initial increase in the production rate is caused by the pressure build-up near the production well together with changes in oil viscosity as temperature increases.

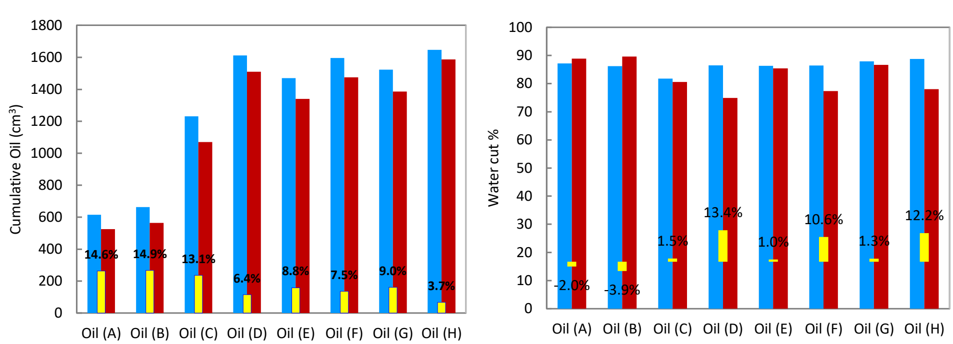
Figure 6 Oil production rate and water cut of different cases (or oil grade) for an oil-wet porous medium that is attributed to the influence of oil grade on steam flooding performance with subject to particular wettability system (see online version for colours)



As time passes, water saturation increases the water mobility which eventually results in higher steam injectivity. It was also observed that in crude oils with various grades, the production rate improves with time regardless of the wettability of the reservoir which might be linked to the presence of favourable oil mobility and capillary forces causing effective displacement efficiency (Punase et al., 2014). On the other hand, the production rate significantly improves for different crude oil grades in the water-wet reservoirs compared to the oil-wet cases. Likewise, water-cut trends are different for each case due to the variations in the production rate. However, for low-quality oil in a water-wet and oil-wet media, the water cut is initially 100% due to the poor oil displacement. This high percentage of water cut at the initial stage decreases with increasing the crude oil quality. This variation in the production rate and water cut can be mainly attributed to the change in the mobility ratio (i.e., the mobility of the displacing fluid over the mobility of the displaced fluid), changes in the relative permeability, residual oil saturation and irreducible water saturation (Kamari et al., 2015; Weinbrandt et al., 1975).

Figure 7 compares the cumulative oil for different crude oil quality and wettability characteristics for the first scenario. For the water-wet rock characteristics, it was observed that the cumulative oil increases with increasing the quality of all crude oils due to the increase in oil mobility and reduction of the oil viscosity which favours the mobility ratio (Sheng, 2013). The maximum oil was produced in the Oil-D for the heavy oil, Oil-F for the moderate oil and Oil-H for the light oil. Comparatively, steam flooding was efficient in Oil-H (light oil) and least feasible for Oil-A (heavy oil). It seems that oil reservoirs with an API of less than 12.6 would not be feasible for steam flooding. For the oil-wet rock characteristics, the trend of the cumulative oil produced is following the similar trends observed earlier for the water-wet reservoir. Comparatively, steam flooding appears to be much more suitable in water-wet reservoirs where lesser adhesion tension in the water-wet system help to have better mobility for oil (Punase et al., 2014). These results are aligned with the study of Kamari et al. (2015) who analysed the impact of wettability alternation due to temperature increase on the ultimate recovery during cyclic steam injection in naturally fractured reservoirs. Figure 7 also shows the water-cut trends obtained in different cases. However, it does not seem that there is any proper correlation between these trends and the crude oil grade or the wettability of reservoirs. However, a water cut of 90% was observed with at least 82% recovery in the Oil-C water-wet reservoir and 75% recovery in the Oil-D oil-wet reservoir which can be further validated by a data-driven approach (Lee, 2020). It was also indicated that water-cut significantly reduces in the oil-wet reservoirs due to the wettability effect in three samples, (i.e., Oil-D, Oil-F, and Oil-H) with a percentage difference of 10.6% to 13.4% compared to the water-cut of the water-wet reservoirs.

Figure 7 Comparison of cumulative produced oil and water cut between water-wet and oil-wet reservoirs with different crude oils and showing cumulative oil increases with increasing the quality of all crude oils, and the water-wet system outperform than the oil-wet system (see online version for colours)



Notes: water-wet, oil-wet, percentage change (water-wet to oil-wet)

Figure 8 Oil saturation variation during steam flooding in different layers of reservoirs over time in the Oil-A case that is indicating the slow displacement posed by the steam which is slightly higher in the water-wet case compared to the oil-wet case (see online version for colours)

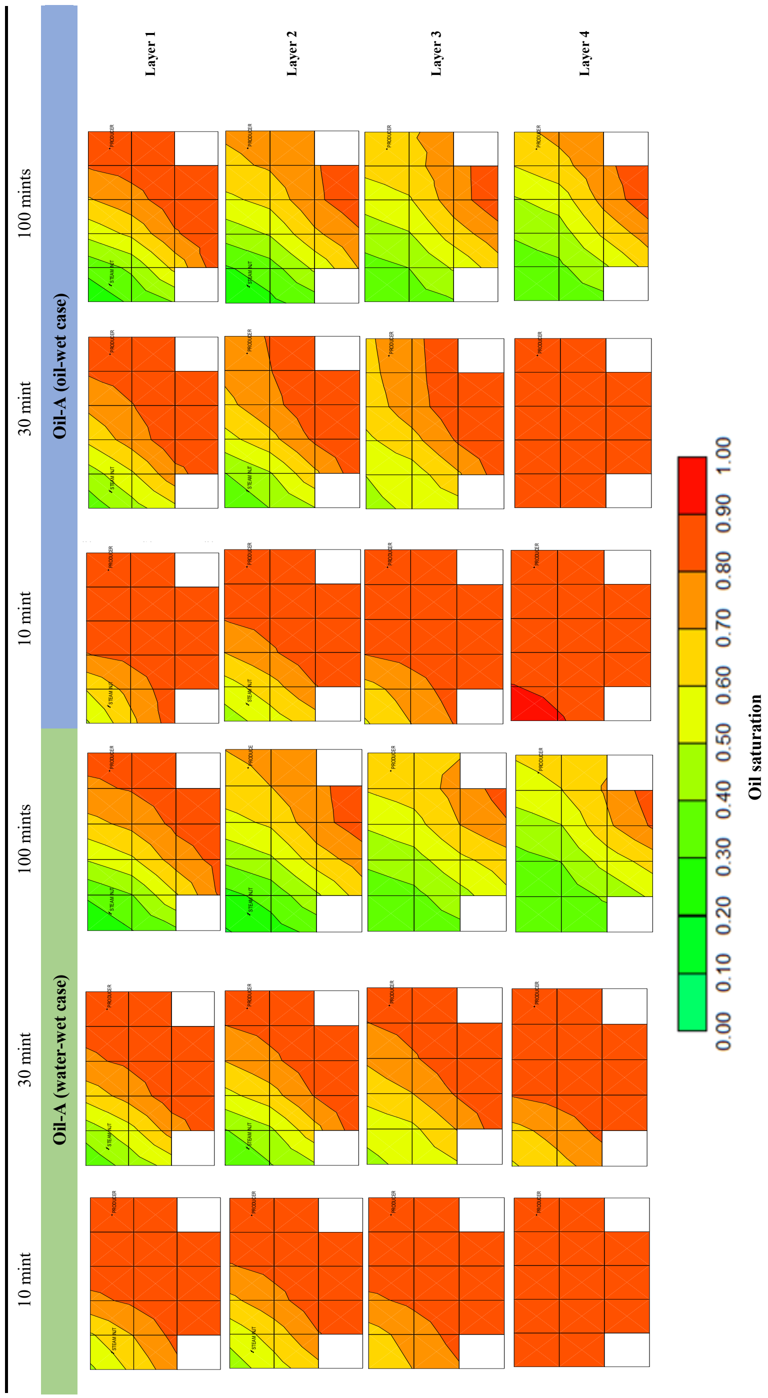
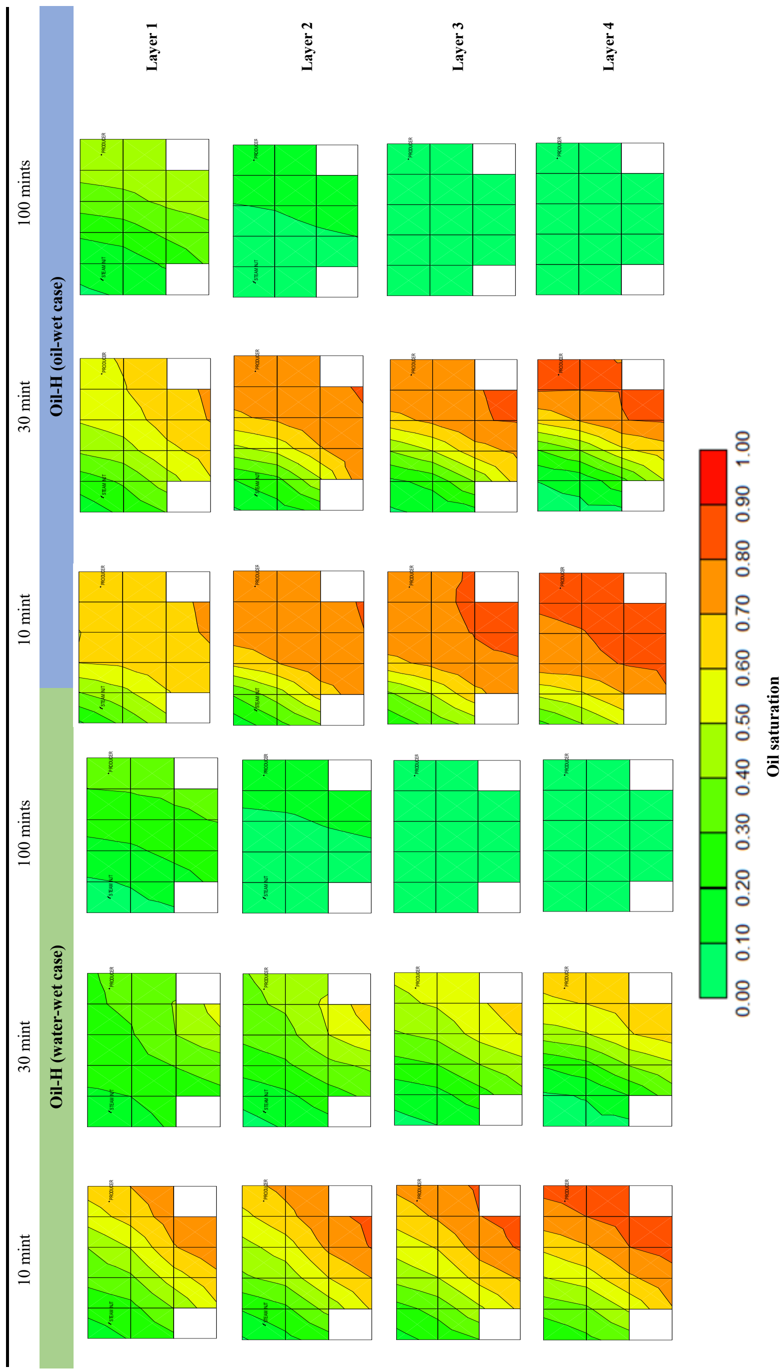


Figure 9 Changes in oil saturation during steam flooding in four layers of the reservoirs over time in the Oil-H case that is indicating the slow displacement posed by the steam which is slightly higher in the water-wet case compared to the oil; the main observation is the displacement process that is quick and uniform in the light oil (Oil-H) which recovery (see online version for colours)



To support the findings and demonstrate the efficiency of the steam flooding for different crude oils and wettability characteristics in the first scenario, changes in the oil saturation in different layers of the reservoirs were monitored over time. Figures 8 and 9 show the variation of oil saturation upon steam flooding in four layers for heavy oil grade (Oil-A) and light oil grade (Oil-H) in water-wet and oil-wet reservoirs. Looking at Figure 8, it was observed that in the Oil-A, oil saturation changes with time in four layers for the water-wet and oil-wet reservoirs. This change in the oil saturation indicates the slow displacement posed by the steam which is slightly higher in the water-wet case compared to the oil-wet case. As time passes, changes in oil saturation were recorded near the production wells in the 2nd layer of the oil-wet reservoir. This could be due to the early reach of the steam front to production wells which reduces the recovery because of the steam breakthrough. Likewise, a similar observation was made in Oil-H with changes in the oil saturation in the first three layers at the early stages while the third and fourth layers were completely swept by steam in the water-wet and oil-wet reservoirs (see Figure 9). Compared to the heavy oil grade (Oil-A), the displacement process is quick and uniform in the light oil (Oil-H) which improves recovery. Fast movement of the steam front in the water-wet reservoirs was also recorded which indicates an effective displacement process. However, the steam channelling issue posed by the large viscosity difference of oil-steam or heterogeneity of formations could affect the outcome. Thus, there is a need to incorporate the effect of the heterogeneity to assess the crude oil behaviour upon steam flooding for different levels of heterogeneity. High temperature-resistant gel during steam flooding in heavy oil reservoirs has been recognised as a good approach to addressing the steam channelling issue (Wang et al., 2016).

Sensitivity analysis of the SQ and IR was done for all nine cases (see Table 4). Cumulative oil production (FOPT), cumulative water production (FWPT) and recovery factor for different crude oil (A, F and H) reservoirs were estimated as shown in Figure 10. Any levels of SQ at a low IR offer different oil and water production trends but similar trends were observed when low to high steam qualities at intermediate and high IRs were considered. These changes in the oil production rate and water cut might be attributed to the changes in the mobility ratio (i.e., the mobility of the displacing fluid over the mobility of the displaced fluid), changes of the relative permeability, residual oil saturation, and irreducible water saturation (Kamari et al., 2015; Weinbrandt et al., 1975).

For the Oil-A reservoir, steam with intermediate quality at a high IR and good SQ at an intermediate IR offer the maximum cumulative oil production with 43% and 39% recovery factor, respectively. Thus, intermediate SQ with a high IR is the best choice to achieve the maximum oil production in the Oil-A reservoir. However, the steam override challenge dominates and as such oil production reduces when high SQ at a high IR is considered in the Oil-A reservoirs. For the reservoirs with Oil-F, high SQ with an intermediate IR or a high SQ at a high IR offers the maximum cumulative oil production. Low and medium SQ with an intermediate IR or a low SQ with a high IR has a favourable impact on the cumulative oil production with 43%, 56%, and 56% oil recovery. For the reservoir with Oil-H, a high SQ with an intermediate IR or a high-level SQ with a high IR offers the maximum cumulative oil production with 91.0%, 90.1%, and 92.7% recovery factor. Low and intermediate level SQ with an intermediate IR or a low SQ with a high IR has a favourable impact on the cumulative oil production with 65%, 75%, and 74% oil recovery factor. This could be linked to the viscosity reduction and the physical displacement of oil which may favour mobility and sweep efficiency (Sheng, 2013). Based on these findings, it can be demonstrated that steam with intermediate quality and a high IR is highly recommended for all kinds of heavy oil reservoirs due to good oil recovery and effective sweep efficiency (Sheng, 2013). Moreover, it is necessary to mention that with the increase in the SQ at a particular IR, oil recovery directly increases which might be linked to the effective thermal mechanisms, improved sweep efficiency and less steam override. These findings are aligned with the concepts of the heat balance model where the increase in the steam oil ratio with the increase in the SQ is discussed (Srochviksit and Maneeintr, 2016). However, for a high SQ, more energy consumption is required while with the increase in the IR at a particular SQ, recovery increases excluding the high-level SQ and IR for the Oil-A reservoir. The effect of the IR on the oil recovery reported in this study is aligned with the results obtained by Ashrafi et al. (2011) where it was concluded that there is an optimum temperature and IR to achieve a good steam flooding performance. Comparatively, the recovery factor of the reservoir (Oil-F and Oil H) for all conditions is higher than the recovery factor of the reservoir (Oil-A) which indicates the suitability of the medium and light oils for steam flooding as shown in Figure 10. Figure 11 shows the production rate of oil and water for Oil-A, Oil-F, and Oil-H reservoirs for only optimum case-8. It can be seen that the steam with an intermediate quality at a high IR can produce a significant amount of immobile oil from Oil-A, Oil-F, and Oil-H reservoirs.

Figure 10 Cumulative oil production and recovery factor in the total of nine cases for different crude oil grades in the water-wet system that is indicating that Oil-H outer performs than Oil-A (see online version for colours)

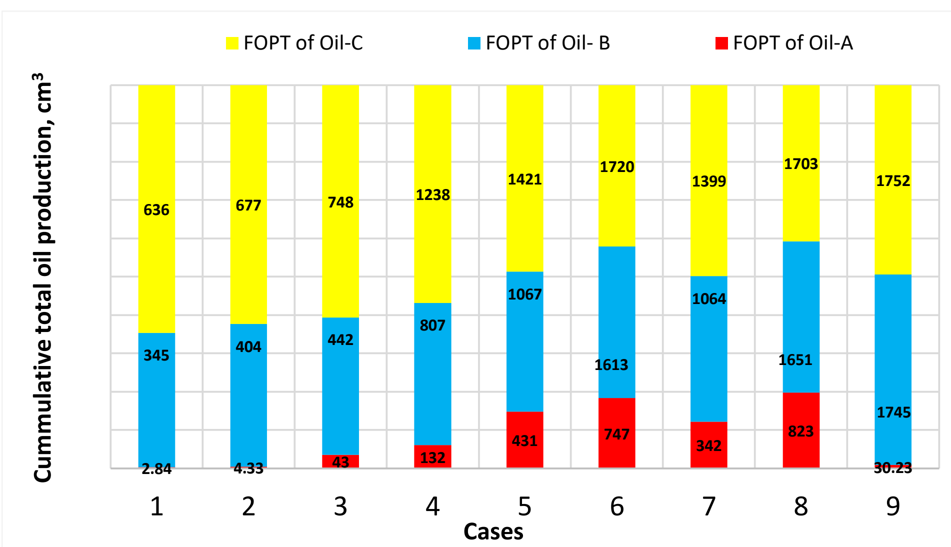


Figure 10 Cumulative oil production and recovery factor in the total of nine cases for different crude oil grades in the water-wet system that is indicating that Oil-H outer performs than Oil-A (continued) (see online version for colours)

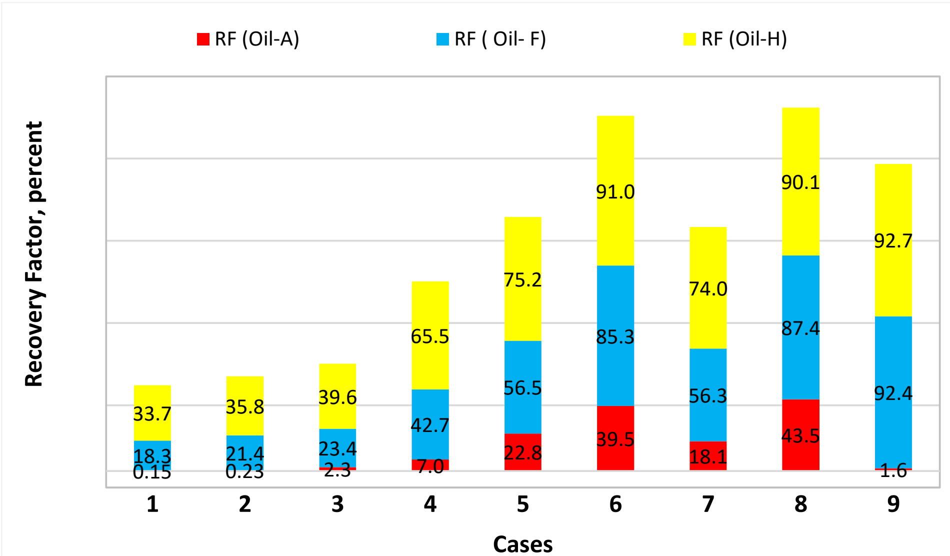


Figure 11 Oil and water production trends for optimum cases of Oil (A), Oil (F), and Oil (H) types (SQ: 0.5 and IR 0.1) in the water-wet medium that is indicating how to sweep displacement is controlled by oil grade at the specific SQ and IR (see online version for colours)

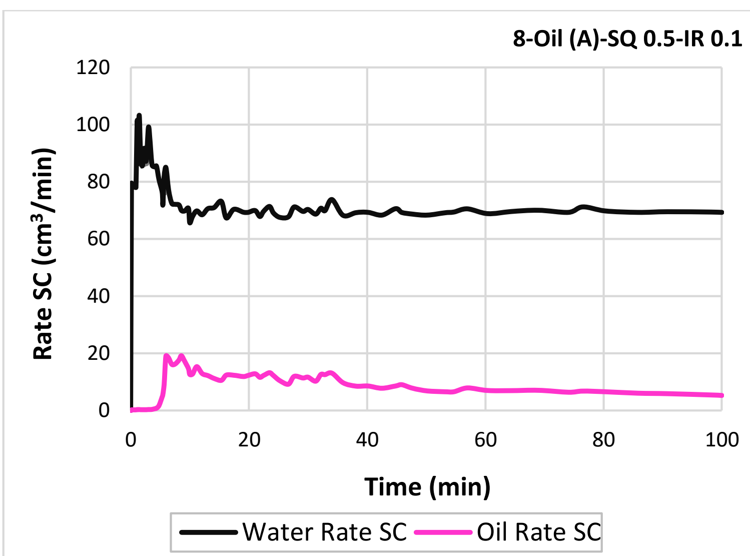
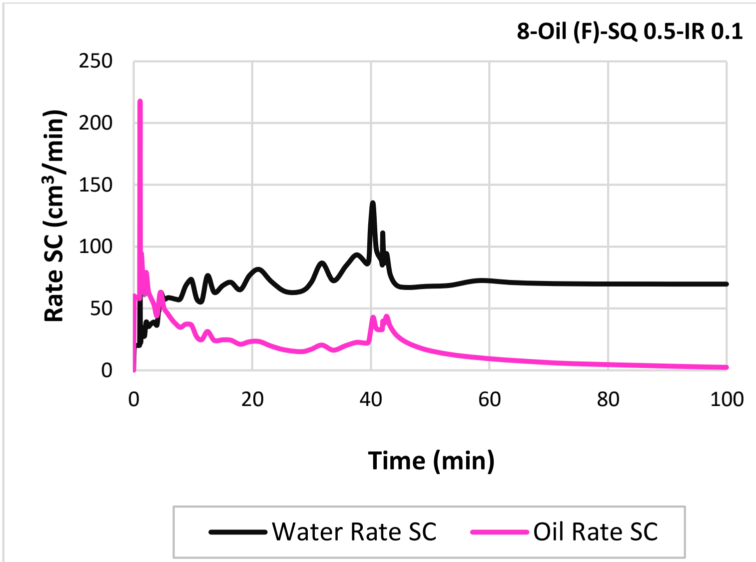


Figure 11 Oil and water production trends for optimum cases of Oil (A), Oil (F), and Oil (H) types (SQ: 0.5 and IR 0.1) in the water-wet medium that is indicating how to sweep displacement is controlled by oil grade at the specific SQ and IR (continued) (see online version for colours)



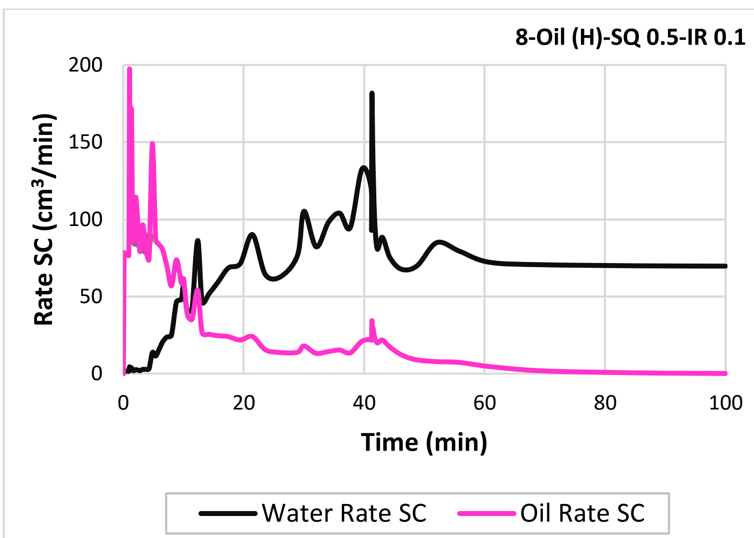
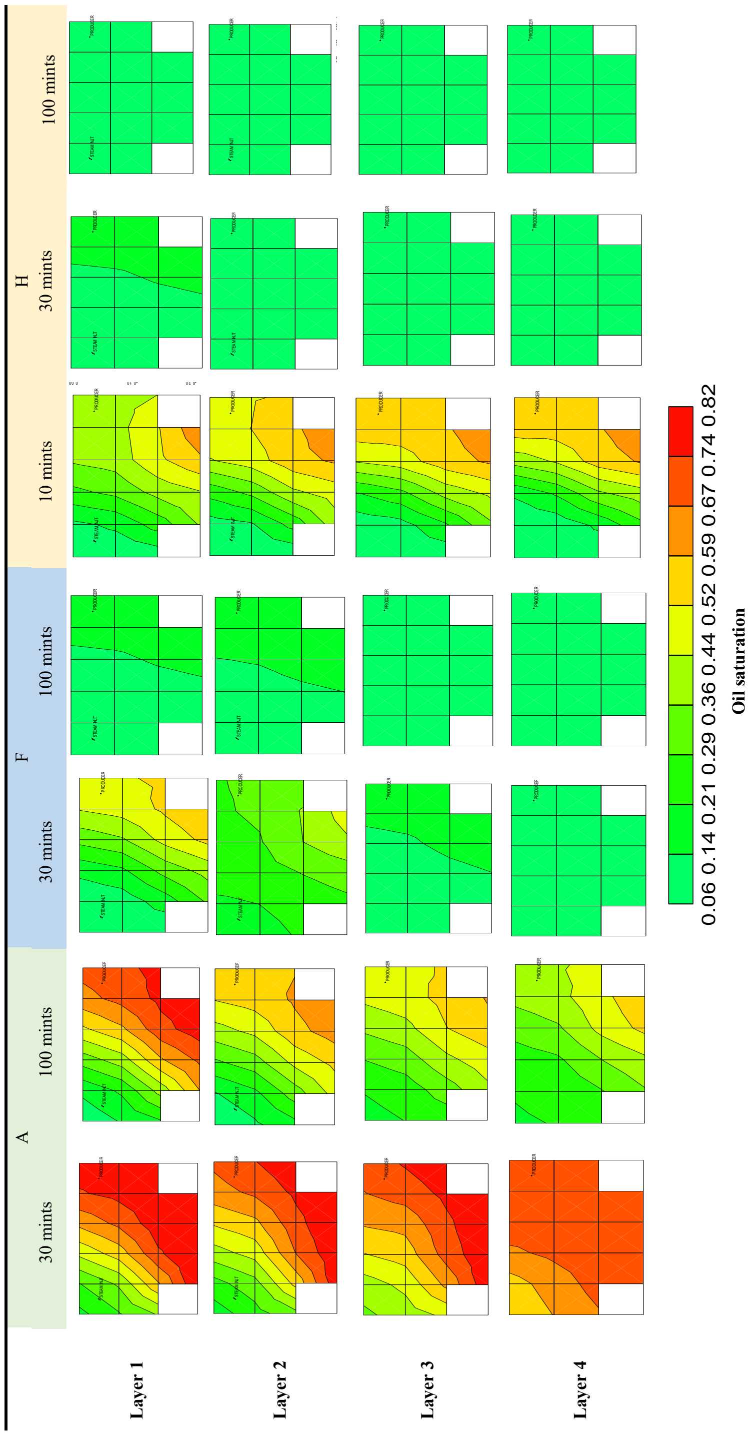


Figure 12 Oil saturation variation steam flooding in four different layers in the different intervals of times in water-wet medium for cases with a high recovery factor in light, medium and heavy oils (e.g. Oil-A, Oil-F, and Oil-H) (see online version for colours)



To support the conclusion and demonstrate the efficiency of the steam flooding for different crude oil qualities, layers were observed for changes in the oil saturation with time only for cases with a high recovery factor in light, medium and heavy oils. Figure 12 show the variation in the oil saturation upon steam flooding in four different layers of heavy (Oil-A), medium (Oil-F) and light (Oil-H) oil at medium SQ with a high IR. It is clear from this figure that displacing oil by steam in all layers is efficient, offering a maximum recovery which could be linked to the effective thermal mechanisms improved sweep efficiency and minor steam override issue. These results may lead to a better understanding of reservoir selection criteria and operational parameters as presented by Hama et al. (2014).

5 Conclusions

Steam flooding was numerically modelled in this study to optimise reservoir and operational parameters. The results obtained for the first scenario indicated the cumulative oil increases with increasing the quality of crude oils due to the increase in the oil mobility and reduction of the oil viscosity which favours the mobility ratio. The maximum oil was produced in the Oil-D, Oil-F and Oil-H cases. Comparatively, steam flooding was efficient in Oil-H (light oil) and least feasible for Oil-A (heavy oil). Steam flooding was also found to be much more suitable for the water-wet reservoirs which could be due to a lesser level of adhesion tension in the water-wet system compared to the oil-wet system.

The results obtained for the operational aspect indicated that high SQ with an intermediate level of the IR or medium SQ with a high IR is the best choice to improve recovery at any kind of heavy oil reservoir. It was also found that with an increase in the SQ at a specific IR, total oil production and oil recovery would increase. With the increase in the IR at a specific SQ, recovery increases except for the high-level SQ and IR for the Oil-A reservoir. Comparatively, the recovery factor of Oil-F and Oil H reservoirs for all conditions is higher than Oil-A which indicates the suitability of the medium and light oils for steam flooding. It is recommended to further evaluate the SQ and IR to get cost-effective recovery by steam flooding.

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