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Investigation of heavy oil displacement by water injection

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ABSTRACT

Escalating worldwide demand for energy imposes obligations on oil companies to increase their current levels of oil production. Therefore, oil producers started to develop unconventional hydrocarbon resources to secure additional energy outputs. Heavy oil reservoirs are considered one of the more extensively distributed unconventional reservoirs due to their high viscosity. Primary oil production mechanisms are usually ineffective in heavy oil reservoirs as they leave substantial quantities of oil unrecovered. Waterflooding is an improved oil recovery (IOR) technique, which is widely implemented to increase oil recovery from depleted light oil reservoirs. This technique is one of the simplest forms of today's IOR mechanisms. Due to their economic attractiveness, waterflooding techniques are quite often implemented on heavy oil reservoirs regardless of the presence of unfavorable mobility ratios. In this study, a numerical sensitivity study was conducted to investigate the performance of waterflooding operations in heavy oil reservoirs under different project design considerations. The study was performed in order to reveal and better understand the functional relationships between several reservoir and project design parameters, which govern the immiscible displacement of heavy oil during waterflooding in homogeneous reservoirs, and ultimately the oil recovery factor. The project design parameters include injection rate, effective aspect ratio of the well pattern unit, API, and injected water temperature. These relationships describe and suggest the optimum operational conditions under existing reservoir conditions in which waterflooding of heavy oil reservoirs may yield better recovery performances. These results have potential applications in modeling immiscible displacements and in the scaling of laboratory displacements to field conditions.

Keywords: heavy oil, waterflooding, unconventional oil, viscous dominant displacement, gravity dominant displacement.

INTRODUCTION

The global oil consumption is expected to reach 120 MMbbl/day by 2040 compared to its current level of 94 MMbbl/day (EIA, 2016). This represents an increase of about 27%, which is driven mainly by the increasing energy demand from emerging economies in the world. Accordingly, new unconventional resources should be explored to cope with this challenge. Despite the current developments in alternative energy fields, fossil fuels will be the predominant source of energy for the next decades. But the current hydrocarbon resources are approaching their maturity and the production from these resources started to decline according to many recent studies (Algharaib, 2009; Jorshari et al., 2013; Morrow and Buckley, 2011; Pamukcu, 2006; Resnyanskiy and Babadagli, 2011). Moreover, several factors are challenging for the exploration of new resources that restrict the economical and safe development. Therefore, reconsideration of the existing unutilized and undepleted hydrocarbon resources is a vital option to meet the expected energy growth.

Unconventional liquid hydrocarbon resources are those oil accumulations that are economically exploitable only by using advanced technologies including massive stimulation treatments, and/or special recovery processes due to their intrinsic rock and fluid properties (Singh, 2006). Examples of these special properties are low matrix permeability, presence of natural fractures, and/or high oil viscosity. In a broad classification, unconventional hydrocarbon resources include tight gas reservoirs, coalbed methane, shale gas, gas hydrates, and heavy oil (Singh, 2006; Singh and Holditch, 2007).

Heavy oil makes a large portion of unconventional resources (Meyer et al., 2007). Heavy oil reservoirs are characterized by having a viscosity range between 100 and 10000 cp, which corresponds to an oil API gravity range of 10 – 20 API. Usually, heavy oil resources are found at shallow depths (<1600 ft) with a high hydrocarbon saturation of 60 to 80%. The worldwide reserve of heavy oil is estimated around 3,396 Bbbl, which is more than two times larger than the light oil reserves of 1,471 Bbbl (EIA, 2011; Meyer et al., 2007). Heavy oil resources are found in many regions around the world. Moreover, heavy oil resources are distributed among 192 sedimentary basins in approximately 1700 fields and the majority of these resources are found in 52 giant fields (Meyer, 1998). Despite the vast availability of heavy oil resources, they are far less developed compared to light oil resources. For example, the production of heavy oil was estimated around 2 MMbbl/d in 2007 as compared to a total of 87 MMbbl/day production of light oil (Sandrea and Sandrea, 2007).

Currently, there is a growing interest in developing heavy oil resources worldwide (Gutiérrez et al., 2013; Liguo et al., 2012; Singh and Babadagli, 2011). Normally, thermal Enhanced Oil Recovery (EOR) techniques are utilized to produce oil from heavy oil reservoirs. Indeed, the oil industry has experienced many successful practices of applying thermal EOR method to boost recovery factor from heavy oil reservoirs (Peterson et al., 2011; Hascakir et al., 2010; Malik et al, 2011). The literature indicates that, in 2010, there were 60 thermal EOR projects in USA alone with a daily production of 290 Mbbl/day (Moritis, 2010). Currently, steam injection is considered as the most widely used thermal EOR method. There were 46 steam flooding projects in USA in 2010, which were accounted for more than 90% of thermal EOR production (Moritis, 2010).

Indeed, steam flooding is an expensive practice, which requires consumption of large volume energy for subsurface injection. As an alternative to steam flooding, hot water injection is less-expensive and less-complicated process (Torabi et al., 2012). Therefore, many researches were focused to investigate the performance of hot water flooding under different conditions. For example, Alajmi et al. conducted an experimental study to evaluate the performance of segmented injection of unheated water and hot water on a reservoir from the Middle East (Alajmi et al., 2009). They concluded that the injection scheme, in which the hot water injection followed the unheated water injection, yielded the best performance among the various investigated scenarios. Practically, hot waterflooding technique is seldom employed because of the high heat losses, which reduces the efficiency in lowering the viscosity of oil. Nevertheless, it is an alternative process in deep heavy oil reservoirs, as indicated by Farouq Ali (Farouq Ali, 1974), where high injection pressure but relatively low temperatures are desired.

Besides thermal EOR processes, water flooding technique is frequently implemented to produce heavy oil. According to the literature, water flooding is among the most widely utilized enhanced oil recovery method (EOR). However, the performance of this technique in heavy oil reservoirs is limited by low sweep efficiency, unfavorable mobility ratio, viscous fingering of the injected water, high water cut, early water breakthrough, and low recovery factor (Willhite, 1986; Forrest and Graig, 2004; Martin and dew, 1968; Farouq Ali, 1974; Adams, 1982; Karakas et al., 1986). Nevertheless, water flooding technique is relatively inexpensive and easy process to implement as compared to thermal recovery methods; therefore, it is still extensively employed in heavy oil reservoirs.

The results of conducting water flooding in heavy oil reservoirs are well documented in the literature (Smith, 1992; Alvarez and Sawatzky, 2013; Hanafy and Mansy, 1999; Brice and Renouf, 2008). In western Canada, for instance, there have been more than 300 water flooding projects in heavy oil reservoirs. In fact, most of these projects revealed good economic incentives even though they were implemented in marginal reservoirs (Mei et al., 2012). Miller presented an overview of water flooding applications in heavy oil reservoirs in Western Canada (Miller, 2006). In his study, Miller presented a number of recommendations to improve the performance of water flooding in heavy oil reservoirs. In another work, Mohammadpoor and Torabi presented an overview of EOR applications in heavy oil reservoirs (Mohammadpoor and Torabi, 2012). They reviewed the range of applicability of EOR methods on heavy oil reservoirs and observed that the conditions to implement water flooding on heavy oil reservoirs are totally different than those for light oil reservoirs. In an experimental work, Mai and Kantzas investigated the effect of water injection rate on heavy oil recovery factor for unconsolidated sand reservoirs (Mai and Kantzas, 2008). They concluded that a significant portion of heavy oil can be recovered after water breakthrough by properly controlling the design of water flooding operations. In another work, Mai and Kantzas tested the performance of water flooding on two fluid systems, with oil viscosities of 4500 cp and 11500 cp, under low-injection rates (Mai and Kantzas, 2009). They stated that, for low-injection rates, water imbibition can be used to stabilize the water flood and improve the oil recovery. Furthermore, they concluded that water flooding can, therefore, be a practical alternative to the thermal-EOR technology, even for fields with high oil viscosity. In a recent work, Mei et al. conducted lab experiments on a water-wet micromodel to investigate the effect of time, viscosity ratio, and water injection rate on the imbibition rate (Mai and Kantzas, 2012). They showed that water flooding became more efficient and significant volumes of oil had been produced intermittently for low-injection rates.

Despite the previous works, there is still a need to explore the performance of water flooding in heavy oil reservoirs. The objective of this research is to investigate the effects of several parameters on the performance of water flooding in heavy oil reservoirs using a numerical simulation tool. These parameters include water injection rate, API gravity of heavy oil, effective aspect ratio of the well pattern unit, and the temperature of the injected water. The sensitivities for these parameters are evaluated with respect to oil recovery factor at water breakthrough. The results reveal the importance of controlled water flooding operations in heavy oil reservoir to attain the maximum possible recovery factor.

METHODOLOGY

A cross section of a typical heavy oil reservoir, encountered in the Middle East, is represented by a 2-Dimensional reservoir model (100×100 cells), which was built and checked for the grid sensitivity using a commercial reservoir simulation tool. The dimensions of the cross section are 2000 ft in length, 50 ft in width, and 75 ft in thickness. A vertical well was imposed at the injection end of the reservoir and another vertical well was imposed at the production end. Figure 1 shows a schematic presentation of the cross section of an injector and a production well in a 2-D setting.

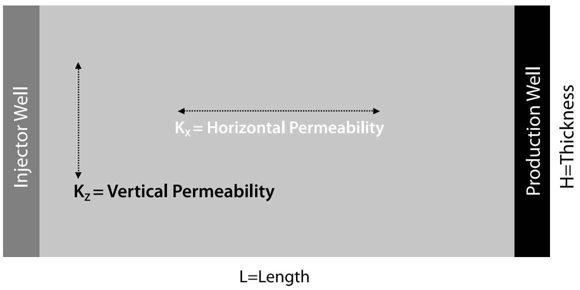

Fig. 1. Schematic of 2-D model used in this study.

Furthermore, rock and fluid data, representing a typical Middle Eastern reservoir (Alajmi, Algharaib, Gharbi, 2009), are shown in Table – 1. The data were fed to the numerical model that represents the typical heavy oil sandstone reservoir considered in this study.

Table 1. Rock and Fluid Properties.

K_x = 1,000 md	ρ_w = 62.4 lbm/ft^3	T = 85 °F
K_z = 0.01 md	ρ_o = 50 lbm/ft^3	ϕ = 0.1

Figure 2 shows the relationship between heavy oil viscosity and temperature for different API oil considered in this study. These relationships were constructed using analytical approach (Farouq Ali et al., 1997). Moreover, Figure 3 shows the relative permeability relationships of heavy oil and water for the different API oil used in this study (Wang et al., 2006).

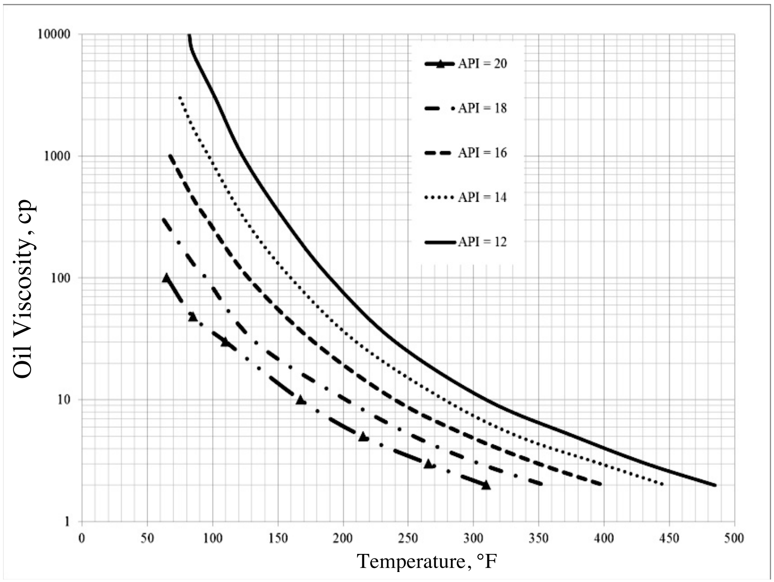

Fig. 2. Oil viscosity versus temperature for various API oils.

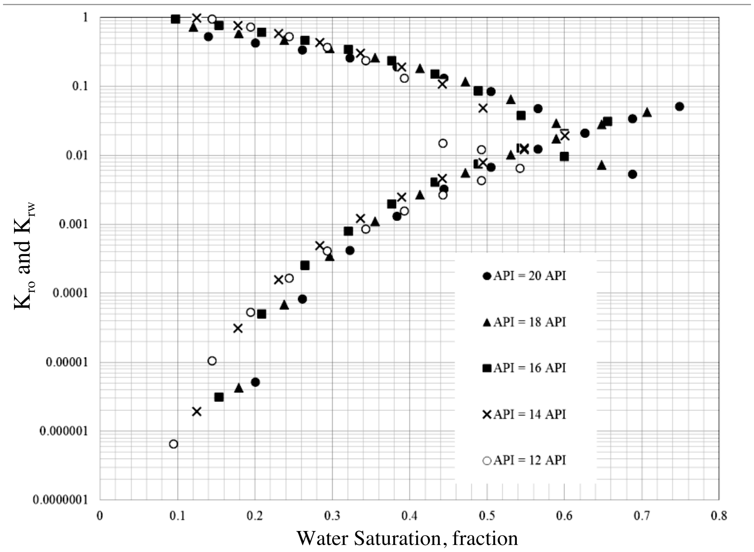

Fig. 3. Oil and water relative permeabilities as functions of water saturation.

The rock and fluids characteristics of the developed simulation model represent the properties of a typical heavy oil reservoir. After developing the simulation model, many simulation runs were conducted under various conditions. The effects of water injection rate, API gravity, effective aspect ratio of the well pattern unit, and injected water temperature on the performance of water flooding were investigated by varying one parameter at a time and recording the oil recovery factor at water breakthrough (RF|BT).

The effect of water injection rate is shown in terms of “Gravity Number (N_g)”. As well known in the literature, the gravity number (N_g) is defined as the ratio of gravity forces to the viscous forces (Green and Willhite, 1998). Mathematically it is represented as

$$\boldsymbol{N_g} = \frac{\boldsymbol{K_{avg}\Delta\rho H}}{\boldsymbol{\upsilon_T \mu_o L}} \qquad \text{Eq- 1}$$

where:

N_g	=	Gravity number.
K_{avg}	=	Average permeability in transverse direction.
$\Delta\rho$	=	Density difference between water and oil.
H	=	Reservoir thickness.
υ_T	=	Velocity in transverse direction.
μ_o	=	Oil viscosity.
L	=	Reservoir length.

Low gravity numbers represent displacement processes where viscous forces are dominant, whereas high gravity numbers represent displacement processes where gravitational forces are dominant. The effect of API degree on the performance of water flooding was investigated through considering the various relationships between oil viscosity and temperature as shown in Figure – 2. In this study, five different degrees of API were considered: 12, 14, 16, 18, and 20 API. Furthermore, the effect effective aspect ratio of the well pattern unit on oil recovery factors at breakthrough was investigated. Mathematically, the effective aspect ratio of the well pattern unit (R_L) is defined as

$$\boldsymbol{R_L} = \frac{\boldsymbol{L}}{\boldsymbol{H}}\sqrt{\frac{\boldsymbol{K_z}}{\boldsymbol{K_x}}} \qquad \text{Eq- 2}$$

where:

R_L	=	Effective aspect ratio of the well pattern unit.
L	=	Reservoir length.
H	=	Reservoir thickness.
K_Z	=	Vertical permeability in z-direction.
K_X	=	Horizontal permeability in x-direction.

Indeed, the effective aspect ratio of the well pattern unit becomes more important in the transition between gravity-dominated and viscous-dominated displacements (Algharaib et al., 2006). As known, low values of R_L represent a displacement when the transverse movement is dominant, whereas high values represent dominant vertical movements. Finally, the effect of the injected water temperature was investigated by varying the temperature of the injected water to 85, 150, and 300 °F while keeping the reservoir temperature at 85 °F.

RESULTS AND DISCUSSION

The results show that the investigated parameters have various degrees of influence on heavy oil recovery factor at water breakthrough. The effect of water injection rate, through gravity number (N_g), is presented first.

1- Effect of Gravity Number

Several numerical experiments were conducted with different water injection rates to investigate the effect of gravity and viscous forces on heavy oil recovery factor. Figure 4 shows the relationship between oil recovery factor at breakthrough and gravity number for a reservoir with $R_L = 0.1$, API = 20 API and an injection temperature of 85 °F for different values of pore volumes of water injected. Specifically, Figure 4 shows the oil recovery factors at water breakthrough (BT), the oil recovery factor at one pore volume of water injected (1 PV), the oil recovery factor three pore volumes of water injected (3 PV), and the oil recovery factor at five pore volumes of water injected (5 PV) as functions of the gravity number (N_g).

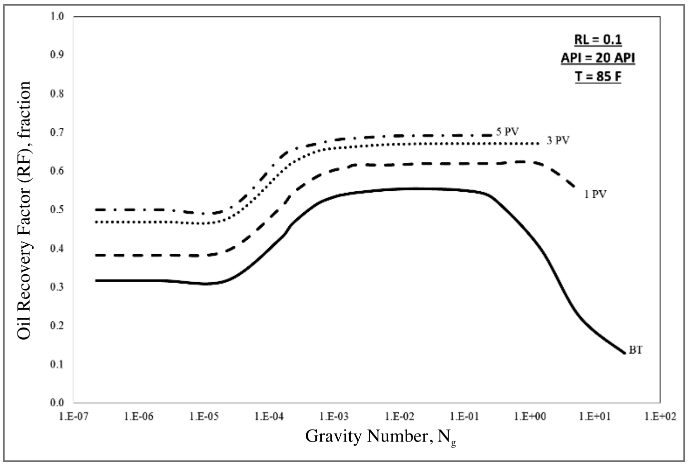

Fig. 4. Oil recovery factor versus gravity number at different points.

The results indicate that oil recovery factor is insensitive to the variations in gravity number during viscous dominant displacements (i.e., low gravity number cases). Figure – 4 suggests that oil recovery factors for cases with gravity number values below 1×10^{-5} remain constant at a specific pore volume of water injected. This is due to the fact that, at low gravity numbers, water is injected at high velocity in which viscous fingering is dominant and the displacement front is unstable. In these cases the injected water penetrates the oil zone toward the production wells without effectively displacing the oil; hence the recovery factor remains unchanged.

In addition, Figure 4 shows that the oil recovery factor at water breakthrough is diminishing for cases with high gravity number, i.e., for cases with low water injection rates. This is due to the fact that the injected water will flow toward the bottom of the formation leaving substantial quantities of oil not displaced in the upper parts of the structure during gravity dominant displacement (high gravity numbers). This trend is also expected for oil recovery factors at other pore volumes of water injected.

Figure 4 shows the presence of an intermediate region between gravity and viscous dominant displacement regions that characterized by higher oil recovery factors. In fact, the differences between oil recovery factors obtained within this intermediate region and viscous dominant region might reach 20%. This observation suggests that operating water flooding projects in heavy oil reservoirs within this region should be considered. It appears that a balance between the transverse displacement, which is supported by viscous force, and the vertical displacement, which is supported by gravity force, is encountered in this region. As shown in Figure 4, this region is bounded between gravity numbers of 1×10^{-3} and 1×10^{-1} for the case studied. The literature shows that this range of gravity numbers is similar to the range for water flooding of light oil reservoirs (Coll et al., 2001; Mai and Kantzas, 2007). Figure 4 shows that a substantial improvement in oil recovery factor is possible if the water injection continues after water breakthrough for gravity dominant displacement (high N_g). It is also displayed in Figure 4 that the continuation of water injection after water breakthrough will result in higher oil recovery factors in viscous dominant displacements (low gravity number). For example, oil recovery factor was increased by 20% after water breakthrough when 5 pore volumes were injected. For low gravity number cases, the relationship between the additional oil recovery factor after water breakthrough and pore volume of water injected is shown in Figure 5. This relationship can be expressed mathematically as in Equation 3, with a correlation coefficient 0.997:

$$\Delta \boldsymbol{RF} = \mathbf{0.0737} \times \boldsymbol{ln}(\boldsymbol{PVI}) + \mathbf{0.0674} \qquad \text{Eq- 3}$$

where:

ΔRF = Additional oil recovery after breakthrough, fraction

PVI = Pore volume of water injected, pv

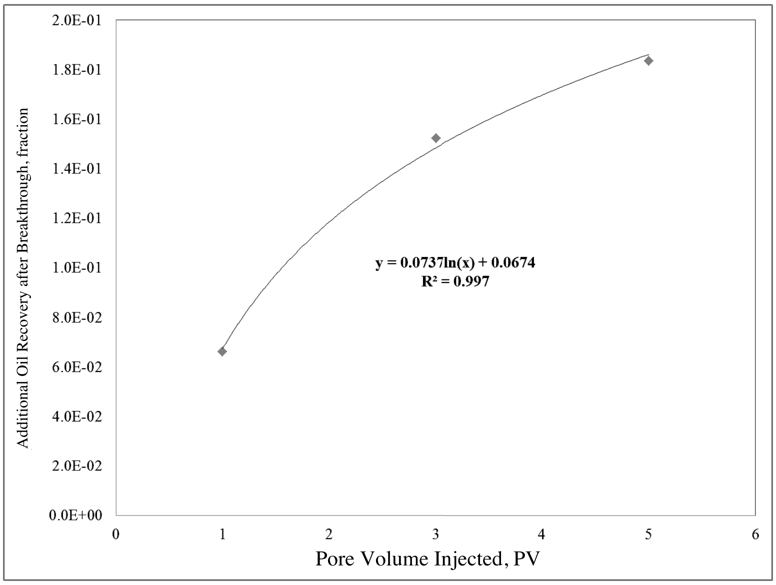

Fig. 5. Additional Oil after Breakthrough versus Pore Volume Injected.

For reservoirs with similar properties as the reservoir considered in this study, Equation -3 can be used to predict the additional oil recovery after water breakthrough as a function of pore volume of water injected.

2- Effect of Oil Viscosity

The effect of oil viscosity on the performance of water flooding operations in heavy oil reservoirs is investigated through conducting several simulation cases under different API gravity, i.e., quality of oil. Besides the base case, with 20 API, four cases were considered with API degrees of 18, 16, 14, and 12. Figure 6 shows the relationship between oil recovery factors at water breakthrough and gravity number as a function of API degree. Figure 6 shows that waterflooding performs poorer in reservoirs with high oil viscosities (Low API degree) during the entire range of gravity number (N_g). Figure -6 shows that higher viscosity of oil moves the curves representing the relationship between oil recovery factor and gravity number downward. Interestingly, the range of gravity numbers, which ensure the highest oil recovery factor, is almost the same regardless of the API degree. It is obvious from Figure 6 that the oil recovery factor for the viscous dominant displacements (low N_g values) can be correlated with API degree.

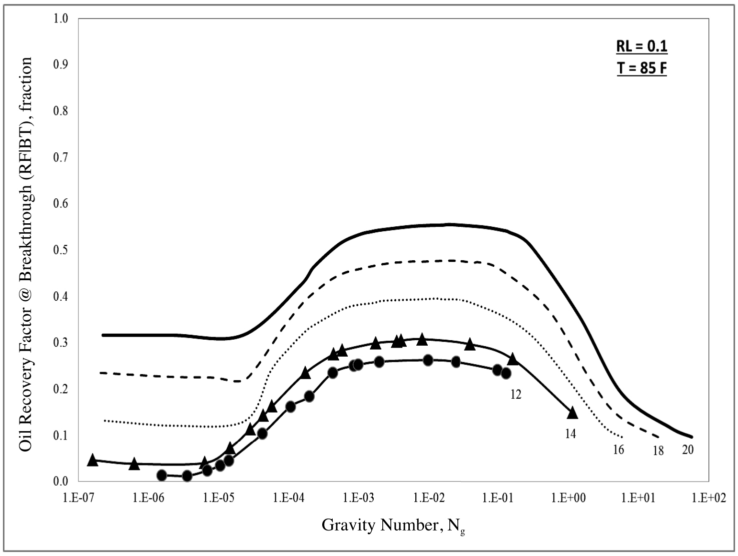

Fig. 6. Oil recovery factor versus gravity number for various API oils.

3- Effect of effective aspect ratio of the well pattern unit (R_L)

The role of effective aspect ratio of the well pattern unit (R_L) on heavy oil recovery factor is investigated in this section. Figure 7 shows the relationship between oil recovery factor at water breakthrough and gravity number under different R_L values when API = 18 °API and water injection temperature is 85 °F. Figure 7 shows a reduction in oil recovery factors at water breakthrough for gravity dominant displacements (high gravity number) when the effective aspect ratio of the well pattern unit is increased. It appears that the gravitational forces lower the oil recovery factors at water breakthrough when the transverse displacement is reduced, i.e., higher R_L values. Moreover, Figure 7 shows that, for gravity dominant displacement, the reduction in oil recovery factor at water breakthrough may reach more than 30% when implementing the water flooding project in high effective aspect ratio of the well pattern unit rather than low effective aspect ratio conditions. Indeed, the magnitude of effective aspect ratio of the well pattern unit can be controlled by managing the distance between the injection and production wells. Therefore, this observation implies that the selection of well spacing is a critical parameter when designing water flooding projects for heavy oil reservoirs.

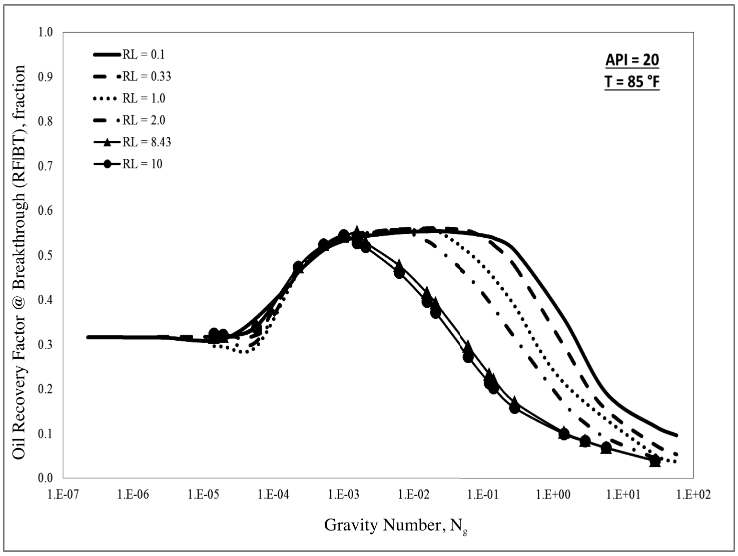

Fig. 7. Oil recovery factor versus gravity number for different RL.

On the other hand, Figure 7 shows that the effect of effective aspect ratio of the well pattern unit on oil recovery factor at water breakthrough is negligible in the viscous dominant displacements (low gravity number). This is due to the fact that viscous forces, and consequently viscous fingering, are affected mainly by fluid properties rather than reservoir dimensions and rock properties. It is worth mentioning that a similar behavior was observed for different API oils, however, with lower values for oil recovery factors at water breakthrough. Figure 7 also shows that the range of gravity numbers, which ensure the highest oil recovery factors, shrinks as the effective aspect ratio of the well pattern unit is increased and reduced to a single point for cases with values of effective aspect ratio of the well pattern unit of more than 10.

Figure 7 suggests that, regardless of effective aspect ratio of the well pattern unit, for heavy oil reservoirs (with API < 20) and water injection temperature of 85 F, operating water flooding projects with gravity numbers conditions of 1×10^{-3} will ensure the highest oil recovery factors.

As discussed earlier, vertical movement is more dominant for cases with higher values of effective aspect ratio of the well pattern unit. Hence, the injected water moves toward the bottom of reservoir, due to density difference between oil and water, resulting in lower values of oil recovery factor at water breakthrough. In other words, the magnitude of gravity number at which displacement is shifted to viscous dominant from transition zone is lowered for cases with high values of effective aspect ratio of the well pattern unit.

4- Effect of Injected Water Temperature

The effect of water temperature to flood heavy oil reservoirs on oil recovery factor is investigated in this section. Figure 8 shows the effect of water injection temperature on oil recovery factors at breakthrough for a heavy oil reservoir with API = 20 API and R_L = 0.1. Three different temperatures of 85, 150, and 300 °F were considered. Figure 8 shows that increasing the temperature of the injected water has insignificant effect on the performance of water flooding in heavy oil reservoirs for cases with viscous and gravity dominant displacements and a slight improvement in-between. This can be explained because, for viscous dominant flow (low gravity number), the effect of temperature is negligible due to the short residency of hot water in reservoir as a result of high injection rate, whereas, for gravity dominant flow (high gravity number), the effect of temperature is negligible due to the loss of heat to the surrounding formations.

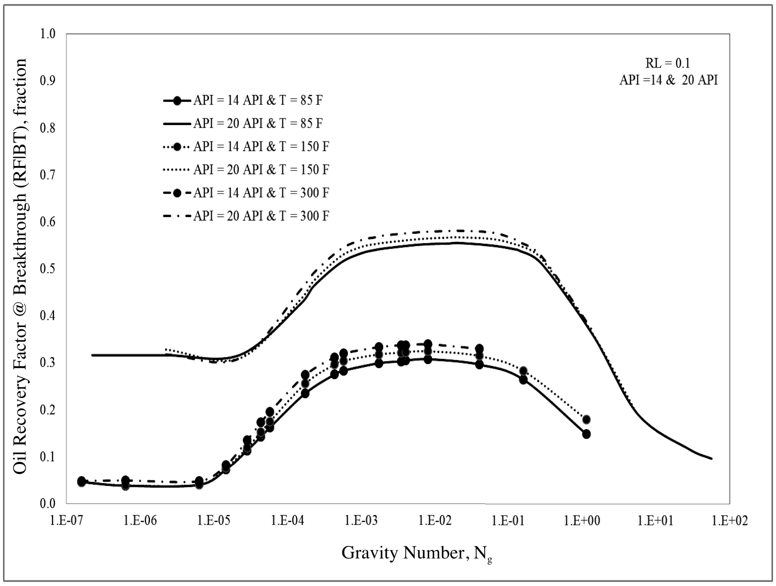

Fig. 8. Oil recovery factor versus gravity number at different temperatures.

Moreover, Figure 8 shows that the gravity number has more influential effect on oil recovery factors at water breakthrough than water temperature. Hence, more oil can be produced by controlling the gravity number rather than the temperature of the injected water.

Scalability of dimensionless parameters and Outcomes verification

The previous observations and discussions about the performance of waterflooding in heavy oil reservoirs were made generic by presenting the results in terms of oil recovery factor at water breakthrough versus gravity number at certain effective aspect ratio of the well pattern unit (R_L), API degree, and water injection temperature. These parameters were shown to be enough to scale up the results. Three different reservoirs were considered to show the scalability of gravity number (N_g) and effective aspect ratio of the well pattern unit (R_L) in waterflooding applications. In Case # 1, k_{avg} = 1000 md, k_z = 0.01, L = 1000 ft, H = 75 ft, μ_o= 48 cp, API = 20 API, T = 85 °F, ρ_w = 62.4 lbm/ft^3, and ρ_o= 50 lbm/ft^3. Case # 1 is considered as the base case. In Case # 2, the oil density was changed to 53.74 lbm/ft^3 and the water injection rate was changed accordingly to obtain the same gravity numbers in each run. Furthermore, in Case # 3, k_{avg} and kz were set to 5000 and 0.05 md, respectively. Cases 1 and 2 were used to show the scalability of gravity number (N_g), whereas Cases 1 and 3 were used to show the scalability of the effective aspect ratio of the well pattern unit (R_L). Figure 9 shows a comparison between Cases 1 and 2 in terms of oil recovery factors at water breakthrough versus gravity number. Figure 9 shows an excellent agreement between Cases 1 and 2, which implies the scalability of gravity number (N_g). Furthermore, Figure 10 shows a comparison between Cases 1 and 3. Figure 10 shows an excellent agreement between the two cases implying the scalability of effective aspect ratio of the well pattern unit (R_L).

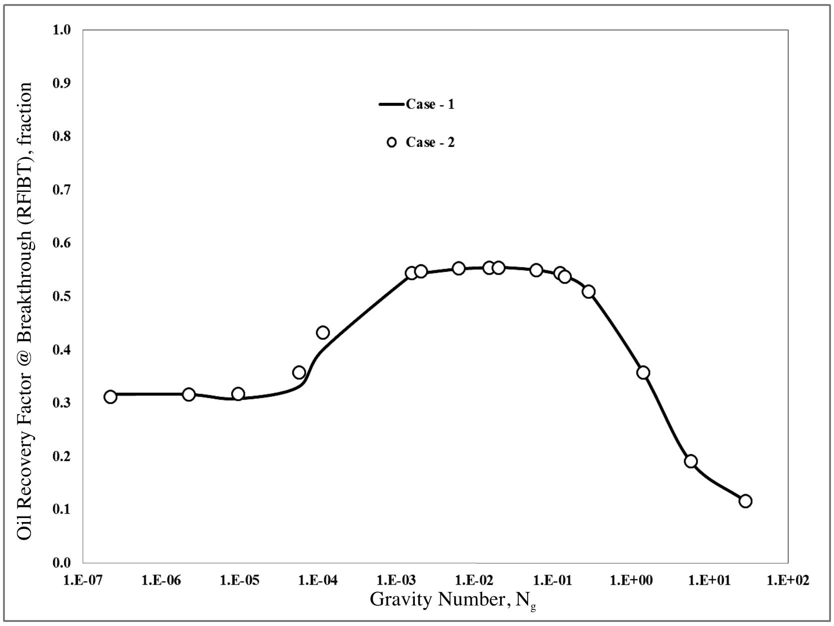

Fig. 9. Scalability of N_g.

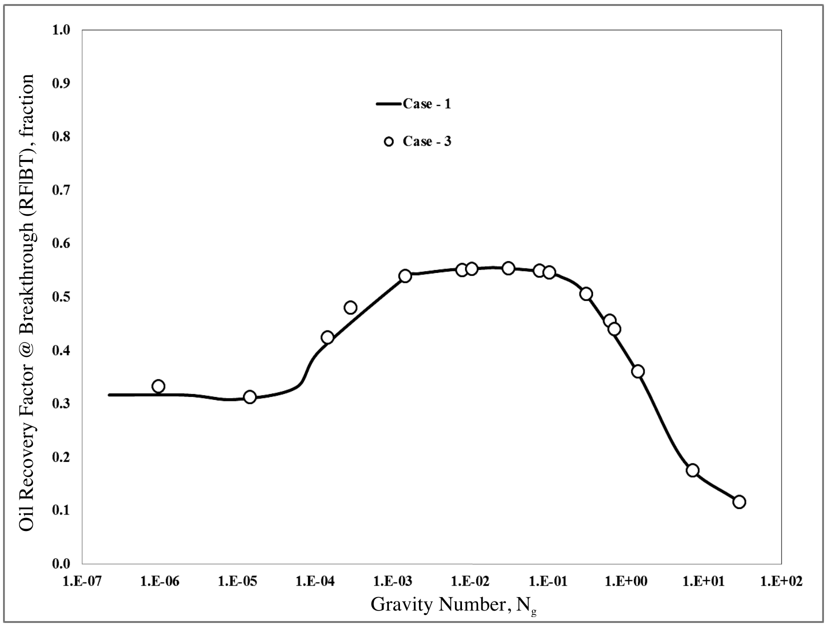

Fig. 10. Scalability of R_L.

Moreover, the outcomes of the simulation model should be validated, against actual cases, in order to increase our confidence on the conclusions drawn from this study. In fact, there are limited numbers of studies that report the oil recovery factor at breakthrough resulting from waterflooding of heavy oil reservoirs. Table 2 shows a comparison between the results of some reported waterflooding cases in the literature with the simulated cases in this study. In this task, we simulated the reported waterflooding cases in Table -2 and compared the oil recovery factors to the reported ones. Due to the limitations on data availability, we limited our comparison to the recovery factor at water breakthrough. This comparison is also presented in graphical format in Figure 11. The figure shows a good agreement between simulation and actual results with a correlation coefficient of 0.726.

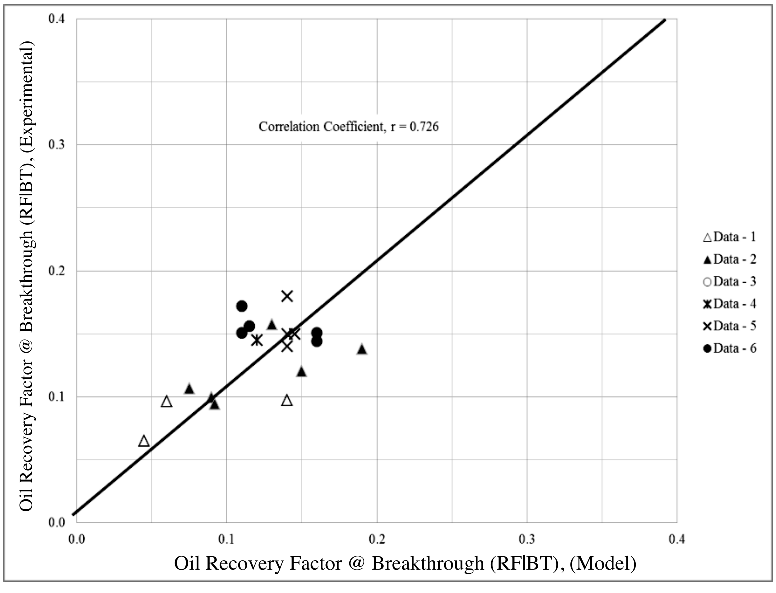

Fig. 11. Validation of simulation model with experimental data.

Table 2. Varification of model outcomes.

Data	K_{avg}	k_z	Diameter	Height	Length	ρ_w,	ρ_o,	μ_o	v_T	N_g	R_L	RF | BT		Ref
	md	md	ft	ft	Ft	lbm/ft^3	lbm/ft^3	cp	ft/d			Reference	This Study	
1	780	780	8.50E-02	8.50E-02	1.75E+00	62.4	61.26	11,500	1.99E-01	8.32E-04	20.53	0.0975	0.14	(Mai and Kantzas, 2008)
	2,790	2,790	1.25E-01	1.25E-01	5.75E-01	62.4	61.26	11,500	9.21E-02	2.87E-02	4.60	0.0963	0.06	
	9,730	9,730	1.19E-01	1.19E-01	6.92E-01	62.4	61.26	11,500	1.02E-01	7.18E-02	5.82	0.0650	0.045	
2	1,860	1,860	1.25E-01	1.25E-01	5.41E-01	65.4	61.15	4,650	6.90E-01	2.52E-02	4.33	0.1382	0.19	(Mai and Kantzas, 2007)
	2,800	2,800	1.25E-01	1.25E-01	5.48E-01	65.4	61.15	4,650	3.45E-01	7.49E-02	4.38	0.1572	0.13	
	2,430	2,430	1.25E-01	1.25E-01	5.45E-01	65.4	61.15	4,650	6.90E-02	3.27E-01	4.36	0.1066	0.075	
	2,790	2,790	1.25E-01	1.25E-01	5.56E-01	65.4	61.25	11,500	6.90E-02	1.45E-02	4.45	0.1203	0.15	
	2,790	2,790	1.25E-01	1.25E-01	5.76E-01	65.4	61.25	11,500	6.90E-02	1.40E-01	4.61	0.0997	0.09	
	2,580	2,580	1.25E-01	1.25E-01	5.56E-01	65.4	61.25	11,500	6.90E-02	1.34E-01	4.45	0.0942	0.092	
3	95,000	95,000	1.31E+00	3.20E-02	1.67E+00	62.4	54.90	419	1.21E+01	1.18E-01	52.06	0.080808	0.08	(Sarma et al., 1994)
	95,000	95,000	1.31E+00	3.20E-02	1.67E+00	62.4	54.90	419	9.69E+00	1.48E-01	52.06	0.05303	0.075	
	95,000	95,000	1.31E+00	3.20E-02	1.67E+00	62.4	54.90	419	2.42E+00	5.92E-01	52.06	0.027778	0.046	
4	3,600	3,600	9.25E-02	9.25E-02	1.53E+00	62.4	54.72	405	3.78E+00	4.79E-02	16.56	0.145	0.12	(Maini et al., 1990)
5	1,210	1,210	1.64E-01	1.64E-01	9.84E-01	62.4	60.72	2,140	8.02E-01	8.70E-03	6.00	0.14	0.14	(Zhang et al., 2006)
	1,060	1,060	1.64E-01	1.64E-01	9.84E-01	62.4	60.72	2,140	8.02E-01	7.62E-03	6.00	0.15	0.145	
	1,130	1,130	1.64E-01	1.64E-01	9.84E-01	62.4	60.72	2,140	8.02E-01	8.12E-03	6.00	0.15	0.14	
	1,130	1,130	1.64E-01	1.64E-01	9.84E-01	62.4	60.72	2,140	8.02E-01	8.12E-03	6.00	0.18	0.14	
6	11,550	11,550	3.61E-02	3.61E-02	3.38E-01	62.4	61.25	11,500	1.67E+00	3.25E-03	9.36	0.151	0.11	(Mai et al., 2009)
	11,810	11,810	3.61E-02	3.61E-02	3.38E-01	62.4	61.25	11,500	1.67E+00	3.32E-03	9.36	0.172	0.11	
	10,240	10,240	3.61E-02	3.61E-02	3.38E-01	62.4	61.25	11,500	1.67E+00	2.88E-03	9.36	0.156	0.115	
	920	920	3.61E-02	3.61E-02	3.44E-01	62.4	61.25	11,500	1.67E+00	2.54E-04	9.55	0.151	0.16	
	970	970	3.61E-02	3.61E-02	3.44E-01	62.4	61.25	11,500	1.67E+00	2.68E-04	9.55	0.144	0.16	

CONCLUSION

In light of the previous discussion, we concluded that the influence of gravity number on oil recovery factor can be characterized into three different regions: low gravity-high viscous forces (region 1), balanced gravity-viscous forces (region 2), and high gravity-low viscous force (region 3). In the low gravity-high viscous forces region (region 1), oil recovery factors are insensitive to the changes in gravity number, due to the dominancy of viscous fingering effect. Similarly, in the high gravity-low viscous forces region (region 3), changes in gravity number show insignificant effects on oil recovery factor. Region 3 experiences very low water injection rates where the injected water tends to underride oil column, due to density differences, and accumulates at the bottom of the formation. On the other hand, the balanced gravity-viscous forces region (region 2) experiences a pronounced impact of gravity number on oil recovery factor. Within region 2, a maximum oil recovery factor was obtained where a balance between gravity and viscous forces is believed to contribute to the gain in oil recovery factor. Therefore, a recommendation can be made to field operators to design their operations to be within the gravity number range of region 2.

The results also indicate that region 2, in which the maximum oil recovery factor is recorded, was shown in different cases of API reservoirs. However, region 2 diminishes as the effective aspect ratio of the well pattern unit is increased. Finally, the results show that the temperature of the injected water has an insignificant effect on oil recovery factor and that more oil can be produced by controlling injection rate rather than the temperature of the injected water.

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التحقيق في نزوح النفط الثقيل عن طريق حقن المياه

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الخلاصة

التصاعد في الطلب العالمي على الطاقة يفرض التزامات على شركات النفط لزيادة مستوياتها الحالية من إنتاج النفط. ولذلك، بدأ منتجو النفط في تطوير موارد هيدروكربونية غير تقليدية لتأمين مخرجات إضافية للطاقة. وتعتبر خزانات النفط الثقيل واحدة من أكثر الخزانات غير التقليدية توزعاً على نطاق واسع بسبب لزوجتها العالية. وعادة ما تكون آليات إنتاج النفط الأولية غير فعالة في خزانات النفط الثقيل لأنها تترك كميات كبيرة من النفط غير مستردة. وتعتبر تقنية الغمر بالمياه تقنية محسنة لاستخلاص النفط التي يتم تطبيقها على نطاق واسع لزيادة استخراج النفط من خزانات النفط الخفيف المستنفدة. هذه التقنية هي واحدة من أبسط أشكال إنتاج النفط الأولية اليوم. وبسبب جاذبيتها الاقتصادية، غالباً ما يتم تطبيق تقنيات غمر المياه على خزانات النفط الثقيل بغض النظر عن وجود نسب التنقل غير المواتية. تم في هذه الدراسة إجراء دراسة حساسية عددية للتحقق من أداء عمليات الغمر بالمياه في خزانات النفط الثقيل في إطار اعتبارات تصميم مختلفة للمشروع. وقد أجريت الدراسة من أجل الكشف عن وفهم أفضل للعلاقات الوظيفية بين العديد من معلمات تصميم الخزان وتصميم المشروع، والتي تحكم النزوح غير قابل للامتزاج من النفط الثقيل أثناء غمر المياه في الخزانات المتجانسة، وفي نهاية المطاف عامل استرداد النفط. وتشمل معايير تصميم المشروع معدل الحقن، ونسبة العرض إلى الارتفاع الفعالة لوحدة نمط البئر، و API، ودرجة حرارة الماء المحقونة. هذه العلاقات تصف وتقترح الظروف التشغيلية المثلى في ظل ظروف المكامن الحالية التي يمكن أن تسفر فيها عمليات الغمر بالمياه من خزانات النفط الثقيل عوائد أفضل. ولهذه النتائج تطبيقات محتملة في نمذجة النزوح غير القابل للامتزاج وفي توسيع نطاق عمليات النزوح المختبري إلى التطبيق الميداني.