ORIGINAL PAPER - PRODUCTION ENGINEERING

# Simulation study of relative permeability and the dynamic capillarity of waterflooding in tight oil reservoirs

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## Abstract

Relative permeability ($k_r$) and the capillary pressure ($P_c$) are the central key elements defining the multiphase fluids flow behavior in the porous media. However, the dynamic capillarity should consider the dynamic relative permeability and the dynamic capillary pressure while performing waterflooding process in extremely low permeable formations. In order to improve the oil production, the advanced horizontal well drilling along with multiple hydraulic fracturing is generally instigated to penetrate the unconventional resources. The aim of this study is to consider the dynamic capillarity in a commercial reservoir simulation, while utilizing the data gained from the dynamic and steady experiments of the relative permeability and the capillary pressure impacts during waterflooding process in the core plugs of unconventional tight oil reservoirs. The commercial reservoir simulation conducted sensitivity analyses using Computer Modeling Group simulator. The outcomes show that the well production of the reservoir is overestimated while implementing steady data for forecasting due to which the oil saturation decreases more equally and further rapidly. Additionally, the forecast of the well production estimated to breakthrough sooner. However, neglecting the dynamic capillarity causes a huge breakthrough of water influx. Therefore, the core objective of this study is to probe the consequences of taking into consideration the dynamic capillarity in ultralow permeable formations while giving an alternative perspective to forecast the production of the hydraulically fractured unconventional tight oil reservoirs.

## Introduction

Low permeable reservoirs have been commonly advanced with the depletion of high-to-medium permeability reservoirs. Waterflooding is broadly utilized to improve oil recovery in unconventional resources (Wang et al. 2017). The multiphase fluids behavior in porous medium, which is delineated by the relative permeability and the relationship of water saturation with the capillary pressure ($P_c$ − $S_w$), is an essential factor to observe the waterflooding performance (Li et al. 2016). In this study, the multiphase flow behavior is described mainly by capillary characters, with respect to capillary pressure and relative permeability.

Traditionally, capillary characters are examined under steady conditions, where the time derivative of fluid saturation is zero (Baldwin and Spinler 1998). This steady condition corresponds to steady capillary pressure and steady relative permeability. The fluid pressures can determine the steady capillary pressure $P_{cs}$ during the steady displacement process as:

$$f\left(S_w\right) = P_{nw} - P_w = P_c^s \tag{1}$$

where $S_w$ is the wetting-phase saturation, and $P_{nw}$ and $P_w$ are the average of non-wetting and wetting fluid phase pressures, respectively. The determination of steady capillarity characters is laborious and time-consuming, and the inflow essentially does not happen under steady situations (Abbasi and

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Ghaedi 2018). Similarly, a significant number of researchers documented the dynamic nature of the multiphase fluid flow in porous media. Kirkham and Feng (1949) demonstrated dynamic capillary pressure in soil sediments. Ngan and Dussan (1982) exposed the presence of the dynamic capillary pressure through pore-scale experiments. Hassanizadeh and Gray (1993) linked the dynamic capillary pressure to the alteration in the open energy of stages and interfaces. A common model is utilized to muzzle the dynamic capillary pressure (Gray and Hassanizadeh 1991; Hassanizadeh et al. 2002):

$$P_c^d = P_c^s - \tau \frac{\partial S_w}{\partial t} \tag{2}$$

where $\partial S_w / \partial t$ is the rate of change in the water saturation with respect to time, and $\tau$ is the dynamic constant, which is positive. The dependence of the dynamic capillary pressure on the alternating fluid saturation is described as the dynamic influence. The dynamic constant is a straight measurement of the dynamic consequence, which means the speed for the flow system to reach a steady state where a high value of $\tau$ should mean that the time period to reach equilibrium is long. Corresponding to the dynamic capillary pressure, the dynamic wetting-phase relative permeabilities are upper than its steady counterpart, whereas the dynamic non-wetting fluid phase relative permeabilities are lesser than its steady counterpart (Barenblatt and Gilman 1987; Barenblatt et al. 1997).

Though highly complex procedures organize the behavior of the fluids in the porous medium, the steady capillarity characters are still more commonly and largely adopted. Over the last decades, the value of the dynamic coefficient is under debate; however, there is no consistent conclusion on the quantity of the dynamic coefficient at different conditions. For example, the dynamic coefficient is measured to be 106-5.7 × 107 Pa s (O'Carroll et al. 2010). Camps-Roach et al. (2010) suggested that minor pore structure needs extra rearrangement time, specifying an advanced dynamic coefficient in lower permeable formation. In low permeability formations, there are diminutive pores and pore throats, robust variation in the formation of permeability, and lack of communications. The dynamic coefficient is found to be much higher (up to 1013 Pa s) in the low permeability porous media than the high-to-medium porous media (Hassanizadeh et al. 2002; Zhang et al. 2015). Hence, the dynamic impact cannot be neglected in ultra-low permeable reservoirs. It is found that the dynamic influence must be taken into account when the permeability is lower than 100 mD (Li et al. 2017). Furthermore, Das et al. (2012) recommended that the waterflooding process in ultra-low permeable reservoirs, the capillary characters, should be called dynamic relative permeability and dynamic capillary pressure. Such occurrence is

called dynamic capillarity as proposed by Li et al. (2017). However, Salimi and Bruining (2012) noted that if the reservoir interpretation does not include the dynamic capillarity, it would overestimate the oil recovery.

Hydraulic fracturing has been broadly used to stimulate production in unconventional reservoirs (Whitmarsh et al. 2015). The triggered fractures significantly affect the multiphase flow behavior, and thus the dynamic capillarity (Tang et al. 2018). In hydraulically fractured reservoirs, the capillary pressure leads to co-current or counter-current imbibition, which is the core mechanism for the water influx recovery from the formation matrix (Salimi and Bruining 2012). Though, how to predict the influence of dynamic relative permeability and the dynamic capillary pressure on the production of unconventional tight reservoirs remains a challenge.

As discussed above, it is clear that despite its significant implications in ultra-low permeable reservoirs, only a meager effort has been made to investigate the dynamic capillarity and its effect on the waterflooding performance in ultra-low permeable reservoirs. Therefore, herein, the major objective is to investigate dynamic capillarity in unconventional reservoirs. Dynamic relative permeability and dynamic capillary pressure are achieved since waterflooding experiments on ultra-low permeable core-plug samples were subjected to the commercial numerical simulator CMG. The waterflooding process was performed on the five-spot pattern model of the target reservoir.
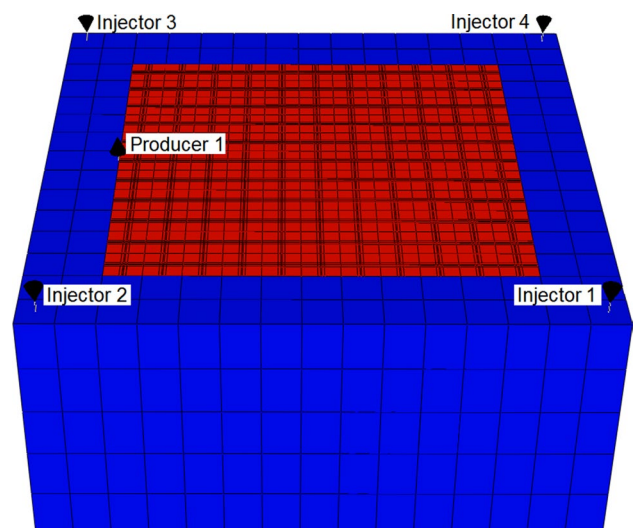


**Fig. 1** Simulated five-spot pattern reservoir with the multifracturing area (Mohammad et al. 2016, 2018)

**Table 1** Input parameters for CMG simulator

| | |
|---|---|
| Domain length (ft.) | 2788 |
| Domain width (ft.) | 2296 |
| Domain thickness (ft.) | 65 |
| Matrix permeability (mD) | 0.324 |
| Matrix porosity (%) | 5.2 |
| Average formation pressure (bar) | 145 |
| Crude oil viscosity (cp) | 1.25 |
| Formation water salinity (g/L) | 38.4 |
| Original water saturation (%) | 32 |
| Bottom hole flowing pressure (bar) | 60 |
| Artificial fracture height (ft.) | 52 |
| Fracture width (ft.) | 0.00328 |
| Fracture permeability (mD) | 18,000 |
| Fracture half-length (ft.) | 820 |
| Fracture porosity (%) | 40 |
| Crude oil density (lb/ft3) | 47.69 |
| Injection pressure (bar) | 230 |
| Fracture length (ft.) | 1970 |
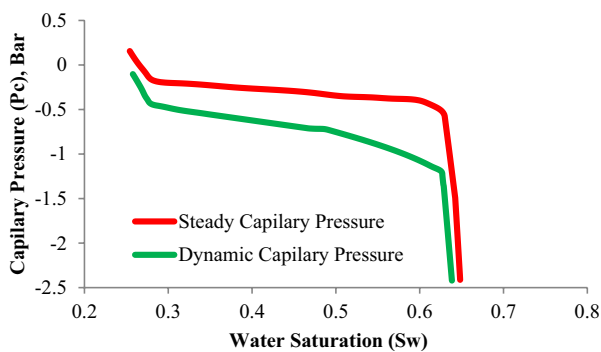


**Fig. 2** Capillary pressure in the matrix for the CMG model

## Reservoir simulation model

The target reservoir is hydraulically fractured around the production well, with a five-spot pattern for waterflooding (Fig. 1 ). One production well is horizontally drilled, and the other four injection wells are vertical. A typical five-spot section of the reservoir is chosen. The IMEX module in the CMG is employed to model the waterflooding process in the reservoir. Fractures have been considered with a separate flow system in this module. The input data parameters for the CMG simulator are shown in Table 1.
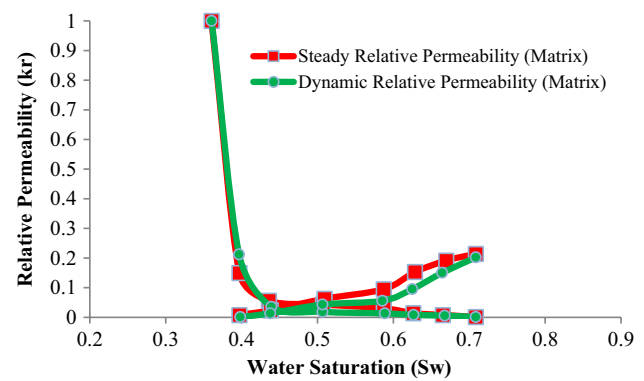


**Fig. 3** Relative permeability in the matrix for the CMG model
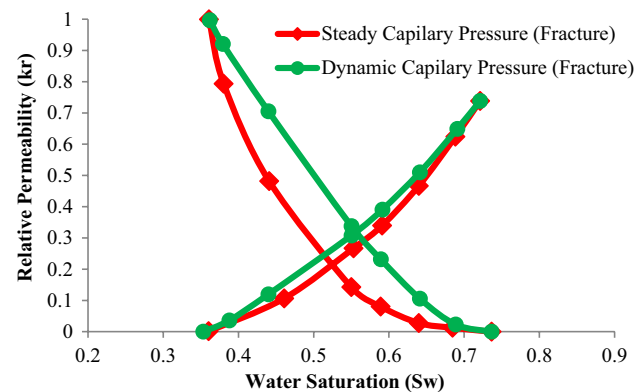


**Fig. 4** Relative permeability in the fractures for the CMG model
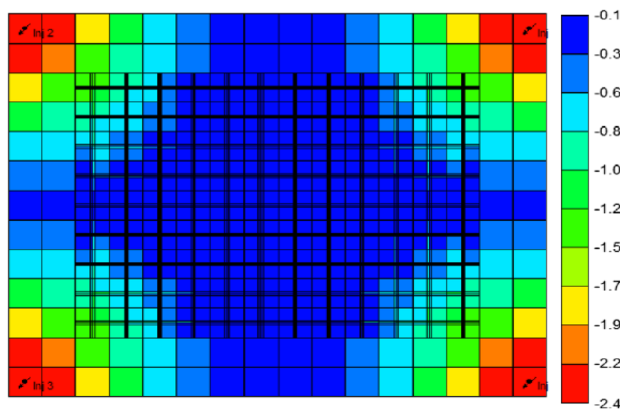
## Dynamic capillarity

The relative permeability and the capillary pressure curves in the formation matrix were attained from waterflooding experiments on the fractured low permeable core-plug samples. The laboratory tests were conducted using a particularly designed apparatus (Li et al. 2018). The relative permeability and the capillary pressure are different in the fracture and the matrix. The capillary pressure in the fracture is neglected, due to its high permeability which makes it low enough (Salimi and Bruining 2012). Figure 2 shows the steady and dynamic capillary pressures in the matrix, while Fig. 3 shows the relative permeability in the matrix was used in the CMG simulator. The dynamic capillary pressure curve demonstrates that the wettability under steady and dynamic capillary pressure is different, and such difference is not demonstrated in the relative permeability curve. The endpoint relative permeability of the wetting phase should be smaller than the endpoint relative permeability of the non-wetting phase, as a reflection of wettability in relative permeability curves, whereas the relative permeability in
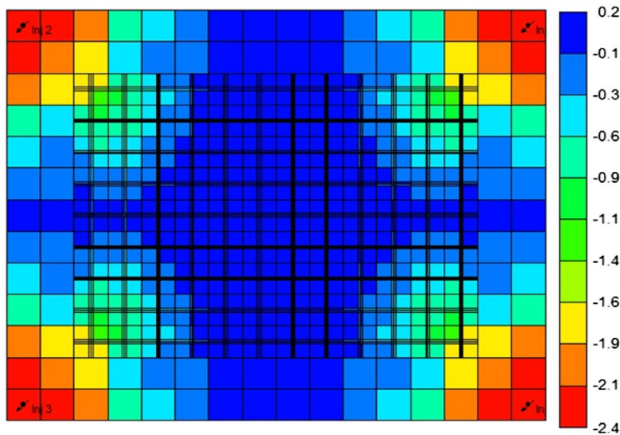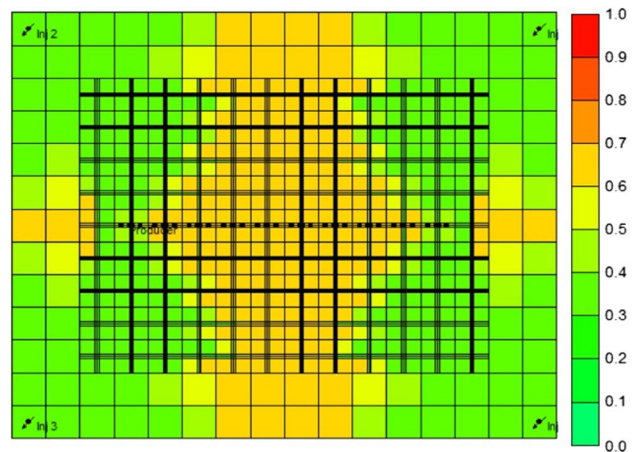
**Fig. 5** Steady capillary pressure distribution after the production for 14 years
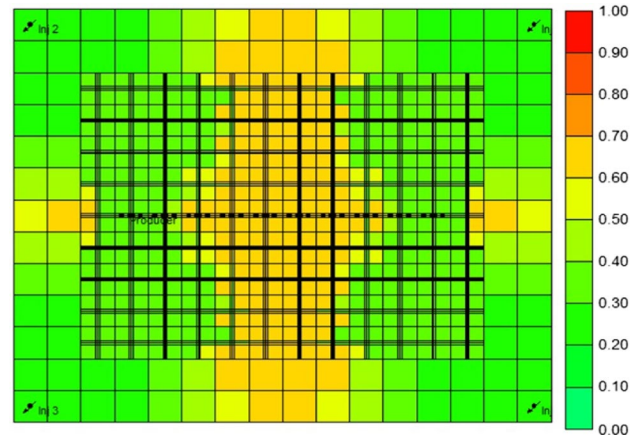


**Fig. 7** Oil saturation distribution under steady condition after the production for 14 years



**Fig. 6** Dynamic capillary pressure distribution after the production for 14 years



**Fig. 8** Oil saturation distribution under dynamic condition after the production for 14 years

the fracture is obtained from the literature as shown in Fig. 4 (Qu et al. 2017).

## Results and discussion

The analyses and optimization of reservoir production rely heavily on pressure distribution. Besides the dynamic coefficient, the dynamic capillary pressure is dependent on the rate of change in water saturation. In turn, the dynamic capillary pressure determines the water saturation by acting as resistance during the displacement.

Figures 5, 6, 7, and 8, respectively, show the capillary pressure distribution and oil saturation distribution after the production of waterflooding for 14 years in the five-spot domain. However, it can be observed in Figs. 5 and 6 that if the steady capillary pressure and the steady relative

permeability are adopted to predict the waterflooding performance, the capillary pressure distributes more uniformly, and the capillary resistance is smaller.

The displacement force should be greater than the capillary pressure to drive fluid. In this case, the dynamic displacement process in the fractured tight reservoirs, which represents the real case, faces higher and uneven resistance than the prediction of the steady case. Moreover, the steady capillary pressure facts are utilized in forecasting, and the oil saturation decreases further equally and extra rapidly, as shown in Figs. 7 and 8 that the oil saturation is lower on an a real basis in the case with dynamic capillary pressure, but the production rates' profiles show that the oil rates for the case implementing dynamic capillary pressure case are consistently less than the those of the case employing steady capillary pressure. This indicates that the water
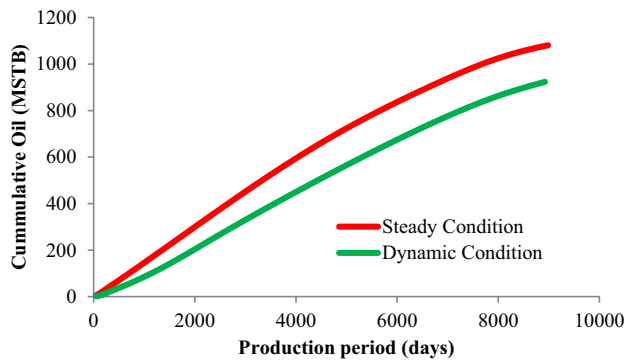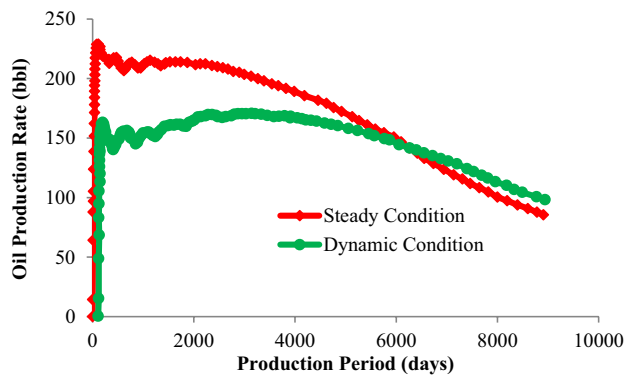
**Fig. 9** Cumulative oil with production period



**Fig. 10** Oil rate with production period



**Fig. 11** Water cut with production period



**Fig. 12** Water–oil ratio with production period

breakthrough time may be wrongly predicted if steady capillarity characters are employed to predict the production.

The different results demonstrate that the dynamic capillarity should be considered and adopted when performing production prediction. The tighter the reservoir, the larger the dynamic capillarity will be (Tian et al. 2018). The fractures can be regarded as the contributing factor to the heterogeneity of the reservoir, which will lead to the nonlinear function between the dynamic coefficient and saturation (Das et al. 2012). Thus, the capillary pressure behaves as an unpredictable resistance, which is responsible for the non-Darcy seepage behavior in fractured tight reservoirs (Tian et al. 2012). This also shows the significance of taking into account the dynamic capillarity.

Figures 9 and 10 compare the oil rate and the cumulative oil production under the steady condition and the dynamic condition. The predicted oil rate and the cumulative oil are more under the steady condition than under the dynamic conditions. This indicates that the recovery proficiency of the reservoir is overestimated if the steady relative permeability and steady capillary pressure are implemented in place of the dynamic ones, i.e., when the dynamic capillarity is neglected. Tian et al. (2012) also reported similar results for
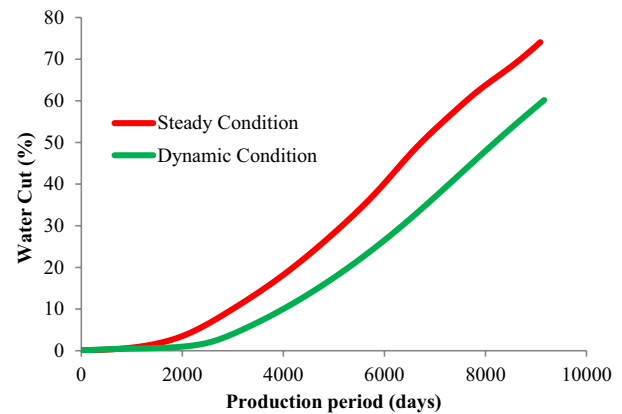
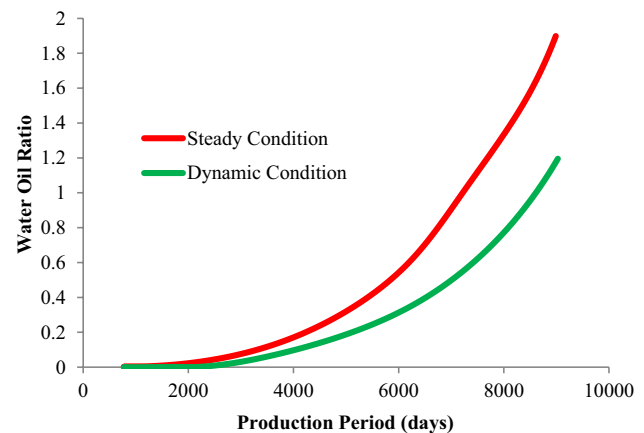low permeability reservoirs. Note that in Fig. 8, the dynamic daily oil rate is not always lower than the steady daily oil rate, and the difference is more significant compared with Li et al. (2017) previous research for low permeability reservoirs. Thus, the production of the fractured low permeability reservoir is more complex than high-to-medium permeability reservoirs.

Water cut is vital in economic analysis since water cut can estimate the ultimate oil recovery. Figures 11 and 12, respectively, show the water–oil ratio and water cut under dynamic condition as well as under steady condition. Both the water–oil ratio and the water cut are higher under the steady condition than under the dynamic condition. This demonstrates that the forecast of the well production estimated to breakthrough sooner. However, neglecting the dynamic capillarity causes a huge breakthrough of water influx. This is an unfavorable and economically unviable situation. Therefore, the dynamic capillarity should be integrated into the production prediction.

# Conclusions

Following are the major conclusions from the numerical simulation conducted by CMG to investigate the role of the dynamic capillarity throughout the waterflooding procedure in hydraulically fractured unconventional tight formations:

1. If the steady capillarity is adopted to predict the waterflooding performance, the capillary pressure distributes more uniformly, and the capillary resistance is smaller, with a more even and quicker reduction in the oil saturation.
2. If the steady capillarity is used to replace the dynamic one, the well production of the formation is overvalued and the predicted oil recovery will breakthrough sooner causing a greater breakthrough of water influx.
3. It is necessary to take into consideration the dynamic capillarity in hydraulically fractured unconventional tight reservoirs. This work gives an alternative standpoint to forecast the production of the hydraulically fractured unconventional tight oil reservoirs

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