Immiscible Gas Injection to Improve Recovery from an Iranian Naturally Fractured Reservoir: a Case Study with Emphasis on Uncertain Parameters

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Abstract
Fractured reservoirs made of matrices and fractures may face a combination of several production mechanisms including gravity drainage and imbibition. These, in some cases, can improve oil recovery significantly. Hence, the final oil recovery in such complex systems depends on the understudy reservoir characteristics. However, there are many uncertain parameters that make the simulation results questionable. In this research work, conventional dual porosity simulator was used first to investigate the oil recovery from an Iranian naturally fractured reservoir under natural depletion; with emphasis on uncertain parameters such as fracture capillary pressure and/or matrix block height. An immiscible gas injection project is applied over the study time period. We observed that the fracture physical properties, which are often uncertain, significantly affect oil recovery. Moreover, the immiscible gas injection project over period of time can improve the oil recovery up to 5.2% depending on the matrix block heights. As a result, fractured reservoirs with a high matrix block height may be a good candidate for implementing the immiscible gas injection operations.

Keywords: Fractured Reservoirs, Capillary Pressure, Reinfiltration, Gas injection

Introduction

The existence of two interconnecting media i.e., matrix and fracture in so-called fracture reservoirs makes them different from conventional reservoirs. The observed production mechanisms in such systems are the result of the gravity, viscous and capillary forces, fluid expansion, and diffusion that depend on the pressure, temperature and composition of the reservoir fluids. In an oil-gas system, for example, the capillary force acts as an impeding force against the gravity force. On the other hand, in a water-oil system the displacement depends on the matrix block wettability that may be changed over the displacement process [1]. There are many parameters or phenomena such as matrix block height, fracture/matrix properties, external displacing forces, capillary continuity and reinfiltration that influence the production mechanisms in fractured reservoirs [2]. Moreover, the position of injection wells and the injection rate can significantly affect the oil recovery.

For non well-defined phenomena such as the capillary continuity, the previous investigations [1, 2] have shown its dependency on the fracture aperture. In particular, Vicencio and Sepehrnoori's [2] showed an increase of the oil recovery from 1 to

2.2 for fracture apertures between 10 to 300 microns. Moreover, the previous studies [3] emphasized the existence of the reinfiltration process and recommended it be taken into account during reservoir prediction. For uncertain parameters such as fracture relative permeability, Romm [4] experimentally showed a linear dependency of fracture relative permeability on the phase saturation. Later Rossen and Kumar [5] applied the effective medium approximation (EMA) and denied Romm's linear dependency; they generated various relative permeability curves as a function of a dimensionless fracture height (H_D).

In this research work we used the data obtained from an oil reservoir located in the south west of Iran under natural depletion to investigate the oil recovery for a period of 40-80 years. We also assess the effectiveness of an immiscible gas injection process. To do so, we need an estimation/ assumption for the uncertain parameters/ phenomena.

Theoretical Background

Consider a simple model of matrix block surrounded by either water or gas. Using simplified assumptions [2], the pressure distribution in surrounding fractures is given by the potential Φ=P+ρgz. Then the Darcy velocities are,

$$U = \frac{g(H-z)(\rho_o-\rho_g)-P_{cm}+P_{cf}}{\frac{\mu_g}{kk_{rg}}\left[MH+(1-M)z\right]} \quad (1)$$

$$U = \frac{g(H-z)(\rho_w-\rho_o)+P_{cm}-P_{cf}}{\frac{\mu_w}{kk_{rw}}z+\frac{\mu_o}{kk_{ro}}(H-z)} \quad (2)$$

where for incompressible wetting and non-wetting phases $U_w=U_{nw}=U$. These compare the role of gravity and capillary forces. This shows that the effect of the block height is stronger for a gas-oil system.

Moreover, the fracture capillary pressure can control the capillary continuity between matrix blocks. The simplest way is to ignore the capillary pressure ($p_{cf}=0,$). From the above relations, fracture capillary pressure plays an accelerating role in gas-oil systems, while it is an impeding parameter against fluid displacement in water-oil systems. It should be noticed that this is true for the case of water wet rocks; however, fracture capillary pressure in oil wet rocks can aid the fluid displacement. Concerning the effect of horizontal fracture on flow rate and ultimate recovery of the stack blocks, most researchers use the *fracture capillary pressure* as a matching parameter. Alternatively we can use equation (2) or (3) respectively for the case of flow parallel to the fracture surface and the case of rough fracture walls, where fracture capillary pressure is neither zero nor constant [6].

$$p_{cf} = \frac{2\sigma\cos\theta}{b} = cons., \quad (3)$$

$$p_{cf} = f(S_o) = p_{cf}^0 - \sigma_f\left[\ln\left(\frac{S_{of}-S_{orf}}{1-S_{orf}}\right)\right]^{n_f}, p_{cf} \geq p_{cf}^0, n_f = 2. \quad (4)$$

Where p_{cf}^0 is threshold capillary pressure for the fracture with an atypical value of 0.0088psi, and σ_f is the capillary pressure coefficient with a typical value of -0.0023psi. Quandalle and Sabathier (1989) assumed zero fracture capillary pressure, but in a test example they are forced to get it to nonzero in order to match the resulted experimental and numerical graphs [7]. Sajjadian et al. (1999) in their analysis indicated that when the fracture aperture is more than its critical value (b_c), the fracture capillary pressure may be assumed equal to zero. The consequence of these is that the ultimate recovery from a stack of matrix blocks will be the same as that expected from a single block with an equivalent height[9, 10].

Considering a stack of matrix blocks, oil produced from the upper matrix blocks may be imbibed by desaturation of the lower blocks. This is called the

Reinfiltration process. This causes the oil to be passed through the matrix blocks before it is produced. In the experiments done by Firoozabadi and Horie [9], drained oil from the upper matrix block did not flow as film on the sides of the lower matrix block in the vertical fracture. Van Golf-Racht [2] demonstrated the reinfiltration process within a gravity drainage mechanism in a gas invaded zone of naturally fractured reservoirs. He relates this to the maximum drainage rate (or gravitational rate) from a matrix block that is affected only by the gravity force (matrix capillary pressure is assumed to be zero). The degree of interaction between the matrix blocks (α) can be determined by comparison between the discharged rate into the lower matrix block (i) and the maximum exited rate from this block. Other researchers have considered the reinfiltration process between matrix blocks. For example, Lefebvre du Prey (1978) in his study on fissured reservoirs assumed that the oil drained from an upper block is sucked completely by the block underneath [11]. The results from the numerical study of de Silva et al. (1989) showed that the oil infiltration effect decreases as the fracture dip angle increases. They determined that the influence of reinfiltration becomes negligible for a fracture dip angle of around 45° [12]. The consequence of considering this phenomenon is a delay in production and a decrease in ultimate oil recovery factor.

Reservoir Description

The under study reservoir consists of 9 permeable and non permeable layers and sub layers. In this study we just used layer 2 (thickness=175 meter), which is permeable and contains 70% of oil in place (2134 MMSTB). The volume of the supported edge aquifer in this layer is about 9056MMbbl, which is small in comparison to the reservoir volume of 2134 MMSTB. Hence, the aquifer may not be considered as an active aquifer and consequently may not have a significant contribution to the oil recovery. The reservoir was initially under-saturated at 5920 psi and 201^{o}f where bubble point pressure was 1595psi. There were 18 production wells with 35000 stb/d production. Also, there are 6 injection wells with a rate of 11000Mscf/d. The position of the wells is shown in Fig. 1.

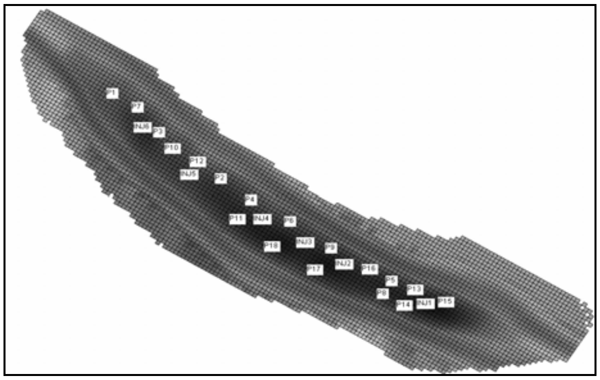

Figure 1. Position of injection and production wells in the reservoir

Average matrix and fracture porosity were 8.1% and 0.1% respectively, while the average matrix and fracture permeability were respectively 0.22md and 88.5md. Moreover, the available flash and differential expansion test at 135^{o}F and 215^{o}F, flash separator test and viscosity test results were used to model the fluid properties.

Model Construction

We used the following economic constraints that have been imposed to the production wells (Table 1) for the under study reservoir, however, it never falls under saturation pressure. Hence, during natural depletion, two zones exist, i.e. Water and Oil.

Table 1. Economic constraints imposed on the production wells

Min bottom hole pressure (psia)	Max allowable GOR (MSCF/STB)	Max Allowable Water Cut (STBW/STBWO)	Min oil production rate (STB/Day)
500	2	0.2	200

Immiscible gas injection process has been implemented to enhance the gas gravity drainage mechanism. The case studies considered include water-oil system in natural depletion and water-oil-gas systems during gas injection scenario, with an initial water saturation of 0.26 for the entire reservoir. Six injection wells have been drilled and completed in the top sub-layer following internal injection technique and 18 production wells have been drilled and completed in the lower sub-layer. The grid system consists of 157×40×6 cells. The upper 3 grid blocks in the z direction belong to the matrices and the lower ones belong to the fractures. Corner point geometry has been used for the grid generation. We used the conventional black oil dual porosity simulator.

Simulation Results and Discussion

i) Effect of the block heights

For the purpose of parametric studies we assigned three different values of 15 ft, 30 ft and 60 ft for the matrix block heights. Let us consider the effect of the matrix block height on the oil recovery factor over a finite time period in the under study reservoir under natural depletion.

Block height sensitivity study results show that the oil recovery factor increases by increasing the matrix block height. However, due to a small value of density difference in the water-oil system, changing the matrix block height has very little effect on the water imbibition process.

Table 2. Effect of matrix block height on ultimate oil recovery factor

Matrix block height, ft	Ultimate recovery factor, %
15	14.4
30	14.9
60	15.9

ii) Effect of the fracture capillary pressure

Now we consider the effect of the fracture capillary pressure. The dimensionless fracture capillary pressure (P_{cfD}) was introduced by Firouzabadi [10] as, $P_{cfD} = 0.145 \times \frac{b_o P_{cf}}{\gamma}$ where $b_o = \sqrt{k_f /(84.4 \times \varphi_f)} \approx 43$ is the half fracture width in microns, γ in dyne/cm (2.6 and 34.2 for oil/gas and water/oil systems respectively), p_c in psi. Having defined an angle β from a specific triangular contact of two matrix blocks, we may use the fracture capillary pressure curve as a function of wetting phase saturation (S_L) and these β values [10]. By considering $\beta = 5^o$, the relationship between P_{cfD} and wetting phase saturation can be derived (Table 3).

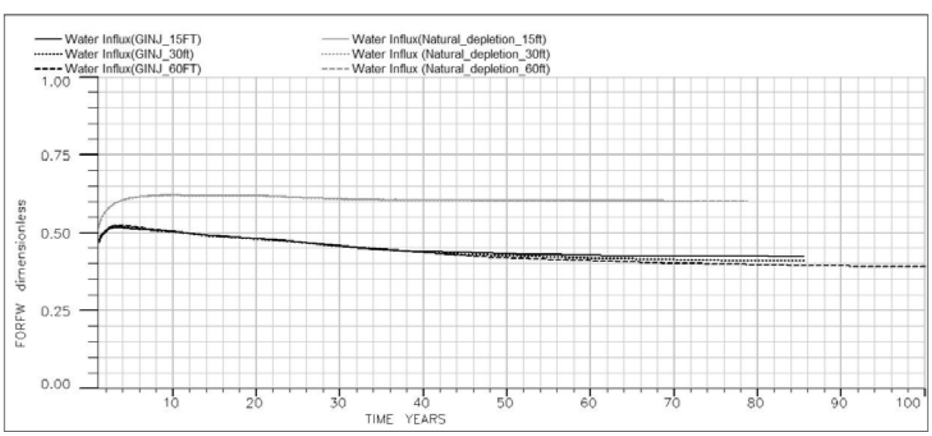

Figure 2. Effect of matrix blocks height on water imbibition mechanism

Table 3: Relationship between P_{cfD} and wetting phase saturation

S_L (%)	0	0.01	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	1
P_{cfD}	17.24	4.74	3.807	3.016	2.585	2.442	2.298	2.154	2.011	1.867	0.86

Fig. 2 shows the effect of capillary continuity on water imbibition mechanisms where FORFW indicates the ratio of the field oil production due to water influx.

To investigate the impact of the capillary continuity on reservoirs with different matrix capillary pressures we applied the fracture capillary pressure curves in two models having matrices with capillary pressures of P_{co}+1.5psi and P_{co}+3psi where P_{co} is the original capillary pressure. The changes in the ultimate oil recovery factor for these cases from the base case are summarized in Table 5.

Table 5. Change in the ultimate recovery assuming non zero capillary pressure

	P_{co}+1.5 psi	P_{co}+3 psi
Change in ultimate recovery	1.5%	2%

Table 4 summarizes the effect of the capillary continuity through different scenarios on the ultimate oil recovery factor under natural depletion compared to the neglecting capillary pressure case. In the first case the numerical value of the fracture capillary pressure by considering $\beta = 5^o$, as discussed previously, with a typical block height of 30 ft was used. In the second case we considered a stack of blocks that are equivalent to a single block height of 180 ft.

Table 4. Effect of the capillary continuity through different scenarios on the ultimate recovery compared to the neglecting capillary pressure case.

Scenarios using:	Increase of ultimate oil recovery factor
capillary pressure curves	1.1%
Stack of blocks equivalent to a single block	9.7%

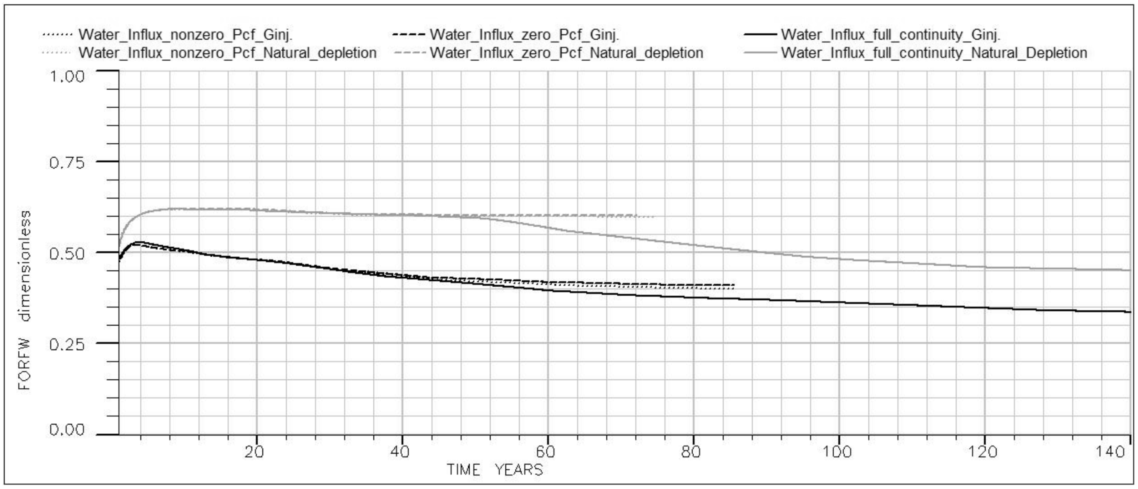

Figure 3. Impact of capillary continuity on water imbibition mechanism

Also , we applied the fracture capillary pressure curves in models having matrices with block heights of 15 ft, 30 ft and 60 ft. Fig. 4 shows the impact of this on water imbibition mechanisms where the ultimate recovery factor decreases from 1.5 to 0.5% . It should be noticed that the terms M_PCF and WM_PCF on this figure refer to, respectively, with and without matrix capillary pressure-non zero fracture capillary pressure assumptions discussed previously.

Reservoirs with more matrix capillary pressure and/or small matrix block heights are observed to be more sensitive to the fracture capillary pressure. Applying nonzero P_{cf} in reservoir simulation with a matrix capillary pressure of P_{co}+ 3 psi, causes an improvement in the oil recovery.

The impact of gas injection on oil recovery is shown in Fig. 5.

iii) Effect of the Reinfiltration phenomenon

The Reinfiltration phenomenon has been recommended to be included during prediction study of the fracture reservoirs [13]. We used GRAVDRM keyword in the software to make this phenomenon active. It is clear that the amount of re-imbibed oil is dependent on the re-infiltration modeling technique. The effect of this assumption on the oil recovery factor through both natural depletion and gas injection is shown in Fig.6.

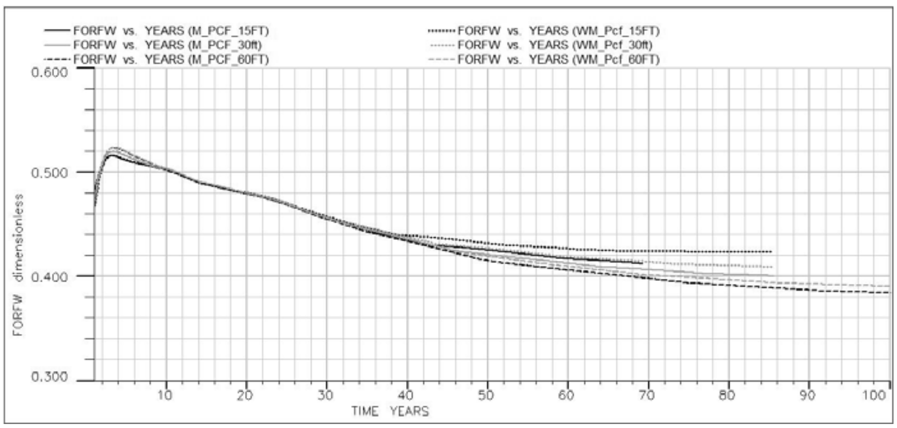

Figure 4. Impact of capillary continuity on water imbibition mechanism in three different matrix block heights cases

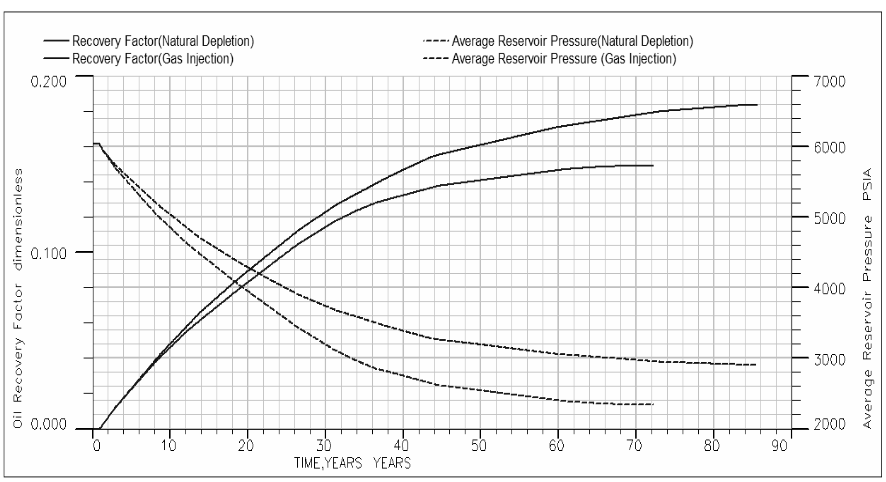

Figure 5. Impact of gas injection on the oil recovery factor and reservoir pressure

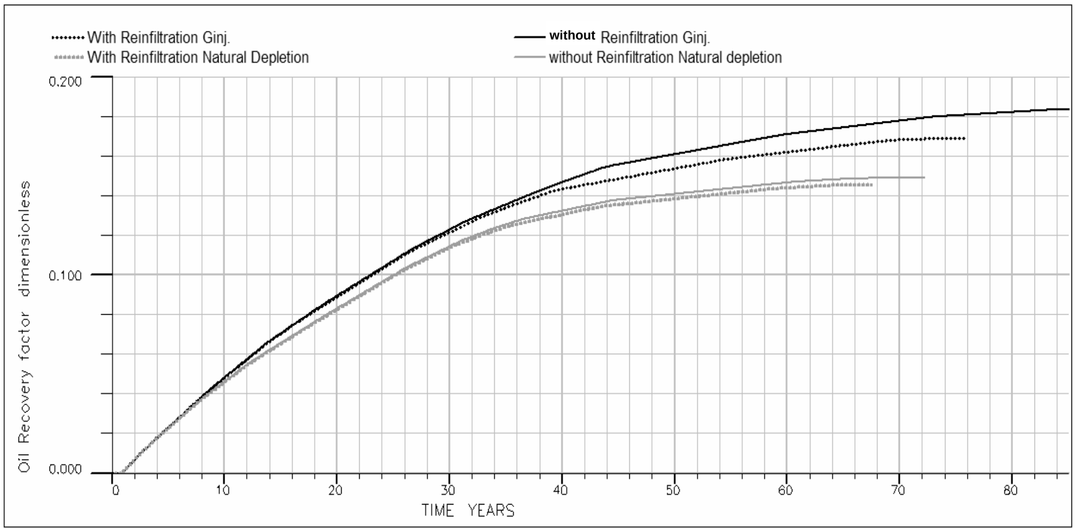

Figure 6. Impact of Reinfiltration on oil recovery factor

Through simulation efforts of gas injection processes, we observed that the recovery is dependent on the gas injection rate as well as the position of the injection well. However, the effect on the major active production mechanisms was observed to be different (Figs. 7, 8).

Assuming reinfiltration to be active through reservoir simulation shows a decrease in oil recovery. This effect is stronger in the gas injection process than in water imbibition.

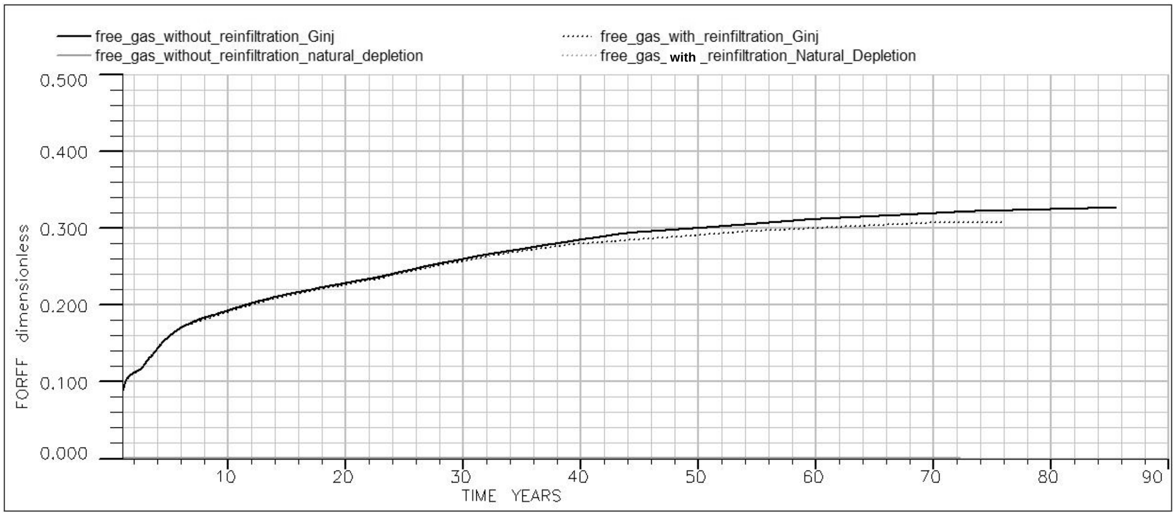

Figure 7. Impact of Reinfiltration on the gravity drainage mechanism

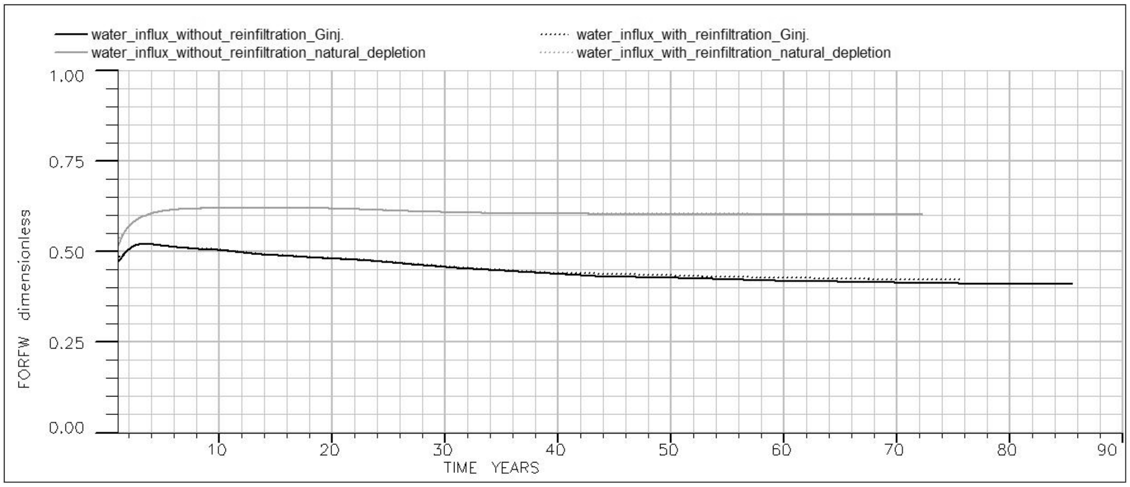

Figure 8. Impact of Reinfiltration on the water imbibition mechanism

Conclusion

We have numerically investigated the effects of uncertain parameters such as fracture capillary pressure and/or matrix block height on the oil recovery from an Iranian naturally fractured reservoir under both natural depletion and immiscible gas injection project. We observed that the fracture parameters are important and should be considered in the simulation setup. Moreover, the following conclusions can be summarized:

- Increase in matrix block height causes an increase in the ultimate oil recovery.
- The effect of matrix block height on water imbibition mechanism is not very strong.
- Considering capillary continuity between matrix blocks causes an increase in the ultimate oil recovery by a range of 1-10%.
- Reinfiltration of oil in matrix blocks causes a decrease in the ultimate oil recovery.
- Applying gas injection is a reasonable scenario for improving oil recovery. Our case study has shown that it can increase oil recovery by 5.2%, depending on the matrix block heights.

Nomenclature

b	Fracture width
b_o	Mean half fracture aperture
H	Matrix block height
H_D	Dimensionless fracture height
k_f	Conventional fracture permeability
k_r	Relative permeability
M	Mobility ratio
P_{cm}	Matrix capillary pressure
P_{cf}	Fracture capillary pressure
P_{cfD}	Dimensionless fracture capillary pressure
S	Phase saturation
U	Fluid velocity
ρ	Fluid density
μ	Fluid viscosity
φ_f	Fracture porosity
γ	Surface tension
p_{cf}^0	threshold capillary pressure for the fracture
σ_f	capillary pressure coefficient in equation 4

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