Special features of fracture network in Iranian fractured reservoirs

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Due to the presence of two different types of porous media, namely matrix blocks and fractures; there are varieties of reservoir performance behaviors in fractured oil reservoirs. Because of this complex structure of fractured reservoirs, oil recovery is the result of the combination of several production mechanisms such as gravity drainage and imbibition. Two main forces controlling these production mechanisms are capillary and gravity forces.

This work is focused on the influence of non-zero fracture capillary pressure, non-straight line fracture relative permeability, reinfiltration phenomenon and matrix block height on the performance of active mechanisms in fractured reservoirs during natural depletion and immiscible gas injection project. The field simulation studies were performed using ECLIPSE commercial simulator with black oil formulation and dual porosity option. Simulator results considering non-zero fracture capillary pressure indicated that the influence of this parameter on reservoir performance depended not only on fracture physical properties, but also it depended on matrix threshold capillary pressure and matrix block height. Simulation results indicated that oil recovery was affected by the range from 1% to 2% considering matrix threshold capillary pressure of 0.1 psi (0.007 bar) to 3.1 psi (0.214 bar). Also oil recovery was affected by the range from 1.5% to 0.5% considering matrix block heights of 15 ft (4.57 m) to 60 ft (18.29 m). Our simulation results suggest that for the fractured reservoirs with small block heights or with large matrix threshold capillary pressure, the appropriate non-zero fracture capillary pressure curve is necessary. Subsequently we have investigated the effect of non-straight line fracture relative permeability on reservoir performance. The results emphasized that the matrix block height depended on the influence of linear line fracture relative permeability. Simulation results acquired by applying different matrix block heights indicated the enhancement in oil recovery by immiscible gas injection in the range from 2.3% to 5.2% considering matrix block heights of 15 ft (4.57 m) to 60 ft (18.29 m). Hence, these results showed that the fractured reservoirs with the highest matrix block heights could be good candidates for implementing the immiscible gas injection operation.

Key words: fractured reservoirs, capillary pressure, reinfiltration, block-to- block interaction

1. Introduction

Fractured reservoirs are composed of two different porous media i.e. matrix and fracture. In such complex system, the gravity and capillary forces are important in production mechanisms. Although other forces such as fluid expansion, viscosity and diffusion may affect the reservoir performance depending on pressure, temperature and composition of reservoir fluids. During fluid exchange between the matrix block and fracture, capillary force can act as an impeding force against gravity in an oil-gas system. Thus this process can take place if the resultant gravity force exceeds the matrix capillary threshold pressure. In water-oil system the displacement of oil by water depends on the matrix block wettability. For strong water-wet matrices, gravity and capillary forces act in the same direction whereas in oil-wet matrix blocks, capillary force acts against gravity.

Generally, there are various parameters influencing the production mechanisms within water-oil and gas-oil systems including matrix block height, rock properties, external displacing forces, capillary continuity between matrix blocks and reinfiltration of oil from fractures in the matrix blocks.

Firoozabadi and Hauge[1] have found that the capillary continuity between matrices depends on the fracture aperture. Vicencio et al's simulation results[9] have indicated that the oil recovery was affected by a factor that ranges from 1 to 2.2 by considering the fracture apertures between 10 to 300 microns.

Reinfiltration of oil from fractures to matrix is the process where oil passes through different matrix blocks before being produced. Saidi[7] has emphasized that this phenomena exists and should be considered during reservoir behavior prediction.

Fracture relative permeability is another key parameter which can control the fluids flow process through fractures. Laboratory studies by Romm[5] which used two parallel glass plates that represented a fracture, indicated a linear dependency of the fracture relative permeability on the phase saturation. Twenty years later, Rossen and Kumar[6] used Effective Medium Approximation (EMA), to show that the fracture relative permeability is not a linear function of saturation. They defined a dimensionless parameter (dimensionless fracture height, HD) and presented the relative permeability curves as a function of this dimensionless parameter.

In this case study we have investigated the impact of matrix block height and capillary continuity on reservoir performance parameters during natural depletion and immiscible gas injection process, as there is a debate on the assumption of capillary discontinuity between matrix

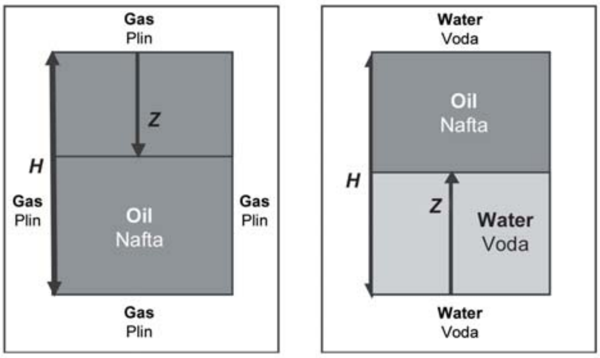

Fig. 1. Representation of oil displacement by gas (a) and water (b) in matrix blocks
Sl. 1. Prikaz istiskivanja nafte plinom (a) i vodom (b) u blokovima matriksa

blocks. We have generated a set of fracture capillary pressure curves for various fracture apertures in the reservoir under study based on the previously published models1. Then we have investigated the impact of the capillary continuity on both the oil recovery factor and major production mechanisms.

Furthermore we have investigated the impact of nonlinear fracture relative permeability on reservoir performance parameters based on the model proposed by Rossen and Kumar[6] for the average half fracture aperture in the reservoir. Reinfiltration is another phenomenon, the influence of which on oil recovery factor and major production mechanisms during immiscible gas injection is being studied.

2. Theoretical Background and Modeling

From theoretical point of view there are some basic concepts in studying the recovery from fractured reservoirs that first need to be introduced. These are:

2.1 Matrix blocks height

Simplified model of single independent acting matrices in two water-oil and gas-oil systems is shown in Fig. 1.

Following the simplified assumptions[8] listed below; matrix fluid displacement can be described by Eqs.1 and 2, provided that the following simplified assumptions are satisfied (a) flow is considered one-dimensional, (b) capillary pressure at the interface is constant, (c) relative permeability is constant, (d) bottom and top of the matrix blocks are open to the flow while the lateral faces are impermeable (e) in surrounding fractures the pressure distribution is approximated by a hydrostatic relationship and hence use the potential $\phi = P + \rho g z$, (f) Darcy's law is applicable to both wetting and non-wetting phases flow, (g) fluids are incompressible, i.e. $u_w = u_{nw} = u$.

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

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

Eqs. 1 and 2 show the role of matrix block heights on the displacement mechanism. Since the density difference in gas-oil system is more than that of water-oil system the gravity term in gas-oil system is more pronounced than that in water-oil system. Due to the same reason, increasing the block height in water-oil system does not have much effect on the displacement process which however is not the case in gas-oil system.

2.2 Capillary continuity

Existence of capillary continuity between matrix blocks backs to the extent of the fracture capillary pressure. However, in practice the capillary discontinuity ($P_{cf} = 0$) between matrix blocks is assumed. According to Eq. 1, fracture capillary pressure plays an accelerating role in gas-oil system while it is an impeding parameter against fluid displacement in water-oil system (Eq. 2).

2.3 Reinfiltration

Considering stack of matrix blocks, oil flowing out of the upper matrix blocks may be imbibed by desaturated lower blocks. This phenomenon causes the oil to pass through different matrix blocks before it is being produced which in turn causes a delay in production and a decrease in ultimate oil recovery factor.

In this case study, we used ECLIPSE commercial simulator with black oil formulation and dual porosity option. Fracture reservoir under study was initially under-saturated and it never fell below saturation pressure due to economic constraints imposed to the production wells (Table 1). Hence, during natural depletion, we have just two zones, i.e. water and oil. Immiscible gas injection process has been implemented to initiate gas gravity drainage mechanism which enables us to study the impact of different parameters on this mechanism. Therefore our case study includes 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 bottom sub-layer. The grid dimensions were 157 × 40 × 6. Note that the upper three grids in the z direction belong to matrices and the lower ones belong to fractures. Corner point geometry has been used for grid generation. Average permeability and porosity of fractures are 88.56 mD and 0.1% respectively while these parameters for matrices are 0.22 mD and 8.12%.

Table 1. Economic constraints imposed to production wells

Minimum bottom hole pressure (psia)	Maximum allowable GOR (Mscf/stb)	Maximum allowable water cut (stbw/stbo)	Minimum oil production rate (stb/day)
500	2	0.2	200

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

Matrix block height (ft)	Ultimate oil recovery factor during natural depletion (%)	Ultimate oil recovery factor during immiscible gas injection (%)	Amount of increase in recovery factor (%)
15	14.4	16.7	2.3
30	14.9	18.3	3.4
60	15.9	21.1	5.2

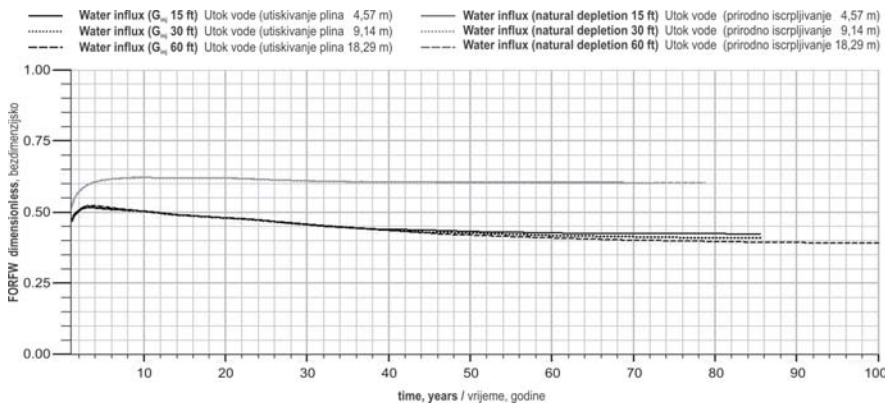

Fig. 2. Effect of matrix blocks height on water imbibition mechanism
Sl. 2. Utjecaj visine blokova matriksa na mehanizam apsorpcije vode

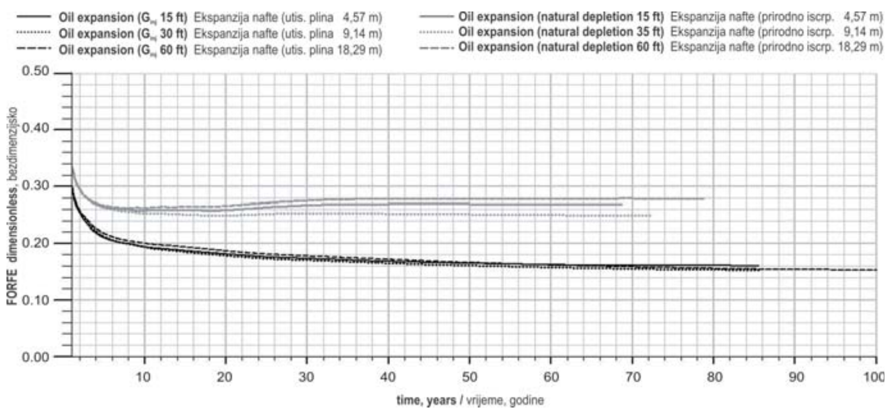

Fig. 3. Effect of matrix blocks height on oil expansion mechanism
Sl. 3. utjecaj visine blokova matriksa na mehanizam ekspanzije nafte

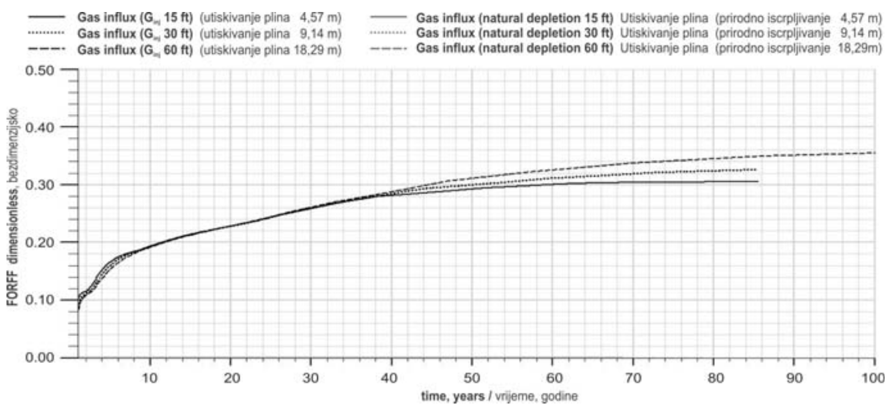

Fig. 4. Effect of matrix blocks height on gravity drainage mechanism
Sl. 4. Utjecaj visine blokova matriksa na mehanizam gravitacijskog dreniranja

3. Results and Discussion

We have investigated the effects of the following parameters on the oil recovery as well as the active mechanisms in the reservoir under study.

3.1 Block Height

To investigate the impact of matrix block height on oil recovery factor and major active mechanisms present in the reservoir under study, we have assigned three different values 15 ft (4.57 m), 30 ft (9.14 m) and 60 ft (18.29 m) for matrix block heights. The results of the simulations are summarized in Table 2.

Figs. 2, 3 and 4 show the impact of matrix block height on water imbibition, gravity drainage and oil expansion mechanisms

3.2 Capillary continuity

Two different approaches were applied in studying of this phenomenon:

a) Deriving and applying fracture capillary pressure curves for fracture apertures present in the reservoir under study using dimensionless fracture capillary pressure (P_{cfD}).[1]

b) Taking a stack of matrix blocks as a single block.

First step for deriving the capillary pressure curves presented in the first approach is to extract the fracture aperture sizes using Eq.3.[8] We classified the aperture sizes in 9 classes. The appropriate capillary pressure curves corresponding to each of these values were generated with Eq. 4. Table 3 shows the relationship between P_{cfD} and the wetting phase saturation.

$$b = \sqrt{\frac{k_f}{84.4 \times \varphi_f}} \tag{3}$$

$$P_{cfD} = 0.145 \times \frac{b_o P_c}{\gamma} \tag{4}$$

Table 3. Relationship between P_{cfD} and the 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

Table 4. Effect of the capillary continuity through different scenarios on ultimate oil recovery factor

Different scenarios	Increase of ultimate oil recovery factor (natural depletion)	Increase of ultimate oil recovery factor (gas injection)
Applying capillary pressure curves	1.1%	1.2%
Stack of blocks = one block	9.7%	10.0%

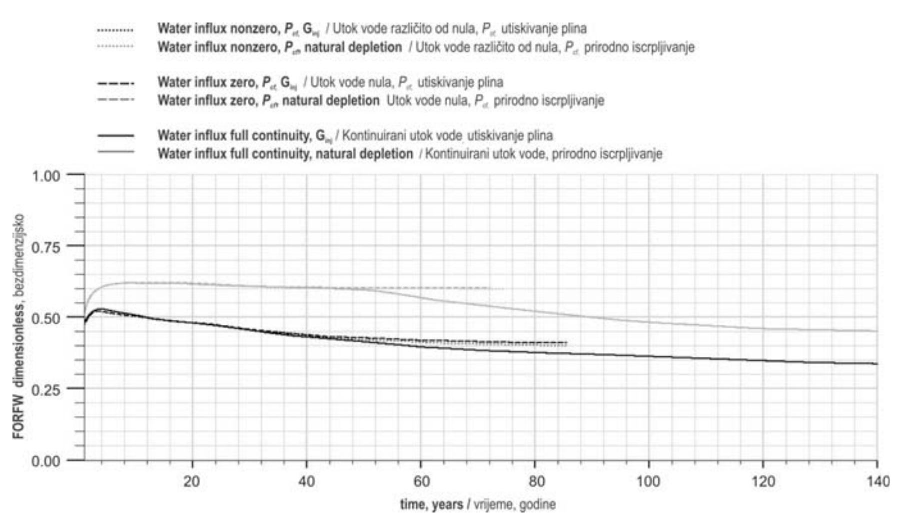

Fig. 5. Impact of capillary continuity on water imbibition mechanism
Sl. 5. Utjecaj kapilarnog kontinuiteta na mehanizam apsorpcije vode

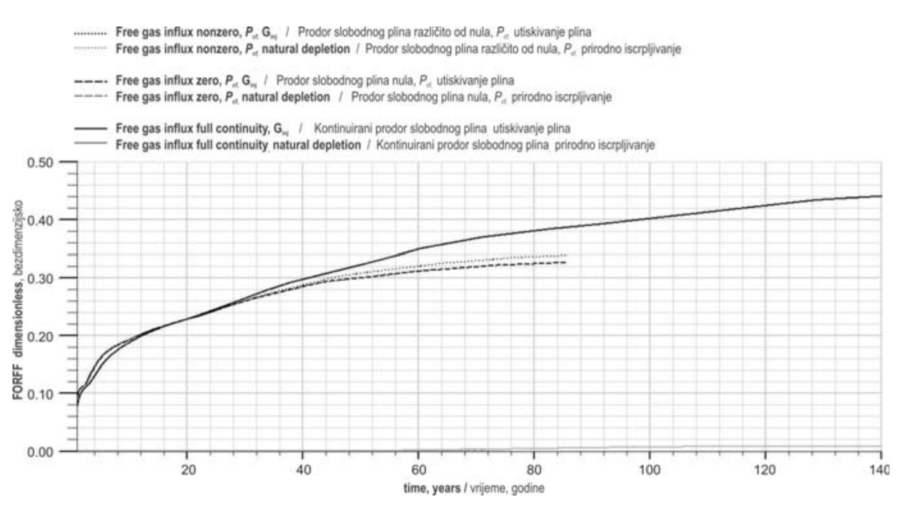

Fig. 6. Impact of capillary continuity on gravity drainage mechanism
Sl. 6. Utjecaj kapilarnog kontinuiteta na mehanizam gravitacijskog dreniranja

Moreover Table 4 summarizes the effect of the capillary continuity through different scenarios on the ultimate oil recovery factor.

Figs. 5, 6 and 7 show the effect of capillary continuity on water imbibition, gravity drainage and oil expansion mechanisms respectively.

To investigate the impact of the capillary continuity on the performance of reservoir with different matrix capillary pressure and/or different matrix block heights, we have applied the fracture capillary pressure curves in three models having matrices with capillary pressures of respectively Pco (original capillary pressure), P_{co}+1.5 psi and P_{co}+3 psi. The changes in the ultimate oil recovery factor for these cases are summarized in Table 5. Figs. 8 and 9 show the impact of capillary continuity on production mechanisms of reservoirs with different matrix capillary pressures. Moreover we applied the fracture capillary pressure curves in three models having matrices with different block heights of 15 ft (4.57 m), 30 ft (9.14 m) and 60 ft. (18.29 m). Table 6 summarizes the changes in the ultimate recovery factor for three cases and Figs. 10 and 11 show the effect of this on gravity drainage and water imbibition mechanisms.

3.3. Fracture relative permeability

Rossen and Kumar[6] have presented a model which relates the fracture relative permeability to gravity and capillary forces in the fracture. These relationships

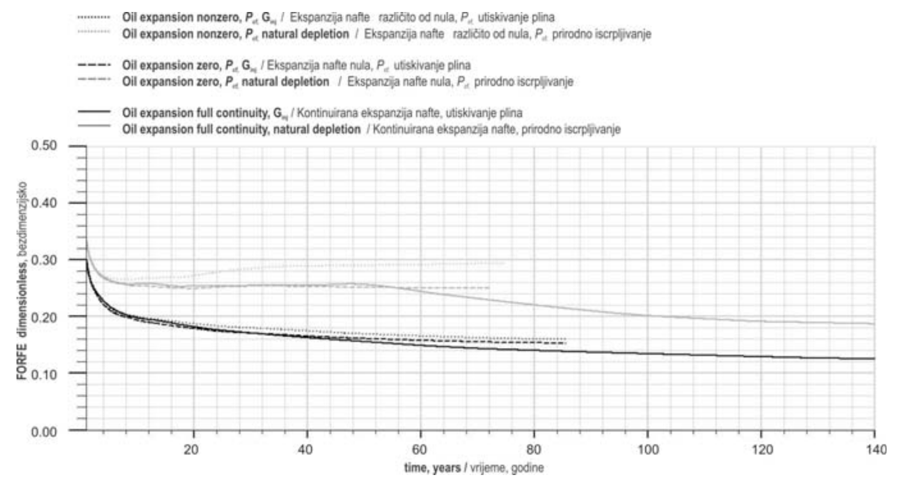

Fig. 7. Impact of capillary continuity on oil expansion mechanism
Sl. 7. Utjecaj kapilarnog kontinuiteta na mehanizam ekspanzije nafte

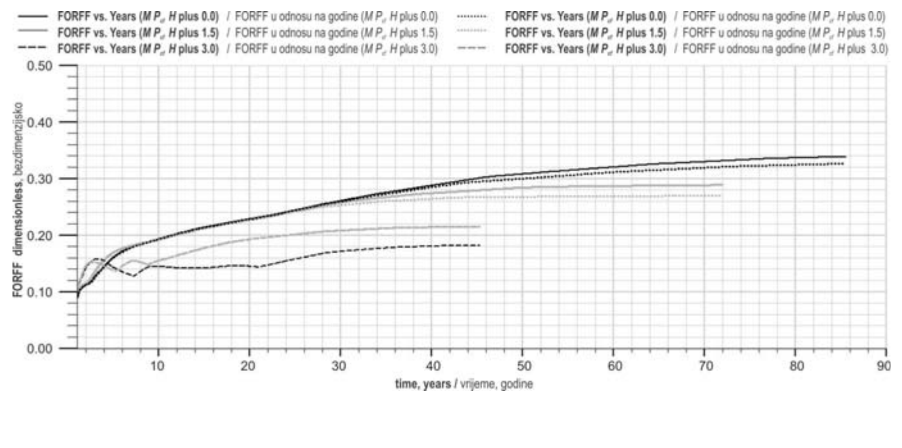

Fig. 8. Impact of capillary continuity on gravity drainage mechanism of three different matrix capillary pressure cases
Sl. 8. Utjecaj kapilarnog kontinuiteta na mehanizam gravitacijskog dreniranja u slučajevima matriksa s tri različita kapilarna tlaka

Table 5. Change in the ultimate oil recovery factor by applying $P_{cf} \neq 0$ in different matrix capillary pressures

	P_{co}	P_{co}+1.5 psi	P_{co}+3 psi
Change in ultimate oil recovery by applying non-zero P_{cf} (%)	1	1.5	2

Table 6. Change in ultimate oil recovery factor by applying $P_{cf} \neq 0$ in different matrix block heights

	H =15 ft	H = 30 ft	H = 60 ft
Change in ultimate recovery factor (%)	1.5	1	0.5

have been gathered in the dimensionless parameter (HD) presented in Eq. 5. Fracture relative permeability data for corresponding HD value in reservoir for different values of logarithmic standard deviations of half fracture aperture distributions have been presented by the authors.[6]

$$H_D = 478.92 \cdot \frac{\Delta\rho \cdot H}{\left(\frac{\gamma}{b_o}\right)} \tag{5}$$

Half fracture apertures were extracted using Eq. 3 (b_o = 20 micron) for the reservoir under study. For sensitivity study on matrix block heights, values of H_D for the oil-water system in the reservoir under study were calculated and the corresponding fracture relative permeability curves were obtained. As recommended[6], linear relative permeability data can be applied for any two phase system with value $H_D > 10$ (e.g. in gas-oil systems). Thus, in this study, natural depletion case has been selected to study this subject in which there is just oil-water system. Appropriate fracture relative permeability curves for two cases $H_D = 5$ ($H = 15$ ft) and $H_D = 1$ ($H = 3$ ft) are shown in Fig. 12.

Fig. 13 shows the impact of nonlinear fracture relative permeability on the behavior of oil recovery factor during reservoir natural depletion.

3.4. Reinfiltration

This phenomenon is recommended to be included during prediction of the fracture reservoirs.[2] The impacts of considering the reinfiltration on the oil recovery factor (Fig. 14) and on the major active production mechanisms (Figs. 15, 16 and 17) are presented.

3.5. Discussion of simulation results

Block height sensitivity study results have shown the increase of oil recovery factor by increasing the matrix block height. Considering data presented in Table 2,

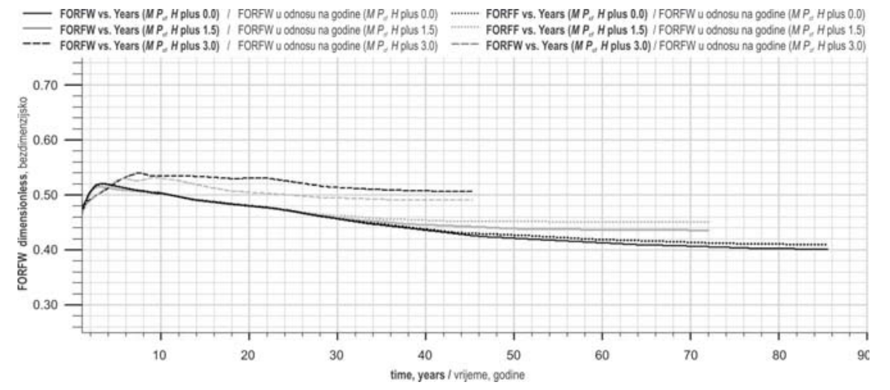

Fig. 9. Impact of capillary continuity on water imbibition mechanism in three different matrix capillary pressure cases

Sl. 9. Utjecaj kapilarnog kontinuiteta na mehanizam apsorpcije vode u slučajevima matriksa s tri različita kapilarna tlaka

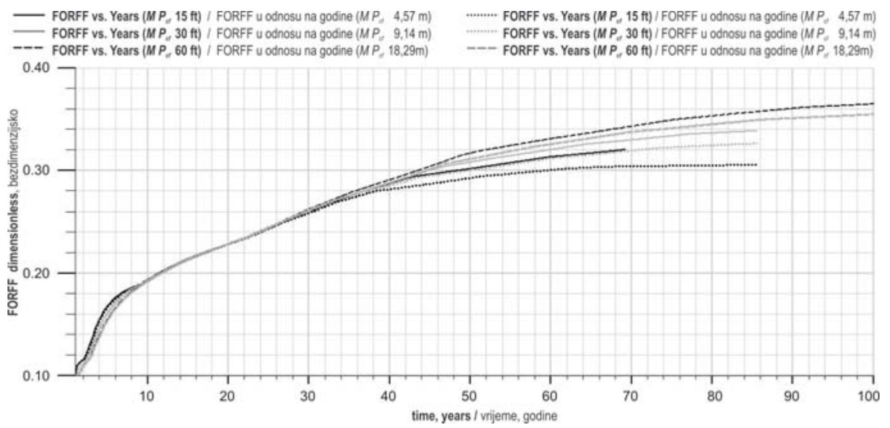

Fig. 10. Impact of capillary continuity on gravity drainage mechanism in three different matrix block heights cases

Sl. 10. Utjecaj kapilarnog kontinuiteta na mehanizam gravitacijskog dreniranja u slučajevima bloka matriksa s tri različite visine

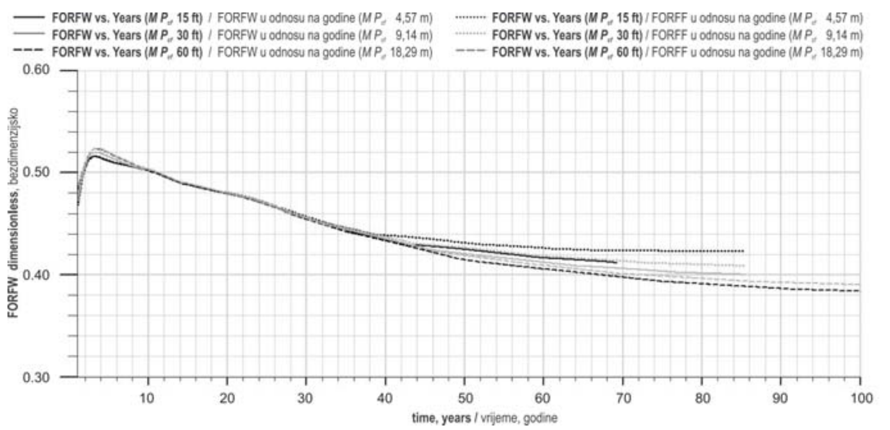

Fig. 11. Impact of capillary continuity on water imbibition mechanism in three different matrix block heights cases

Sl. 11. Utjecaj kapilarnog kontinuiteta na mehanizam apsorpcije vode u slučajevima bloka matriksa s tri različite visine

the improvement in oil recovery factor by gas injection is more pronounced in reservoirs with bigger block heights. Investigating the performance of different mechanisms (Figs. 2, 3 and 4) have shown that increasing matrix block height causes increase in the activity of gravity drainage mechanism. Due to the smaller density difference in water-oil system, changing the matrix block height does not have much effect on water imbibition process. The strange point in Fig. 4 was the increase in the activity of gravity drainage mechanism by decrease in matrix block height during early years of production. This phenomenon can be attributed to the delay in surrounding the full matrix block height by gas in tall blocks than in shorter blocks.

Capillary continuity sensitivity studies showed that applying capillary continuity causes an increase in the ultimate oil recovery factor by the range of 1.1% to 10% depending on the implemented scenario (Table 4). This phenomenon does not have sensible effect on water imbibition process (Fig. 5) but it causes an increase in the amount of oil produced by the gravity drainage mechanism (Fig. 6). Fig. 7 has shown the performance of oil expansion mechanism in which, capillary continuity by nonzero fracture capillary pressure causes more reservoir pressure drop and as a result it increases the amount of oil production by this mechanism.

Reservoirs with higher matrix capillary pressure and/or small matrix block heights are more sensitive to the fracture capillary pressure. According to Table 5, by applying nonzero P_{cf} in the reservoirs with matrix capillary pressure of P_{co} + 3 psi, causes this effect to be doubled related to those of P_{co}. Table 6 has shown the increase in the effect of fracture capillary pressure by 1% in $H = 15$ ft (4.57 m) with respect to that in $H = 60$ ft (18.29 m).

According to Fig. 13, using non-linear fracture relative permeability causes two different behaviors of reservoir performance

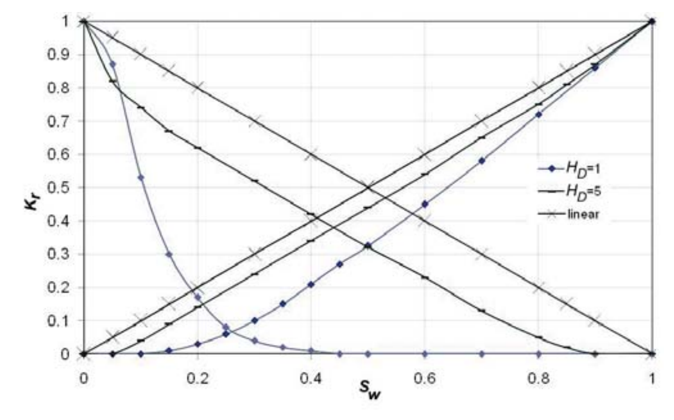

Fig. 12. Fracture relative permeability curves for two case H_D = 5 (H = 15 ft) and H_D = 1 (H = 3 ft)

Sl. 12. Krivulje relativne propusnosti pukotina za dva slučaja H_D = 5 (H = 4,57 m;15 ft) i H_D = 1 (H = 0,91 m; 3 ft)

during natural depletion. During first 35 years of production, applying nonlinear fracture relative permeability causes oil recovery factor to increase (with respect to the case of linear k_{rf}). After this period, the rate of increase in oil recovery factor decreases and finally the ultimate oil recovery factor becomes smaller than that of the linear krf case. This phenomenon can be described considering the relative permeability ratio of water to oil in different cases presented in Fig. 18.

Applying reinfiltration in reservoir prediction studies has shown a decrease in the ultimate oil recovery factor. According to Fig. 14, this is more effective during gas injection process. Figs. 15 to 17, have shown that this phenomenon has more effect on the gravity drainage and oil expansion mechanisms.

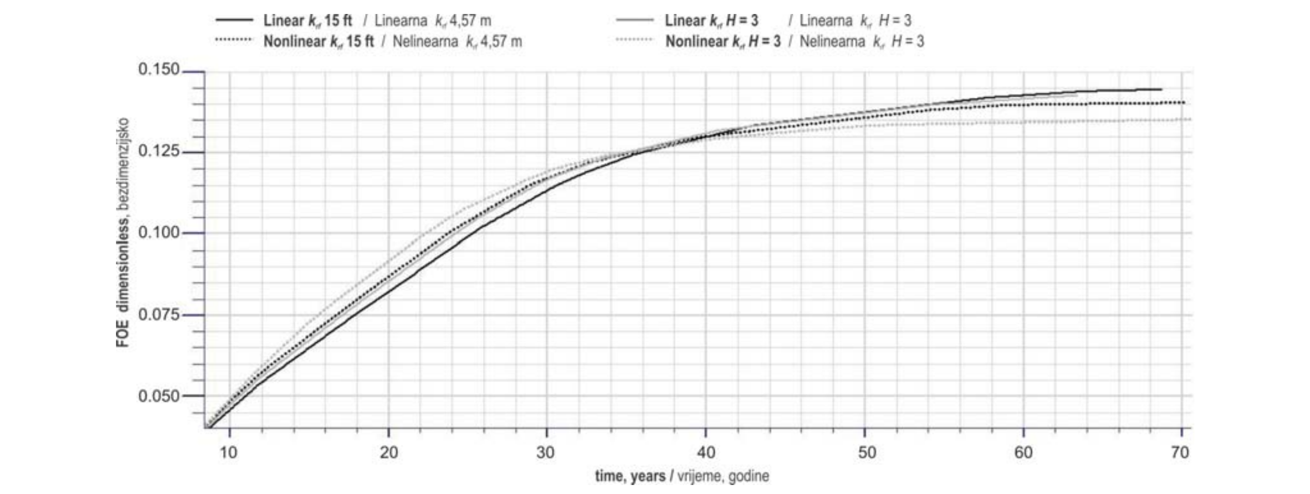

Fig. 13. Impact of nonlinear fracture relative permeability on behavior of oil recovery factor during reservoir natural depletion

Sl. 13. Utjecaj nelinearne relativne propusnosti pukotina na ponašanje koeficijenta iscrpka nafte tijekom prirodnog iskorištavanja ležišta

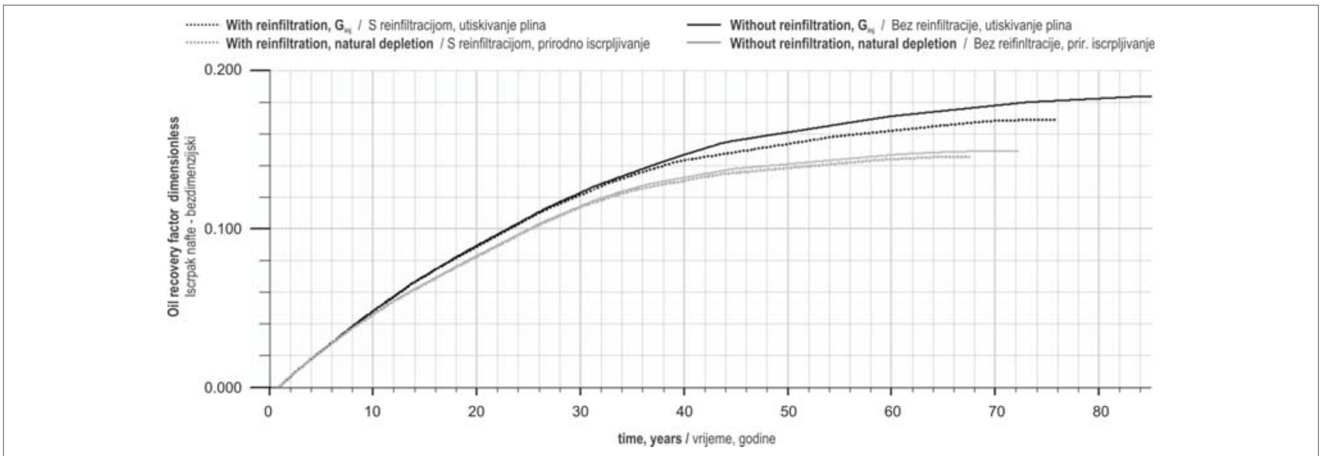

Fig. 14. Impact of Reinfiltration on oil recovery factor

Sl. 14. Utjecaj reinfiltracije na koeficijent iscrpka nafte

Fig. 15 Impact of Reinfiltration on gravity drainage mechanism
Sl. 15. Utjecaj reinfiltracije na mehanizam gravitacijskog dreniranja

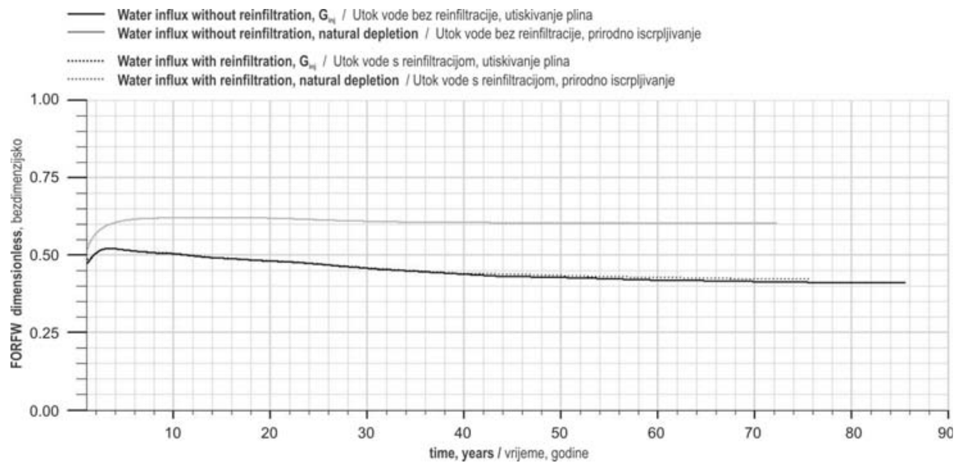

Fig. 16. Impact of Reinfiltration on water imbibition mechanism
Sl. 16. Utjecaj reinfiltracije na mehanizam apsorpcije vode

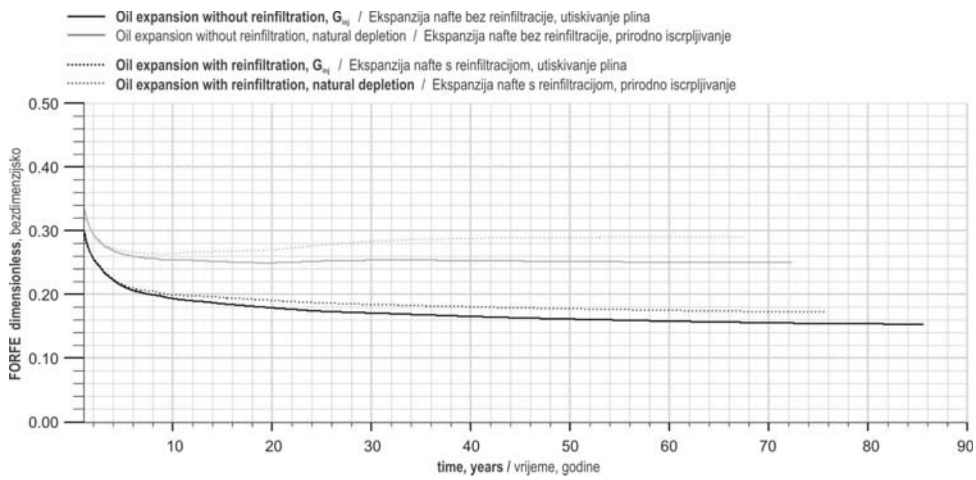

Fig. 17. Impact of reinfiltration on oil expansion mechamism
Sl. 17. Utjecaj reinfiltracije na mehanizam ekspanzije nafte

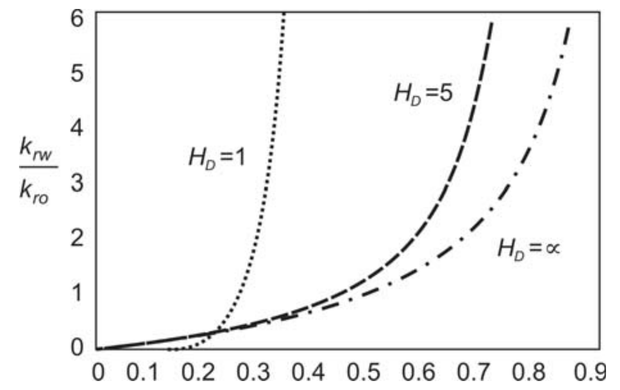

Fig. 18. Relative permeability ratio of water to oil in different cases
Sl. 18. Omjer relativne propusnosti za vodu u odnosu na naftu za različite slučajeve

4. Conclusions

1. Fracture reservoirs have large potential for oil production using gravity drainage mechanism. Gas injection in such reservoirs could activate/accelerate this mechanism and result in the increase in ultimate oil recovery factor.

2. Increase of the matrix block height causes an increase of the ultimate oil recovery factor.

3. Matrix block height has more effect on the gravity drainage mechanism but its effect on the water imbibition mechanism is negligible.

4. Applying capillary continuity between matrix blocks causes an increase in the ultimate oil recovery factor by the range of 1.1% to 10%. This is stronger in reservoirs with short matrix blocks and/or matrices with higher capillary pressure.

5. Applying nonlinear relative permeability curves causes a decrease in the ultimate oil recovery factor.

6. Reinfiltration of oil in matrix blocks causes a decrease in the ultimate oil recovery factor.

Nomenclature

b	fracture width
b_o	mean half fracture aperture
H	matrix block height
H_D	dimensionless fracture height
FOE	oil recovery factor
FORFF	fraction of oil produced by free gas gravity drainage
FORFE	fraction of oil produced by oil expansion
FORFW	fraction of oil produced by water influx
kr	relative permeability
k_f	conventional fracture permeability
M	mobility ratio
P_{cm}	matrix capillary pressure
P_{cfD}	dimensionless fracture capillary pressure
P_o	original capillary pressure
S	phase saturation
S_w	water saturation
u	fluid velocity
φ_f	fracture porosity
γ	surface tension
μ	fluid viscosity
ρ	fluid density

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