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Investigation of the Impact of Block-to-Block Interaction on the Performance of Naturally Fractured Reservoirs Using Numerical Simulation

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Abstract

In fractured reservoirs with primary gas cap, the gas, having high mobility, moves faster than oil and consequently forms a new zone above the oil zone. In this zone, which is named gas invaded zone, gravity drainage is the major mechanism contributing to oil recovery. In a system comprising matrix blocks, a portion of oil drained from the upper matrix block can re-infiltrate the lower block through the top or lateral faces. In this two-part study, first, a single porosity simulation was used with a fine grid in the space occupied by the stack of matrix blocks and fractures. The particular characteristics and properties of each medium were allocated to different portions occupied by these systems in the grid. The impact of fracture and matrix capillary pressure values, as well as the matrix permeability on the oil recovery from each block, was investigated in this part. In the second part, a dual porosity simulation was employed, and a coarse grid was built having the same dimensions of the single porosity fine grid. The gravity drainage process was then simulated, and the results of the dual porosity and single porosity approaches were subsequently compared. The results indicate the block height and matrix permeability to have the most significant influence on the ultimate recovery and oil production rate, whereas re-infiltration shows to have no effect on the ultimate recovery.

***Keywords**: Fractured reservoir; Gravity drainage; Single porosity; Dual porosity; Re-infiltration.*

1. Introduction

Containing more than 50% of the world hydrocarbon reserves, naturally fractured reservoirs are heterogeneous porous media comprising two types of pores, i.e., fractures and matrix pores [1-2]. The two major forces in fractured reservoirs are known to be the capillary and gravity [3]. The oil production performance of these kinds of reservoirs are strongly affected by matrix and fracture capillary forces in the multiphase flow [4].

Gas-oil gravity drainage, which is the dominant mechanism of oil recovery from gas invaded zones of fractured reservoirs is deeply affected by the total height in capillary continuity. Matrix blocks could be regarded as discontinuous blocks by assuming the fracture capillary pressure to be zero. It is nonetheless not always the case since the quantity of fracture capillary pressure may possibly be non-zero. The most important parameter affecting the oil recovery from fractured reservoirs by gravity drainage is often capillary continuity. Complete segregation in the fracture system takes place in the absence of re-infiltration. In that condition, the drainage rate of a column of n blocks is equal to n times of the drainage rate of a single block. As the rate of gravity drainage nears the flow rate of a block with height which is equal to the height of the column of blocks above the gas-oil level, the maximum infiltration occurs. The matrix blocks of actually fractured reservoir practically are not all horizontal nor are they isolated from each other. Flow performance for the case of blocks with contact areas is different from that for the case of a single block or a column of isolated blocks. As oil is dropped at the top face of a block, it is imbibed into the said block at a rate which is comparable with the maximum drainage rate. The gravity drainage performance of matrix blocks with re-infiltration which have contact with each other is a function of time, and it widely differs from that of a stack of isolated blocks. As a result of block to block re-infiltration, the oil recovery is delayed. Hence, the gravity drainage, initial production rates, and the fluid (oil and gas) distribution in the reservoir are affected due to the delay time [5-6].

Saidi *et al.* [7] were the first to introduce the interactions between matrix blocks. They related the block to block interaction to the capillary continuity between the matrix blocks through liquid bridges and the re-infiltration process. It was concluded by Saidi [8] that the capillary continuity between matrix blocks cannot be considered if the fracture opening is 50 μm or higher. In the process of gas-oil gravity drainage in a fractured reservoir, the oil which is drained from various blocks mostly does not exhibit a two-phase flow in the fracture network surrounding the blocks. Due to the fact that in most cases the fracture is not wide enough, it is possible that the lower matrix blocks rapidly re-imbibe the oil drained from the upper blocks. There are some particles present in fractures which can impede the rapid flow of the drained oil from matrix blocks through the fracture network toward the gas oil level. Therefore, some portion or all of the drained oil can be re-imbibed to the next block. Hence, the re-imbibition process impacts the two-phase gas-oil flow in fractured reservoirs. The amount of re-imbibition is a function of factors such as fracture opening, matrix permeability, and the presence of particles in fractures. Capillary continuity and re-infiltration are two important re-imbibition phenomena occurring in a collection of blocks [8-10].

Thomas *et al.* [11] demonstrated the existence of capillary continuity across the fractures by the observation of excess gas-oil-ratio production while using a measured matrix gas/oil capillary pressure function. Festoy and van Golf-Racht [12], using a conventional single-porosity numerical model, simulated the drainage rate as a function of the contact area size and location for a stack of two matrix blocks. It was concluded that the final oil recovery for the case of partial physical connection between the two blocks is higher than the case no connection existed between the two blocks. Firoozabadi and Ishimoto [13] developed a one-dimensional model for there-infiltration process in fractured porous media. They demonstrated that the oil drained from the upper matrix block, instead of flowing through the fracture network, is totally discharged into the lower block. Firoozabadi *et al.* [14] numerically modeled the re-infiltration phenomenon in fractured porous media using a two-dimensional approach. They developed the expression for the re-infiltration rate across the faces of a block by solving the fractional flow equation in a two dimensional space with mixed boundary conditions. Rezaei Sani *et al.* [15], using a commercial simulator, investigated the effects of the block to block interaction, gravity drainage, and capillary continuity, on oil recovery from South Pars oil layer. They asserted that the flow of re-infiltrated oil, which stems from the oil pressure in the lower block being less than in the fracture, delays the recovery from a block. The delay was found to be most significant at high re-infiltration rates. Sharifi and Shadizadeh [16] performed the mathematical modeling of oil gravity drainage with presence of block-to-block and dispersion processes. Their results illustrated that the existence of the block-to-block process causes the gas concentration to increase gradually into the stack during production.

In this study, first, a single porosity simulation is used with a fine grid in the space occupied by the stack of matrix blocks and fractures. The particular characteristics and properties of each medium are allocated to different portions occupied by these systems in the grid. The impact of fracture and matrix capillary pressure values, as well as the matrix permeability on the oil recovery from each block, is investigated in this part. In the second part, a dual porosity simulation is employed, and a coarse grid is built having the same dimensions of the single porosity fine grid. The gravity drainage process is then simulated, and the results of the dual porosity and single porosity approaches are subsequently compared

2. Simulation of gravity drainage

The gravity drainage mechanism is modeled by applying the following assumptions:
1) Only vertical flow
2) Constant system pressure
3) Incompressible fluids
4) Initially, fully oil saturated blocks completely surrounded by gas
5) Constant viscosities

The fluid and rock properties used for this simulation are summarized in Table 1.

Table 1. Saturation functions of matrix and fracture

Fracture saturation functions				Matrix saturation functions			
S_g	K_{rg}	K_{ro}	P_c (atm)	S_g	K_{rg}	K_{ro}	P_c (atm)
0	0	0.8	0.0005	0	0	0.8	0.0007
0.1	0.05	0.72	0.00051	0.1	1E-07	0.72	0.00073
0.2	0.1	0.64	0.00052	0.2	0.1	0.64	0.00076
0.3	0.15	0.56	0.00053	0.3	0.15	0.56	0.00079
0.4	0.2	0.4	0.00054	0.4	0.2	0.48	0.00082
0.5	0.25	0.4	0.00055	0.5	0.25	0.4	0.00085
0.6	0.3	0.32	0.00056	0.6	0.3	0.32	0.00088
0.7	0.35	0.24	0.00057	0.7	0.35	0.24	0.00091
0.8	0.4	0.16	0.00058	0.8	0.4	0.16	0.00094
0.9	0.45	0.08	0.00059	0.9	0.45	0.0001	0.00097
1	0.5	0	0.0006	1	0.5	0	0.001

Fluid and rock properties										
μ_o, cp	μ_g, cP	ρ_o, g/cc	ρ_g, g/cc	B_{oi}, rcc/scc	B_g, rcc/scc	$Ø_m$	k_m, md	k_f, md	$Ø_f$	C_{rm}, 1/atm
0.831	0.02	0.7298	0.0012	1.00002	0.01	0.5	20	72.2	1	7E-07

2.1. Single-porosity model

The single porosity model comprises of two matrix blocks initially oil saturated and two tanks, i.e., a supply tank and a storage tank, which are initially 100% gas saturated. The matrix blocks were represented by a slab having the dimensions 3 cm × 0.07 cm × 10 cm. The model which was created with Cartesian coordinates contains two matrix blocks and two tanks (supply tank and storage tank). There are 8 grids in the x-direction, while one of which represents the right fracture, 6 grids refer to the matrix blocks, and the other grid represents the left fracture. There is only one grid in the y-direction having thickness of 0.007cm, while the z-direction contains 126 grids.

2.2. Dual-porosity model

The dual porosity model consists of two matrix block initially oil saturated and two tanks, i.e., supply tank and storage tank, initially 100% gas saturated. The matrix blocks were represented as slabs having dimensions of 3 cm × 0.07 cm × 10 cm. The model, created with Cartesian coordinates, contains two matrix blocks and two tanks (supply tank and storage tank). This model entails four regions, i.e., the first two regions (R1 and R2) represent the matrix and others (R3 and R4) represent the fractures. The value of matrix-fracture transfer function is 0.0277.

3. Results and discussion

In order to investigate the effects of various parameters on the there-infiltration process in fractured porous media, the gravity drainage mechanism in fractured reservoir was simulated by modeling the process.

3.1. Tall matrix and two matrix blocks in single porosity model

A tall matrix model and two short matrix blocks were used to investigate the influence of capillary discontinuity between two matrix blocks. The oil recovery from the tall matrix block and the two matrix blocks with capillary continuity are shown in Fig. 1 (a). Based on the results of the simulation study, the oil recovery from a tall block is higher in comparison with two matrix blocks.

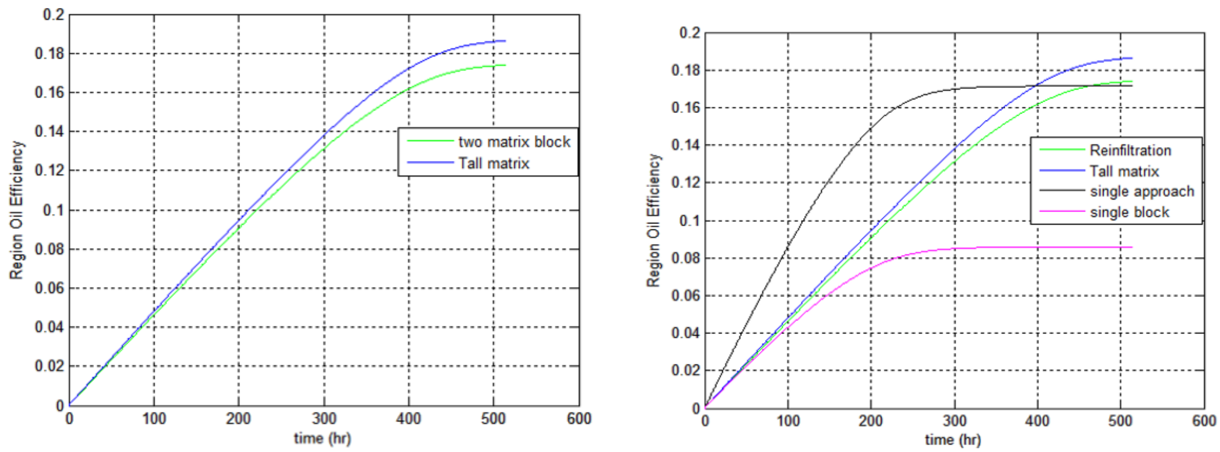


Figure 1. Ultimate oil recovery in single porosity model; a) Oil recovery from tall and two matrix blocks, b) Effect of re-infiltration process

3.2. Re-infiltration effect in single porosity model

The impact of the there-infiltration process on the ultimate oil recovery in a single porosity model is depicted in Fig. 1 (b). The oil production rate from one matrix block in the single porosity approach was doubled so that it can be compared with the case of two matrix blocks (re-infiltration model).

3.3. Single porosity model sensitivity analysis

3.3.1. Block height

As can be seen in Fig. 2 (a), the ultimate oil recovery increased as the matrix block height increased, even though the initial production rate was lower.

3.3.2. Grid sensitivity

Table 2 shows the various grid sizes assigned to the model. The single porosity approach exhibits sensitivity to numerical block size, as shown in Fig. 2 (b). It is indicated by the grid sensitivity that the small grid blocks bring about variation in matrix oil recovery.

3.3.3. Matrix permeability

The impacts of upper and bottom matrix permeability values on the oil recovery in single porosity model are shown in Figs. 2 (c-d). The variety of the permeability values used in the simulation is indicated in Table 2. Although the ultimate oil recovery was not affected by increasing the matrix permeability, this increase did raise the initial oil production rate.

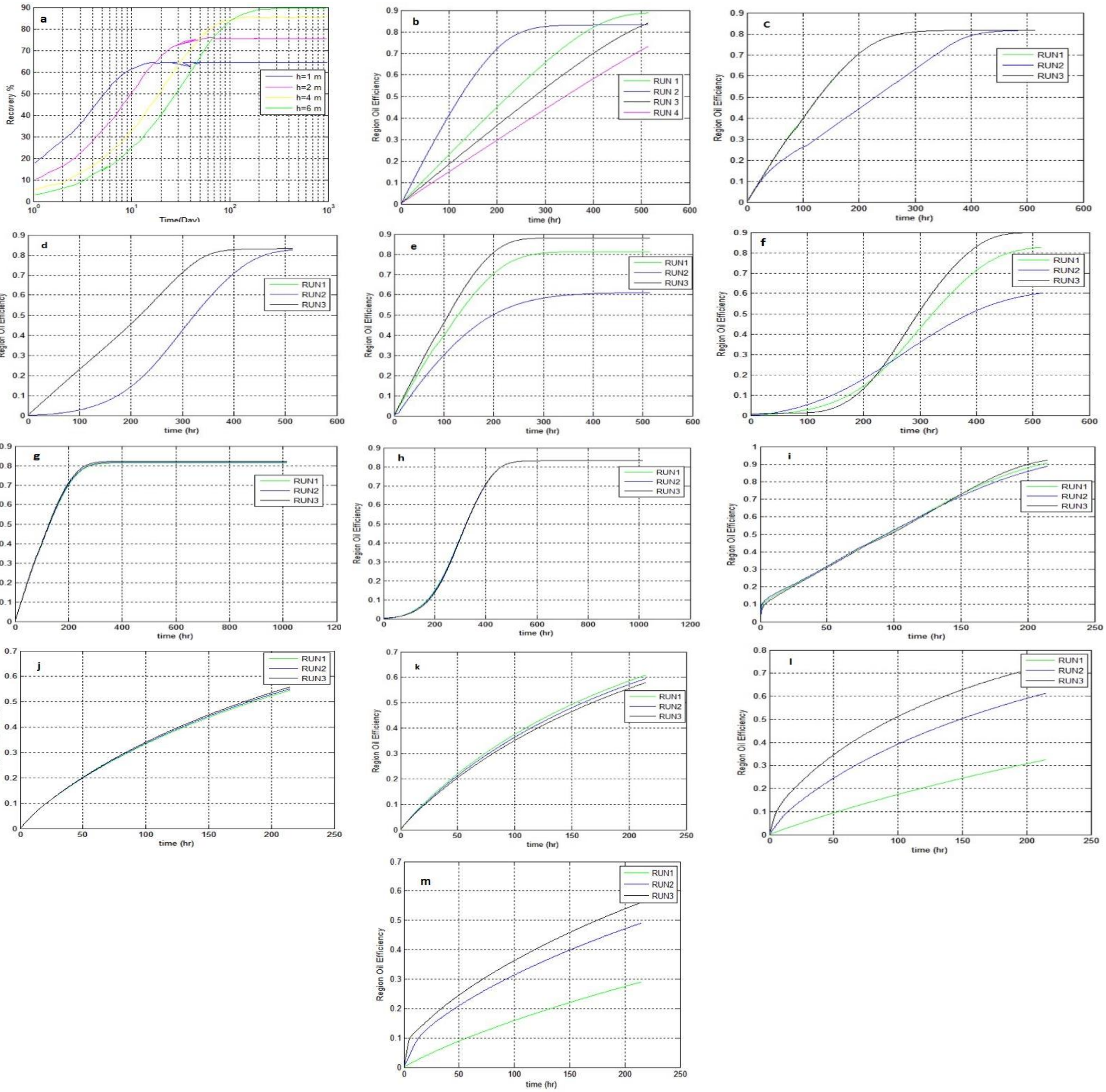


Figure 2. Effect of various parameters on regional oil efficiency versus time; a) Block heights, b) matrix grid size, c) matrix permeability (upper matrix), d) matrix permeability (bottom matrix), e) Fracture capillary pressure (upper matrix), f) Fracture capillary pressure (bottom matrix), g) Fracture width (upper matrix), h) Fracture width (bottom matrix), i) Matrix capillary pressure (upper matrix), j) Block-to-Block interaction (upper matrix), k) Block-to-Block interaction (bottom matrix), l) Matrix-Fracture transfer function (upper matrix), m) Matrix-Fracture transfer function (bottom matrix)

3.3.4. Fracture capillary pressure

Figures 2 (e-f) depict the influence of fracture capillary pressure on the performance of the upper and bottom matrix blocks in the single-porosity model. Increasing the fracture capillary pressure results in the ultimate recovery to be obtained earlier. The variety of fracture capillary pressure values used in the simulation is shown in Table 2.

Table 2. Sensitivity analyses on various parameters

Grids for single porosity simulation			
RUN	Number of grid cells in the matrix	Total number of grid cells in matrix and fracture	Oil recovery at 515 hours
1	6×1×80	8×1×124	89%
2	6×1×40	8×1×84	83%
3	18×1×80	20×1×124	84%
4	18×1×100	20×1×144	73%

Matrix permeability sensitivity			Fracture capillary pressure sensitivity	
RUN	$k_{upper\ matrix}$	$k_{bottom\ matrix}$	RUN	Fracture capillary pressure (atm)
1	300 md	300 md	1	P_{cf} = 0.0015
2	300 md	100 md	2	P_{cf} = 0
3	300 md	500 md	3	P_{cf} = 0.002

Fracture width sensitivity		Matrix capillary pressure sensitivity	
RUN	Fracture width	RUN	Matrix capillary pressure
1	0.01 cm	1	P_{cm}
2	0.07 cm	2	1.5P_{cm}
3	0.2 cm	3	0.5P_{cm}

Matrix block-to-block interaction sensitivity		Matrix-fracture transfer function sensitivity	
RUN	Block-to-block interaction coefficient	RUN	Matrix-fracture transfer function
1	0.01	1	0.01
2	0.05	2	0.04
3	0.1	3	0.1

3.3.5. Fracture width

Figures 2 (g-h) illustrate that altering the degree of capillary discontinuity by means of increasing the fracture width (Table 2) has little or no impact on the oil recovery from fractured porous media by gas-oil gravity drainage.

3.3.6. Matrix capillary pressure

The impact of matrix capillary pressure on the oil recovery in the single porosity approach is illustrated in Fig. 2 (i). As the matrix capillary pressure is changed (Table 2) and the simulator is run, it can be seen that the ultimate recovery decreases as the matrix capillary pressure is increased.

3.4. Dual porosity model sensitivity analysis

3.4.1. Block-to-block interaction coefficient

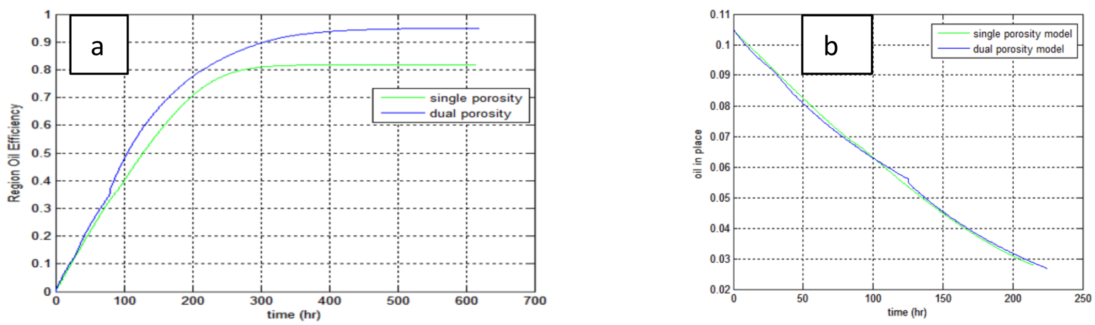
Figures 2 (j-k) depict the impact of block-to-block interaction coefficient on the performance of the upper and bottom matrix blocks in the single porosity model. Given the fact that there is no re-infiltration process for the upper matrix cell, it is expected not to be sensitive to different values of block-to-block interaction coefficient. The variety of block-to-block interaction coefficient values is shown in Table 2.

3.4.2. Matrix-fracture transfer function

Figures 2 (l-m) illustrate the influence of matrix-fracture transfer function on the performance of the upper and bottom matrix blocks in the single porosity model. The results obtained by the sensitivity runs indicate that the (ROE) in the upper matrix is more sensitive to different matrix-fracture transfer function values than to different multiplier values for the block-to-block interaction coefficient. Table 2 presents a variety of matrix-fracture transfer function values.

3.5. Comparison of single and dual porosity models

The results of primary runs reveal considerable differences in oil recovery efficiency (ROE) of various scenarios of the single model (base case) and the dual porosity models. It is known that in the gravity drainage process, the capillary pressure forces oppose the gravity forces. Figure 3 (a) displays that when the gas column in the fractures is greater than the threshold height, i.e., $(\gamma_o-\gamma_g).\,h>P_{th}$, oil displacement will continue. Once equilibrium is reached, i.e., $(\gamma_o-\gamma_g).h=P_{th}$, no more oil will be produced by the gravity drainage mechanism.



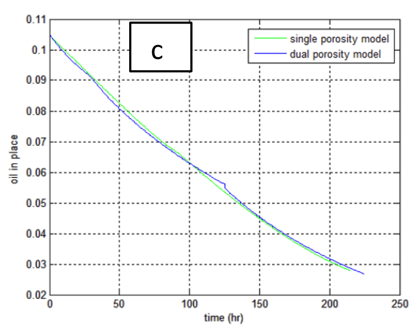


Figure 3: a) Comparison between single and dual porosity models for upper matrix, b) Matching oil in place for upper matrix, c) Matching oil in place for lower matrix

3.6. Matching ROIP

As mentioned earlier, in order to model the amount of remaining oil-in-place (ROIP) in matrix and fracture as a function of time, four different regions were defined in the single and dual porosity models. Given the fact that matching the ROIP in regions two and three will automatically lead to the ROIP in R1 and R4 to be matched, it is attempted to match the ROIP in R2 and R3, and the focus is hence turned to ROIP in these two regions. The results obtained by the sensitivity runs are used for obtaining a good match between the single porosity model and the equivalent dual porosity model. While the ROIP in the upper matrix block shows sensitivity to different matrix-fracture transfer function values, the ROIP in the lower matrix block appears to be sensitive to different multiplier values for block-to-block interaction coefficient and values of matrix-fracture transfer function. As the sensitivity runs' results indicate, different values of multipliers were assigned for the block-to-block interaction coefficient, while at the same time, the matrix-fracture transfer function value is changed for the lower matrix block. As can be seen in Figs. 3 (b-c), an acceptable match exists between the single and dual porosity models.

4. Conclusion

In this study, the impact of different parameters on oil recovery and the gravity drainage mechanism performances of both single and dual porosity approaches were investigated. It is mainly concluded that while re-infiltration causes a reduction in the oil production rate, it does not affect the ultimate recovery.

1) Fracture capillary pressure in gas-oil gravity drainage enhances the oil recovery in both single and dual porosity models.
2) Horizontal fracture width appears to have no effect on the oil recovery in the single porosity model.
3) As the matrix capillary pressure increases, the matrix oil recovery in both models decreases.
4) While the matrix permeability had no effect on the ultimate recovery, it did improve the initial production rate.
5) The block height and matrix permeability are ascertained to be the most effective parameters on the ultimate recovery and oil production rate.
6) Although altering the matrix-fracture transfer function impacts the oil in place in both upper and bottom matrix blocks, alteration of block-to-block coefficient only influences the oil in place of the bottom matrix block.
7) The re-infiltration process impeded the reaching of the ultimate recovery.
8) As the single-porosity model appears to be time consuming, it is more fitting to employ the dual porosity approach to model fractured reservoirs.

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