Simulation of Block-to-Block Interaction in Fractured Reservoirs by Single Porosity Model

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Abstract

In a fractured reservoir that has a gas cap, pressure reduction results from oil production causes the gas cap to expand and hence the gas-oil contact moves downward. Because of its high mobility, gas moves much faster than oil in the fractures to form a gas invaded zone right above the oil column. As such all matrix blocks located in the invaded zone are partially or totally surrounded by the gas within the fractures. The difference between oil and gas density results in gravity forces that push gas into the matrix blocks and drain oil from them under a mechanism that known as "gravity drainage". The question is whether the drained oil flows through the fracture network characterized with its high permeability or reinfiltrate into the lower matrix blocks in a process known as block-to-block interaction? The answer to this question is crucial to decide about the reliability of the oil production rate predicted by dual porosity simulation which assumes that there is no block to block interaction and the drained oil from the gas invaded zone moves through the fracture network. In this study by using a fine single porosity simulation, firstly it is shown that block-to-block interaction is a dominant process within the gas invaded zone of fractured reservoir and secondly the rate of reinfiltration in dense fractured reservoir is calculated.

Introduction

Fractured reservoirs are generally simulated by dual-porosity model which assumes that a fractured reservoir consists of a huge number of matrix blocks that are separated by a fracture network. Fluids within the reservoir are mainly contained in the matrix block system because it possesses a high pore volume. On the other hand the fracture network because of its high permeability provides the path through which oil moves from the matrix blocks towards the producers [1, 2]. In other words dual-porosity simulation is based on the assumption that oil can not move from one matrix block to another but flows through the fracture network. When using dual-porosity model to simulate fractured reservoir with a gas cap, this assumption could have a substantial impact on the rate calculation. In this type of reservoirs, during the downward movement of gas-oil contact, because of its high mobility, gas moves much faster than oil in the fractures and hence forms a gas invaded zone right above the oil column [3, 4]. As such all matrix blocks located in the gas invaded zone are partially or totally surrounded by the gas within the fractures. The difference between the density of the oil within the blocks and the gas in the surrounding fractures, results in gravity forces that push gas into the matrix blocks and drain oil from them under a mechanism known as "gravity drainage". The drained oil could flow either through the blocks underneath in a process known as reinfiltration or via the fracture network. The object of this study is mainly to answer the following questions:

A- Does the oil drained from a block due to gravity drainage travel through the low permeable matrix system or move down via the extremely high permeable fracture network?
B- In low permeable rocks (Dense Carbonate) what percent of the drained oil reinfiltrate into the blocks underneath?
C- What is the rate of reinfiltration?

Phenomena associated with Gravity Drainage

The two important phenomena associated with gravity drainage in gas-oil system, are reinfiltration and capillary continuity[5] which are explained in the following.

Capillary Continuity

When a matrix block saturated with oil is surrounded by gas, the difference between oil and gas densities cause a pressure difference between the two phases. This pressure acts in a way to push the gas into the block and drain oil out of it in the vertical direction. This process is known as gravity drainage, and takes place when the exerted pressure is greater then the capillary forces that retain the oil within the pores of the matrix. Once these two forces come to equilibrium the drainage process will come to end. The exerted pressure difference depends mainly to the block height and the difference between oil and gas densities. Densities difference is a function of fluid properties whereas the block height depends on the fracture density or the capillary continuity between the blocks. The greater the capillary continuity between the blocks the greater the block height and hence the larger the volume of oil ultimately recovered from the system. It is clear that in the fractured reservoir there are no totally separated blocks, instead there is some points of contact in between that lead to a degree of capillary continuity. However in some cases the fractures are filled with non- permeable materials such as shale which prevent the continuity.

Reinfiltration

At the first glance it seems that the oil drained from a block due to gravity drainage, moves down through the high permeable fracture system without passing through the matrix blocks below. This means that all the blocks act independently so that the total rate of drainage can be simply calculated by multiplying the rate of drainage of a single block by the total number of the blocks.
This results from the fact that one has no real picture from the rate of production caused by gravity drainage. As it was indicated before the driving force behind the gravity drainage is the pressure resulted from the difference between oil and gas densities. For example if a block of 20 feet height is saturated with oil and surrounded by gas, and if the density difference between oil and gas is 0.2 psi /ft then the pressure is at most 4 psi which is too small when compared to the pressures cause the viscose flow in the vicinity of the well bore that could have an order of magnitude of hundreds psi and could results in flow rate of hundreds of barrels per day.
Therefore the rate of drainage is too small to fill the horizontal and vertical fractures and cause overflow. As such the oil has enough time to imbibe into the block underneath due to the spontaneous imbibition and gravity forces and flows through the matrix system[6, 7, and 8]. The main object of this work is to verify the occurrence of this process and quantities it by using single porosity model.

Model Description

The numerical model consists of three matrix blocks saturated with oil and surrounded by vertical and horizontal fractures that are filled with gas. The fractures pore volume was defined large enough to supply the total volume of gas which is necessary to drain all of the oil that might be drained under the gravity drainage process. Therefore there was no need to inject gas into the fracture system.

The capillary pressure and permeability of the fracture system assumed to be zero and 100 md respectively to insure that viscose forces are negligible and the whole system work only under the interaction between gravity and capillary forces. This bear a resemblance to a matrix block that is located at a zone far enough from any injector or producer such that lateral pressure gradients are zero which is the case of the blocks in the gas invaded zone.

Furthermore it was assumed that the relative permeability of the fractures is equal to the phase saturations. The average pressure is 236 atm.

Since the fluids mainly flow in the vertical direction then it was necessary to fine the model in the Z direction to prevent numerical dispersion and detect the fluid movement precisely.

Fluid and rock properties along with the general specification of the model are shown in Table- 1 to 3.

A single porosity model is used because all assumptions and differential equations applied in this model are physically meaningful as such it is usually used as a reference to verify the outcomes of other methods of simulation.

Simulating the Reinfiltration process

In a cascade of matrix blocks separated by horizontal and vertical fractures, the oil drained from a block under gravity drainage moves vertically downward and enters the horizontal fractures. Depending on the forces applied and the rate of drainage, this oil could flow either through the blocks underneath or through the vertical fractures.

The only forces exist are the weight of the oil which acts in the vertical direction and capillary forces which act in a way to imbibe oil into the matrix block because oil is the wetting phase in a gas-oil system.

The rate of oil drainage from a matrix block is calculated by Eq. (1).

$$\frac{\partial}{\partial z}\left[\frac{k_z k_{ro}}{\mu_o}(\Delta\rho g - \frac{dp_c}{dz})\right] = \phi \frac{\partial S_o}{\partial t} \qquad (1)$$

According to this Equation the rate of oil drainage depends on the absolute permeability of the matrix, oil relative permeability, capillary pressure, oil viscosity, block height and the difference between oil and gas densities. As it is discussed in the following sections, in fractured reservoir that are characterized by their low porosity all of the above parameters vary in such a way that the rate of drainage is very small so that generally oil trickles from one block on the upper face of the block beneath, and hence there is no accumulation of the drained oil to fill the horizontal fractures, even in the early time of the drainage process when the flow rate is at its maximum value.

If the reinfiltration process does not take place and the drained oil flows through the vertical fractures only, then the saturation profile of all of the blocks must be the same. However if reinfiltration occurs then the block in the top must always possesses the

lowest oil saturation and the last block which is in the base must be at its maximum oil saturation. Besides the oil saturation of the rest must be in between.
For the model of this study which is composed of three blocks, oil saturation calculated by the single porosity model is shown in Figure-2. It is clear that at each time step the third block has the maximum oil saturation and the first one has the minimum value, which demonstrates that the block to block interaction takes place and it must be take into account when calculating the production rate results from gravity drainage process in fractured reservoir.

Percent of oil reinfiltration

Preceding section showed that reinfiltration process takes place within the gas invaded zone of fractured reservoirs, therefore it is necessary to determine how much of the drained oil is subjected to reinfiltration and flows through the matrix system of the gas invaded zone. As Eq.(1) shows, the rate of oil drained from a block is a function of time and the maximum rate is at the beginning of the drainage where $t=0^{+}$. In this case Eq(1) is changed as[9]:

$$q = \frac{k_z k_{ro} L_x L_y}{\mu_o}(\Delta \rho g - \frac{dp_c}{dz}) \qquad (2)$$

So it seems that at the beginning of the process the horizontal fracture which separates the two blocks is more likely to be filled by the drained oil which in turn would creep on the vertical sides of the block[6]. As such the time steps were defined small enough to observe and follow the oil movement in the earliest times. Oil saturation of the cells of the vertical fracture that are adjacent to the second and third blocks was monitored and plotted versus time in figure-3. These plots demonstrate that the volume of oil flows through the vertical fractures even in the early time of the process, is negligible and consequently the drained oil moves down only through the matrix blocks underneath.

Rate of Reinfiltration

As it is shown in figure-1, the rate of reinfiltration can be calculated by writing a material balance for each of the matrix blocks.
In the following equations, OIP, Qf and Rein stand for, oil in place, rate of oil enters the vertical fractures and rate of reinfiltration, respectively.

Material balance for block 1:

$$\frac{d(OIP1)}{dt} = \mathrm{Re}\,in2 + Qf1 \qquad (3)$$

Since $Qf1$ is equal to zero then Eq. (3) could be rewritten as follows:

$$\mathrm{Re}\,in2 = \frac{d(OIP1)}{dt} \qquad (4)$$

Similarly the material balance for the second block is written below

$$\frac{d(OIP1)}{dt} = \mathrm{Re}\,in3 - \mathrm{Re}\,in2 + Qf2 \qquad (5)$$

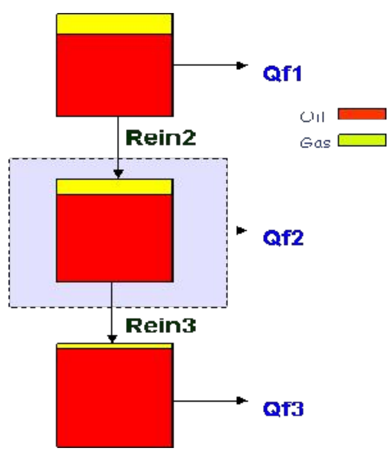
Setting *Qf*2 equal to zero and rearranging it Eq. (5) could yield Eq. (6) below.

$$\mathrm{Re}\,in3 = \mathrm{Re}\,in2 + \frac{d(OIP2)}{dt} \qquad (6)$$

In the above equations oil in place of the blocks is calculated by the model and hence its derivative with respect to time can be calculated either numerically or analytically.
As it was proved before the volume of oil flows through the vertical fractures is practically zero. As such the number of unknowns in the equations above reduces to 2 (Rein2 and Rein3) which are equal to the number of the equations.
In order to calculate the rate of reinfiltration by equations (4) and (6) it is necessary to calculate the derivative of the oil in place of each block with respect to time. This can be done either numerically or analytically. The following formula can be used to calculate the oil in place variation with time[10].

$$\frac{d(OIP)}{dt} = L_x L_y L_z \phi (1 - S_{cw} - S_{or})(\lambda e^{-\lambda t}) \qquad (7)$$

λ is a constant value equals to the inverse of the time when the recovery of a block is 63 percent of the ultimate oil recovery.



Figur-1 – A schematic of the three blocks model

Since the oil in place of the blocks is available at each time, λ is simply calculated and hence the oil in place variation of each block with time could be derived by Eq.(7).
Applying the above procedure, oil in place variation and rate of reinfiltration have been calculated for the second and third blocks and plotted in figure-4 and 5. As it is shown in figure-5 the rate of reinfiltration for a block of a height of 5 feet is at most 120 cc/hr. As it was discussed before the smallness of this rate is the main cause behind reinfiltration occurrence. It must be noted that in the present study it was assumed that the initial oil saturation is 100 percent, whereas the oil saturation of the blocks within the gas invaded zone of a fractured reservoir is much more less than 100 percent , therefore the order of magnitude of the reinfiltration rate must be smaller.

Conclusion

1-Block-to-Block Interaction is a dominant process in fractured reservoir that should be taken in to account in predicting oil production rate by gravity drainage for these type of reservoirs.
2-The rate of the oil drained from the matrix blocks that are located in the gas invaded zone of a fractured reservoir is too small, hence it has enough time to be subjected to gravity and capillary forces and re-entered into the lower matrix blocks.
3-In dense fractured reservoir, all of the oil drained from the gas invaded zone by gravity drainage, moves down through the matrix system.

NOMENCLATURE

symbol	=	definition
$\Delta\rho$	=	Oil and gas density difference, [atm/m]
ϕ	=	Porosity
K	=	Matrix absolute permeability, [cm^2]
Kr	=	Relative permeability
L	=	length, [m]
μ	=	viscosity, [cp]
OIP	=	oil in place, [m^3]
Pc	=	capillary pressure, [atm]
Scw	=	connate water saturation, [fraction]
Sor	=	residual oil saturation, [fraction]
t	=	time [hr]

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Appendix

Oil recovery of a block by gravity drainage in gas-oil system can be predicted by the exponential equation of Arnofesky[4]:

$$R(t) = R_\infty (1 - e^{-\lambda t}) \quad (1)$$

Substituting the equivalent of R(t) and R∞ in terms of OIP results in Eq.(2).

$$\frac{OIP_i - OIP(t)}{OIP_i} = \frac{OIP_i - OIP_\infty}{OIP_i}(1 - e^{-\lambda t}) \quad (2)$$

Rearranging Eq.(2) and differentiating it with respect to time yields Eq.(3).

$$\frac{dOIP(t)}{dt} = (OIP_i - OIP_\infty)(\lambda e^{-\lambda t}) \quad (3)$$

Where

$$OIP_i = L_x L_y L_z \phi (1 - S_{cw}) \quad (4)$$

$$OIP_\infty = L_x L_y L_z \phi (1 - S_{cw} - S_{or}) \quad (5)$$

Substituting (4) and (5) into Eq.(3)

$$\frac{dOIP(t)}{dt} = L_x L_y L_z \phi (1 - S_{cw} - S_{or})(\lambda e^{-\lambda t})$$

Tables:

Pressure (atm.)	Rs (SCC/SCC)	Bo (RCC/SCC)	Oil Viscosity (cp)	Bg RCC/SCC	Gas Viscosity (cp)
1.020693	0	1.007	1.441	1.1994311	0.003
13.60924	18.59637	1.0741	1.042	0.080156692	0.01158
34.02309	30.61988	1.1069	0.858	0.032278816	0.01215
68.04619	49.37656	1.1528	0.674	0.015501938	0.01323
102.0693	68.45387	1.1997	0.532	0.009922184	0.0146
136.0924	87.8518	1.2487	0.508	0.007189288	0.01638
170.1155	107.41	1.2996	0.457	0.00566228	0.01842
204.1386	127.7699	1.3558	0.4093	0.004772461	0.02058
229.5198	143.6409	1.4067	0.378	0.004371622	0.0222
236.3244	143.6409	1.4047	0.3782		

Table-1 Oil and Gas Properties

SL	Krg	Kro	Pc (atm)
0.2	0.7	0	0.204082
0.3	0.54	0.0005	0.07483
0.35	0.46	0.001	0.05102
0.4	0.38	0.002	0.043537
0.45	0.3	0.0065	0.038776
0.5	0.24	0.017	0.035374
0.6	0.14	0.062	0.032653
0.7	0.074	0.16	0.031293
0.8	0.033	0.35	0.029932
0.85	0.019	0.49	0.027891
0.9	0.009	0.65	0.02449
0.95	0.0035	0.83	0.017007
0.98	0.001	0.93	0.006803
1	0	1	0

Table-2 Rock Properties

Lx,Ly	**0.91 m**
Lz	**1.52 m**
Km	**5 md**
Kf	**100 md**
Pressure	**236 atm**
Nx	**6**
Ny	**1**
Nz	**102**
Fracture Thickness	**0.001 m**

Table-3 Model Specification

Figures:

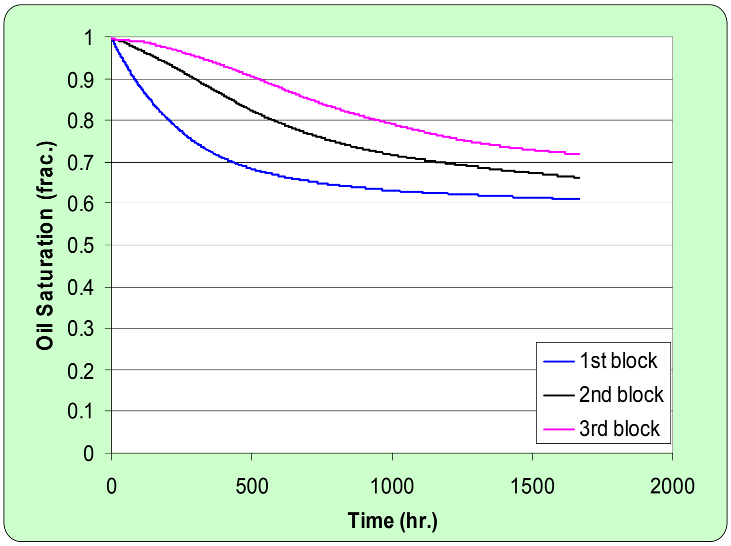

Figure-2 Comparison of Block Oil Saturation – The lower block has the maximum oil saturation because the oil drained from the upper blocks enters it.

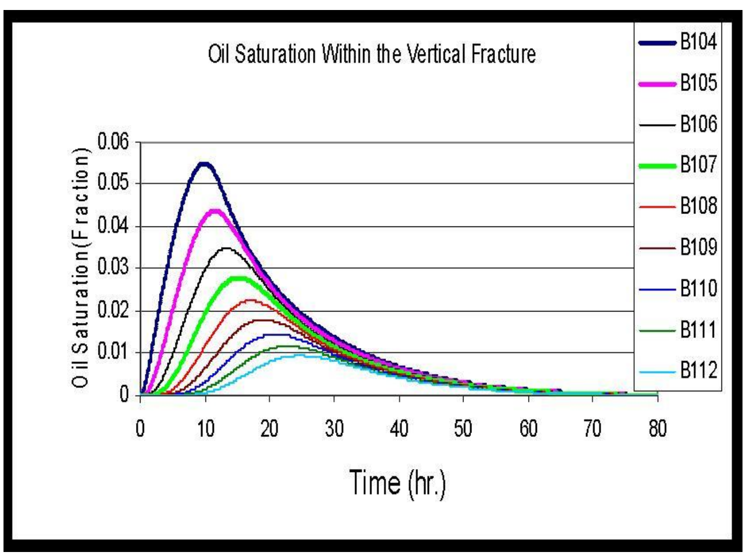

Figure-3 Oil saturation of fracture cells adjacent to the top of the middle block

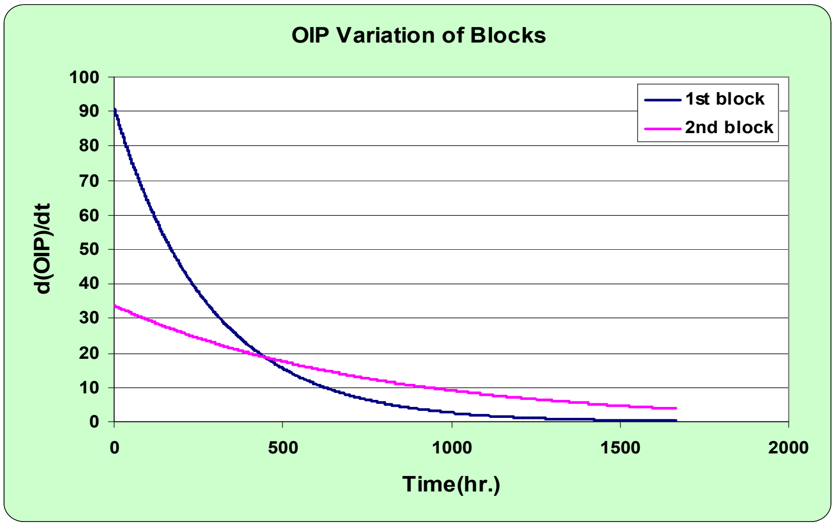

Figure-4 Variation of the oil in place of the first and second block

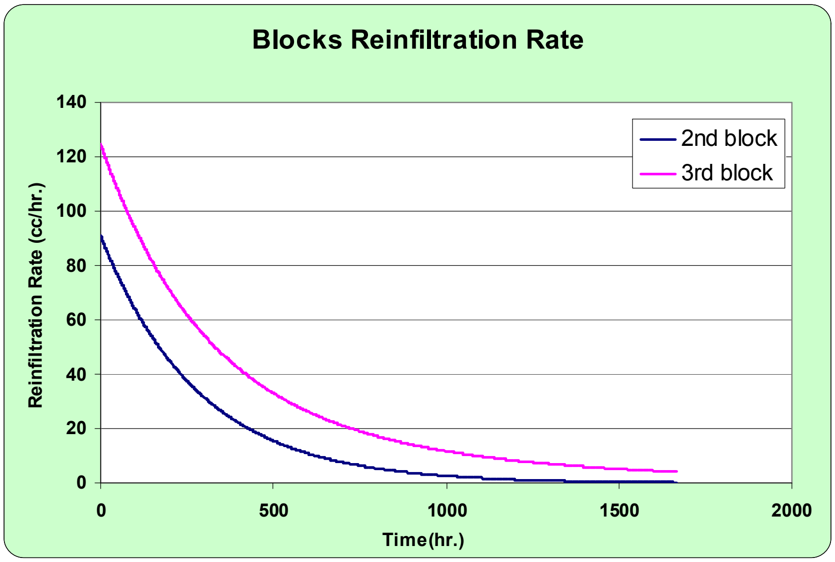

Figure-5 Rate of Reinfiltration of the drained oil into the second and third Blocks