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Development of a New Material Balance Equation for Naturally Fractured Reservoir

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ABSTRACT

Reservoir engineers are no more fascinated to use the simplified Material Balance Equation (MBE) for naturally fractured reservoir. Because of the complexity of naturally fractured reservoir, reservoir engineers are trending to a modified version of the material balance equation for a good estimation of hydrocarbon. This study presents a new material balance equation for naturally fractured reservoir considering laminar fluid flow. The proposed model will be a reliable tool to estimate the initial hydrocarbon in place for fracture and matrix. A general material balance equation has been derived for the naturally fractured reservoir. By using the fundamentals of fluid flow, a velocity term has been incorporated to derived model. This velocity term defines the condition of flow such as laminar and turbulent. Velocity for the laminar flow has been used to validate the model. By using field data, fracture compressibility versus original oil in place plot has been generated. The plot shows some deviation with one established model where no velocity was considered. A big number of hydrocarbons is left because of a significant pressure drop in later stage of production. By using the material balance equation for low velocity fluid flow reservoir, the estimation of reserve can be optimized.

Keywords: Fractured System; Reserve Estimation; Oil In Place

1. Introduction

Material balance method is nothing but an application of conservation of mass to the reservoir engineering. Schilthuis [1] primarily presented a general MBE for the homogeneous reservoir. In hydrocarbon reservoir, to determine drive mechanism and estimate their performance Schilthuis' MBE was the only means until 1950. And later, several MBE has been offered for single porosity reservoir [2-6], [7]. A graphical representation of MBE as a straight line was recommended by Havlena and Odeh [8]. Likewise, Campbell [9] offered a proposal to identify the new method of depletion mechanisms, e.g. gas cap or water drive. However, in the case of the complex reservoir, the scenario becomes completely different.

During the last few years, research on material balance has been conducted for the fractured reservoir to improve the reservoir analysis. However, all previous works are applicable to limited ranges of data. Porosity and permeability throughout the reservoir are assumed uniform in case of conventional MBE. As dual porosity system is generated for the naturally fractured reservoirs (NFR), the assumption is not valid. The compressibility of fractures is much higher than the matrix. In addition, the porosity of fracture and matrix changes when there is a change in pressure [10].

In the case of storage capacity, fractured reservoirs have much more influence on production engineering. Three types of storage can be identified in this kind of reservoir. Matrix blocks, which is the main storage for hydrocarbon, is denoted by Type A. Fracture networks are included with the matrix in Type B storage. The storage capacity of fracture networks is Type C [11]. In a reservoir of Type A, the matrix contains a significant portion of hydrocarbon whereas very small amount in fractures [12].

Two equations will be formulated based on the model assumptions provided below. Equation (26) and equation (30) will be an excellent method to calculate original oil in place (OIIP) in a fractured reservoir. The proposed equations are formulated for the initially undersaturated black oil reservoir by considering both porous media (matrix) and fracture network. Solution of Havlana and Odeh is applied to both fracture and matrix for calculating initial oil in place.

2. Model Assumptions

The derivation of the model follows some logical assumptions. These are:

1. The reservoir condition is isothermal
2. The reservoir has four components: a) stock tank oil, b) produced surface gas, c) produced water and d) naturally fractured rock
3. Four phases are available in the reservoir: oil, gas, water and solid (rock).
4. The stock tank oil does not have any dissolved gas or water.
5. Fracture and matrix of the reservoir are compressible.
6. The water production is negligible and there is no water encroachment.

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7. No water or gas has been injected to the reservoir.
8. Porosity of fracture and matrix is almost same throughout the reservoir.
9. The reservoir has the uniform water saturation.
10. No horizontal or vertical pressure gradient is present in the reservoir.

3. General MBE for Fractured Reservoir

The general form MBE for fractured reservoir is different from the MBE for converntional reservoir. Conventional reservoir has only the hydrocarbon storage of matrix whereas the fractured reservoir has both the matrix and fracture as storage. That's why MBE derived for fractured reservoir calculate the material balacne for both matrix and fracture.

According to the assumed condition, the derivation of MBE for naturally fractured reservoir is made based on the idealistic model shown in figure 1.

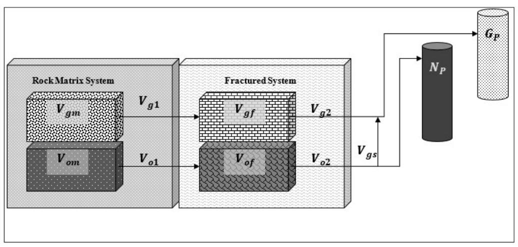

Fig.1 Volumetric Material Balance for NFR (redrawn) [13].

A volumetric material balance for the fractured reservoir shows

$$V_{ofi} + V_{gfi} = V_{of2} + V_{gf2} + V_{o1} + V_{g1} - V_{o2} - V_{g2} + \Delta V_{fw} - \Delta V_f + (W_e - W_p) \quad (1)$$

The initial oil in the fractured structure is

$$V_{ofi} = N_2 B_{oi} \quad (2)$$

The initial gas in the fractured structure is

$$V_{gfi} = 0 \quad (3)$$

as there is no free gas since an initially-undersaturated condition was assumed.

After a pressure drop, the volume of oil in the fracture system-

$$V_{of2} = N_2 B_o \quad (4)$$

After a pressure drop, the volume of free gas in the fracture system-

$$V_{gf2} = N_2 (R_{si} - R_s) B_g \quad (5)$$

where the original oil in place is calculated as

$$N_2 = \frac{V_b \phi_{fi} (1 - S_{wfi})}{B_{oi}} \quad (6)$$

The volume of oil that released by matrix is

$$V_{o1} = N_1 B_o + \Delta V_p + \Delta V_w - N_1 B_{oi} \quad (7)$$

where

$$N_1 = \frac{V_b \phi_{mi} (1 - S_{wi})}{B_{oi}} \quad (8)$$

$$\Delta V_p = V_b \phi_{mi} C_m \Delta p \quad (9)$$

$$\Delta V_w = V_b \phi_{mi} S_{wi} C_w \Delta p \quad (10)$$

Replacing equation 8 to 10, equation 7 becomes

$$V_{o1} = N_1 \left[B_o - B_{oi} + \left(\frac{S_{wi} C_w + C_m}{1 - S_{wi}} \right) \Delta p B_{oi} \right] \quad (11)$$

Because of the pressure reduction, the free gas will be evolved from the matrix and it is assumed that this free gas flows directly to the fracture. The volume of this free gas-

$$V_{g1} = N_1 (R_{si} - R_s) B_g \quad (12)$$

The volume of the released oil from fracture is-

$$V_{o2} = N_p B_o \quad (13)$$

The volume of the produced gas from fracture is-

$$V_{g2} = N_p (R_p - R_s) B_g \quad (14)$$

The expanded pore volume of the fracture due to pressure drop is-

$$\Delta V_f = V_b \phi_f C_f \Delta p \quad (15)$$

Due to pressure drop in the fracture system, the net expansion of the connate water volume is-

$$\Delta V_{fw} = V_b \phi_f S_w C_w \Delta p \quad (16)$$

Recalling equation (1),

$V_{ofi} + V_{gfi} = V_{of2} + V_{gf2} + V_{o1} + V_{g1} - V_{o2} - V_{g2} + \Delta V_{fw} - \Delta V_f + (W_e - W_p)$

Replacing the previous equations into equation (1), the material balance equation for naturally fractured reservoir can be found. Which is-

$$N_2 B_{oi} + 0 = N_2 B_o + N_2(R_{si} - R_s)B_g + N_1\left[B_o - B_{oi} + \left(\frac{S_{wi}C_w + C_m}{1 - S_{wi}}\right)\Delta p B_{oi}\right] + N_1(R_{si} - R_s)B_g - N_p B_o - N_p(R_p - R_s)B_g + V_b \phi_f S_w C_w \Delta p - V_b \phi_f C_f \Delta p + (W_e - W_p) \quad (17)$$

$$N_p[B_o + (R_p - R_s)B_g] = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right)\Delta p B_{oi}\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right)\Delta p B_{oi}\right] + V_b \phi_f \Delta p(S_w C_w - C_f) + (W_e - W_p) \quad (18)$$

where oil initially in place in the fracture by N_2 and oil initially in place in the matrix is denoted by N_1, N_p represents the cumulative whereas R_p represents the produced gas-oil ratio. Average matrix compressibility and average fracture compressibility are denoted by C_m and C_f respectively. The other notations are briefly described in the nomenclature section. As it is assumed that there is no water encroachment as well as no water production, we can write as:

$$W_e = 0 \quad (19)$$

$$W_p = 0 \quad (20)$$

Hence, equation (18) becomes:

$$N_p[B_o + (R_p - R_s)B_g] = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right)\Delta p B_{oi}\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right)\Delta p B_{oi}\right] + V_b \phi_f \Delta p(S_w C_w - C_f) \quad (21)$$

It is recognized that there is a proportional relationship between pressure drop through a granular bed and fluid velocity at low flow rates, and which is square of the velocity at high flow rates. Osborne Reynolds [14] first formulated this relationship which is as follows-

$$\frac{\Delta p}{L} = au + b\rho u^2 \quad (22)$$

As it is assumed that, the flow is laminar, so velocity of the fluid is very tiny. Eventually the square of the value of velocity will be negligible. That's why the term $b\rho u^2$ can be considered as negligible. Mathematically,

$$b\rho u^2 \to 0$$

So, the equation (22) becomes

$$\frac{\Delta p}{L} = au \quad (23)$$

$$\Rightarrow \Delta p = auL \quad (24)$$

From the experiment $a = 1$,

So, $\Delta p = uL$ (25)

Therefore, equation (21) becomes-

$$N_p[B_o + (R_p - R_s)B_g] = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right)B_{oi}uL\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right)B_{oi}uL\right] + V_b \phi_f (S_w C_w - C_f)uL \quad (26)$$

Equation (26) is the proposed material balance equation for estimating the reserve in a naturally fractured reservoir when the flow is considered as laminar.

Again, according to Darcy's law;

$$Q = -\frac{kA}{\mu L}(p_a - p_b)$$

$$\Rightarrow uA = -\frac{kA}{\mu L}(p_a - p_b)$$

$$\Rightarrow u = -\frac{k}{\mu L}(p_a - p_b) \quad (27)$$

The above equation is applicable for single phase (fluid) flow. The negative sign indicates that fluid flows from high pressure region to low pressure region. For the negative change of pressure (where $p_b > p_a$), the flow will follow the positive direction. If p_i is the initial pressure of the reservoir, then equation (27) becomes;

$$u = -\frac{k}{\mu L}(p - p_i) \quad (28)$$

Where p is the average reservoir pressure.
As most of the cases, $p_i > p$;
We can rewrite the equation (28) as:

$$u = \frac{k}{\mu L}(p_i - p) \quad (29)$$

Replacing equation (29) into equation (26), we get-

$$N_p[B_o + (R_p - R_s)B_g] = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right) B_{oi} \frac{k}{\mu L}(p_i - p)L\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right) B_{oi} \frac{k}{\mu L}(p_i - p)L\right] + V_b \phi_f (S_w C_w - C_f)\frac{k}{\mu L}(p_i - p)L$$

$$\Rightarrow N_p[B_o + (R_p - R_s)B_g] = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right) B_{oi} \frac{k}{\mu}(p_i - p)\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right) B_{oi} \frac{k}{\mu}(p_i - p)\right] + V_b \phi_f (S_w C_w - C_f)\frac{k}{\mu}(p_i - p) \quad (30)$$

Equation (30) is another proposed model for estimating the reserve in a naturally fractured reservoir when the permeability of the reservoir and viscosity of the fluid are clearly mentioned.

4. Results and discussions

Recalling equation (26),

$$N_p[B_o + (R_p - R_s)B_g] = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right) B_{oi} uL\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right) B_{oi} uL\right] + V_b \phi_f (S_w C_w - C_f) uL$$

$$\Rightarrow N_p[B_o + (R_p - R_s)B_g] - V_b \phi_f (S_w C_w - C_f) uL = N_1\left[B_o - B_{oi} + (R_{si} - R_s)B_g \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right) B_{oi} uL\right] + N_2\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right) B_{oi} uL\right] \quad (31)$$

Now, one of the goals to derive the previous equation is to calculate the oil volume trapped in the matrix and fracture. To do it easily and avoid the complexity, let;

$$N_p[B_o + (R_p - R_s)B_g] - V_b \phi_f (S_w C_w - C_f) uL = F \quad (32)$$

$$\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right) B_{oi} uL\right] = E_{o1} \quad (33)$$

$$\left[B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right) B_{oi} uL\right] = E_{o2} \quad (34)$$

Therefore, the equation (31) can be rewritten as:

$$F = N_1 E_{o1} + N_2 E_{o2} \quad (35)$$

Where E_{o1} the net expansion is term of the matrix system in oil phase and E_{o2} is the net expansion term of the fracture network in original oil phase.
Equation (35) can be rearranged according to the established MBE model of Havlena and Odeh [7].

$$\frac{F}{E_{o1}} = N_1 + N_2 \frac{E_{o2}}{E_{o1}} \quad (36)$$

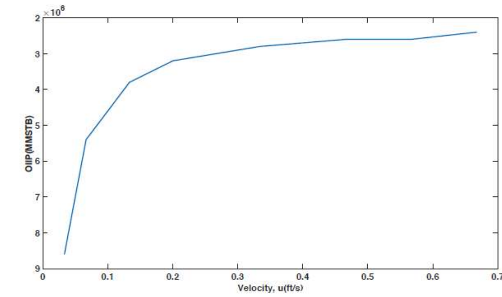

Fig. 2 Effect of increasing fluid velocity on Original Oil in Place

The mentioned objective of this paper is to develop a modified material balance equation by which hydrocarbon reserve can be estimated when velocity term is considered. By using PVT data and rocks and fluid properties, the above plot has been generated.

Fig. 2 is the representation of OIIP vs velocity plot. The velocity has been calculated by using Reynolds number. Equation (34) has been used to calculate OIIP. All this calculation has been done on my master's thesis. [15] Now, by explaining fig. 2, the effect of velocity can be figured out. The figure shows that, when the fluid velocity increases, the OIIP decreases which means because of the higher velocity of fluid, accumulation of hydrocarbon is being disturbed. Therefore, incorporating velocity parameter in the material balance equation, the estimated reserve can be optimized. If no velocity effect is considered, the overestimation might hamper on the proper economics of the production.

Now, one of the goals to derive the previous equation is to calculate the oil volume trapped in the matrix and fracture. For equation (26), the reserve calculated when fluid velocity is considered. This time it is being calculated when permeability, viscosity and pressure terms are incorporated. To do it easily and avoid the complexity, let;

$$N_p[B_o + (R_p - R_s)B_g] - V_b \phi_f (S_w C_w - C_f)\frac{k}{\mu}(p_i - p) = F \quad (37)$$

$$B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wi} + C_m}{1 - S_{wi}}\right) B_{oi} \frac{k}{\mu}(p_i - p) = E_{O1} \quad (38)$$

$$B_o - B_{oi} + (R_{si} - R_s)B_g + \left(\frac{C_w S_{wfi} + C_m}{1 - S_{wfi}}\right) B_{oi} \frac{k}{\mu}(p_i - p) = E_{O2} \quad (39)$$

Therefore, the equation (4.32) can be rewritten as:

$$F = N_1 E_{o1} + N_2 E_{o2} \quad (40)$$

Where $E_{o1}$the net expansion is term of the matrix system in oil phase and E_{o2} is the net expansion term of the fracture network in original oil phase.
Equation (40) can be rearranged according to the established MBE model of Havlena and Odeh [7].

$$\frac{F}{E_{o1}} = N_1 + N_2 \frac{E_{o2}}{E_{o1}} \quad (41)$$

Now, by using OIIP data from my thesis, PVT data, rocks and fluid properties data on Matlab software, the value of all the important parameters (F, Eo1, Eo2, F/EO1, EO2/EO1) of equation (41) can be calculated. [15]

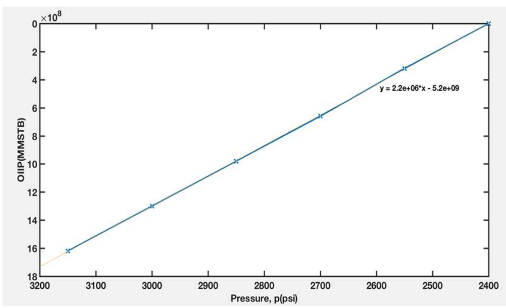

Fig. 3 Effect of increasing pressure on Original Oil in Place.

The mentioned objective of this paper is to develop a modified material balance equation by which hydrocarbon reserve can be estimated when Darcy flow is considered. The reserve has already been estimated in the other study. Now, it is crucial to see how pressure term affecting on the estimated reserve. PVT data and rocks and fluid properties have been used to generate the above plot (fig. 3).
Now, by explaining figure 3, the effect of pressure can be figured out. The figure shows that, when the reservoir pressure decreases with the production, the OIIP decreases which means because of continuous production, the remaining hydrocarbon is going to decrease. This is the common trend for all other established material balance equation. So, in one sense it can be stated that, the model is showing the normal behaviour which is expected. The figure is also showing that, though 2400 psi is an enough pressure to lift the hydrocarbon up but maybe within this pressure the reservoir has already depleted. That's why at 2400 psi, the OIIP is 0. Finally, using this pressure and OIIP relationship, a straight-line equation can be proposed to calculate the reserve for any pressure of low-pressured reservoir. Which is:

$$OIIP = 2.2e6 * P - 5.2e9$$

The above equation provides the original oil in place for any reservoir pressure. But this model is applicable only when the reservoir fluid flow is laminar, and the reservoir pressure is under 3500 psi. More studies and experiments are needed to validate this equation.

5 Model Validation

In the previous section, the reserve for matrix and fracture has been calculated separately. In almost all cases, the reserve of matrix and fracture is same. Someone might think that the calculation has some error and that's why the reserve is same for all cases. To clarify the issue, the result can be compared to previous research. Penuela (2001) derived some similar model and calculated the reserve for both matrix and fracture. To test the accuracy of his proposed MBE, three cases were designed. In first case, he assumed that the oil in fracture media is twice the matrix. Secondly, it was assumed that the initial oil in both systems is equal. In third cases, he assumed that, the OIIP in the matrix system is twice the oil in fracture media.

Because of the deficiency of field data, the reserve calculated in this study is not same with Penuela (2001) but the reserve of matrix and fracture support the second case of Penuela (2001). Table 1 shows the summary of the reserve of Penuela (2001).

Table 4.18: Original Oil in place calculation (Penuela, 2001)

MMSTB	Simulator		MBE for NFR	
	N_1 (OIIP in Matrix)	N_2 (OIIP in Fracture)	N_1 (OIIP in Matrix)	N_2 (OIIP in Fracture)
Case 1	2.38	4.75	2.49	4.60
Case 2	4.75	4.75	4.79	4.54
Case 3	9.50	4.75	9.80	4.58

6. Conclusion

From the analyses described above, the following conclusions are offered:

a) Two modified material balance equation has been derived. In the first model, velocity term has been incorporated and in the second one, Darcy's law has been applied. For both cases, the result calculated for matrix and fracture.

b) The literature and simulation indicate the same reserve for matrix and fracture in this study. But the amount of total reserve depends on the velocity of the fluid and reservoir pressure. Within the laminar flow range, when the fluid velocity increases, the original oil in place decreases. When the reservoir pressure increases, the OIIP decreases. That means both models show the inverse relationship between respective parameters.

c) A straight-line model has been proposed to calculate the oil reserve in any pressure of the reservoir. When the fluid flow is laminar and the pressure is under 3500 psi, the model could be applied properly but more research needed to validate it completely

d) Finally, because of lack of proper field data, the result might have a small percentage of error which can be easily minimised with accurate field data.

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NOMENCLATURE

B_{gi}	: Bg at initial reservoir pressure, *rb/scf*
B_o	: oil formation volume factor, *rb/stb*
B_{oi}	: initial oil formation volume factor, *b/stb*
B_w	: water formation volume factor, *rb/stb*
B_{wi}	: B_w at initial reservoir condition, *bbl/stb*
C_f	: rock compressibility, psi^{-1}
C_g	: gas compressibility, psi^{-1}
C_m	: matrix compressibility, psi^{-1}
c_s	: reservoir rock formation compressibility at a reduced pressure p, psi^{-1}
C_o	: oil compressibility, psi^{-1}
C_w	: water compressibility, psi^{-1}
P_i	: Initial pressure, psi
R_p	: Cumulative gas oil ratio
R_{si}	: initial solution gas oil ratio
R_{soi}	: initial solution gas oil ratio
R_{swi}	: Initial solution oil water ratio
S_{gi}	: initial gas saturation
S_{oi}	: initial oil saturation
S_{wi}	: initial water saturation
μ_o	: oil viscosity
ΔP	: pressure difference, psi
K	: Reservoir Permeability, mD
M	: Mobility Ratio
P	: Reservoir pressure, psi
u	: fluid velocity, ft/sec