PREDICTIVE MODELING OF THE EFFECTS OF RESERVOIR PROPERTIES ON THE EFFECTIVE APPLICATION OF MICROBIAL ENHANCED OIL RECOVERY (MEOR)

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Abstract— The increasing need to improve recovery of residual oil from the reservoir had prompted the discovery of Microbially Enhanced Oil Recovery (MEOR) technology as an enviable and effective method of enhancing oil recovery. For optimum recovery, this technique requires the prediction of favourable conditions of reservoir parameters in addition to microbial and operating parameters. To achieve this, this work incorporates reaction engineering into the reservoir engineering aspects of MEOR, treating the bounded reservoir as a bioreactor. The models developed are based on the principle of mass conservation. A C++ program source code was used to analyze and evaluate the effectiveness of the models. Results from the simulation show that reservoir properties greatly affect the applicability, suitability and performance of any MEOR project.

Index Terms— MEOR, Predictive MEOR Modeling, Reservoir Properties, MEOR modelling, EOR,

1 INTRODUCTION

Microbial activity has been known as a potential means of enhancing the yield of trapped oil [1], [2], [3]. Microbially Enhanced oil recovery (MEOR) can be defined as a microbiological method for the improvement of oil recovery from underground reservoir. Primarily, the term refers to procedures which include water diversion and downhole polymer and surfactant loss which are based on products produced directly in the reservoir matrix by living microorganisms especially the bacteria [4], [5]. This technology finds its role mainly in selective plugging in the control of waterflood, polymer and surfactant floods, the stability of microbial products for oilfield use and heavy oil recovery [6].

The growth of microbes in-situ in the reservoir has a number of important interactions with the inorganic materials and the oil present in the formation. These microbes will produce biogenic gases which will mix with the oil and dissolve in the heavy crude and act as a mobilizing agent [7]. These fermentation and metabolic processes produce other useful products like polymer and surfactants downhole that aid further petroleum recovery. These result in modifications of the rock and fluid properties necessary for production, and may include permeability modification, viscosity reduction and provision of favourable mobility control.

MEOR is not a single technology based on a common approach but an adaptation of microbial systems to specific problems of oil recovery from a chosen target reservoir. Consequently, understanding the target reservoir, microbial and operating conditions are vital for effective application of the technology to obtain an optimum recovery [2], [8].

The use of microbes introduces reaction engineering into reservoir engineering, with associated concepts including bioreactor volume, nutrient reaction kinetics and selectivity, and minimum required level of conversion. These concepts permit quantitative relationships to be established between reservoir characteristics, operating conditions and microbial performance as will be developed in this work. These quantitative relationships between microbial performance, reservoir/fluid characteristics (permeability, porosity, thickness, viscosity etc.) and operating conditions (well spacing, injection rates, residual oil saturation) can be developed from the adoption of a reservoir engineering perspective focusing on issues such as scale up of laboratory results, process design and field implementation and operation [9]. Analysis with plausible values of reservoir and microbial parameters indicates, from literatures, that a MEOR process using the in-situ carbon must overcome severe performance constraints [2], [7], [10]. Use of an ex-situ carbon source avoids these technical/performance constraints but eliminates the logistical and cost advantages of an in-situ source.

The selected, cultured, naturally occurring species (microbes) produce several compounds that have the potential for enhanced oil recovery. These microbial degradation by-products include solvents, gases, alcohols, acids, biosurfactants and biopolymers [11], [12], [13]. The in-situ produced gases may increase reservoir pressure and decrease the viscosity and gravity of the crude oil, allowing it to move more freely to the producing wells. The gases, solvents and weak acids cause a reduction in the viscosity and the pour point of the crude and an increase in its API (or specific) gravity. Microbial plugging due to biomass activity is also reported [1], [3], [6], [10].

It is also important to point out that some of the microorganisms inhibit the activity of SRB (Sulphate-reducing bacteria) which also occur naturally in reservoirs and are often responsible for the production of corrosive hydrogen sulphide gas. The surfactants, acids and solvents clean out paraffin, wax and the heavy crude depositions in the pores of the rock improving the permeability and partially restoring the rock's original porosity [4], [5]. These solvents are also responsible

for the reduction in Interfacial tension (IFT) and wettability alteration. An illustration of the above effects is given in the table below.

TABLE 1.
CHANGES IN OIL PROPERTIES DUE TO MICROBIAL EOR [2], 3]

Parameter	Conventional	MEOR
API Gravity	39.4	41.9
Viscosity (cp)	15	9
Pour Point (°F)	98	81
% Solvents*	40	52
% Paraffin Wax	60	48

*Solvents include gasoline, kerosene and diesels

2 Formulation of Models

The following analysis introduces the concepts of reaction engineering considerations into the reservoir engineering analysis.

2.1 Time Models

Two basic time models for microbial systems are residence time τres, the amount of time species spends within the reactor, and the characteristic reaction time, τrxn, the amount of time required for the concentration of a reaction product to reach a desired level [14], [15]. In the MEOR process, the residence time depends on operating conditions – well spacing, injection rates, residual oil saturations and the reaction time depends on the behaviour of the microbial system (i.e., microbial conditions) – concentration of species, pore fraction of the retained species, conversion efficiency of species etc.

If we assume that the retention (or residence) time is a function of the injection rate and that the bioreactor is of a continuous-flow type, then the retention time is expressed as:

$$\tau_{res} = \frac{\varphi \pi r_m^2 h(1-S_{or})}{Q} \quad (1)$$

where,

τ_{res} = residence time, day

ϕ = porosity, volume fraction

r_m = radial extent of bioreactor, ft

h = thickness of formation, ft

S_{or} = residual oil saturation, volume fraction

Q = injection rate, bbl/day/injector

The reaction time, τrxn depends on the microbial conditions. Assuming that the concentration of the produced bioproduct C, is proportional to the change in concentration of injected nutrients and that at the reaction time, the concentration of the produced bioproduct is the required concentration, C_{req}, for efficient recovery, then:

$$\tau_{rxn} = -\frac{1}{K_1} \ln\left[1 - \frac{C_{req}}{V_N N_o}\right] \quad (2)$$

2.2 In-situ Carbon Source Conversion Model

For effective interaction with the interstitial oil, the microbes should be able to exhibit stability or steady-state conditions. Also, reaction engineering considerations suggest that the conversion efficiency of the respective medium is the maximum concentration, Cmax (in mass fraction) of the recovery – enhancing chemical that can be produced within the bioreactor, given by:

$$C_{max} = V_H \frac{S_{or}}{1-S_{or}} \frac{\rho_o}{\rho_w} \quad (3)$$

Since the maximum volume of recovery-enhancing chemical (the maximum slug volume, Vmax) should be the same as the reactor volume, then, for 'n' number of injectors:

$$V_{max} = n\pi\tau_m^2 h\varphi(1 - S_{or}) \quad (4)$$

Equation (4) models the maximum slug volume of the recovery-enhancing chemical that can be produced within the bioreactor

Assuming a 100% conversion process and expressing Vmax as a fraction of the reservoir pore volume yields:

$$f_{slug} = \frac{\rho_o}{\rho_w} \frac{\pi r_m^2 S_{or} V_H}{AC_{req}} \quad (5)$$

where fslug is the slug size in reservoir pore volume (PV) and A is the injection-well spacing.

Equations (3), (4) and (5) are the in-situ carbon source conversion models.

2.3 Nutrient Supply Model

Nutrient supply to in-situ reactors of microbial systems are through the injection water. Consider the finite aqueous solubility of nutrients which will lead to the concept of limiting reactant – the first species to be used up as fluids move through the bioreactor. Consider that the assumed kinetics of the microbial system depend only on concentrations in the flowing phase, and no dispersion, the extent of reaction at a given position will depend only on the time required for the fluid to move from the reactor inlet (the wellbore) to that position. Hence, the maximum extent of reaction will be reached when the fluid arrives at the radial location, rlim, is given as:

$$r_{lim} = \left[-\frac{Q}{K_1 \pi h\varphi(1-S_{or})} \ln\left(1 - \frac{M_{o,max}}{V_N N_o}\right)\right]^{1/2} \quad (6)$$

If N is the rate-controlling nutrient, a similar analysis can be considered when other reactants are present in excess while the concentration of N depends on the radial position, r. In this case, the amount of nutrient at a given radial distance from the bioreactor inlet (wellbore) becomes:

$$N_t = N_o \exp\left[-\frac{K_1 \pi \varphi h(1-S_{or})}{Q} r^2\right] \quad (7)$$

Equation (7) is the model for nutrient supply to in-situ reactors.

2.4 In-situ Gas Production Model

Viscosity reduction through in-situ gas production enhances miscible displacement of the target oil [7], [16]. Major biogenic gases of interest are CO_2 and CH_4 and nutrient supply is essential for their production.

Practical in-situ generation of CO_2 requires an alternative external source like a carbohydrate or an alternative microbial mechanism that abstracts Oxygen from water molecules. In-

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situ generation of Methane requires no external source material, unlike CO_2 production. Since one kilogram of crude oil contains approximately 0.17kg H (hydrogen atom), and if we assume that microbes were able to use that hydrogen completely, then 4H (from CH_4) would consume 0.68 Kg of Hydrogen. Considering this limiting conversion efficiency, we can develop a relationship that establishes a maximum slug size in a manner similar to that obtained for other recovery-enhancing chemicals to give:

$$f_{gas} = \frac{0.68\pi\tau_m^2}{A}\frac{S_{or}\rho_o}{\rho_g} \quad (8)$$

If we consider the analysis of another in-situ gas, other than CH_4 production, assuming that the gas production is proportional to the nutrient consumption, we have:

$$G_p = V_N N_o\left[1 - \exp\left(-\frac{K_1\pi\varphi h(1-S_{or})}{Q}r^2\right)\right] \quad (9)$$

2.5 Porosity Model

From (7), making the porosity ϕ, the subject of the formula,

$$\varphi = \frac{Q}{K_1\pi r^2 h(1-S_{or})}\ln\left(\frac{N_o}{N_t}\right) \quad (10)$$

For porosity reduction due to pore plugging, we write:

$$\varphi_i = \varphi_o(1-\sigma) \quad (11)$$

Where ϕ_0 is the initial porosity, ϕ_i is the instantaneous porosity and σ (= 1 - S_{or}) is the pore fraction occupied by the sessile phase.

Substituting (10) for ϕ_0 in (11):

$$\varphi_i = \frac{Q}{K_1\pi r^2 h}\left(\frac{1}{\sigma}-1\right)\ln\left(\frac{N_o}{N_t}\right) \quad (12)$$

2.6 Permeability Modification Model

From the fines migration theory of Civan et al [17]], the rate of change in permeability due to selective plugging by microorganisms as:

$$\frac{K_i}{K_o} = \left[\frac{\varphi_i}{\varphi_o}\right]^3 \quad (13)$$

Substituting (12) in (13) results in:

$$K_i = K_o\left[\left(\frac{K_1\pi r^2 h\varphi}{Q\ln\left(\frac{N_o}{N_t}\right)}-1\right)\frac{K_1\pi r^2 h\varphi}{Q\ln\left(\frac{N_o}{N_t}\right)}\right]^{\frac{1}{3}} \quad (14)$$

2.7 Saturation and Recovery Models

Assume the deposited biomass (sessile phase) occupies a portion of the pore space during the MEOR process. The saturation balance equation can be written as:

$$S_o + S_w + S_g + \sigma = 1 \quad (15)$$

MEOR depends on the production of metabolites, hence, its recovery can be expressed as:

$$(\Delta S_o)_{MEOR} = (\Delta S_o)_{plugging} + (\Delta S_o)_{gas} + (\Delta S_0)_{surfactant} + (\Delta S_o)_{polymer} \quad (16)$$

where ΔS_o is the respective incremental oil recovery.

Since the surfactant and polymer enhance the plugging and repressurisation process of MEOR, (16) can be simplified thus:

$$(\Delta S_o)_{MEOR} = (\Delta S_o)_{plugging} + (\Delta S_o)_{gas} = f(\sigma, C_g) \quad (17)$$

where σ is the pore volume fraction of the retained cell bodies and C_g is the gas concentration. But where microbial plugging is considered to be dominant in the MEOR process, (17) can be written as:

$$(\Delta S_o)_{MEOR} = f(\sigma) \quad (18)$$

If a linear relationship is assumed, it becomes

$$(\Delta S_o)_{MEOR} = \lambda\sigma \quad (19)$$

where λ is a constant.

It is evident from the equation that the additional oil recovery due to the MEOR process is proportional to the plugging volume in the pore space by cell bodies.

The recovery is calculated by assuming that,

$$(\Delta S_o)_{MEOR} = (S_{OR})_{EOR} - (S_{OR})_{MEOR} \quad (20)$$

However, for the purpose of this work, recovery is calculated based on the relationship proposed below:

$$\text{Recovery} = (\Delta S_o)_{MEOR} = \sigma(S_{OR})_{EOR} \quad (21)$$

3 Results and Discussion

The C++ program source code is the chosen simulation program. The simulator is used to test the sensitivity of MEOR performance and development strategy to variations in reservoir properties within a range of possible values. The reservoir and microbial system characteristics employed are given in the table below.

TABLE 2
RESERVOIR AND MICROBIAL SYSTEM CHARACTERISTICS

Parameter	Symbol	Value	Formula/ Units
Formation thickness	H	30	ft
Reservoir porosity	Φ	0.25	Volume fraction
Permeability	K	148	mD
Residual oil saturation	S_{or}	0.35	Volume fraction
Injection rate	Q	100	B/D/injector
Gas Density	ϱ_g	86.3	Kg/m^3
Oil Density	ϱ_o	800	Kg/m^3
Water Density	ϱ_w	1000	Kg/m^3
Bioreactor extent	r_m	10	ft
Required concentration of bioproduct C	C_{req}	0.01	Mass fraction
Injected concentration of rate-controlling nutrient N	N_o	0.05	Mass fraction
Reaction-rate constant	K_1	0.19	day^{-1}
Carbon yield	V_H	0.5	Mass of bioproduct produced/mass of carbon
Conversion efficiency of Nutrient N to product C	V_N	0.5	Mass of bioproduct produced/mass of nutrient

			N consumed
Stoichiometric coefficient of co-reactant M	V_M	0.001	Mass of M consumed/mass of nutrient N consumed

The results of the simulation and sensitivity analyses are as follows.

3.1 Residence Time and Bioreactor Extent

The table below shows the relationship between the microbial residence time and the bioreactor extent.

TABLE 3
VARIATION OF RESIDENCE TIME WITH BIOREACTOR EXTENT

Radial extent of Bioreactor, r_m (ft)	Residence time, τ_{res} (day)
0	0
1	0.004875
2	0.0195
3	0.043875
4	0.078
5	0.121875
6	0.1755
7	0.238875
8	0.312
9	0.394875
10	0.4875

It is observed that as the microbial residence time increases, the bioreactor extent increases. This is true as large bioreactor extent will require high microbial residence time to ensure the survival of the microbes within the reactor. The relationship is shown graphically below.

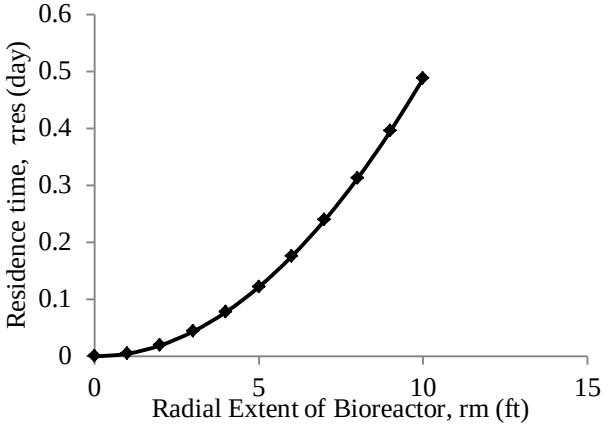

Fig. 1. Variation of Residence time with distance

It is observed that as the bioreactor extent increases, the time taken by the microbes to migrate through its extent increases.

3.2 Reaction time and concentration

The rate of microbial kinetics depends on the concentration of the injected nutrients. Higher concentration of nutrients will require lower reaction time. On the other hand, lower concentration of nutrients will take higher reaction time. This is illustrated in the table and figure below.

TABLE 4
VARIATION OF REACTION TIME WITH CONCENTRATION

Initial Concentration of Injected nutrients (mass fraction)	Reaction Time, T_{rxn} (hr)
0.05	63.853202
0.1	27.892944
0.15	17.887605
0.2	13.170064
0.25	10.422701
0.3	8.624109
0.35	7.355063
0.4	6.411662
0.45	5.682797
0.5	5.102749

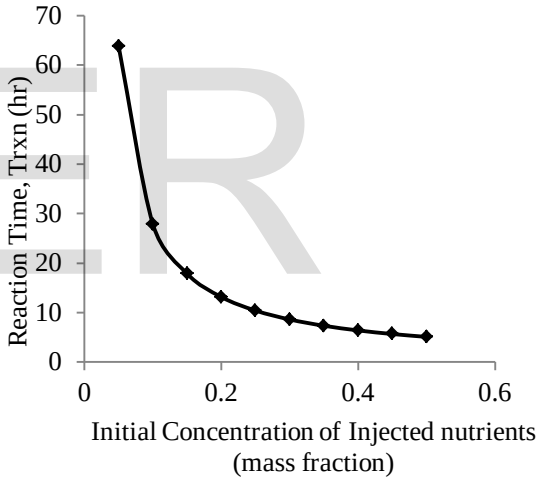

Fig. 2. Variation of Reaction time with concentration

Indications from Table 4 and Figure 2 show that the growth rate of microbes increases with concentration, resulting in a decrease in reaction time.

3.3 Slug size and Injection well spacing

The slug size in the reservoir pore volume (PV) that can be produced within the bioreactor is modeled by Eq. (5). It varies inversely with the injection well spacing. This relationship is further expressed in table 5 and figure 3 below.

TABLE 5
VARIATION OF SLUG SIZE WITH INJECTION WELL SPACING

Injection well spacing (A)	Slug size (F_{slug})
435600	0.009642
871200	0.004821
1306800	0.003214
1742400	0.00241
2178000	0.001928
2613600	0.001607
3049200	0.001377
3484800	0.001205
3920400	0.001071
4356000	0.000964
4791600	0.000877

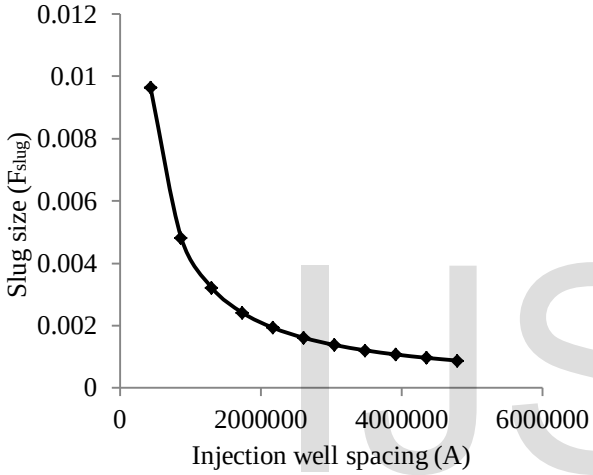

Fig. 3. Variation of slug size with injection well spacing

It is also evident from the model that if other parameters are constant, the slug size varies directly with the residual oil saturation and also with the square of the radial extent of the bioreactor.

3.4 Nutrient supply and radial distance

Nutrient supply to in-situ bioreactors of microbial systems are through the injection water. Eq. (7) is the model for nutrient supply to in-situ reactors. It gives the amount of nutrient at a given radial distance. It further shows that the nutrient required for microbial activity is proportional to the porosity of the reservoir rock, if other parameters remain constant. Low porosity rock requires less nutrient and vice versa.

The inverse variation of amount of nutrient and radial distance is clearly shown in table 6 and figure 4 as follows.

TABLE 6
VARIATION OF NUTRIENT WITH RADIAL DISTANCE

Radial distance (ft)	Amount of nutrient (N_t)
0	0.05
1	0.049942
2	0.049767
3	0.049476
4	0.049073
5	0.048559
6	0.047938
7	0.047214
8	0.046393
9	0.045479
10	0.044479

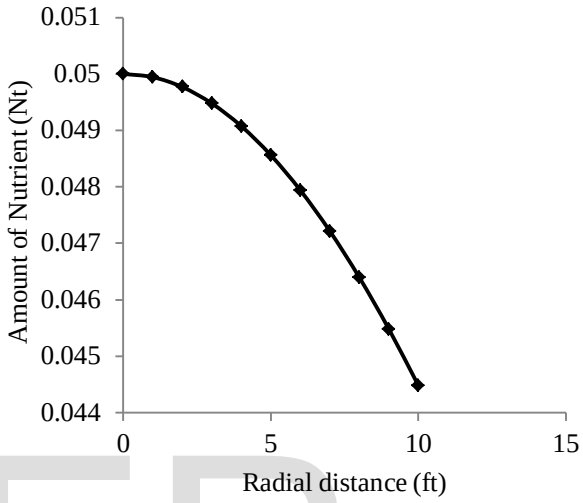

Fig. 4. Variation of amount of nutrient with radial distance

3.5 Gas size and Injection well spacing

The gas size in the reservoir PV is modeled by Eq. (8). It predicts an inverse relationship with injection well spacing and a linear relationship with the residual oil saturation. The table and figure below show the simulation results.

TABLE 7
VARIATION OF GAS SIZE IN RESERVOIR PORE VOLUME AS A FUNCTION OF INJECTION WELL SPACING

Injection well spacing (A)	Gas size (F_{gas})
435600	0.001519
871200	0.00076
1306800	0.000506
1742400	0.00038
2178000	0.000304
2613600	0.000253
3049200	0.000217
3484800	0.00019
3920400	0.000169
4356000	0.000152
4791600	0.000138

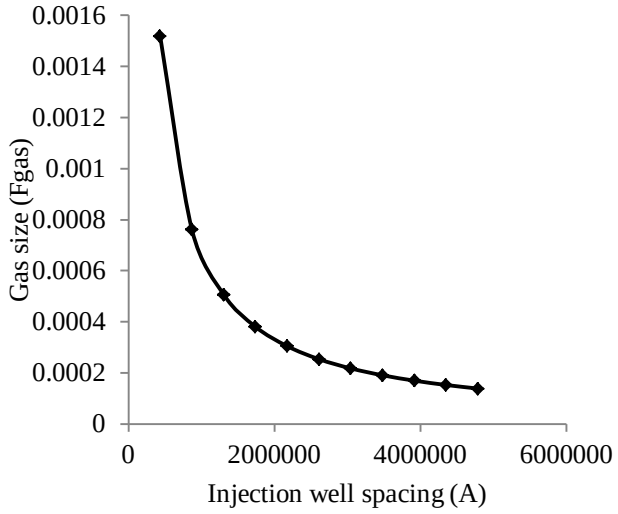

Fig. 5. Gas size in Reservoir Pore volume as a function of injection well spacing

It can be seen that at lower injection well spacing, a higher gas size will be produced within the bioreactor, the converse of which would also be true.

3.6 Porosity and Amount of Nutrient

The amount of nutrient needed for microbial activity in the reservoir varies with the reservoir rock porosity. It has been established that since the microbial activity takes place in the pores of the reservoir rock, the amount of nutrient required for effective inoculation of the residual oil will depend on the porosity of the reservoir rock. Higher porosity rock will require higher amount of nutrient and lower porosity rock lower amount of nutrient. The results of the simulation presented in table 8 and figure 6 are in agreement with this argument.

TABLE 8
VARIATION OF NUTRIENT WITH ORIGINAL AND INSTANTANEOUS POROSITIES

Original porosity	Instantaneous porosity	Amount of nutrient (N_t)
0	0	0.05
0.0025	0.001346	0.049942
0.01	0.005385	0.049767
0.0225	0.012115	0.049476
0.04	0.021538	0.049073
0.0625	0.033654	0.048559
0.09	0.048462	0.047938
0.1225	0.065962	0.047214
0.16	0.086154	0.046393
0.2025	0.109038	0.045479
0.25	0.134615	0.044479

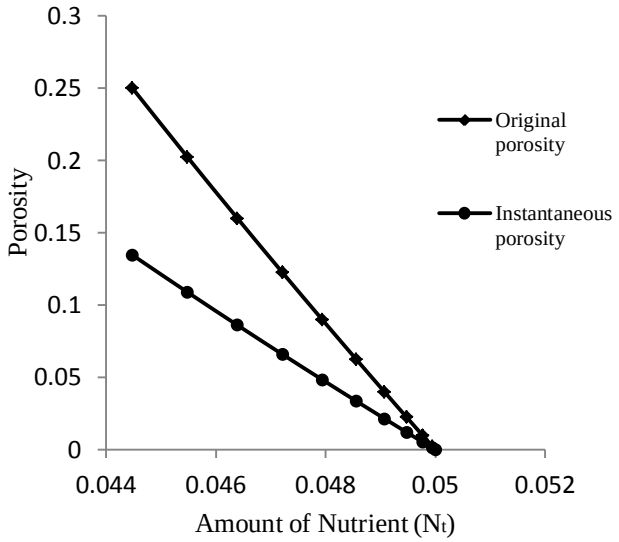

Fig. 6. Variation of amount off nutrient with porosity

3.7 Recovery and Residual oil saturation

It has been shown that recovery is directly proportional to the pore volume fraction (i.e. concentration) of the retained cell bodies. This is due to the fact that the recovery will depend on the extent to which the microbes inoculate the residual oil. It is also true that since residual oil is a source of carbon (nutrient) for the microbes, a high residual oil saturation will imply high microbial activity which will lead to higher rate of inoculation and subsequently higher recovery. This is illustrated as follows.

TABLE 9
RECOVERY AS A FUNCTION OF RESIDUAL OIL SATURATION

Residual oil saturation (S_{or})	Recovery (S_{MEOR})
0	0
0.05	0.0475
0.1	0.09
0.15	0.1275
0.2	0.16
0.25	0.1875
0.3	0.21
0.35	0.2275
0.4	0.24
0.45	0.2475
0.5	0.25

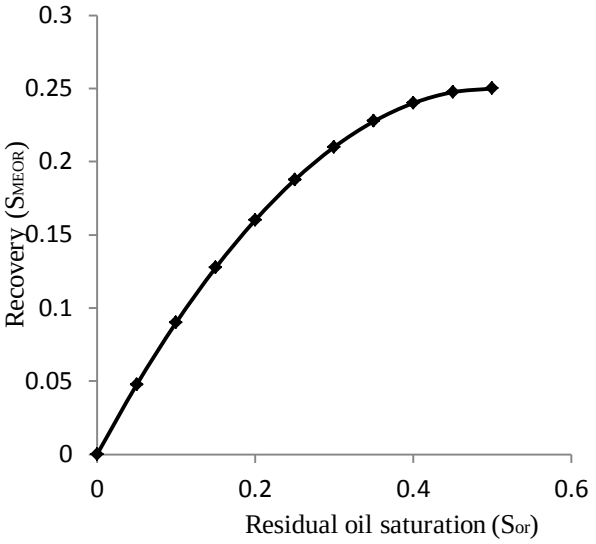

Fig. 7. Recovery as a function of Residual oil Saturation

As expected, a higher residual oil saturation would imply more oil possibly recoverable and consequently, if successful, greater recovery from MEOR application.

4 CONCLUSION

The modeling of the effects of reservoir properties on MEOR is an important predictive tool for quantitative analysis of the reservoir/microbial system, as has been presented. To ensure the best possible results from a MEOR project, four considerations are indispensable – laboratory analysis of the crude, reservoir engineering studies, correct determination of the microbial culture to be used and proper implementation and monitoring of the injection process [18]. Although MEOR will be effective in almost any reservoir scenario, it is advised that only the best candidates, as determined by the factors given above should be considered for MEOR.

However, it is recommended that further studies in this respect incorporate reservoir heterogeneity in models proposed.

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