Model Development for Analysis of Entrainment Deposition of Biomass in a Reservoir Undergoing Microbial Enhanced Oil Recovery

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Abstract

Microbial Enhanced Oil Recovery (MEOR) technique has been thought and proven to be one of the most reliable and cost effective method of Enhanced Oil Recovery (EOR). In this work, models have been developed to analyze the likely implications of continuous biomass deposition on the pore walls of reservoir formations. The results of the model simulations revealed that use of microbes in oil recovery not only records positive results but negative implications as well which makes the model non-conservative. The development of the model has been based on the application of usual classical material balance principle and some assumptions. An injection period of 30 days was used to evaluate the effect of biomass entrainment concentration and its consequent effects. An average of 3.2430lb/cu-ft of entrained biomass concentration over a 30-day period was recorded from an initial value of zero-entrained biomass concentration. The effect of this biomass entrainment is investigated with empirical models to analyze other reservoir rock properties. The porosity and permeability of the formation decreased from 0.20 to 0.1975 and 122.8926 mD to 118.9364 mD respectively over 30 days of investigation. The formation tortuosity over the 30 day period of biomass entrainment also increased in magnitude from 2.2876 to about 2.2976 as a result of deposition. Graphical representation of these distinct properties also provides an elaborate understanding on how they change with time.

Keywords: *Biomass; Entrainment; Deposition; Porous Medium; Microbial enhanced Oil Recovery.*

I. INTRODUCTION

Microbial Enhanced Oil Recovery (MEOR) biotechnology-based oil recovery method which involves the use of microorganisms to enhance oil production from candidate petroleum reservoirs. When compared to other existing EOR processes, MEOR poses a cost-effective and eco-friendly mode of operation. (Bryant, 1987; Hitzman, 1991). There are a wide range of mechanisms by which microorganisms can contribute to oil recovery, these mechanisms includes the production biogenic gases which increases the system pressure and reduces the oil viscosity; bioacid production which alters the reservoir rock flow channels by permeability improvement, though peculiar of limestone formations; Biosurfactant production which enhances reduction in interfacial tension between oil/water and oil/rock and biomass accumulation leading to selective plugging of highly permeable zones (Al-Sulaimanii *et al*., 2011).

Earlier reports on oil recovery studies have shown that the major factor limiting oil recovery is the variation of permeability, as a result, water flows through the highly permeable zones, leaving a substantial amount of oil present in the low permeable zones unrecovered (Jenneman. *et al.*, 1996.). Selectively plugging-off highly permeable regions of the reservoir reduces the tendency of permeability discontinuities and improves oil recovery. A variety of techniques has been developed to selectively plug-off high-permeable petroleum reservoirs which include the use of polymers, clays, cements, and waxes (Knapp. *et al.*, 1988.). The instability and difficulty in control placement of some of these agents has limited their usage. The use of microorganisms to resolve permeability variation has been suggested by several scholars. EPS-producing microbes form a large amount of biomass, which selectively plug the highly permeable zones and diverts the water flow to oil-rich zones in order to thrust out oil from theses reservoirs (Civan *et al.*, 1988.).

Biomass is produced from microorganism such as *Bacillus Licheniformis, Leuconostoc, Mesenteroides* and so on are candidate microorganisms than can serve perfectly for selectively plugging off thief zones and for wettability alteration processes. In selective plugging, this is achieved by an increase in microbial cell mass within the reservoir. Production of biomass can be achieved by stimulating either indigenous microbial populations or by injecting microorganisms with growth nutrients. The injected nutrient and microbes are preferentially entrained in the high permeable zones of the reservoir as cells growth and transportation.

In the transport of microorganisms through the porous media during Microbial Enhanced Oil Recovery, particles are in continuous contact with the surfaces of the pore walls. Nutrients usually do not adsorb significantly, but metabolites such as bio-surfactant which exists in smaller percentages has a greater tendency to adsorb on the rock surfaces. The degree of adsorption of these metabolites is to a large extent lower than that of the microbial attachment to the rock surface (Kim, 2006). Microbes generally stick to all kind of surfaces forming biomass (Strappa *et al*., 2014; Udegbunam *et al*., 1991). These accumulations consist of a number of immobile cells, sticky polysaccharides, dissolved components, other metabolic materials and water. The biomass acts as a micro-environment, where the biofilm matrix water exchanges solutes such as nutrients and waste products with the surroundings. There may be limitations in transport to and from the biomass, mainly determined by the thickness of the biofilm and the internal biofilm porosity (Thullner, 2004; Nmegbu and Pepple). Bacteria such as *Pseudomonas* form biofilms with only one layer of cell, where other species form multilayered biofilms (Strappa *et al*., 2014). The multilayered biofilms can form large mushroom shaped structures on the pore surfaces that can reduce fluid transport within the porous media. (Adetunji, 2012; Thullner, 2004). Bacterial growth in the adsorbed phase is occasionally lower, which is considered as a consequence of the limitations in transport of nutrient (Bryant and Lockhart, 2002; Desoukey *et al*., 1996). In the porous media context, pore size may also constrain how many layers of cells form a within a film. If pore sizes are small, biomass accumulation can be enhanced by the process of filtration (Bryant and Lockhart, 2002), otherwise the retention of bacteria is primarily determined by the adsorption process (Bailey *et al.*, 2004). In 2006, Kim suggested that attachment of biomass on pore walls is primarily dependent on the properties of media, rock surface and cell surface. Some studies suggest that microorganisms perform active adhesion/detachment processes as a response to the local nutrient availability and as a survival mechanism (Islam and Gianetto, 1993). Detachment of the biomass on pore walls can also be caused by erosion, which is the removal of small particles from the surface as a result of shear stresses (Fujiwara *et al*, 2004; Gremlin *et al*, 2002).

MEOR processes traditionally associated with channeled fluid flow changes include in-situ biomass and biopolymer production. Successful engineering of an in-situ microbial plugging system must take into consideration, the microbe's ability to transport and the required growth nutrients through the reservoir, as well as the ability of the microorganism to selectively plug off extremely high permeable zones in candidate reservoirs through metabolic activities. (Knapp *et al.,* 1988; C*hang et al*., 1991). When biomass formation becomes more than desired and its accumulation becomes excessive, the resultant consequence becomes problematic. The permeability of the reservoir is reduced as a result of reduction in average reservoir porosity; the reservoir becomes more tortuous in nature, all of which may cause a decreased recovery factor during the MEOR process. This work therefore tends to reveal the negative effects of excessive biomass accumulation on the pore walls of the formation during MEOR

II. RESEARCH METHODOLOGY

The deduced model takes into account the dynamic and static adsorption of microorganisms as well as nutrients and other metabolites on the pore walls of the reservoir rock. Adsorption of microbes from aqueous phase to the surfaces of rock during MEOR is as a result of certain macro-processes, which includes simultaneous particle exchanges between its flowing and stationary phases.

The rate adsorption of biomass, assuming a continuous microbial injection process is given as;

$$\frac{\partial C_{bs}}{\partial t} = R_r - R_d \qquad (1)$$

Where;

C_{bs} = Adsorbed biomass per unit pore volume (lb/cu-ft).

R_r = Rates of bacterial retention.

R_d = Rates of bacterial detachment.

Bacterial retention rate, R_r is a function of the plugging capacity of these phases and biomass influx in a given pore area open to flow. Mathematically, the microbial retention rate is given as;

$$R_r = K_r|U_w|C_b(1-\sigma) \qquad (2)$$

On the other hand, the microbial detachment rate, R_d is inversely proportional to the retained biomass and the shear force between the flowing and stationary phases, the detachment rate is expanded to;

$$R_d = K_r[U_w]\, K_d\, (\sigma\, \rho_b)\, \nabla\Phi_w \qquad (3)$$

Where;

K_r = Coefficient of biomass retention

K_d = Biomass detachment coefficient.

U_w= Velocity of water carrying the biomass (ft/day)

C_b = Concentration of bacteria (lb/cu-ft)

σ= Sessile phase concentration. (lb/cu-ft)

ρ_b= Bacteria density, (lb/cu-ft)

Φ_w = Flowing fluid potential (water and sessile phase), (psi)

For adequate deposition on the pore wall, rate of bacteria retention must be greater than the rate of bacteria detachment. i.e. $R_r > R_d$.

Since R_d is usually small and can be assumed to be negligible, then Eqn (1) can be re-written as;

$$\frac{\partial C_{bs}}{\partial t} = R_r \qquad (4)$$

The expanded form of the above can be expressed as;

$$\frac{\partial C_{bs}}{\partial t} = K_r|U_w|C_b(1-\sigma) \qquad (5)$$

Equation (5) defines the entrainment deposition of micro-organisms only in a reservoir undergoing MEOR process. If the adsorption of metabolic products or substrates as defined by Langmuir Isotherm is incorporated, Eqn (5) becomes;

$$\frac{\partial C_{bs}}{\partial t} = \left(K_r|U_w|C_b(1-\sigma)\right) + C_{ks} \qquad (6)$$

Where Langmuir Isotherm, C_{ks} is definedas;

$$C_{ks} = \frac{a_k C_k}{1+b_k C_k}$$

Where;

C_{ks} is the adsorbed mass of metabolites/substrates in the porous medium.

a_k and b_k are Langmuir adsorption constants for the metabolites and substrates

C_k is the mass concentration of metabolites/substance in the aqueous suspension

Therefore, rate equation now becomes

$$\frac{\partial C_{bs}}{\partial t} = \left(K_r|U_w|C_b(1-\sigma)\right) + \frac{a_k C_k}{1+b_k C_k} \qquad (7)$$

Gruesbeck, & Collins, 1982 asserted that plugging of porous media by bacteria cells occur in such a way that:

i. Cells may deposit on pore surface to reduce pore spaces available to fluid flow or
ii. Cells may be trapped or retained in pore throat to clog or bridge flow channels through which fluid transport occur. This in turn leads to a reduction in porosity and permeability of the reservoir

The accumulation of bacterial cells deposited on pore surfaces in the reservoir forms stationary biofilms (sessile bacteria). The sessile biomass development depends on bacterial retention (R_r), detachment (R_d) and growth (R_{bs}). Incorporating the microbial growth function into Eqn 7, we obtain:

$$\frac{\partial C_{bs}}{\partial t} = \left(K_r|U_w|C_b(1-\sigma)\right) + \frac{a_k C_k}{1+b_k C_k} + R_{bs} \qquad (8)$$

R_{bs} is the growth of bacteria, defined by Monod's model

$$\dot{\mu_m} = \mu_{max}\frac{C_n}{k_s + C_n} \qquad (9)$$

Where
μ_{max} is the maximum specific growth rate obtained in excess substrates (day^{-1})
k_s is the substrate concentration corresponding to half μ_{max}. In general this property is usually very small.
C_n is the nutrient concentration (1b/cu-ft).

Having incorporated all the factors, the expanded rate equation defined in Eqn (8) is now given as;

$$\frac{\partial C_{bs}}{\partial t} = \left(K_r|U_w|C_b(1-\sigma)\right) + \frac{a_k C_k}{1+b_k C_k} + \mu_{max}\frac{C_n}{k_s + C_n} \tag{10}$$

The above equation will be used to predict the rate adsorption of sessile biomass on the pore walls of the reservoir rock

Solution techniques

Equation (10) is a partial differential equation to be resolves using Finite Difference Approximation solutions.
For a 1st order derivative, the LHS of the PDE in Eqn (10) can be written in finite difference form to represent the biomass concentration at new time base levels n+1. A block–Centered grid system is assumed for the finite element analysis.

$$\frac{\partial C_{bs}}{\partial t} = \frac{C_{bs}^{n+1} - C_{bs}^{n}}{\Delta t} \tag{11}$$

Substituting Eqn (11) into Eqn (10), we obtain;

$$\frac{C_{bs}^{n+1} - C_{bs}^{n}}{\Delta t} = \left(K_r|U_w|C_b(1-\sigma)\right) + \frac{a_k C_k}{1+b_k C_k} + \mu_{max}\frac{C_n}{k_s + C_n}$$

Eqn (12) above can be rearranged in terms of concentrations at several time levels, C_{bs}^{n+1}, to account for concentration variations within the reservoir

$$C_{bs}^{n+1} = C_{bs}^{n} + \left(\left(K_r|U_w|C_b(1-\sigma)\right) + \left(\frac{a_k C_k}{1+b_k C_k}\right) + \left(\mu_{max}\frac{C_n}{k_s + C_n}\right)\right)\Delta t \tag{13}$$

Where;
C_{bs}^{n+1} is the biomass concentration at time base level n + 1
C_{bs}^{n} is the initial biomass concentration at base time level n;

Also, Porosity reduction is considered only due to biomass development on pore surfaces; and is determined by the presence of the sessile phase(σ). Therefore, the altered porosity is calculated as follows;

$$\emptyset_1 = \emptyset_0(1-\sigma) \tag{14}$$

Where $\emptyset_1$ is the altered average porosity of the reservoir, the values of porosities obtained at different time intervals due to biomass deposition will be used to determine its effects on formation permeability. The altered permeability of the reservoir due to porosity alteration is estimated using Aigbedion's method presented in 2004 for several ranges of known porosities. The relationship is given as;

$$k_1 = a\emptyset_1^b \tag{15}$$

where a and b are constants (18044 and 3.10 respectively) and $\emptyset_1$ is the altered porosity

Also, formation tortuosity variation is investigated using an empirical relationship defined by Matyka & Koza, in 2012

$$\tau = 1 - ꝑ ln\emptyset_1 \tag{16}$$

On the assumption that reservoir rock matrix under investigation is well-sorted, homogeneous and spherically overlaying, the packing factor parameter, ꝑ for these rock types range from 0.80 - 0.86

The following assumptions are the governing principles upon which the rate model is developed.

1) The effect of shear between the flowing and stationary phases of the biomass is ignored.
2) Biomass retention rate exceeds Biomass detachment rate.
3) Reservoir temperature effects on the injected microbe is negligible
4) Bacteria, nutrients and metabolic products are all in the aqueous phase.
5) No production during the period of microbial soaking
6) Slightly compressible fluid flow system.
7) Gravitational effects were neglected
8) The entire reservoir is considered to be a homogeneous system.

III. RESULTS AND DISCUSSION

Parameters obtained from field –X provides the basic reservoir rock information required for resolution of the rate equation. With some microbial parameters obtained experimentally and others from literature, these parameters are presented as follows;

$\phi_0 = 0.20,\ K_r = 0.5,\ U_w = 1.223 \mathrm{ft/hr}\ ,\ \Delta t = 5\mathrm{days}\ ,\ C_{b=}0.050 \mathrm{lb/ft^3},$
$C_n = 0.051 \mathrm{lb/ft^3}\ ,\ \sigma = 0.0021 \mathrm{lb/ft^3},\ a_k = 0.8,\ b_k = 0.9,\ \mu_{max} = 1.3 \mathrm{day^{-1}}$
$C_k = 0.4 \mathrm{lb/ft^3},\ k_s = 0.000023$

Calculating Constants

$$C_{ks} = \frac{a_k C_k}{1+b_k C_k} = \frac{0.8\times0.4}{1+(0.9\times 0.4)} = 0.0235$$

$$\mu_{max}\frac{C_n}{k_s + C_n} = 0.0542 \times \frac{0.0510}{0.000023+0.0510} = 0.0541 \mathrm{day^{-1}}$$

$$R_r = 0.5 \times 1.2230 \times 0.0500 \times (1 - 0.0021) = 0.0305$$

At time, t = 0 i.e before the entire microbial process, the initial adsorbed biomass per unit pore volume, $C_{bs} = 0$.

$C_{bs} = 0$ at first time base level n. Therefore, Eqn (13) can now be used to predict adsorption of biomass on the pore walls of the reservoir for a period of 30days at a constant time increment of 5 days.

$$C_{bs}^{5} = 0 + (0.0305 + 0.0235 + 0.0541) \times 5 = 0.5405$$
$$C_{bs}^{10} = 0.5405 + (0.0305 + 0.0235 + 0.0541) \times 5 = 1.0810$$
$$C_{bs}^{15} = 1.0810 + (0.0305 + 0.0235 + 0.0541) \times 5 = 1.6215$$

$C_{bs}^{20} = 1.6215 + (0.0305 + 0.0235 + 0.0541) \times 5 = 2.1620$
$C_{bs}^{25} = 2.1620 + (0.0305 + 0.0235 + 0.0541) \times 5 = 2.7025$
$C_{bs}^{15} = 2.7025 + (0.0305 + 0.0235 + 0.0541) \times 5 = 3.2430$

Adopting Eqn (14), (15) and (16), the modified average porosity of the reservoir can be deduced as well as their corresponding permeabilities and tortuosities.

Table 1: Deduced Biomass Concentration, Porosity, Permeability and Tortuosity Values

Period of Microbial action (days)	Biomass conc. σ (lb/ft)	Average reservoir Porosity, (φ)	Average reservoir Permeability, k (mD)	Average reservoir tortuosity, τ
0.0	0.0000	0.2000	122.8926	2.2876
5.0	0.5406	0.1996	122.1323	2.2892
10.0	1.0810	0.1992	121.3751	2.2908
15.0	1.6215	0.1988	120.6212	2.2924
20.0	2.1620	0.1983	119.6831	2.2944
25.0	2.7025	0.1979	118.9364	2.2960
30.0	3.2430	0.1975	118.1927	2.2976

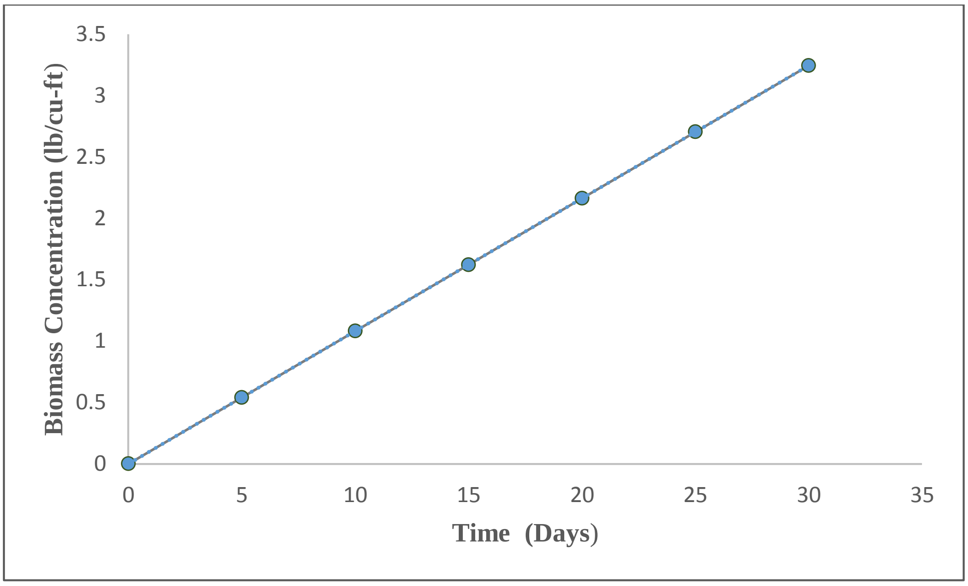

Figure 1: Relationship between Biomass concentration and Time

Figure 1 above shows the increasing level of entrained biomass, C_{bs} in lb/cu-ft with time. The plot indicates a proportional increase in biomass concentration in the reservoir as time of microbial action increased. During microbial activities in petroleum reservoirs, bacteria colonies are trapped within reservoir pores in course of their migration. An initial entrained concentration of biomass of 0lb/cu-ft as shown in Figure-1 after 30days of microbial action increased to 3.2430lb/cu-ft. A continuous injection of these microorganisms into the reservoir will result in a continuous increase in biomass concentration, these may impose negative implications on the reservoir flow characteristics over time.

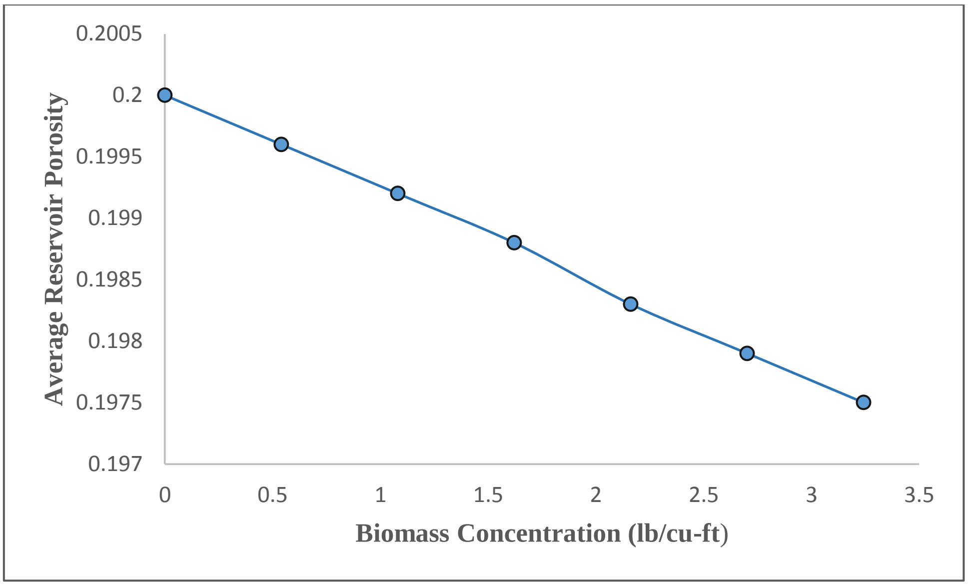

Figure 2: Relationship between Porosity and Biomass Concentration

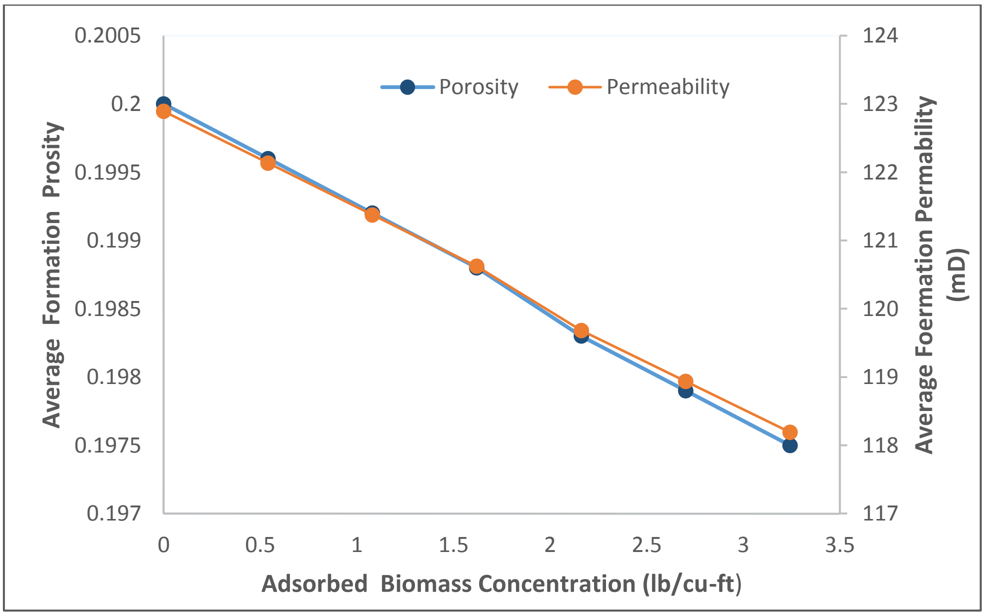

Figure 3: Porosity-Permeability Variation with Biomass Concentration

The relationship between the average formation porosity and biomass concentration in Figure 2 shows that an increasing biomass concentration with time will cause a reduction in the formation porosity; this is to say that the biomass concentration with time is inversely proportional to the average formation porosity. This reduction in porosity is as a result of microbial clogging fn the pore throats in the reservoir. During microbial transport in petroleum reservoirs, they tend to utilize available nutrients, these in-situ nutrients serves as survival and growth support for these microorganisms. The more they feed, higher their tendency to increase in mass per unit reservoir volume.

Porosity reduction will probably result in a reduction in reservoir permeability in the same magnitude. Once this parameter is altered, flow problems may occur; a phenomenon known as “skin” in reservoir engineering. This is phenomenon is challenging because it brings about a decrease in oil production as well as increasing the cost of production if well stimulation programs will be considered. From Figure 3, an initial porosity of 0.20 reduced to about

0.1975 as a result of biomass entrainment over time. The figure also shows the effect of increasing biomass concentration in the reservoir during the microbial process on permeability, reducing it from an initial average permeability of 122.8930mD to about 118.193mD.

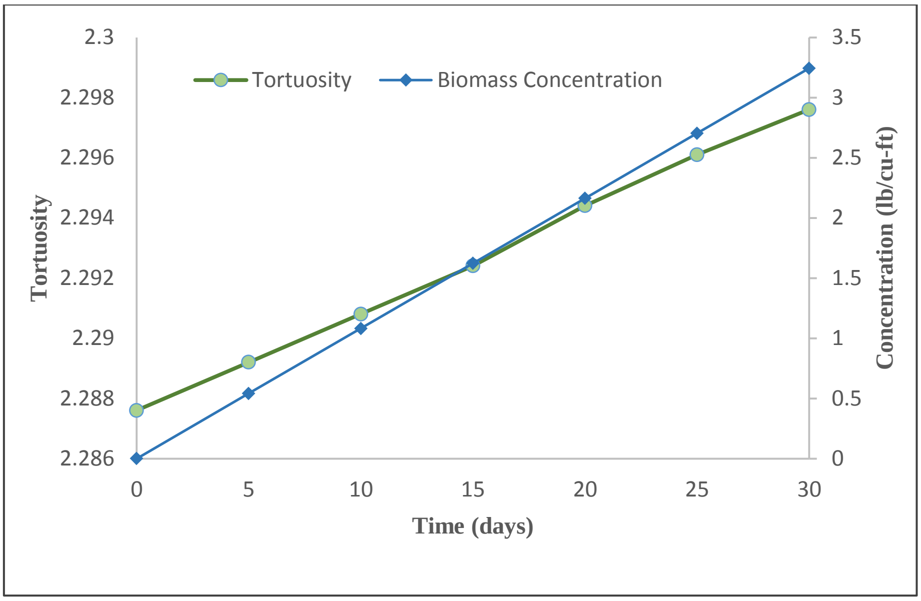

Figure 4: Variations in Tortuosity and Biomass Concentration with Time

Figure 4 shows that the more compacted a formation, the more tortuous it tends to be. In other words, as an increasing magnitude of biomass concentration continually occurs in the reservoir, the higher its tendency of being even more tortuous. For this case, this dimensionless quantity (tortuosity) increases directly with time and biomass concentration. Fluid flow problems may arise due to an increased magnitude of flow restrictions within the pore throats of the formation, caused by the deposition of these microorganisms.

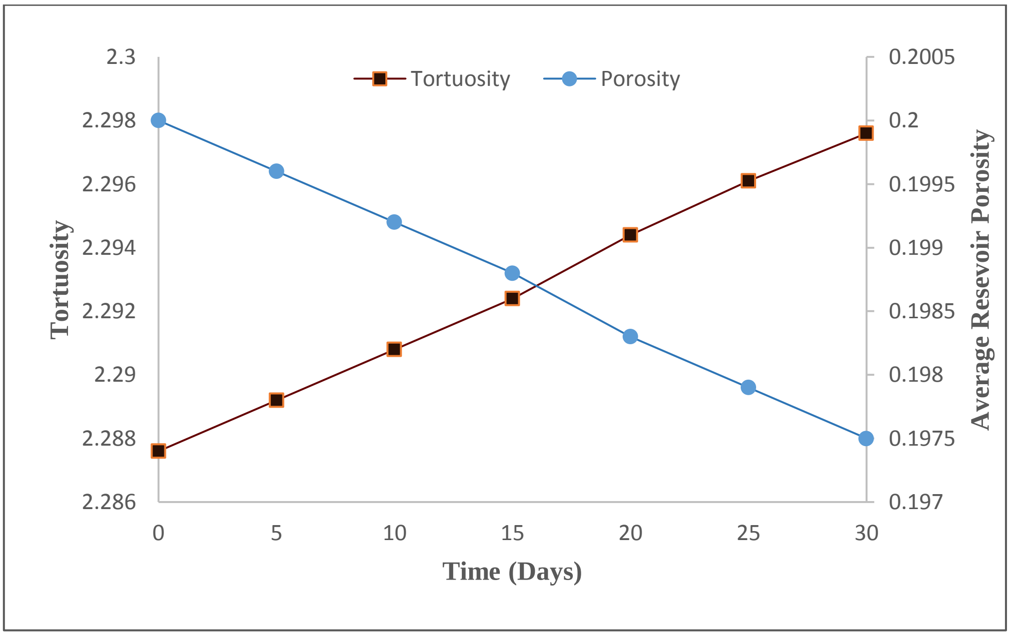

Figure 5: Tortuosity and Porosity Variation with Time

The more tortuous the formation, the less porous it becomes with time. From Figure 5, an increasing magnitude of biomass concentration resulted in a more tortuous system. Since these microorganisms increase in mass per unit reservoir volume they occupy over time, the net pore volume fraction (porosity) decreases. Figure 5 shows that an initial formation porosity of 0.20 with a corresponding tortuosity of 2.2876 reduced after 30days of biomass entrainment to about 0.1975, the magnitude of the tortuosity corresponding to this porosity value is 2.2976 as compared to an initial tortuosity of 2.2876.

CONCLUSION

The importance of Microbial Enhanced Oil Recovery as a tertiary method of oil production cannot be over-emphasized. Its multi-dimensional recovery mechanisms, eco-friendly approach and economic viability has proven that it can be a target for oil recovery in reservoirs to be recovered by unconventional methods. This technique offers a wide range of improving the reservoir flow performance by altering its wettability, interfacial tension, viscosity and so on. However, it is imperative that sound engineering of these microbial processes to be used for oil recovery is put into consideration. The concept of injection into petroleum reservoirs operates on the principle of mass balance processes, if the concentration of injected microbes are not properly investigated, flow restrictions may occur due to an increasing magnitude of entrained biomass on flow channels. Some reservoir rock properties such as porosity, permeability and tortuosity may be altered over a prolonged period of microbial action. Flow restrictions may also arise when there is an alteration in any of these rock properties which will have an effect on the overall recovery of oil in candidate reservoirs.

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