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Quantitative Modeling Of Formation Damage On The Reservoir During Microbial Enhanced Oil Recovery

Nmegbu, Chukwuma Godwin Jacob *
*(Department of Petroleum Engineering, Rivers State University of Science and Technology, Nigeria)

ABSTRACT
Microbial enhanced oil recovery is an inexpensive, environmentally friendly method of oil recovery, utilizing the potentials of certain microbes to significantly influence oil productionwith wide range of oil recovery mechanisms including oil mobilization, reservoir re-pressurization, permeability alteration, mobility control and a range of other exploitable recovery techniques. This study presents an investigation on the degree of damage to the reservoir as a result of microbial injection. Results from this analysis shows that for a continuous microbial injection process, the pore area of the formation reduces equivalently due to microbial plugging and or as a result of biomass accumulation in the reservoir. The prevailing effects of formation damage (skin) due to these microbes are also presented. Residual fluid flow rates and corresponding velocities were found to reduce in magnitude with deducing pore area after several days of injection.
Keywords–Damage, MEOR,Microbes, Modeling Pore Area.

I. INTRODUCTION

The process of biotechnology has advanced from just laboratory investigations to large scale applications in the petroleum industry. Certain processes such as bio-filtration, bioremediation, biodegradationetc, utilizing the potentials of microbes has now been an area of intensive study and interest in the oil and gas industry, with records of a field applications in Europe and other parts of the world. [1], [2].The use of microbes for EOR processes entails maximizing the full potentials of certain microbe to produce metabolites capable of recovering residual oil [3], [4], [5], [6]. Production of biogases for residual oil viscosity reduction as well as reservoir pressurization, production of biopolymers for selective plugging, bioacid production for well stimulation purposes, biosurfactant production for wettability and interfacial tension alteration and quite a number of other mechanisms are some of the bioproducts affiliated with the adaptation of this inexpensive recovery technique [7], [8], [9].Experience with injection of microbes in microbial enhanced oil recovery studies and also the study of the growth and activity of microbes in porous media, suggests that the growth may result in clogging of the media near the injection point. transport and dispersal of bacterial cells in porous media will have a profound effect on the effective permeability of the formation[10]. The understanding of subsurface bacteria behavior, metabolic products of bacteria, attendant consequences of the formed metabolites and subsequently their relativity to the performance of MEOR and other theories affiliated to the application of MEOR creates a basis for this study. The metabolic by-products of microbes can exert either positive or negative effects on the flow properties of reservoirs. This is well illustrated by Donaldson et al. who studied the effects of bacterial metabolites on pore structures of sandstone and carbonate reservoir materials [11]. Damage in petroleum reservoirs normally called skin effect poses a big problem toward the production and deliverability of the reservoir. It is hence imperative to predict or forecast the degree of damage during microbial enhanced oil recovery so as to ascertain the optimum microbial concentration applicable for the recovery process.

II. METHODOLOGY

2.1 Microbial Selection

Before a Microbe is selected for an EOR process, thorough investigation must be done to ascertain its constraints. Hyperthermophiles which are microbes with the highest reservoir temperature tolerance are often considered for this recovery technique. Other investigations may include salinity tolerance, pH, pressure etc. This study is limited to the investigation of the effects of injected microbes to the formation pore area, not considering metabolite production. This implies that no specific microbe is investigated; rather a wholistic overview is presented for all species of microbes applicable to the reservoir for oil recovery.

2.2 Microbial Mass Balance Account.

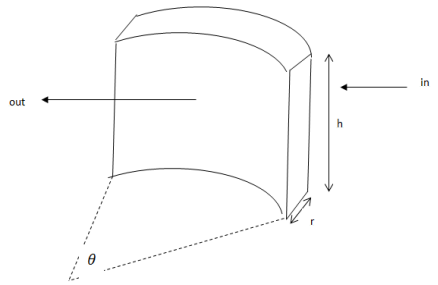

Fig 1 Schematic of control volume showing mass entry and exit though a differential radius

Mass in is given as $M_{in} = \rho AV|_{in}$ (1)

Similarly, mass out, $M_{out} = \rho AV|_{out}$ (2)

Therefore mass accumulation;

$$M_{acc} = \Delta r\left[\frac{\rho \emptyset A|_{t+\Delta t} - \rho \emptyset A|_t}{\Delta t}\right] \quad (3)$$

Assuming constant density

$$AV_{in} - AV_{out} = \Delta r\left[\frac{\emptyset A|_{t+\Delta t} - \emptyset A|_t}{\Delta t}\right] \quad (4)$$

Re-arranging the above, we have;

$$\frac{AV|_{in} - AV|_{out}}{\Delta r} = \frac{\emptyset A|_{t+\Delta t} - \emptyset A|_t}{\Delta t} \quad (5)$$

Taking the limits as $\Delta r, \Delta t \rightarrow 0$

$$\frac{\partial (AV)}{\partial r} = \frac{\partial (\emptyset A)}{\partial t} \quad (6)$$

For a constant height;

Pore area, $A_p = \emptyset A$ (7)

Accounting for formation damage as a result of microbial plugging,

we model for the change/reduction in pore area;

$$\frac{\partial (AV)}{\partial r} = \frac{\partial A_p}{\partial t} \quad (8)$$

The above is as a result of substituting (7) into (8) from Darcy's law.

Velocity of flow, $V = \frac{k}{\mu}\frac{\partial p}{\partial r} = \frac{q}{A}$ (9)

Therefore equation 3.8 now becomes;

$$\frac{\partial}{\partial r}\left(\frac{KA}{\mu}\frac{\partial p}{\partial r}\right) = \frac{\partial Ap}{\partial t} \quad (10)$$

Further expanding the term on the left hand side, we have;

$$\frac{k}{\mu}\left[A\frac{\partial^2 p}{\partial r} + \frac{\partial p}{\partial r}\frac{\partial A}{\partial r}\right]\frac{\partial Ap}{\partial t} \quad (11)$$

$$A\frac{\partial^2 p}{\partial r} + \frac{\partial A}{\partial r}\frac{\partial p}{\partial r} = \frac{\mu}{k}\frac{\partial A_p}{\partial t} \quad (12)$$

Now taking $A_{in} = r\theta h$,

$A_{out} = (r + \Delta r)\theta r - r\theta h$

$$A_{out} - A_{in} = (r + \Delta r)\theta h - r\theta h \quad (13)$$

Taking out like terms in the above equation, we have; $r\theta h + \Delta r\theta h - r\theta h = \Delta r\theta h$

$$\therefore \frac{A_{out} - A_{in}}{\Delta r} = \theta h \quad (14)$$

Taking limits as $\Delta r \rightarrow 0$ for a constant reservoir height

$$\frac{\partial A}{\partial r} = h\frac{\partial t}{\partial r}$$

$$A\frac{\partial^2 p}{\partial r^2} + h\frac{\partial t}{\partial r}\frac{\partial p}{\partial r} = \frac{\mu}{k}\frac{\partial A_p}{\partial t} \quad (15)$$

Simplifying the model above and assuming a constant volume reservoir giving;

$$V\frac{\partial A}{\partial r} = \frac{\partial A_p}{\partial t} \quad (16)$$

For a Cartesian coordinate system, the model becomes

$$\frac{\partial}{\partial x}\left(\frac{kA}{\mu}\frac{\partial p}{\partial x}\right) = \frac{\partial A_p}{\partial t} \quad (17)$$

The above now becomes

$$\frac{k}{\mu}\left[A\frac{\partial^2 p}{\partial x} + \frac{\partial A}{\partial x}\frac{\partial p}{\partial x}\right] = \frac{\partial A_p}{\partial t}$$

$$A\frac{\partial^2 p}{\partial x^2} + \frac{\partial A}{\partial x}\frac{\partial p}{\partial x} = \frac{\mu}{k}\frac{\partial A_p}{\partial t} \quad (18)$$

For a cylindrical core;

$$A = \pi r^2, \quad \frac{\partial A}{\partial x} = 0$$

$$A\frac{\partial^2 p}{\partial x^2} = \frac{\mu}{k}\frac{\partial A_p}{\partial t} \quad (19)$$

Assumptions

- No flow boundary condition
- Metabolites not yet produced.
- Microbial multiplication not considered
- Isothermal system as reservoir fluctuations in temperature is regarded minimal.
- Fluid flow is in a single dimension in the x direction.
- Residual oil is Incompressible
- Negligible capillary action.
- No break in injection rates of microbes
- No indigenous microbe present.
- Chemotaxis not considered.
- Equilibrium isotherm not considered.
- Gravitational effects considered negligible.
- Electrokinetic effects negligible.
- Unsteady state flow conditions.
- Other factors affecting growth rates such as salinity and pH remains constant.

III. RESULTS AND DISCUSSION

3.1 Solution to the proposed Model

From (19), it is seen that accounting for damage (pore area reduction) due to microbial action can be resolved using finite difference approximation. Applying central difference in space, and forward difference in time. Resolving the model explicitly, we obtain;

$$\frac{\partial^2 P}{\partial x^2} = \frac{P_{i+1}^n - 2P_i^n + P_{i-1}^n}{\Delta x^2} \quad (20)$$

And

$$\frac{\partial A}{\partial t} = \frac{A_p^n - A_p^{n-1}}{\Delta t} \quad (21)$$

Substituting (20) and (21) into (19), we obtain;

$$A\left[\frac{P_{i+1}^n - 2P_i^n + P_{i-1}^n}{\Delta x^2}\right] = \left(\frac{\mu}{k}\right)\frac{A_p^n - A_p^{n-1}}{\Delta t} \quad (22)$$

Rearranging (22) we have;

$$\frac{A}{\Delta x^2}[P_{i+1}^n - 2P_i^n + P_{i-1}^n] = \left(\frac{\mu}{k\Delta t}\right)A_p^n - A_p^{n-1} \quad (23)$$

(23) Now becomes

$$\left[\frac{A}{\Delta x^2}P_{i+1}^n - 2\frac{A}{\Delta x^2}P_i^n + \frac{A}{\Delta x^2}P_{i-1}^n\right] = \left(\frac{\mu}{k\Delta t}\right)A_p^n - A_p^{n-1}$$

(24)

Accounting for Damage after microbial injection (ie. The reduction in pore area), we first multiply through by $\left(\frac{k\Delta t}{\mu}\right)$, we obtain;

$$\left(\frac{k\Delta t}{\mu}\right)\left[\frac{A}{\Delta x^2}P_{i+1}^n - 2\frac{A}{\Delta x^2}P_i^n + \frac{A}{\Delta x^2}P_{i-1}^n\right] = A_p^n - A_p^{n-1}$$

(25)

Setting $\left(\frac{k\Delta t}{\mu}\right) = \dot{T}$ and $\frac{\dot{A}}{\Delta x^2} = \dot{M}$

(25) Now becomes

$$\dot{T}\left[\dot{M}P_{i+1}^n - 2\dot{M}P_i^n + \dot{M}P_{i-1}^n\right] = A_p^n - A_p^{n-1} \quad (26)$$

Accounting for average pore area in the reservoir after microbial action, (26) now becomes;

$$A_p^n = A_p^{n-1} + \dot{T}\left[\dot{M}P_{i+1}^n - 2\dot{M}P_i^n + \dot{M}P_{i-1}^n\right] \quad (27)$$

Where

A_p^n = the average pore area of reservoir due to microbial injection (ft^2).

A_p^{n-1} = initial average pore area of the formation before microbial injection (ft^2).

P_{i+1}^n and P_{i-1}^n are the Initial reservoir pressures before microbial injection (psi).

P_i^n = the injection pressure (psi)

3.2 Model validation.

Given the following reservoir and microbial parameters, the model is validated as thus;

Table 1.reservoir parameters for model validation

parameters	**value**
Initial reservoir pressure	1000psi
Injection pressure	1200psi
Reservoir thickness	50ft
Reservoir length	6000ft
Formation permeability	20mD
Injected water viscosity	1.3cp
Microbial viscosity	10cp
Water/microbial mixture ratio	60:40
Formation porosity	20%
Reservoir area	40acres
Residual oil viscosity	10cp
Time increment Δt	5days

First we deduce the mixture viscosity of the injected fluid.

Recall

$$\mu = \mu_w f_w + \mu_m f_m \quad (28)$$

Where μ_w and μ_m are the viscosities of the water and microbe respectively,

f_w and f_m are the fractions of the water and microbes in the injection fluid mixture

$$\mu = (1.3 \times .6) + (10 \times .4) = 4.78cp$$

$$\text{pore area open to flow} = \frac{\text{bulk vlume}}{\text{length of reservoir}} \quad (29)$$

Bulk volume=43560AHØ(30)

pore area open to flow, A_p

$$= \frac{43560 \times 40 \times 50 \times .20}{6000} = 2904\text{ft}^2$$

The above calculated is the initial pore area before the microbial injection.

Also calculating the total area of the reservoir A,

$$\text{Bulk area} = \frac{\text{bulk vlume}}{\text{length of reservoir}} = \frac{43560 \times 40 \times 50}{6000} = 14520\text{ft}^2$$

Deducing the above, the matrix area can now be calculated as thus;

14520-2904=11616ft^2

Recalling

$$A_p^n = A_p^{n-1} + \dot{T}\left[\dot{M}P_{i+1}^n - 2\dot{M}P_i^n + \dot{M}P_{i-1}^n\right]$$

Calculating constants, we have

$$\dot{M} = \frac{\dot{A}}{\Delta x^2} = \frac{14520}{6000^2} = 0.00403$$

For the first five days of injection,

$$\dot{T} = \left(\frac{k\Delta t}{\mu}\right) = \frac{20 \times 5}{4.78} = 20.92$$

Deducing the above parameters, (27) can now be used to determine the reduction in pore area of the reservoir as a result of formation damage (skin) due to the microbial injection.

With pore area of the formation originally 2904ft^2

After 5 days,

$$A_p^5 = A_p^{n-1} + \dot{T}\left[\dot{M}P_{i+1}^n - 2\dot{M}P_i^n + \dot{M}P_{i-1}^n\right]$$

$$A_p^5 = 2904 + 20.92[(0.000403 \times 1000) - (2 \times 0.000403 \times 1200) + (0.000403 \times 1000)] = 2900ft^2$$

After 10days

$$\dot{T} = \left(\frac{k\Delta t}{\mu}\right) = \frac{20 \times 10}{4.78} = 41.84$$

$$A_p^{10} = 2904 + 41.84[(0.000403 \times 1000) - (2 \times 0.000403 \times 1200) + (0.000403 \times 1000)] = 2897\text{ft}^2$$

After 15 days

$$\dot{T} = \left(\frac{k\Delta t}{\mu}\right) = \frac{20 \times 10}{4.78} = 62.76$$

$$A_p^{15} = 2904 + 62.76[(0.000403 \times 1000) - (2 \times 0.000403 \times 1200) + (0.000403 \times 1000)] = 2894ft^2$$

After 20 days

$$\dot{T} = \left(\frac{k\Delta t}{\mu}\right) = \frac{20 \times 20}{4.78} = 83.68$$

$$A_p^{20} = 2904 + 83.68[(0.000403 \times 1000) - (2 \times 0.000403 \times 1200) + (0.000403 \times 1000)] = 2891ft^2$$

After 25 days

$$\dot{T} = \left(\frac{k\Delta t}{\mu}\right) = \frac{20 \times 10}{4.78} = 104.6$$

$$A_p^{25} = 2904 + 104.6[(0.000403 \times 1000) - (2 \times 0.000403 \times 1200) + (0.000403 \times 1000)] = 2887ft^2$$

After 30 days

$$\dot{T} = \left(\frac{k\Delta t}{\mu}\right) = \frac{20 \times 10}{4.78} = 125.5$$

$$A_p^{30} = 2904 + 125.5[(0.000403 \times 1000) - (2 \times 0.000403 \times 1200) + (0.000403 \times 1000)] = 2884ft^2$$

The calculations above show the reduction in average pore area in the reservoir due to microbial action (damage) for different days of injection. The pore volume for the microbially subjected reservoir can now be deduced. For 5-30days of investigation, the pore volume is calculated as thus;

At 0days, $2904 \times 6000 = 17424000ft^3$
At 5days, $2900 \times 6000 = 17400000ft^3$
At 10days, $2897 \times 6000 = 17382000ft^3$
At 15days, $2894 \times 6000 = 17364000ft^3$
At 20days, $2891 \times 6000 = 17346000ft^3$
At 25days, $2887 \times 6000 = 17322000ft^3$
At 30days, $2884 \times 6000 = 17304000ft^3$

4.2:influence of formation damage on fluid flow

Recall the Darcy equation for an incompressible fluid

$$q = \frac{0.001127\,KA(P_1 - P_0)}{\mu L} \quad (31)$$

Adopting and calculating fluid flow rate relationship with the reduction in pore area of the reservoir, we recall that;

Area of reservoir open to flow of fluid = pore area of reservoir(32)

Therefore each day of investigation for 0-30days of injection, the pore area is substituted to deduce the corresponding flow rate of the residual fluid.

Recalling that fluid velocity v is given as

$$v = \frac{\text{Fluid flow rate}}{\text{Reservoir Area}} = \frac{q}{A} \quad (33)$$

The velocity at which the residual fluid travels in the reservoir will then be deduced for the days of investigation.

$$v == \frac{q}{A} = \frac{q_n}{14520} (34)$$

Table 2 Deduced reservoir parameters after microbial injection.

Days	Pore Area (PA)	Pore volume (PV)	Flow rate (q)	Fluid velocity (v)
0	2904	17424000	0.2181	1.502×10^{-5}
5	2900	17400000	0.2178	1.500×10^{-5}
10	2897	17382000	0.2176	1.499×10^{-5}
15	2894	17364000	0.2174	1.497×10^{-5}
20	2891	17346000	0.2172	1.495×10^{-5}
25	2887	17332000	0.2169	1.493×10^{-5}
30	2884	17304000	0.2167	1.490×10^{-5}

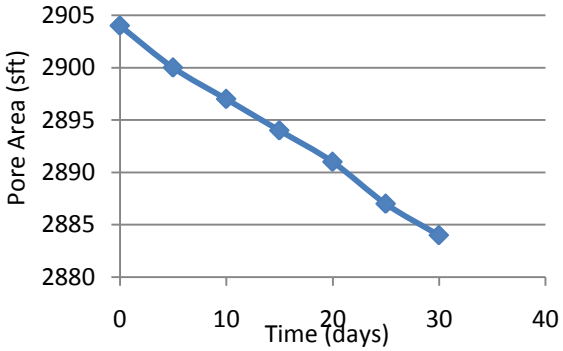

Fig 2 plot of pore area against time

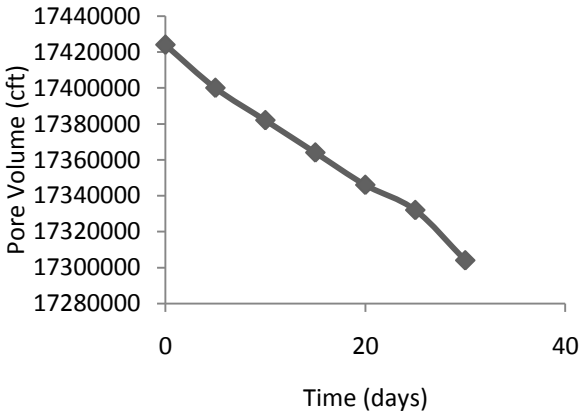

Fig 3 plot of pore volume against time

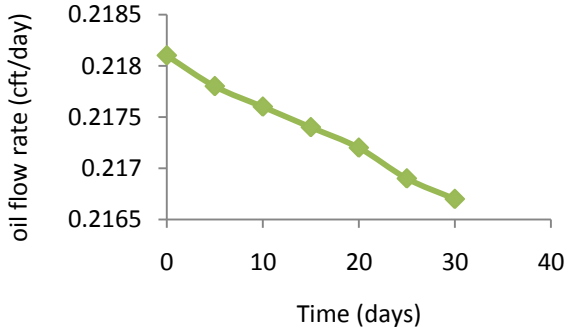

Fig 4 plot of oil flow rate against time

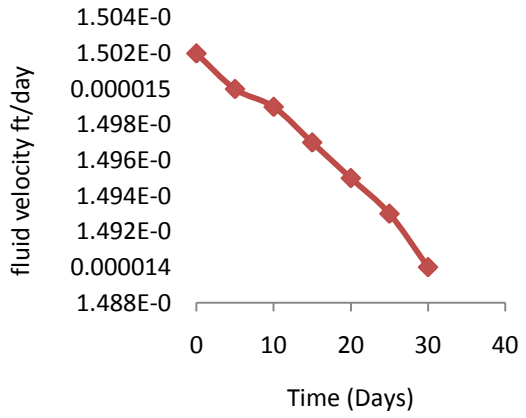

Fig 5 plot of oil velocity against time

The figures above presents a graphical representation of the effects of formation damage due to microbial injection, propagation and activities within the petroleum reservoir. Figure 2 and 3 shows the reduction in the average pore area and pore volume respectively in the formation at different days for a continuous injection process. The relationship between residual fluid flow rate and its corresponding velocities with the pore area reduction is presented in Fig 4 and Fig 5 respectively.

IV. CONCLUSION

Microbial application for EOR processes has proven to be highly efficient in records of both laboratory and field investigation. This multi-recovery technique of injected microbes due to the production of some metabolites that alter certain rock and fluid properties that improves production can also be problematic if not closely monitored. Injected microbe concentration investigation is most paramount for every MEOR process. From results above, it is seen clearly that irrespective of the advantages of the microbial conception for oil recover, damage (skin) to the native formation in inevitable. The reduction in fluid velocity, flow rates and area open to fluid flow will significantly retard oil production rates generally.

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