Modeling the Pressure Distribution in a Reservoir Undergoing MEOR for a 2-Dimensional Flow System

Nmegbu, Chukwuma Godwin Jacob

Abstract—The inexpensive and environmentally friendly examination of MEOR as an integrated lab and field research effort in the identification and comprehension its mechanisms of oil recovery has been a dynamic trend for researchers in the oil and gas industry for the past few years. For this study, a mathematical model was developed to account for the pressure distribution across the reservoir for 2-Dimensional fluid flow system. A significant pressure increase was observed in the well producing block during the Microbial flooding process. This pressure increase was traceable to the formation of a strong gas cap in the reservoir by produced CO₂ and N₂.

Keywords — MEOR, microbes, modeling, pressure profile.

I. INTRODUCTION

Increasing energy demand has propted the oil and gas industry to understudy a wide range of hydrocarbon production from aging, under-producing fields, artic and ultra-deep subsea fields; tight sands, shale and thermal Oil sands; HP/HT, long distance, deep water complex pre-salt or lower tertiary formations. Therefore the need to exploit sound recovery methods has been under intensive investigation by the oil and gas industry for a decade [1]. Microbial Enhanced Oil Recovery (MEOR) is a tertiary Oil recovery process where microorganisms and their metabolites are used to retrieve unrecoverable Oil from matured reservoirs [2]. MEOR can recover tertiary oil by improving macroscopic sweep efficiency through microbially induced permeability profile modification; or reducing interfacial tension between oil and water with biocatalysts to lower the capillarity trapping forces, or stimulating the reservoir porosity and permeability with microbial products such as acids, or combining all three mechanisms [3]. More importantly, microbial products are biodegradable and less toxic [4], [5], [6]. Because microbial growth occurs at exponential rates, it should be possible to produce large amounts of useful products quickly from inexpensive and renewable resources with an estimated cost of about USD10/bbl of produced incremental oil [2], [3], [7]. These microbes in MEOR are simply hydrocarbon utilizing, non-pathogenic due to their natural occurrence in petroleum reservoirs, hence are safe for plants, animals, and humans (Bryant et. al, 2004)[8].

This research is aimed at developing a model for the petroleum engineer to monitor and predict quickly the pressure distribution in a petroleum reservoir from MEOR processes. By so doing, information can be obtained that aids in optimizing the operation of the matured reservoir to yield the most.

A. MEOR Laboratory and Field Tests

Knapp et al conducted microbial investigation for oil recovery by isolating 22 microorganisms to produce bio polymers and emulsifiers. One strain was isolated that grew in 10% salt concentrations, over a pH range of 4.6 to 9.0, at temperatures up to 50°C, and in the presence of crude oil. They demonstrated in the laboratory that glucose, ammonium sulfate, potassium sulfate were easily transported through sandstone cores The addition of glucose to cores previously inoculated with bacteria resulted in a significant decrease in permeability, indicating that bacteria were multiplying and plugging the pores. Bacteria indigenous to all of the cores treated were pseudomonas Sp, was in cores determining how much of the plugging by Sp., Bacillus [9], [10].

The process of injecting bacteria spores along with nutrients into a reservoir was presented by Hitzman. He asserted that the spores would germinate in the reservoir and enhance removal of oil from reservoir rock. The hypothesis was tested in the laboratory by using an oil – saturated sand packed column. An aqueous solution containing spores of clostridium roseum and molasses was passed through the column and an improved release of oil (about 30%) was obtained [11]. The Injection of 150 stripper wells in the U. S. that produced, on an average, 2 bbl/day, with no wellhead pressure was conducted in1979. The reservoir porosities were 10 to 30%, depths 200 to 1000ft, with on average temperature of 38°C. This was done within 1977 – 81. The inoculums was 1 to 10gal of a mixed culture of Bacillus and Clostridium sp. (non-hydrocarbon-utilizing) with crude molasses and mineral salts. In typical situation, the bacterial inoculum required 10 to 14 days to adequately multiply within the treated area of the reservoir. The results varied, but in suitable reservoirs, 20 to 30% additional Oil in place was recovered.
These suitable conditions include oil of 15 to 30\textdegree API gravity, formation water of less than 10 x 10\textsuperscript{6} ppm salt content, preferably a carbonate reservoir, and a temperature of approximately 38\textdegree C [12].

Sayyouh et. al investigated the possibility of applications of MEOR to the Arabian oil fields. The applicability of MEOR for increase in productivity under the Arab oil fields conditions was based on analysis of data obtained from 300 formations in seven Arab countries (Saudi Arabia, Egypt, Kuwait, Qatar, UAE, Iraq and Syria). The parameters studied were formation permeability, reservoir pressure and temperature, crude oil viscosity and API gravity, formation connate water saturation and its salinity. It was discovered that Saudi, Iraqi and Egyptian Oil fields can be very good candidates for MEOR processes. Also Qatar, Kuwait and Syria have some potentials for MEOR. U. A. E, however has no potential for MEOR under its reservoir conditions. It was put forward that MEOR should be able to recover up to 30\% of the residual oil under the Arab reservoir conditions [13]. The Isolates of five Bacillus subtilis strains from oil samples were investigated. The studies reservoir was characterized by alternated oil and water sand layers, with an average porosity of 25\% and a permeability of 50mD. It was a flat structure at 450m depth, with an initial pressure of 32.4 bars and a temperature of 42.5\textdegree C. The oil was also paraffinic, with low viscosity, high pour point and a gravity of 250 API, with no gas dissolved [2]. A sand pack column model was designed to simulate the increase in productivity by the micro – organisms.

Later, a one dimensional multi-component model that simulated biomass growth, metabolic product formation and nutrient consumption in a MEOR process was developed by Zhang et al. The model used a modified Monod equation to describe bacterial growth when two nutrients (substrates) were present. Permeability reduction was assumed to be caused by pure surface retention and pore throat plugging by the microbes [14].

Sidsel developed a one-dimensional isothermal model which comprises displacement of oil by water containing bacterial and substrate for their feeding. Different methods for incorporating surfactant induced reduction of interfacial tension into models were investigated. The results predicted that substantial amount of surfactant is produced in the reservoir affecting the final recovery. Also, a considerable effect was not reached at the entrance of the reservoir like under surfactant flooding, but rather after a given period of time needed for bacteria growth. The partitioning of surfactant and the injection composition were found to have a significant influence on the saturation distribution in the reservoir as well as the ultimate oil recovery [15].

Sakar et al. presented a one dimensional, two phase compositional numerical model for bacterial transport in a MEOR process where oil recovery was by bio-surfactant based interfacial tension reduction and selective plugging of higher permeability regions by biomass generated by microbial growth. Islam then presented a mathematical formulation that described microbial movement in a multidimensional system where microbe and nutrient transport equations were coupled to phase flow equations. A drawback of this formulation was that it neglected physical dimension as a transport mechanism. [15], [16].

Xu in 2011 presented a mathematical model for Bio surfactant production in Indigenous Microbial Enhanced Oil Recovery (IMEOR). The model represent a two-step activation process for the bio surfactant production bacteria in food chain between aerobic and anaerobic in oil reservoir, and it elaborates the impacts of bio surfactant on physical parameters such as interfacial tension, capillary pressure, residual oil and relative permeability. The model is a great development for the current mathematical models of the biosurfactant production bacteria in MEOR, and it supplies theoretical basis for the study on mathematical model software [17].

Recently, Nmegbu and Dadge presented a model to account for the soaking period of Bacteria in MEOR an application, which is the time it takes the bacteria from the point injection point to multiply, distribute and spread throughout the entire reservoir.
The reservoir was assumed to be a perfect rectangular shape and the volume was subdivided into volume blocks for simplification determining the effects of bacteria and nutrients were injected into the first grid block for the period of 10 days before shutting in the well. The time step was 10 days. The study was done till the fourth time step (40 days). After shutting, calculations of the concentration of bacteria and nutrient consumption rate in other grid blocks with time was done. The results should that bacteria concentration increased as the nutrients were consumed with time. They compared their results with a plant data obtained from Garzan oil field in Turkey. In which the boundaries of the percentage deviation was 2.6 and 18.9, depicting an acceptable result.

The mathematical model equations were solved for concentrations of bacteria and nutrients in different grid blocks at different time steps. The equations were solved numerically using implicit finite difference technique, depicted an acceptable result. The pressures were calculated using field parameters. The results were then compared with solution to fluid flow equation excluding MEOR Parameters. The pressure profile for the comparison is as shown below.

**Fig. 2 Pressure profile comparison with point 2 as the producer**

This indicated the efficiency of MEOR. A pressure increase within the wellbore of about 1121 psi. Shows an improved oil flow within the wellbore vicinity. [19]

**II. METHODOLOGY**

**A. Microbial selection**

*Pseudomonas stutzeri* proves the best microbes in terms of biogenic gas production as its major metabolite. This microbe is capable of producing Nitrogen and Carbon dioxide, using glucose as substrate and nitrate. The microbe is facultative (both aerobic and anaerobic) microorganism. It is rod-like with length within 1.4 - 2.8µm, diameter 0.75 – 0.85 µm. *Pseudomonas stutzeri* had been isolated in the production plant from bottom residues of Oil- water separator, and was analyzed in terms of generation time and gas production by denitrification of glucose in the laboratory as adopted by Deilmann and Erdgas 1993. The Optimal living conditions of the bacterium strain are given below.
International Journal of Emerging Technology and Advanced Engineering  

Table I  
Microbial Tolerance For Ph, Salinity And Temperature  

<table>
<thead>
<tr>
<th>Salinity range</th>
<th>20 – 80 g NaCl/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (Max)</td>
<td>41°C</td>
</tr>
<tr>
<td>pH Value (opt)</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Also, under laboratory conditions, *Pseudomonas stutzeri* is capable of producing CO₂ utilizing glucose as shown by the equation below (Gottschalk 1986).

\[ 2C_6H_12O_6 \rightarrow C_6H_12O_8 + C_6H_12O_8 + 4H_2 + 5CO_2 \quad (7) \]

(Glucose) (Butanoic) (Acetone) (Hydrogen) (Carbon dioxide)

And N₂ by utilizing Nitrate as an electron acceptor, as shown below:

\[ 4KNO_3 \rightarrow 2K_2O + 2N_2 + 5O_2 \]

(Potassium Nitrate) (Potassium Oxide) (Nitrogen) (Oxygen) (8)

It can be seen together with liquid products such as acetone and butanol, 4 moles of H₂ and 5 moles of CO₂ gases are produced on consumption of 2 moles of glucose.

The laboratory experiment has shown that Pseudomonas stutzeri can effectively withstand reservoir must challenging conditions particularly temperature and salinity.

Additionally, the following criteria led to the selection of *Pseudomonas stutzeri* for this work:

i. The *Pseudomonas Stutzeri* originates from the area surrounding a reservoir.

ii. Denitrification is the most effective gas production process of bacteria.

iii. The *pseudomonas stutzeri* usually do not compete with sulphate – reducing bacteria, as they cannot tolerate the presence of nitrate.

B. Model Development

The general fluid transport equation in a porous media for an unsteady state conditions is given as follows:-

\[ \frac{\partial}{\partial x} \left( U \frac{1}{B} \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( U \frac{1}{B} \frac{\partial}{\partial y} \right) + \frac{\partial}{\partial z} \left( U \frac{1}{B} \frac{\partial}{\partial z} \right) + q \cdot \phi = \frac{V_s \phi}{a_n B_i C_i} \frac{dp}{dt} \quad (9) \]

Assuming a 2 – Dimensional, single phase flow system in (9), we have

\[ \frac{\partial}{\partial x} \left( U \frac{1}{B} \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y} \left( U \frac{1}{B} \frac{\partial}{\partial y} \right) + \frac{\partial}{\partial z} \left( U \frac{1}{B} \frac{\partial}{\partial z} \right) + q \cdot \phi = \frac{V_s \phi}{a_n B_i C_i} \frac{dp}{dt} \quad (10) \]

From Darcy’s law for fluid flow,

\[ U_x = - \beta \frac{K_x}{\mu_o} \frac{dp}{dn} \quad \text{And} \quad U_y = - \beta \frac{K_y}{\mu_o} \frac{dp}{dy} \quad (11) \]

Substituting for \( U_x \) and \( U_y \), we have

\[ \frac{\partial}{\partial x} \left( \beta \frac{A K_x}{B \mu_o} \frac{dp}{dn} \right) \Delta x + \frac{\partial}{\partial y} \left( \beta \frac{A K_y}{B \mu_o} \frac{dp}{dn} \right) \Delta y + q_n = \frac{V_s \phi}{B a_n} \frac{dp}{dt} \quad (12) \]

For slightly compressible fluid flow, it is assumed the fluid compressibility is small and remains constant within the pressure range of interest.

Formation volume factor (B) can be approximated as

\[ B = \frac{B^o}{1 + c(p - p_o)} \quad (13) \]

Where \( C = \text{Compressibility} \)

\[ B^o = FVF \text{ at reference pressure, } p^o \]

Substituting (13) into (12) and differentiating yields.

\[ \frac{\partial}{\partial x} \left( \beta \frac{A K_x}{B \mu_o} \frac{dp}{dn} \right) \Delta x + \frac{\partial}{\partial y} \left( \beta \frac{A K_y}{B \mu_o} \frac{dp}{dn} \right) \Delta y + C \frac{\partial q_n}{\partial x} = \frac{V_s \phi C_o \phi}{B a_n} \frac{dp}{dt} \quad (14) \]

Introducing microbial concentration (C₀), we have;

\[ \frac{\partial}{\partial x} \left( \beta \frac{A K C_o}{B \mu_o} \frac{dp}{dn} \right) \Delta x + \frac{\partial}{\partial y} \left( \beta \frac{A K C_o}{B \mu_o} \frac{dp}{dn} \right) \Delta y + C_o \frac{\partial q_n}{\partial x} = \frac{V_s \phi C_o \phi}{B a_n} \frac{dp}{dt} \quad (15) \]

(15) is known as the component microbial transport equation.

Specific Rate of Reaction constant (R₁₀₀), which considers growth and lysis processes (Bailey and Ollis 1986) is given as:

\[ R_{bl} = \mu - K_{lys} \quad (16) \]

Accounting for \( R_{bl} \), the equation is upgraded to

\[ \frac{\partial}{\partial x} \left( \beta \frac{A K C_o}{B \mu_o} \frac{dp}{dn} \right) \Delta x + \frac{\partial}{\partial y} \left( \beta \frac{A K C_o}{B \mu_o} \frac{dp}{dn} \right) \Delta y + (C_o q_n + R_{bl}) = \frac{V_s \phi C_o \phi}{B a_n} \frac{dp}{dt} \quad (17) \]

405
Recall that, for slightly compressible fluids,

\[
B = \frac{B^o}{[1 + c (p - p_o)]}
\]

For slightly compressible fluids, in many cases, it can be assumed that \(1 + C (P - P^o)\) \(\approx 1\), because \(C\) is very small. Therefore, \(B = B^o\). Consequently,

\[
\frac{\partial}{\partial x} \left( \beta_i \frac{A_i K_i c_i \partial p}{B_{pi}} \right) \Delta x + \frac{\partial}{\partial y} \left( \beta_i \frac{A_i K_i c_i \partial p}{B_{pi}} \right) \Delta y + (C_{\beta_i} + K_i) = \frac{V_i c_i \partial p}{B_{pi}} \frac{\partial \phi_i}{\partial x} \Delta x
\]

(18)

18 is the proposed model to be used in this study.

C. Major Assumptions

The mathematic, model utilized in this study incorporates the following assumption:

1. Fluid flow is in a single phase, two-dimensional and takes place in a uniform porous medium.
2. Isothermal system as reservoir fluctuations in temperature is regarded minimal (Sarkar et al, 1994).
3. Incompressible fluid, therefore density remains constant.
5. No indigenous bacterial present.
6. Chemo taxis not considered.
7. Continuous injection of nutrient and bacteria takes place.
8. Constant viscosity.
9. No inhibition of growth by substrates or metabolites.
10. No substrate and metabolite adsorption on the pore walls.
11. Unsteady state flow condition was considered.
12. Negligible gravity effects.
13. Flow is laminar.
14. Electrokinetic effects negligible.
15. PH salinity temperature and other factors affecting growth are constant.
16. The pressure difference remains at a level where injectivity can be maintained.
17. No volume change in reaction; when reaction converts components of same density.
18. \(H_2, N_2, K_2O\) are insoluble in water and Oil.

III. RESULTS AND DISCUSSION

Presenting the solution to the proposed model a finite difference approximation in space and time is written for (18). The positions of investigation are shown below:

![Fig 3. Discrete point representation in two dimensions](image)

In terms of transmissibility

\[
T_{i+1/2} = \left( \beta_i \frac{A_i K_i c_i}{B_{pi}} \right)_{i+1/2} \frac{p_{i+1}^{n+1} - p_{i+1}^{n}}{\Delta \tau}
\]

(24)

\[
T_{i+1/2} = \left( \beta_i \frac{A_i K_i c_i}{B_{pi}} \right)_{i+1/2} \frac{p_{i+1}^{n+1} - p_{i+1}^{n}}{\Delta \tau}
\]

(25)

\(T_{i+1/2} J\) and \(T_{i+1/2 J}\) is known as the microbial transmissibility in the of the porous media.

Expanding the above and collecting like terms in the above, we have
\[
T_{y,j-1/2}^n P_{y,j+1}^n + T_{y,j+1/2}^n P_{y,j-1}^n - \left( T_{x,l+1/2}^n + T_{x,l-1/2}^n + \right) \left( C_0 q_{sc(i,j)} + R_{hi} \right) = \frac{V_b \theta c_i C_b}{a_{c B \Delta t}} \frac{P_{y,j+1}^n - P_{y,j}^n}{P_{y,j}^n} \quad (26)
\]

Let
\[
M = \left( \frac{V_b \theta c_i C_b}{a_{c B \Delta t}} \right)^{-1} = \frac{a_{c B \Delta t}}{V_b \theta c_i C_b} \quad (27)
\]

Setting
\[
N_{i,j} = T_{y,j+1/2}^n \quad (28)
\]
\[
E_{i,j} = T_{x,l+1/2}^n \quad (29)
\]
\[
S_{i,j} = T_{x,l-1/2}^n \quad (30)
\]
\[
W_{i,j} = T_{x,l-1/2}^n \quad (31)
\]

Fig 4. Vector notation for positions

Naming the convection for the coefficients of the equation, NEWS is north, east, west and south respectively. Rearranging in Consequently, (26) now becomes.
\[
P_{i,j}^{n+1} = P_{i,j}^n + M \left[ N_{i,j} P_{i,j+1}^n + S_{i,j} P_{i,j-1}^n - (N_{i,j} + E_{i,j} + W_{i,j} + \right] S_{i,j} P_{i,j}^n + E_{i,j} P_{i,j}^n + W_{i,j} P_{i,j-1}^n + M \left( q_{sc(i,j)} C_b + R_{hi} \right) \quad (32)
\]

From the equation above, the initial boundary conditions, all pressure values at any position \(i, j \pm 1, j \) and \( i, j \pm 1 \) at a present time step “n” are the same so the values of \( P_{i,j+1}^n, P_{i,j}^n, P_{i,j-1}^n \) etc are all equal and are of known values. The only unknown will be the pressure value at position “I, j” at a new time step “n+1”.

The above equation can be applied in 2-dimensional reservoir discretization system as shown in the diagram below.

Fig 5 block centered grid system of discrete points in the reservoir

The table below shows the reservoir parameters for model validation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial reservoir pressure</td>
<td>1600psi</td>
</tr>
<tr>
<td>( \Delta x )</td>
<td>400ft</td>
</tr>
<tr>
<td>( \Delta y )</td>
<td>400ft</td>
</tr>
<tr>
<td>( \Delta z )</td>
<td>100ft</td>
</tr>
<tr>
<td>Formation volume factor ( B )</td>
<td>1.0 rsb/stb</td>
</tr>
<tr>
<td>Formation porosity, ( \phi )</td>
<td>25%</td>
</tr>
<tr>
<td>Oil viscosity, ( \mu_o )</td>
<td>20cp</td>
</tr>
<tr>
<td>Volume conversion factor, ( \alpha_c )</td>
<td>5.615</td>
</tr>
<tr>
<td>Reservoir permeability, ( K_x K_y )</td>
<td>30mD</td>
</tr>
<tr>
<td>Time increment, ( \Delta t )</td>
<td>10days</td>
</tr>
<tr>
<td>Total compressibility, ( C_t )</td>
<td>( 5 \times 10^{-6} \text{ (psi)} )</td>
</tr>
</tbody>
</table>

Transmissibility coefficient, \( \beta_c \)

Note for Fig 5, Gb2, 3 and 3, 2 are injectors while GB 2, 2 is the producing well.

For microbial and nutrient parameters and finally calculating the constants \( T \) and \( M \)

\[
K_s = 12.8 \text{ (mg/l)} , \ S = 45 \text{ (mg/l)} , \ \mu_{max} = 0.35 \text{hr}^{-1}
\]

From Monod equation \( \dot{m} = \mu_{max} \frac{S}{K_s + S} = 6.552 \text{day}^{-1} \)

\[
R_{bi} = \dot{m} - K_d = 6.53 \text{day}^{-1}
\]

\[
N_{i,j} = E_{i,j} = W_{i,j} = S_{i,j} = \left( \beta_c \frac{A_{CB}}{P_{mu} \mu_{max}} \right)_{i,j+1/2} = 1.775
\]

\[
M = \left( \frac{a_{c B \Delta t}}{V_b \theta c_i C_b} \right) = 0.0267
\]
The reservoir pressure profile can now be deduced using the proposed model.

\[
\begin{align*}
\frac{\partial}{\partial x} \left( \frac{p_{i,j}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,j}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,j}^n}{\rho} \right) &= \nabla \cdot \mathbf{F} + q^n_{i,j} - q_{i,j}^n \\
\end{align*}
\]

For GB 1.1

\[
q_{sc,1} = 0, \quad w_{1,1} = 0 \quad \text{and} \quad q_{sc,1} = 0
\]

Therefore

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,1}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,1}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,1}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,1} = 0
\]

For GB 2.1

\[
q_{sc,2,1} = 0, \quad a_{1,1} = 0
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,1}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,1}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,1}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,2,1} = 0
\]

For GB 3.1

\[
q_{sc,3,1} = 0, \quad a_{1,1} = 0
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,1}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,1}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,1}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,3,1} = 0
\]

For GB 1.2

\[
q_{sc,2} = 0, \quad w_{2,1} = 0
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,2}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,2}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,2}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,2} = 0
\]

For GB 2.2

\[
q_{sc,2,2} = -ve, \quad C_b = 1
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,2}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,2}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,2}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,2,2} = 1
\]

For GB 3.2

\[
q_{sc,2} = 0
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,2}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,2}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,2}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,2} = 0
\]

For GB 1, 3

\[
q_{sc,1,3} = 0, \quad w_{1,3} = 0 \quad \text{and} \quad N_{1,3} = 0
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,1}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,1}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,1}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,1,3} = 0
\]

For GB 2, 3

\[
q_{sc,3,3} = 0, \quad e_{1,3} = 0 \quad \text{and} \quad q_{sc,3,3} = 0
\]

\[
\frac{\partial}{\partial x} \left( \frac{p_{i,2}^n}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{p_{i,2}^n}{\rho} \right) - \frac{\partial}{\partial z} \left( \frac{p_{i,2}^n}{\rho} \right) + \nabla \cdot \mathbf{F} + q_{sc,3,3} = 0
\]

Deducing the above equations for the two dimension model, the following value of pressures were generated using the field and microbial parameters as well as application of the stated boundary conditions.

\[
P_{1,1} = 1600.17 \text{psi}
\]

\[
P_{1,2} = 1600.17 \text{psi}
\]

\[
P_{1,3} = 1600.17 \text{psi}
\]

\[
P_{2,1} = 1600.17 \text{psi}
\]

\[
P_{2,2} = 1586.48 \text{psi}
\]

\[
P_{2,3} = 1684.28 \text{psi}
\]

\[
P_{3,1} = 1600.17 \text{psi}
\]

\[
P_{3,2} = 1684.28 \text{psi}
\]

\[
P_{3,3} = 1600.17 \text{psi}
\]

Updating pressure values from time step one into the equations for subsequent time steps at same Δt of 10days, the below can now be generated.
Removing the microbial parameters in () to account for an ordinary water flooding process, the constants $M$ and $N_{ij} = E_{ij} = W_{ij} = S_{ij}$ is calculated as thus

$$M = \left( \frac{u_{ij,\Delta t}}{V_0 \sigma_{ij}} \right) = 0.28075$$

<table>
<thead>
<tr>
<th>Time steps</th>
<th>1,1</th>
<th>2,1</th>
<th>3,1</th>
<th>1,2</th>
<th>2,2</th>
<th>3,2</th>
<th>1,3</th>
<th>2,3</th>
<th>3,3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1600.17</td>
<td>1600.17</td>
<td>1600.17</td>
<td>1600.17</td>
<td>1586.48</td>
<td>1684.28</td>
<td>1600.17</td>
<td>1684.28</td>
<td>1600.17</td>
</tr>
<tr>
<td>2</td>
<td>1600.34</td>
<td>1599.7</td>
<td>1604.28</td>
<td>1599.7</td>
<td>1583.52</td>
<td>1775.95</td>
<td>1604.33</td>
<td>1775.95</td>
<td>1608.32</td>
</tr>
<tr>
<td>3</td>
<td>1600.45</td>
<td>1599.36</td>
<td>1612.37</td>
<td>1599.36</td>
<td>1585.98</td>
<td>1835.03</td>
<td>1612.42</td>
<td>1835.03</td>
<td>1624.38</td>
</tr>
<tr>
<td>4</td>
<td>1600.5</td>
<td>1599.57</td>
<td>1622.53</td>
<td>1599.57</td>
<td>1597.33</td>
<td>1886.97</td>
<td>1622.53</td>
<td>1886.97</td>
<td>1664.52</td>
</tr>
<tr>
<td>5</td>
<td>1600.59</td>
<td>1600.77</td>
<td>1634.15</td>
<td>1600.77</td>
<td>1611.47</td>
<td>1933.50</td>
<td>1634.15</td>
<td>1933.50</td>
<td>1669.43</td>
</tr>
<tr>
<td>6</td>
<td>1600.78</td>
<td>1603.03</td>
<td>1646.94</td>
<td>1603.03</td>
<td>1627.46</td>
<td>1975.82</td>
<td>1646.94</td>
<td>1975.82</td>
<td>1694.63</td>
</tr>
</tbody>
</table>

The figures below show the pressure profile in the reservoir during MEOR and without the microbial injection, both showing profiles for 6 time steps at $\Delta t=10$days.

![Fig 6 showing the pressure distribution across the reservoir for various time steps at different reservoir positions during MEOR](image_url)
Fig 6 shows the increasing trend of reservoir pressure across the grid blocks of the reservoir. The pressure in GB 2, 2 also known as the producing well pressure shows an increasing trend during the 60days injection period. This invariably means an increase in the flow rate of the producing well, since pressure is directly proportional to flow rate. On the other hand, Fig 7 depicts how the pressure in the reservoir increased during the Microbial injection with 2, 3 and 3, 2 as injectors.

During the water flooding process there was an increase in the reservoir pressure but the wellbore flowing pressure required to improve the flow rate of the residual crude at 2, 2 was found to be constantly dropping as injection period increased sequentially from 10days to 60 days. This drop in pressure could be as a result wellbore vicinity damage during the waterflooding process. The increase in GB 2, 2 during Microbial injection is traceable to Interfacial tension reduction and/or improved mobilization of the heavy residual crude by biosurfactant production from the microbes. Fig 9 simply shows the decreasing trend of pressure in the producing block (2,2) during the water flooding process.
The figure above shows the comparison of the MEOR process and the waterflooding process after 60 days of injection for both. The biogenic gases produced by the microbes were considered insoluble in the oil, and as such did not go into solution. The gases were assumed to form a gas cap that was observed to pressurize the reservoir. The increasing trend of pressure for the MEOR process is shown in Fig 10.

IV. CONCLUSION

The MEOR process has proven to be a preferred method of recovery recording a considerable increase in the reservoir pressure as a result of biogenic gas produced when compared to water injection. It is highly recommended that the pressure distribution for a 3-dimensional and radial fluid flow condition be investigated so as to ascertain pressure profiles for complex reservoir conditions.

Acknowledgement

The Author highly appreciates the efforts of Falola Yusuf and Pepple Daniel Dasigha for the fruitiness of this research.

REFERENCES