Nmegbu Int. Journal of Engineering Research and Applications www.ijera.com
ISSN : 2248-9622, Vol. 4, Issue 6(Version 3), June 2014, pp.165-169

RESEARCH ARTICLE OPEN ACCESS

Model for The Diffusionof Biogenic Gases In Heterogeneous Reservoirs Undergoing Transient Flow

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ABSTRACT
Microbially enhanced petroleum reservoirs confirms a recovery of about 30-40 % residual oil, with an integral composition of wide range of oil recovery mechanisms including wettability alteration by biosurfactant production, selective plugging of highly permeable channels by biopolymer production, creating fluid flow channels in carbonate reservoirs by rock dissolution attributed to bioacid formation, and a range of other exploitable recovery techniques. This study presents an investigation of biogenic gas produced in-situ and its concentration profile across the reservoir. An increasing concentration trend in the grids was observed and these increments were owed to the fact that diffusion of the biogenic occurred. It was also observed that after 40days of *Desulfovibro* injection, the produced CO_2 across the reservoir was tending towards being even in values of concentration, implying that diffusion rate was approaching a zero value. Also, the distorting effect of reservoir heterogeneity on biogenic gas concentration profile was also resolved by adopting the method of averaging for permeability and porosity in the reservoir.
***Keywords*–**Biogenic gases, Concentration, Heterogeneity, Microbes

I. INTRODUCTION

Microbial enhance oil recovery is an aspect of biotechnology that utilizes the potentials of some microbes injected into petroleum reservoirs for certain oil recovery mechanisms. These mechanisms attempt to overcome the some obstacles in efficient oil recovery such as the low permeability, high viscosity of the residual crude oil, and high oil-water interfacial tensions that may result in high capillary forces retaining the oil in the reservoir rock, etc. [1].MEOR involves the use of specific bacteria capable of producing useful metabolites in-situ such as gases, acids, surfactants, solvents and polymers in order that their presence will aid further reduction of residual oil left in the reservoir after secondary recovery[1], [2]. Webb in 1998 outlined the production of biogenic gases creates a free gas phase that can account for incremental oil recovery in MEOR processes either by reduction of the oil viscosity by solution of the gas in the oil, or by re-pressurization of the reservoir through gas cap formation, causing displacement from trapped capillaries and enhancing mobilization of the oil to the producing wells [3], [4]. The most important gas-producing microbes include; Clostridium, Desulfovibrio, Pseudomonas, and some methanogen. The composition of the biogenic gas from bacteriametabolism can include carbon dioxide, hydrogen, methane and nitrogen [5], [6], [7]. This study not only aims at investigating the concentration profile of produced biogenic gases, but also tends to investigate the effects of reservoir heterogeneity on biogenic gas distribution across the reservoir. The knowledge of biogenic gas concentration profiles in heterogeneous reservoirs are of great importance when accounting for the overall recovery efficiency of the MEOR process either by solution gas drive or gas-cap formation.[2], [8].

II. METHODOLOGY

2.1 Microbial choice

An anaerobic microbe was selected for this investigation. Its morphology confirms its ability to produce bioacids and biogases with a higher production of the later. Desulfovibrio having an excellent transport mechanism, tolerable pH range and extremely low decay rate in subsurface conditions proves the suitable microbe for this study. The biogenic gas produced was assumed to be Carbon dioxide (CO_2) after microbial utilization of the residual hydrocarbon.

2.2 Biogenic gas concentration and diffusion account.

Assuming that the rate at which microbes act on the oil is = microbial injection rate
and
Microbial injection rate = biogenic gas production rate (1)

We can say that the governing statement above automatically tends to neglect microbial retention time.
We Recall that the volume of biogenic gases produced = gas generated in pore volume of the reservoir, PV. (2)
Where

$$PV = Ah\,\phi(1-S_{or}) \qquad (3)$$

A = area of the reservoir (ft^2)
H is the height of the reservoir (ft)
$\phi$is the average porosity of the heterogeneous reservoir
The rate at which these biogenic gases are formed is given as;

$$\frac{\text{volume of produced biogenic gases}}{\text{microbial retention time}} = \frac{V_{bg}}{\vartheta} = \frac{Ah\,\phi(1-Sor)}{\vartheta} \qquad (4)$$

But recalling (1), we have
Biogenic gas production rate= $Ah\,\phi(1-Sor)$ (5)

Consider the horizontal reservoir below undergoing microbial injection for Improved oil recovery with no flow boundary condition and rectangular geometry with a microbial injection rate of 500bbl/day (microbe- water mixture).

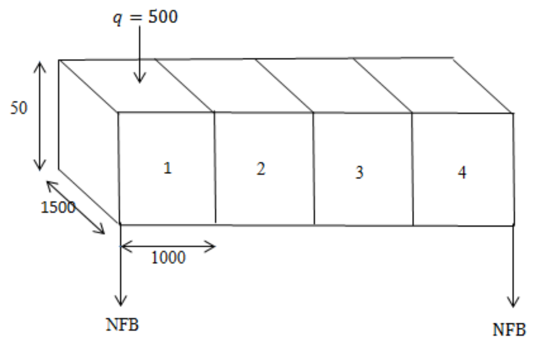

Fig.1 schematic of discretized reservoir undergoing microbial injection

Assuming
Recalling the gas flow equation in 1D

$$\frac{\partial}{\partial x}\left[\frac{AK}{\mu_g B_g}\frac{\partial C}{\partial x}\right]\Delta x + q_g + q_w R_{sw} + q_o R_{so} = \frac{V_b \phi C_t}{\alpha_c}\frac{\partial C}{\partial t} \qquad (6)$$

Assuming that the biogases produced is not soluble in the residual oil and water, we have;

$$\frac{\partial}{\partial x}\left[\beta\frac{AK}{\mu_g B_g}\frac{\partial C}{\partial x}\right]\Delta x + q_g = \frac{V_b \phi C_t}{\alpha_c}\frac{\partial C}{\partial t} \qquad (7)$$

Recalling Fick's law and replacing the transmissibility coefficient with diffusivity coefficient. Writing the above in a 2nd order derivative, we have

$$\frac{\partial^2 C}{\partial x^2}\left[-D_g\frac{AK}{\mu_g B_g}\right]\Delta x + q_g = \frac{V_b \phi C_t}{\alpha_c}\frac{\partial C}{\partial t} \qquad (8)$$

For a second order derivative, the equivalent finite difference notation for the LHS in terms of concentration is given as

$$\frac{\partial^2 C}{\partial x^2} = \frac{C_{i-1}^t - 2C_i^t + C_{i+1}^t}{\Delta x^2} \qquad (9)$$

For the RHS, change in concentration is with respect to time, the equivalent finite difference approximation is given as

$$\frac{\partial C}{\partial t} = \frac{C_i^{t+1} - C_i^t}{\Delta t} \qquad (10)$$

(8) can be written as

$$\frac{C_{i-1}^t - 2C_i^t + C_{i+1}^t}{\Delta x^2}\left[-D_g\frac{AK}{\mu_g B_g}\right]\Delta x + q_g = \frac{V_b \phi C_t}{\alpha_c}\frac{C_i^{t+1} - C_i^t}{\Delta t} \qquad (11)$$

Rearranging the above we have

$$C_{i-1}^t - 2C_i^t + C_{i+1}^t\left[-D_g\frac{A\,K}{\mu_g B_g \Delta x}\right] + q_g = \frac{V_b \phi C_t}{\alpha_c \Delta t}(C_i^{t+1} - C_i^t) \qquad (12)$$

Considering the heterogeneous reservoir system with varying permeability values shown below, we recall the method of averaging for permeability.

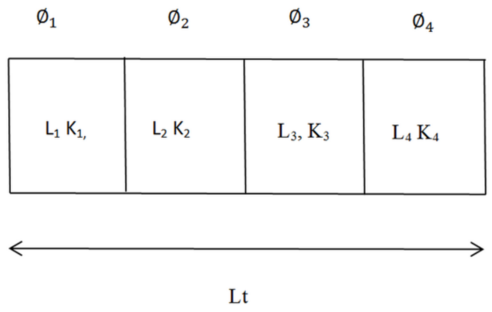

Fig 2. A rectangular heterogeneous reservoir with varying K values

$$K_{avg} = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n}\frac{L_i}{K_i}} \qquad (13)$$

(12) now becomes

$$C_{i-1}^t - 2C_i^t + C_{i+1}^t - \left(D_g\frac{A\,K_{avg}}{\mu_g B_g \Delta x}\right) + q_g = \frac{V_b \phi C_t}{\alpha_c \Delta t}(C_i^{t+1} - C_i^t) \qquad (14)$$

The diffusion of the biogenic gases produced by the microbe will be accounted for using the biogas concentration profile across the heterogeneous reservoir at various positions i and time t.

Setting $\left[-D_g\frac{A\,K_{avg}}{\mu_g B_g \Delta x}\right]$ as the diffusive flux, J' and neglecting the negative sign, we have;

$$C_{i-1}^t - 2C_i^t + C_{i+1}^t[J'] + q_g = \frac{V_b \phi C_t}{\alpha_c \Delta t}(C_i^{t+1} - C_i^t) \qquad (15)$$

Rearranging the above

$$[(J')C_{i-1}^t - 2(J')C_i^t + (J')C_{i+1}^t] + q_g = \frac{V_b \phi C_t}{\alpha_c \Delta t}(C_i^{t+1} - C_i^t) \qquad (16)$$

Accounting for biogas concentration at various reservoir positions, we multiply through by $\frac{\alpha_c \Delta t}{V_b \phi C_t}$

$$\frac{\alpha_c \Delta t}{V_b \phi C_t}[(J')C_{i-1}^t - 2(J')C_i^t + (J')C_{i+1}^t] + \frac{\alpha_c \Delta t}{V_b \phi C_t} q_g = C_i^{t+1} - C_i^t \qquad (17)$$

Setting transient tern as Z, we obtain

$$Z[(J')C_{i-1}^t - 2(J')C_i^t + (J')C_{i+1}^t] + Zq_g = C_i^{t+1} - C_i^t \qquad (18)$$

The biogenic gas prediction equation in terms of concentration with respect to position at any given time is thus

$$C_i^{t+1} = C_i^t + Z[(J')C_{i-1}^t - 2(J')C_i^t + (J')C_{i+1}^t] + Zq_g \quad (19)$$

Assumptions

- Mass transfer occurs only by diffusion.
- Negligible gas influx, ie no flow boundary condition
- Gas composition is homogenous, only CO_2 produced.
- Diffusion occurs predominantly in the horizontal direction
- Metabolite production mostly biogenic gases.
- Isothermal system as reservoir fluctuations in temperature is regarded minimal.
- Negligible capillary action.
- No break in injection rates of microbes
- Microbial decay not considered.
- No indigenous microbe present.
- Chemotaxis not considered.
- No substrate and metabolite adsorption on the pore walls, so Langmuir
- 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

Table 1.Reservoir and microbial parameters for biogenic gas concentration analysis.

Parameters	Value
Produced biogenic gas diffusion coeff, D_{bg}	1.05×10^{-6} ft^2/day
K_1 K_2 K_3 K_4	150, 200, 180, 129 (mD)
$\Phi_1, \Phi_2, \Phi_3, \Phi_4$	20, 36, 30, 16
Initial gas concentration, C_{gi}	100lb/ft^3
Microbial injection rate q_g	500bpd
Reservoir thickness Δy	50 ft
Reservoir grid length Δx	1000ft
Reservoir breadth Δz	1500ft
Reservoir length	4000ft
Time increment, Δt	10days
Volume conversion factor, α_c	5.615
Total compressibility, C_t	3.0×10^{-6}
Gas formation volume factor, B_g	0.000512scf
Gas viscosity, μ_g	0.017cp

Assuming that microbial injection rate = rate at which microbes act on the oil= biogenic gas production rateCalculating constants (diffusivity component and transient term)

$$J' = \left[D_g \frac{AK_{avg}}{\mu_g B_g \Delta x}\right] = 9.23$$

$$Z = \frac{\alpha_c \Delta t}{V_b \phi C_t} = 0.959$$

Recalling (19),

$$C_i^{t+1} = C_i^t + Z\{[J']C_{i-1}^t - 2[J']C_i^t + [J']C_{i+1}^t\} + Zq_g \quad (20)$$

The concentration profile of the diffusing biogenic gas is then predicted using the above and applying the following boundary conditions.

$C_1 = C_o$, for all time steps.

$C_4 = C_5$, for all time steps.

No net or bulk influx of biogenic gases at the boundaries of the reservoir.

The table below shows the concentration of the biogas across the reservoir.

Table 2.Deduced concentration values of Produced biogenic gas across the heterogeneous reservoir for various time steps.

Grid blocks (ft)	1	2	3	4
C_i^{10} (lb/ft^3)	580	524	476	433
C_i^{20} (lb/ft^3)	585.05	535.57	490.66	484
C_i^{30} (lb/ft^3)	591.41	545.24	532.41	526.86
C_i^{40} (lb/ft^3)	595.07	579.40	569.10	564.24

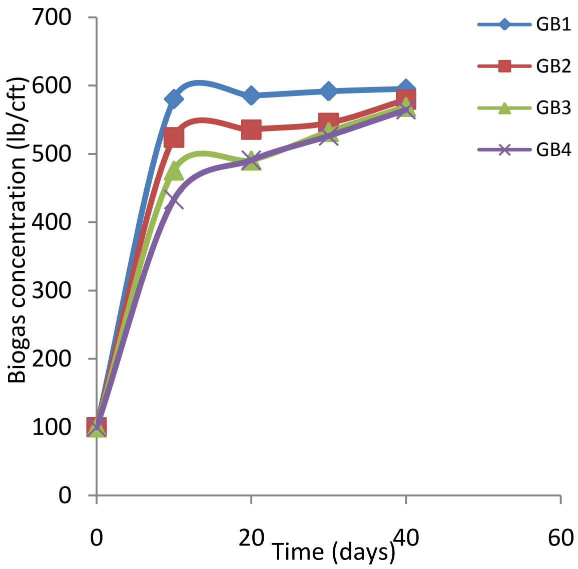

Fig 3. Plot of CO_2 concentration against time in individual reservoir grids

Fig 3 shows the increasing concentration of biogenic gases in each discrete point of the reservoir at different periods during the microbial action. Initial gas concentration in the reservoir was recorded to be 100lb/ft^3, but was observed to increase to certain levels during the breaking down process of the residual crude by the microbes. The trend observed in virtually all the grids shows that biogas distribution across the heterogeneous reservoir was tending towards the same value at a higher time step of 40 days. For grid block 4, which is farther away from the gas production point (injector), its trend with time shows a continuous increment in gas concentration and will only attain a value equal those closer to the injector only by continuous biogas diffusion phenomenon.

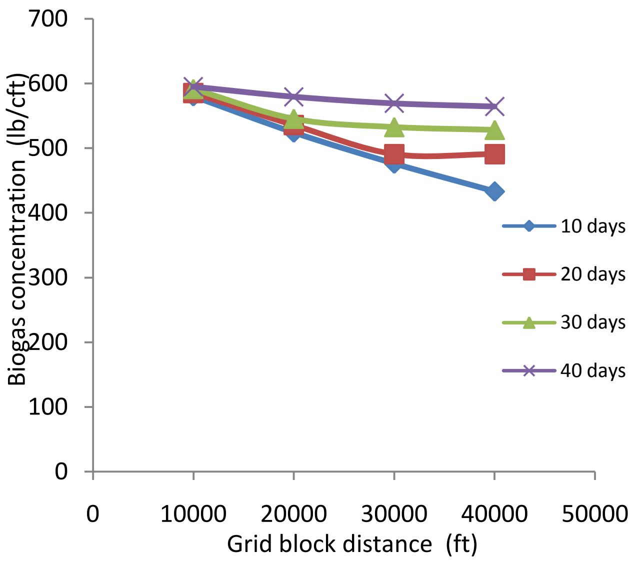

Fig 4. Biogas concentration profile across the horizontal reservoir

It is established from the diffusion laws that whenever equilibrium is reached, diffusion stops [5], [9]. This statement is evident in Fig 4, showing the concentration profile of the diffusing biogenic gas for various reservoir positions of investigation at different time. The concentration profiles of Biogenic gases can only be ascertained if there is transport of the gaseous phase (diffusion) through the porous media. The linear and systematic orderly patterns observed in the concentration profile across the reservoir are traceable to the assumption that the produced biogenic gases are insoluble in the oil. This implies that since these gases do not go into solution with the oil to cause viscosity reduction, these produced biogenic gases continuously form a strong gas cap layer that will re-pressurize the reservoir to enhance oil flow. Consideration of gas solubility in oil will cause a distortion in the gas concentration profile across the reservoir. Another explanation to the regular concentration profile seen above is the adaptation of the method of averaging for permeability and porosity. For the horizontal heterogeneous reservoir of varying rock properties, it is expected of the profile to take an irregular pattern [8].

IV. CONCLUSION

Biogenic gases produced in-situ is a major contributory factor in the whole microbial recovery process. The above figures have revealed that the concentration of the biogenic gas across the reservoir tends to be evenly distributed across the reservoir through the diffusion process. Since the gases do not go into solution with the residual oil in the reservoir, it should be, concluded that recovery mechanism of the microbially produced biogenic gases is by reservoir re- pressurize by gas cap formation. It is therefore recommended that further study and investigation should be conducted to ascertain relationships for heterogeneous biogenic gas compositions and gases solubility so as to account for both viscosity reduction of the heavy crude and gas cap formation.

V. ACKNOWLEDGEMENTS

The authors will like to acknowledge the countless relentless efforts ofEzeagala Anthony and Pepple Daniel Dasigha in making this research work possible.

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