ELSEVIER

Journal of Petroleum Science and Engineering 15 (1996) 309–320

JOURNAL OF PETROLEUM SCIENCE & ENGINEERING

Modelling and laboratory investigation of microbial enhanced oil recovery

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Received 1 February 1995; accepted 3 May 1995

Abstract

A one-dimensional model was developed to simulate the process of enhanced oil recovery by microorganisms. The model involves five components (oil, water, bacteria, nutrient and metabolites), with adsorption, diffusion, chemotaxis, growth and decay of bacteria, nutrient consumption, permeability damage and porosity reduction effects. Experiments were conducted to identify the parameters affecting the transport and growth of three bacterial strains: *Streptococcus, Staphylococcus and Bacillus* in porous media. Several correlations were developed from the experimental laboratory data and were used in the simulator.

Comparison between the experimental and simulated results emphasized the validity of the developed simulator and determined its degree of accuracy (average absolute relative error = 8.323%). The simulator was used to investigate the effects of indigenous bacteria, slug size, incubation time, residual oil saturation, absolute permeability, and injection flow rate on oil recovery.

Results show that more oil can be recovered by using *Streptococcus* with molasses as a medium. Oil recovery is sensitive to variation in concentration of injected indigenous bacteria, size of bacterial culture slug, incubation time and residual oil saturation. The change of absolute permeability, or injection flow rate, has no effect on oil recovery efficiency by bacteria.

1. Introduction

Bacteria are the only microorganisms that have been proposed for enhanced oil recovery processes. They are small in size, grow exponentially and produce metabolic compounds such as gases, acids, surfactants and polymers. Bacteria also tolerate harsh environments such as: formation high water salinity, high pressure and high temperature. Bubela (1983) found that the optimum metabolic temperature and growth rate of rod-shaped bacteria increase with an increase in pressure. Moses and Springham (1982) observed that bacteria are catalytically active at high pressure. Grula et al. (1983) readily grew *clostridium* in salt concentrations up to 75 000 ppm.

The earliest realization that bacteria are beneficial to the production of oil was suggested by Beckman (1926). ZoBell (1946) presented a process for secondary oil recovery using anaerobic, sulfate-reducing bacteria in situ. Later, ZoBell (1953) used other types of bacteria to enhance oil recovery in laboratory tests.

SSDI 0920-4105(95)00044-5

In 1963, Kuznetsov et al. (1963) found that bacteria discovered in some oil reservoirs in the Soviet Union produced 2 g of CO_2 per day per ton of rock. Later, Senyukov et al. (1970) employed microorganisms to aid the recovery of oil.

Laboratory studies of specific microorganisms are conducted either for the surface production of various compounds or for the injection of cells into a reservoir for in situ production of metabolic products. Both will enhance oil recovery. Grula et al. (1985) conducted laboratory tests to isolate salt-tolerant strains of bacteria, and then conducted field tests using them. Donaldson and Grula (1985) found that some species of bacteria produce emulsifiers in salt concentrations up to 75 000 ppm. Laboratory results of Torbati et al. (1986) showed that the larger pores of Berea Sandstone cores are plugged by the bacteria, producing a reduction of permeability leading to increased oil recovery due to improved mobility ratio. Another laboratory research conducted by Bryant and Douglas (1988) presented a discussion of crude oil displacement mechanisms by microorganisms.

A review of many field applications of MEOR was presented by Bryant and Burchfield (1989). Bryant (1991) found that MEOR screening criteria fit 27% of United States oil reservoirs. Recently, MEOR field applications were presented in the Proceedings of the International Conference on MEOR edited by Donaldson (1990). Hitzman (1987) recently published a review of MEOR field testing.

Although several attempts have been made to describe the MEOR process, no model has yet fully incorporated all of the factors that strongly affect the mechanisms of oil displacement, growth and transport of bacteria in porous media (Jenneman et al., 1982; Jang et al., 1982; Islam, 1990; Chang et al., 1991; Sarkar, 1992).

The MEOR simulators developed by previous investigators did not incorporate the following factors :

1. Growth and transport of indigenous bacteria.
2. Nutrient consumed by indigenous bacteria.
3. Metabolites produced by indigenous bacteria.
4. Compatibility between indigenous bacteria and the injected one.
5. Calculations of fluid properties at reservoir conditions.
6. Chemotaxis.
7. Dip of the formation.
8. Capillary pressure.
9. Deposition of bacteria, nutrients and metabolites due to sedimentation and straining in the pores.

The need for a model that incorporates most of the above factors with close coordination between laboratory mechanistic studies and oil displacement experiments under controlled conditions are necessary for designing an optimal MEOR project. An accurate simulator for MEOR can best be developed by using an integrated program of acquisition of laboratory data with feedback from a simulation model.

In this study, an attempt has been made to investigate the mechanisms of transport of oil in-situ MEOR processes. A mathematical model and a numerical simulator for MEOR processes are presented. The developed simulator incorporates the effects of indigenous bacteria and chemotaxis, which were not considered in the previous MEOR simulators. Experiments were conducted on growth and decay of bacteria, production of metabolic compounds, adsorption of bacterial cells and metabolites on sand grains, interfacial tension between crude oil and bacterial cultures, rheological characteristics of oleic and aqueous phases and displacement of oil by bacterial cultures. Several correlations were developed for the simulator computations. Displacement results were used to check the validity of the simulator and to determine its degree of accuracy.

2. Experimental work

Application of the developed simulator to MEOR processes requires first the determination of its degree of accuracy. This can be obtained by comparing the simulator's results with the experimental laboratory data.

The experimental work starts with the isolation of bacterial strains, identification of their metabolites, and determination of the nutrient compositions. Three bacterial strains: *Streptococcus* (O_{6a}), *Staphylococcus* (O_9) and *Bacillus* (O_{12}) were isolated from Saudi crude oils and formation waters. The appropriate nutrients for these bacteria are glucose and mo-

Table 1
Laboratory tests

Test	Bacterial culture no.
1. Production rates of metabolites	1, 2, 3, 4
2. Growth and decay rates	1, 2, 3, 4
3. Adsorption of bacterial cells and metabolites on sand grains	1, 2, 3, 4
4. Interfacial tension between the crude oil and bacterial cultures	1, 2, 3, 4, 5, 6
5. Rheological behavior	1, 2, 3, 4, 5, 6
6. Displacement tests	1, 2, 3, 4, 5, 6

lasses. The bacterial cultures used in the experiments are the following :

(1) Strain-O_{12} in glucose, (2) strain-O_{12} in molasses, (3) strain-O_9 in molasses, (4) strain-O_{6a} in molasses, (5) indigenous bacteria with glucose, and (6) indigenous bacteria with molasses.

The laboratory experiments for the six bacterial strains are given in Table 1. The porous media employed in the experiments consisted of unconsolidated sand (250 and 500 mesh-size). The displacement runs were conducted in a linear model.

3. Mathematical formulation

The model variables and their relation to phases and components are given in Table 2. The composition variables, the three saturation variables and the pressure represent the thirteen model variables for which thirteen independent relations were formulated as follows.

Five continuity equations representing the mass conservation of the bacteria, nutrient, metabolites, oil and water were developed. These equations are :

Table 2
The mathematical model variables

Component	Phase		
	Aqueous	Oleic	Adsorbed
Water	C_{ww}	–	–
Oil	–	C_{oo}	–
Bacteria	C_{bw}	C_{bo}	σ_b
Nutrient	C	–	–
Metabolites	C	C	σ_m
Saturation	θ_w	θ_o	θ_r
Pressure	–	P	–

1. Bacteria

$$\phi\frac{\partial}{\partial t}(\theta_w\rho_w C_{bw}+\theta_o\rho_o C_{bo}+\sigma_b\rho_r\theta_r)-\phi(u-k)(\theta_w\rho_w C_{bw}+\theta_o\rho_o C_{bo}+\sigma_b\rho_r\theta_r)=\phi\frac{\partial}{\partial x}\left[\theta_w\rho_w D_{bw}\frac{\partial C_{bw}}{\partial x}+\theta_o\rho_o D_{bo}\frac{\partial C_{bo}}{\partial x}\right]-\phi k_m\frac{\partial}{\partial x}\left[\frac{\partial C_n}{\partial x}\frac{1}{C_n}(\theta_w\rho_w C_{bw}+\theta_o\rho_o C_{bo})\right]+\frac{\partial}{\partial x}\left[\frac{\partial p}{\partial x}(\lambda_w\rho_w C_{bw}+\lambda_o\rho_o C_{bo})\right]+\frac{q_w\rho_w C_{bw}+q_o\rho_o C_{bo}}{V_p} \quad (1)$$

2. Nutrient

$$\phi\frac{\partial}{\partial t}(\theta_w\rho_w C_n)=\phi\frac{\partial}{\partial x}\left[\theta_w\rho_w D_n\frac{\partial C_n}{\partial x}\right]-\phi N_{cn}+\frac{\partial}{\partial x}\left[\frac{\partial p}{\partial x}(C_n\rho_w\lambda_w)\right]+\frac{q_w\rho_w C_n}{V_p} \quad (2)$$

3. Metabolite

$$\phi\frac{\partial}{\partial t}(\theta_w\rho_w C_{mw}+\theta_o\rho_o C_{mo}+\sigma_m\rho_r\theta_r)=\phi\frac{\partial}{\partial x}\left[\theta_w\rho_w D_{mw}\frac{\partial C_{mw}}{\partial x}+\theta_o\rho_o D_{mo}\frac{\partial C_{mo}}{\partial x}\right]+\frac{\partial}{\partial x}\left[\frac{\partial p}{\partial x}(\lambda_w\rho_w C_{mw}+\lambda_o\rho_o C_{mo})\right]+\frac{(q_w\rho_w C_{mw}+q_o\rho_o C_{mo})}{V_p} \quad (3)$$

4. Oil

$$\phi\frac{\partial}{\partial t}(\theta_o\rho_o C_{oo})=\frac{\partial}{\partial x}\left[\frac{\partial p}{\partial x}(\lambda_o\rho_o C_{oo})\right]+\frac{q_o\rho_o C_{oo}}{V_p} \quad (4)$$

5. Water

$$\phi\frac{\partial}{\partial t}(\theta_w\rho_w C_{ww}) = \frac{\partial}{\partial x}\left[\frac{\partial p}{\partial x}(\lambda_w\rho_w C_{ww})\right] + \frac{q_w\rho_w C_{ww}}{V_p} \quad (5)$$

3.1. Restriction relations

There are four restrictions:

$$\theta_w + \theta_o + \theta_r = 1.0 \quad (6)$$

$$C_{ww} + C_{bw} + C_{mw} + C_n = 1.0 \quad (7)$$

$$C_{oo} + C_{bo} + C_{mo} = 1.0 \quad (8)$$

$$\sigma_b + \sigma_m = 1.0 \quad (9)$$

The adsorption of bacteria on the grain particles is (Jenneman et al., 1982):

$$\sigma_b = \frac{Ac_{bw}}{1 + bC_{bw}} \quad (10)$$

The metabolites produced by injected and indigenous bacteria are (Kowalski et al., 1991):

$$C_{mw} = (a_1 + b_1 t)C_{bw} \quad (11)$$

$$C_{mo} = (a_2 + b_2 t)C_{bo} \quad (12)$$

where: a_1, b_1, a_2 and b_2 are experimentally determined.

The adsorbed phase saturation is given by:

$$\theta_r = f(C_{bw}, C_{ww}, t, V_p) \quad (13)$$

The above function is experimentally determined.

4. Development of correlations

Laboratory experiments were conducted to derive correlations for production rates of metabolites, growth and decay rates, adsorption, interfacial tension and rheological characteristics. The displacement results were used to check the validity of the developed mathematical model and to determine its degree of accuracy.

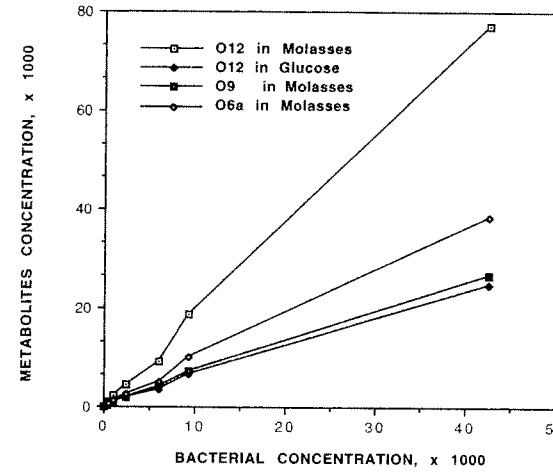

Fig. 1. Variation of metabolites concentration with bacterial concentration.

4.1. Production rates of metabolites

Figs. 1 and 2 show the concentrations of the produced metabolites versus bacterial concentration and time. The data of both curves were used to derive the following relations:

1. For bacterial strain-O_{12} in molasses:

$$C_{mw} = (1.81 + 4.1 \cdot 10^{-5} t)C_{bw} \quad (14)$$

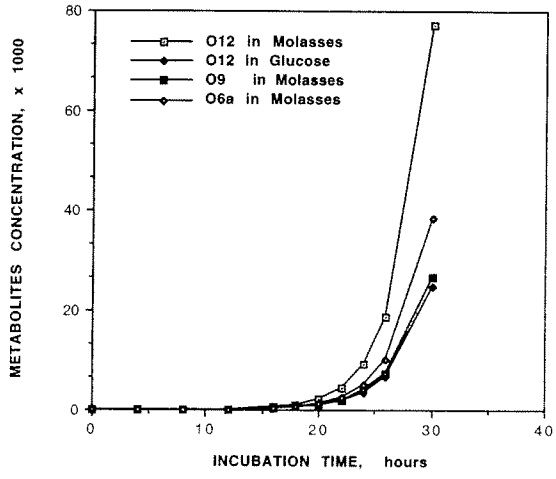

Fig. 2. Variation of metabolites concentration with time.

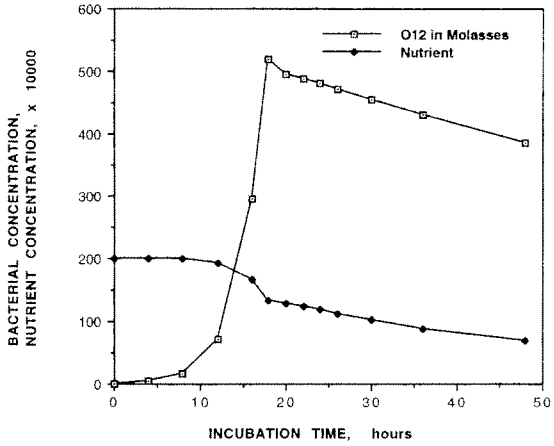

Fig. 3. Growth and decay curves for bacterial strain-O_{12} in molasses.

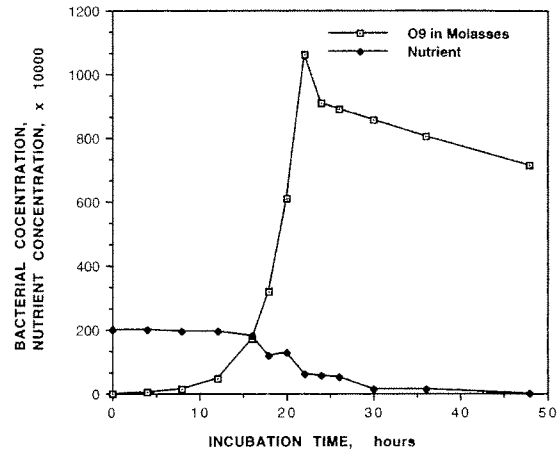

Fig. 5. Growth and decay curves for bacterial strain-O_9 in molasses.

2. For bacterial strain-O_{12} in glucose:

$$C_{mw} = (1.732 + 3.86 \cdot 10^{-5} t) C_{bw} \quad (15)$$

3. For bacterial strain-O_9 in molasses:

$$C_{mw} = (1.762 + 3.85 \cdot 10^{-5} t) C_{bw} \quad (16)$$

4. For bacterial strain-O_{6a} in molasses:

$$C_{mw} = (1.795 + 3.97 \cdot 10^{-5} t) C_{bw} \quad (17)$$

Bacterial strain-O_{12} was isolated from the used crude oil; therefore, Eqs. 14 and 15 can be used to predict the metabolites production by the indigenous bacteria using the nutrients molasses and glucose, respectively.

4.2. Growth and decay rates

Experimental results of the four bacterial cultures are shown in Figs. 3–6. The values of growth and decay rates and yield coefficients were calculated from Figs. 3–6 and are listed in Table 3.

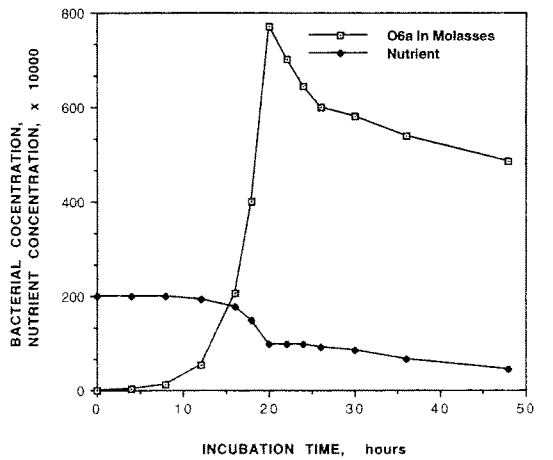

Fig. 4. Growth and decay curves for bacterial strain-O_{6a} in molasses.

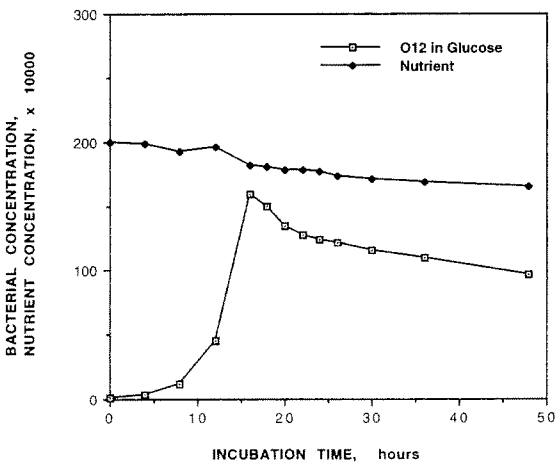

Fig. 6. Growth and decay curves for bacterial strain-O_{12} in glucose.

Table 3
Growth and decay rates, and yield coefficients of bacterial strains

Bacterial strain	u, s^{-1}	k, s^{-1}	Y, ratio
Strain-O_{12} in molasses	9.87×10^{-5}	2.55×10^{-6}	0.5
Strain-O_{6a} in molasses	8.82×10^{-5}	2.98×10^{-6}	0.5
Strain-O_9 in molasses	8.91×10^{-5}	2.81×10^{-6}	0.51
Strain-O_{12} in glucose	9.23×10^{-5}	2.68×10^{-6}	0.49

4.3. Adsorption

Adsorption of bacterial cells and metabolites on sand grains are shown in Figs. 7 and 8, respectively. The correlations obtained are:

$$\sigma_b = \frac{\phi}{[1.4796 + 3455.4/t + C_{bw}]} \quad (18)$$

$$\sigma_m = \frac{\phi}{[1.4796 + 3455.4/t + C_{mw}]} \quad (19)$$

4.4. Interfacial tension

Interfacial tensions for bacterial culture/oil ratios of 1.0, 0.8 and 0.6 are shown in Figs. 9–11, respectively. The correlation obtained is:

$$\delta = \frac{A\delta_1 V_o C_{bw}}{t\mu V_{bc} C_{bo}} \quad (20)$$

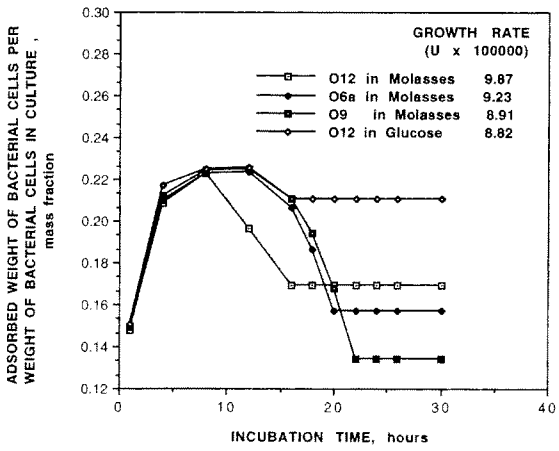

Fig. 7. Adsorption of bacterial cells on rock surface.

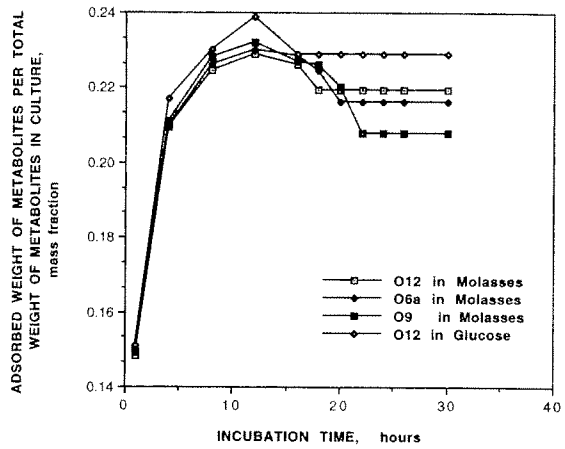

Fig. 8. Adsorption of metabolites on rock surface.

where the constant A characterizes the bacterial culture and is equal to 0.891, 1.89, 0.25, 0.351, 0.0905 and 0.437 for strain-O_{12} in molasses, strain-O_{12} in glucose, strain-O_9 in molasses, strain-O_{6a} in molasses, indigenous bacteria with molasses, and indigenous bacteria with glucose, respectively.

4.5. Rheological properties

The rheological properties measured after incubation times of 25 and 50 hours are given in Figs. 12

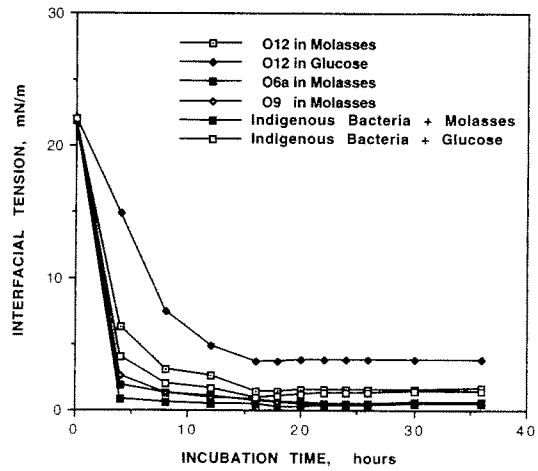

Fig. 9. Interfacial tension of bacterial cultures for bacterial culture/oil ratio of 1.

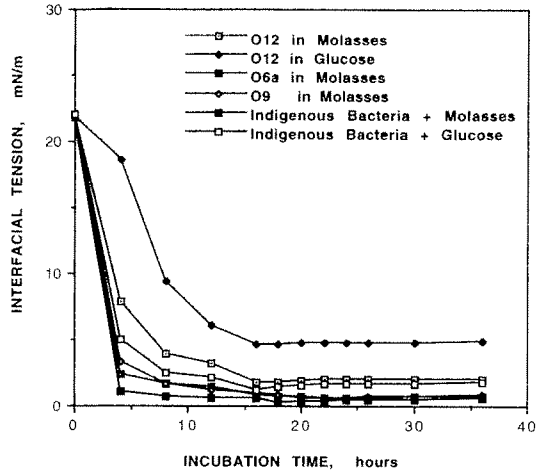

Fig. 10. Interfacial tension of bacterial cultures for bacterial culture/oil ratio of 0.8.

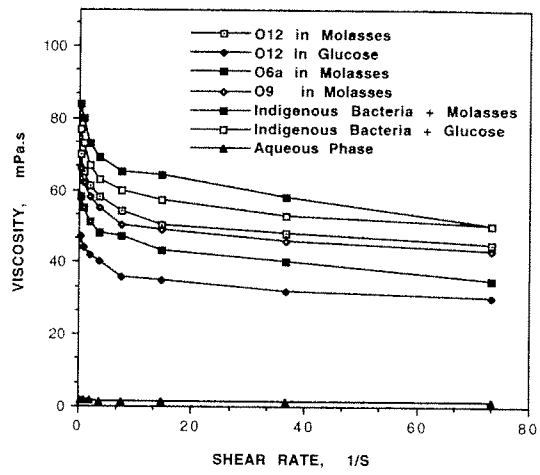

Fig. 12. Rheological properties of oleic and aqueous phases after 25 hours of incubation time.

and 13, respectively. The viscosities of the oleic and aqueous phases are:

$$\mu_o = 0.054 C_{oo} \gamma^{C_{oo}-1.0} \quad (21)$$

$$\mu_w = 0.0012 C_n \gamma^{C_{mw}} \quad (22)$$

5. Displacement results

Displacement results include: (1) pressure measurements during incubation periods, and (2) oil recovery measurements. During the incubation period, the pressure builds up due to gas generation. The results are plotted in Fig. 14. They show that the pressure increases with increasing time and then slightly decreases with increasing time for all the bacterial types studied. The increase in pressure is the result of bacterial growth and leads to production of carbon dioxide, nitrogen, hydrogen and other gases. The reasons for a gradual decline of buildup pressure during the last 5 hours of incubation are not clear. One possibility is that the bacteria have com-

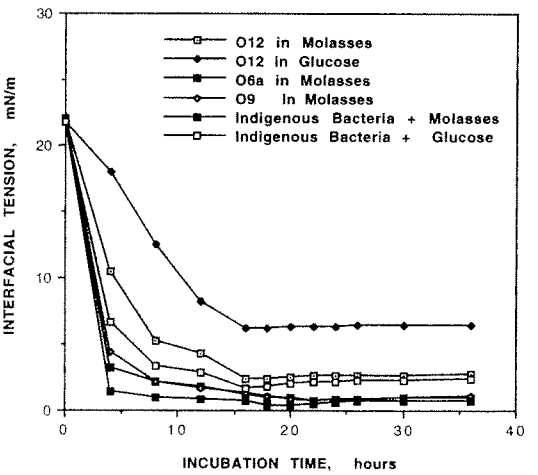

Fig. 11. Interfacial tension of bacterial cultures for bacterial culture/oil ratio of 0.6.

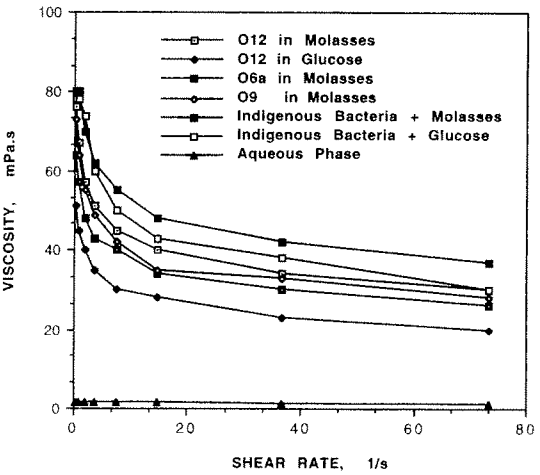

Fig. 13. Rheological properties of aqueous and oleic phases after 50 hours of incubation time.

pletely consumed the nutrient, and then consumed the nitrogen that existed in the generated gases. This process is known as nitrogen fixation and occurs after other more easily assimilable sources of carbon or nitrogen have been exhausted (Sarkar, 1992). The displacement results will be discussed together with the effects of bacterial type and nutrient type on oil recovery.

5.1. Effect of bacterial type

The effect of bacterial type on oil recovery was investigated using three bacterial cultures in molasses: (1) strain-O_{12}, (2) strain-O_{6a}, and (3) strain-O_9. Production history and cumulative oil recovery of the three runs are plotted in Fig. 15, which shows that the oil bank is immediately formed after injection of 0.2 pore volume. Production gradually decreases with increasing injected pore volume, whereas the cumulative oil recovery increases with increasing injected pore volume. The bacterial strain-O_{12} in molasses gives the least oil recovery, whereas the strain-O_{6a} in molasses yields the greatest oil recovery. These results can best be interpreted by interfacial tension results shown in Figs. 9–11. Strain-O_{12} gives rise to the largest value of interfacial tension compared with those obtained using strain-O_{6a} and strain-O_9. This, however, is not a general rule. In some cases, the compatibility between the injected bacteria and indigenous ones enhance the oil recovery (Research Council of Oil, 1985). Therefore, for field applications of MEOR processes, the compatibility between the injected and indigenous bacteria should be checked to determine if they will enhance the oil recovery or not. In the case of negative results, it is advisable to use a different type of bacterial strain from that existing in the crude oil, or only using nutrient such as molasses.

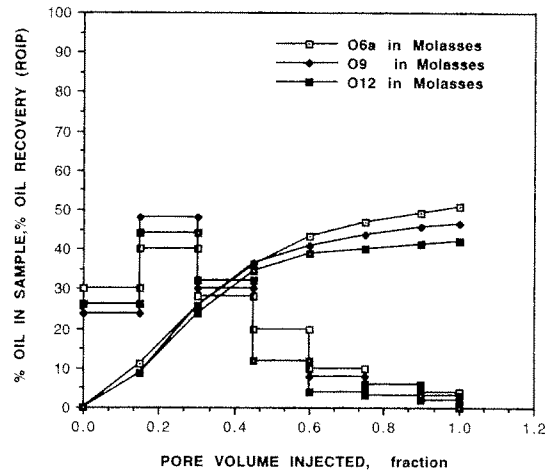

Fig. 15. Effect on bacterial type on production history and oil recovery.

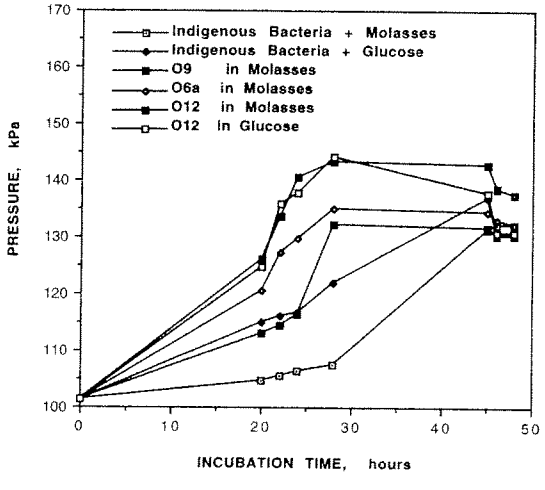

Fig. 14. Buildup pressures during incubation time.

5.2. Effect of nutrient type

The effect of nutrient type on oil recovery was investigated for the bacterial culture and indigenous bacteria. Results obtained using bacterial cultures and indigenous bacteria are shown in Figs. 16 and 17, respectively. Fig. 16 shows the production history and cumulative oil recovery versus the volume of injected water. The oil recovery using the bacterial strain-O_{12} in molasses was higher than that of using the same strain in glucose. Referring to Figs. 9–11, the values of interfacial tensions between the crude oil and strain-O_{12} in molasses are lower than those of strain-O_{12} in glucose. The nutrient molasses is a richer medium than glucose, because it contains higher amounts of sucrose and carbohydrates.

Fig. 17 shows the production history and cumula-

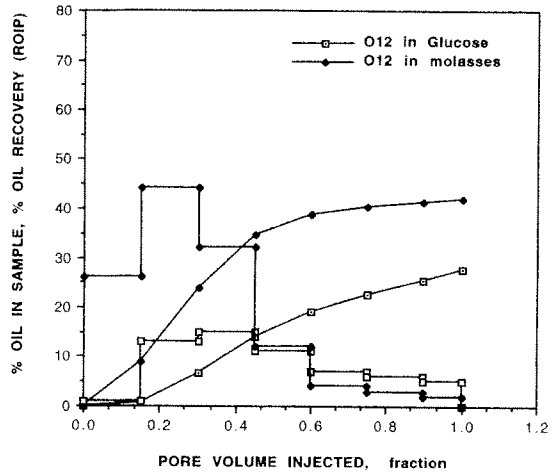

Fig. 16. Effect of nutrient type on production history and oil recovery injected bacteria.

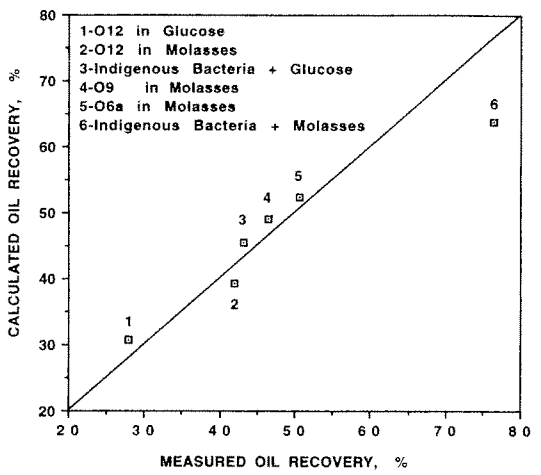

Fig. 18. Cross-plot for the measured oil recovery and calculated one.

tive oil recovery for activated indigenous bacteria using molasses and glucose. It is clear that the molasses gives higher oil recovery than glucose.

6. Verification of the validity of the simulator

The validity of the simulator was checked by comparing the oil recovery calculated from the equations with those obtained from the experimental data. The results are plotted in Fig. 18. A 45° straight line is drawn on the same plot. The average absolute relative error between the measured oil recoveries and the calculated ones was found to be 8.323%.

7. Factors affecting oil recovery

The simulator was used to investigate the factors affecting the oil recovery such as the indigenous-bacteria/injected-bacteria ratio, slug size of nutrient,

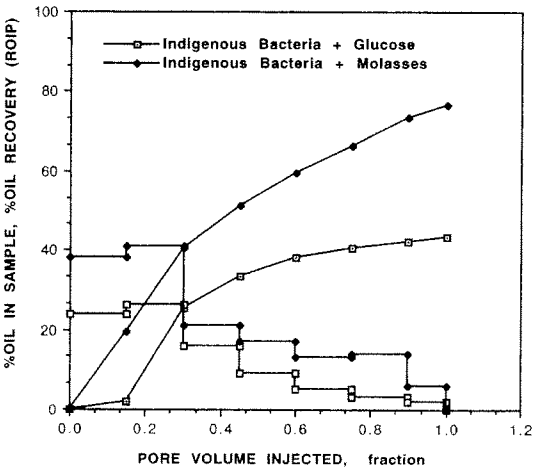

Fig. 17. Effect of nutrient type on production history and oil recovery (indigenous bacteria).

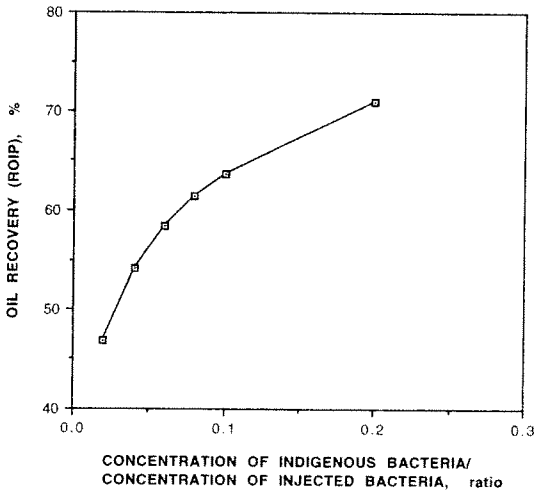

Fig. 19. Effect of the ratio of concentration of indigenous bacteria to the concentration of injected bacteria on oil recovery.

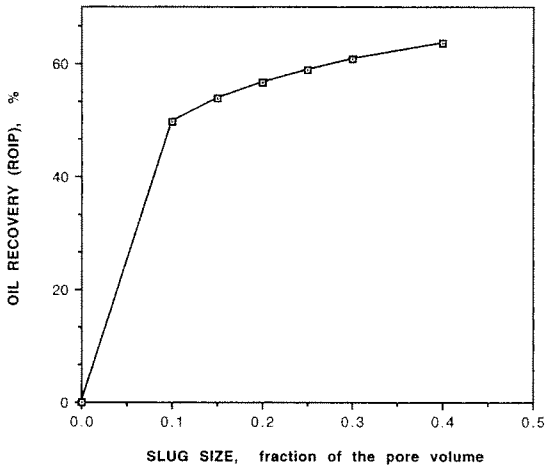

Fig. 20. Effect of slug size on oil recovery.

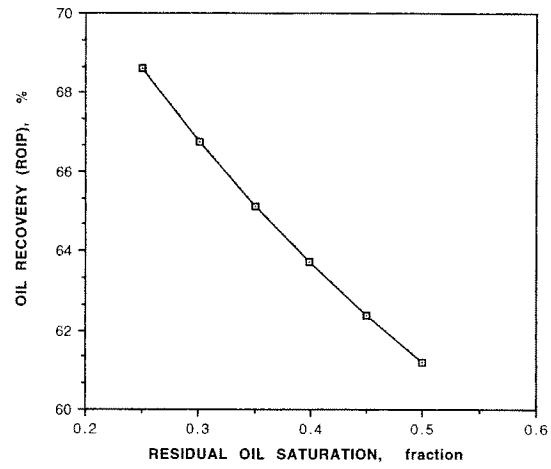

Fig. 22. Effect of residual oil saturation on oil recovery.

incubation time, residual oil saturation, permeability and injected flow rate.

7.1. Effect of indigenous bacteria / injected bacteria ratio (R_{cbow})

The calculated oil recovery is plotted versus values of (R_{cbow}) in Fig. 19, which shows that oil recovery increases with increasing value of (R_{cbow}). This ensures that the role of indigenous bacteria in recovering more oil can not be ignored.

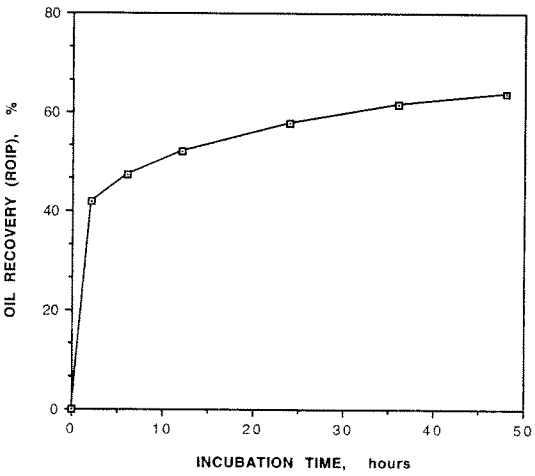

Fig. 21. Effect of incubation time on oil recovery.

7.2. Effect of slug size

Fig. 20 shows the effect of slug size on oil recovery. Oil recovery sharply increases as the slug size increases from 0.1 to 0.3, and then slightly increases by increasing slug size from 0.3 to 0.4. It is important to note that a 0.4 slug size was used in most field applications of MEOR projects (Bryant and Burchfield, 1989; Bryant, 1991; Donaldson, 1990; Hitzman, 1987).

7.3. Effect of incubation time

Oil recovery is plotted against incubation time in Fig. 21. The oil recovery increases with increasing incubation time. The maximum time of the incubation period was determined from the value of slug size and consumption rate of nutrient.

7.4. Effect of residual oil saturation

Residual oil saturation after waterflooding is a guide for the efficiency of MEOR process. The simulator results are plotted in Fig. 22, which shows that oil recovery is inversely proportional to the residual oil saturation. This occurs because at constant size of nutrient slug, the increase in residual oil saturation leads to reduction in the volume of displacing fluid (water) and, consequently, reduction in the sweeping efficiency.

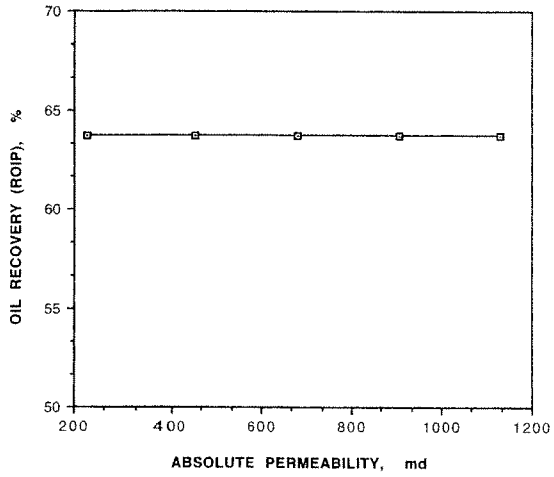

Fig. 23. Effect of absolute permeability on oil recovery.

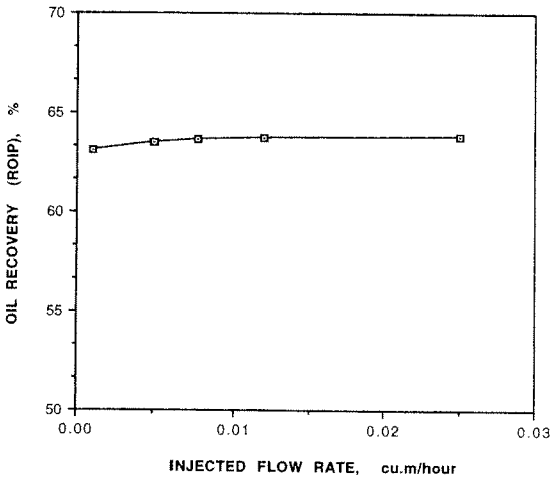

Fig. 24. Effect of injected flow rate on oil recovery.

7.5. *Effects of permeability and injected flow rate*

Figs. 23 and 24 show the effects of absolute permeability and injected flow rate on oil recovery, respectively. Both figures show that oil recovery is not affected by changing either the absolute permeability or injection flow rate. These results were also obtained from the experimental work.

8. Conclusions

1. A one-dimensional, three-phase, multiple-component simulator that includes all required mechanisms and transport phenomena of microbial systems in porous media was developed. The average absolute relative error between simulator results and experimental data was 8.323%.
2. Laboratory experiments were successful in determining the input parameters of the microbial transport system for the developed simulator.
3. Oil recovery is strongly affected by changing the indigenous-bacteria/injected-bacteria ratio, incubation time, slug size, and residual oil saturation. The change in absolute permeability, or injection flow rate, does not affect the oil recovery.

9. Nomenclature

a = constant in Eq. 10
a_1 = constant in Eq. 11
A = constant in Eq. 20
b = constant in Eq. 10
b_1 = constant in Eq. 12
C = concentration, mass fraction
D = diffusion coefficient, m^2/s
f = a function of
k_m = chemotaxis coefficient, m^2/s
q = flow rate, m^3/s
p = pressure, Pa
t = time, s
v_p = pore volume, m^3
x = distance, m
y = yield coefficient, ratio

Subscripts

bo = bacteria in oleic phase
bw = bacteria in aqueous phase
cn = consumption of nutrient
mo = metabolites in oleic phase
mw = metabolites in aqueous phase
n = nutrient
o = oleic phase
oo = oil in oleic phase
r = adsorbed phase
w = aqueous phase

Greek letters

γ = mobility ratio
ϕ = porosity
ρ = density, g/ml
μ = viscosity, Pa.s
θ = saturation

σ = weight of deposition/weight of porous medium

δ = interfacial tension, Mn/m

Acknowledgements

The authors are grateful to Professors George V. Chilingarian and Erle Donaldson for helpful suggestions.

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