MICROBIAL ENHANCED OIL RECOVERY (MEOR) USING BIOSURFACTANT SLUG

BY

HARRY HUMPHREY

G2014/MENG/PNG/FT/1001

SUBMITTED TO

THE DEPARTMENT OF PETROLEUM AND GAS ENGINEERING, FACULTY OF PROCESS AND ENERGY SYSTEM ENGINEERING, COLLEGE OF GRADUATE STUDIES, UNIVERSITY OF PORT HARCOURT IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF MASTERS OF ENGINEERING DEGREE IN PETROLEUM ENGINEERING

[RESERVOIR OPTION]

JULY, 2019

DEDICATION

To my shadows; Fortress and Adora

ACKNOWLEDGEMENT

With much gratitude, I acknowledge the efforts of all those that contributed to the success of this work. Much thanks to my supervisor for his positive criticisms and the laboratory attendants of microbiology department, Uniport, for their assistance in the bacterial isolation, biosurfactant formulation and characterization.

Thanks to all those who contributed immensely to make me self-reliable.

ABSTRACT

This work is a laboratory investigation of residual oil displacement using biosurfactant slug extracted from a culture of pseudomonas species. The bacterial isolates were gotten from local sand and water samples. The effect of the biosurfactant slug on the permeability of the core samples and the oil viscosity were also studied. The results of the residual oil displacement experiment showed that 35.97% of the residual oil was recovered at zero hour biosurfactant incubation time (BIT) following a chase brine flooding.as the BIT increases, the percentage recovery (%R) increased as well, up to a maximum of 88.59% at 120 hours BIT.

The oil viscosity decreased significantly while the core permeability remained relatively unchanged. These results demonstrate that biosurfactants reduce the interfacial tension between oil and water and forms micelles, providing a physical mechanism whereby oil can be displaced by an aqueous phase.

Keywords: Biosurfactant Incubation Time (BIT), Microbial Enhanced Oil Recovery (MEOR), Biosurfactant Slug, Pseudomonas.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND Of STUDY

Oil reservoirs are conventionally explored, developed and produced in phases. The initial phase of production is the primary production phase where the natural pressure and flow characteristics of the reservoir drive the oil to surface facilities. The secondary phase utilizes several techniques to mobilize the reservoir oil towards the producing facilities. The percentage recovery (of the oil originally in place) in most cases could be about 35%. The remaining oil is held back by oil-reservoir rock characteristics and oil-water characteristics.

One of the known processes employed to recover the trapped oil in the native rock is microbial enhanced oil recovery (MEOR).

MEOR involves the use of microbes and their metabolites to enhance oil recovery.

1.2 Biosurfactants

Enhancement of oil recovery using microbes is as a result of biosurfactant production by the microbes. The biosurfactants have two major effects;

1. reduction of oil-water interfacial tension and
2. Formation of micelles.

The reduction of the interfacial tension leads to a reduction of the hydrostatic pressure required to overcome the capillary effect. The formation of micelles provides a mechanism whereby oil can be displayed by a moving aqueous phase.

1.2.1 Types of Biosurfactants

The major types of biosurfactants are glycolipids, lipoproteins and lipopeptides, phospholipids, and polymeric biosurfactants.

1.3 STATEMENT Of PROBLEM

The need for an EOR technique that has a smaller environmental footprint has increased in recent years. The common MEOR methods can lead to undesirable detrimental effects such as corrosion of wellbore, permeability reduction and the consumption of hydrocarbons by bacteria. This work, therefore, employs cell-free supernatant fluid (rhamnolipid), a biosurfactant to avoid this problem.

Lack of a comprehensive mathematical model of MEOR relating nutrient concentration to bacterial concentration can increase the uncertainty of MEOR. It is therefore pertinent to generate a mathematical equation relating these important factors that can determine the success of MEOR projects.

1.4 STUDY OBJECTIVES

This research work is aimed at examining the effects of biosurfactant slug on porous media (the extent of permeability reduction), its effect on the crude oil (viscosity reduction), and a laboratory study of the mobilization and displacement of residual oil in five different core samples by varying the soaking time[biosurfactant incubation time] using biosurfactant slug.

1.5 METHODOLOGY

The biosurfactant to be employed in the laboratory investigation will be extracted from a culture of pseudomonas species grown in a mineral salts medium supplemented with kerosene as the carbon source.

A dual transparent core barrel will be used to contain the sand pack. This will allow for visual observation of the flooding process and monitoring of the breakthrough time. In the dual-core flooding, the effluent from the first core will be used to flood the second core. The first core represents the near-wellbore region while the second core represents a distance away from the wellbore.

1.6 SCOPE Of STUDY

In this study, unconsolidated sand samples derived from the Niger Delta oil province of Nigeria were used to conduct residual oil recovery experiment. Biosurfactant (Rhamnolipid) derived from a culture of Pseudomonas sp was employed. The culture formulation and surfactant characterisation were performed at the microbiology laboratory of the department of microbiology, while the core preparation and flooding experiment were carried out at the reservoir engineering laboratory of the department of petroleum and gas engineering, University of Port Harcourt, Choba, Nigeria.

CHAPTER TWO
LITERATURE REVIEW

2.1 ENHANCED OIL RECOVERY (EOR) TECHNOLOGIES

EOR plays a progressively more crucial role in the oil industry. The efficiency of an EOR method is a measure of its ability to provide greater oil recovery than by natural depletion, at an economically attractive production rate. The efficiency depends on:

1. The reservoir characteristics
2. The nature of the displacing and displaced fluids.

Common EOR techniques are miscible and solvent injection methods, thermal methods, chemical methods, and microbial processes.

2.2 MICROBIAL PROCESSES (MEOR)

This is a fast-evolving method of oil recovery and is becoming a developed tertiary production technique. Microorganisms or their metabolites are utilized to enhance the recovery of residual oil (Banat, 1995).

The influence of microbial activity in oil reservoirs can be summarized as follows:

- The beneficial effects which include the breaking down of heavy components (viscosity reduction), release of gas (providing an additional driving force) and production of surfactants (reducing interfacial tension).
- The detrimental effects include well-bore casings corrosion (production of hydrogen sulfide), hydrocarbon consumption by bacteria. Reduction of Permeability, due to metabolic products or bacteria themselves, can lead to positive as well as negative effects, by causing secondary flow paths to becoming active.

Improvement of oil recovery through microbial activity can be achieved through several means such as reduction of oil-water interfacial tension and alteration of wettability by the bacterial presence and surfactant production, selective plugging by microorganisms and their metabolites, acid production which improves absolute permeability by dissolving the rock minerals and oil viscosity reduction by gas production or degradation of the heavier components of the hydrocarbon, (Nielsen et al., 2010).

2.2.1 Classification of MEOR

MEOR is mainly classified as surface MEOR and underground MEOR based on the mode of microbial application. For surface MEOR, biopolymer (xanthan gum), biosurfactant (Rhamnolipid), an enzyme, are produced in the surface facilities and injected into target zones in the reservoir. While, for underground MEOR, microbes and nutrients are introduced into the reservoir and allowed to grow and metabolize underground.

Depending on the source of microbes, underground MEOR can be sub-divided into indigenous MEOR and in-situ MEOR. While according to procedures of processes, underground MEOR is grouped as;

- Cyclic microbial recovery
- Wax removal and paraffin inhibition
- Microbial flooding recovery
- Selective plugging recovery

2.2.2 Cyclic Microbial Recovery

In this method, a solution of microbes and nutrients is introduced into the target reservoir. An incubation period is provided, allowing microbes to produce carbon dioxide and biosurfactants that helps to mobilize the reservoir oil.

2.2.3 Microbial Flooding Recovery

In this technique, the reservoir is initially conditioned by a water pre-flush, then a solution of microbes and nutrients is introduced and as this solution is pushed through the reservoir by chase water, the by-products of microbial activity (gases and surfactants) helps to mobilize the oil.

2.2.4 Selective Plugging Recovery

This involves the introduction of bacterial suspensions, followed by nutrients to produce biopolymers and microbes which may plug the high permeability zones in the reservoir, thereby forcing water to produce oil from previously upswept parts of the reservoir.

The microorganisms utilized in MEOR should possess the following characteristics;

- Small size, resistance to high temperatures, ability to withstand high pressure, the capability to withstand brine and seawater, anaerobic use of nutrients, and adequate biochemical construction for producing suitable amounts of MEOR chemicals.

2.2.5 Advantages of MEOR

(i) The injected bacteria and their nutrients are not expensive, easily obtained and handled in the field/ laboratory.

(ii) It is economically attractive for marginal fields.

(iii) Only slight modifications of the existing field facilities are required for the process to be implemented

2.2.6 Problems of MEOR

The common problems associated with MEOR techniques are outlined below. (Lazar, 2007):

1. Microbial plugging of the wellbore: to avoid wellbore plugging, care must be taken such as filtration before injection, avoidance of biopolymer production, and minimization of adsorption of microbes to rock surfaces through the use of ultra-micro-bacteria or dormant cell forms.
2. Deployment of all necessary constituents to the site of interest.
3. Optimization of the target in-situ metabolic activity to annul the influence of variables such as pH, salinity, temperature, and pressure for any in-situ MEOR application.
4. Selection/isolation of microbial strains, adaptable to the extreme reservoir conditions of pH, temperatures, pressure and salinity.
5. The low in-situ concentration of bacterial metabolites.

CHAPTER THREE

MATERIALS AND METHODS

This chapter presents the procedures used for the determination of the petrophysical properties of the core samples, method of bacteria isolation (pseudomonas sp) and characteristics of pseudomonas used in presumptive identification of the bacterial isolates, the procedure for the core flooding (brine pre-flush and residual oil displacement using the biosurfactant slug), the method of biosurfactant production, analysis and characterization, the brine preparation procedure and also the procedure for determining the fluid properties.

3.1 APPARATUS/MATERIALS USED

Electronic mass balance, beaker, measuring cylinder, density bottle, calliper, aluminium foil, filter paper, mesh (size 120/200), retort stand and clamp, electric pump, vacuum pump desiccator, soxhlet, oven, stopwatch, pressure gauge, common salt (NaCl), distilled water, methanol, centrifuge, sand, $MgS0_4.7H_20$, KH_2P0_4, Na_2HP0_4, KCl, NH_4N0_3.

3.2 ISOLATION OF PSEUDOMONAS SPECIES

The water and soil samples were collected and inoculated on pseudomonas isolation agar (PIA) and cetrimide agar in aseptic condition, and plates were incubated at 37^{o}C. After incubation, twenty isolates were selected. These isolates were characterized and identified by morphological and various biochemical tests by comparing with Bergey's manual of bacteriology.

Table 3.1: Summary of morphological/cultural characteristics and biochemical reactions used for identification of the bacterial isolates

Bacterial species	Morphological/cultural characteristics	Biochemical reactions
Pseudomonas	Rods, short endospores formed, motile and gram-positive, occur in pairs, colonies, creamy and translucent.	Strict aerobes, oxidation metabolism, catalase-positive, starch hydrolyzed, nitrate reduced.

3.3 BIOSURFACTANT PRODUCTION AND ANALYSIS

This section highlights the steps followed in the production of the biosurfactant slug.

1000ml mineral salts medium supplemented with kerosene (0.4%, w/v) as carbon source was employed. The composition of the medium is shown below:

Table 3.2: Composition of the medium

$MgS0_4.7H_20$	0.45g/l
KH_2P0_4	0.87g/l
Na_2HP0_4	1.28g/l
KCl	0.30g/l
NH_4N0_3	0.42g/l
pH	7.2

The medium was then, inoculated with 100ml of the 4-day old culture of pseudomonas species and incubated at 37^{o}C for seven days. The culture was sampled and centrifuged at 3000rpm for 15 minutes. The supernatant fluid (cell-free fluid) was decanted and filtered immediately through filter paper. The resultant filtrate was employed as the biosurfactant slug.

3.4 CORE PREPARATION

This section deals with the procedure followed in preparing the core sample.

(i) Fried sand samples were collected and washed to remove any carbonate present, the sand samples were dried afterwards.
(ii) Using a known weight of aluminium foil and mesh sizes of 120/200, the sand samples were wrapped into a cylindrical shape of height 5cm and 2cm diameter.
(iii) The double mesh size was used to cover the top and bottom of the core to prevent sand mobilization during flooding.
(iv) The core was saturated with methanol using a vacuum pump desiccator to remove all mineral salts present.
(v) The samples were oven-dried for 24 hours.

3.5 DETERMINATION OF CORE PROPERTIES

The method applied in determining the petrophysical properties of the core is highlighted below.

- **Porosity**

(i) Measured the weight of the dry core sample (this weight includes the weight of the foil, mesh sizes and sand).
(ii) Measured and recorded the diameter and height of the core sample with a calliper.

(iii) Subtracted twice the thickness of the mesh from the measured height and twice the thickness of the foil from the measured diameter to obtain the true height and diameter of the core samples.

(iv) Calculated the bulk volume (BV) of the core samples using

$$BV = \frac{\pi}{4} d^2 h \qquad (1)$$

(v) Saturated the core sample with brine in a vacuum pump desiccator for 30 minutes.

(vi) Measured and recorded the weight of the saturated sample.

(vii) Oven-dried the sample for 24 hours and measured the weight of the dry core samples.

(viii) Subtracted the weight of the dry samples from the weight of the saturated sample; this is equal to the weight of brine in the pore space of the core samples.

(ix) Estimated the capacity (volume) of the brine in the pore space of the sample, this approximates the pore volume of the core sample.

The volume of brine = $\frac{weight\ of\ brine\ in\ the\ pore\ space}{density\ of\ brine}$

$$\frac{weight\ of\ brine\ in\ the\ pores\ pace}{densiity\ of\ brine} = pore\ volume\ of\ core \qquad (2)$$

$$\text{Porosity} = \frac{pore\ volume}{bulk\ volume} \qquad (3)$$

PERMEABILITY

(i) Using the experimental set up for the core flooding, insert the core sample into the core holder.

(ii) With the electric pump, flush the core sample with the brine of known viscosity using a constant flow rate.

(iii) Measure the pressure differential with the gauge.

(iv) Estimate the permeability using the Darcy equation;

$$K = \frac{qHL}{\Delta p} \qquad (4)$$

BRINE FORMULATION

This section X-rays the basic steps employed in the brine formulation used for the core pre-flush.

(i) Measure 20g of common salt (NaCl) using electronic weighing balance.

(ii) Dissolve the 20g of NaCl in a beaker with a little distilled water; stir until the salt dissolves completely.

(iii) Pour the salt solution into a 1000ml measuring cylinder and add distilled water up to the 1000ml mark of the cylinder.

(iv) This implies that the concentration of the brine used = 20g x 1000ml = 20,000ppm

CRUDE OIL/BRINE PROPERTIES

The procedure for determining the density, API gravity and viscosity of the crude oil and brine are outlined below.

- **Density/API gravity of the crude oil/brine**

(i) Weigh the empty density bottle and record as m_1

(ii) Fill the density bottle with water, re-weigh and record as m_2

(iii) Calculate the weight of water in the bottle as:

(iv) $M_{w=}m_2 - m_1$

Estimate the volume of the bottle using

$$V = \frac{M_w}{\rho_w} \qquad (5)$$

$$\rho_w = \text{density of water} = 1\text{g}/cm^3$$

(v) Empty the bottle and fill it with crude oil, re-weigh and record as m_3

(vi) Calculate the weight of the crude oil alone using

$$m_0 = m_3 - m_1$$

(vii) Calculate the density using

$$\rho = \frac{mass}{volume} = \frac{mass\ of\ crude\ oil(m_0)}{volume\ of\ density\ bottle} \quad (6)$$

(viii) Determine the specific gravity using

$$\gamma_0 = \frac{\rho_0}{\rho_w} \quad (7)$$

$$API = \frac{141.5}{\gamma_0} - 131.5 \quad (8)$$

(ix) Repeat the experiment for the brine to obtain the density of brine.

VISCOSITY DETERMINATION

The cannon u-tube viscometer was used in estimating the viscosity of the crude oil sample. The procedure is as follows;

(i) Pour the fluid into a beaker, measure and record the temperature of the fluid with a thermometer.

(ii) With the cannon u-tube viscometer, suck the fluid up to the top calibrated point of the apparatus.

(iii) Using a stopwatch, record the efflux time (the time it takes the fluid to drop from the top calibrated point to the lowest point).

(iv) Read off the viscometer constant from the viscometer chart using the measured temperature of the fluid.

(v) Calculate the kinematic viscosity in mm^2/s (CST) by multiplying the efflux time in seconds by the viscometer constant. i.e.

kinematic viscosity = efflux time in seconds x viscometer constant

(vi) Calculate the dynamic viscosity of the fluid in cp (centipoise) by multiplying the kinematic viscosity by the fluid density. i.e. dynamic viscosity = kinematic viscosity x fluid density

DETERMINATION OF VOLUME OF OIL IN THE CORE SAMPLE

This section discusses the steps followed in determining the volume of oil in the core sample.

(i) Saturate the core with methanol to clean all brine

(ii) Oven dry the core sample, measure its dry weight and record as m_1

(iii) Soak the core sample in crude oil and allow it to age

(iv) After 30 days or more, re-weigh the core sample and record the new weight as m_2

Calculate the weight of oil in the core sample using $m_0 = m_2 - m_1$

(v) Calculate the volume of oil in the core sample using

$$V = \frac{m_0}{\rho_0} \quad (9)$$

Where ρ_0= density of the crude oil.

This is particularly important as it will aid in determining the residual oil in the core after flooding.

3.6 PROCEDURE FOR CORE FLOODING/RESIDUAL OIL DISPLACEMENT EXPERIMENT

The core sample saturated with crude oil will be pre-flushed with brine; the volume of oil recovered will be recorded. The residual oil in the core sample will be the target of the biosurfactant slug.

The procedure for the core flooding and the displacement of the residual oil using the biosurfactant slug is as follows:

(i) Saturate the core with crude oil.

(ii) Insert the saturated core into the core holder.

(iii) Connect the flow line from brine reservoir (storage) to the pump and from the pump to the core holder.

(iv) Place a beaker under the core holder to collect oil flushed out.

(v) Start the electric pump and open the chokes (there are two chokes, one before the pressure gauge and another after the gauge).

(vi) Allow flooding to continue until oil is no further produced.

(vii) Measure and record the volume of oil recovered and also note the pressure drop.

(viii) Estimate the volume of residual oil in the core which is the target of the biosurfactant slug.

(ix) Saturate the core with the biosurfactant slug, followed by chase brine flooding, until no more oil is produced. This will serve as the zero hour biosurfactant incubation time (BIT). BIT is the time allowed for the biosurfactant to act in the core before the chase brine flooding (soaking time).

(x) Repeat the experiment for a BIT of 24, 48, 72, 96 and 120 hours and measure and record the volume of oil recovered for each BIT.

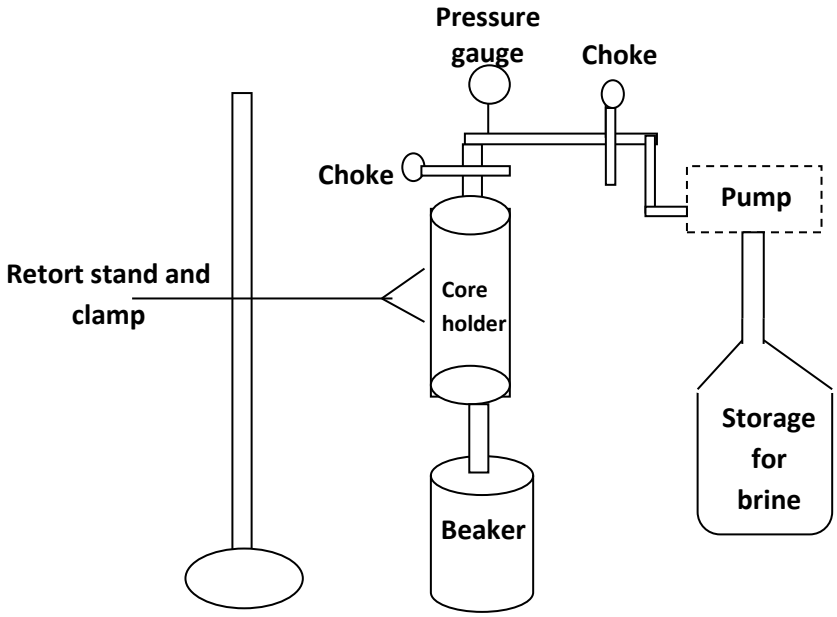

Figure 3.1: Experimental set up for core flooding

Figure 3.2: Brine Saturator

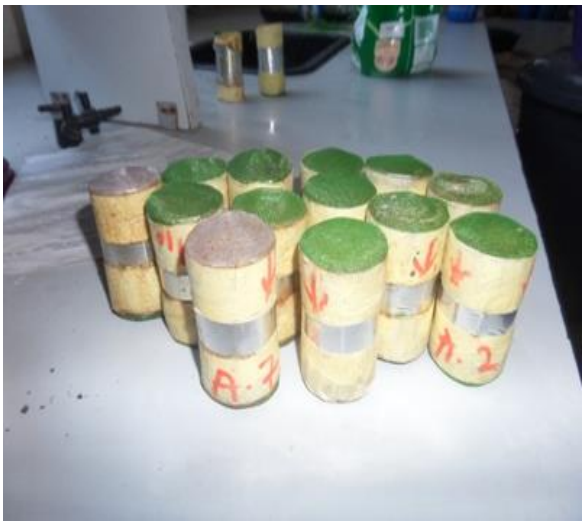

Figure 3.3: Some core Samples

Figure 3.4: Electronic Weighing Machine

Figure 3.5: Two end-stems

Figure 3.6: Digital Caliper

Figure 3.7: Sand Holder fitted with end-stem

Figure 3.8: Vacuum pump

Figure 3.9: Oil Recovery

CHAPTER FOUR

RESULT AND DISCUSSION

This chapter presents the results of the experiment in chapter three. This includes the properties of the crude oil and brine, the petrophysical properties of the core samples the result of the brine pre-flush and residual oil displacement using the biosurfactant slug.

4.1 DENSITY AND API GRAVITY

Table 4.1 Result of Density and API Gravity measurement

Fluid sample	**Weight of density bottle (g)**	**Weight of density bottle + fluid (g)**	**Weight of fluid alone (g)**	**Volume of fluid (cm^3)**	**Density of fluid g/cm^3**	**Specific gravity**	**API gravity (API)**
Brine	8.67	47.85	39.18	38.53	1.02	1.02	7.65
Crude oil	8.67	43.57	34.90	38.53	0.91	0.91	24.72

Brine

Weight of density bottle (m_1) = 8.67g

Weight of density bottle + water (m_2) = 47.82g

Weight of water in the bottle $m_w = m_2 - m_1 = 47.2 - 8.67 = 38.53g$

∴Volume of the density bottle $v = \frac{m_w}{\rho_w} = \frac{38.53g}{1g/cm^3} = 38.53cm^3$

Weight of bottle + brine (m_3) = 47.85g

Weight of brine = 47.85 – 8.67 = 39.18g

Density of brine = $\frac{massofbrine}{volumeofdensitybottle} = \frac{39.18}{38.53} = 1.016869971 g/cm^3$

Specific gravity of brine

$$\gamma_b = \frac{\rho_b}{\rho_w} = \frac{1.016869971 g/cm^3}{1 g/cm^3} = 1.016869971$$

API = $\frac{141.5}{\gamma_b} - 131.5 = \frac{141.5}{1.016869971} - 131.5 = 7.6525$

Crude oil

Weight of bottle + crude oil = 43.57g

Weight of crude oil = weight of bottle + crude oil – weight of bottle above = 43.57g – 8.67g = 34.9g

Density of crude oil=$\frac{massofcrudeoil}{volumeofdensitybottle} = \frac{34.7g}{38.53cm^3}$

$$= 0.905787697 g/cm^3$$

Specific gravity of crude oil $\gamma_0 = \frac{\rho_0}{\rho_w} = \frac{0.905787697 g/cm^3}{1 g/cm^3}$

= 0.905787697

API gravity = $\frac{141.5}{\gamma_0}$ - 131.5 = $\frac{141.5}{0.905787697} - 131.5 = 24.71762178$

The API gravity of the crude is 24.72°API, this shows that it is an heavy crude, and thus very suitable for EOR studies.

4.2 VISCOSITY

Table 4.2: viscosity of fluid samples

Fluid sample	Temperature (^{0}C)	Efflux time (s)	Viscometer constant	Density g/cm^3	Kinematic viscosity (CST)	Dynamic viscosity (cp)
Brine	28	25.32	0.036417	1.016869	0.922089	0.937649
Crude oil	28	613.94	0.036417	0.957876	22.359937	20.253356

VISCOSITY BRINE

Temperature = 28^{0}C

Efflux time = 25.32s

Viscometer constant = 0.03641743

Density of brine = 1.016869971g/cm^3

Kinematic viscosity = efflux time in seconds x viscometer constant = 25.32s x 0.03641743 = 0.922089327cst

Dynamic viscosity = Kinematic viscosity x density

= 0.922089327 x 1.016869971 = 0.937644947cp

Viscosity of Crude Oil

Temperature = 28^{0}C

Efflux time = 613.99s

Viscometer constant = 0.03641743

Density of crude oil = 0.905787697g/cm^3

Kinematic viscosity = efflux time x viscometer constant

= 613.99s x 0.03641743 = 22.35993785cst

Dynamic viscosity = kinematic viscosity x density

= 22.35993785 x 0.905787697 = 20.25335661 cp

The crude oil viscosity from the above calculations is 20.25cp while that of the brine is 0.94cp. This shows that the oil is more viscous than the brine. This will affect the mobility ratio and will be reflected in lower recovery obtained in the brine pre-flush experiment.

4.3 CORE PROPERTIES

4.3.1 Pore Volume

Table 4.3 pore volume results

Core sample	**Weight of mesh (120/200)**	**Weight of aluminium foil (g)**	**Weight of aluminium foil + mesh (g)**	**Dry weight of core (g)**	**Weight of core saturated with brine (g)**	**Weight of brine in the pores (g)**	**Pore volume (cm^3)**
C_1	1.43	2.69	4.12	111.98	131.14	19.16	18.84
C_2	1.43	2.69	4.12	110.32	130.6	20.28	19.94
C_3	1.43	2.69	4.12	116.38	135.99	19.61	19.28
C_4	1.43	2.69	4.12	115.21	137.53	22.32	21.95
C_5	1.43	2.69	4.12	112.16	132.47	20.31	19.97

PORE VOLUME

Dry weight of core sample = 111.98g

Weight of core when saturated with brine = 131.14g

∴Weight of brine in the pores = 131.14g – 111.98g = 19.16g

Volume of brine in the pores

$= \frac{weight of brine in the pores}{density of brine} = \frac{19.16g}{1.016869971 g/cm^3}$

= 18.84213375cm^3≅ $pore\ volume\ of\ the\ core\ sample$

4.3.2 BULK VOLUME

Table 4.4: Bulk Volume Calculation results

Core sample	**Mesh thickness (mm)**	**Aluminium foil thickness (mm)**	**Total height of core (mm)**	**Total core diameter (mm)**	**True height (mm)**	**True diameter (mm)**	**Bulk volume (cm^3)**
C_1	0.58	0.12	59.15	35.61	57.99	35.37	56.98
C_2	0.58	0.12	60.13	36.17	58.97	35.93	59.79
C_3	0.58	0.12	62.31	35.26	61.15	35.02	58.90
C_4	0.58	0.12	58.16	35.64	57.00	35.40	56.10
C_5	0.58	0.12	60.24	35.72	59.08	35.48	58.41

Bulk Volume Calculation

True height of core = (total height of core) – (2 x mesh thickness)

(59.15) – (2 x 0.58) = 59.15 – 1.16 = 57.99mm

True diameter of core sample = (total diameter of core sample) – (2 x aluminum foil thickness) = (35.61) – (2 x 0.12)

= 35.61 – 0.24 = 35.37mm

Bulk volume = $\frac{\pi}{4} d^2 h = \frac{\pi}{4} x\ (35.37)^2 x\ (57.99)$

= 56978.77523mm^3

= 56.97877523cm^3

4.3.3 POROSITY

Table 4.5: Table of porosity values

Core sample	**Bulk volume (cm^3)**	**Pore volume (cm^3)**	**Porosity (%)**
C_1	56.98	18.84	33.06
C_2	59.79	19.94	33.35
C_3	58.90	19.28	32.73
C_4	56.10	21.95	39.13
C_5	58.41	19.97	34.19

$$\text{Porosity} = \frac{pore\ volume}{bulk\ volume}$$

Table 4.6: Determination of volume of oil in the core

Core sample	Weight of dry core (g)	Weight of core saturated with crude oil (g)	Weight of crude oil in the core (g)	Density of crude oil g/cm^3	Pore volume of core (cm^3)	Bulk volume of core (cm^3)	Porosity Ø (%)	Volume of oil in the core (cm^3)
C_1	111.98	128.85	16.87	0.9058	18.84	56.98	33.06	18.62
C_2	110.32	127.23	16.91	0.9058	19.94	59.79	33.35	18.67
C_3	116.38	132.4	16.02	0.9058	19.28	58.90	32.73	17.69
C_4	115.21	132.52	17.31	0.9058	21.95	56.10	39.13	19.11
C_5	112.16	129.22	17.06	0.9058	19.97	58.41	34.19	18.83

Weight of crude oil occupying the pore spaces = weight of core saturated with crude oil – weight of dry core

= 128.85 – 111.98 = 16.87g

Volume of oil in the core = $\frac{\text{weight of oil in the core}}{\text{Density of oil}}$

$$= \frac{16.87g}{0.905787697g/cm3} = 18.62cm^3$$

Core flooding results

Table 4.7 Result of brine pre-flush

Core sample	Oil volume in the core (cm^3)	Cumulative volume of oil recovered (cm3)	Unrecovered volume (cm3)	Percentage oil recovery (%)
C_1	18.62	8.0	10.62	42.96
C_2	18.67	8.2	10.47	43.92
C_3	17.69	8.1	9.59	45.79
C_4	19.11	9.0	10.11	47.09
C_5	18.83	8.4	10.43	44.61

Unrecovered volume = volume of oil originally in the core – volume of oil recovered = 18.62 – 8.0 = 10.62cm3

Percentage oil recovery= $\frac{8.0}{18.62} x\ 100\%$ = 42.96%

Table 4.8: Recovery of residual oil using biosurfactant slug based on biosurfactant incubation time (BIT)

Core sample	BIT (hours)	Residual oil (cm^3)	Cumulative volume of oil recovered	Unrecovered volume (cm^3)	Percentage oil recovery (%)
C_1	0	10.62	3.82	6.8	35.97
C_2	24	10.47	6.88	3.59	65.71
C_3	48	9.59	7.10	2.49	74.03
C_4	72	10.11	7.92	2.19	78.34
C_5	120	10.43	9.24	1.19	88.59

PERMEABILITY CHANGE

Table 4.9: Change in permeability after soaking with biosurfactant

Core sample	Initial perm	BIT	Perm after soaking
C_1	824.3	0	823.1
C_2	874.4	24	873.2
C_3	912.6	48	911.5
C_4	931.4	72	930.2
C_5	907.3	120	906.9

Table 4.10: Variation of oil viscosity

Core sample	Initial oil viscosity (dynamic) cp	BIT (hours)	Recovered oil viscosity (cp)
C_1	20.25	0	14.24
C_2	20.25	24	13.23
C_3	20.25	48	12.12
C_4	20.25	72	11.61
C_5	20.25	120	10.14

4.4 DISCUSSION ON LABORATORY EXPERIMENT

The result of the residual oil experiment (also shown in the graph of percentage recovery against biosurfactant incubation time, fig 4.1) shows an initial recovery of 35.97% of the residual oil following a chase brine flooding at zero hour BIT. Increasing the BIT led to a corresponding increase in the percentage recovery (%R) up to a maximum of 88.59% at 120 hours BIT. This shows that the time the biosurfactant is allowed to act on the core plays a significant role in the degree of interfacial tension reduction and wettability alteration.

The reduction of the oil-water interfacial tension and formation of micelles provides a mechanism whereby oil can be displayed by a moving aqueous phase.

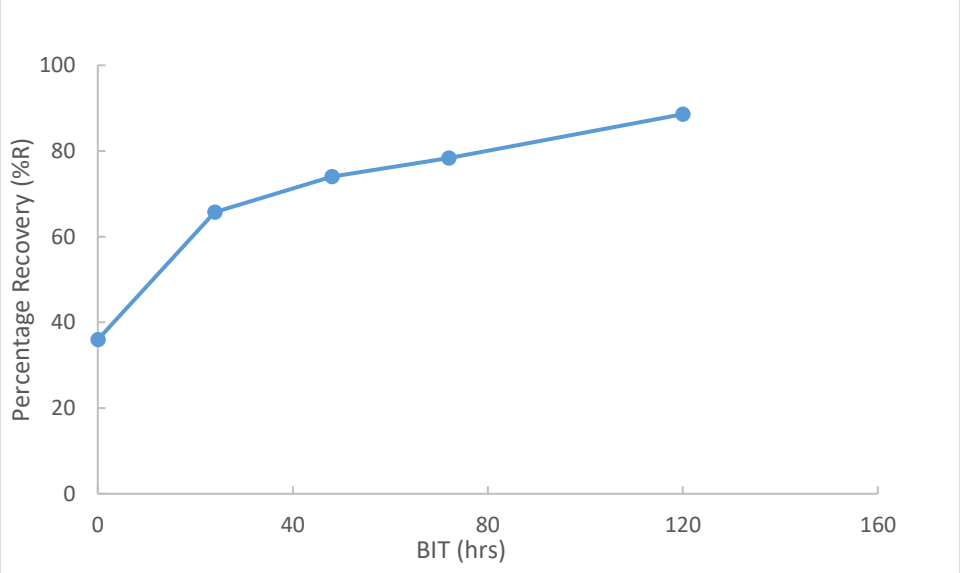

Figure 4.1: Graph of Percentage Recovery (%) Vs Biosurfactant Incubation Time (Bit)

The permeability of the core samples decreased minimally after soaking (fig 4.2), this indicates that the use of biosurfactants obtained from local pseudomonas isolates can avoid the negative/detrimental effect of considerable permeability

reduction and physical clogging as shown by other MEOR methods. Thus, the environmental footprint is small.

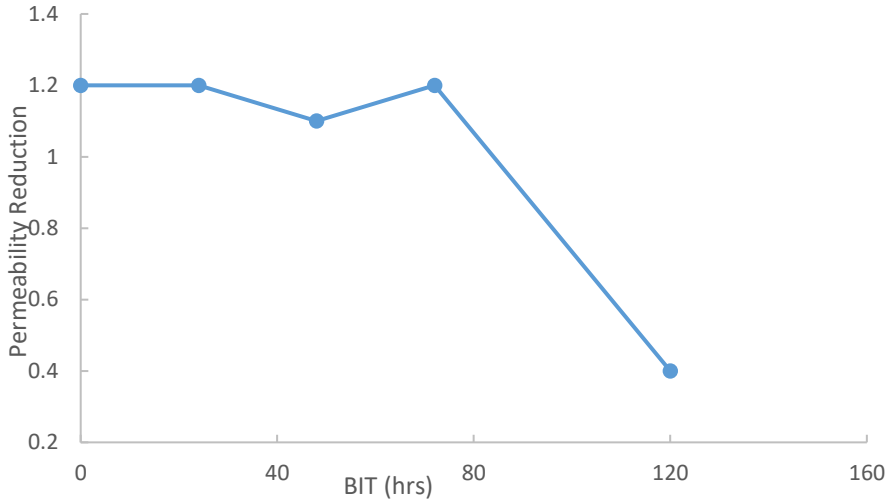

Figure 4.2: A Chart Showing the Variation in Permeability after Soaking

Fig 4.2 shows the change in permeability after soaking with the biosurfactant slug, for each biosurfactant incubation time (BIT). This further shows that the use of biosurfactant slug leaves a smaller environmental footprint.

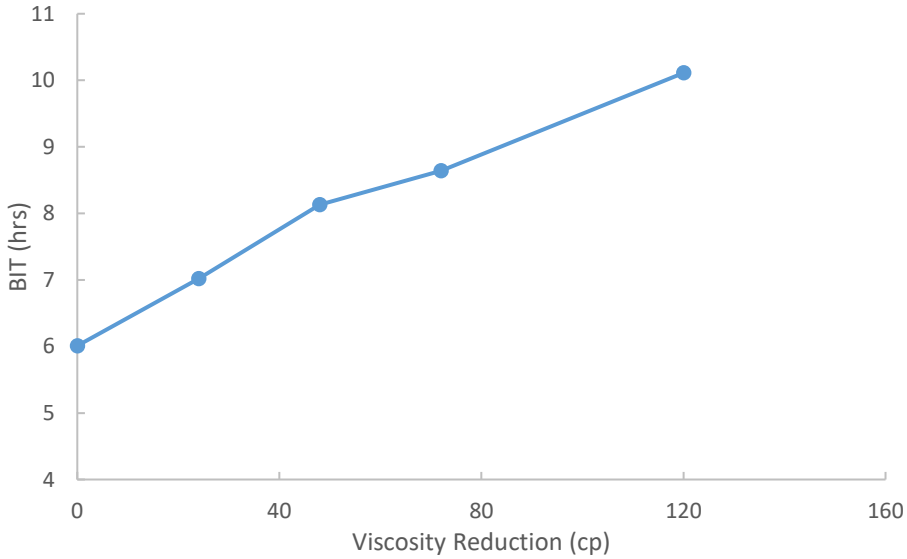

Figure 4.3: A Chart Showing Changes in Oil Viscosity after Soaking at Various Biosurfactant Incubation Time

The chart above (fig 4.3) shows the change in oil viscosity for the five different core samples and BIT. It shows the initial oil viscosity and the oil viscosity at various BIT. This indicates that the use of biosurfactant slug reduces the oil viscosity and thus increases the oil mobility.

It indicates that the higher the BIT (the soaking time), the higher the change in oil viscosity obtained.

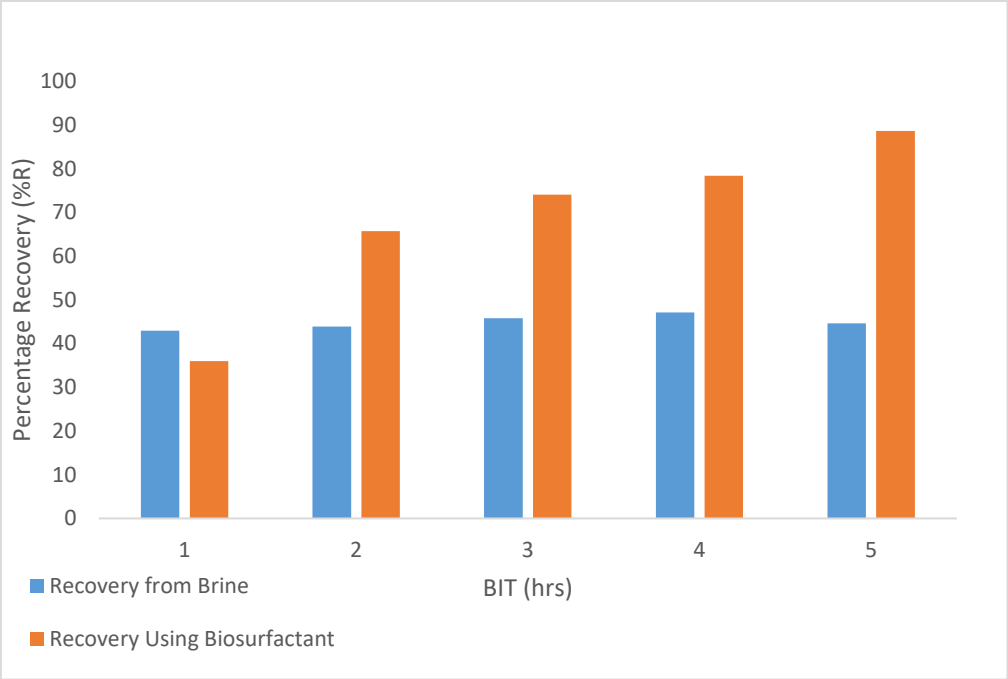

Figure 4.4: A Chart Showing of Percentage Recovery (%) Using Brine Vs % Recovery with Biosurfactant.

Fig 4.4 shows the percentage oil recovery obtained using brine and the percentage recovery obtained after soaking with biosurfactant. Higher percentage recoveries were obtained through the use of biosurfactant after zero hour BIT.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

(i) The result of the residual oil displacement experiment using biosurfactant slug produced from a culture of pseudomonas species successfully demonstrates that microbially enhanced oil recovery could lead to additional oil production with very low capital investment and much smaller environmental footprints compared to other EOR techniques.

(ii) The amount of oil produced is dependent on how long the biosurfactant is allowed to act in the core/reservoir (biosurfactant incubation time) before followed by an aqueous moving phase. This is shown in the graph of percentage oil recovery (%R) versus BIT.

(iii) The decrease in oil viscosity shows that the biosurfactant reduces the interfacial tension between oil and water, the degree of reduction depends on the soaking time(BIT)

(iv) The core samples showed a minimal decrease in permeability. This implies that the application of biosurfactant slug causes less damage to the reservoir.

5.1 RECOMMENDATIONS

In further studies, I recommend a comparison of bacterial concentration to surfactant characteristics and a dual-core experimental set-up, each core with different properties, depicting reservoir heterogeneity, such that the effluent from the first core will be used to flood the second core.

REFERENCES

Banat I.M. Biosurfactants production and possible uses in microbial enhanced oil recovery and oil pollution remediation: a review. Bioresource Technology, 51: 1--12, 1995a.

Banat I.M. Characterization of biosurfactants and their use in pollution removal - state of the art (review). Acta Biotechnolgica, 15: 251--267, 1995b.

Banat I.M., Makkar R.S., and Cameotra S.S. Potential commercial applications of microbial surfactants. Applied Microbiology and Biotechnology, 53: 495—508, 2000.

Fiona L. Jordan, Susannah K. Sandrin, Robert J. Frye, Markm L. Brusseau, and Raina M. Maier. The influence of system complexity on bacterial transport in saturated porous media. Journal of Contaminant Hydrology, 74: 19--38, 2004.

Dong-Shik Kim and H. Scott Fogler. Biomass evolution in porous media and its effects on permeability under starvation conditions. Biotechnology and Bioengineering, 690 (1): 47-56, 2000.

Hae Ok Lee, Jae H. Bae, Keith Hejl, and Aimee Edwards. Laboratory design and field implementation of microbial profile modification process [Paper SPE 49074]. In Proceedings of the 1998 SPE Annual Technical Conference and Exhibition, New Orleans, LA, September 27--30 1998, pages 393--404. Society of Petroleum Engineers.

Lazar, I. (1997). International and Romanian experience in using suitable microbial systems for residual oil release from porous media. Annual Sci. Session Institute Bio. Bucharest, pp. (225–234).

Marshall, S.L. (2008). Fundamental aspects of microbial enhanced oil recovery: A Literature Survey, CSIRO Land and Water Floreat, Western Australia, pp. (1-42).

Martin Thullner, Josef Zeyer, and Wolfgang Kinzelbach. Influence of microbial growth on hydraulic properties of pore networks. Transport in Porous Media, 49: 99--122, 2002 a.

McInerney M.J., Javaheri M., and Nagle D.P. Properties of the biosurfactant produced by the Bacillus Licheniformis strain JF-2. Journal of Industrial Microbiology, 5: 95--102, 1990.

Nemati M., Greene E.A., and Voordouw G. Permeability profile modification using bacterially formed calcium carbonate: comparison with enzymatic option. Process Biochemistry, 400 (5): 925--953, 2005.

Nielsen, S.M., Shapiro, A.A., Michelsen, M.L., & Stenby, E.H. (2010). 1D Simulations for Microbial Enhanced Oil Recovery with Metabolite Partitioning. Transp. Porous Med., Vol. 85, pp. (785–802).

Rahman K.S.M., Thahira-Rahman J., McClean S., Marchant R., and Banat I.M. Rhamnolipid biosurfactants production by strains of Pseudomonas Aeruginosa using low-cost raw materials. Biotechnology Progress, 18: 1277--1281, 2002.

Zhaodong Nan and Zhicheng Tan. Thermokinetic investigation of the effect of temperature on optimum NaCl concentration for petroleum bacterial growth. Thermochimica Acta, 386: 17--22, 2002.