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INVESTIGATION OF THE RATE OF RESIDUAL OIL VISCOSITY REDUCTION BY THE APPLICATION OF MICROBIAL ENHANCED OIL RECOVERY USING DEAD CRUDE OIL

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Abstract:-*In this paper, the rate of residual oil viscosity reduction has been investigated. The aim of this study is to identify the rates of oil viscosity reduction by microorganisms using dead crude oil as samples during microbial enhanced oil recovery. Concisely, the investigation was conducted in five (5) phases which comprised: 1. Brine flooding of cores; 2. Oil flooding of cores to displace brine; 3. Brine back flooding to displace oil to mimic a depleted and matured reservoir; 4. Injection of microorganisms and nutrient to recover the residual oil for the period of 72hrs and 96hrs intermittently; 5. The received constituents of microbes' biomass, microbes, and nutrients were separated from the oil Product, and subjected to post dynamic viscosity tests. The study inferred that, the slopes, which were the rates of change along the regression lines of the microbes' residual oil viscosity reduction, were identified. These rates of change were identified as -0.00441, 0.00351, and -0.00278, for the Bacillus Sp culture, Pseudomonas Sp culture, and the microbes mixed cultures, respectively. Consequently, It was observed that the combined effect of Pseudomonas Sp and Bacillus Sp microbes mixed cultures in solution were more effective in the reduction of residual oil viscosity reduction than the individual culture in solutions. Therefore, the mixed microbes' culture in solution is effective in residual oil recovery at prevailing reservoir conditions.*
Keywords: *Microbes, Microbial Enhanced Oil Recovery, Oil Viscosity Reduction, Rate of Oil Viscosity Reduction.*

1. BACKGROUND OF STUDY

In recent times, the recovery of residual oil-in-place from matured or producing oil reservoirs have been a major concern for the production sector of the petroleum industry. With regards that oil productions have been experiencing decline in many parts of the world due to oil field maturity. On this backdrop, the injection of microorganisms (bugs) alternatively the bugs' metabolic by-products into matured or producing oil reservoirs enhances the oil mobility of the residual oil [1]. However, after production-wells have been drilled, the reservoir produces hydrocarbon to the surface using its reservoir prevailing natural energy, known as primary oil recovery. In addition, when it is obvious that this *in-situ* energy cannot produce the desired commercial quantity of the oil reservoir and maintain the reservoir pressure; first degree supplementary pressure maintenance is applied by water or immiscible-gas injection through injection wells, known as secondary oil recovery [2]. Regrettably, Coss´e [3] stated that the combination of primary and secondary oil recovery methods may only produce approximately between 30-60% of the original oil-in-place (OOIP) leaving about 40% of the OOIP as residual oil-in-place. In contrast, Craft *et al.* [4] concluded that a considerable quantity of residual oil-in-place can be exploited using tertiary methods as a standalone or in combination with any of the aforementioned oil recovery techniques. Furthermore, Sarma and Maini [5] opined that tertiary oil recovery is synonymous with enhanced oil recovery (EOR), and it is classified miscible flooding, immiscible flooding, chemical flooding, microbial flooding and thermal flooding. Consequently, in a recent research, Ikporo and Okotie [6] prioritised microbial flooding to be the best applied EOR methods compared to the conventional EOR methods. However, in most petroleum literatures, research have shown that MEOR is still in the domain of "research and development", R&D [7]. Thus, research has focused on the application of microbes in the recovery of residual oil-in-place, in viscosity reduction of the residual oil-in-place to enhance oil mobility; without investigating the rate of viscosity reduction. Interestingly, Ikporo and Okotie [6] concluded that bugs such as Bacillus and pseudomonas species have proven to be effective in the recovery of residual oil-in-place in Niger Delta Reservoirs. In another study, Terry [8] stated that the possibility of the microorganisms to have reacted with reservoir fluids to generate either surfactants or polymers in the reservoir depending on the reservoir characteristics, while mobilising and recovering the residual oil. In addition, ZoBell [9] opined that during the mobilisation of the residual oil, the main mechanisms which underpinned the possible oil release from porous formation were processes such as bugs' metabolites. This process involves the break-up of inorganic carbonates, which generates bacterial gases that reduce the viscosity of oil, thereby increasing the residual oil flow. Furthermore, [10], [11] affirmed that microorganisms reduces the capillary forces retaining the residual oil inside the reservoir formation and decreases its viscosity. In terms of the rate of residual oil viscosity reduction [12], [13] described residual oil viscosity as the property of residual oil that measures the resistance of the oil to flow. In addition, Sitnikov, Eremin, and Ibatullin [14] opined that, residual oil viscosity property is influenced by acids and gases metabolites produced when microorganisms and residual oil react. Nevertheless, these metabolites (see table 1.1) by the bacteria in the reservoir's pay-zone-formation do not only improved the reservoir pressure maintenance, rock

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permeability and porosity, but reduce the residual oil viscosity, to enable reservoir fluid flow [14]. Specifically, Behlülgil and Mehmetoglu [15] stated that the measurements carried out after certain stage show that gas (mainly CO_2) production by the bacteria decreases the oil viscosity effectively. However, reservoir brines can inhibit the growth of the microorganisms. Therefore, affect the rate of oil viscosity reduction [16]. Despite these rigorous researches, there still exists the vacuum of published models on the rate of oil viscosity reduction by microorganisms. With regards to this, Chang *et al.* [17], Desouky *et al.*, [18], Nmegbu and Pepple [19] developed some numerical models for MEOR. These involved solution of coupled nonlinear parabolic partial differential equations, which were functions of reservoir simulators. These simulation used existing computer codes to be augment the developed equations for the rate of diffusion of bacteria and their capture by the porous medium, including expressions for the effect of bacterial deposition on the permeability; differential balance equation(s) for the transport of nutrient(s), including the possible effects of adsorption; and the assumption of a kinetic model for the bacterial growth kinetics. Unfortunately, the work of Ikporo and Okotie [7] shows that, the test results obtained from the shut in experiment in order to see the effect of the bacterial culture used (bacillus and pseudomonas) on the pressure in the reservoir model and viscosity of the crude oil. However, mathematical models to show the rates of residual oil viscosity reduction were not expressed vividly.

Sequel to the selected reviewed literatures, it was deduced that microorganism during metabolism; surfactants or polymers were formed as by-products. While gaseous emissions due to the metabolic processes were released, to have contact with the residual oil. After which the capillary forces retaining the residual oil inside the reservoir formation and viscosity are decreased. Although, among these researches the absence of clear model (s) to explain the rate of residual oil viscosity reduction by the application of microbial enhanced oil recovery still prevails. Therefore, this research is aimed at investigating the rate of residual oil viscosity reduction by the application of MEOR using dead crude oil. This was realized based on the underpinned objectives: to investigate the rate of residual oil viscosity reduction by the desired microorganism, and to develop a model for the rate of the residual oil viscosity reduction.

Table 1: Microbial bio-products and their applications in oil recovery [20]

Product	Microorganism	Application in oil recovery
Biomass	*Bacillus licheniformis*, *Leuconostoc mesenteroides*, *Xanthomonas campestris*	MPPM, selective plugging, viscosity reduction, oil degradation, wettability alteration
Biosurfactants	*Acinetobacter calcoaceticus*, *Arthrobacter paraffineus*, *Bacillus* sp., *Clostridium* sp., *Pseudomonas* sp.	Emulsification, interfacial tension reduction, viscosity reduction
Biopolymers	*Bacillus polymyxa*, *Brevibacterium viscogenes*, *Leuconostoc mesenteroides*, *Xanthomonas campestris*, *Enterobacter* sp.	MPPM-Injectivity profile modification, mobility control, viscosity modification
Bio-solvents	*Clostridium acetobutylicum*, *Clostridium pasteurianum*, *Zymomonas mobilis*	Emulsification, viscosity reduction
Bio-acids	*Clostridium* sp., *Enterobacter aerogenes*	Permeability increase, emulsification
Biogases	*Clostridium* sp., *Enterobacter aerogenes*, *Methanobacterium* sp.	Increased pressure, oil swelling, interfacial tension reduction, viscosity reduction, permeability increase

2. METHODOLOGY

2.1 MATERIALS AND METHODS

2.1.1 Materials and Equipment

The equipment used for the analyses include: Hydrometer, 1000ml Measuring Glass Cylinders, 500ml Beaker, Core holders, Thermometers, Weighing Balance, and Chandler Engineering Viscometer. While the materials that were used for the analyses include: Dead Crude Oil, Brine, Core plugs, De-ionized Water, and Cultured Bacteria.

2.1.2 Methods

The aim of this research is to develop a model on the rate of oil viscosity reduction by microorganisms using dead crude oil as samples. To achieve this aim, three (3) major objectives were examined. These underpinned objectives were: the identification and isolation of the best microorganisms for reducing residual oil viscosity from some relevant literatures [21], [20], [6] and the investigation of the microorganisms on the rate of residual oil viscosity reduction. However, before the investigating these underpinned objectives, some preliminary primary tests (Specific gravity, ^{0}API gravity, and Dynamic viscosity) were conducted on the dead crude oil samples collected from some selected tank farms in the onshore Niger Delta region, Nigeria. Thus, 2000ml of dead crude oil samples were collected from seven different tank farms. Furthermore, some of the bulk properties of the sampled dead crude oil were measured. Consequently, 800ml of each of the samples were measured and subjected to ASTM test methods for Specific gravity [22], [23], and ^{0}API gravity [24], [23]; while 250ml of each of the samples were used to conduct ASTM tests for Dynamic viscosity [25]. Besides, the investigation of the preliminary primary tests, flow tests on the sampled dead crude oils were conducted, which generated data for the development of model(s) for the rate of the residual oil viscosity reduction by the identified and isolated microorganism. Generally speaking, the flow tests used in this research were adopted and modified from Ikporo and Okotie's [6] methodology used for the investigation of the efficacy of enhanced oil recovery by means of micro-organisms in Niger Delta Reservoir", but at stimulated reservoir conditions. The sectionalized methods employed in this research are presented as follows:

2.1.3 Identification And Isolation Of The Best Microorganisms For Reducing Residual Oil Viscosity

The microbes were cultured and identified at the biochemical laboratory in the Niger Delta University, Nigeria. The microorganisms suitable and used to conduct these experiments were Bacillus *sp*. and Pseudomonas *sp*. which both products are biomass and have the application capabilities of emulsification, interfacial tension reduction in oil recovery.

2.1.4 The Investigation Of The Microorganisms On The Rate Of Residual Oil Viscosity Reduction

One of the three (3) major objectives of this research is the investigation of the microorganisms on the rate of residual oil viscosity reduction. This was determined by the insertion of each of the core samples into the rubber sleeve with both inlet and outlet of the stems tightly fixed, these were load onto the core holder intermittently. Each time the core holder was loaded, water and dead crude oil were pre-

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introduced at simulated reservoir conditions: at isothermal-ambient temperature and pressure of 2100psi. Subsequently, crude oil and brine mixture were discharged into the accumulator's two-chambers. The accumulator was connected to the pump, while the flood head and end stem were connected to the pump via the plug. The seven (7) core samples used for the analyses had an approximate average of: diameter (d) as 3.60cm; height (h) as 6.22cm; area (A) as 90.74cm^2; bulk volume (V_b) as 63.34cm^3; pore volume (V_p) as 66.34cm3; effective porosity (P_{ef}) as 0.36; and Liquid permeability ($Perm_L$) as 5,123.67mD. Each of these cores was subjected to brine flooding until a water breakthrough was observed, with an approximate average brine saturation of 96.56%. In reverse, the sampled dead crude oils were used to back flood the core saturated with brine until an oil breakthrough was observed. These flooding and back flooding processes were conducted intermittently. However, the volumes of oils used to displace the brine were recorded. This mimicked the original oil-in-place in the reservoir's formation at simulated reservoir conditions. To mimic the reservoir production concept, the system was back-flooded with brine until water breakthrough was observed. In this research it is assumed that both the primary and secondary methods of reservoir oil recovery are encapsulated in the brine-back-flooding process. Explicitly, the remaining oil in the core's pores after brine-back-flooding process is termed the initial residual oil-in-place. Furthermore, the routine injections of micro-organisms into the cores were conducted. Thereafter, these were shut-in for the period of 72hrs, to recover the irreducible oil-in-place after the shut-in period – Microbial Enhanced Oil Recovery (MEOR). Finally, the collected oils from the MEOR process were subjected to post oil viscosity tests after the microbial enhanced oil recovery has been separated from the microbes' constituents. concisely, these investigations were conducted in five (5) phases which comprises: 1. Brine flooding of cores; 2. Oil flooding of cores to displace brine; 3. Brine back flooding to displace oil to mimic a depleted and matured reservoir; 4. Injection of microorganisms and nutrient to recover the residual oil for 72hrs.; 5. The constituents of microbes' biomass, microbes, and nutrients were separated from the oil Product obtained from the tertiary oil recovery and subjected to post viscosity tests. The post viscosity tests' results derived from the data collection and data analyses were recorded accordingly.

2.2 DATA COLLECTION AND DATA ANALYSIS

The quantitative Primary data collected using the aforementioned methods were subjected to data analysis. In this study, the analyses were conducted with multivariate statistics and regression tools in Microsoft Excel 2012. This aided the development of the models.

3. RESULTS AND DISCUSSION

3.1 The Results Of The Microorganisms Effects On The Rate Of Residual Oil Viscosity Reduction

Tables 2, 3, and 4 show the results of the effect of microbes in solution on the residual oil viscosity reduction. Column four in each of the tables shows that the shut-in periods were varied between 72hrs and 96hrs. Sequel to this, the post-dynamic viscosity column in each of the tables shows that at a shut-in period had effects on the oil viscosity reduction.

Table 2: The Effect of Bacillus *Sp* Microbes in Solution on the Residual Oil Viscosity

CORE SAMPLES	MICROBE SOLUTION TYPE	MICROBE SOLUTION VOLUME (CM^3)	SHUT-IN PEROID (hrs)	Pre-Dynamic Viscosity (cP)	Post-Dynamic Viscosity (cP)
CRS001	Bacillus *Sp.*	15	72	0.52	0.36
CRS002	Bacillus *Sp.*	15	72	0.52	0.34
CRS003	Bacillus *Sp.*	15	72	0.52	0.32
CRS004	Bacillus *Sp.*	15	72	0.52	0.31
CRS005	Bacillus *Sp.*	15	96	0.52	0.24
CRS006	Bacillus *Sp.*	15	96	0.52	0.23
CRS007	Bacillus *Sp.*	15	96	0.52	0.21

Table 3: The Effect of Pseudomonas *Sp* Microbes in Solution on the Residual Oil Viscosity

CORE SAMPLES	MICROBE SOLUTION TYPE	MICROBE SOLUTION VOLUME (CM^3)	SHUT-IN PEROID (hrs)	Pre-Dynamic Viscosity (cP)	Post-Dynamic Viscosity (cP)
CRS001	Pseudomonas *Sp.*	15	72	0.52	0.38
CRS002	Pseudomonas *Sp.*	15	72	0.52	0.36
CRS003	Pseudomonas *Sp.*	15	72	0.52	0.33
CRS004	Pseudomonas *Sp.*	15	72	0.52	0.32
CRS005	Pseudomonas *Sp.*	15	96	0.52	0.28
CRS006	Pseudomonas *Sp.*	15	96	0.52	0.27
CRS007	Pseudomonas *Sp.*	15	96	0.52	0.24

Consequently, in table 2 the shut-in time of 72hrs with Bacillus *sp* microbe reduced the residual oil viscosity to an average viscosity of 0.33cP, while at a shut-in period of 96hrs the residual oil viscosity was reduced to an average viscosity of 0.23cP. These results inferred that the microbe, Bacillus *sp* has the ability to reduce residual oil viscosity effectively.

Table 4: The Effect of Pseudomonas *Sp* and Bacillus *Sp* Microbes in Solution On The Residual Oil Viscosity

CORE SAMPLES	MICROBE SOLUTION TYPE	MICROBE SOLUTION VOLUME (CM^3)	SHUT-IN PEROID (hrs)	Pre-Dynamic Viscosity (cP)	Post-Dynamic Viscosity (cP)
CRS001	*P + B	15	72	0.52	0.27
CRS002	P + B	15	72	0.52	0.23
CRS003	P + B	15	72	0.52	0.22
CRS004	P + B	15	72	0.52	0.2
CRS005	P + B	15	96	0.52	0.18
CRS006	P + B	15	96	0.52	0.16
CRS007	P + B	15	96	0.52	0.15
	Pseudomonas *Sp.* + *Bacillus Sp.*				

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In contrast, table 3 shows that pseudomonas *sp* microbes exhibit some poor performance in reduction of residual oil viscosity compared to what were obtained from Bacillus *sp* microbe. From the results obtained in table 3, the shut-in time of 72hrs with pseudomonas *sp* microbe reduced the residual oil viscosity to an average viscosity of 0.35cP, while at a shut-in period of 96hrs the residual oil viscosity was reduced to an average viscosity of 0.26cP. However, table 4 shows a set of improved performance of residual oil viscosity reduction obtained as a result of the combined effects of pseudomonas *sp and* Bacillus *sp* solution. This result shows that the average oil viscosity reduction at 72hrs and 96hrs are 0.23cP and 0.16cP, respectively. The overall results show that these microbes reduce the residual oil viscosity, but a better oil viscosity reduction can be obtained when these microbes are combined in solution during the injection stage. Consequently, the reduction of residual oil viscosity by pseudomonas *sp and* Bacillus *sp* microbes, to enhance the recovery of the simulated residual oil was a function of time, at prevailing simulated reservoir conditions. To model the rate of residual oil viscosity reduction by the aforementioned microbes, the results in figures 1, 2 and 3 were discussed accordingly.

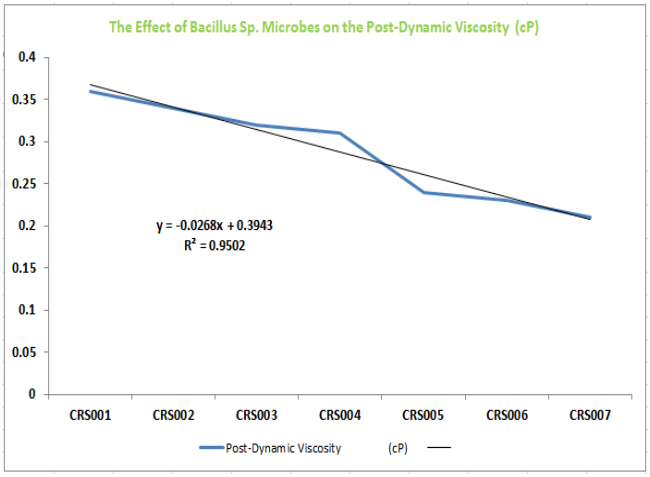

Figure 1: The effect of Bacillus *Sp* microbes in Solution on the residual oil viscosity reduction.

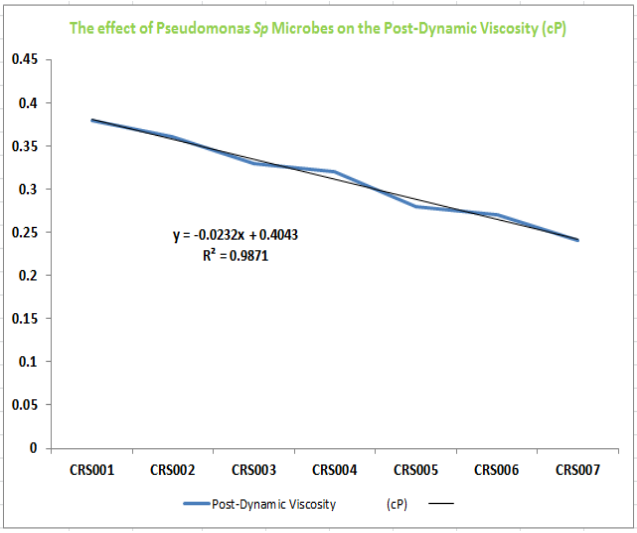

Figure 2: The effect of pseudomonas *Sp* microbes in Solution on the residual oil viscosity reduction.

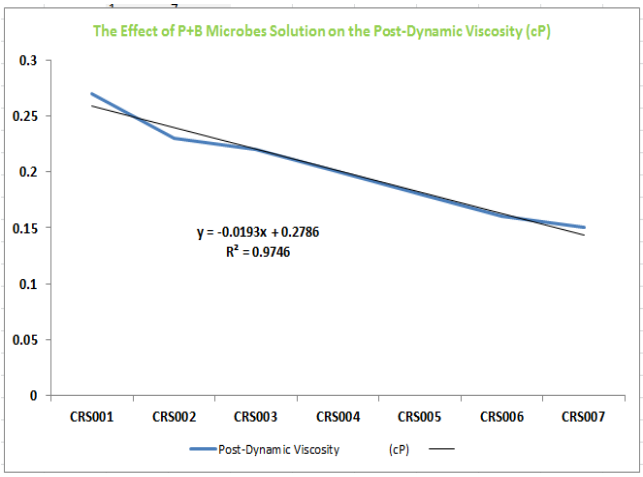

Figure 3: The Effect of Pseudomonas *Sp* and Bacillus *Sp* microbes in solution on the rate of residual oil viscosity reduction.

The figures 3.1, 3.2, and 3.3 show that, the data evaluations from the regression analyses conducted were at 95% confidence level. In addition, the results obtained from figures 3.1, 3.2, and 3.3 indicated that the R square were at 0.95, 0.99 and 0.97, respectively. These explained that the data sets collected for the experiments have a strong relationship and were suitable for the analyses. Hence, the results were reliable. The slope, which is the rate of change along the regression line of the residual oil viscosity reduction during MEOR are illustrated in figures 3.1, 3.2, and 3.3. The rate of change obtained for figures 3.1, 3.2 and 3.3 were -0.00441, -0.00351, and -0.00278, respectively. These results opined that the type of microbe(s)' solution affected the rate of residual oil viscosity reduction during MEOR at prevailing reservoir conditions. This implies that the combined effects of Pseudomonas *Sp* and Bacillus *Sp* microbes mixed cultures were more effective in the reduction of oil viscosity.

4. CONCLUSION

- It was observed that the pre-viscosity estimated values of the sampled oil were higher than the post-viscosity estimated values of the microbial enhanced recovered oil.
- The research inferred that, the slopes, which are the rates of change along the regression line of the microbes' residual oil viscosity reduction during MEOR were identified as -0.00441, -0.00351, and -0.00278, for the Bacillus *Sp* culture, Pseudomonas *Sp* culture and mixed cultures, respectively.
- It was observed that the combined effects of Pseudomonas *Sp* and Bacillus *Sp* microbes mixed cultures in solution were more effective in the reduction of residual oil viscosity than the individual cultures in solutions.
- The rate of change along the regression line of the mixed microbes, in the reduction of residual oil viscosity was estimated as -0.00278.

With regards to its application in MEOR, the Authors recommend that the mixed microbes' culture in solutions should be used as one of the best methods, for effective residual oil recovery at prevailing reservoir conditions.

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