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Laboratory Investigation on Permeability Change and Economic Analysis Using Some Selected Nanoparticles for Enhanced Oil Recovery

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ABSTRACT: Enhanced oil recovery using nanoparticles is an emerging technique that can potentially alter permeability and wettability of porous media for improved oil mobilization. This study experimentally investigates the permeability alteration caused by three commonly used nanoparticle types – copper (ii) oxide, zinc oxide and silicon oxide. Core flooding experiments were conducted on reservoir rock samples before and after treatment with nanoparticle dispersions. Results show decrease in permeability by 35% for copper (ii) oxide, 30% for zinc oxide and 10% silicon oxide respectively. Pore-scale analysis indicates that permeability change occurs through mechanisms like pore throat blocking/wettability alteration. Nanoparticle concentration is also found to influence the permeability variation, with optimal dosage. Among the systems tested, Silicon oxide is the most effective formulation for enhancing oil recovery applications based on its ability to recover oil with minimal alteration to formation permeability. From the result, Silicon oxide had a cumulative recovery of 17ml, 18.0ml and 18.5ml thereby generating a percentage recovery of 73.91%, 78.26% and 80.43% while Zinc oxide had a cumulative recovery of 15.5ml, 18.0ml and 16.5ml thereby generating a percentage recovery of 77.50%, 78.26% and 71.74ml%, lastly Copper (ii) oxide had a cumulative recovery of 16.5ml, 17.0 and 16.0 generating a percentage recovery of 75%, 73.91% and 72.72% respectively with a concentration of 0.1%, 0.3%, and 0.5%. This study demonstrates the potential of Silicon oxide nanoparticles for enhanced oil recovery through permeability manipulation in porous media, however, the economic analysis shows that it's quite expensive due to its cost of production and won't be ideal for use. Hence Zinc oxide which also has a high volume of oil recovery, and less production cost can be used.

KEYWORDS: Enhanced Oil Recovery, Economics Analysis, Nanoparticles, Niger Delta Formation, Permeability Change

1. INTRODUCTION

In the ever-evolving landscape of energy resources, the quest for efficient and sustainable oil extraction methods remains paramount. Conventional techniques often fall short in maximizing reservoir potential, leaving substantially untapped resources beneath the earth's surface. This gap necessitates a paradigm shift towards innovative strategies, and one such promising avenue lies in the integration of nanoparticles. Recently, most conventional oil wells across the globe have had a middle-late period of production, which has been because of inevitable and important changes in production regarding conventional reservoirs. The exploration and development of conventional oil reservoirs has shifted to low permeability and ultra-low permeability, heavy oil, shale oil and, other unconventional oil and gas reservoirs [1], [2], [3]. Low permeability reservoirs are now an important petroleum resource in recent times [4]. However, the unique characteristics of low permeability, low porosity and high injection make recovery difficult in these reservoirs. But on considering enhanced oil techniques, nanomaterials have emerged with high values in this reservoir [5].

Enhanced oil recovery (EOR) techniques are employed to extract additional oil from reservoirs that cannot be efficiently recovered through primary and secondary recovery methods (Fig. 1). Primary recovery relies on the natural pressure in the reservoir, while secondary recovery involves injecting fluids (such as water, gas, chemicals, etc.) to displace oil in the reservoir. Emphasis is laid on enhanced oil recovery (EOR) methods because two-thirds of the original oil in place is left unproduced when most of the oilfields in the world is approaching maturity [6]. The recovery efficiency of the oil can be improved by EOR processes, where about 37% of the original oil in placed can be recovered by EOR. EOR techniques go a step further by altering the reservoir conditions to improve oil recovery rates. Several commonly used EOR techniques include the thermal method, Gas injection, Chemical method, Microbial EOR. The quest for enhanced oil recovery methods has led to the exploration of innovative techniques, among which the integration of nanoparticles stands as a promising avenue. The field of enhanced oil recovery (EOR) has witnessed

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a significant evolution with the advent of nanotechnology. Nano particles, characterized by their minute size and substantial surface area, have demonstrated promising potential in altering reservoir permeability for enhanced hydrocarbon recovery. Among these, notable candidates of nano particles include iron oxide, zinc oxide, and silicon oxide, copper (II) oxide, aluminum oxide, tin oxide etc, each possessing distinct properties that render them compelling subjects for investigation.

This study embarks on an experimental journey to scrutinize the impact of these nano particles on permeability within the reservoir matrix. The outcomes of this research hold the potential to revolutionize conventional EOR strategies, ushering in a new era of precision-engineered reservoir modification. Conventional oil recovery techniques like waterflooding can recover only 30-35% of the oil trapped in reservoirs, leaving a significant amount of oil locked in the pores and cracks of the rock formation. Enhanced oil recovery techniques aim to extract this residual oil by altering the properties of the rock-fluid system. Nanoparticles have emerged as a potential EOR method that can effectively alter permeability and wettability. However, the degree and mechanisms of permeability change induced by different nano particles like copper(ii)oxide, zinc oxide and silicon oxide need to be experimentally investigated and compared to identify the most suitable nanofluid for a given reservoir. Thus, the main problem this study aims to address is to ascertain through core-flooding experiments the extent and nature of permeability alteration caused by each nano particle type and evaluate their potential for enhanced oil recovery applications.

Most emphasis are laid on enhanced oil recovery (EOR) methods because two-third of the original oil in placed is left unproduced when most of the oil field in the world is approaching maturity [6]. The recovery efficiency of the oil can be improved by EOR processes. About 37% of the original oil in placed can be recovered by CEOR. There are three phases or stages of hydrocarbon recovery namely: primary, secondary, and tertiary (EOR) stages. Primary recovery method means using energy sources that naturally exist in the reservoir to produce oil. The energy sources include natural water drive, gas cap drive, solution gas drive, fluid expansion etc. The reservoir pressure decreases as oil production continues until a point where the pressure that exists in the reservoir is not enough to produce the oil to the surface [7]. At that condition the pressure of the reservoir can be maintain to displace oil toward the production well by injecting water or gas into the reservoir. This stage of oil recovery is referred to as secondary recovery or water flooding recovery method. After the secondary flooding method, due to the viscosity of the water is less than that of oil, part of the crude oil that cannot be produce remains as a residue and trapped in the reservoir, and at that moment secondary recovery method is no longer effective, EOR is mostly introduced.

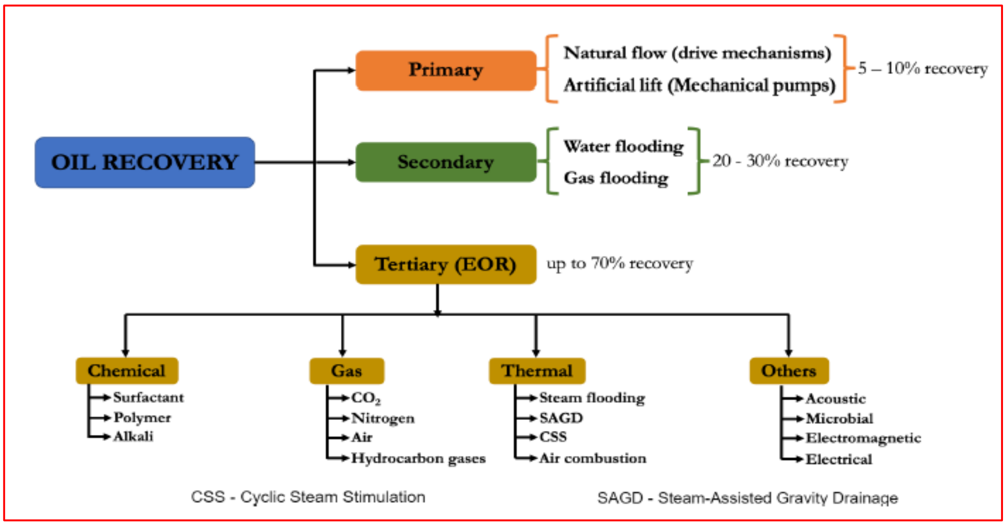

Fig. 1. Stages of oil recovery [8].

To release and produce extra trapped or residual crude oil from the reservoir with the use of other recovery techniques such as chemical flooding, thermal flooding, and gas flooding methods beyond that recoverable by secondary recovery methods, this is called tertiary recovery methods or Enhanced Oil Recovery [9]. These methods can be categorized into thermal, gas, and chemical recovery methods as shown Fig. 1.

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Nanoparticles boost the oil recovery by mechanism of reduction in mobility ratio which reduces the viscosity of heavy oil and interfacial tension and increases in fault line permeability ([10], [11], [12], [13]). [11] did a work on permeability alteration using silica and Alumina oxide nanoparticles for enhanced oil recovery. They conducted the experiments using core samples made with Niger Delta sand samples for both homogeneous and heterogeneous formation. The nanofluids were prepared using two different nanoparticles, with brine as the dispersing medium and different concentrations were used to flood the core sample. They concluded from their research that the use of nanoparticles increases recovery but reduced the permeability of the formation after flooding process.

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2. NANOTECHNOLOGY

Nanotechnology refers to the manipulation and control of matter at the nanoscale, typically between 1 and 100 nanometres. It involves the understanding, creation, and application of materials, devices, and systems with unique properties and functionalities due to their nanoscale dimensions. Nanotechnology has the possibilities to solve problems in the oil and gas industry. The introduction of nanoparticle into the formation has altered certain factors in the formation and in oil properties which makes it to be commonly used enhanced oil recovery [6]. Nanoparticles are particles with sizes ranging from 1 to 100 nanometers (nm), where one nanometer is equal to one billionth of a meter. Nanoparticles exhibit unique physical, chemical, and biological properties that differ from their bulk counterparts. Due to these distinctive properties, nanoparticles have found applications in various fields, including materials science, electronics, medicine, environmental remediation, and energy.

Nanotechnology used in oil and gas industry to recover more trapped in reservoir. Nanotechnology enhanced oil recovery by reducing the interfacial tension between oil and water interface, the wettability of rock surface and improve the mobility ratio (i.e., increasing the viscosity of the injection fluid (water) and decreasing the viscosity of the oil phase. Nanoparticles can resist high temperatures and pressure in subsurface oil reservoir system and exhibit different properties compared to the same fine or bulk molecules. Due to its small size, it increases surface area and creates massive diffusion driving force at higher pressure and temperature. In a small surface area, it contains a much higher concentration of fluids. Nanoparticles are used to modify optical, specific, thermal, and interfacial properties of tight oil reservoirs with 5-50 mm size pore diameter which consists of trapped oil in place [14]. Study reveals that by controlling nano-mineral complexes can increase the recovery of oil in the oil field due to capillary hysteresis value change and the specific behaviour of clay minerals.

2.1. Challenges of using nanoparticles in EOR

The use of nanoparticles in Enhanced Oil Recovery (EOR) techniques holds great potential for improving oil recovery efficiency. However, there are several challenges associated with their application. Some of the key challenges of using nanoparticles in EOR include ([15], [16], [17]).

Cost: The production and implementation costs of nanoparticles can be relatively high, especially for large-scale oilfield operations. Nanoparticles often require specialized synthesis methods and purification processes, which can add to the overall cost of their production. Additionally, the cost of nanoparticle injection and monitoring equipment needs to be considered.

Nanoparticle Stability: Nanoparticles may experience stability issues when introduced into complex reservoir conditions. Aggregation and settling of nanoparticles can occur due to interactions with reservoir fluids, temperature, pressure, and salinity. Maintaining the stability and dispersion of nanoparticles throughout the injection process is crucial for their effectiveness in EOR.

Transport and Mobility: Nanoparticles may face challenges in their transport through the reservoir matrix. Their small size can lead to significant retention and immobilization within the porous media, reducing their ability to reach the targeted oil-bearing zones. Understanding the transport mechanisms and optimizing nanoparticle properties to enhance their mobility is a key research area [18].

Reservoir Compatibility: The compatibility of nanoparticles with the reservoir fluid and rock formation is essential for successful EOR applications. Some nanoparticles may interact with reservoir fluids, leading to changes in their properties or potential precipitation issues. Compatibility studies need to be conducted to ensure that nanoparticles do not negatively impact the reservoir or cause formation damage.

Reservoir Heterogeneity: Reservoir heterogeneity, including variations in permeability, wettability, and pore structure, can affect the distribution and effectiveness of nanoparticles in EOR. Nanoparticles may preferentially flow through high-permeability zones, leaving behind untapped oil in low-permeability regions. Designing nanoparticle formulations and injection strategies to overcome reservoir heterogeneity is a significant challenge.

Scale-Up and Field Implementation: Scaling up nanoparticle-based EOR techniques from laboratory-scale to field-scale operations presents numerous challenges. The logistics of injecting and distributing nanoparticles throughout a large reservoir, monitoring their performance, and optimizing injection strategies require careful planning and consideration. Field implementation also necessitates addressing issues related to nanoparticle supply, storage, and disposal.

Environmental Impact and Regulatory Compliance: The potential environmental impact of nanoparticles and their long-term behavior in the subsurface are areas of concern. Regulatory compliance regarding the use, handling, and disposal of nanoparticles must be addressed to ensure their safe and sustainable application in EOR. Environmental risk assessments and monitoring protocols are necessary to mitigate any potential adverse effects.

2.2 Controlling factors for the success of Nano flooding

With regards to wettability modification, emulsification, and foam stability, laboratory data shows that nano flooding outperforms traditional flooding techniques. Nanomaterials must be evaluated to effectively perform enhanced oil recovery so as not to damage the reservoir. The quality of nano flooding could be influenced by several variables. Nanotechnology has the potential to play a vital role in the industry but however, there are still some vital challenges that need to be addressed before nano technology can be widely deployed in the field. Some of these challenges include developing a more accurate and reliable nanoparticle transport and retention model. Another challenge is the need to develop better engineering methods to produce nanoparticles with the optimal properties for nano flooding. If their challenges are addressed, we can accelerate the commercialization of nanotechnology for enhanced oil recovery.

Developing Nanoparticle transport and retention model: It is quite necessary to develop nanoparticle transport and retention model to predict nano flooding performance accurately ([19], [20]). These models consider generally the characterization (shape, size, and surface chemistry) of nanoparticles. Several nanoparticle transport and retention models have been generated but these models are still in their early stages and need more development.

Engineering Nanoparticles for Optimal Suspension and flow in Reservoirs: There is a need to engineer nanoparticles for optimal suspension and flow in the reservoir, this can be done by controlling the size, shape, and surface chemistry of the nanoparticle. For example, the smaller size of nanoparticle tends to be suspended in reservoir fluids and flow through the reservoir fluid more easily. Nanoparticles with hydrophilic surfaces tend to suspend more in reservoir fluids. More research and development are needed in this area for better oil recovery.

3. METHODLOGY

3.1 Equipment and Materials

3.1.1 Equipment

Encapsulated plug sample (unconsolidated Sand-packs), Venire caliper, Density bottle, PH meter, Hydrometer, Thermometer, Canon U-tube Viscometer, Electronic Weighing balance, Stopwatch, Retort Stand, Pump, Flooding Pump Setup, Core-holder, Sieve and Stirrer.

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3.1.2 Materials

The materials utilized in this research work are brine (mixture of industrial salt, and water), copper (ii) oxide nanoparticle, Silicon oxide nanoparticle, zinc oxide, sand core and crude oil.

Brine Preparation: Laboratory prepared brine of 30g/L concentration was used which contain 29.52g sodium chloride (NaCl) and 0.48g potassium Chloride (KCl) in distilled water. The brine has the density of 1.0211g/cm^3.

Crude Oil Properties: The crude oil sample was obtained from a field from Niger Delta of Nigeria and has the following properties: specific gravity of 0.860, density of 0.8958g/cm^3, viscosity of 43.022cP and °API gravity of 33.99 at the 29°C.

Nanofluids Preparation: The copper oxide, silicon oxide and zinc oxide nanoparticles used in this research were gotten from JoeChem Chemical Shop Port Harcourt, River's state, Nigeria. 0.1g, 0.3g, 0.5g of silicon oxide, copper (ii) oxide, zinc oxide was dissolved in equal volume of 100ml of brine respectively as to acquire homogeneous mixture of different enhanced oil recovery agents.

3.2 Core Plugs Flooding Experiment

The experimental set-up was locally designed as a flooding and liquid permeameter flow loop. The loop design has the following fixture: Electric pump, Flow meters (two), core holder (rubber butt), stem heads (two) and valves (two). After setting up the equipment for the flooding process, the following steps were carried out. The nine unconsolidated Niger - Delta core samples labeled B1 to B9 were cleaned and fully dried in an oven. B1 - B3, B4 - B6 and B7-B9 are different core samples that were flooded with nanofluids of zinc oxide, copper (ii) oxide and silicon oxide respectively at 0.1wt.%, 0.3wt.% and 0.5wt.% concentrations respectively.

i. Saturate the plug sample in brine (30,000ppm) and determine the permeability (K) using Equ. 1.
ii. Flood the saturated plug with crude oil to obtain the original oil in place (OOIP) by displacement.
iii. Commence secondary recovery by injecting the brine into the core holder to displace the oil originally in place.
iv. Start tertiary recovery by injecting the nanofluid through the core holder and record the oil recovered.
v. Restart the permeability (K_f) after enhanced oil recovery processes (EOR).

Permeability: $$K = \frac{Q\mu_{NaCl/KCl}L_{plug}14700}{A_{plug}\Delta P} \quad (1)$$

Where, Q = flow rate, μ_{NaCl} = viscosity of NaCl/KCl (Brine), L_{plug} = length of plug, A_{plug} = cross section area of plug, ΔP = differential pressure and K = permeability.

4. RESULTS AND DISCUSSION

The results provided useful insights into how some selected nanoparticles impact permeability. The results also displays the economics analysis with respect to their various concentrations and cost.

4.1. Permeability Change for the Selected Nanoparticles

The calculated permeability alteration (ΔK) in Table 1 and Fig. 2 quantifies the extent of change, which ranges from 33.37 mD to 152.21 mD. The samples with the highest initial permeabilities (B1, B4, B6) also experienced the most significant reductions, underscoring the potential impact of nanofluids on flow patterns within more permeable zones.

ZnO had the moderate permeability enhancement, likely due to its optimal 10-15nm size and positive zeta potential. This allows deeper pore penetration without much deposition. The positive charge helps ZnO strongly adsorb onto the negatively charged rock surface, altering wettability towards a more water-wet state, and easing trapped oil flow. Electric double layer mapping confirms a ZnO-rich layer formation, indicating wettability modification. A concentration of 0.3wt% ZnO gave the best results due to balancing placement and particle interactions and the moderate nanoparticles concentration.

Silicon oxide gave the best permeability change and the permeability loss occurred gradually with increasing SiO_2 concentrations (33.37md, 34.24md and 58.78md). The smaller size of silicon oxide nanoparticle (5nm) enables easy pore access, the neutrally charged SiO_2 does not interact strongly with the surface. This causes SiO_2 to simply disperse away into the void space. Some amounts may get trapped in narrow pore throats, restricting flow over long exposure times. Wettability alteration was more prominent than ZnO due to the strong particle-surface interactions. Copper (ii) oxide exhibited a permeability decrease because it has larger 15-25nm size, facing difficulty permeating small pores. Its neutral zeta potential results in weaker adsorption compared

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to positively charged ZnO. Consequently, CuO is more prone to deposition/plugging of pore throats over multiple pore volumes of injection. This restricts flow pathways more severely than the non-reactive SiO_2. In summary, a balance between sufficient pore access and strong surface interactions appears critical to optimize permeability enhancement by nanoparticles. SiO_2 best achieves this among the systems studied.

Table 1. Determination of Permeability Alternation

Dispersing particle	Conc. of EOR Fluid	Ki (mD)	K_f (mD)	$\Delta K = K_i - K_f$ (mD)
SF1	ZnO 0.1%/brine	353.87	283.1	70.77
SF2	ZnO 0.3%/brine	282.17	235.14	47.03
SF3	ZnO 0.5%/brine	281.79	156.55	125.24
SF4	CuO 0.1%/brine	347.19	277.75	64.44
SF5	CuO 0.3%/brine	281.96	234.97	46.99
SF6	CuO 0.5%/brine	355.16	202.95	152.21
SF7	SiO_2 0.1%/brine	233.59	200.22	33.37
SF8	SiO_2 0.3%/brine	238.85	204.73	34.12
SF9	SiO_2 0.5%/brine	235.09	176.31	58.78

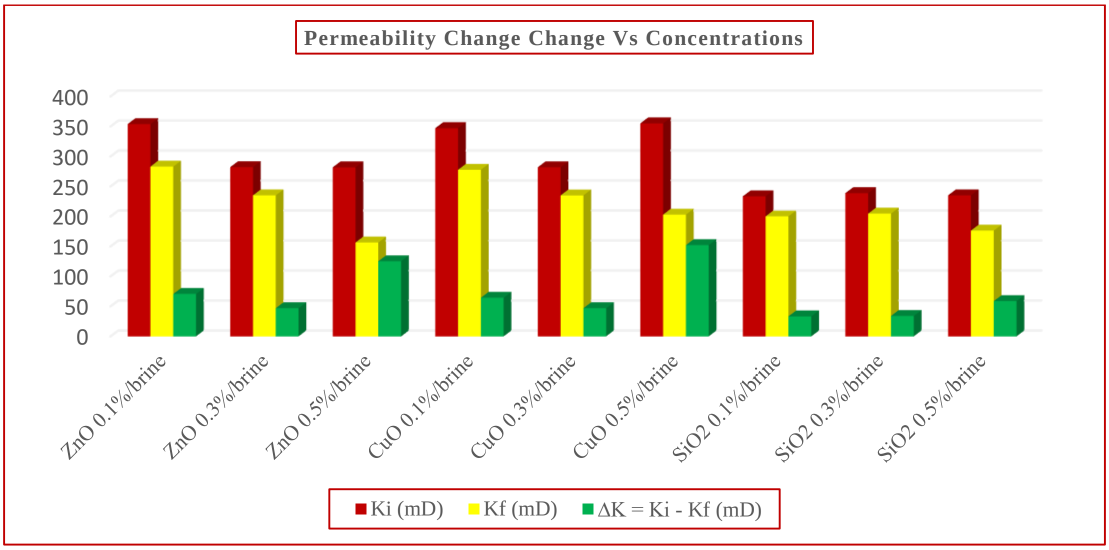

Fig. 2. Permeability Alternation Vs. Concentration.

4.2 Recovery of Crude Oil by Water and Tertiary Methods

Table 2 showcases the oil recovery results from a series of EOR experiments using nanofluids and brine. The initial oil saturation (OOIP) in the plug samples ranged from 20ml to 23ml, indicating a moderate oil content. Secondary recovery with brine achieved a Maximum of 14.5% oil recovery, demonstrating the limited effectiveness of conventional flooding techniques. Tertiary recovery using nanofluids of different concentrations (0.1%, 0.3%, 0.5%) yielded additional oil recovery, ranging from 2.5% to 4%. ZnO nanofluids generally achieved a tertiary recovery of (2.5%-4%), CuO (3%-3.5%) and SiO_2 (3%-4%). However, residual oil remained after nanofluid injection, ranging from 4.5 to 6.5, suggesting incomplete displacement.

Cumulative oil recovery, combining secondary and tertiary recovery, reached up to 80.43%, indicating a positive impact of nanofluids. Water cuts, representing the proportion of produced water, increased as expected with oil recovery, ranging from 42.53%

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to 62.02%. Breakthrough time and pressure drop during drainage varied slightly between experiments, requiring further analysis to identify correlations with fluid properties or reservoir conditions.

Table 2 and Fig. 3 depicts the highest percentage recovery is 80.43%, 78.26%, and 78.26% for plug samples B9, B8, and B2 using 0.5% and 0.3% of Silicon oxide and 0.3% of Zinc oxide in a dispersing agent of brine while the cumulative recovery from the samples ranges from 18.5ml, 18ml and 15.5ml. The recovery is at the lowest percentage rate at 0.5% conc. of ZnO and 0.1% conc. of SiO_2. Looking at Table 2, the percentage recovery is all in the range of 71% to 78.3%, so to say they have recovery tendency given the concentration percentage of the Nanofluids while some are slightly more efficient than others.

Table 2. Oil Recovery Performance with Nanofluids and Brine Flooding

Dispersing particle	Conc. of EOR Fluid	Pore volume (cm3)	OOIP(ml)	Secondary recovery (ml)	Tertiary recovery (ml)	Cumulative recovery(ml)	% Recovery
SF1	ZnO 0.1%/brine	25.16	20.00	13.00	2.50	15.50	77.50
SF2	ZnO 0.3%/brine	28.85	23.00	14.00	4.00	18.50	78.26
SF3	ZnO 0.5%/brine	26.32	23.00	13.00	3.50	16.50	71.74
SF4	CuO 0.1%/brine	25.39	22.00	13.00	3.50	16.50	75.00
SF5	CuO 0.3%/brine	26.21	23.00	14.00	3.00	17.00	73.91
SF6	CuO 0.5%/brine	24.94	22.00	13.00	3.00	16.00	72.72
SF7	SiO_2 0.1%/brine	25.18	23.00	14.00	3.00	17.00	73.91
SF8	SiO_2 0.3%/brine	27.28	23.00	14.50	3.50	18.00	78.26
SF9	SiO_2 0.5%/brine	25.76	22.00	14.50	4.00	18.50	80.43

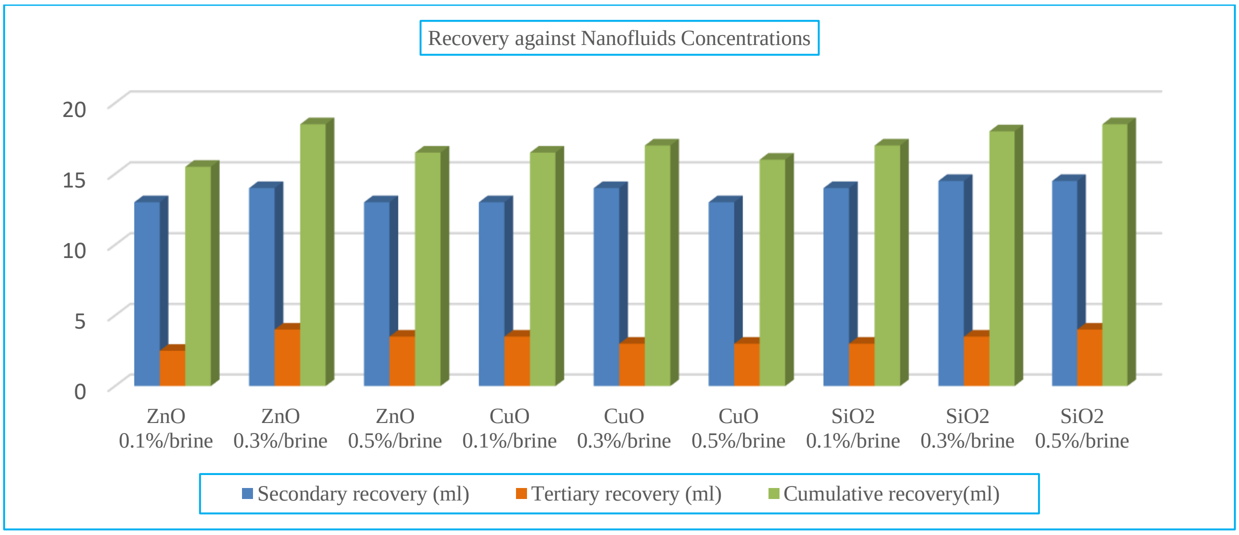

Fig. 4. Summary of the oil recoveries from samples

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4.3 Economic Analysis Results using Different Nanoparticles

The pore volume and tertiary oil recovery were considered in upscaling the data during the economic analysis. This work was done using the method adopted by [6] for economic analysis.

Table 3 shows the values of pore volume and tertiary oil recovery which is upscaling data. The upscaling data presented in Table 3 were scaled as 1 cm³ = 1 (ml) = 500bbl. The average price of the fluids is 4,795.00(N/bl) for ZnO, 15,344.00(N/bl) for CuO and 47,950.00(N/bl) for SiO_2 at the prize obtained from JeoChem in Choba, Port Harcourt River state. The economics was based on the current average crude oil price of ₦76,644.00 ($80.00) per barrel, as reported on January 5th, 2024.

The formula for calculating the cost of the dispersing particle is given as:

$$\text{Particle Concentration (\%wt)} \times \textit{Density of Brine}\left(\frac{lb}{bbl}\right) \times \textit{Particle price}\left(\frac{₦}{bbl}\right) \times bbl$$

The density of brine from this experiment is 1.0218 g/Cm³, con rting density of brine g/Cm³ t b/bbl will be giving:

But $^{1g/}{}_{Cm^3} = 8.3454\ ^{lb/}{}_{us\ gal}$; 1 bbl = 42 us gal; Thus, $^{1g/}{}_{Cm^3} = 8.3454 \times 42\ ^{lb/}{}_{bbl} = 350.5068\ ^{lb/}{}_{bbl}$

0.5 pore volume of the dispersing fluids prepared with brine were injected into the formation. Table 4 displays the overall cost of producing each dispersing fluid at various concentrations. Table 5 provides data on profit and loss, as well as revenue generated, based on the average cost of crude oil and total production cost. It is observed from Fig. 5 that an increase in the concentration of dispersing particles leads to a corresponding increase in the total cost of preparing the nanofluids. Figures 5 and 6 demonstrate that the SF2 solution which is 0.3%wt of ZnO is more economically viable than the other Table 4.

Table 3. Upscaling Data for Economics Analysis at 0.1, 0.3 and 0.5 % wt

Dispersing particles	Conc. of EOR Fluid	Pore volume (bbl)	Tertiary recovery (bbl)
SF1	ZnO 0.1%/brine	12,580	1,250
SF2	ZnO 0.3%/brine	14,425	2,000
SF3	ZnO 0.5%/brine	13,160	1,750
SF4	CuO 0.1%/brine	12,695	1,750
SF5	CuO 0.3%/brine	13,105	1,500
SF6	CuO 0.5%/brine	12,470	1,500
SF7	SiO_2 0.1%/brine	12,590	1,50
SF8	SiO_2 0.3%/brine	13,640	1750
SF9	SiO_2 0.5%/brine	12,880	2000

The nanofluids of SF7, SF8 and SF9 (0.1wt%,0.3wt% and 0.5wt% of SiO_2) lead to a massive lose which was because of high production cost, though from Fig. 4, it had a high cumulative recovery still its production cost is high. It is very efficient yet extremely expensive to use thus, it's not optimal for use. Also, SF6 (0.5wt% Copper(ii)oxide) led to a loss; its production cost is high which was read from Table 5. SF1, SF2, SF3 and SF4 concentrations gave profits with SF3 having the highest numerical profit of N116,129,516.60 and SF5 gave a marginal profit which was the least as presented in Table 5.

Table 4. Total cost of producing Dispersing fluids 0.1%wt,0.3%wt, and 0.5%wt

Nanoparticles	Conc. of EOR Fluid	0.5 pore volume (bbl)	Price (N/bbl)	Total cost of production (N)
SF1	ZnO 0.1%/brine	6290	1,717.32	10801935
SF2	ZnO 0.3%/brine	7212.5	5,151.96	37158483
SF3	ZnO 0.5%/brine	6580	8,586.59	56499785
SF4	CuO 0.1%/brine	6347.5	5,495.42	348829640

SF5	CuO 0.3%/brine	6552.5	16,486.26	107829640
SF6	CuO 0.5%/brine	6235	27,477.10	171319714
SF7	SiO_2 0.1%/brine	6295	17,173.19	108105212
SF8	SiO_2 0.3%/brine	6820	51,519.56	351363454
SF9	SiO_2 0.5%/brine	6440	85,865.94	552976622

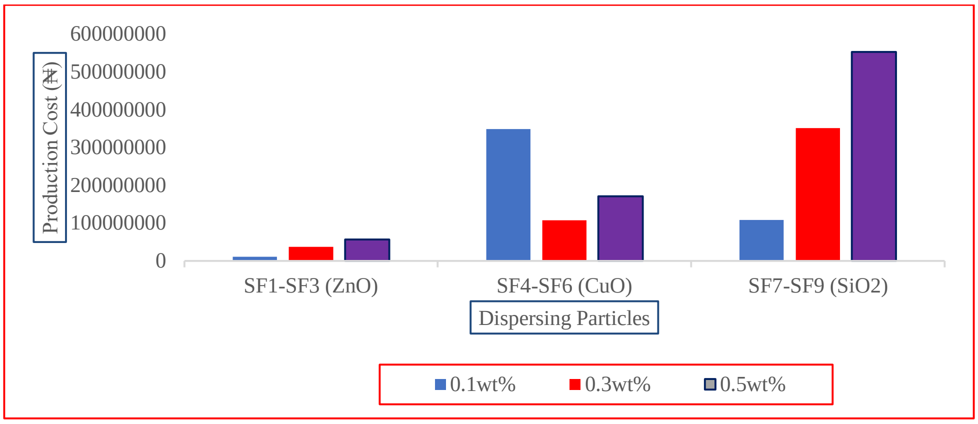

Fig. 5. Production Cost Chart for all the Dispersing Particles

Table 5. Profit/loss and Revenue Generated at 0.1-0.3%wt Concentration.

Dispersing particles	Conc. of EOR Fluids	0.5 Pore volume(bbl)	Tertiary Recovery(bbl)	Revenue Generated (N)	Profit/loss (N)
SF1	ZnO 0.1%/brine	6290.0	1250.0	95,805,000.00	85 003,065.38
SF2	ZnO 0.3%/brine	7212.5	2000.0	153,288,000.00	116,129,516.60
SF3	ZnO 0.5%/brine	6580.0	1750.0	134,127,000.00	77,627,214.77
SF4	CuO 0.1%/brine	6347.5	1750.0	134,127,000.00	99,244,822.84
SF5	CuO 0.3%/brine	6552.5	1500.0	114,966,000.00	7,136,359.60
SF6	CuO 0.5%/brine	6235.0	1500.0	114,966,000.00	- 56 353,713.5
SF7	SiO_2 0.1%/brine	6295.0	1250.0	95,805,000.00	-12,300,212.20
SF8	SiO_2 0.3%/brine	6820.0	1500.0	114,966,000.00	-236,397,453.80
SF9	SiO_2 0.5%/brine	6440.0	1500.0	114,966,000.00	-438,010,622

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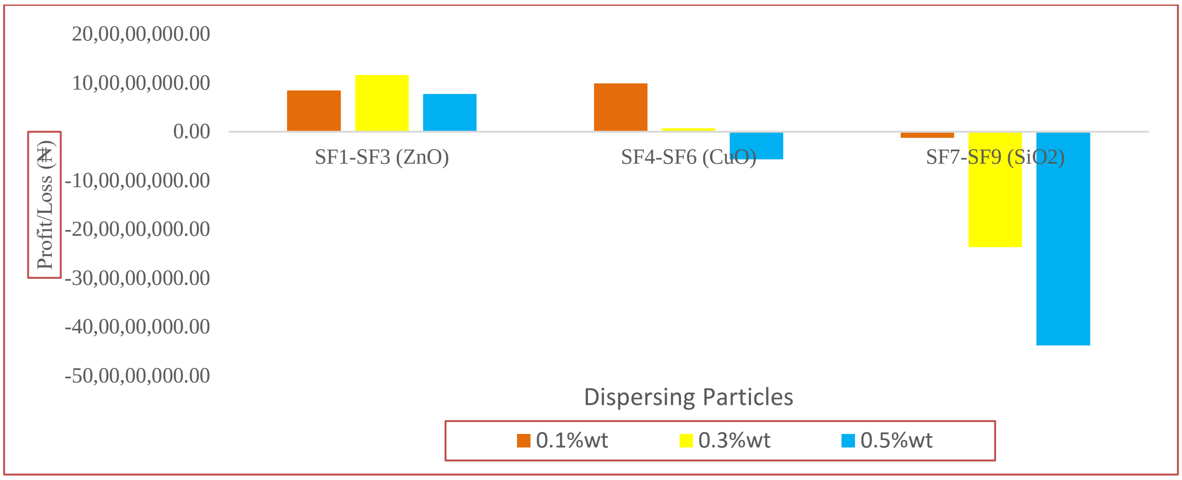

Fig. 6. Profit/Loss Chart

5. CONCLUSION

The results of this experimental study have successfully achieved the objectives of comparing the permeability alteration caused by copper (ii) oxide, zinc oxide and silicon oxide nanoparticles in oil-bearing reservoir rock. Of the three nanoparticles tested, Zinc oxide was found to be the most suitable formulation for enhancing oil recovery based on its ability to give minimal alteration on permeability of the formation, it is also economical viable as it has less cost of production and high oil recovery rate. The degree and mechanism of permeability variation due to different nanoparticles has been characterized. The findings provide insights into optimizing nanoparticle properties for maximizing recovery but at a lower cost. While this was a laboratory-based investigation, the results suggest that 0.3wt% of ZnO has promising applications in oil fields for enhanced oil recovery through permeability manipulation. Further research is recommended to translate these laboratory findings to field pilots and optimize them.

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