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Research Article

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Experimental Investigation of Some Selected Nanoparticles for Enhanced Oil Recovery using Niger Delta Formation

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Abstract The use of nanoparticles dispersed in fluid overcomes the limitation of conventional enhanced oil recovery (EOR) methods such as high cost and degradation of chemicals. Nano flooding has been proposed as the cutting-edge technology for accessing the remaining oil in the reservoir after primary and secondary production methods due their unique property of small size that can easily penetrate reservoir pore spaces. This study investigates three different nanoparticles of copper oxide, silicon oxide and zinc oxide on enhanced oil recovery using different concentration of 0.1wt.%, 0.3wt.% and 0.5wt%. The flooding experiment was done using the three different formulated nanofluids (Copper oxide, Zinc oxide and silicon oxide) on the Niger Delta sand samples plugs at 29°C temperature. The effect of viscosity and P^H was also evaluated using different concentrations of the formulated nanofluids. The result shows that three investigated nanoparticles increased oil recovery with different trend, but silicon oxide gave the highest cumulative recovery. Silicon oxide nanofluid gave the highest oil recovery with the cumulative value of 80.43% at 0.5wt.% concentration followed by zinc oxide and copper oxide nanofluids that gave cumulative oil recovery of 78.26% (0.3wt.%) and 75% (0.1wt.%) respectively. This research recommends a study on the economics analysis of these nanoparticles with respect to these concentrations as to ascertain the best nanoparticle and concentration that is economically viable for Niger Delta formation.

Keywords Concentration, Enhanced Oil Recovery, Nanoparticle, Viscosity, Petrophysical Properties

1. Introduction

The global energy landscape has undergone significant transformations, marked by an ever-increasing demand for hydrocarbon resources [1]. Conventional oil recovery methods have been the backbone of the energy industry, enabling the extraction of vast amounts of crude oil from reservoirs. However, as these conventional reservoirs reach maturity, their natural pressure declines, resulting in decreased oil production rates. This has spurred the need for more efficient and innovative techniques to recover the remaining trapped oil from reservoirs. Enhanced Oil Recovery (EOR) methods have emerged as a crucial avenue to maximize oil production and extend the lifespan of existing oilfields [2]. It encompasses a spectrum of techniques that aim to improve the displacement of oil within reservoirs. These techniques, including water flooding, gas injection, chemical flooding, and thermal methods, seek to alter reservoir conditions and fluid interactions to enhance oil mobility. Despite their successes, these methods often face challenges such as poor sweep efficiency, capillary trapping, and the inability to access certain oil pockets ([3],[4]). As a result, researchers and engineers have sought novel approaches to overcome these limitations and unlock additional oil reserves.

In recent years, nanotechnology has garnered significant attention for its potential to revolutionize EOR strategies [5]. Nanoparticles, with their unique physical and chemical properties, offer opportunities to address the shortcomings of traditional EOR methods [6]. By exploiting the nanoscale properties of materials, nanoparticles can interact with reservoir rocks and fluids in ways previously unattainable. This interaction opens avenues for modifying rock wettability, altering interfacial tensions, and enhancing fluid displacement within the reservoir ([7], [8]).

Among the various nanoparticles investigated for EOR, Iron Oxide, Zinc Oxide, and Silicon Oxide nanoparticles stand out due to their distinct properties and potential applications [9]. Iron Oxide nanoparticles, encompassing both magnetite (Fe_3O_4) and hematite (Fe_2O_3) phases, exhibit magnetism and can potentially be manipulated within the reservoir using external magnetic fields [1]. This characteristic offers the possibility of directing nanoparticles to specific reservoir regions, thereby optimizing their impact on fluid flow. Zinc oxide nanoparticles, characterized by their semiconducting behavior and photocatalytic activity, introduce an innovative mechanism for EOR. Under ultraviolet (UV) irradiation, Zinc Oxide nanoparticles generate reactive oxygen species that can modify the viscosity of heavy crude oil components [10]. This photocatalytic activity holds the promise of reducing oil viscosity and improving its mobility, particularly in challenging reservoir conditions [11]. Silicon Oxide nanoparticles, represented mainly by silica (S_iO_2), possess exceptional stability and compatibility with reservoir environments [12]. These nanoparticles have shown potential for altering rock wettability and interfacial tension, leading to improved oil displacement [5]. Moreover, their chemical inertness ensures long-term stability under reservoir conditions, extending their effects on permeability alteration [13].

Over the past years, numerous studies have shown promising results of nanomaterials application for improving hydrocarbon recovery ([14], [15], [16], [17], [18]). [15] did research on enhanced oil recovery using selected nanoparticles like Aluminium, Zinc, Magnesium, Iron, Zirconium, Nickel, and Silicon oxides. They employed different dispersing agent of diesel, distilled water, brine, and ethanol. The authors reported from their experimental result that Aluminium oxide and Silicon oxide are good, enhanced oil recovery agent as to compare to other nanoparticle investigated using ethanol as the dispersing agent. They concluded that oxides of magnesium and Zinc dispersed in distilled water and brine cause permeability problem, which limited the recovered oil.

[16] did a study on enhancing heavy oil recovery using Tin oxide nanoparticle (T_iO_2). He reported that TiO_2 nanoparticles gave 80 % increase in oil recovery in an oil-wet sandstone. [18] did an investigation work on the effect of Copper Oxide and Alumina nanoparticles on Enhanced oil recovery in carbonate reservoirs. The flooding process was carried out using eight limestone core samples with a salinity water as the dispersing agent. They concluded that the nanoparticles gave a best recovery at low concentration than at higher concentration. [14] did research on Nanofluid coreflood experiments in Arad. He studied the flooding performance of modified nanoparticles and reported that the carbon-based fluorescent NPs increase the oil recovery factor in carbonate reservoir by more than 96%.

Few studies have explored the potential of nanoparticles for EOR, a comprehensive and systematic investigation into the permeability alteration effects of some selected nanoparticles within reservoir rocks is lacking ([19], [20], [21]). [19] 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. They also built two mathematical regression models for predicting changes in permeability for Aluminium Oxide and Silica Oxide. [20] researched on the effect of Magnesium oxide, Aluminium Oxide and Silicon oxide in porous media at 45^{o}C and 3000 – 3500 Pisa. They reported that Aluminium oxide gave the highest recovery as to compare to other nanoparticles investigated. The authors also mentioned that increase in nanoparticle concentration increases the oil recovery but decreases the permeability of the reservoir formation after the flooding procedures. They reported that only Aluminium Oxide is economical at 0.2%.

[21] 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 samples. They concluded from their research that the use of nanoparticles increases recovery but reduced the permeability of

the formation after flooding process. They also built two mathematical regression models for predicting changes in permeability for Aluminum Oxide and Silica Oxide.

[22] did a review study on application of nanoparticles for EOR purposes with respect to history and current challenges. The authors suggest that the selection of the best nanoparticle type for an EOR application is critical to the reservoir rock properties and conditions, reservoir fluids type, EOR mechanism, chemicals type, chemicals concentration used in the flooding process, and NPs properties and concentration. The depletion of easily recoverable oil reserves necessitates the development of advanced EOR techniques which is the use of nanoparticle in dispersing agents. This study seeks to employ nanoparticles of copper Oxide, Zinc Oxide, and Silicon Oxide in enhancing oil recovery at different concentration.

2. Nanoparticles

Nanomaterials are nanosized particles that are smaller than one micrometre. They are classified according to their structure and shape as nanoparticles, nano-clays, and nano-emulsions, as shown in Fig. 1 [(23), (24)]. Nanoparticles are divided into inorganic nanoparticles, including ceramic and metal nanoparticles, and organic nanoparticles, including polymer, carbon, and lipid-based nanoparticles. Nano-clays consist of layers of silicate minerals such as saponite and kaolinite, while nano-emulsions are suspended systems consisting of water in oil, oil in water, and bi-continuous nano emulsions [25]. [22] showed more literature on nanoparticle.

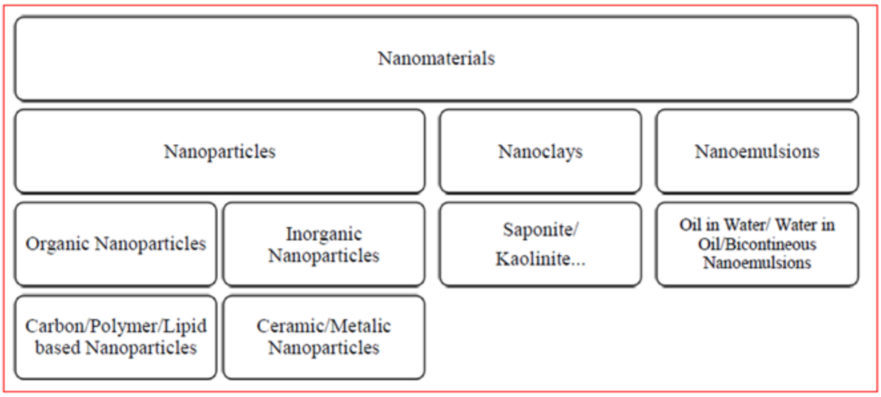

Figure 1: Types of Nanomaterials [22]

2.1 Properties of Nanoparticles used in this Study

The properties of the selected nanoparticles for this research are essential as it gives us an insight to its probability of success and failure. The diverse and unique properties of these nanoparticles offer the potential to revolutionize permeability modification strategies in Enhanced Oil Recovery, presenting novel pathways for improving fluid-rock interactions and enhancing oil recovery.

2.1.1 Iron Oxide nanoparticle

Magnetic Properties: Iron Oxide nanoparticles, consisting of magnetite (Fe_3O_4) and hematite (Fe_2O_3) phases, exhibit superparamagnetic behavior due to their nanoscale dimensions. This unique property enables them to respond to external magnetic fields, facilitating their manipulation and control within reservoirs. By applying magnetic fields, these nanoparticles can be precisely positioned and concentrated in specific regions, offering the potential for targeted permeability alteration and enhanced oil recovery [26].

High Surface Area*:* Iron Oxide nanoparticles possess an elevated surface area-to-volume ratio owing to their nanoscale size. This high surface area enhances their interaction with reservoir fluids and rock surfaces, potentially increasing the efficiency of adsorption, dissolution, and surface reactions that contribute to permeability modification [26].

Enhanced Dispersibility: The surface of Iron Oxide nanoparticles can be modified and functionalized to improve their dispersibility in various reservoir fluids. This modification ensures uniform distribution of nanoparticles within the reservoir, promoting consistent and targeted permeability alteration effects [12].

Compatibility*:* Iron Oxide nanoparticles are known for their compatibility with reservoir conditions, retaining their stability and performance across a range of temperature, pressure, and salinity conditions. This robustness makes them suitable for long-term applications in reservoirs without compromising their permeability alteration capabilities [26].

Responsive Behavior: Iron Oxide nanoparticles' superparamagnetic behavior offers a unique responsiveness to external magnetic fields. This property can be exploited to alter pore throat geometry, manipulate fluid flow paths, and enhance sweep efficiency, ultimately improving fluid conformance within the reservoir [26].

2.1.2 Silicon Oxide nanoparticles

Thermal Stability: Silicon Oxide nanoparticles, composed primarily of silica (S_iO_2), possess exceptional thermal stability. This property allows them to withstand the high-temperature conditions encountered within reservoirs, ensuring their integrity and performance during EOR operations [9].

Chemical Inertness: Silicon Oxide nanoparticles are chemically inert, making them resistant to reactivity with reservoir fluids and rock components. This inert nature preserves the stability of the nanoparticles and ensures their suitability for EOR applications without introducing unintended chemical interactions [27].

Surface Modification: The surface of Silicon Oxide nanoparticles can be modified through functionalization to tailor their interactions with reservoir rock surfaces. This modification can influence adsorption, wettability, and interfacial tension, enabling precise and targeted permeability alteration effects [9].

Reduced Interfacial Tension: Silicon Oxide nanoparticles have been shown to reduce interfacial tension between oil and water. This reduction promotes the mobilization of trapped oil by minimizing capillary forces and enhancing fluid flow, ultimately contributing to improved oil recovery and sweep efficiency [9].

Long-Term Stability: Silicon Oxide nanoparticles exhibit long-term stability under reservoir conditions. This stability ensures that the effects of nanoparticle-induced permeability alteration are sustained over extended periods, providing a consistent and durable strategy for EOR [27].

2.1 3 Zinc Oxide Nanoparticles

Semiconducting Behavior: Zinc Oxide nanoparticles exhibit semiconducting properties, particularly when exposed to ultraviolet (UV) irradiation. These properties give rise to photocatalytic activity, allowing the nanoparticles to generate reactive oxygen species that contribute to the degradation of heavy crude oil components.

Photocatalytic Activity: Under UV irradiation, Zinc Oxide nanoparticles initiate a photocatalytic process that results in the generation of reactive oxygen species. These species facilitate the breakdown of complex hydrocarbons, reducing oil viscosity and improving fluid mobility within the reservoir. This photocatalytic activity can lead to enhanced oil recovery through improved oil displacement [6].

Surface Chemistry: The surface of Zinc Oxide nanoparticles can be engineered and tailored to achieve specific interactions with reservoir fluids and rock surfaces. This ability to modify surface chemistry provides a means to optimize adsorption, wettability alteration, and interfacial tension reduction, all of which contribute to permeability modification [12].

Wettability Alteration: Zinc Oxide nanoparticles have the potential to influence the wettability characteristics of reservoir rock surfaces. By altering contact angles and fluid-solid interactions, these nanoparticles can impact capillary forces and fluid distribution within porous media, leading to improved sweep efficiency and oil recovery [12].

Chemical Stability: Zinc Oxide nanoparticles exhibit chemical stability under reservoir conditions. This stability ensures the long-term effectiveness of nanoparticle-induced permeability alteration and oil recovery, making them a viable option for EOR applications [6].

2.3 Factors Affecting Nano-Fluid Flooding Recovery

The choice of nanoparticles used: The choice of nanoparticles used for nano-fluid flooding determines the oil recovery factor and for typical reservoir conditions, the choice of appropriate nanoparticles is of great importance. Different nanoparticles have different characteristics on altering reservoir or fluid properties.

Concentration of the Nanoparticles: The nanoparticles concentration used when conducting a nano flooding assisted EOR process, is the most essential factor to consider irrespective of its bilateral influence on nano-fluid flooding. On the other hand, an increase in the nanoparticles concentration results in a reduction in porosity and permeability of the reservoir rock due to the increased rate of nanoparticle deposition on the rock surfaces. Increase in nanoparticle concentration also increases oil displacement efficiency and this can occur due to the distribution of nanofluids on the surface and increases the viscosity of fluid ([28], [29]).

*Size of nanoparticles***:** Size of nanoparticles and the corresponding charge density also affect the disjoining pressure. The smaller the size of nanoparticles, the higher the repulsive force and thus the higher the disjoining pressure that exist between them. The size of nanoparticles should be in the range, it cannot be big to be trapped or too small to cause log-jamming [30].

*Salinity***:** Ideally, the stability of nanoparticles reduces as the salinity of the system increases. In fact, increasing the salinity of the system, causes a reduction in zeta potential and hence, results in agglomeration of colloidal particles. This is due to the lack of modification of nanoparticles that maintains the disjoining pressure functionality and stability in this environment. However, increasing the salinity of the system by adding different ions doesn't prevent nanoparticles from its movement, rather, it significantly increases the deposition of nanoparticles on the rock surfaces ([30]).

*Dispersing Agent***:** The type of base fluid also has effect on the functionality of nanoparticles. Some of the dispersing fluids are distilled water, diesel, brine, and ethanol. Some of this dispersing fluid has characteristics of increasing viscosity, alteration of rock wettability and aids in giving better homogeneity with nanoparticle

3. Methodology

3.1 Materials

The experiment involved the use of nanofluids on encapsulated cores of unconsolidated Niger Delta sandstone formation. Materials include encapsulated plug sample, Crude oil, Brine, Distilled water, Potassium Chloride, Nanoparticles (Copper (ii) oxide, Silicon oxide and Zinc oxide).

3.2 Laboratory Equipment

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

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 ^{o}API gravity of 33.99 at the 29^{o}C.

Preparation of Laboratory Brine: The brine was prepared using 29.52g industrial sodium chloride (NaCl) and 0.48g potassium Chloride (KCl) in 1000liters of distilled water. The density of the formulated brine is 1.0218g/cm^3.

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 oxide, zinc oxide was dissolved in equal volume of 100ml of brine respectively as to acquire homogeneous mixture of different enhanced oil recovery agents.

3.3 Experimental Procedure

i. The nine unconsolidated Niger - Delta core samples labeled B1 to B9 were cleaned and fully dried in an oven. B1 to B3, B4 to B6 and B7-B9 are different core samples that will be flooded with nanofluids of zinc oxide, silicon oxide and copper oxide respectively.
ii. The various core’s weight, length and diameter were measured, and the results are presented in Table 2.
iii. The cores were fully submerged or saturated in a laboratory brine water as to measure the saturated weight of the individual core samples.
iv. The pore volume of each core sample was calculated using Equation 1, by subtracting the saturated weight from dry weight and the result was divided by the density of the brine solution and result is shown in Table 4.
v. The porosity was determined by using the result obtained from bulk volume (Table 2) and pore volume (Table 4) using Equation 2.
vi. The flooding experiment started by injecting crude oil into the core to displace the brine solution. It should be noted that not all the brine solution was displaced, and the remaining water is known as connate water.
vii. The same quantity of oil that entered the unconsolidated core is equivalent to brine solution displaced from the core sample at constant flow rate.

viii. The brine was injected (secondary recovery) into the core to displace crude oil and the amount of oil recovered was measured and recorded. The laboratory brine water injection was a control experiment.

ix. Other laboratory experiments were carried out following the above procedures. The water breakthrough time was recorded.

x. The different concentrations of nanofluid EOR agents as presented Table 5 were injected into the individual core until no oil could be recovered at the residual oil saturation.

xi. Finally, the unconsolidated core was removed from the core-holder and re-weighted, the recovered oil was measured and permeability was determined using Equation 3 and was presented in Table 5.

Pore Volume Equation: $PV = \frac{W_{sat.plug} - Weight_{dry\ plug}}{P_{NaCl}}$ (1)

Where; $W_{sat.plug}$ = weight of saturated plug, $Weight_{dry\ plug}$ = weight of dry sample, P_{NaCl} = density of Brine

Porosity: $Porosity, \emptyset = \frac{P.V}{B.V} \times 100\%$ (2)

Where, P.V = pore volume, B.V = bulk volume

Permeability: $K = \frac{Q\mu_{NaCl/KCl} L_{plug} 14700}{A_{plug} \Delta P}$ (3)

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 of the experimental evaluation using different nanoparticles of copper oxide, zinc oxide and silicon oxide for enhanced oil recovery using brine as the dispersing agents is presented. It examines the physical characteristics of plug samples, rheological properties, fluid properties, and their effects on oil recovery and permeability.

4.1 Petrophysical Results

Understanding the physical properties of the plug samples is paramount for interpreting flow behavior and fluid-rock interactions during enhanced oil recovery (EOR) processes. This section presents a detailed characterization of the encapsulated plug samples, encompassing their bulk volume, pore volume, and porosity.

The measured bulk volumes of the encapsulated plug samples varied from 5 7.48 cm³ and 62.18 cm³, as shown in Table1. This observed range highlights the natural heterogeneity of reservoir rocks, even within a single formation. Such variations can be attributed to differences in mineral composition, grain size distribution, and geological history. Understanding this heterogeneity is crucial for designing effective EOR strategies that account for varying flow patterns and fluid-rock interactions.

Table 1: Experimental Result of Bulk volume of an Encapsulated plug Sample

Plug Id	Plug Length (cm³)	Plug Diameter (cm³)	Plug radius (cm³)	Bulk Volume $\pi r^2 h$(cm³)
B1	6.56	3.34	1.67	57.48
B2	6.93	3.38	1.69	62.18
B3	6.64	3.36	1.68	58.88
B4	6.41	3.38	1.69	57.52
B5	6.66	3.36	1.68	59.05
B6	6.68	3.34	1.67	58.53
B7	6.70	3.38	1.69	60.12
B8	6.98	3.34	1.67	61.16
B9	6.68	3.36	1.68	59.23

Table 2 reveals the pore volumes of the plug samples, ranging from 25.16 cm³ to 28.85 cm³. This range reflects the storage capacity of the reservoir, with higher pore volumes indicating a greater potential for oil accumulation. The variability in pore volumes likely stems from differences in pore size distribution, connectivity, and the presence of natural fractures. These factors significantly influence fluid flow and oil recovery during EOR processes.

The calculated porosity values using Equation 2, are also presented in Table 2, which range from 41.88% to 46.40%. Porosity is a critical measure of the accessible pore space within the rock matrix, directly impacting fluid flow and oil recovery potential. The observed variations in porosity suggest a degree of heterogeneity in pore structure and connectivity within the reservoir. This heterogeneity needs to be considered when modeling and predicting fluid displacement mechanisms during EOR.

Generally, the analysis of plug characterization results underscores the importance of capturing reservoir heterogeneity and its implications for EOR processes. The observed variations in bulk volume, pore volume, and porosity highlight the complexities of the reservoir system and the need for tailored EOR strategies that can address these variations effectively. Understanding these characteristics is essential for designing efficient and successful EOR operations that maximize oil recovery while minimizing potential risks and uncertainties.

Table 2: Experimental Result of pore volume of an Encapsulated plug Sample

Plug ID	Wt of Dried plug + screen + foil (g)	Wt of saturated plug + screen + foil (g)	Wt of saturation within the pore (g)	Density of saturated fluid 30,000ppm g/dm^3	Pore volume (cm^3)	Porosity (%)
B1	131.87	157.58	25.71	1.0218	25.16	43.77
B2	143.73	173.21	29.48	1.0218	28.85	46.40
B3	133.89	160.78	26.89	1.0218	26.32	44.70
B4	131.89	157.68	25.94	1.0218	25.39	44.14
B5	131.74	160.52	26.78	1.0218	26.21	44.39
B6	126.27	151.75	25.48	1.0218	24.94	42.61
B7	133.10	158.83	25.73	1.0218	25.18	41.88
B8	138.89	166.75	27.86	1.0218	27.28	44.60
B9	133.58	159.90	26.32	1.0218	25.76	43.49

4.2 Fluid Properties

Table 3 shows the measured values for density and pH for each nanofluid examined. These properties govern fluid flow, displacement mechanisms, and interactions with the rock matrix, ultimately shaping the effectiveness of EOR strategies. A meticulous examination of these tables will illuminate trends and variations in fluid properties, sparking insights into their potential impact on oil recovery.

Table 3 reveals subtle variations in density and pH among brine, crude oil, and the different nanofluid concentrations. The density values mostly hover around 1.02 g/cm³, with negligible difference between brine and nanofluids, suggesting minimal impact on buoyancy-driven flow mechanisms. However, the crude oil stands out with a significantly lower density (0.9996 g/cm³), highlighting its buoyancy potential for improved oil mobilization during EOR. The pH remains relatively constant across all fluids, ranging from 6.6 to 7.2 for nanofluids and 8.4 for brine. This narrow range indicates minimal risk of fluid incompatibility or rock matrix alteration through pH changes.

Table 3: Experimental Result of Fluid Density and pH

Fluid sample ID	Fluids concentration	Wt. pycnometer	Volume of Pycnometer	Wt. pycnometer + fluid (g)	Wt. fluid (g)	Density of fluid sample (g/cm³)	pH
SF 1	ZnO 0.1%/brine	22.66	56.39	80.08	57.42	1.0183	7.10
SF 2	ZnO 0.3%/brine	22.66	56.39	80.28	57.62	1.0218	7.10
SF 3	ZnO 0.5%/brine	22.66	56.39	80.39	57.73	1.3400	7.20
SF 4	CuO 0.1%/brine	22.66	56.39	79.87	57.21	1.0145	6.70
SF 5	CuO 0.3%/brine	22.66	56.39	80.27	57.61	1.0216	6.90
SF 6	CuO 0.5%/brine	22.66	56.39	80.33	57.67	1.0227	7.20

SF 7	SiO 0.1%/brine	22.66	56.39	80.27	57.61	1.0216	6.80
SF 8	SiO 0.3%/brine	22.66	56.39	80.31	57.65	1.0227	6.70
SF 9	SiO 0.5%/brine	22.66	56.39	80.32	57.66	1.0225	6.60
	Brine 30,000ppm	22.66	56.39	80.28	57.62	1.0218	8.40
	Crude oil 33.0API	22.66	56.39	79.03	56.37	0.9996	

Table 4 showcases the kinematic viscosity values for each fluid at 29°C. Notably, crude oil exhibits the highest viscosity (12.22 cp), significantly hindering its flow compared to brine and nanofluids. Among nanofluids, a slight increase in viscosity is observed with increasing nanoparticle concentration, indicating potential changes in flow behavior and interaction with the rock matrix. However, these increases are relatively small compared to the viscosity of crude oil, suggesting potential benefits for enhanced oil mobility with nanofluids.

Dividing kinematic viscosity with fluid density, we can calculate the dynamic viscosity for each sample. Crude oil again shines a spotlight with its high dynamic viscosity (12.22 cp), further emphasizing its flow resistance. The nanofluids, despite a minor rise in kinematic viscosity, show a limited increase in dynamic viscosity compared to brine. This observation reinforces the potential of nanofluids to improve flow conditions and facilitate oil displacement within the reservoir.

The analysis of fluid properties highlights crucial factors for EOR effectiveness. The low density and viscosity of nanofluids compared to crude oil suggest their potential to overcome oil's inertia and enhance flow. Additionally, the minimal variations in pH between fluids minimize concerns about rock alteration or incompatibility. Further investigating the interplay between these properties and oil recovery data in subsequent sections will reveal the true impact of nanofluids on EOR performance.

The fluid properties of brine, crude oil, and nanofluids play a crucial role in EOR. Crude oil's high viscosity and density compared to brine hinder its flow, while nanofluids offer a promising alternative with their lower viscosities. Table 4 reveals a slight increase in viscosity with increasing nanofluid concentration, suggesting potential trade-offs between enhanced flow and nanoparticle aggregation. Density variations within the tested fluids are minimal, suggesting negligible impact on buoyancy-driven flow mechanisms.

Table 4: Kinematic and Dynamic Viscosity of Fluids

Fluid sample ID	**Fluids concentration**	**Fluid Temp(ºC)**	**Viscometer Constant (150/601B)**	**Efflux time (Sec)**	**Kinematic Viscosity (cst)**	**Fluid Density (g/cm3)**	**Dynamic Viscosity (cp)**
SF 1	ZnO 0.1%/brine	29	0.03641492	24.64	0.8973	1.0183	0.9137
SF 2	ZnO 0.3%/brine	29	0.03641492	24.98	0.9096	1.0218	0.9295
SF 3	ZnO 0.5%/brine	29	0.03641492	25.83	0.9402	1.3400	1.2599
SF 4	CuO 0.1%/brine	29	0.03641492	24.77	0.9020	1.0145	0.9151
SF 5	CuO 0.3%/brine	29	0.03641492	25.03	0.9115	1.0216	0.9312
SF 6	CuO 0.5%/brine	29	0.03641492	25.12	0.9147	1.0227	0.9355
SF 7	SiO 0.1%/brine	29	0.03641492	24.75	0.9013	1.0216	0.9207
SF 8	SiO 0.3%/brine	29	0.03641492	24.81	0.9035	1.0227	0.9240
SF 9	SiO 0.5%/brine	29	0.03641492	25.04	0.9118	1.0225	0.9323
	Brine 30,000ppm	29	0.03641492	24.94	0.9082	1.0218	0.9280
	Crude oil 33.0API	29	0.03641492	335.68	12.2238	0.9996	12.2189

4.3 Result for Oil Recovery

The flooding experiment unveils the oil recovery results achieved with different nanofluids formulated with zinc oxide, silicon oxide and copper oxide in comparison to conventional brine flooding. By meticulously analyzing the results, we have uncovered the hidden mechanisms behind oil mobilization and the unique contributions of nanofluids in unlocking previously inaccessible reserves.

Table 5 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 20 to 23 ml, indicating a moderate oil content. Secondary recovery with brine achieved a maximum of 13.5ml oil recovery, demonstrating the limited effectiveness of conventional flooding techniques hence introduction of EOR methods. Tertiary recovery using nanofluids of different concentrations of 0.1wt.%, 0.3wt.% and 0.5wt.% yielded additional oil recovery, ranging from 2.5ml to 4ml. The zinc oxide nanofluid achieved a tertiary recovery of 2.5ml to 4ml while Copper oxide gave recovery of 3ml to 3.5ml and Silicon oxide 3ml to 4ml. However, residual oil remained after nanofluid injection, ranging from 4.5ml to 6.5ml suggesting incomplete displacement (Fig. 4).

Percentage cumulative oil recovery was gotten by combining secondary and tertiary recovery which gave up to 80% for all the fluid investigated, indicating a positive impact of nanofluids on oil recovery (Table 5 and Fig. 1). Silicon oxide nanofluid gave the highest oil recovery with the cumulative oil recovery of 80.43% among all the nanofluids evaluated. It increases oil recovery as the concentration increases from 0.1% to 0.5% and the highest recovery was gotten at 0.5% weight. It shows that silicon oxide was able to reduce the interfacial, modifies the formations and increased the stability.

Table 5: Oil Recovery Performance with Nanofluids and Brine Flooding

Plug ID	OOIP (ml)	Sec. Recovery	Conc. of EOR Fluid	Tertiary Recovery (ml)	Residual oil (ml)	H_2O Cut	Breakthrough time @ drainage	ΔP @ Drainage (Psia)	Cumm. Recovery (ml)	Oil Recovery (%)
B1	20.0	13.0	ZnO 0.1%/brine	2.5	4.5	52.0	42.53	6.5	15.5	77.50
B2	23.0	14.0	ZnO 0.3%/brine	4.0	5.0	62.0	57.15	7.0	18.0	78.26
B3	23.0	13.0	ZnO 0.5%/brine	3.5	6.5	63.0	59.05	7.0	16.5	71.74
B4	22.0	13.0	CuO 0.1%/brine	3.5	5.5	61.0	46.12	6.5	16.5	75.00
B5	23.0	14.0	CuO 0.3%/brine	3.0	5.0	63.0	60.56	7.0	17.0	73.91
B6	22.0	13.0	CuO 0.5%/brine	3.0	6.0	57.0	48.02	6.5	16.0	72.72
B7	23.0	14.0	S_iO_2 0.1%/brine	3.0	6.5	62.0	59.48	7.0	17.0	73.91
B8	23.0	14.5	S_iO_2 0.3%/brine	3.5	6.0	60.0	61.02	7.0	18.0	78.26
B9	22.0	14.5	S_iO_2 0.5%/bri	4.0	5.5	55.0	48.23	6.5	18.5	80.43

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Zinc oxide nanofluid increases oil recovery from 77.50% to 78.26% for the concentrations of 0.1% and 0.3% but reduces at 0.5% wt. The recovery at 0.3% wt. concentration is 78.26% as to compare with recovery at 0.5% wt. concentration which gave 71.74% cumulative recovery (Figs. 2 and 3). The results show that at higher concentration of 0.5%wt, the zinc oxide nanoparticle blocked the reservoir pore thereby reducing the oil recovery. This result is in line with the result reported by [15]. Copper oxide nanofluid decreases in recovery as the concentrations increases from 0.1%, 0.3% and 0.5% with the cumulative oil recovery of 75%, 73.91% and 72%. The experimental study showed that the 0.1% copper oxide weight gave the best positive result as to compare with other concentrations.

Water cut, representing the proportion of produced water, increased as expected with oil recovery, ranging from 42.53% to 62.02% (Table 5). Breakthrough time and pressure drop during drainage varied slightly between experiments, requiring further analysis to identify correlations with fluid properties or reservoir conditions. Table 5 and Fig. 3 shines a spotlight on the transformative power of nanofluids. Tertiary recovery with nanofluids consistently surpassed brine flooding, demonstrating their ability to mobilize previously trapped oil. S_iO nanofluids generally achieved slightly higher oil recovery compared to CuO and ZnO, indicating potential differences in their interaction with the rock-oil interface and mobilization mechanisms. However, residual oil remains after nanofluid injection, suggesting further optimization of nanofluid formulation and injection strategies is needed to maximize oil extraction (Fig. 4).

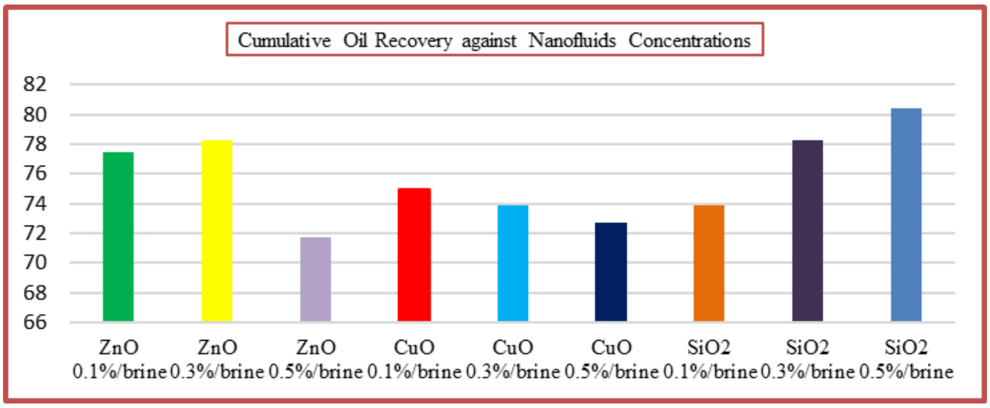

Figure 2: Cumulative Oil Recovery vs Fluid Concentration

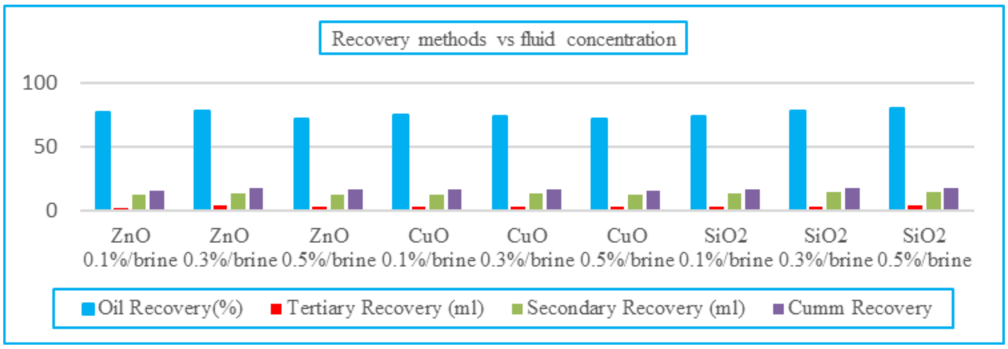

Figure 3: Recovery methods vs fluid concentration

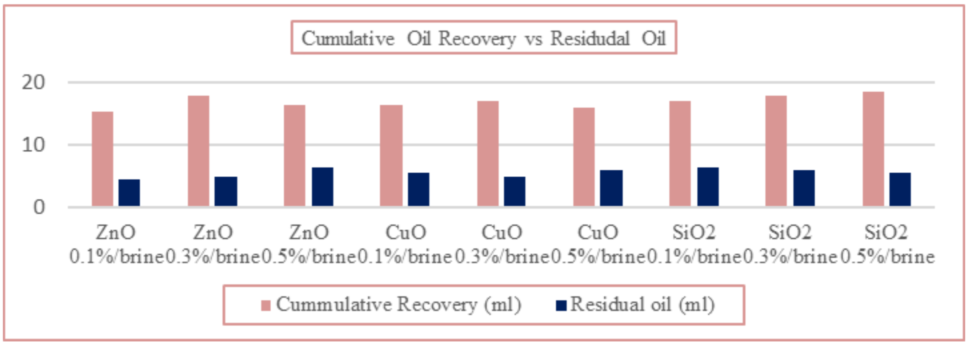

Figure 4: Cumulative Oil Recovery vs Residual Oil

5. Conclusion

Copper oxide, zinc oxide and silica Oxide nanomaterials were used to investigate enhanced oil recovery using different concentrations of 0.1wt.%, 0.3wt.% and 0.5wt.%. Based on the experimental results, all the nanoparticles studied gave the highest oil recovery based on the different concentrations. Silicon oxide nanofluids gave the highest cumulative oil recovery of 80.43% at 0.5wt.% concentration, while copper oxide and zinc oxide gave the highest oil recovery 73.91% and 78.26% at the different concentrations of 0.1wt.% and 0.2wt.% respectively. Economics analysis using these nanoparticles at these concentrations is required as that will help to select the best nanoparticle that will yield the highest profit. Nanofluids demonstrated the ability to enhance oil recovery beyond conventional brine flooding, albeit with varying degrees of success. Further investigations are crucial to optimize nanofluid concentration and composition, assess long-term reservoir impacts, including permeability changes, explore the mechanisms behind oil mobilization by nanofluids as well as evaluate economic feasibility and field-scale application potential.

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