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Laboratory Investigation of Effects of Nanoparticles and Carbon Dioxide Flooding on Heavy Crude Recovery

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ABSTRACT
In this research, the effectiveness of carbon-dioxide (CO_2) enhanced oil recovery/production is systematically assessed along with various mass percent (%) concentration of nanoparticles. This study investigates experimentally, the Production rate of the crude oil recovered, cumulative oil recovered and the recovery factor using magnesium oxide (MgO), aluminum oxide (Al_2O_3) and combination of both magnesium and aluminum oxide in various mass percent concentrations (5 – 25 grams) with carbon-dioxide assisting in the drive. After measuring ten (10) liters of heavy crude oil, Magnesium and Aluminum Oxide (MgO and Al_2O_3) nanoparticles in amounts of 5, 10, 15, 20, and 25 grams were added and mixed. The nanoparticles were combined in equal mass percent concentrations and allowed to soak for 24hrs and all pumped at 1bar of CO_2 in an enhanced-oil-recovery system set up in the laboratory. The density, viscosity, flow rate, and heavy crude oil recovered were measured at the different mass percent of the nano-particles. The result shows that increase in mass percent concentration reduced the density from 1.02g/cc to 0.977g/cc for MgO nanoparticle and CO_2, 0.974g/cc density was also recorded for Al_2O_3 and CO_2 and 0.985g/cc was recorded after the combination of both nanoparticles. Concentrations increased API from 5.98°API to 13.3°API for MgO, 14.8°API was also recorded for Al_2O_3 and 14.2°API after the combination. The Viscosity also increased with increase in mass percent concentration from 5.83cp to 9.19cp for MgO, 8.35cp for Al_2O_3 and 7.89cp after the combination. The Production rate increased from 0.7 ml/s to 0.89 ml/s for MgO, 0.7ml/s to 0.8ml/s for Al_2O_3 and 0.7 ml/s to 0.89 ml/s after the combination. Cumulative production increased from 7litres to 8.96litres for MgO, 7litres to 8litres for Al_2O_3 and 7litres to 8.9litres for the combination with increase in the mass percent concentration of the nanoparticles. This result establishes that nanoparticles and carbon dioxide gas injection activities undoubtedly improved the recovery of heavy crude oil from a depleted reservoir using enhanced oil recovery method.

KEYWORDS: Carbon-dioxide, Heavy Crude Laboratory Investigation, Nanoparticles, and Recovery.

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1.0 INTRODUCTION

According to Lake and Venuto (1990), the primary and secondary oil recovery procedures, which are commonly thought of as traditional recovery methods, only recover around one-third of the initial oil that was in the reservoir. The estimated size of the world's oil reserves is 1.5 trillion barrels, with a sizable portion of the oil still trapped after conventional recovery as residual oil saturation (ROS) (Council, 1976). Thermal recovery, chemical flooding (alkaline-polymer (AP), surfactant-polymer (SP), surfactant-polymer-polymer (SPP), and alkaline-surfactant are some of the enhanced oil recovery (EOR) techniques that are categorized as tertiary production schemes (Alboudwarej *et al.,* 2010).
After primary and secondary recovery, there is still need to find a cost-effective and efficient approach to extract the residual oil, and current

tertiary procedures are reliant on crude oil prices (Maggio & Cacciola, 2009; Kong & Ohadi, 2010). Therefore, further research is required to present strategies that are environmentally friendly, economical, efficient, and sustainable. Any EOR system generally aims to reduce residual oil saturation (ROS), which is what is left over after primary and secondary recovery methods have reached their maximum output. The three fundamental phases of producing crude oil from an oil reservoir are primary, secondary, and enhanced recovery.

These actions occur in the correct order. Each stage of a well's development happens as it is initially completed, then as the oil needs to be taken artificially since the natural formation pressure is insufficient (Jie *et al.,* 2021). When a well is finished and starts to spontaneously flow, this is known as the first or primary phase of recovery. It also involves the use of basic artificial lift techniques, such as various mechanical, hydraulic, and electrical lifts. The early recovery stage is also said to include the basic phases of treatment and well stimulation (Abdullah *et al.,* 2006).

Secondary recovery is the process of recovering fluid after an operation has begun by flooding it with water or injecting gas to force it toward the well. In order to recover oil that has not yet been recovered using primary or secondary oil recovery procedures, enhanced oil recovery, also known as "tertiary recovery," is performed (Amani *et al.,* 2010). EOR techniques are becoming more crucial, particularly in view of the limited global crude oil reserves. The properties of a reservoir and the fluids it contains determine the type of EOR technology to be used to it. To economically recover as much original oil *in situ* (OOIP) as possible is the aim of improved oil recovery (Congge *et al.,* 2019; Ghafoor & Arvin 2010). The Microbial Enhanced Oil Recovery (MEOR) approach has been devised and tested in order to improve the recovery of heavy crude oil (Nmegbu *et al.,* 2022a). By lowering the viscosity and interfacial tension of the heavy crude oil, microbes introduced into the reservoir boosted recovery (Nmegbu *et al.,* 2022b). By reducing oil viscosity and enabling miscible or partially miscible displacement of the oil, carbon(iv) oxide has also been tested to boost output (Rojas *et al.,* 1991). Even if carbon-dioxide miscibility in heavy oil instances is seldom achieved, oil recovery can still be greatly enhanced. The main mechanism of carbon dioxide methods in heavy oil is viscosity reduction. The viscosity of heavy oil can be reduced by 10 times even when carbon dioxide is only partially dissolved in it (Roja *et al.,* 1991). Recently, nanotechnology has found use in oil recovery. According to Bera and Belhaj (2016), some nanoparticles (NPs) have been shown to improve oil recovery (EOR) by altering wettability, fluid properties, trapped oil mobility, sand consolidation, and interfacial tension (IFT). Given that wettability has a significant impact on oil recovery, numerous analyses of the impact of nanoparticles on wettability have been conducted (Gomari et al., 2006). Roustaei and Bagherzadeh (2015) looked into how SiO_2 nanoparticles affected the wettability of carbonate reservoir rocks and found that they act as wettability modifiers for carbonate systems, changing the strongly oil-wet state of wettability of carbonate rocks to a strongly water-wet state. In order to solve the issue of residual oil in heavy and semi-heavy oil reservoirs, new EOR techniques have been developed using nanomaterials over the past 10 years (Roustaei & Bagherzadeh, 2015; Homayoni *et al.,* 2009). The use of nanomaterials in thermal and chemical enhanced oil recovery is now the most cutting-edge method.

Various research projects have used silicon oxide nanoparticles (SiO_2), aluminum oxide nanoparticles (Al_2O_3), and other common types of nanoparticles (NPs) for mobility control with excellent results in minimizing water cut, enhancing sweep efficiency, and increasing oil recovery (Diaz-Munoz & Farouq 1975).

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By reducing the capillary force and relative permeability of the water, these chemicals can change the water flow channel in porous media. As well as patterns of density variation with change in nanoparticle concentrations, zinc oxide nanoparticles have also demonstrated a tendency to decrease the density and increase the API gravity of heavy crude oil (Uranta *et al.,* 2022).

In the quest to enhance heavy crude oil recovery, the need to combine the various techniques is necessary. Most research done were limited to use of the conventional tertiary techniques tested. This work evaluates the effectiveness of carbon(iv) oxide with Magnesium and Aluminum Oxide for enhanced heavy crude oil recover.
The objectives of this study were to investigate the effects of Nanoparticles and Carbon-dioxide on the physical properties of heavy crude oil at different mass percent concentrations (5, 10, 15, 20 and 20 grams). This study also considered the evaluation of the flowrate of the heavy crude oil recovered at various mass percent concentration of nanoparticles.

2.0 MATERIALS AND METHODS

2.1 Materials

The following materials were used during this investigation; they include Distillate water, Heavy Crude Oil, Nanoparticles (MgO and Al_2O_3), CO_2 (gas), EOR apparatus, Redwood Viscometer, Digital weighing balance, stop watch pycnometer, measuring cylinder and separating.
The size of nanoparticles that were used in the course of this research were 30nanometer for MgO and 40 nanometers for Al_2O_3 respectively.

2.2 Methods

2.2.1 Heavy Crude Oil Density Determination

Before setting the pycnometer on the weighing balance, the pycnometer's exterior and interior was wiped with a dried towel to make sure it was dry. The weight of the empty pycnometer was recorded and filled with 50 ml of the heavy crude oil at room temperature, the stopper was then engaged. The pycnometer containing the heavy crude oil was re-weighed on a weighing balance and the reading was also recorded. The following mathematical expression was used to calculate the density.

$$Density\ (\rho) = \frac{Mass}{Volume} \quad (1)$$

$$Mass = W_2 - W_1 \quad (2)$$

Where;
W_2 = Weight of pycnometer filled with crude
W_1 = Weight of pycnometer without sample

$$API\ (°) = \frac{141.5}{S.G} - 131.5 \quad (3)$$

Specific Gravity (S.G)

$$S.G = \frac{\rho_o}{\rho_w} \quad (4)$$

Where;
$\rho_o = Density\ of\ Oil$
$\rho_w = Density\ of\ water$

2.2.2 Heavy Crude Oil Viscosity Determination

The water bath was filled with water with a thermometer inserted to measure the temperatures of both the water and the crude oil, and the cylindrical oil cup was filled with heavy crude oil to the reference mark in the cup. The ball-ended spindle was raised and oil was collected in the 50 ml beaker at room temperature as shown in Figure 1. The time it took for the oil to completely drain the 50 ml crude was measured using a stop watch, it is significant to highlight that the kinematic viscosity of the crude material determined by the Redwood device cannot be used as a substitute for viscosity in viscosity-related calculations. As a result, once density is determined (known), the kinematic viscosity acquired from the Redwood viscometer will be translated to dynamic viscosity.
Kinematic Viscosity of the Redwood Viscometer

$$\mu\ (cp) = At - \frac{B}{t} \quad (5)$$

Where;

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t = Time (sec)
A and B are Redwood constant parameters
A= 0.026   B = 0.188

Figure 1: Redwood Viscometer (Department of Petroleum Engineering Laboratory, Rivers State University)

2.2.3 Enhanced Oil Recovery (EOR) of the Heavy Crude Oil

This was accomplished using an improved oil recovery laboratory setup, which may be used for a number of enhanced oil recovery methods, including polymer flooding, gas injection, and water injection. In this study, nanoparticles and carbon dioxide were used to enhance the recovery of heavy crude oil. Carbon dioxide (CO_2) was employed in this experiment as the reservoir driving force to increase the pressure after the primary energy has been depleted. The setup is made up of a series of equipment that resembles the setup of a typical example of a reservoir and a well head.

The 12-liter metal tank that serves as the reservoir is connected to a cylindrical pipe that has a tap handle (that sits at the well head valve) and a pressure gauge that measures the inlet pressure P_1 that is connected to a cylinder that holds carbon dioxide (reservoir inlet pressure). A pressure gauge that shows the P_2 output pressure, a condenser to condense any possible gas, a second tap handle that acts as a valve to send oil to the collection container, and a condenser. A test run was performed after the carbon dioxide cylinder was correctly turned off to ensure there was no liquid in the tank or flow line. This trial run also demonstrated that the valve was almost certainly shut as shown in Figure 2.

After determining the properties of the crude oil to be injected, 10 liters of the crude were measured, poured into a large bowl, and then moved to the tank (reservoir) and flooded using the carbon dioxide that acts as the basis (control). Following that, 5 grams' mass percent of individual Al_2O_3 and MgO nanoparticles were measured and added to the bowl containing the crude oil. To achieve homogeneity, a mixer was used to properly combine the crude and nanoparticle. After that, the mixture was poured into the tank, which was then filled with carbon dioxide gas and left to soak for 24 hours. When the cylinder containing the carbon dioxide is opened, the valves must also be opened, and a stopwatch should be set for 10 seconds.

As the fluid moves through the flow-line, the intake pressure P_1 and the output pressure P_2 were noted. The carbon dioxide cylinder valve should be closed when the ten seconds have passed, and the flow-line valves should likewise be put back in their closed positions. After flooding, a 1000 ml measuring cylinder was used to record the amount of recovered crude after the first 10 seconds of flow. Using a retort stand, a known volume of the recovered mixture was put into a separating funnel and let to stand for 24 hours. Following a 24-hour standing period, the crude was separated, and its petro physical characteristics were assessed using the industry-standard techniques. The steps were repeated with varied nanoparticle mass percent

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concentrations (10, 15, 20, and 25 grams) of the nanoparticles respectively.

Figure 2: Enhanced Oil Recovery Laboratory Set-up (Department of Petroleum Engineering Laboratory, Rivers State University).

3.0 RESULTS AND DISCUSSION

3.1 Initial Properties and Result After Flooding the Heavy Crude with CO_2.

Table 1 shows the initial properties and result after flooding the heavy crude with CO_2. The density of the crude decreased by 0.02g/cc from 1.0292g/cc after the crude was flooded with carbon-dioxide (CO_2), API increased by 0.03 °API. The viscosity increased to 5.83 cp from 5.64 cp in viscosity and a flowrate of 0.7ml/s, the volume of the crude that was recovered was 7 liters from the 10 liters that was measured and poured into the reservoir (tank). The temperature of the injected CO_2 was 24°C

Table 1: Initial Properties and Result After Flooding the Heavy Crude with CO_2.

S/No	Parameters	Initial Oil Properties	After flooding with CO_2
1	Density (g/cc)	1.019	1.0292
2	API (°)	5.985	6.022
3	Viscosity (cp)	5.64	5.83
4	Flowrate(ml/s)	nil	0.7
5	Volume Recovered (L)	nil	7
6	Pressure (psi)		1Ibar = 14.504psi

3.1.1 Enhanced Oil Recovery Process

a. Effect of Nanoparticles and CO_2 on Density of the Heavy Crude Oil

The effects of nanoparticles and carbon-dioxide on the heavy crude oil density is presented in Figure 3. The density of the heavy crude oil decreases rapidly from 1.03g/cc to 0.98g/cc after 5grams of the MgO nanoparticle was introduced into the system. The density decreased by 0.4g/cc when another 10grams was added. A further decrease of about 0.17g/cc was recorded at 15gram of the same nanoparticle, however at 20g, there was an increased. The density increased to 0.984g/cc from 0.954g/cc and decreased to 0.977g/cc for 25 grams, the reason for the sudden increase in density could be because the optimum density has not been reached. For aluminum oxide nanoparticle, it is shown that the density of the crude oil decreased rapidly from 1.03g/cc to 0.967g/cc after 5 grams of the stated nanoparticle was introduced into the system. The density remained steady when another 5 grams of the constitute was added. A decrease of about 0.0004g/cc was recorded at 15 gram of the same nanoparticle, however at 20 grams, the movement was rather upwards. The density increased to 0.9684g/cc from 0.966g/cc then further upwards to 0.974g/cc for 25. Considering both nanoparticles with equal proportions, the density of the crude oil dropped rapidly from 1.03g/cc to 0.97g/cc after 5grams of the stated nanoparticle was introduced into the system, signifying the nanoparticles had high effect on the oil. However, for 10grams of the constitutes, the density was higher than that of 5g. Similarly, for 15grams, the density was higher than 10grams. A decrease of about 0.007g/cc was recorded between 15 and 20grams of the same nanoparticle with a slight increase of 0.001g/cc at 25grams.

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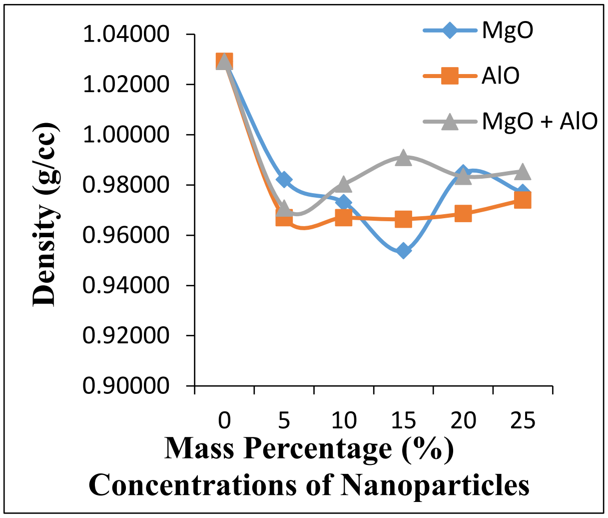

Figure 3: Effect of Nanoparticles and Carbon dioxide on Density of the heavy crude oil at different mass percent concentrations

b. Effect of Nanoparticles and CO_2 on API Gravity of the Heavy Crude Oil

The effects of nanoparticles and carbon-dioxide on API Gravity of heavy crude is presented in Figure 4. The API gravity of the crude oil increased rapidly from 5.98° API gravity to 12.5°API after 5grams of magnesium oxide nanoparticle was added into the system. The API then increased by 1.4°API gravity when 10grams of mass percent of magnesium oxide nanoparticle was added. The API increased to 17°API gravity for 15gram. However, at 20grams the API gravity decreased to 12.8°API gravity from 17°API gravity before increasing slightly to 13.3°API for 25gram. The API of the heavy crude oil increased rapidly from 5.9°API gravity to 14.8 °API gravity after 5grams of mass percent of aluminum oxide nanoparticle was added into the system. The API remained steady for 10gram of the concentration. An increase of about 0.009°API was recorded at 15gram of the same nanoparticle, however at 20grams, the trend was rather downwards. The API decreased to 14.5°API from 14.9 °API gravity and later to 13.77 °API gravity at 25gram. With equal mass percent concentration of the magnesium and aluminum oxide nanoparticle on the API gravity of the heavy crude oil, the API gravity of the crude oil increased rapidly to 14.2°API gravity from 5.9°API gravity after 5grams of the stated nanoparticle was introduced into the system, signifying the nanoparticles had high effect on the oil. However, for 10gram of concentration, the API gravity was lower than that of 5grams. Similarly, there was a decrease in the API gravity when 15grams of Al_2O_3 and MgO was added. At 20grams the API gravity was12.3°API gravity signifying an increase of about 1.1°API between 15 and 20g of the same nanoparticle with a slight decrease of 0.03°API at 25g.

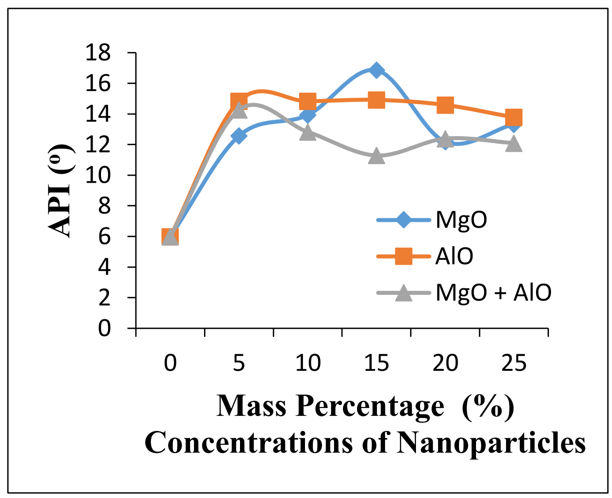

Figure 4: Effect of Nanoparticles and Carbon dioxide on API Gravity on the Heavy Crude Oil at different mass percent concentrations.

c. Effect of Nanoparticles and CO_2 on Viscosity of the Heavy Crude Oil

Figure 5 shows the effect of different mass percent of nanoparticles on the heavy crude viscosity. The findings show that the addition of magnesium oxide (MgO) nanoparticle caused the viscosity of the heavy crude sample to reduce from 5.83 to

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5.80cp for a 5-gram addition and by 0.36cp between 5-gram and 10-gram. Between 10 and 15 grams, there was a decrease of 0.25 cp, 0.27 cp between 15 and 20 grams, and 4.79 cp to 3.94 cp when it was increased to 25 grams.

The outcome reveals that when the crude was flooded with carbon dioxide (CO_2) and aluminum oxide at a 5-gram concentration, the viscosity also dropped from 5.83 cp to 5.80 cp (Al_2O_3). The viscosity then dropped to 4.73 cp and 4.78 cp for aluminum oxide nanoparticle doses of 10 and 15 grams, respectively. The viscosity dropped to 4.62 at 20 grams of aluminum oxide, and it further dropped to 4.20 grams of nanoparticles. Magnesium and aluminum oxide nanoparticle results demonstrate that the viscosity dropped from 5.83 cp to 5.49 cp for 5-grams. Between 10 and 15 grams, however, there was a severe reduction of 4.74 and 4.68 cp, and between 15 and 20 grams, there was a decrease of 4.05 and 3.71 cp and a loss of 0.59 cp for 25-grams.

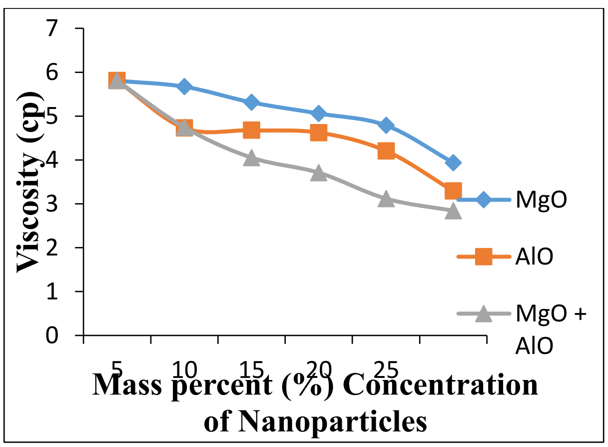

Figure 5: Effect of Nanoparticles and Carbon dioxide on Viscosity at different concentrations.

d. Effect of Nanoparticles and CO_2 on Flowrate of the Heavy Crude Oil

Figure 6 shows the effect of nanoparticles and carbon-dioxide on the flowrate of the heavy crude oil. The flow rate is seen to rise sharply from 0.7 ml/s to 0.896 ml/s when 5g of MgO was added to the system. The flowrate increased gradually to 0.9 ml/s for10gram of the concentration before decreasing to 0.88 liters for 15gram, 0.84 ml/s for 20grams and 0.78 ml/s for 25grams respectively. For aluminum oxide, the flow rate increased gradually from 0.7 liters to 0.8 liters when 5gram mass percent concentration was added to the system. The flowrate continued to increase slowly to 0.81 liters for10gram of the constitute and further increased to 0.83 ml/s for 15grams, 0.86 liters for 20gram respectively before recording a slight decrease of 0.83 liters for 25gram. On combining both nanoparticles (magnesium and aluminum oxide), the flowrate increased with increasing amount of concentration. From the plot, the flowrate increased from 0.7 ml/s to 0.89 ml/s. the flowrate increased substantially from 0.89 ml/s to 0.97 liters at 10gram and further increased from 0.97 ml/s to 1.15 ml/s at 15grams. However, a decline from 1.15 ml/s to 1 ml/s was observed for 20grams before a sharp increase was seen at 25grams.

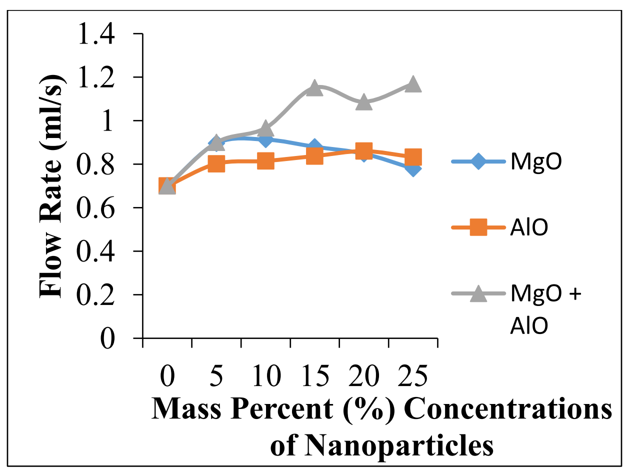

Figure 6: Effect of Nanoparticles and Carbon dioxide on flowrate of the Heavy Crude Oil at different mass percent concentrations.

e. Effects of Nanoparticles and CO_2 on the Volume Recovered of the Heavy Crude Oil

The effects of the nanoparticles and carbon-dioxide is presented in Figure 7. The volume recovered increased from 7litres to 8.96litres when 5grams concentration of MgO was added. The volume increased gradually to 9litres for10grams of the concentration before decreasing to 8.8litres for 15grams, and 8.4litres for 20grams. After 25grams MgO was added, the recovered volume decreased to 7.8 liters. For Al_2O_3, the volume increased gradually from 7litres to 8litres when 5grams of Al_2O_3 was added. The volume continued to increase to 8.1litres for10gram and further increased to 8.3litres for 15grams. For 20gram of Al_2O_3 the volume increased to 8.6litres before decreasing to 8.3litres for 25grams. combination of the both nanoparticle (MgO and Al_2O_3), for 5grams the volume increased from 7litres to 8.9litres. When 10 grams of the nanoparticles was added, the volume increased from 8.9 liters to 9.7litres and at 15grams mass percent concertation the volume increased to 11.5litres. However, the volume decreased from 11.5litres to 11litres when 20grams of both nanoparticles was added to the system, and an increase for 25grams of the constitute.

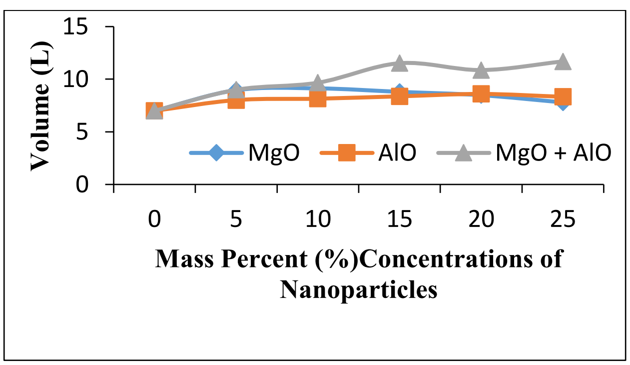

Figure 7: Effect of Nanoparticles and Carbon dioxide on Volume Recovered of the Heavy Crude Oil at different mass percent concentrations.

4.0 CONCLUSION

This study evaluated the impact of carbon dioxide (CO_2) and magnesium and aluminum oxide nanoparticles (MgO and Al_2O_3) on heavy crude oil recovery. the conclusions are as follows:

i. The density of the heavy crude sample decreased with increasing mass percent concentrations of (MgO, Al_2O_3).
ii. The API gravity increased with increase in the mass percent concentration of (MgO, Al_2O_3) nanoparticles.
iii. The viscosity of the heavy crude sample decreased as the mass percent concentration of (MgO, Al_2O_3) nanoparticles increased.
iv. The flowrate of heavy crude oil increased with increase in the mass percent concentration of (MgO, Al_2O_3) nanoparticles
v. The volume of the heavy crude oil increased together with the concentration of the (MgO, Al_2O_3) nanoparticles.

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6.0 ABBREVIATIONS

AP Alkaline - polymer

EOR Enhanced Oil Recovery

MEOR Microbial Enhanced Oil Recovery

IFT Interfacial Tension

NPs Nanoparticles

OOIP Original Oil Initially in Place

ROS Residual Oil Saturation

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