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# Effect of viscosity on reservoir deliverability of green field, Niger-Delta, Nigeria

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## Abstract

Reservoir deliverability has been a concern in exploration geosciences as it determines the volume of hydrocarbon that is exploitable from a reservoir. In this research, we recorded the viscosity ($\eta$) of fluid from Green field in order for us to have an idea of its deliverability. Different quantity of heat was injected in the form of steam into Green reservoir fluids at every 30 minutes interval and the changes in the viscosity at every considered temperature were estimated to determine the reservoir deliverability. Reservoir fluid from Green field were collected every 30 minutes interval to obtain its terminal velocity ($V_T$) which is needed to estimate $\eta$. The viscosity and deliverability of the reservoir in percentage were 5.073 $Nsm^{-2}$ and 40% before the injection of steam. Each of the 30 minutes interval of temperature increase after the injection of steam showed a direct variation of the temperature with $V_T$ and an indirect variation with $\eta$ of the fluids. Each of the reservoir fluids collected for five different times from Green field were divided into five portions. After steam injection, the first, second, third, fourth and the fifth collected fluids, respectively, produced an average $V_T$ and $\eta$ of 2.83 $ms^{-1}$ and 2.164 $Nsm^{-2}$, 3.89 $ms^{-1}$ and 1.576 $Nsm^{-2}$, 4.82 $ms^{-1}$ and 1.272 $Nsm^{-2}$, 5.92 $ms^{-1}$ and 1.034 $Nsm^{-2}$ and 7.07 $ms^{-1}$ and 0.865 $Nsm^{-2}$ which depicts easy movement of hydrocarbon as temperature increases. The percentage average deliverability of the reservoir after the application of heat at five different 30 minutes interval temperature change becomes 53.44% which showed clearly that for non-volatile hydrocarbon, reservoir deliverability can be improved upon by injecting heat as it reduces viscosity and enhances easy mobility of hydrocarbon up the wells.

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## 1. Introduction

The hydrocarbon saturation of a reservoir does not necessarily translate to its deliverability. Viscosity of reservoir fluids is one of the major factors on which the reservoir deliverability depends [1]. Reservoir deliverability is the maximum natural ability of

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hydrocarbon reservoirs to deliver hydrocarbon during exploitation. Nigeria as at today is still unable to meet up with the minimum quota of crude oil production pegged at 1.80 million barrel per day (bpd) by the Organization of Petroleum Exporting Countries (OPEC) for oil producing countries of the world as only 0.94 million bpd is being produced in the last quarter of 2022 [2]. The entire world depends heavily on oil for both domestic and industrial energy consumption. As at 2014, the global demand for oil has risen by 0.8% and this has reached 10.1 million bpd [3].

The question of how oil producers will cope with the world rising oil demands is still begging for answers as 60 – 80 percent of oil is still left unexplored. There is an urgent need to explore more hydrocarbons through other means so as to generate more revenue for the country. Unfortunately, the diverse approaches that have been used to enhance the recovery of oil in the Niger Delta region have not successfully helped to recover more than 50% of inherent oil in the reservoir [2]. The high viscosity of the oil which doesn't allow for easy mobility still remains an issue to be sorted out. Injection of heat to reduce the viscosity and enhance the mobility of hydrocarbon is one major way through which reservoir deliverability can be enhanced. In enhancing the recovery rate of hydrocarbon reservoirs through injection of heat, engineers must take into consideration, the volatility of the reservoir fluids as volatile hydrocarbons such as Benzene, Toluene, Methylene Chloride, Acetone, Butadiene, Formaldehyde, Xylene and Butyraldehyde can be lost through evaporation when heat is applied because their boiling points occurs between 0 – 100 ° C [4]. Heat should be injected into reservoirs with non-volatile hydrocarbon such as methyl palmitate, glycerol, alkyl alkanolamine and soy oil which respectively have boiling points of 332 ° C, 290 ° C, 283 ° C and 250 ° C. The Passage of heat in the form of steam which is 100 ° C through a certain reservoir will no doubt evaporate the volatile hydrocarbon compounds and at the same time reduce the viscosity of inherent non-volatile hydrocarbon compounds [4]. Another important factor which will also change due to the passage of steam is the water saturation of the reservoir as more fluid is added in the process of injection Kumar and Ziegler [5].

Steam injection facilitates thermal stimulation of hydrocarbon from the reservoir. This is done by producing oil using condensed steam on the surface of the same exploration well. Heat at the surface is injected into the well. This is done to put an unproductive or a less productive well back on tracks of production as the producibility indicators will be increased after the passage of steam [6]. Cyclic steam injection process occurs in three stages. The first of the stages is injection which involves introduction of a predetermined amount of heat in the form of steam into the reservoir. The next stage is the soak period which involves shutting in the well over a period of time; usually some weeks to allow for even distribution of heat in the reservoir, so as to raise the temperature above a known pour point of hydrocarbons (reservoir oil) [6]. The last stage is the production of new mobile hydrocarbon through the same well. This cycle is repeated for several times until oil flow diminished in the reservoir to a point where little or no oil can be exploited. This does not necessarily affect the quality of the inherent hydrocarbons in the well as fractional distillation done during refining makes each of the compounds to be collected at different temperature without interfering with another. Viscosity is the internal friction that exists in fluids as a result of the movement of the layers of the fluids. Viscosity of fluids determines the terminal velocity which is determined from the upwards viscous force (V) and upthrust (U) and the downwards weight (W) of the object moving down the fluids when the acceleration equals zero [7]. The decrease in the viscosity helps in reducing the surface tension, increasing the permeability of hydrocarbon and improving the reservoir hydrocarbon leakage condition from the subsurface which is likely to occur from the fracture of the cap rocks [7]. Vaporization of oil gives rise to free flow of oil through the reservoir and formation of better oil after condensation.

Research shows that almost all the hydrocarbon reservoirs in the Niger Delta region of Nigeria release some and not its entire hydrocarbon during exploration processes unless the recovery rate is enhanced [2]. About 60 percent of the hydrocarbons in the reservoirs are trapped in the reservoirs even after exploration. Heat injection in the form of steam is more environmental friendly than any other means of enhancing oil recovery as it is accompanied by fewer complications when used. The injected steam does not pose any threat to the reservoir fluids as it will eventually condense to water without polluting the reservoir environment. Just as all other recovery methods, steam injection has a number of challenges and drawbacks. some of which are: addition of extra operational cost as more water is added when steam cools in the well, damage of the underground well structure as some of the reservoirs are prone to geologic rearrangement which is dangerous to workers, equipments and other inhabitants around the well and economic setback which is one of the major determining factors for steam injection into the reservoirs [8]. When starting heat injection for the first time, one barrel of injected steam is capable of recovering 30 barrels of incremental HC. A second attempt of steam injection after some times is characterized by a considerable drops in the efficiency of the process, as one barrel of steam is only capable of recovering about 0.2 barrel of incremental HC. Consequently the approach becomes less economical, since the price of steam increases to amount in between $20 and $30 per barrel of incremental HC explored, if natural gas is employed for steam production [8]. When these conditions are experienced, producers eventually shut the well until times when oil prices increase or implementation of another improved technology. Razeghi *et al*. [9] worked on the determination of the effectiveness of some important petrophysical parameters and their effects on the efficiency of heat injection.

The Eclipse – 300 simulators was used to model the injection and production processes. Result obtained showed optimal values of oil obtained from the pressure of the injected steam, steam quality, depth of injection and the steam quality. Jacob *et al.* [10] stressed that steam injection optimization can be achieved by developing simulators that will serve as tools to achieve effective processes. Jacob *et al*. [10] explained that the tools are computer controlled numerical processes for the purpose of optimization and that they are also necessary to pass the steam over a very wide range of depth in order to achieve optimal steam injection. The response of the reservoirs to heat injection in the form of steam was also required to detect the extent and depth to which injection can be carried out [10]. The work of Cardona *et al.* [11] was focused on steam quality effect on the upgrading of extra heavy crude and Recovery carried out with the aid NiO and PdO-Functionalized Aluminum oxide Nanoparticles. This work is centered on evaluating the steam quality effect on recovering of heavy crude oil presence of some nanofluids. Overtime in the Green field, the thickness and viscosity of oil has been one of the major reasons the reservoirs have not yielded optimally. This research finding seeks to inject heat into the reservoirs to a considerable depth where oil is situated, so as to reduce its viscosity and aid mobility and recovery. Findings from this research are expected to increase oil yields from available oilfields in the Niger Delta if well practised.

## 2. Study area

The part of Niger Delta from which this study was carried out occurs between longitudes 40 – 80° E and Latitude and latitudes 50 - 70° N. The Green field is situated between the boundaries of the Calabar flank in the east and the Benin flank in the west. The field is also extended to the southern and northern widths both of which are respectively bounded by the Gulf of Guinea and the syncline of Afikpo, the uplift of Abakaliki and the Anambra basin [12]. The Niger Delta covers a large area of land of about 105,000 km$^2$ [13]. It actually covers from the start, parts of the Cameroun particularly the east and western direction and it projected to parts of the ridges in Okitipupa in the south-western region of Nigeria [14]. The Green field is highly prolific and rich in lucrative economic crudes which can serve as a source of huge revenue for the country if well controlled. The stratigraphy of the Niger Delta region is made up of the Akata formation which is composed of potentially mature rocks, the Agbada formation which is made up of specific water-depths reservoirs and considerable quantity of shale and silt and the Benin formation which is characterized by alternated sequences made up of combinations of shale and sandstones, channels dividing into parts, plains emanating from deltas, sand and gravels [15]. All these formed the exploitable petroleum resources in the area. Figures 1 and 2 show the map of the study area and the Niger Delta lithostratigraphy.

## 3. Materials and methods

Reservoir fluid from Green field was firstly obtained for laboratory assessment before the injection of heat. The viscosity was measured with the viscometer and terminal velocity was thereafter estimated using the Stokes' law. The quality of steam was firstly assessed judging from the purity test done on the water used. This test was done by normal boiling and testing with a laboratory thermometer to detect the boiling point. The boiling point suggests whether the initially used water is pure or not. After ascertaining the purity of the steam, it is injected into the reservoirs and allowed to be evenly distributed for 30 minutes so as to cause reduction in the viscosity of the fluids. Reservoir fluids obtained after the first 30 minutes was then collected and divided into five portions. Each of these portions was assessed for viscosity with the viscometer and also the ball bearing-experiment for terminal velocity through the upwards viscous drag ($F_D$) and buoyant force ($F_B$) and the downwards gravitational force ($F_G$). This was done to allow for variations due to instruments used. The process is repeated for the second, third, fourth and the fifth next 30 minutes and in each case the viscosity and the corresponding values of the terminal velocities were obtained through the Stokes' law. The percentage deliverability was also estimated using the initial and enhanced viscosity values and average percentage deliverability is thereafter employed to assess the effectiveness of the steam injection approach.

### *3.1. Tests for the quality of steam*

Apart from building models to ascertain the quality of steam injected into the reservoir, the purity of water heated to obtain the steam is another important factor that determines its quality. As pure and distilled water boils at 100° C, impure water boils at a temperature higher than 100° C. Since distilled water boils at 100°C, it is utilized to obtain the steam injected into the reservoir.

### *3.2. Stokes law and ball-bearing experiment*

The viscous drag, $F_D$ on a spherical ball bearing of radius, r, moving through a fluid of viscosity, , with a velocity, $v$ can be expressed by Stokes' law given as

$$F_D = 6\pi\eta r v. \tag{1}$$

The viscous drag on the spherical ball bearing is proportional to the velocity, $v$, the viscosity, and the radius of the ball bearing, r. Consider a spherical ball bearing of radius, $r$ and density, $\rho$ allowed to fall through a fluid of density, $\sigma$ and viscosity. The forces acting on the spherical ball bearing include the viscous drag, $F_D$, shown in equation (1) which is acting upwards against the weight of the sphere [8].

The buoyant force is

$$F_B = \frac{4}{3}\pi r^3 \sigma g. \tag{2}$$

This is also acting upwards just as the viscous drag and the force of gravity, $F_G$, acting downwards

$$F_G = \frac{4}{3}\pi r^3 \sigma g. \tag{3}$$

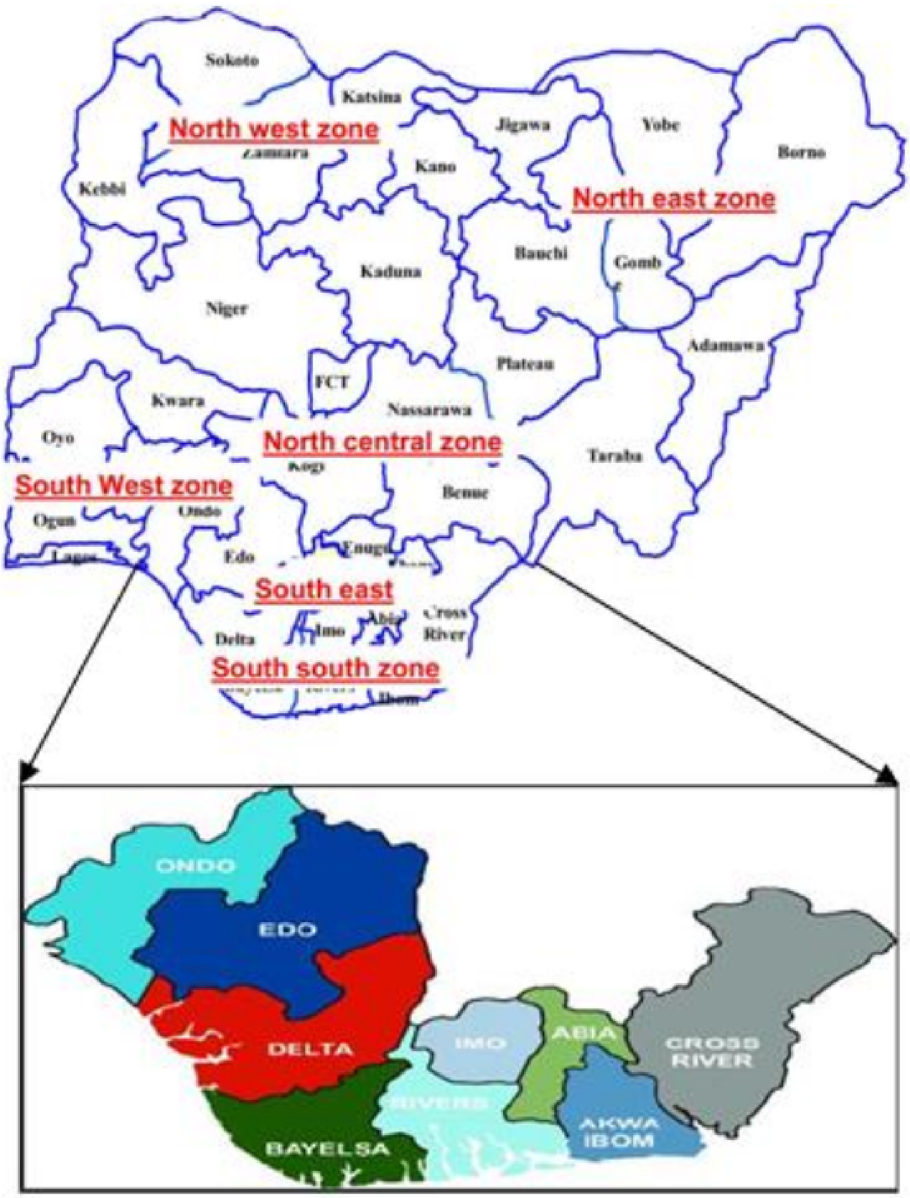


Figure 1. Map of the study area.

The terminal velocity, $V_T$ is the velocity of the ball bearing when it is moving with a constant acceleration. At terminal velocity, the acceleration due to gravity, g equals zero

$$F_D + F_B - F_G = mg. \tag{4}$$

But at terminal velocity, $g = 0$, we therefore have

$$F_D + F_B = F_G. \tag{5}$$

$$V_T = \frac{2r^2 (\rho - \sigma) g}{9\eta}. \tag{6}$$

The density, $\rho$, of the ball bearing can be calculated firstly by measuring the mass, m with the beam balance and its volume calculated using the statistical relation $V = \frac{4}{3}\pi r^3$. The ratio of the mass of the spherical ball to its volume gives its density expressed in $kgm^{-3}$. The density, $\sigma$ of fluid can also be determined by dividing its mass measured with the beam balance and the volume measured with the measuring cylinder

The ball bearing moves down the container but moves upwards if its density is higher than that of the fluid. The terminal velocity increases as the viscosity decreases with increase in temperature. If the ball bearing is allowed to fall from rest, the velocity of the

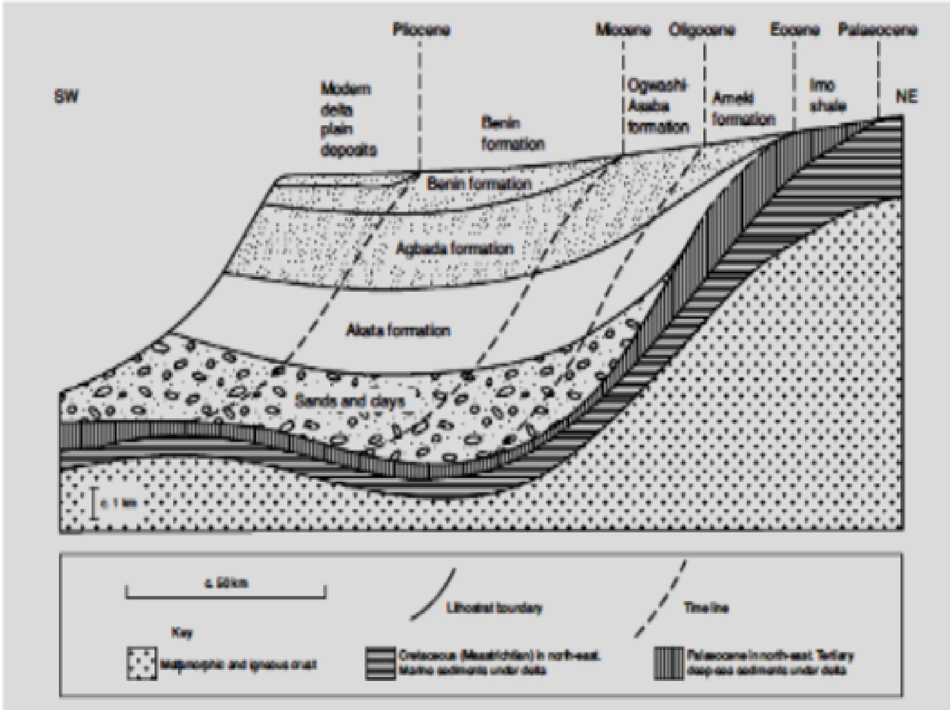


Figure 2. Litho-stratigraphic sequence of the Niger-Delta.

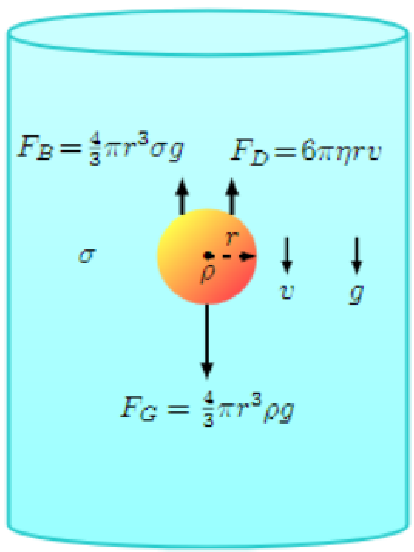


Figure 3. Determination of the Terminal Velocity, $V_T$ from $F_B$, $F_D$ and $F_G$.

ball varies with time as shown below. Figures 3 and 4, respectively show a diagrammatic representation of the action of a steel ball bearing falling through a viscous liquid and relationship between the terminal velocity, $V_T$ and the time, *t*.

### *3.3. The viscometer*

The viscometer is used to detect the viscosity of fluids. A specific type of viscometer known as the rheometer is used to measure the viscosities of some fluids which vary with the condition of flow such as fluid alternating between laminar conditions of flow and that of the turbulent. The viscometer measures the viscosity of fluids under just one condition of flow and for the reservoir fluids, it is laminar. The viscosity of fluids reveals the internal resistance of a fluid to the condition of flow. Statistically, the viscosity is the ratio the shear stress to the velocity gradient of fluids. The type of viscometer that was used for this study is the one known as the Ostwald viscometer. The Ostwald viscometer is named after a German philosopher and chemist, Wilhelm Ostwald. The peculiarity

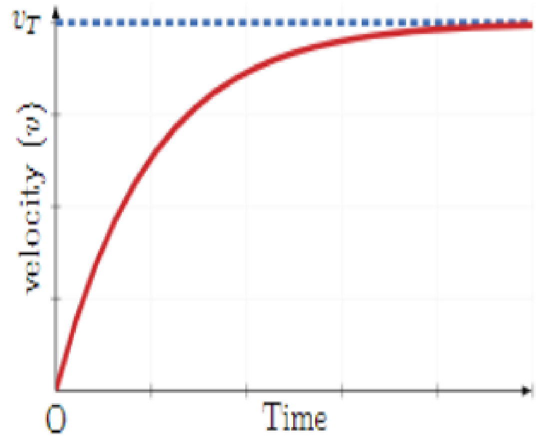


Figure 4. Relationship between the terminal velocity, $V_T$ and the Time, *t*.

of the Ostwald viscometer is that it measures only the viscosities of Newtonian liquids (fluids). Newtonian fluids are the fluids which viscosities do not change with the conditions of flow. The Ostwald viscometer uses the Poiseuille's law to detect the viscosity. It is also known as capillary viscometer. This is because it utilizes the flow rate of fluids passing through capillary tubes to detect the viscosities. It is important to make the fluids flow through capillary tubes situated between two identified or marked points on the tube usually a glass one. The fluid flow between the two points can be detected by s stopwatch. The Ostwald viscometer is a glass "U" shaped instrument with wide limb located on a side of the capillary tube. The limb is utilized as the opening through which the fluid is poured. It is made up of two bulbs which are attached by the "U" shaped glass tube. One of the bulbs is attached to the capillary tube and the rubber on opposite sides. The other bulb is characterized by two marked points (upper point-A and the lower point-B) on both sides meant to track the fluids flow limits in the capillary tube. The opening attached to the rubber is meant for sucking in the liquid.

## 4. Results and discussion

Reservoir fluids which comprises chiefly non-volatile hydrocarbons and minor content of volatile hydrocarbons were collected from Green reservoirs and divided into five portions PRTN A, PRTN B, PRTN C, PRTN D and PRTN E. Each of the portions is divided into two, one of which is poured into limb of the Ostwald viscometer to determine its viscosity in $N.sm^{-2}$ and the other is poured into a measuring cylinder for ball-bearing experiment in order to determine its velocity in $ms^{-1}$. The viscosity values detected by the viscometer for PRTN A, PRTN B, PRTN C, PRTN D and PRTN E before steam injection are respectively 4.928, 6.037, 4.400, 4.644 and 5.357 $N.sm^{-2}$ with respective corresponding values of the terminal velocity of 1.25, 1.00, 1.40, 1.30 and 1.15 $ms^{-1}$. After the first 30 minutes interval of steam injection, the viscometer recorded viscosity values of 2.053, 2.156, 2.369, 2.118 and 2.124 $N.sm^{-2}$ with respective corresponding values of 3.00, 2.80, 2.60, 2.85 and 2.90 $ms^{-1}$ as shown in Table 1. The second 30 minutes interval of steam injection produced a fluid of viscosity values of which are 1.540, 1.589, 1.634, 1.560 and 1.559 $N.sm^{-2}$ for PRTN A, PRTN B, PRTN C, PRTN D and PRTN E with respective corresponding values of terminal velocity of 4.00 $ms^{-1}$, 3.80 $ms^{-1}$, 3.77 $ms^{-1}$, 3.87 $ms^{-1}$ and 3.95 $ms^{-1}$ as shown in Table 2. The viscosity and the corresponding terminal velocity after the third 30 minutes interval for portions PRTN A, PRTN B, PRTN C, PRTN D and PRTN E are, respectively, 1.185, 1.357, 1.289, 1.324 and 1.232 $N.sm^{-2}$ and 5.20, 4.45, 4.78, 4.56 and 5.10 $ms^{-1}$ as shown in Table 3. The fourth 30 minutes interval recorded on the viscometer respective viscosity of values of 1.002, 1.032, 1.064, 0.986 and 1.086 $N.sm^{-2}$ for portions PRTN A, PRTN B, PRTN C, PRTN D and PRTN E with respective corresponding values of terminal velocity of 6.15, 5.85, 5.79, 6.12 and 5.67 $ms^{-1}$ as shown in Table 4. After the fifth 30 minutes interval of steam injection, the viscometer recorded a respective viscosity of values 0.868, 0.875, 0.922, 0.809 and 1.086 $N.sm^{-2}$ with respective corresponding values of the terminal velocity of 7.10, 6.90, 6.68, 7.46 and 7.22 $ms^{-1}$ as revealed on Table 5. The variation in the viscosity and terminal velocity of portions from the same reservoir fluid is attributed to the volatility and the rate of evaporation of the hydrocarbons inherent in the fluids.

### *4.1. Discussion on average viscosity and terminal velocity*

Viscosity is the term used to describe the type of friction that exists in fluids due to the movement of the layers of the fluids. Due to the intermolecular forces of the particles in one of layers and the adjacent layer of the reservoir fluids, viscosity occurs. The viscous reservoir fluids poured into the limb of the viscometer to determine the viscosity of each of the collected reservoir fluids. The terminal velocity of a ball bearing falling through the viscous reservoir fluids was determine when the acceleration of the ball is

Table 1. Viscosity and the corresponding terminal velocity in the first collected reservoir fluids.

| Time Interval | Portions | $\eta$/ $Nsm^{-2}$ | Initial $\eta$/ $Nsm^{-2}$ | $V_T$/ m/s | Initial $V_T$/ m/s |
|---|---|---|---|---|---|
| $1^{st}$ 30 minutes | PRTN A | 2.053 | 4.928 | 3.00 | 1.25 |
| $2^{nd}$ 30 minutes | PRTN B | 2.156 | 6.037 | 2.80 | 1.00 |
| $3^{rd}$ 30 minutes | PRTN C | 2.369 | 4.400 | 2.60 | 1.40 |
| $4^{th}$ 30 minutes | PRTN D | 2.118 | 4.644 | 2.85 | 1.30 |
| $5^{th}$ 30 minutes | PRTN E | 2.124 | 5.357 | 2.90 | 1.15 |

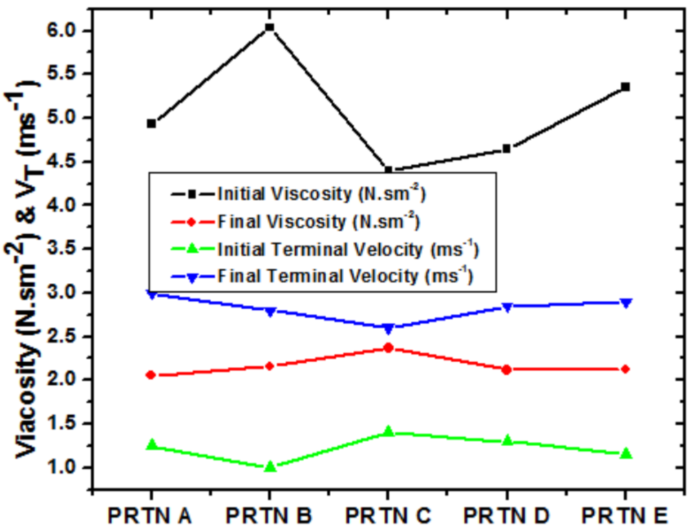


Figure 5. Relationship between the viscosity and the terminal velocity after the first steam injection.

constant and the change in the acceleration becomes zero. The determination of the terminal velocity became necessary because it serves as a major pointer to a reduce viscosity which is the target of the research. The first, second, third, fourth and the fifth collected reservoir fluids for this research respectively recorded an average terminal velocity and viscosity of 2.83 $ms^{-1}$ and 2.164 $N.sm^{-2}$, 3.89 $ms^{-1}$ and 1.576 $N.sm^{-2}$, 4.82 $ms^{-1}$ and 1.272 $N.sm^{-2}$, 5.92 $ms^{-1}$ and 1.034 $N.sm^{-2}$ and 7.07 $ms^{-1}$ and 0.865 $N.sm^{-2}$.

### *4.2. Discussion on reservoir deliverability*

The deliverability of reservoirs is anchored on the viscosity of the reservoir fluids, volatility of the reservoir fluids and the improved technology put in place for exploration. The deliverability of the reservoir due to the reservoir pressure before steam injection was 40%. The first, second, third, fourth and the fifth collected reservoir fluids yielded 60.9, 55.2, 52.3, 50 and 48.8%. On the average, the Green reservoirs deliver 53.44% which is 13.44% more than what was obtainable before steam injection. Differences in the rate of evaporation of the constituents of the reservoir fluids and the continual decrease in the viscosity due to the five stages of steam injection may be responsible for the reduction in the deliverability from the first to the fifth collected reservoir fluids.

Figure 5 shows a drop in the viscosity after steam injection. The lowest and highest values of viscosity before steam injection are ranges from 4.50 to 6.00 $N.sm^{-2}$. These values drastically dropped to a range from 2.00 to 2.25 $N.sm^{-2}$ after steam injection. This is evident in the increase in the range of the terminal velocity after steam injection. The terminal velocity before steam injection ranges from 1.00 to 1.35 $ms^{-1}$. These values increased to a range of 2.55 to 3.00 $ms^{-1}$. A decrease in the viscosity might have been responsible for the increase in the terminal velocity and an increase in the terminal velocity will no doubt bring about an increase in the reservoir deliverability. This is similar to the work of Penney *et al.* [16] in which a new approach of steam injection was done in order to enhance the recovery of the reservoir fluids. This was done by using TA-GOGD which worked differently from the convectional steam injection mechanism and helped to distribute steam through the reservoir. Penney *et al.* [16] managed both steam distribution alongside the recovery of oil. In this case, the cost of putting up another mechanism for recovering was minimized.

Figure 6 shows an increase in the terminal velocity as the viscosity decreases just as what is obtainable with figure 6. The viscosity and terminal velocity of the first, second, third, fourth and the fifth collected fluids from Green reservoirs before and after steam injection respectively range from 1.50 to 1.51 $N.sm^{-2}$ and 4.50 to 6.00 $N.sm^{-2}$ and 1.00 to 1.30 $ms^{-1}$ and 3.70 to 4.00 $ms^{-1}$. A gradual decrease in the viscosity results into a gradual increase in the terminal velocity as five successive steam injections are done at 30 minutes interval. A decrease in the viscosity and an increase in the terminal velocity is the reason for the increase in the percentage deliverability of the reservoirs. A similar work done by Foroozanfer [17] emphasized on the need to make use of thermal injection in reservoirs which contain fluids of high viscosity. According to Foroozanfer [17], heat injection has been practiced in

Table 2. Viscosity and the corresponding terminal velocity in the second collected reservoir fluids.

| Time Interval | Portions | $\eta$/ $Nsm^{-2}$ | Initial $\eta$/ $Nsm^{-2}$ | $V_T$/ m/s | Initial $V_T$/ m/s |
|---|---|---|---|---|---|
| 1st 30 minutes | PRTN A | 1.540 | 4.928 | 4.00 | 1.25 |
| 2nd 30 minutes | PRTN B | 1.589 | 6.037 | 3.80 | 1.00 |
| 3rd 30 minutes | PRTN C | 1.634 | 4.400 | 3.77 | 1.40 |
| 4th 30 minutes | PRTN D | 1.560 | 4.644 | 3.87 | 1.30 |
| 5th 30 minutes | PRTN E | 1.559 | 5.357 | 3.95 | 1.15 |

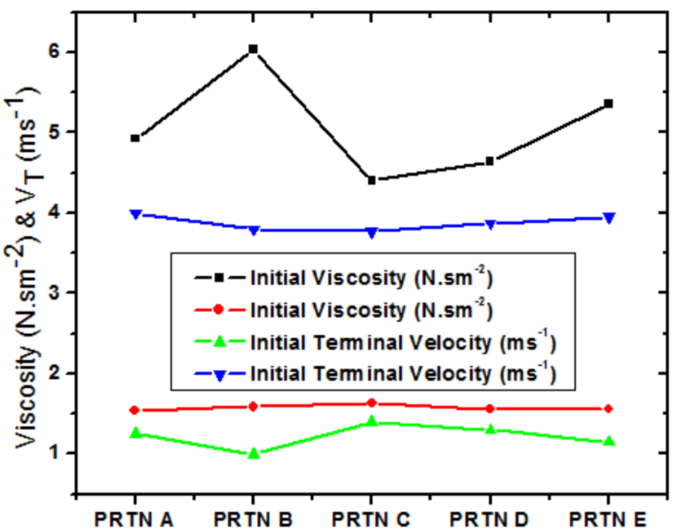


Figure 6. Relationship between the viscosity and the terminal velocity after the second steam injection.

Table 3. Viscosity and the corresponding terminal velocity in the third collected reservoir fluids.

| Time Interval | Portions | $\eta$/ $Nsm^{-2}$ | Initial $\eta$/ $Nsm^{-2}$ | $V_T$/ m/s | Initial $V_T$/ m/s |
|---|---|---|---|---|---|
| 1st 30 minutes | PRTN A | 1.185 | 4.928 | 5.20 | 1.25 |
| 2nd 30 minutes | PRTN B | 1.357 | 6.037 | 4.45 | 1.00 |
| 3rd 30 minutes | PRTN C | 1.289 | 4.400 | 4.78 | 1.40 |
| 4th 30 minutes | PRTN D | 1.324 | 4.644 | 4.56 | 1.30 |
| 5th 30 minutes | PRTN E | 1.232 | 5.357 | 5.10 | 1.15 |

Table 4. Viscosity and the corresponding terminal velocity in the fourth collected reservoir fluids.

| Time Interval | Portions | $\eta$/ $Nsm^{-2}$ | Initial $\eta$/ $Nsm^{-2}$ | $V_T$/ m/s | Initial $V_T$/ m/s |
|---|---|---|---|---|---|
| 1st 30 minutes | PRTN A | 1.002 | 4.928 | 6.15 | 1.25 |
| 2nd 30 minutes | PRTN B | 1.032 | 6.037 | 5.85 | 1.00 |
| 3rd 30 minutes | PRTN C | 1.064 | 4.400 | 5.79 | 1.40 |
| 4th 30 minutes | PRTN D | 0.986 | 4.644 | 6.12 | 1.30 |
| 5th 30 minutes | PRTN E | 1.086 | 5.357 | 5.67 | 1.15 |

China, U.S, Brazil and Canada. The idea behind this work is the same with that of this research because it is centered on heating the reservoir to reduce the viscosity of the inherent fluids for easy deliverability.

Figure 7 revealed an increase in the terminal velocity as the viscosity decreases due to steam injection. The reservoir fluids collected for the first, second, third, fourth and fifth times, each at 30 minutes interval respectively produced a reduced viscosity and an increased terminal velocity which respectively range from 1.15 to 1.30 $N,sm^{-2}$ and 4.30 to 6.00 $N.sm^{-2}$ and 1.00 to 1.40 $ms^{-1}$ and 4.40 to 5.20 $ms^{-1}$. Easy mobility of the reservoir fluids is facilitated by the decrease in the viscosity due to increase in temperature as steam injections are being carried out. The increase in the reservoir deliverability experienced is as a result of the reduced viscosity of the fluids. Nwidee *et al*. [18] stressed that enhanced oil recovery by steam injection similar to that of this research can only be effective in thick and shallow reservoirs with high permeability and viscosity. This can be justified as deep reservoirs are not likely to get even distribution of heat. High permeability of the reservoir will also facilitate easy deliverability of fluid-which is the target of this research.

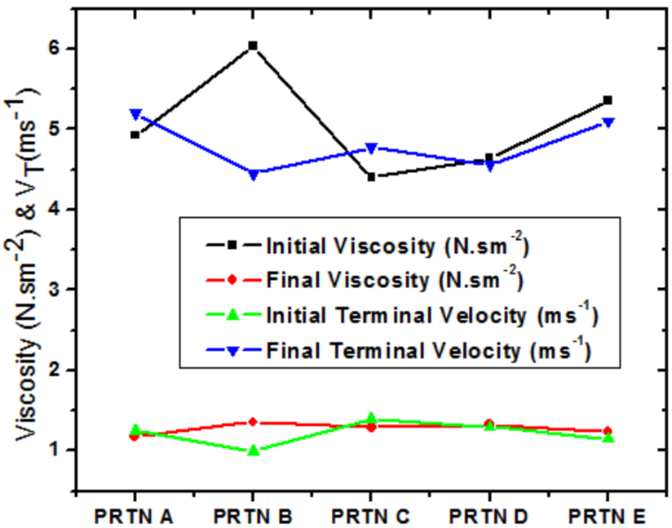


Figure 7. Relationship between the viscosity and the terminal velocity after the third steam injection.

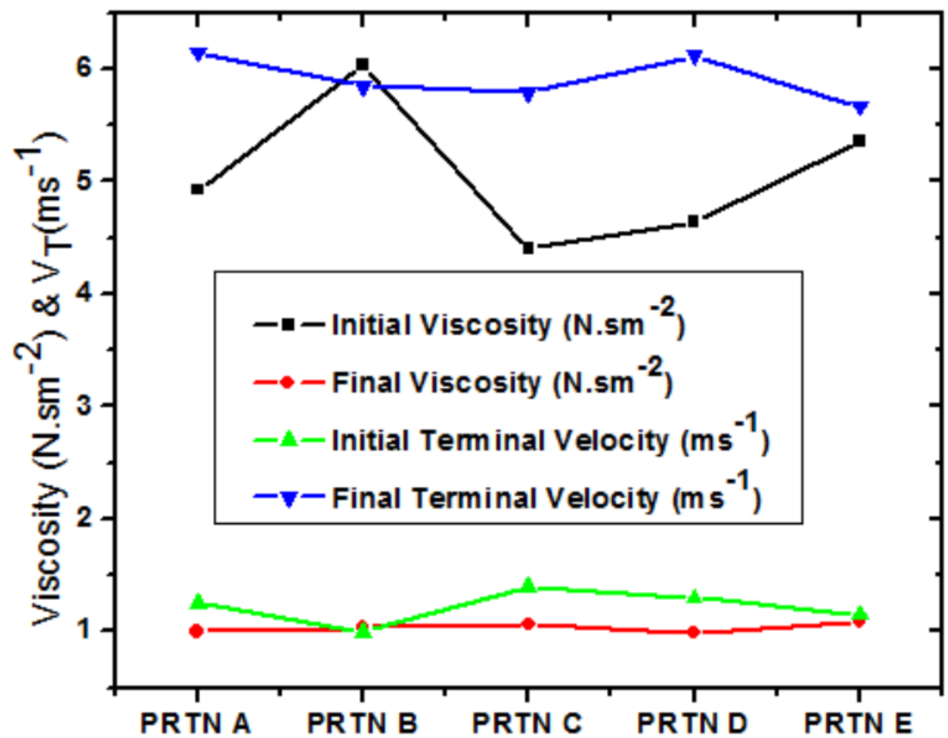


Figure 8. Relationship between the viscosity and the terminal velocity after the fourth steam injection.

Figure 8 gives a clear relationship between the reservoir viscosity and the terminal velocity. The terminal velocity increases with a decrease in the viscosity of the reservoir fluids. The first, second, third, fourth and the fifth collected reservoir fluids from Green field respectively yielded viscosity and terminal velocity which range from 1.00 to 1.10 $N.sm^{-2}$ and 4.40 to 6.10 $N.sm^{-2}$ and 1.00 to 1.35 $ms^{-1}$ and 5.60 to 6.20 $ms^{-1}$. The reduced viscosity and increased terminal velocity is the reason for the increase in the reservoir deliverability. A similar work done by Khan *et al*. [19] focused on the differences between thermal and non-thermal methods of enhanced oil recovery. The reduction in the viscosity facilitates easy mobility of oil and this was done by injecting heat into the reservoir. Khan *et al*. [19] itemized the various types of injections and the categories under which each of them is applicable. Injection of hydrocarbon, alkaline and bio-surfactants were all categorized under the non-thermal injection method because they do not involve application of heat. Steam injection is just a way of increasing the reservoirs temperature to enhance easy mobility of oil.

Similar to Figures 5, 6, 7 and 8, Figure 9 shows an indirect variation of the terminal velocity with the viscosity of the reservoir

Table 5. Viscosity and the corresponding terminal velocity in the fifth collected reservoir fluids.

| Time Interval | Portions | $\eta$/ $Nsm^{-2}$ | Initial $\eta$/ $Nsm^{-2}$ | $V_T$/ m/s | Initial $V_T$/ m/s |
|---|---|---|---|---|---|
| 1st 30 minutes | PRTN A | 0.868 | 4.928 | 7.10 | 1.25 |
| 2nd 30 minutes | PRTN B | 0.875 | 6.037 | 5.90 | 1.00 |
| 3rd 30 minutes | PRTN C | 0.922 | 4.400 | 6.68 | 1.40 |
| 4th 30 minutes | PRTN D | 0.809 | 4.644 | 7.46 | 1.30 |
| 5th 30 minutes | PRTN E | 1.086 | 5.357 | 7.22 | 1.15 |

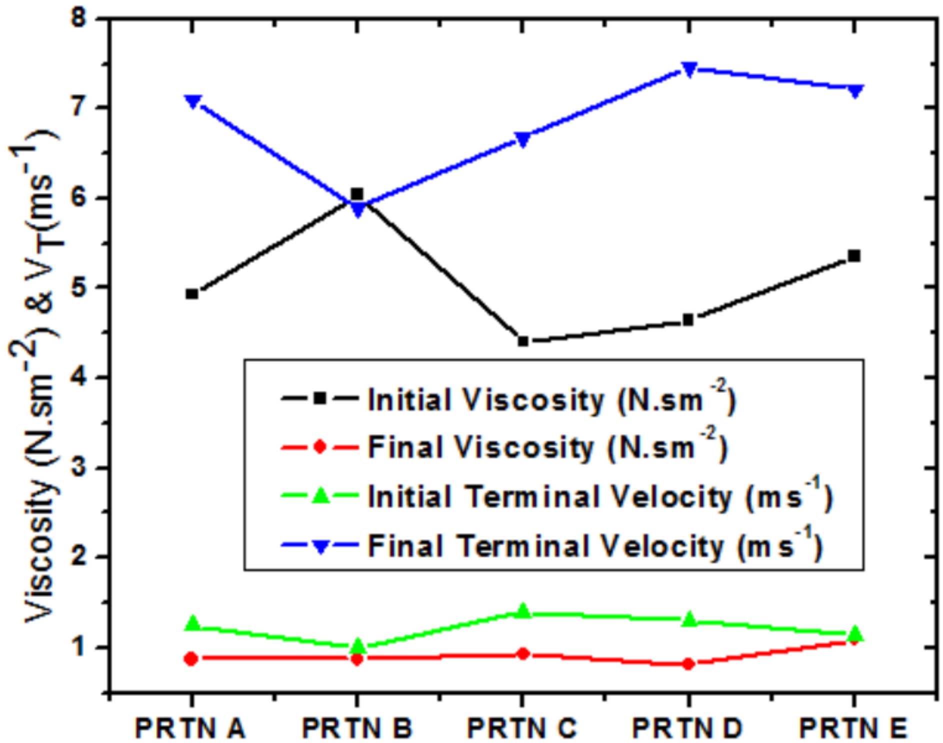


Figure 9. Relationship between the viscosity and the terminal velocity after the fifth steam injection.

fluids. The first, second, third, fourth and fifth collected reservoir fluids respectively recorded a decrease in the viscosity and an increase terminal velocity which range from 0.90 to 1.10 $N.sm^{-2}$ and 4.40 to 6.00 $N.sm^{-2}$ and 1.00 to 1.30 $ms^{-1}$ and 5.90 to 7.10 $ms^{-1}$. The reduction in the reservoir fluids viscosity facilitated an increase in the terminal velocity of the ball bearing in the fluids. The increased terminal velocity engenders a proportional increase in the percentage reservoir deliverability. A similar work done by Mokheimer *et al*. [20] explained the three stages involved in oil production. The first stage is centered on oil recovery through the natural reservoir pressure and the second stage can easily be achieved by passing sea fluid to increase the pressure of the well for easy recovery while the third stage is divided into the thermal and non-thermal approaches [20]. It is basically on enhancing the recovery of oil from the well through a thermal approach which involves reducing heavy oil components into a light one for easy mobility up the well [20].

## 5. Conclusion

Highly viscous fluid obtained from the Green reservoir showed a very low terminal velocity and hence a very low percentage deliverability. Experimental analyses done on the fluids reveal the presence of some volatile and non-volatile hydrocarbons in the Green field: although the scope of this research did not allow for, actual identification of the specific inherent hydrocarbons. Evaporation, reduction in the viscosity, increase in the terminal velocity and the percentage deliverability after steam injection actually showed a promising approach through which oil trapped in the Niger Delta reservoirs after primary and secondary recovery approaches can be recovered. The additional percentage deliverability obtained after heat injection showed little improvement in oil recovery. This can be attributed to the likely presence of volatile hydrocarbons such as Benzene, Toluene, Methylene Chloride, Acetone, Butadiene, Formaldehyde, Xylene and Butyraldehyde which became evaporated after the application of heat in the form of steam. Re-estimated percentage deliverability showed higher oil production when compared to the initial value. Heat injection is hereby recommended for use in the Niger Delta as it reduces the viscosity and enhances the mobility of oil up the reservoirs.

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## References

[1] A. Al-Bahlani & T. Babadagli, "Steam-over-solvent injection in fractured reservoirs (SOS-FR) technique as a new approach for heavy-oil and bitumen recovery: an overview of the method", Energy Fuels **25** (2011) 4528. https://doi.org/10.1021/ef200809z.
[2] A. Abayomi, S. O. Adam & A. I. Alumbugu, "Oil exportation and economic growth in Nigeria", Developing Country studies **15** (2015) 83. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://core.ac.uk/download/pdf/234682516.pdf.
[3] R. Arezki, Z. Jakab, D. Laxton, A. Matsumoto, A. Nurbekyan, H. Wang & J. Yao, *Oil prices and the global economy*, International Monetary Fund Working Paper, 2017, pp. 30. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.imf.org/en/Publications/WP/Issues/2017/01/27/Oil-Prices-and-the-Global-Economy-44594.
[4] H. Yongmao, L. Mingjing, D. Chengshun, J. Jianpeng, S. Yuliang & S. Guanglong, "Experimental investigation on oil enhancement mechanism of hot water injection in tight reservoirs", Open Physics **14** (2016) 703. https://doi.org/10.1515/phys-2016-0079.
[5] M. Kumar & V. M. Ziegler, "Injection schedules and production strategies for optimizing steam flood performance", SPE Reservoir Engineering, **8** (1993) 101. https://doi.org/10.2118/20763-PA.
[6] L. Songyan, W. Zhoujie, H. Rui, W. Lei & H. Zukang, "Experimental study on the cyclic steam stimulation assisted by flue gas under shallow heavy-oil reservoir conditions: optimization of the steam-flue gas ratio", Frontiers in Energy Research **1** (2020) 8. https://doi.org/10.3389/fenrg.2020.599370.
[7] B. T. Hoffman & A. R. Kovscek, "Efficiency and oil recovery mechanisms of steam injection into low permeability, hydraulically fractured reservoirs", Petroleum Science and Technology **22** (2004) 5. https://doi.org/10.1081/LFT-120034187.
[8] D. V. Boldyrev, B. A. Grigoriev, A. A. Evdokimov & A. I. Koldaev, "Prediction the liquid petroleum products viscosity", Journal of Earth and Environmental Science **1** (2022) 1315. https://doi.org/10.1088/1755-1315/979/1/012136.
[9] S. A. Razeghi, V. Mitrovic & S. A Marfo, "The influence of steam injection for enhanced oil recovery (EOR) on the quality of crude oil", Petroleum Science and Technology **35** (2017) 1334. https://doi.org/10.1080/10916466.2017.1327970.
[10] N. C. G. Jacob & O. E. Favour, "An integrated well-reservoir steam injection modeling for steam injection optimization", International Journal of Advance Engineering Research and Science **5** (2018) 110. https://doi.org/10.22161/ijaers.5.11.16.
[11] L. Cardona, O. E. Medina, S. Cespedes, L. H. Lopera, F. B. Cortes & C. A. Franco, "Effect of steam quality on extra-heavy crude oil upgrading and oil recovery assisted with PdO and NiO-functionalized $Al_2O_3$ nanoparticles", Processes **9** (2021) 23. https://doi.org/10.3390/pr9061009.
[12] J. E. Ejedawe, "Pattern of Incidence of Oil Reserves in Niger Delta Basin", American Association of Petroleum Geologists Bulletin **65** (1981) 1574. https://doi.org/10.1306/03B59620-16D1-11D7-8645000102C1865D.
[13] B. Evamy, D.J. Haremboure, R. Kammerling, W. A. Knaap, F. A. Molloy & P. H. Lowlands, "Hydrocarbon habitat of tertiary Niger Delta", American Association of Petroleum Geologists Bulletin **1** (1978) 1. https://doi.org/10.1306/C1EA47ED-16C9-11D7-8645000102C1865D.
[14] H. Kulke, "Regional petroleum geology of the world, Part 2: Africa, America, Australia and Antarctica", Berlin, Gebruder Borntraeger, 1995, pp. 143. https://www.osti.gov/etdeweb/biblio/44379.
[15] H. Doust & E. Omatsola, "Stratigraphy of the Niger Delta basin", American Association of Petroleum Geologists Memoir **48** (1990) 239. https://www.abebooks.com/9780891813262/DivergentPassive-Margin-BasinsBook-Map-Aapg-0891813268/plp.
[16] R. K. Penney, R. Moosa, G. T. Shahin, F. Hadrami, A. KoK, G. Engen, O. V. Ravesteijn, K. Rawnsley & B. Kharusi, *Steam injection in fractured carbonate reservoirs: starting a new trend in EOR*, International Petroleum Technology Conference, Doha, Qatar, 2005. https://doi.org/10:2523/IPTC-10727-MS.
[17] M. Foroozanfer, "Classification of enhanced oil recovery method by lithology", Journal of Fundamental and Applied Sciences **8** (2016) 228. http://dx.doi.org/10.4314/jfas.8vi2s.18.
[18] L. N. Nwidee, S. Theophilus, A. Barifcani, M. Sarmadivaleh & S. Iglauer, *EOR processes, opportunities and technological advancements*, Intechopen, 2015. http://doi.org/10.5772/64828.
[19] A. Khan, S. Saxena, S. Baloni, M. Sharma & J. Kodavaty, "Overview and methods in enhanced oil recovery", Journal of Physics: Conference Series **2070** (2021) 012061. https://doi.org/10.1088/1742-6596/2070/1/012061.
[20] E. M. A. Mokheimer, M. Hamdy, Z. Abubakar, M. R. Shakeel, M. A. Habib & M. Mahmoud, "A comprehensive review of thermal enhanced oil recovery techniques evaluation", ASME Journal Energy Resources and Technology **10** (2019) 141. https://doi.org/10.1115/1.4041096.