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PHYSICAL AND CHEMICAL TREATMENT OF PRODUCED WATER FROM CRUDE OIL TO OBTAIN INJECTED WATER PROPERTIES SUITABLE FOR RESERVOIR

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Abstract

The physicochemical characteristics of produced water from crude oil obtained from five oil wells in the Niger Delta area of Nigeria were determined using standardised methods of American Society of Testing and Materials (ASTM) to ascertain the baseline properties of the individual wells. Results obtained before any form of treatment shows that except for the Sulphate reducing bacterial (SRB) concentration, salinity and scale forming properties as shown in the sulphate, carbonate and bicarbonate concentrations, all the characteristics of the produced water from wells TA2 and CA9 were within specification as stipulated by Environmental Guidelines and Standards for Petroleum Industries in Nigeria (EGASPIN). All the physicochemical characteristics of wells TA1, CA7 and QA2 as well as those of the commingled produced water from the five wells were not within EGASPIN acceptable limit. Results obtained after physical treatment of the commingled produced water shows that the Total suspended solids (TSS), Silt density Index (SDI), Total dissolved solids (TDS), conductivity, chloride and salinity of the commingled produced water were 7.50 mg/l, 6.10 mg/l, 1251.67 mg/l, 1868.16 µs/cm, 166.00 g/l and 14536.67 mg/l respectively (within acceptable limit). Physical treatment of the produced water was made possible by installations and equipment within the oil and gas process facility such as separators, floatation packages, water injection tanks and filtration units. Continuous chemical treatment of the commingled produced water with at least 20 ppm of flocculant and oxygen scavenger respectively reduced the TOG, TPH, turbidity and dissolved oxygen to an acceptable level of 27.50 mg/l, 24.60 mg/l, 7.20 NTU and 25.00 ppb respectively while a 30 ppm concentration of continuous treatment with scale inhibitor reduced the sulphate, carbonate and bicarbonate concentrations to an acceptable level of 175 mg/l, 190 mg/l and 231 mg/l respectively. A batch treatment with 40 ppm of bactericide was required to reduce the SRB concentration to an acceptable level of 10 CFU/ml. The pH of the commingled produced water after physical treatment was 8.30 and 6.50 after chemical treatment with 40 ppm of each of the treatment chemicals which is still within acceptable limit. The use of produced water with inadequate physicochemical properties as injected water can cause a lot of damages to the reservoir ranging from Clogging or bridging of reservoir pore spaces by suspended solids, plugging challenges within the production formation, plugging of surface piping and downhole equipment as well as premature failure of formation and production equipment amongst other damages.

Key Words

Physicochemical, plugging, separators, concentration, Filtration

Introduction

Petroleum is a major source of energy and foreign exchange for most nations of the world as such crude oil exploration and production is of immense importance. Crude oil production however is accompanied with the production of liquid wastes generally known as produced water accounting for nearly 80% of the entire production especially in ageing oil fields *(Khatib and Verbeek, 2003)*. Produced water in most cases are in the form of natural or formation water and is always found together with petroleum in reservoirs, they are slightly acidic and sits below hydrocarbons in porous reservoir media. Generally, produced water to oil ratio is 3:1 in oil reservoirs and are regarded as waste during crude oil production *(Mojarad and Settari 2007)*. Produced water which is also known as oilfield brine can be obtained as water breakthrough from outside the reservoir area and account for the largest volume of byproduct generated during oil and gas recovery operations *(Khosravi and Alamdari, 2009)*. Produced water can be classified into oil field produced water, natural gas produced water and coal bed methane produced water depending on their source. Oil fields are responsible for 60% produced water generated worldwide daily *(Khatib and Verbeek, 2003)*. The geological formation and lifetime of the reservoir as well as the type of hydrocarbon produced are responsible for the organic and inorganic characteristics of the produced water (*Mojarad and Settari, 2007)*. Generally produced water is composed of dissolved and dispersed oil components, suspended solids, dissolved formation minerals, dissolved gases, sulphate reducing bacteria etc. Due to the reduction of reservoir pressure during crude oil and gas production, additional water is usually injected into the reservoir water layer to maintain hydraulic pressure and enhance oil recovery (*Chikwe and Ogwumike,2016; Morrow and Buckley, 2011)*. In most cases, produced water are injected into its formation or other formation especially in onshore locations as such adequate treatment of the produced water is required to prevent damage of reservoirs and pollution of underground waters. Produced water is therefore a mixture of injected water, formation water, hydrocarbons, and treatment chemicals *(Daniel et al., 2005)*. Produced water can be injected into the reservoir between impermeable layers of rocks to avoid polluting surface waters. The construction of water injection wells involves the construction of solid walled pipe to a deep elevation to prevent contamination with surrounding environment (*Fakhru'l-Razi et al., 2009)*. The water injection wells use the earth as a filter to treat the produced water before it reaches the aquifer through the reservoir hence, adequate treatment is needed to ensure that the produced water is suitable to the surface environment (earth), the reservoir and the water aquifer *(Daniel et al., 2005)*. Produced water can undergo primary, secondary and tertiary treatment depending on their level of contamination and characteristics required for reinjection. Primary or physical treatment of produced water are often made possible by mechanical installations in the process. Figure 1 shows the process flow diagram of crude oil from oil well to wash tank indicating physical treatment. From the figure it can be deduced that liquid crude which includes crude oil and produced water flows into the MP (Medium Pressure) Separator through the MP manifold where separation of the produced water and gas from the crude takes place at pressures between 230 - 700 psi. Gas from the crude flows into the HP (High pressure compressor) while the liquid crude (oil and produced water) flows into the LP (low pressure) Separator through the LP manifold where separation takes place at pressures between 10 – 180 psi. Gas from the LP Separator flows into the MP compressor while liquid crude (oil and produced water) flows into the LLP (Low low pressure) Separator through the LLP manifold where separation takes place at pressures between 5 - 40 psi. Gas from the LLP Separator flows into the LP compressor while the oil flows into the atmospheric Separator through heat exchangers. The atmospheric Separators operate at atmospheric pressure (<15 psi). Produced water from the LLP Separator flows into the water flash drum. Both the oil in the atmospheric separator and the produced water from the water flash drum flow into the wash tank to commence another series of physical and chemical treatment for both the oil and the produced water *(Hayes and Arthur, 2004; Fakhru'l-Razi et al.,* *2009)*. This study however focuses on physical and chemical treatment of produced water. Further treatment of produced water can be enhanced using secondary or biological treatment. Biological treatment is the elimination of organic matter in produced water by oxidation or the process of incorporating them into the cells of microorganisms such as algae, fungi, or bacteria under aerobic or anaerobic conditions however this treatment is optional *(Kaur et al., 2009).* The final line of treatment for produced water is tertiary or chemical treatment which involves the use of chemicals at specified concentrations to treat produced water to make them suitable for either disposal into the environment or reinjection into the reservoir to enhance oil recovery. Figure 2 shows chemical injection points for different chemicals such as demulsifier, bactericide, scale inhibitor, flocculant and oxygen scavengers respectively *(Chikwe and Okoli 2018)*. The aim of this study is to characterize untreated produced water from crude oil and then employ a combination of the primary (physical) and tertiary (chemical) treatment to ascertain their respective imparts on the produced water from the crude. This study is also aimed at obtaining produced water with physicochemical properties suitable as injection water for reservoirs.

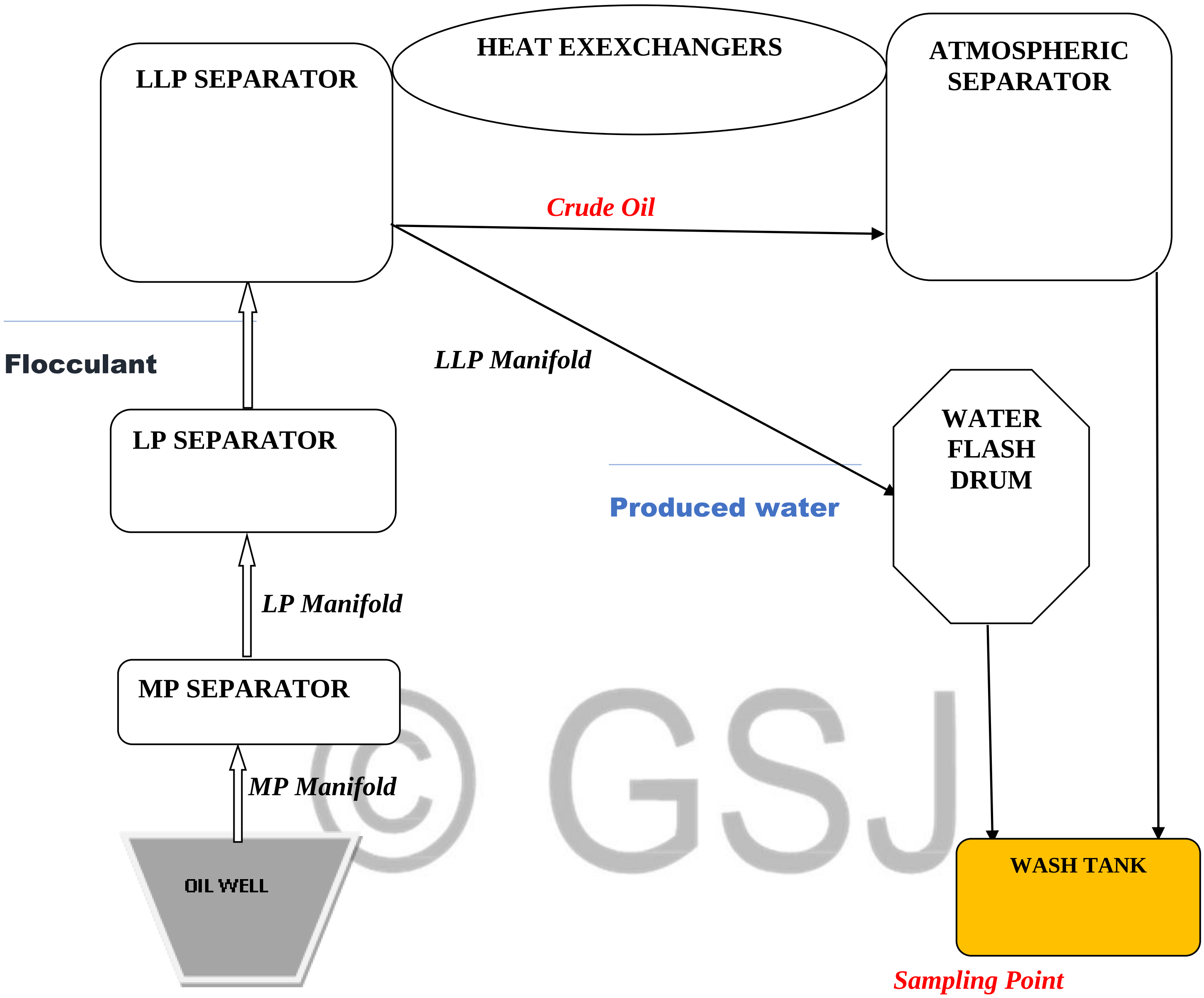

Figure 1: Process Flow Diagram of Crude Oil from Oil Well to Wash Tank Indicating Physical Treatment

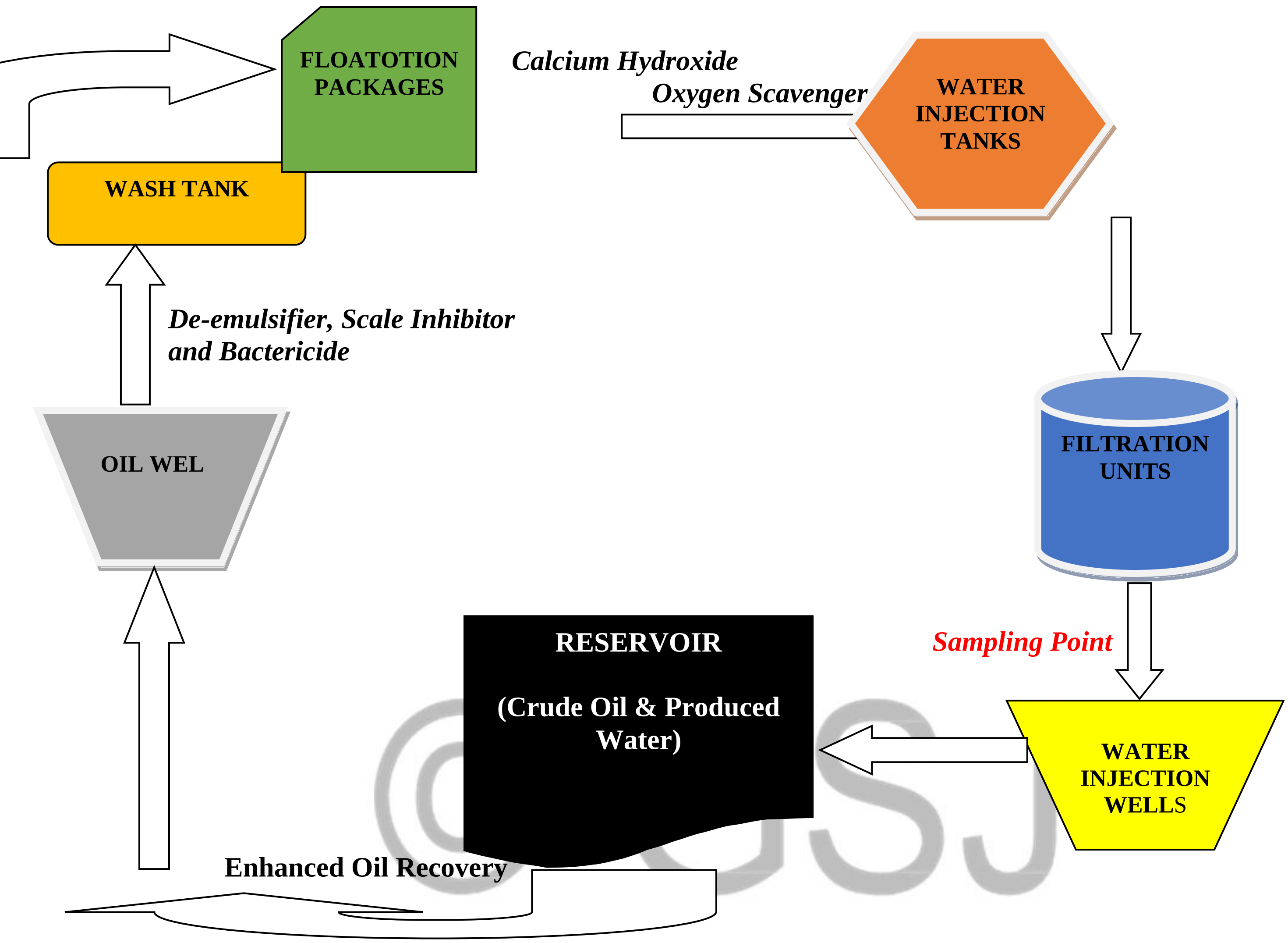

Figure 2: Flow Chart of Physical and Chemical treatment of Produced water from Wash Tank to Oil Well


Figure 3: Three Phase Separator

Materials and Methods

Sample Collection / Preparation

- Produced water from crude oil obtained from five ageing oil wells namely TA1, TA2, CA7, CA9 and QA2 in an onshore Location in the Niger Delta area Nigeria were collected respectively using a 1-Litre glass bottle previously cleaned with acetone and dried in an oven. Three samples were obtained per oil well. Some drops of demulsifier were added to the sample to aid separation of the oil from water. Samples with relatively low water content were spined with petroleum Centrifuge to recover the produced water. Recovered produced water devoid of physical and chemical treatment was characterized to obtain the physicochemical characteristics and this serves as the baseline result.
- All the produced water from the oil wells was obtained as a commingled sample

at the outlet of the filtration unit after undergoing physical treatment orchestrated through the process. Triplicate Samples was obtained at three different periods of the month respectively. These samples were devoid of any form of chemical treatment

- Produced water was obtained after treatment with different concentrations of oxygen scavenger, scale inhibitor and bactericide chemicals respectively to ascertain the impact of the different concentrations of the chemicals on the physicochemical parameters of the produced water

Methodology

Produced water obtained at each stage will be analyzed for the following physicochemical parameters:

- Total suspended solids (TSS) and Total dissolved solids (TDS) using American Society for testing and Materials (ASTM D5907, 2018)
- Silt density Index (SDI) using American Society for testing and Materials (ASTM D4189, 2016)
- Turbidity using American Society for testing and Materials (ASTM D7937, 2019)
- pH using American Society for testing and Materials (ASTM D1293, 2018)
- Total oil and grease (TOG) and Total hydrocarbon in water (TPH) using American Society for testing and Materials (ASTM D3921, 2013)
- Conductivity using American Society for testing and Materials (ASTM D1125, 2023)
- Sulphate Reducing Bacteria (SRB) using American Society for testing and Materials (ASTM D4412, 2019)
- Dissolved oxygen in water using American Society for testing and Materials (ASTM D888, 2018)
- Non-metallic ion concentration such as chloride, sulphate, bicarbonate, carbonate in water using American Society for testing and Materials (ASTM D4327, 2019)

Results

Table 1- Physicochemical Characteristics of Produced Water from Oil Wells before Physical and Chemical Treatment

PARAMETERS	TA1	TA2	CA7	CA9	QA2	EGASPIN

TOG (mg/l)	55.20	22.50	38.7	29.2	74.5	30.00
TPH (mg/l)	52.60	20.10	35.3	26.3	71.6	30.00
TSS (mg/l)	21.50	7.80	22.6	8.5	30	10.00
SDI	17.70	5.60	10.5	8.9	25.5	10.00
TDS (mg/l)	2200.00	1100.00	2600	1300	3500	2000.00
Conductivity (μs/cm)	3283.58	1641.79	3880.60	1940.30	5223.88	2000.00
Turbidity (NTU)	24.50	6.80	15.70	9.70	28.80	10.00
pH	9.2	7.50	8.00	7.80	8.50	6.5-8.5
Dissolved Oxygen (mg/l)	45.00	18.00	36.00	25.00	50.00	30.00
Chloride (g/l)	265.00	188.00	250.00	146.00	302.00	200.00
Sulphate (mg/l)	298.00	307.00	410.00	285.00	495.00	200.00
Carbonate (mg/l)	314.00	274.00	286.00	265.00	360.00	200.00
Bicarbonate (mg/l)	383.00	334.00	349.00	323.00	439.00	250.00
Salinity (mg/l)	37500.00	10800.00	55000.00	22000.00	98000.00	15000.00
Discharge Temp. (^{0}C)	28.50	28.50	28.70	28.60	28.80	-

Table 2- Physicochemical Characteristics of Commingled Produced Water from Wash Tank before Physical and Chemical Treatment

PARAMETERS	1st	2nd	3rd	Average	EGASPIN
TOG (mg/l)	50.00	52.00	50	50.67	30.00
TPH (mg/l)	47.80	47.80	47.5	47.70	30.00
TSS (mg/l)	20.50	20.20	20.5	20.40	10.00
SDI	14.80	14.50	14.5	14.60	10.00
TDS (mg/l)	2350.00	2355.00	2352	2352.33	2000.00
Conductivity (μs/cm)	3507.46	3514.93	3510.45	3510.95	2000.00
Turbidity (NTU)	16.50	16.70	16.50	16.57	10.00
pH	8.20	8.50	8.20	8.30	6.5-8.5
Dissolved Oxygen (mg/l)	40.50	40.50	40.50	40.50	30.00
Chloride (g/l)	245.00	245.00	245.00	245.00	200.00
Sulphate (mg/l)	355.00	355.00	355.50	355.17	200.00
Carbonate (mg/l)	268.00	270.00	268.00	268.67	200.00
Bicarbonate (mg/l)	326.83	329.27	326.83	327.64	250.00
Salinity (mg/l)	48500.00	48600.00	48550.00	48550.00	15000.00
Sulphate Reducing Bacteria (CFU/ml)	10^6	10^6	10^6		10
Discharge Temp. (^{0}C)	32.70	32.70	32.70		-

Table 3- Physicochemical Characteristics of Commingled Produced Water Downstream the Filtration Unit after Physical Treatment

PARAMETERS	1st	2nd	3rd	Average	EGASPIN
TOG (mg/l)	44.00	44.00	44.20	44.07	30.00
TPH (mg/l)	41.50	41.60	41.60	41.57	30.00
TSS (mg/l)	7.50	7.50	7.50	7.50	10.00

SDI	6.00	6.00	6.30	6.10	10.00
TDS (mg/l)	1250.00	1255.00	1250	1251.67	2000.00
Conductivity (µs/cm)	1865.67	1873.13	1865.67	1868.16	2000.00
Turbidity (NTU)	12.50	12.50	12.00	12.33	10.00
pH	8.20	8.30	8.30	8.25	6.5-8.5
Dissolved Oxygen (mg/l)	40.50	40.50	40.50	40.50	30.00
Chloride (g/l)	165.00	165.00	168.00	166.00	200.00
Sulphate (mg/l)	335.00	336.00	335.00	335.33	200.00
Carbonate (mg/l)	260.00	260.00	260.00	260.00	200.00
Bicarbonate (mg/l)	317.07	317.07	317.07	317.07	250.00
Salinity (mg/l)	14500.00	14550.00	14560.00	14536.67	15000.00
Sulphate Reducing Bacteria (CFU/ml)	10^6	10^6	10^6		10
Discharge Temp. (^{0}C)	28.70	28.70	28.70		-

Table 4- Commingled Produced Water Downstream the Filtration Unit after Treatment with Scale Inhibitor, Flocculant, Oxygen Scavenger and Bactericide.

	Chemical Concentrations for Flocculant, Antiscale Oxygen Scavenger and Bactericide in ppm				
PARAMETERS	**10**	**20**	**30**	**40**	**EGASPIN**
TOG (mg/l)	33.50	27.50	22.5	15.00	30.00
TPH (mg/l)	30.80	24.60	19.9	12.80	30.00
TSS (mg/l)	7.80	8.00	8.1	8.20	10.00
SDI	6.50	6.50	6.7	6.80	10.00
TDS (mg/l)	1300.00	1315.00	1320	1340.00	2000.00
Conductivity (µs/cm)	1940.30	1962.69	1970.15	2000.00	2000.00
Turbidity (NTU)	7.70	7.20	6.50	6.10	10.00
pH	7.20	6.90	6.80	6.50	6.5-8.5
Dissolved Oxygen (mg/l)	30.00	25.00	22.00	15.00	30.00
Chloride (g/l)	175.00	181.00	186.00	192.00	200.00
Sulphate (mg/l)	250.00	220.00	175.00	150.00	200.00
Carbonate (mg/l)	245.00	220.00	190.00	162.00	200.00
Bicarbonate (mg/l)	298.78	268.29	231.71	197.56	250.00
Salinity (mg/l)	14500.00	14480.00	14430.00	14411.00	15000.00
Sulphate Reducing Bacteria (CFU/ml)	10^4	10^3	10^2	10	10

Table 5- Commingled Produced Water Downstream the Filtration Unit before and after 40 ppm Bactericide Batch Treatment

Observation		
Inoculation	**Date of inoculation**	**Dilution (Bacterial Count, CFU/ml)**

		10^0 (<10)	10^{-1} (1-10)	10^{-2} (10-100)	10^{-3} (100-1000)	10^{-4}(1000-10000)	10^{-5} (10000-1000000)
Before batch treatment	**01/05/2023**	3D	5D	9D	9D	12D	15D
Batch Treatment							
After batch treatment	**03/05/2023**	10D	28D	NC	NC	NC	NC

Where: D = Number of days bacteria was formed after Inoculation
NC = No change indicating no bacteria

Discussion

Physical treatment of produced water is the primary treatment made possible by the equipment within the process of an oil and gas facility. Figure 1 shows several Separators required within the process of an oil and gas facility namely the MP, LP, LLP and atmospheric separators (*Hayes and Arthur, 2004)*. An oil and gas production separator is a cylindrical or spherical pressure vessel required for the separation of the fluid components of petroleum, they can either be vertical or horizontal and can be classified into a two phase or three phase separator. A two-phase separator only deals with oil and gas while a three-phase separator deals with oil, water and gas *(Fakhru'l-Razi et al., 2009)*. A typical three-phase separator is shown in figure 3. Separators are categorized based on their operating pressure and they separate the fluid components of petroleum by gravity segregation leaving the heaviest fluid at the bottom and the lightest fluid at the top of the separator. The degree of separation in separators are dependent on several factors which includes operating pressure, residence time of the fluid mixture and the type of fluid flow (turbulent or laminar flow). The higher the operating pressure of a separator, the lower the equilibrium constant of the components of the petroleum fluid which ultimately makes more molecules of the components to reside within the liquid phase. Separators with low operating pressure like the LLP and atmospheric separators separates low particle sized deposits in the produced water which cannot be handled by the MP and LP Separators *(Daniel et al., 2005; Hayes and Arthur, 2004)*. Table 1 shows the physicochemical characteristics of produced water from crude oil obtained from five oil wells prior to either physical or chemical treatments.

Results obtained shows that wells TA2 and CA9 had parameters that are within standard as specified by Environmental Guideline and Standard for Petroleum Industries in Nigeria (EGASPIN). Parameters such as TOG, TPH, TSS, SDI, TDS, Conductivity, turbidity, and pH were all within specification whereas the concentrations of the non-metallic ions such as the chloride, sulphate, carbonate, bicarbonate and other parameters like salinity, dissolved oxygen and Sulphate reducing bacteria (SRB) concentrations were above EGASPIN specified standard. The other wells TA1, CA7 and QA2 had all their measured parameters off specification. Table 2 shows the physicochemical parameters of the commingled produced water obtained from the wash tank containing produced water from the five wells. Results obtained shows that produced water from wells TA1, CA7 and QA2 has contaminated the produced water from wells TA2 and CA9 resulting in a commingled produced water not within acceptable standards for the water injection wells and environment as specified by EGASPIN. Table 3 shows the physicochemical characteristics of the commingled produced water obtained downstream the filtration unit after physical treatment by all the equipment within the process. Results obtained shows a remarkable reduction of all the parameters that were above EGASPIN specification before the treatment. Parameters such as TSS, SDI, TDS, Conductivity, pH, chloride and salinity were within specification. The MP and LP separators due to their design and operating pressure ensures that the TSS of the produced water are within specification, while the LLP and atmospheric separators isolates other finer particles responsible for the SDI, TDS and conductivity of the produced water thereby making it suitable for injection. The floatation packages, water injection tanks and filtration units as shown in figure 2 filters the hydrocarbon content of the produced water reflected in the TOG and TPH *(Fakhru'l-Razi et al., 2009)*. Results obtained from Table 3 shows a reduction in the TOG and TPH of the commingled produced water obtained downstream the filtration unit however results were still above EGASPIN specification hence will require chemical treatment. It is worthy to note that the floatation packages and filtration units also separates ultrafine solid particles not handled by the separators. Oil deposits in the produced water in the water injection tanks can be skimmed off from time to time to reduce the TOG and TPH and improve the quality of produced water released to the filtration units. The filters in the filtration unit can also be cleaned occasionally to improve the properties of the produced water injected into the injection wells *(Chikwe and Ogwumike, 2018)*. Parameters such as sulphate, carbonate, bicarbonate and SRB concentrations were above EGASPIN specification as shown in Table 3 and so will require chemical treatment. The TOG in produced water refers to the concentration of non-volatile hydrocarbons, animal fats, vegetable oils, waxes and greases present the produced water. The TOG does not consist of a single chemical compound but a measure of many different types of organic materials that respond to a specific analytical procedure. It is important to note that not all produced water contain the same constituent of oil and grease as there are different constituents of oil and grease even with the same oil and grease content *(Chikwe and Okwa, 2016)*. There are at least three forms of oil and grease which includes free oil, dispersed oil and dissolved oil. Free oils are large oil droplets which are easily removed by gravity separation through physical treatment, this is responsible for the reduction in TOG and TPH moving from Table 2 to Table 3. Dispersed oils are small oil droplets which are more difficult to remove whereas dissolved oils are hydrocarbons and other similar materials which can only be separated by chemical treatment *(Chikwe and Ogwumike, 2018)*. Petroleum hydrocarbons are organic chemicals consisting of only carbon and hydrogen and they pose the greatest environmental concern in produced water. Petroleum hydrocarbons are classified into saturated and aromatic hydrocarbons with the one ring aromatic hydrocarbon BTEX (benzene, toluene, ethylbenzene and xylene) being the most abundant. It is usually not practical to measure individual petroleum hydrocarbon because of their number hence they are measured collectively as Total petroleum hydrocarbon (TPH). TPH just like TOG also exist in both the dispersed and dissolved forms respectively *(Khatib and Verbeek, 2003)*. The use of produced water with TOG and TPH above acceptable limits as injection water into reservoir can cause several injectivity impairment in injection wells which can jeopardize the quantity of oil produced, plug the reservoir pores leading to uncontrolled fracturing of wells by high bottom hole pressures (*Chikwe and Ogwumike, 2018*). The salt content of produced water is measured in terms of the conductivity, TDS, salinity and chloride content. The conductivity of produced water refers to the ability or potential of the water to conduct electricity that is the conductible particles present in the water while TDS refers to the concentration of dissolve solids both conductible and non-conductible present in the water both describes the salinity level of the produced water (Sirivedhin et al., 2004). Salinity of produced water refers to the concentration of all non-carbonate salts dissolved in water while the chloride concentration in produced water refers to the concentration of only chloride ions in produced water. These chloride ions usually emanate from sodium chloride or calcium chloride. Several research supported by field trial have suggested that oil recovery can be enhanced by ensuring that the salinity of injection water is not above acceptable limit. Produced water with high salinity, conductivity, TDS and chloride content can negatively affect oil recovery for both carbonate and sandstone reservoirs depending on the formation minerals and brine composition (*Utvik, 2003*; *Chikwe and Okwa, 2016).*

Suspended solids include sand, silt, corrosion particles, live or dead bacteria etc.

The Silt Density Index (SDI) measurement indicates the extent of particulate matter suspended in water. The quantification and segregation of the particles by way of size or weight is not achieved by the SDI rather the result presents an index indicating a ratio of time taken to pass the same amount of water through the same filter after some time interval at the same pressure (*Chikwe and Ogwumike, 2018*). Produced water with Total suspended solids (TSS) and SDI above acceptable limit can lead to the development of normal and reverse emulsions, plugging of reservoir or production equipment as well as loss or reduction in the injectivity of injection wells. Clogging or bridging of reservoir pore space by suspended solids can be fast and serious resulting in formation damage if the particles are not removed before use *(Mojarad and Settari, 2007*). Results obtained from Table 3 indicates that the Turbidity, dissolved oxygen, sulphate, carbonate, bicarbonate and SRB concentrations were above EGASPIN acceptable limit. Turbidity refers to the cloudiness of water due to the presence of dispersed oil, suspended solids, silt, clay, waste effluents and other particulate matter. High turbidity leads to increased temperature, the cloudier the water the easier it is warmed up by sunlight due to heat absorption by particles in water. Injected water with high temperature favors the formation of calcium carbonate and calcium sulphate scales which is reflected in the concentrations of sulphate, carbonate and bicarbonate ions *(Chikwe and Okwa, 2016*.) Scales can lead to plugging challenges within the production formation, surface piping equipment and downhole equipment. Corrosion resulting from scale deposits can lead to premature failure of production equipment *(Daniel et al., 2005)*.

Dissolved oxygen in produced water refers to the concentration of dissolved oxygen in the water. Dissolved oxygen in produced water has the tendency of reducing hydrogen sulphide to elemental sulphur; it also oxidizes iron present in sweet production systems to iron oxide. These solids (elemental sulfur and iron oxide) can cause plugging problems within surface and downhole equipment*)*. Dissolved oxygen also results in the growth of aerobic bacteria which can cause corrosion of the metallic parts of production equipment *(Utvik, 2003; Kaur et al., 2009)*. The pH of produced water usually is controlled by the CO_2/bicarbonate system this is because the solubility of CO_2 is directly proportional to temperature and pressure. Results obtained from Tables 2 through Table 4 shows that the pH of the produced water were within EGASPIN acceptable limit. Reduced pH can affect the oil /water separation process and can impact receiving waters when discharged, it can also obstruct the oil / water separation process (*Chikwe and Okwa, 2016).* Table 4 shows the different concentrations of different chemicals applied in the treatment of produced water to ensure that all the parameters characterized were within acceptable limit. Specific chemicals are required for the treatment of specific parameters and are injected at specific injection points for optimal performance, for instance de-emulsifier, scale inhibitor and bactericide are injected at LP/LLP manifold which is upstream the wash tank (*Chikwe and Okoli, 2018*). A manifold can be defined as a system of headers and branched piping necessary for the smooth distribution of fluid from a single source to multiple outputs or vice versa, for instance from wells to test lines or from storage tank to production line *(Hayes and Arthur, 2004)*. De-emulsifier concentration of 10 ppm was injected in the LP/LLP manifold and this is responsible for the commingled water characteristics obtained in Table 2. De-emulsifier ensures proper oil/water interface at the wash tank, while Scale inhibitors prevents and treats scale formation from sulphate, carbonate and bicarbonate ions. Flocculant was injected upstream the floatation package and it is necessary for the treatment of the TOG, TPH and turbidity of the produced water ensuring that these parameters were within acceptable limit (*Chikwe and Okoli, 2018*). Bactericides eliminates anaerobic Sulphate reducing bacteria (SRB) while Oxygen scavenger kills aerobic bacteria by depleting the dissolved oxygen concentration thereby making it difficult for them to survive. Oxygen scavenger is injected upstream the water injection tank as shown in figure 2. SRB can survive even without oxygen therefore cannot be eliminated with oxygen scavenger. SRB can convert sulphates to hydrogen sulphide (H_2S) and subsequently to elemental sulphur. H_2S is both soluble in oil and aqueous solution and is dangerous to humans at temperatures as low as 1000 ppm. Bacterial agents can produce H_2S as much as 10,000 ppm in produced fluids *(Chikwe, 2020; Kaur et al., 2009)*. From Table 4 it can be deduced that 20 ppm of Flocculant and oxygen scavenger injected at the appropriate injection points will produce water from crude with all the parameters except sulphate, carbonate, bicarbonate and SRB concentrations within EGASPIN acceptable limit. To obtain acceptable sulphate, carbonate and bicarbonate concentrations, 30 ppm of scale inhibitor will be required. To obtain produce water with acceptable SRB concentration of 10 CFU/ml, 40 ppm of bactericide will be injected through batch treatment. Flocculant and Scale inhibitors are injected continuously while oxygen scavenger is injected curatively whenever the dissolved oxygen is above 30 ppb. Table 5 shows bacterial inoculation of commingled produced water 24 hours before batch treatment and 24 hours after batch treatment using SRB test kit containing six bottles. Inoculated bottles were observed for 28 days to confirm the presence of SRB. The presence of SRB is confirmed by the appearance of a black residue in the bottle. Results obtained shows that the produced water contains as much as between 10000 – 1000000 CFU/ml before bactericide batch treatment which appeared within 15 days after inoculation. On the other hand, only 10 CFU/ml of SRB was observed with the bottles inoculated 24 hours after bactericide batch treatment. Produced water with SRB of 10 CFU/ml is within EGASPIN acceptable limit as such does not require further bactericide treatment *(EGASPIN, 2022)*.

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Conclusion

The management of produced water obtained during crude oil exploration is very critical considering that they constitute over 60% of crude produced especially from ageing wells. Reinjection of produced water into the reservoir for enhanced oil recovery is one of the best ways of managing and disposing produced water however adequate treatment is essential to ensure that characteristics of the produced water is suitable for the reservoir and the environment in general. The physicochemical parameters of produced water are key performance indicators that guarantees their suitability and this is made possible by both physical (primary) and chemical (secondary) treatment. Physical treatments involve the equipment within the process of an oil and gas facility and they include various types of separators (classified based on their operating pressures), heat exchangers, flash drums, floatation packages, water injection tanks and filtration units. Whilst the physical treatment plays some roles in the reduction of produced water parameters such as TOG, TPH and turbidity they are basically critical in ensuring that parameters like TSS, TDS, SDI, chloride, conductivity and salinity are within internationally approved acceptable limit. Oil and hydrocarbon concentrations of the produced water calculated by the TOG and TPH, Scale forming properties of the water orchestrated by the sulphate, carbonate, bicarbonate concentrations as well as the aerobic and anaerobic bacterial concentrations of the produced water are reduced within acceptable limits using adequate concentrations of suitable chemicals at adequate injection points within the process. Untreated produced water with inadequate characteristics can cause a lot of damages to the reservoir when used as injected water.

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