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Recovery of Crude Oil Losses to Effluent Water Disposal System in the Production Platform Using Sand Filter

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Abstract — The work entails research on recovery of crude oil losses to effluent water disposal system in the production platform using sand as the filtration media. In this dissertation a glass column filled with sand is used as a low-cost filtration media for the removal of crude oil from synthetic oil produced water (SOPW) and real produce water PW from oil and gas wells. The objective of this work is to examine the filtration efficiency of sand grains tilled in a glass column as sand filter in recovering crude oil from produced water. This work investigates the influence of process parameters such as physical characteristics of sand, column height, types of effluent (oilfield produced water and synthetic oil produced water), and oil concentration on oil removal efficiency. The sand fractions used for this work was selected using a set of Tyler sieves. After the different grain sizes were selected, the sand was washed several times to remove impurities. The sand samples were oven dried at 1000C for 24h. The gravel was washed and also dried at 1000C, for l2h. Oil was removed from laboratory-produced water in a batch process at standard atmospheric conditions. The effect of contact time, physical characteristics of sand, column height, pH as well as temperature on the removal efficiency of oil was investigated. The optimum parameters for oil removal were: pH 9.5, contact time 40.0 minutes and temperature 55.00C. The results showed that the oil concentration decreased significantly after the filtration process. The oil removal efficiency was influenced by the sand particle size and bed height, reaching 90% using a 30 cm high sand bed composed by mixed grain sizes.

Keywords— Crude Oil Losses, Effluent Water, Disposal System, Production Platform and Sand Filter..

I. INTRODUCTION

Petroleum is a major source of energy and revenue for many countries today, and its production has been described as one of the most important industrial activities in the twenty-first century (Oliveira et al., 2005). It is estimated that world daily petroleum consumption would increase from 85 million barrels in 2006 to 106.6 million barrels by 2030. Despite its significance, petroleum is produced with large volumes of waste, with wastewater accounting for more than 80% of liquid waste (Amso-Scott et al., 2007). However, the performance of each of these technologies will depend on process variables for each facility, such as the type of reservoir and oil, temperature, pressure. viscosity, emulsion stability, size of the oil drops, salinity and speed flow among others (Lawrence et al., 1995).
The conventional system of oil produced water treatment used on offshore platforms is basically composed of hydro cyclones and floaters. The water coming from the separator vessel undergoes removal stages of oily residue in hydro cyclones batteries and is forwarded to floaters by induced or dissolved gas (Hansen. 1 994). Other technologies have been developed seeking a better management of oil produced water. Amongst these technologies, adsorption, the electrochemical process, filtration and flotation may be mentioned. The viability of the treatment technologies has low operating cost and high efficiency. In the case of offshore installations (off-shore field), these technologies should also be compact, due to space and weight constraints (Metcalf, 2003).

Adsorption is based on the principle that a solid surface in contact with a fluid, tends to accumulate a surface layer of solute molecules due to the imbalance of existing surface forces.

According to Braga et al. (2010).
A method which has been used commercially to remove the free oils and suspended solids from water in refineries is the walnut shell filter. In this method, water is introduced into a down flow where the oil is adsorbed and suspended solids are filtered. Queiros et al. (2006) conducted research using columns packed with polymeric resins such as alternative materials for treatment of oily water. The water after the treatment, showed the OC as less than 1.0 mg/L. The authors observed that the maximum performance was achieved at a rate of 7 mL/min: however, the flow range from 5.0-50.0 mL/min, the column efficiency was not less than 98% of oil reduction.

Silva (2002) conducted studies on the potential of clay and vermiculite expanded organoclay hydrophobized as an adsorbent in the treatment of oil-water emulsions. According to Silva et al. (2014), flotation is one of the processes most commonly used for oil recovery in oil produced water by means of gravitational separation. The present flotation efficiency

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ranges between 85% and 90% removal of oil. In addition, clectroflotation is distinguished by its simplicity of operation and application for the treatment of many types of effluent. Cerqueira and Marques (2011). Rosa et al., (2009) studied the crossflow microfiltration treatment in oil produced water. The filter system used was composed by a porous ceramic type of filter media wrapped in a PVC casing with outlets for the power suspension and the concentrated tangential removed to the surface of the filter medium. AWWA (2001), Torrens et al. (2009), Anderson et al. (1985), and Woelkers et al. (2006) states that the successful choice of a filter media as sand filter to produced satisfactory desired pollutant removal performance depended upon the proper choice of the depth of the filters, type of sand, sand size and distribution, conditions of influent water, quality of effluent, the filtration rate, and dosing regime and resting period duration, all affected the hydraulic performance and purification efficiency of the filters.

The schmutzdecke breaks down organic particles in the water biologically, and is also very effective in straining out even very small inorganic particles from water (MECC, 2002). The mechanism of particle does not use biological filtration and depend primarily on adsorption and some straining (MECC, 2002). Total Suspended Solids (TSS) are solids in water that can be trapped by a filter. TSS can include a wide variety of materials, such as silt, decaying plant and animal matter. industrial wastes, and sewage. 1-ugh concentrations of suspended solids can cause many problems for stream health and aquatic life (Buechter, 2008). Woelkers et al. (2006) states that the likely minimum effluent concentrations are as tbllows: 10 mg/L for suspended solids, 50 HACI-1 color units, and 10 NTU for turbidity.

II. MATERIALS

The materials used for this work include:
- Beaker
- Measuring cylinder
- Scaled tiltranon glass column
- Tyler sieves
- Valve
- Microwave
- tripod stand
- Wire mesh
- Sand
- Crude oil
- Gravel
- Effluent water (PW and SOPW)

1. Method

Process Design Description

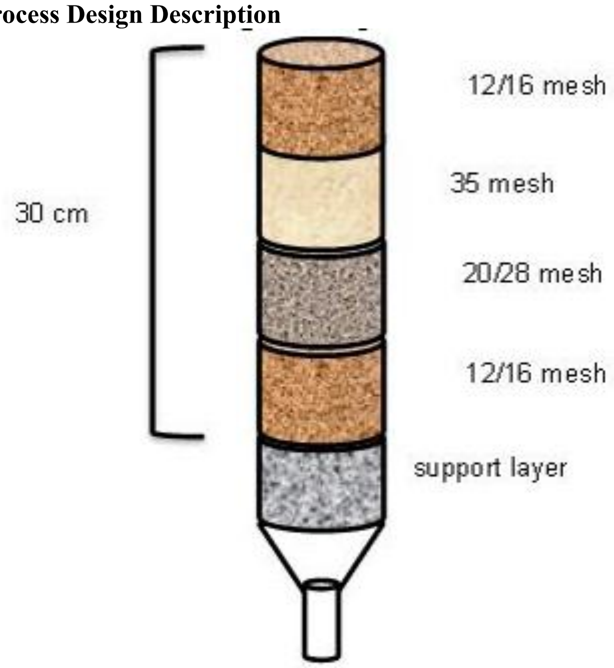

Figure 1: Schematic Diagram of a Mixed Grain Size Filter

This research is basically an experimental work carried out by the use of sand filter media to recover crude oil losses to effluent water. A laboratory apparatus was locally assembled and used in this study for the purpose of filtration. The filtration system consisted of a glass column (height 40 cm, diameter = 10 cm). Figure 3.1 shows a schematic diagram of the system. The upper part of the column was filled gravitationally with sand and gravel. The lower part, a 10 cm support layer, was composed by coarse gravel. Coarse gravel was used as a support layer for the sand filter. The equipment is designed for multi-phase flow in porous media and the basis of design of the equipment adopts the same basic principle as employed by the oil and gas industry, column. An outlet valve is placed at the end of the glass column lot the out flow out the filtered water. The equipment is designed to inject fluid(s) into the glass column via constant flow-rate.

Experimental Procedure

In order to evaluate the efficiency of 'FOC' removal, two filtration systems were used iii this work: one mixed—media tiller, consisting of four sand layer with grain sizes arranged in the sequence 12/16. 20/28. 35, and 12/16 mesh (as shown in Figure 3.1), and another consisting of sand bed with a fixed grain size of 12/16 mesh for the controlled experiment. The sand beds used were 15 and 30 cm high for both systems. To optimize the filtration process through experimental design, the

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efficiency of total oil content (TOC) removal was investigated using solely synthetic oil produce water (SOPW). In the latter case, a control experiment for measuring any loss in oil concentration during the experiment was carried out. A sand bed (15 and 30 cm high) with a fixed grain size of 12/16 mesh was used with the same solution. However, there was no change observed in the oil concentration after the control experiment. The mechanism of filtration and removal depended on the type of sand filter which is either slow or rapid.

Anderson et al. (1985) summarized the mechanism process that occurs to some degree within the filter as physical, chemical, and biological treatment processes. Straining, sedimentation, inertial impaction, interception, adhesion, flocculation, diffusion, adsorption and biological activity have been suggested as mechanisms of contaminant removal in filtration.

- Straining: involves a mechanical sieve action as well as lodging of particles in crevices.
- Sedimentation: occurs as gravity settling takes place in the interstices of' the media.
- Inertial impaction, interception, and adhesion: occur as particles moving through the filter strike media granules and are removed.
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- Flocculation: Particles moving through the pores will also collide with each other and flocculate causing subsequent removal by other mechanisms.
- Diffusion: is important in the removal of very small particles such as viruses, and occurs because of the small interstices in porous media and the fact that laminar flow exists.
- Physical adsorption of pollutants takes place on media surfaces due to electrostatic, electrokinetic and van der Waals forces while chemical adsorption occurs due to bonding and chemical interaction between polluted water constituents and the filter media.
- Biological activity on the filter media results in removal of polluting materials by biological assimilation and biosynthesis.

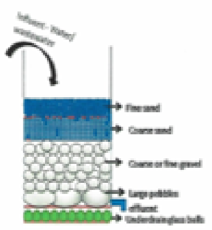

Figure 2: Sand Filter Experimental Setup

Analytical Procedures

The total oil content (TOC) concentration in the samples of synthetic and oilfield produced water (SOPW and OPW) before and after the filtration was determined using an Infraclass analyzer (Wilks enterprise Corp, model HATR-T2 TOG/TPH). This parameter was measured by spectrophotometry in the infrared region, based on the absorbance of C-H bonds (USLPA methods 4.12.2 and 41 8.1). The grain size distribution of the sand sample was performed by a laser granulometry (Cibas. model 920). Oilfield produced water (OPW) was characterized given its variable composition. Copper, sodium, iron, potassium, cadmium, nickel, and calcium contents were determined using flame atomic absorption spectrophotometry (Varian. model AA240). A multiparametric probe (TROLL, model 9500) was used to determine nitrate, turbidity, pH, conductivity and chloride.

Experimental Design

To optimize the filtration process, considering sand bed height and initial TOC concentration on the removal efficiency of SOPW, a 22 factorial design was carried out in duplicate, with eight experiments. This factorial has two factors (bed height and initial concentration of TOC) and two levels for each factor, the lowest level (-) and the highest level (+). The bed height ranged from 15 to 30cm and the initial concentration of TOC ranged from 101 to 204 mg L^(-1) The response variable was the TOC removal efficiency (ε, %) named γi. The essays were pertormed randomly. The number of experimental points (eight) was delineated as enough to assess the linear model. Based on statistical modeling, a linear mathematical model was proposed.

$$\gamma_i = 64.55 + 0.979x_i + 9.946x_2 - 3.628x_1x_2 \qquad (1)$$

Where x_1 is the oil concentration, x_2 is the bed height, and yi corresponds to TOC removal efficiency.

Calculation

Porosity($\emptyset$)**:** this is been calculated mathematically as:

$$\emptyset = \frac{PV}{V_n} \times 100 \qquad (2)$$

Salinity

The salinity was calculated based on chloride concentration in the sample

$$\text{Salinity} = 1.80655\ (\text{CL}) \qquad (3)$$

Where (CL) is the Chloride concentration (mgL^{-1})

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Filtration Efficiency

The filtration was assessed in terms of the efficiency of oil removal and the consequent reduction of TOC concentration in OPW and SOPW. The TOC removal efficiency $(\varepsilon, \%)$ was calculated from the equation below:

$$(\varepsilon, \%) = \frac{\mathrm{TOG_0} - \mathrm{TOG_F}}{\mathrm{TOG_0}} \times 100 \qquad (4)$$

Where;

- $(\varepsilon, \%)$ is the removal efficiency of TOC
- $\mathrm{TOC_0}$ *and* $\mathrm{TOC_F}$ are initial and final concentration of total oil $(\mathrm{mgL^{-1}})$, respectively

Testing Parameters

The following parameters were tested in the study:

- The total oil content (TOC) concentration in the samples of synthetic and oilfield produced water (SOPW and OPW)
- The grain size distribution of the sand samples and bed height

System Operation

- After testing the sand filter media, the apparatus was assembled. Fol1owing this, the system was operated first using clean water so that to wash the sand filter media and to remove any impurities that may exist on it: this step continued till reaching a steady state flow and till water runs clean.
- It was important to wash the media after each experiment stage and to remove the top layer of dirt on the surface of' sand tilter o as to reflect the actual performance of the system and to ensure obtaining accurate results.

III. RESULTS AND DISCUSSION

1. Grain Size Distribution of Filter Materials

Figure 3 shows the grain size distribution of sand materials used for the purpose of filtration. The filtration mechanism used is slow sand filter as the average size of particles ranges from 0.15 to 0.60 mm. This allows for elective recovery of TOC of oil in both OPW and SOPW

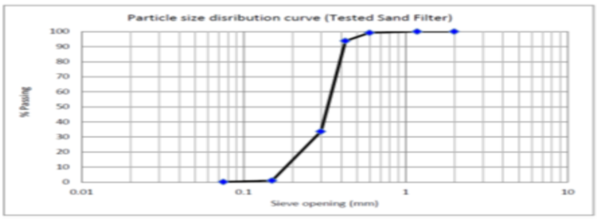

Figure 3: Grain Size Distribution of Filter Materials

2. Results of Characterization of Sand Bed

The results of grain size and frequency distribution in sand samples are represented by granulometric curves, shown in Figure 4, 5, and 6. Thus, the sand samples retained in the sieves with 12/16, 20/28, and 35 meshes have a mean diameter of 997, 902, and 479 µm, respectively. The high mean diameter values (> 100 tm) indicate the presence of void spaces between sand grains, which allows better penetration and distribution of the wastewater flow along the entire bed.

Figure 4 shows Dl0, D30, and D60, corresponding to 10%, 30%, and 60% particles with smaller diameters, presented in Table 4.1, along with other physical characteristics of the three sand grain sizes used in the filter, i.e., coefficient of curvature (Cc) and coefficient of uniformity.

(C_0). According to the American Society for Testing Materials (ASTM). the 12/16 mesh grain size (42 mm) is classified as coarse sand, and the 20/35 mesh (2 0.425 mm), as medium, sand. Also, according to the ASTM. the coefficient of uniformity (C_0)60/1)10), which allows assessing the distribution of sand particle size, should be between 4 and 6 to indicate uniformity distribution. Regarding to the sand bed, the coefficient of uniformity was around .0 for all grain size ranges, and therefore exhibiting non-uniform distribution, corroborating the results showed in particle size distribution curves (Figure 4, 5. and 6). In regards to the coefficient of curvature (Cc (D30)2/[)60x D10), the values were approximately 1.0, indicating a proportional distribution of particle size, being that the void spaces left among larger particles can be occupied by smaller particles. This makes the bed more suitable for slow filtration, which in turn, is good for effective oil recovery as shown on Table 1.

Table 1: Parameters of Sand Bed

Particle size (mesh)	[1]Cu	D10	D30	D60	[2]Cc
12/16	1.38	1.95	2.40	2.71	1.08
20/28	1.35	1.37	1.70	1.90	1.11
35	1.22	0.49	0.56	0.60	1.06

[1]Cu = Coefficient of uniformity
[2]Cc = Coefficient of curvature

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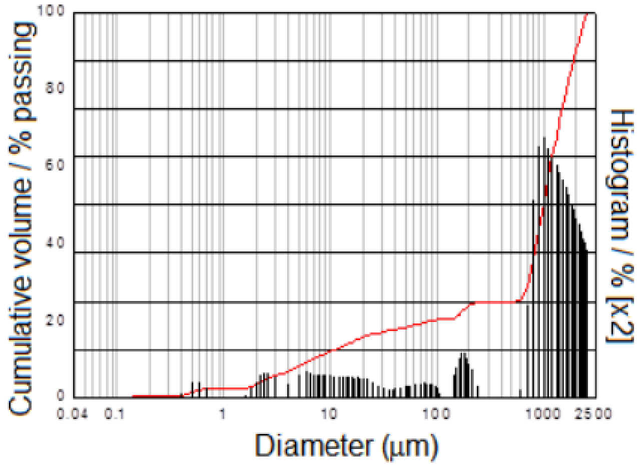

Figure 4: Particle Size Distribution Curves of the Sand Samples 12/16 Mesh

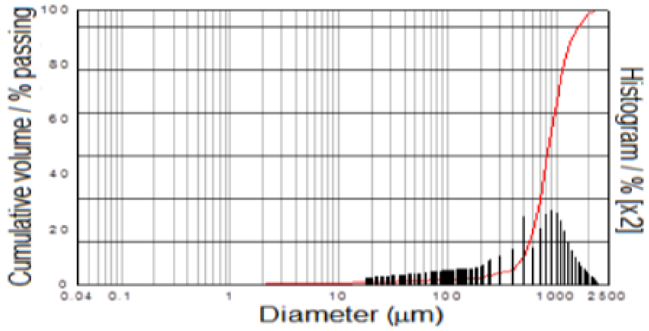

Figure 5: Particle Size Distribution Curves of the Sand Samples 20/28 mesh

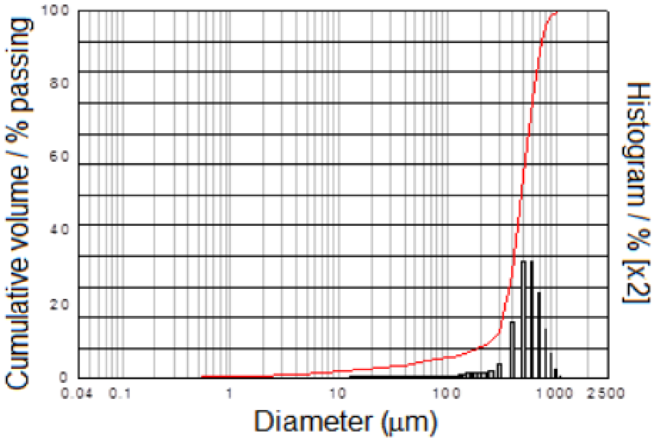

Figure 6: Particle Size Distribution Curves of the Sand Samples 35 Mesh

3. Results of Characterization of OPW
The results of the characteristics of the oilfield produced water (OPW) are presented in Table 2. TOC concentration is higher than the minimum value allowed by CONAMA (20 mgL^{-1}) and USEPA (29 mgL^{-1}). Produced water has a very variable composition, which depends on the characteristics of the production oilfield as well as the nature of injected fluids. The chloride concentration (737-2,949 mgL^{-1}) of our sample. for example, is lower when compared to the data obtained for a produced water from an onshore oilfield in the United States (Murray-Guide *et al.*, 2003) and one in Bacia de Campos offshore oilfield. Brazil (Lima *et al.*, 2008), with concentrations of 3,361 and 29,830 mgL^{-1}, respectively. Moreover, the pH (7-7.5) was between neutral and slightly basic, similar to the ones obtained for the Devecatagi oil production well (pH 7.1) and those for Vakiflar gas and oil production well (pH 7.8), in Turkey (Çakmakce *et al.*, 2008).

The produced water from the Curirnã platform (Petrobras, Potiguar Basin. State of CearálBrazil), which disposes around 1000 m^3 day^{-1} (mean in 2004), exhibited a pH of around 8.7, differing completely from our produced water sample. Among the various inorganic components present in produced water the most representative elements arc K; Na, and $Ca2^+$, at high concentrations (Arnold & Stwart. 2008). Regarding heavy metals, cadmium, lead, nickel, zinc, and chromium arc the ones with the highest concentrations (Neff, 1987), Therefore, these heavy metals deserve more attention, since they impact not only the environment, but also human health (Chen *et al.*, 2012; Balistricre & Mebane, 2014). It is important to underscore that the copper concentration is higher than the minimum value allowed by CONAMA (0.001 mgL^{-1}) as shown on Table 2.

Table 2: Characteristics of the Oilfield Produced Water from Operating Unit

Parameters	Concentration range
Nitrate (mg L^{-1})	0.75– 3.0
Chloride (mg L^{-1})	737 – 2,949
Salinity (mg L^{-1})	1,331 – 5,327
pH	7 – 7.6
Turbidity (NTU)	30 – 120
Conductivity (mS cm^{-1})	1.75 – 7.12
Potassium (mg L^{-1})	4.48 – 17.9
Iron (mg L^{-1})	0.005075 – 0.0203
Nickel (mg L^{-1})	0.0025 – 0.01
Copper (mg L^{-1})	0.5753 – 2.301
Cadmium (mg L^{-1})	0.0225 – 0.09
Sodium (mg L^{-1})	3.25 – 13
Calcium (mg L^{-1})	10 – 40
TOC (mg L-1)	32 – 500

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4. Effect of Operating Parameters 011011 Recovery
Oil removal efficiency is affected by the variation in the temperature, pH, salinity and filter load (sand grains). The effect of pH, salinity, temperature and filter load quantity' on oil removal efficiency was investigated. The initial pH of the SOPW varied between 0.1-13.7. The experimental conditions for this experiment were sand loading of 10 g/L. oil content of 300 mg/L and contact time of 50 minutes. Likewise, the salinity was varied from 0 mg/L to 2000 mg/L by using NaCl and adjusting the initial pH to 9.5. Moreover, the temperature effect on sorption was studied by varying the solution temperature in the range of 25-700C at a constant initial pH of 9.5.

Results of the Effect of Contact Time
Figure 6 shows the investigation of the effect of contact time on the removal efficiency of the sand filter. A close look at this figure shows 50 minutes to be the optimum contact time for the filtration process. Moreover, it can be seen in the figure that the oil removal efficiency increases as the initial oil concentration decreases at a given contact time. In sped tic terms, the oil removal efficiency increased from 76% to 95°/a as the initial oil concentration decreased from 1600 to 200 pm at 60 minutes contact time. One explanation for this finding is that increase in bed height with high contact time, leads to low final oil concentration results, thus increasing removal efficiency of the sand filter.

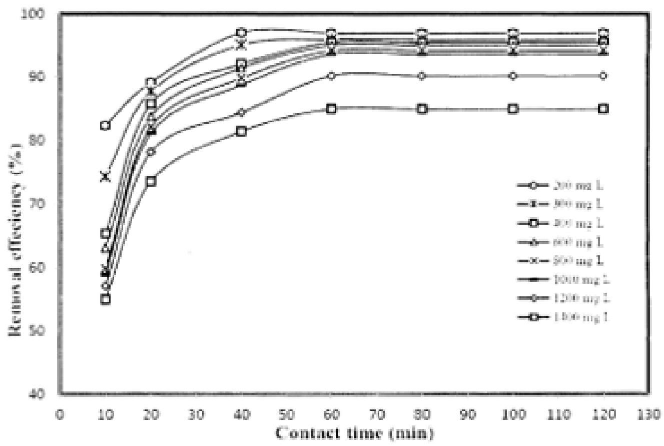

Figure 6: Effect of Contact Time and Initial Oil Concentration on Oil Removal Efficiency by Sand Flitter. Initial pH: 9.5 ± 0.2, temperature: 25 ± 2 UC, filter load 10.0 g/L, and standards deviation: I .0.

Results of the Effect of pH
Among the parameters that control the filtration process is pH. This work covers the investigation of the effect of pH on the removal of crude oil by sand filter at 50 minutes contact time. 300 ppm initial concentration of oil, and a filter load of 10.0 g/L Figure 7 is a presentation of this data. A decrease in the removal efficiency as the pH increased from 0.100 to 3.50 can be seen in this figure. However, a sharp increase in the removal efficiency of crude oil by sand filter accompanies a Further increase in pH from 4 ±0.2 to 10 0.2. The high efficiencies at pH = 0.1 can be attributed to the electrostatic attractions between the protonated binding sites on the surface of the sand filter and oil molecules are very high, thus leading to the observed high efficiency at this pH (Chiou & Li, 2003).

Furthermore, the decrease in the efficiency of oil removal at pH between 0.100 to 3.50 which could he due to the availability of proton ions in the solution competing with the oil molecules at this interval. Two factors can be deemed responsible for the sharp increase in the efficiency of oil removal above a pH of 4. First, presumably, is the production of floes of oil due to the oil water getting destabilized at a high pH (Ahmad et al., 2005). This resulted in larger oil droplet size and coalescence of oil, enabling larger efficiency. A second factor can be the increasing hydrophobicity of the sorbent surface as the pH value rises. The oil adsorption efficiency reduced slightly at pH 1 2±0.2, which could be credited to a rise in oil emulsion stability resulting in a reduced contact area between sand filter and oil droplets. Inspection of Figure 4.6 reveals that the optimum pH is 9.5.

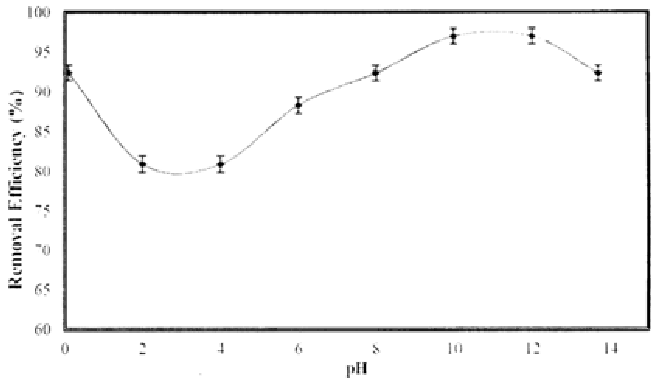

Figure 7: Effect of pH on Adsorption of Crude Oil. Initial oil concentration is 300 mg/L, temperature is 25±20C, filter load is 10.0 g/L, contact time is 50 mm and shaking/stirring speed is 40 rpm.

Results of the Effect of Salinity
A set of adsorption experiments was performed studying crude oil removal from SOPW at NaCl concentrations of 0 to 2000 mg/L. The salinity study was performed at an initial oil concentration of 300 mg/L, initial pH of 9.5±0.2. 50 minutes of contact time, 140 rpm of shaker stirring and a lilter load of 10.0 g/L. The increase in the oil removal efficiency along with the

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increase in salinity is shown in Figure 8. At the highest salinity, 96% of the oil was removed. The solubility of oil in SOPW declines as the concentration of NaCI in the SOPW increases, leading to an increased oil uptake (Moreno-Castilla, 2004).

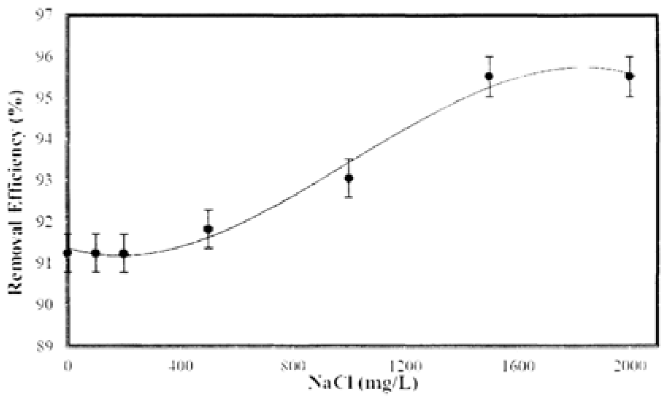

Figure 8: Effect of Salinity on Crude Oil Removal Efficiency. Initial oil concentration is 300 mg/L, initial pH is 9.5±0.2, temperature is 25±20C, fliter load is 10.0 /L, contact time is 50 minutes, and shaking/stirring speed is 140 rpm.

Results of the Effect of Temperature

One of the most important factors which may have a significant impact on the removal of oil from produced water is temperature. The effect of temperature on the oil sorption was studied in this work. Experiments were conducted at temperatures between 25 and 700C. The study of temperature was executed at an initial oil concentration of 300 mg/L. initial pH 9.5±0.2. 50 minutes of contact time. 140 rpm of shaker stirring and a filter load of 10.0 g/L. Figure 4.8 shows that the oil removal efficiency increased by four percent (92 to 96%) by increasing the temperature from 25 to 550C. However, when the temperature is raised beyond 600C. a decrease in oil removal efficiency was observed. The rise in the oil removal efficiency up to 550C caused by the drop in the surface tension of oil and water emulsion. Moreover, the oil uptake of the sand tilter improves as the viscosity of the oil diminishes. The viscosity of oil is inversely proportional to the oil penetration rate into the interior surfaces of the sand filter.

The adsorbate molecules are in random Brownian motion in the liquid phase and effective collisions are responsible for getting them adsorbed when they are close to the sand filter. In fact, raising the temperature increases the velocities or the movement of the molecules. Ibis rise in the Brownian motion leads to an instability of the oil molecules and increases interaction between the filter and the oil particles. Thus, with temperature. the oil removal efficiency improves. The reduction in the oil removal efficiency after 600C indicates that the exothermic process controls the rate of adsorption. Therefore, increase in the adsorption shows that the rate of adsorption is controlled by kinetics of adsorption process. Less efficiency at higher temperature may also he attributed to the loss of some organic compounds by vaporization.

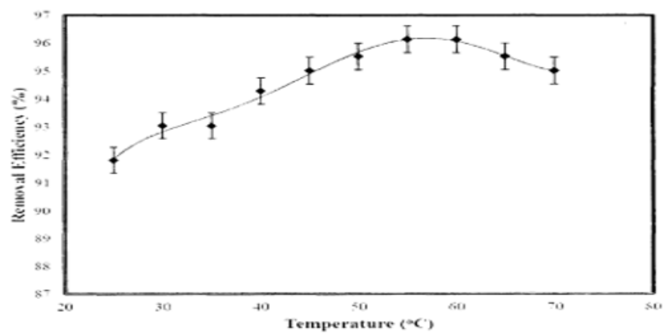

Figure 9: Effect of Temperature on Crude Oil Removal Efficiency. Initial oil concentration is 300mg/L, initial pH is 9.5±0.2, temperature is 25±20C, filter load is 10.0 g/L. contact time is 50 minutes, and shaking/stirring speed is 140 rpm.

5. Validity of the 22 Factorial Modal in Optimizing Experimental Design

The validity of the model was verified using Analysis of Variance (ANOVA), as shown in '[able 4.3. The coefficient of determination (R2) was applied to evaluate model fit to experimental data. The closer R is to l the better the correlation between values calculated by the model and those observed in the experiments is.

The F-value calculated was compared to critical F-value at a 95% confidence level. Table 4.3 show that the linear model (Equation 1) obtained is significant at a 95% confidence level (F_calculated greater than F_critical). In addition, the correlation coefficient (R2) reached 0.9791 indicating that the model explains 97.91% of the variation in experimental data. The F_calculated was 9.5 times higher than F_critical implying that the proposed model can be considered predictive, significant, and, therefore, adequate to describe the response variable as a function of' the factors (Silva et al.. 2015: Anchieta et al.. 2016). Figure 4.9 and figure 4.10 shows the response surface and the Pareto chart determined from experimental design. Factorial experimental design allowed determining the effects of initial TOC concentration and the sand bed height on the oil removal efficiency in SOPW.

The height and concentration variations in the maximum removal region (optimal region), Figure 9. provide an analysis of the response tendency of the dependent variable (efficiency) predicted by the model (Equation 3.1). They suggest that the

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efficiency of removing the TOC from SOPW increases with the increase of sand bed height. Furthermore, the initial concentration of TOC does not affect the overall removal efficiency in the range of oil concentration (101 and 204 mgL^(-1)) and bed height (1 5 and 30 cm) studied. The Pareto chart (Figure 4.10) shows statistically significant effects. According to results, the significant effects are height of the sand bed and interaction between it and initial concentration of TOC, which act positively on filtration efficiency.

Table 3: Variance Analysis for Adjusting the Linear Model

Source of variation	QS	DF	MS	$F_{calculated}$	$F_{calculated}/F_{value}$
Regression	904.43	3	301.47	62.47	9.48
Residual	19.30	4	4.82		
Total	923.73				

QS = Quadratic sum
DF = Degrees of freedom
MS = Mean square
$F_{calculated} = MS_{Regression}/MS_{Residual}$

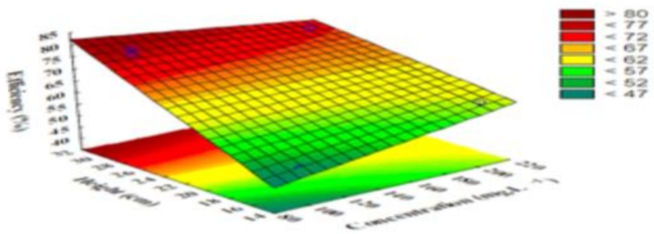

Figure 9: Response Surface for Factorial Experimental Design

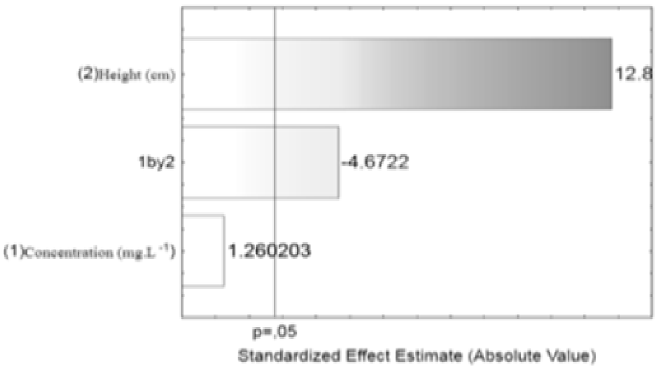

Figure 10: Pareto Chart for Factorial Experimental Design

6. Results of Experimental Design

Table 4.4: Real and Coded (in Parentheses) Variables and Results for the Experimental Design

Run	Height (cm)	Concentration (mg L-1)	*yi (Ɛ,%)*
1	15 (-1)	204 (+1)	61.4
2	30 (+1)	204 (+1)	73.7
3	15 (-1)	101 (-1)	50
4	30 (+1)	101 (-1)	76
5	15 (-1)	201 (+1)	57
6	30 (+1)	204 (+1)	70
7	15 (-1)	101 (-1)	50
8	30 (+1)	101 (-1)	78.3

7. Results of Filtration Efficiency of Sand Filter

The results show that in the 15 cm-high sand beds with a fixed grain size of 12/16 mesh (Figure 4.18), TOC removal from SOPW was around 50%, whereas for oil field wastewater a small reduction was obtained (40%). The poor TOC removal efficiency observed for both wastewaters can be explained by the use of a lower sand bed height (15 cm). In the case of the 30cm column (12/16 mesh) (Figure 4.19), TOC removal efficiency for both wastewaters (QPW and SOPW) increased considerably (> 60%), confirming that the bed size is an important parameter in the efficiency of the removal process. The experiment with the 30 cm sand bed with mixed grain size (in the sequence 12/16, 20/28, 35, and 12/16 mesh) presented efficiency higher than 85% (Figure 4.20), exhibiting better removal than experiments under other conditions. This confirms that the decrease in grain size along the bed is an important factor in filtration.

The enhanced removal in relation to the smaller particle size may be due to their smaller effective diameter (Dl0), resulting in a slower filtration speed and consequent improvement in quality, since permeability tends to decrease as fine particles fill the empty spaces (Fang & Daniels, 2006). A similar filtration process was used by Cha et al. (2010). However, associated with the ozonation method. The authors did not evaluate the TOC removal, but the turbidity of' the effluent was reduced from 200 to 2 NTU. The best removal results were observed when using a mixed grain size filter, reaching efficiency higher than 90%. Under all the experimental conditions tested, the efficiency in removing the TOC from synthetic oilfield produced water (SOPW) was greater than that of oilfield produced water (OPW), given that the synthetic waste water exhibits a less complex composition.

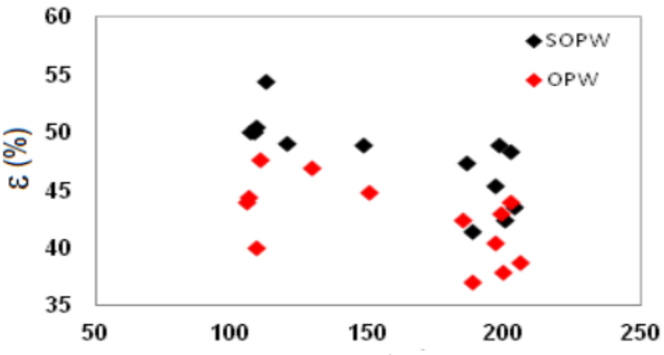

Figure 11: Removal Efficiency of TOC from SOPW and OPW using Sand Bed 15 cm

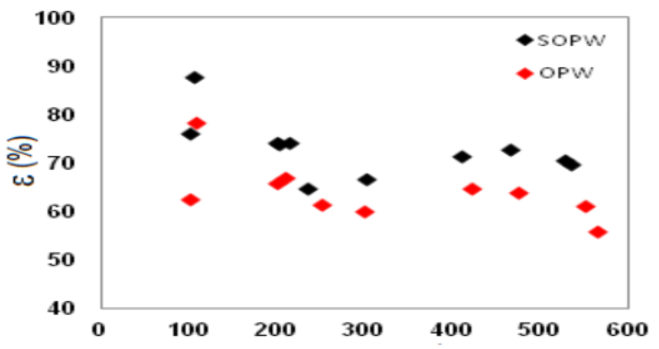

Figure 12: Removal Efficiency of TOC from SOPW and OPW using Sand Bed 30 cm

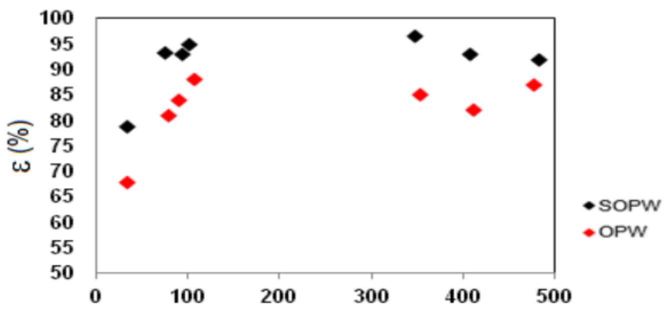

Figure 13: Removal Efficiency of TOC from SOPW and OPW using Mixed Grain Size

IV. CONCLUSION

After the research was conducted, the following conclusions were drawn;

The grain-size distribution analysis showed that the selected sand possessed suitable physical characteristics for slow sand filtration. The coefficient of curvature (Cc) values of approximately 1.0 indicated good particle gradation, while the coefficient of uniformity (Cu) confirmed that the filter media contained adequate void spaces for effective wastewater flow and oil retention.

Laboratory analysis showed that the oilfield produced water contained appreciable concentrations of Total Oil Content (TOC), chloride, salinity, conductivity, turbidity, nitrate, and dissolved metals. The TOC concentration exceeded the permissible discharge limits, confirming that untreated produced water poses significant environmental risks and requires effective treatment before disposal or reuse.

The experimental results demonstrated that filtration efficiency was highly dependent on the grain-size distribution of the filter media. The mixed grain-size filter exhibited the highest oil removal efficiency because the combination of coarse and fine particles produced an effective pore structure capable of retaining both large and small oil droplets. Conversely, single grain-size filters exhibited comparatively lower removal efficiencies due to either excessive pore spaces or rapid clogging of the filtration bed.

The experimental results showed that increasing the bed height improved filtration performance by providing greater contact time between the wastewater and the filter media. The 30 cm sand bed consistently produced higher oil removal efficiencies than the 15 cm bed because of increased opportunities for oil droplet interception, adsorption, and sedimentation within the filter media.

The results demonstrated substantial reductions in TOC after filtration for both synthetic and oilfield produced water. The highest removal efficiencies were achieved using the mixed grain-size sand bed, confirming that properly designed sand filtration systems can effectively reduce petroleum hydrocarbon concentrations in produced water. However, filtration efficiency was consistently higher for synthetic produced water than for actual oilfield produced water due to the more complex composition of the latter, including dissolved salts, suspended solids, and naturally occurring contaminants.

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The factorial analysis demonstrated that both sand-bed height and initial TOC concentration significantly influenced filtration efficiency. The statistical model adequately predicted system performance and confirmed that bed height was the most significant factor affecting crude oil removal. The optimized operating conditions produced the highest filtration efficiencies, demonstrating the suitability of the developed filtration system for produced water treatment.

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