



Design, Fabrication, and Evaluation of Produced Water Treatment System for Effective Removal of Oil and Salt

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Abstract

Inappropriate disposal of Produced Water is one of the causes of degradation of the environment in the Niger-Delta. The effect on farmlands and aquatic life has been disastrous and this disposal continues because of lack of treatment equipment or inability to maintain treatment equipment. This work has developed a method for produced water treatment focusing on oil and salt removal. A small scale produced water treatment system was fabricated. The system's processes were based on thermal energy; thermal phase separation was used for oil removal and humidification-dehumidification was used for salt removal. The water obtained at the various process stages was tested to ascertain the oil content and salinity. Results obtained showed that oil levels in the produced water dropped from 3034.28mg/l to 380.58mg/ after phase separation which is significant but not meeting the Department of Petroleum Resources (DPR) requirement. However, after the humidification – dehumidification process, it was reduced to 4.02mg/l which meets the DPR requirement of 10mg/l. The salinity also reduced from 887.50mg/l to 35mg/l, this meets DPR acceptable limits for land disposal of 600mg/l

Keywords: Produced Water Treatment, Oil Removal, Desalination, Humidification/Dehumidification

1.0 INTRODUCTION

Produced water is water that is returned to the surface through an oil or gas well. It is made up of natural formation water as well as water injected into the formation as part of a fracture stimulation process or an enhanced recovery operation. Produced water is typically generated for the lifespan of a well [1].

Nigeria has a thriving oil and gas industry but all technologies for oil and gas exploration, production and refining are foreign. The government – through the Nigerian Content Development and Monitoring Board has long had a bid for technology transfer to indigenous engineers as they work with foreign expatriates [2].

However, while this has improved the area of technical knowhow and expertise for Nigerian engineers in operations, maintenance, facility design and construction, it has not achieved much in equipment design and manufacture. Adding produced water treatment system to the list of acquired in-country technologies would be beneficial to the Nigerian oil and gas Sector.

The available methods of Produced Water treatments, though effective are not easily maintained in

Nigeria because the Original Equipment Manufacturers are not easily available. Studies have shown that this has led to disposal of untreated or insufficiently treated Produced Water [3], this has a negative effect on the environment.

This presents the need for a Produced Water treatment system that is appropriate to the Nigerian Oil and Gas industry, that can be easily manufactured and maintained in Nigeria to limit and furthermore end improper disposal of Produced Water to our environment.

1.1 Produced Water Disposal in Nigeria

An Evaluation done in 2011 on Produced water discharge in the Niger- Delta showed that – Produced water discharged into the environment in the Niger Delta is yet to meet set standards for disposal as concentration of oil/grease content, total dissolved solids, total suspended solids and some other parameters are still very high [4].

Table 1 shows values of various measured produced water parameters after treatment and disposal at some flow stations (X, Y, and Z) and terminals (A and B) in the Niger-Delta. Studies have also shown disposal of produced water with high salinity in onshore fields is a common practice in the Niger-delta and this is against the standard of the regulatory body. [5].

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Table 1: Produced Water Discharge in the Niger-Delta [4]

Parameter	Allowed Limit	Terminals		Flow Stations		
		A	B	X	Y	Z
pH @ 75°F	6.5-8.5	8.12	8.53	7.88	8.10	8.43
Resistivity @ 69°F		0.45	0.68	1.58	0.37	8.40
Oil/Grease content (mg/l)	10	55.0	42.0	64	80	40
Copper (mg/l)	1	0.25	0.01	0.37	0.44	0.08
Lead (mg/l)	0.05	0.05	0.03	ND	ND	0.04
Iron (mg/l)	1	0.04	0.15	0.35	0.17	1.13
Nickel (mg/l)	1	0.50	0.49	0.54	0.33	0.65
Barium (mg/l)	-	16.0	8.00	5	20	11
Zinc (mg/l)	1	0.10	1.80	0.98	0.09	0.85
Magnesium (mg/l)	-	56.0	34.4	165	4.86	14.75
Chloride (mg/l)	600	5100	2583	3589	4678	3970
Sulphate (mg/l)	200	12.0	2.0	-	-	38
Carbonate	-	16.0	330	200	180	110
Bicarbonate (mg/l)	-	2000	980	4720	1036	710
Total dissolved solid	2000	9000	3978	5300	6850	6440
Total suspended sold	30	60	80	138	104	94
BOD (mg/l)	10	500	8.5	4.5	8.68	5.33
Discharge Temp °F		85	84	92	85	82

1.2 Produced Water Disposal Guidelines in Nigeria

The Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) put quality

level before disposal to environment as 10 milligram per litre for land facilities. The Table 2 below shows the acceptable disposal limit.

Table 2: Treated Produced Water Properties for disposal [6]

Produced Water Properties	Inland	Near Shore
pH	6.5 - 8.5	6.5 - 8.5
Temperature, °C	25	30
Total Hydrocarbon Content, mg/l	10	20
Salinity as Cl, mg/l	600	2000
Turbidity, NTU	Less than 15 (of receiving Medium)	
Total Dissolved Solids (TDS), mg/l	2000	5000
Total Suspended Solids (TSS), mg/l	2.0	Less than 50 (of receiving Medium)
COD, mg/l	10	125
BOD ₅ , mg/l	10	125
Pb ⁵⁺ , mg/l	0.05	No Limit
Total Iron (Fe), mg/l	1.0	No Limit
Cu ²⁺ , mg/l	1.5	- do -
Cr ⁶⁺ (total) mg/l	0.03	0.5
Zn ²⁺ , mg/l	1.0	5

1.3 Produced Water Treatment Technology

The option to dispose produced water must also comply with environmental guidelines. To achieve set

disposal limits, several technologies are available for effective treatment prior to disposal. There are several technologies for oil removal and for salt removal.

1.3.1 Oil removal technologies

Common technologies for oil removal from Produced

Water are shown in Table 2.

Table 3: Oil Removal Technologies [7]

Technology	Minimum size of droplets removed (μm)
API gravity separator	150
Corrugated plate separator	40
Induced gas flotation (no flocculant)	25
Induced gas flotation (with flocculant)	3-5
Hydrocyclone	10-15
Media Filter	5
Centrifuge	2
Membrane Filter	Sub micron, even 0.01

1.3.2 Salt removal technologies

Some of the common salt removal technologies for produced water include Electrodialysis, Reverse osmosis [8] and Ion exchange, Capacitive deionization, Evaporation [9]. Other applicable Seawater Desalination Technologies include Multistage flash (MSF) distillation, Vapour compression distillation (VCD), Multieffect distillation (MED) [8] and Humidification/Dehumidification (HDH) [10]

2.0 CONCEPTUAL DESIGN

Conceptual design for a Produced Water treatment system resulted a gravity separator using thermal energy to improve oil water separation and Humidification Dehumidification for Salt removal. To develop this system, information on the effect of temperature and time on oil removal and design considerations for HDH systems are required.

2.1 Effect of Temperature and Time

In a study, the effect of temperature on the oil recovery was investigated. The result showed that increase in temperature will decrease the viscosity in liquids which leads to increase in velocity of separation. It was observed that after 50°C the oil removal percent decreased sharply [11]

A study investigated the effect of time on the oil recovery, it was found that the percentage of oil removed increases during the first 5-10 min, the maximum oil recovery occurred at 15 min with and without flocculants. [11]

2.2 Design Recommendation for HDH Systems

The following recommendations were made in a study on the design of HDH systems

1. The productivity of the HDHSDS is significantly affected by the temperature of the feed water
2. The effect of the air temperature on the productivity of the HDHSDS is insignificant
3. The system with closed cycle of heated air and water is the most efficient
4. They concluded that the productivity increases with increasing the mass flow rate of air and decreasing the mass flow rate of feed water. [12]

3.0 MATERIALS AND METHODS

This research work will consider a system designed to handle 1 BWPD (158.99 litres per day or 6.62 litres per hour). This will be treated to meet the Department of Petroleum Resources disposal limit for oil and salts which is 10mg/l for oil and 600mg/l for salts

3.1 Process Description

Produced Water flows from Tank 01 to the Oil skimmer tank. The inlet flow is controlled by a float valve. The produced water is heated to 50°C by an electric heater controlled by a thermostat. It is held at this temperature for 20minutes. The oil is then skimmed off via slotted pipe. Ball valve V02 is opened to allow water into boiler, the water is further heated to 80°C. Ball Valve V03 is opened to allow water into the humidifier; the water enters the humidifier in fine sprays via small end openings. Blower blows air through heater to the humidifier. The air becomes humidified and flows to the dehumidifier where it is cooled, and water condenses.

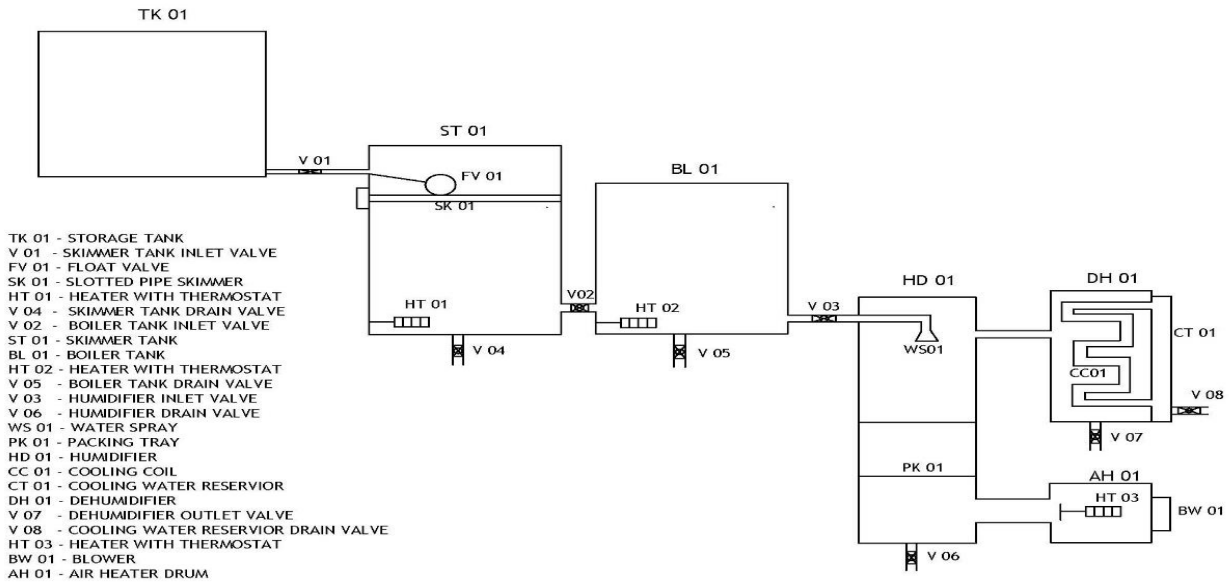


Figure 1: Process Description

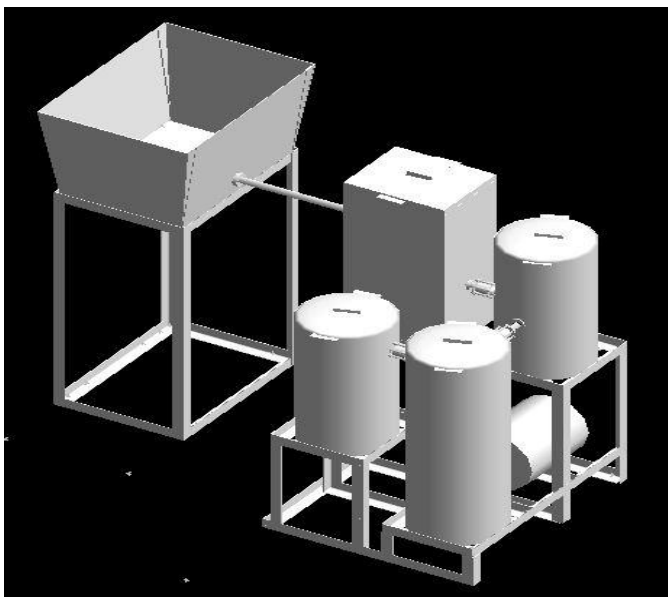


Figure 2 shows the 3-d model of the system

$$\dot{m}_{air}(h_2 - h_1) = KaV \left[\frac{(h_{HD_in} - h_2) - (h_{HD_out} - h_1)}{\ln \left(\frac{h_{HD_in} - h_2}{h_{HD_out} - h_1} \right)} \right]$$

Parameters

For air

$$\dot{m}_{air} = \text{volume flowrate of air} \times \text{density of air}$$

At normal temperature and pressure (NTP – 20°C, 1atm)

$$\text{density of air} = 1.204\text{kg/m}^3$$

$$\text{volume flowrate of air} = 2.8\text{m}^3/\text{min} = 0.047\text{m}^3/\text{s}$$

$$\dot{m}_{air} = 0.047 \times 1.204 = 0.057\text{kg/s}$$

$$\omega_1 = \text{Humidity of air into humidifier}$$

Assuming air at 20°C is at 50% relative humidity, after exiting the blower it is heated

The range of air temperature to the humidifier is between 25°C to 60°C

Assuming inlet temperature of 50°C

And the inlet air was saturated at it initial temperature of 20°C, the specific humidity would be 0.0073 from the psychometric chart

$$\omega_1 = 0.0075\text{kg of water/kg of air}$$

3.2 Process Design for Humidification Dehumidification

3.2.1 Humidifier outputs calculations

Mass Balance [13]

$$\dot{m}_{HD_in} + \dot{m}_{air}\omega_1 = \dot{m}_{HD_out} + \dot{m}_{air}\omega_2$$

Energy Balance [13]

$$\dot{m}_{HD_in}h_{HD_in} + \dot{m}_{air}h_1 = \dot{m}_{HD_out}h_{HD_out} + \dot{m}_{air}h_2$$

Enthalpy Balance [13]

ω_2 = Humidity of air exiting humidifier

Designing for the air to be humidified by $4\omega_1$

$$\omega_2 = 0.03 \text{ kg of water/kg of air}$$

h_1 = Enthalpy of air at humidifier inlet

From psychometric chart $T = 50^\circ\text{C}$ and $\omega_1 = 0.0075 \text{ kg of water/kg of air}$

$$h_1 = 70 \text{ kJ/kg}$$

For Produced Water

$\dot{m}_{\text{HD}_{\text{in}}}$ = Mass flow rate of water into humidifier

Volume of water from boiler is 0.025 m^3

It should completely flow into the humidifier in 4 hours

Therefore, the flowrate is

$$Q = \frac{0.025}{4 \times 3600}$$

$$Q = 6.94 \times 10^{-6} \text{ m}^3/\text{s}$$

$$\dot{m}_{\text{HD}_{\text{in}}} = Q \times \text{density}$$

$$\dot{m}_{\text{HD}_{\text{in}}} = 6.94 \times 10^{-6} \times 1000$$

$$\dot{m}_{\text{HD}_{\text{in}}} = 0.00694 \text{ kg/s}$$

$h_{\text{HD}_{\text{in}}}$ = Enthalpy of water at humidifier inlet

From Steam tables, Enthalpy of water at 80°C

$$h_{\text{HD}_{\text{in}}} = 2643.7 \text{ kJ/kg}$$

$h_{\text{HD}_{\text{out}}}$ = Enthalpy of water at humidifier outlet

Assuming water exiting at 40°C

From Steam tables, Enthalpy of water at 40°C

$$1.304 = \text{KaV} \left[\frac{22.34}{0.0089} \right]$$

$$\text{KaV} = 0.00052$$

$$0.021 \times 0.46905 \times V = 0.00052$$

$$V = 0.05279$$

$$h_{\text{HD}_{\text{out}}} = 2574.3 \text{ kJ/kg}$$

$\dot{m}_{\text{HD}_{\text{out}}}$ = Mass flow rate of water out of humidifier

h_2 = Enthalpy of air at humidifier outlet

KaV is the humidifier performance parameter and

$$K = \text{Mass transfer coefficient of water} \\ = 0.021 \text{ kg/m}^2\text{s (assumed value)}$$

$$a = \text{Surface area of packing} = 0.46905$$

V = Volume of humidifier

Solving for $\dot{m}_{\text{HD}_{\text{out}}}$

$$\dot{m}_{\text{HD}_{\text{in}}} + \dot{m}_{\text{air}}\omega_1 = \dot{m}_{\text{HD}_{\text{out}}} + \dot{m}_{\text{air}}\omega_2$$

$$0.00694 + (0.057 \times 0.015) = \dot{m}_{\text{HD}_{\text{out}}} + (0.057 \times 0.03) \\ 0.007795 = \dot{m}_{\text{HD}_{\text{out}}} + 0.00171$$

$$\dot{m}_{\text{HD}_{\text{out}}} = 0.006085 \text{ kg/s}$$

Solving for h_2

$$\dot{m}_{\text{HD}_{\text{in}}}h_{\text{HD}_{\text{in}}} + \dot{m}_{\text{air}}h_1 = \dot{m}_{\text{HD}_{\text{out}}}h_{\text{HD}_{\text{out}}} + \dot{m}_{\text{air}}h_2$$

$$(0.00694 \times 2643.7) + (0.057 \times 70) \\ = (0.006085 \times 2574.3) + (0.057 \times h_2)$$

$$6.67 = 0.057h_2$$

$$h_2 = 117.06 \text{ kJ/kg}$$

Also

$$\dot{m}_{\text{air}}(h_2 - h_1) = \text{KaV} \left[\frac{(h_{\text{HD}_{\text{in}}} - h_2) - (h_{\text{HD}_{\text{out}}} - h_1)}{\ln \left(\frac{h_{\text{HD}_{\text{in}}} - h_2}{h_{\text{HD}_{\text{out}}} - h_1} \right)} \right]$$

$$0.057 \times (92.88 - 70)$$

$$= \text{KaV} \left[\frac{(2643.7 - 117.06) - (2574.3 - 70)}{\ln \left(\frac{2643.7 - 117.06}{2574.3 - 70} \right)} \right]$$

3.2.2 Dehumidifier output

Mass Balance [13]

$$\dot{m}_{\text{air}}\omega_2 = \dot{m}_{\text{air}}\omega_1 + \dot{m}_d$$

$$\dot{m}_{\text{air}}\omega_2 = \dot{m}_{\text{air}}\omega_1 + \dot{m}_d$$

$$0.057 \times 0.03 = 0.057 \times 0.015 + \dot{m}_d$$

$$\dot{m}_d = 0.000855$$

Expected Water recovery in 4hours

$$m_d = 0.000855 \times 4 \times 60 \times 60$$

$$m_d = 12.312\text{kg}$$

$$v_d = 0.0123\text{m}^3$$

3.3 Testing

Produced water was collected from Egbaoma flowstation, OML (Oil Mining Licence) 38 which is operated by Platform/Newcross joint venture after obtaining permission from the Department of Petroleum Resources (DPR). The sample collected was downstream of the well head as the well had 80% water cut. The decision to take from the well head was to obtain produced water without chemical injection. The crude oil sample with high water cut was left to settle then produced water was collected. The set-up is as shown in fig 3.3. Test samples A for oil and water content analysis was collected from the storage tank.



Figure 2: Experimental Set-up

The produced water in the storage tank was at 29°C, Valve 01 was opened and the water flowed to the oil separation tank. It was heated to 50°C and held for 10minutes. The floating oil was removed

Test samples B for oil and salt were collected from the settled produced water for analysis. The produced water then entered the boiler as Valve 02 was opened where it was heated to 80°C. Valves 03 and 04 were opened and adjusted for effected flow into the humidifier where ceramic packing were arranged.

The system ran for one hour. Test samples C were collected from the bottom of the humidifier and test sample D was collected from the bottom of the dehumidifier. The Samples are defined as shown in Table 4.

Table 4: Description of Test Sample

SAMPLE	DESCRIPTION
Sample A	Untreated Produced Water
Sample B	Oil removal treatment only
Sample C	Waste Product (Brine)
Sample D	Oil and Salt removal treatment

4 RESULTS

The samples A, B, C, D were analysed for oil and salt content, the results are tabulated in Table 5.

4.2 Process

The heat treatment for oil removal did not achieve the DPR requirement for oil removal as Sample B hydrocarbon content was 380.58mg/l as against DPR requirement of 10mg/l. However the oil removed was significant as it shows a hydrocarbon drop from 3034.28mg/l to 380.58mg/l, a drop of 87.5%

It was noted that more oil was removed in sample C – 15.43mg/l, during the process when the boiler was heated to 80

Table 5: Test Results

SAMPLE ID	SALINITY as Cl (mg/l)	TOTAL HYDROCARBON CONTENT(mg/l)	DESCRIPTION
A	887.50	3034.28	Untreated Produced Water
B	875.67	380.58	Oil removal treatment only
C	1065.00	15.43	Waste Product (Brine)
D	35.5	4.02	Oil and Salt removal treatment

It was noticed that more oil floated on top of the produced water, contradicting the existing literature cited that the optimal temperature for oil removal was 50°C. The salt content increase in sample C is consistent with the salty

waste expected from the humidifier. However, the volume of saline waste was relatively high and suggests need for multi-stage humidification or recycling. From the design calculations, the expected water recovery in the

dehumidifier was 0.0123m³ in 4 hours.

In 1 hour, it would be 3075ml. However the water recovered in 1 hour was 51ml. The water recovery was not efficient due to the following;

1. Heat losses in boiler and humidifier
2. Vapour losses boiler, humidifier and dehumidifier
3. Simple dehumidification process employed

This suggests the need for lagging, proper fabrication to ensure closed system for the water flow and a simple refrigeration process to aid in efficient dehumidification. However the water recovered met the DPR requirement for disposal.

4.3 Water Quality Analysis

From the results in Table 5;

1. The Sample A contained oil and salt far above the DPR recommendation.
2. Sample B treatment for oil removal removed most of the oil content but did not still meet the DPR requirement for land disposal.
3. Sample C result shows the salt retention in the by-waste product and more oil removal.
4. Sample D result meets the requirement for salt and oil limits for land disposal

5.0 CONCLUSION

A small scale produced water system was fabricated with in-country resources, and the quality of water for disposal – 4.02mg/l for oil content and 35.5mg/l for salt content met the DPR requirement of 10mg/l for oil and 600mg/l for salt for inland disposal. However the water recovery was low, 51ml per hour as compared to the design value of 3075ml per hour. The system also has heat losses and humidified air losses.

However, the final water quality testifies to possibilities of produced water treatment with heat treatment for oil removal and humidification – dehumidification method for secondary oil removal and salt removal.

Future work on Design and Fabrication of a Produced Water treatment System with in-country resources using heat treatment and humidification/dehumidification method should be done to improve on the efficiency of the process of the system designed, fabricated and tested in this work.

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