PROCESS DESIGN OF ANAEROBIC REACTOR FOR THE TREATMENT OF PETROLEUM SLUDGE

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ABSTRACT

The disposal of untreated petroleum sludge causes environmental and health hazards because of disease pathogens present in the untreated petroleum sludge. The treatment of petroleum sludge destroys the disease pathogens to enable an industry meet environmental protection agency regulations for petroleum sludge disposal. Moreover, the treatment of petroleum sludge in Anaerobic reactor yield the environmentally friendly and renewable energy source, biogas a substitute for natural gas and biosolids a substitute for petrochemical based fertilizer. Under microbial substrate limiting mesophilic anaerobic digestion, a fed-batch anaerobic reactor was designed using kinetic model developed from Monods kinetics. The dimensions of the Anaerobic reactor were obtained by substituting experimental and kinetic data into the design equations. This gave anaerobic reactor volume of 183.50 $m^{3.}$ A purchased equipment cost of £148,906.4103 gave an optimum bioreactor diameter of 3.83 metres and bioreactor height of 15.93 metres. A heat generation per unit volume of 0.35 $jm^{-1}hr^{-1}$ show that there is little heat loss in the Anaerobic Reactor hence lagging with suitable lagging material such as foam glass was necessary. A reasonable volume 10,500 m^3 of biogas produced show that the anaerobic reactor process could enhance Nigeria quest for self sufficiency in energy production. . For 5000 kg per day of petroleum sludge plant capacity, total cost £14,861,000.00 economic analysis gave 2 years payback period and 47% rate of return on investment. This show that an anaerobic reactor digestion process plant if well managed could be economically viable in Nigeria. With the anaerobic reactor design provided, Nigerian industries and environmental agencies could construct and install anaerobic reactors to enhance the treatment of their sludge at affordable cost and in such a way that suit their needs. A private investor or government is encouraged to source for capital and set-up the plant.

KEYWORDS: Petroleum sludge; Anaerobic Reactor; Anaerobic Digestion; Kinetic model; Design equations; Costing; Economic analysis.

Introduction

An anaerobic reactor is reactor designed to carry out chemical process that involve organisms and biochemically active substances derived from these organisms in the absence of oxygen. In this process, micro-organisms breakdown harmful substances such as sludge to harmless biosolids and also produces useful products such as biogas, a substitute for natural gas useful for electrical power generation and heating.

The reaction stoichiometry is given as:

$$C_5H_7\,0_2\,N + \;4\,H_2O \xrightarrow{Methanobrevibacter} 2.5\,CH_4 + 1.5\,CO_2 + \mathrm{N}H_4 + HCo_3 \quad (1)$$

(Quist, 2007)

Perry & Green (1997) state that an anaerobic digester is a non recycle complete mix reactor, thus its performance is independent of organic loading but is controlled by hydraulic retention time (HRT). Based on pseudo constants for *methanogenic* bacteria, a minimum hydraulic retention time of 3 to 4 days is used but to compensate for loading variation and also to provide a safety factor, a hydraulic retention time of 10 to 30 days is used.

In the design of anaerobic reactors, there are four pseudo constants viz: k_m is minimum substrate utilization rate, L/time; μ_m is the half minimal velocity concentration or the maximum specific growth rate; Y is the yield coefficient; k_d is the endogenous respiration coefficient or specific maintenance rate, L/time. The value of these pseudo constants is a function of: the microbes, the pH, temperature and the components or composition of the sludge.

The pseudo constants are not under the control of the design engineer as they are functions of the sludge and the micro-organisms. Perry & Green (1997) give the dominant parameters in determining system performance as biomass solids retention time (BSRT) and the pseudo constants. The design engineer can only control BSRT, the ratio of biomass in the reactor to biomass produced from the waste each day.

The minimum biomass solids retention time that can be utilized is that which will produce the degree of treatment required. This is always less than that used in the design so as to provide a factor of safety in the design. For anaerobic digestion, a minimum biomass solids retention time of eight days is needed. Tchobanoglous *et al*. (2004) state that providing sufficient residence time in well mixed anaerobic reactors allow for significant destruction of volatile suspended solids (VSS).

Solids retention time (SRT) is the average time the solids are held in the digestion process. It can be evaluated using equation (2)

$$SRT = \frac{Mass\ of\ solids\ in\ the\ reactor}{Mass\ of\ solids\ removed\ daily} \quad (2)$$

Hydraulic Retention Time (HRT) is the average time liquid is held in the digestion process.It can be evaluated using equation (3)

$$\text{HRT} = \frac{\text{Volume of liquid in the reactor}}{\text{volume of biosolids removed daily}} \quad (3)$$

For digestion systems without recycle the solids retention time is equal to the hydraulic retention time. Tchobanoglous *et al.* (2004) state that an increase or decrease in solids retention time result in increase or decrease in the extent of reaction, namely: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. There is minimum solids retention time for each of these reactions. According to WEF (1998) if the solids retention time is less than the minimum SRT, the bacteria cannot grow rapidly enough and the digestion process will eventually fail. Kavitha & Pharm (2006) state that continuous stirred tank anaerobic reactors are constructed according to recognized standards as published by International Standards Organization and British Standard Institution. These dimensions take into account both mixing, effectiveness and structural consideration. A mechanically stirred tank anaerobic reactor is filled with a rushton turbine type impeller. A Continuous Stirred Tank Anaerobic Reactor (CSTAR) is a mixed flow anaerobic reactor with the flow rate of feed equal to the flow rate of product out of the reactor with the contents well mixed with the help of a stirrer.

Fed-batch or semi-continuous stirred tank anaerobic reactor is an anaerobic reactor initially started as variable volume batch with no output until the desired volume is achieved. It is then switched on to continuous flow mode but the input feed rate and output flow rates are not constant. These feed rates depend on an appropriate metabolic function, the respiratory Quotient of the process organism (Tapobrata, 2011).

Rao (2010) give a generalized model for a Fed-batch anaerobic reactor as in equation (4)

$$\frac{\text{dci}}{\text{dt}} = \frac{\text{v (t)}}{\text{VR)}} (\text{Ci, o} - \text{Ci}) + \text{rfi} \quad (4)$$

Where $V(t)$ is the volumetric feed rate at time t; V_R = reactor volume and is function of time; r_{fi} is the rate of reaction of component i. If there is a suitable analytical expression for $r_{fi,}$ equation (4) can be integrated. $C_{i,o}$ is the initial concentration of component. i. C_i is final concentration of component i.

In plug flow anaerobic reactors there is no mixing of reactants, but conversion occurs as the reactants move from one end of the reactor to the other. Batch-fed anaerobic reactor is a reactor initially started as variable volume with product withdrawn when it is formed and feed injected only when some product is removed (Tapobrata, 2011).

Lopez *et al.* (1997) state that Micro-organisms growing in anaerobic may be submerged in liquid medium or attached to the surface of a solid medium. Submerged cultures may be suspended or immobilized. Immobilization is useful for continuously operated processes, since the organisms will not be removed with the reactor effluent. Therefore, for a continuous stirred tank anaerobic reactor, submerged immobilized micro-organisms should be used. Waste streams can be treated biologically either by degradation of harmful materials to ones with reduced environmental consequences, or, upgrading to useful products by means of natural, selected or engineered micro-organisms and microbial enzymes. When degradation or upgrading are not feasible, micro-organisms may be used to concentrate such pollutants as heavy metals in very dilute waste streams for subsequent disposal by other means. Bio treatment of wastes may be done in situ, in the place of occurrence of the waste (Halden 1991; Irvine & Ketchua, 1989), as in bioremediation of contaminated soil in the field (fouhy & Shanley, 1991). Alternatively, the contaminated material may be treated in anaerobic reactors as in the treatment of most wastewaters and produced water – where better containment and superior environmental controls may allow faster, more complete and cost-effective treatment (Ujile & Dagde, 2014; Choi *et al.,* 1992; Eckenfelder *et al.,* 1989).

In this study, Materials balances and Energy balances are carried out across each equipment in an anaerobic reactor process. Costing and Economic Evaluation of the anaerobic reactor process is also inculcated.

Materials and Methods

Materials used for the Research

The following materials were used for the research:

Petroleum sludge collected from a typical oil and gas industry in Port Harcourt, Rivers State, Nigeria; *Methanogenic (Methanobrevibacter*) bacteria isolated from the intestine of cow and stored in glcerine; Oxoid Anaero Gen TM AN 0035A gas Park in Labtech anaerobic Jar to create Anaerobic condition; Chloroform; Mineral salt water; Starch indicator; Winkler reagent A & B; Concentrated Sulpuric acid; 0.025N Sodium Thiosulphate; Distilled water; Tissue Paper; Filter Paper; Nutrient agar (Lab M); Physiological Saline; Hard smooth stone and Rubber hose.

Method for the Research

Pretreatment of the Sludge

The petroleum sludge was heated on a hot plate and dried in an oven to remove water to a moisture of 25 % after which it was crushed with the help of a stone. This helped break the cell walls and membranes to enhance microbial reaction rate after which TABC, BCOD and VSS measurements were carried out on the sludge sample.

Microbial Digestion of the Sludge

200 grams of the sludge was measured using a chemical weighing balance and put into a beaker. 2 grams of *methanogenic methanobrevibacter* bacteria was pipetted and put into the sludge in the beaker after which the beaker was put into a Labtech anaerobic jar with improvise for gas collection point. Anaerobic condition was maintained with the help of Oxoid Anaerobic Gen TM AN 0035A gas park and catalyst. The anaerobic jar was corked airtight and kept in a Gallenkamp incubator maintained at 37 ^{0}C (Mesophillic) for a solids retention time of Sixteen days.

Sizing of the Bioreactor

The sizing was on the basis of 5 tons per day plant capacity. The assumption is that the anaerobic reactor is a pressure vessel and the hemispherical head was adopted from ASME Code VIII (Ujile, 2014).

Design Equations

Mass of Biological Solids

The mass of biological solids can be calculated using a relationship from Tchobanoglous *et al.*(2014)

$$P_X = \frac{[YQ(So - S)(\frac{10^3 g}{kg})^{-1}]}{\{1 + K_d\ (SRT)\}} \qquad (5)$$

Where: P_x is the mass of biological solids synthesized daily, Y is the yield coefficient given as mass of sludge or biomass produced per unit biosolids removed. (g VSS Volatile Suspended Solids / g BCOD); Q is the flow rate m^3/d; K_d is the endogenuous respiration coefficient or specific maintenance rate, per day (d^{-1}) ranging from 0.02 to 0.04.

Volume of Anaerobic Reactor

Levenspiel (2001) give rate of reaction as

$$-r_A = KC_A \qquad (6)$$

But $C_A = C_{A_O}(1 - X_A)$

$$-r_A = KC_{A_O}(1 - X_A) \qquad (7)$$

Substituting this for $-r_A$ in the equation obtained from Levenspiel (2001)

$$V_R = \frac{NA_o}{t} \int_O^{XA} \frac{dX_A}{(-r_A \quad)} \tag{8}$$

$$V_R = \frac{NA_o}{t} \int_O^{XA} \frac{dX_A}{KCA_o\,(1-X_A \quad)} \tag{9}$$

$$V_R = \frac{NA_o}{tKCA_o} \int_O^{XA} \frac{dX_A}{(1-X_A \quad)} \tag{10}$$

Substituting K_m for K, $X_{2,0}$ for C_{A_O} and considering the fractional change in volume

$$V_R = \frac{NA_o}{tK_m X_{2,0}} \int_O^{XA} \frac{dX_A}{(1-X_A)(1+E_A X_A)} \tag{11}$$

Materials Balance Equations

Anaerobic reactor:

$$kg[Sludge + methanobrevibacter] = kgbiogas + kgbiosolids \tag{12}$$

$$kg[Biogas] = kg[sluge + methanobrevibactrer] - kg[biosolids] \tag{13}$$

Dryer:

$$B = D+W \tag{14}$$

$$BX_B = DX_D + Wx_w \tag{15}$$

$$W = B - D \tag{16}$$

Energy Balance Equations

General:

$$\Delta H + \Delta KE + \Delta KP = Q + W_S \tag{17}$$

Where ΔH is the change in enthalpy

ΔKE,Change in Kinetic energy

ΔKP,Change in potential Energy

Q,Heat Energy

W_S,Shaft work

Neglecting shaft work and considering that velocity and height did not change Audu (1999) give the following equations:

$$M\Delta \mathrm{H} = \mathrm{Q} = \mathrm{M} \int_{\mathrm{T}_1}^{\mathrm{T}_2} \mathrm{C_P}\, d\mathrm{T} \qquad (18)$$

$$\mathrm{C_P} = \mathrm{a} + \mathrm{BT} + \mathrm{CT}^2 + \mathrm{DT}^3 + \mathrm{T}^4 \qquad (19)$$

$$\mathrm{M}\Delta \mathrm{H} = \mathrm{MC_{P\ mean}}\, \Delta \mathrm{T} = \mathrm{M} \int_{\mathrm{T}_1}^{\mathrm{T}_2} \mathrm{C_P}\, d\mathrm{T} \qquad (20)$$

Where a,b,c and d are constants to be obtained from table.

Anaerobic Reactor

$$\mathrm{C_{P\ mean}} = \frac{\int_{\mathrm{T1}}^{\mathrm{T2}} \mathrm{C_{p\ mixture}}}{\mathrm{T}_2 - \mathrm{T}_1} \qquad (21)$$

$$\mathrm{M}\Delta \mathrm{H} = \mathrm{MC_{p\ mean}}\, \Delta \mathrm{T} \qquad (22)$$

$$\Delta \mathrm{H_{r,t}} = \Delta \mathrm{H^0}_{\mathrm{r}} + \Delta \mathrm{H_{prod}} - \Delta \mathrm{H_{react}} \qquad (23)$$

Where –ΔHr.t is heat of reaction at temperature t

ΔH_{react},Enthalpy change to bring reactants to standard temperature

ΔH_{prod},Enthalpy change to bring products to reaction temperature t.

$\Delta H^O{}_{r}$,,Enthalpy change,negative for exothermic reaction and positive for endothermic reaction. Where $\Delta H^0{}_r$ is negative, $-\Delta H^0{}_r$ is positive.

The process heat added to the reactor to maintain the required reactor temperature is given by:

$$\mathrm{Q_P} = \mathrm{H}_2 - \mathrm{H}_1 - \mathrm{Q_s} \qquad (24)$$

Where H_2 is the enthalpy of the Outlet stream.

H_1 is the enthalpy of the inlet stream and Q_s is the heat generated in the system. Positive for exothermic processes and negative for endothermic processes.

Being an exothermic reaction, the heat of reaction is positive.

$$\Delta \mathrm{H_{Biogas}} = \mathrm{MC_P}\Delta \mathrm{T} \qquad (25)$$

$$\Delta \mathrm{H_{wetbiosolids}} = \mathrm{MC_P}\Delta \mathrm{T} \qquad (26)$$

$$\Delta \mathrm{H_{Products}} = \Delta \mathrm{H_{Biogas}} + \Delta \mathrm{H_{Biosolids}} \qquad (27)$$

Dryer: (Rotary)

$$C_P \text{ of air} = C_1 + C_2 \times T + C_3 \times T^2 + C_4 \times T^3 + C_5 \times T^4$$
(28)

$$\text{Energy inlet of Anaerobic reactor} + \text{Heat of reaction} =$$
$$\text{Energy outlet of the Anaerobic reactor} = \text{Energy inlet of the Dryer} \quad (29)$$

$$Q = W_W - W_G \quad (30)$$

$$W_W = Q + W_G \quad (31)$$

$$Q = \frac{H_G(t_G - t_W)}{\lambda w} \quad (32)$$

$$Q = \frac{H_G(t_G - t_w)}{\lambda w} = W_w - W_G \quad (33)$$

Where H_G is the enthalpy of gas read from the psychrometric chart at λw, *the latent heat of vapourization = 2,117 kJ/kg*

$T_{G,}$ inlet temperature of the air

$T_{W,}$ temperature of water vapour

W_w, the weight of water vapour

W_G the weight of air

$$Q_T = G^{/}G_s \times h \times t_{G1} - t_{G2} \quad (34)$$

Where Q_T is the total heat supplied by the hot air

$G^{/}$ $G_{s,}$ the mass transfer rate of the air

h, the humid heat of air= 1.074 as read on the psychrometric chart.

$t_{G1,}$ inlet temperature of hot air

T_{G2},outlet temperature hot air

$$Q_T = Q_1 + Q_2 \quad (35)$$

$Q_{1,}$heat required to raise product to a discharge temperature

Q_2,heat required to remove moisture

$$Q_1 = M_s Cp_s(T_{2s} - T_{1s}) + M_W Cp_w(T_{2w} - T_{1w}) \quad (36)$$

$$Q_2 = M_m Cp_w (T_w - T_1) + M_m \lambda_w + M_m Cp_{wv} (T_{G2} - T_{G1}) \quad (37)$$

$$Q_{air\ in} = G/G_s CpT \quad (38)$$

$$Q_{air\ out} = G/G_s\ Cp_{mean}\ T \quad (39)$$

$$Q_{biosolids\ \ in} = MCp_{mean}\ T \quad (40)$$

$$Q_{biosolids\ \ out} = MCp_{\ mean}\ T \quad (41)$$

$$Q_{waterin} = MCpT \quad (42)$$

$$Q_{water\ \ out} = MCpT \quad (43)$$

Pelletizer:

$$\Delta H = MCp_{mean}\ T(\text{where no temperature change}) \quad (44)$$

$$\therefore \mathit{Energy\ lost\ by\ the\ biosolids}$$

= [oulet energy of the Biosolids from the dryer] – [Energy of the biosolids in the pelletiser]

$$\therefore \mathit{Energy\ lost\ by\ the\ biosolids}$$

$$= Q_{biosolids\ \ out} - \Delta H \quad (45)$$

Part of the energy lost by the biosolids is used by the biosolids for formation of pellets.

$$\therefore \mathit{Energy\ \ used\ by\ the\ biosolids\ for\ formation\ of\ Pellets}$$

= [Inlet energy of the biosolids in the pelletiser] - [Energy lost by the biosolids]

$\therefore$ *Energy used by the biosolids* for formation of pellets

$$= \Delta H - [\text{Energy lost by the biosolids}] \quad (46)$$

Percentage Energy Used by the biosolids for formation of pellets

$$= \frac{[\mathit{Energy\ \ Used\ by\ the\ biosolids\ \ for\ formation\ \ of\ pellets}\ ]}{[\ \mathit{Energy\ \ of\ the\ biosolids\ \ in\ the\ pelletiser}\ ]} \times \frac{100}{1} \quad (47)$$

Compressor

Work of Compression:

Green & Perry (1997) give Actual work (Ws) as

$$Ws = \frac{n\gamma_{AV}RT_1}{0.8(\gamma_{AV}-1)}\ [(\frac{P_2}{P_1})^{(\gamma_{AV}-1)}/^{(n\gamma_{AV})}\ \ -1] \quad (48)$$

n, the number of stages = 1 and 0.8, the efficiency.

The effect of irreversibility is accounted for in the isentropic efficiency.

Where R, the gas constant = 8.3144 kJ/kmol K

T_1,initial temperature of biogas = 310 ^oK

P_1,initial pressure of biogas = 1 bar

P_2,final pressure of biogas = 5 bars

$$\gamma_{AV} = \text{Average } \frac{Cp}{Cv} \quad (49)$$

Where this average Cp/Cv can be found by summation of the product of mole fractions of each component in the biogas and the Cp/Cv of each component in the biogas.

Cp,Specific heat capacity at constant pressure

Cv,Specific heat capacity at constant volume

$$\gamma_{AV} = \sum(\text{mole fraction } \times \frac{Cp}{Cv}) \quad (50)$$

$$\text{Volume flow rate of cooling water} = \left[\frac{\text{Mass flow rate}}{\text{Density}}\right] \quad (51)$$

Scale -up Equation

$$\text{Scale up factor} = \frac{\text{Production capacity}}{\text{Amount produced}} \quad (52)$$

Equations for Heat Generation in Anaerobic reactor

$$Q = \Delta H_{rxn} F_{Ao} X_A \quad (53)$$

Where ΔH_{rxn} is the heat of reaction per unit mole of reactantFA_0, the amount reacted

$$U = \left[\frac{Q}{V_R}\right] \div A\Delta T \quad (54)$$

$$U = [\frac{\Delta H_r FA_o XA}{\frac{NA_o}{CA_0 tkm}\int_o^{XA}\frac{dX_A}{(1-X_A)(1+\epsilon_A X_A\}}}] \div A\Delta T \quad (55)$$

$$A = 2\pi r^2 + 2\pi rh = 2\pi r\,(r+h) \quad (56)$$

$$\text{Heat generated per unit volume} = \frac{q}{V_R} \quad (57)$$

Costing and Economic Evaluation Equations

Costing Equations

Coulson & Richardson (2009) gives the following costing equations:

$$PEC = a + bs^n \times MF \quad (58)$$

$$\text{Cost in year A} = \text{cost in year B} \times \frac{\text{Cost index in year A}}{\text{cost index in year B}} \quad (59)$$

$$PPC = PEC(1 + F_1 \ldots \ldots \ldots .. + F_9) \quad (60)$$

$$FC = PPC\,(1 + F_{10} + F_{11} + F_{12}) \quad (61)$$

$$WC = 10\,\%\ \text{of fixed capital} \quad (62)$$

$$\text{Total investment} = \text{Fixed capital} + \text{Working capital} \quad (63)$$

$$\text{Operating Cost} = \text{Fixed cost} + \text{variable cost} \quad (64)$$

$$\text{Total cost} = \text{Total investment} + \text{Direct Production cost} \quad (65)$$

$$\text{Direct Production cost} = \text{operating cost} + 20\,\%\ \text{of operating cost} \quad (66)$$

$$\text{Total cost} = \text{Total investment} + 20\,\%\ \text{of operating cost} + \text{operating cost} \quad (67)$$

Economic Evaluation Equations

Sales of Product $= \text{Mass flowrate of product} \times \text{operating time}$

$\text{per day} \times \text{no. of days of operation per year} \times \text{cost per kilogramm}$ (68)

Coulson & Richardson (2009) give the following economic evaluation equations:

$$\text{Net Annual Profit (NAP)} = [\text{Product Sales}] - [\text{Operating Cost} + \text{Fixed Capital}] \quad (69)$$

$$\text{Net present value} = \frac{(NAP)^n}{(1+r)^n} \quad (70)$$

$$\text{Rate of Return on investment (ROI)} = \frac{\text{Net annual profit}}{\text{Total investment}} \times \frac{100}{1} \quad (71)$$

$$\text{Pay Back Period} = \frac{\text{Total investment}}{\text{Net annual profit}} \quad (72)$$

$$\text{OR: } \frac{1}{\text{Rate of return on investment}} \quad (73)$$

Appels *etal*.(2008) give equationNet mass of cell tissue produced per day:

$$P_x = \frac{YES_0}{1+k_d\theta_c} \quad (74)$$

Volume of Biogas produced: $V_{CH4=}(0.35)(S_0 - s)(Q)(10^3 g/kg)^{-1} - 1.42P_x$ (75)

Where S_0 is the biochemical carbonaceous oxygen demand in the influent sludge

S,the biochemical carbonaceous oxygen demand in the effluent biosolids

Q,the volume flow rate of methane

Anaerobic Reactor Fundamental Dimensions

Recall equation (11) for volume of Anaerobic Reactor

$$(V_R) = \frac{N_{A_o}}{C_{A0.}\,t.km}\int_o^{X_A}\frac{dx_A}{(1-X_A)(1+\varepsilon_A X_A)}$$

Tapobrata (2011) give the following equations for Anaerobic Reactor fundamental dimensions

Height of Anaerobic Reactor

$$h = \frac{4V_R}{\pi D^2} \quad (76)$$

Where D is the diameter of the Anaerobic reactor determined by interpolation

RESULTS

Scale up results in higher values. A scale up factor of 2 was used.

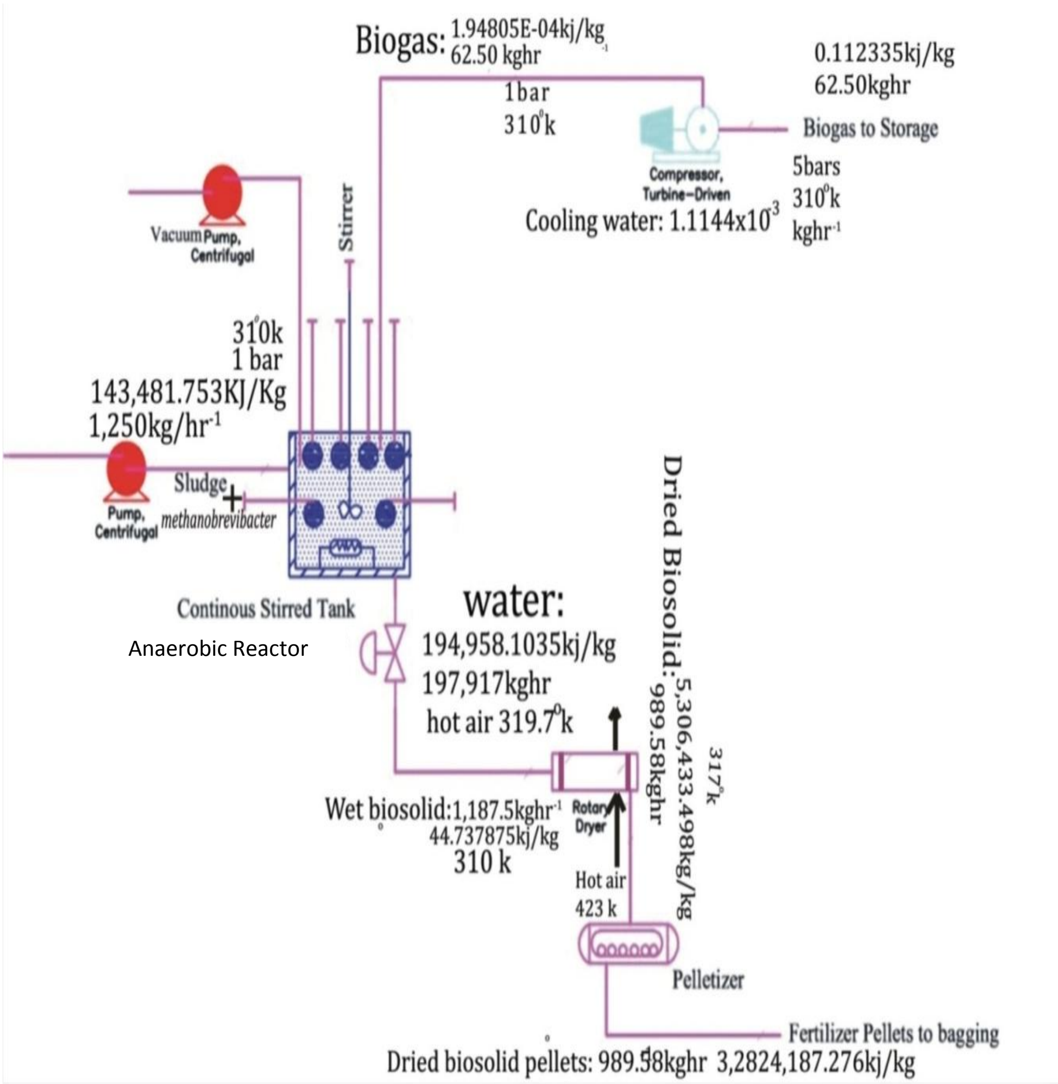

Fig. 1: Process Flow for the Scaled Up Anaerobic Reactor Process

Material Balance across the Anaerobic Reactor

Table 1: Materials balance across the Anaerobic Reactor.

Component	**Mass in** $(\boldsymbol{kghr^{-1}})$	**Mass out** $(\boldsymbol{kghr^{-1}})$
$(sludge + methanobrevibacter)$	625	-
Biogas (Methane + CO_2)	-	31.25
Biosolids	-	593.75
Total	**625**	**625**

Materials Balance across the Dryer

Table 2: Mass Balance across the Dryer

Component	**Inlet** $(\boldsymbol{kghr^{-1}})$	**Outlet** $(\boldsymbol{kghr^{-1}})$
Wet biosolid	593.75	-
Dried biosolid	-	494.7916667
Water removed	-	98.9583333
Total	**593.75**	**593.75**

Materials Balance across the Pelletizer

Table 3: Mass balance across the Pelletiser.

Component	**Inlet** $(\boldsymbol{kghr^{-1}})$	**Outlet** $(\boldsymbol{kghr^{-1}})$
Dried biosolids	494.7916667	494.7916667

Materials Balance across the Compressor

Table 4: Mass balance across the compressor

Component	Inlet **(kg/hr)**	Outlet (**kg/hr**)
Biogas	31.25	31.25

Energy Balances

Energy Balance across the Anaerobic Reactor

Table 5 : Inlet Energy to the Anaerobic Reactor

Component	**Specific heat capacity of inlet components to the Bioreactor (kJ/kg K)**
Sludge	4.186
Methanobrevibacter	2.4179336
Water	4.2
Organic matter	1.95000
Total	**12.7539336**

Table 6: Energy Balance across Anaerobic Reactor

Component	Inlet $(\boldsymbol{kJ/kg})$	Outlet $(\boldsymbol{kJ/kg})$
$\{Sludge + methanobrevibacter$	71,740.85	-
Biosolids	-	22.36869375
Biogas	-	9.74025×10^{-5}
$\Delta H_{r,t}$	-	$+71{,}718.50971$
Total	**71,740.875**	**71,740.8765**

Energy Balance across the Dryer

Table 7: Enthalpy Balance across the Dryer

Component	Inlet (kJ/hr)	Outlet (kJ/hr)
Biosolid	2,594,6283.37	2,653,216.749
Air	1.379361211E18	1.042510116E18
Water	193,265.625	97,479.05173
Dryer Walls & Surroundigs	-	0.336851095E18
TOTAL	1.3793612118	1.3793612118

Energy Balance Across The Pelletizer

Table 8: Energy balance across the pelletizer

Component	Inlet (kj/hr)	Outlet (kj/hr)
Biosolids	2,653,216.749	-
Pellets	-	1,912,093.639
Pelletizer	-	741,123.11
Total	**2,653,216.749**	**2,653,216.749**

Energy Balance Across The Compressor

Table 9: Biogas composition

Component	$kgmass/(molar\ mass\ (kmol))$	Mole fraction
Methane	1.5625	0.912195122
Hydrogen sulphide	0.036764705	0.021463414
Carbondioxide	0.113636363	0.066341463
Total	**1.712901068**	**1.0**

Table 10: Cp/Cv of Components

Components	Cp/Cv
CH_4	1.31
H_2S	1.32
CO_2	1.304

Source: Green & Perry (1997)

Cooling Water

Mass Flow rate of Cooling water = $1.114434524 \times 10^{-3}$ kg/hr

Volume Flow rate of Cooling Water = $1.114434524 \times 10^{-6}$ m^3hr^{-1}

Table 11 : Energy Balance across the Compressor

Component	Inlet (kJ/kg)	Outlet (kJ/kg)
Biogas	9.74025×10^{-5}	0.056165

Heat Generation

Table 12: Heat Generation in the Anaerobic Reactor

Total Surface area (m^2)	Change in Temperature (K)	Overall heat Transfer Coefft. $(Jm^{(2}\ o)\ K)$	Heat generated (J/hr)	Volume of Bioreactor m^3	Heat generation per unit volume $(Jm^{(-3)}\ hr)$
214.7442317	9	0.033	68.73	183.5	0.35

Cost Analysis, Economic Analysis and Project Evaluation

Table: 13: Purchased Equipment Cost in the year 2010

Equipment	PEC
CST Bioreactor	$PEC =$ £ 75,972.65833
Rotary drier	$PEC =$ £ 91,758.02356
Pelletizer	$PEC =$ £ 61,999.02325
Compressor	$PEC =$ £ 714,050.5631
Pumps	$PEC =$ £ 13,896.7886
Conveyors	$PEC =$ £ 76,000.00

$$\sum PEC\ in\ 2010 = £\ 1,033,677.057$$

Cost in the Year 2018

Table14: Purchased Equipment cost in the year 2018 (Cost in 2010 x 1.96)

Equipment	PEC
CST Bioreactor	$PEC =$ £ 148,906.4103
Rotary drier	$PEC =$ £ 179,845.7262
Pelletizer	$PEC =$ £ 121,518.0856
Compressor	$PEC =$ £ 1,399,539.104
Pumps	$PEC =$ £ 27,237.70566
Conveyors	$PEC =$ £ 148,000.00

$\sum \llbracket PEC\ in\ 2016 = \rrbracket$ £ 2,026,007.032

Physical Plant Cost (PPC)

Table 15: Cost Factors for PPC

Item	Cost factor
f_1, equipment erection	0.5
f_2, piping	0.6
f_3, instrumentation and Control	0.3
f_4, electrical	0.2
f_5, civil	0.3
f_6, structures and buildings	0.2
f_7, lagging and painting	0.1
f_8, utilities, storage and offsites	0.1
f_9, site development	0.05
TOTAL	2.35

$$PPC = £6{,}787{,}123.557$$

Fixed Capital (FC)

Table 16: Cost factors for FC

Item	Cost factor
$f\_10, Design\ and\ Engineering$	0.25
$f\_11, Contractor\ Fee$	0.05
$f\_12, Contingency$	0.10
$TOTAL$	0.4

$Fixed\ Capital = £\ 9{,}501{,}972.98$

Table 17: Total Cost of the Anaerobic Reactor Process

Parameter	**Value**
Fixed capital	£ 9,501,972.98
Working capital	£ 950,197.298
Total investment	£ 10,452,170.28
Fixed cost	£ 1,724,855.136
Variable cost	£ 1,947,904.461
Operating cost	£ 3,672,759.597
Direct production cost	£ 4,408,000.00
Total cost	**£ 14,861,000.00**

Economic Analysis

Table 18: Economic Evaluation

Parameter	Value
Sales of product	£ 18,112,500.00
Net Annual Profit	£ 4,937,767.42
Net Present Value	£ 54,678,442.00
Total Investment	£ 10,452,170.28
Net Present Value – Total Investment	£ 44,226,271.72
Rate of return on Investment	47 %
Pay- back period	2 years

Experimental Data Obtained

Table 19: Data Obtained

Parameter	Value
Volatile suspended solids (VSS)	99.6 %
Biochemical carbonaceous oxygen demand (influent sludge)	6080 mg/l
Biochemical carbonaceous oxygen demand in effluent Biosolids	20.4 mg/l
Yield coefficient (Y)	0.016
Maximum specific growth rate (μ_m)	0.0738 hr^{-1}
Endogenous respiration Coefficient (K_d)	0.025 d^{-1}

Volume of Biogas Produced

Table 20 : Volume of Biogas Produced

Influence BCOD (mg/l)	Effluent BCOD (mg/l)	Flow rate of Biogas (m^3/d)	Net mass of cell Tissue Produced Per day (kg/d)	Volume of Biogas m^3/d	Volume of Biogas from one gramme of sludge (m^3)
6080	20.4	5000	62.54	10,500	840

Sizing the Anaerobic Reactor

Recall : Quist (2007) give equation (1)

Where ε_{A} is given by

ΣCR : 1 + 4 = 5

ΣCP : 1.5 + 2.5 + 1 + 1 = 6

$\varepsilon_A = \frac{\Sigma CP - \Sigma CR}{\Sigma CR} = \frac{6-5}{5} = \frac{1}{5} = 0.2$

Levenspiel (2001) give formula for conversion

$$X_A = 1 - CA/CA0$$

$$X_A = 1 - X_2/X_{2,0}$$

$X_{2,0}$ = 0.3383 mg/l

X_2 = 0.228893 mg/l

$X_A = 1 - \frac{0.2289}{0.3383}$

$X_A = 1 - 0.6766$

$X_A = 0.3234$

Coulson & Richardson (1991) give the Monod's constant

Km : 0.02 mol/m^3

t: solids retention time, 16 days

C_{Ao}: initial concentration of sludge

$C_{Ao} = X_{2,0} = 0.3383$

N_{Ao} : Number of moles of sludge

Molar mass of $C_5 H_7 O_2N$: (12×5) + (1×7) + (16×2) + (14×1) = 60+7+32+14 =113

$$= \frac{\text{Mass}}{\text{Molar Mass}} = \frac{5000\text{kg}}{113}$$

= 44.24778761 kmol/day

= 44.24778761×10^3 moles/day

= 44,247.78761 moles/day

$$V_R = \frac{N_{AO}}{C_{AO}.\text{t.Km}} \int_0^{XA} \frac{d\,X_A}{(1-\text{x A})(1+\varepsilon_A X_A)}$$

Substituting $X_{2,0}$ for C_{A0} ; $X_{2,0} = C_{A0}$

$$V_R = \frac{N_{Ao}}{X_{2,0}tKm} \int_0^{0.3234} \frac{dX_A}{(1-XA)(1+\varepsilon_A X_A)}$$

$$V_R = \frac{44{,}247.78761}{0.3383x16x0.02} \int_0^{0.3234} \frac{d\,(0.3234)}{(1-0.3234(1+0.2x(0.3234)}$$

9

$X_A = 0.3234$

$K_m = 0.02\ mol/m^3$

$C_{Ao} = 0.3383$ mg/L

t = 16 days

N_{Ao} = 44,247.78761 moles/day

$\varepsilon_A = 0.2$

Using MATHCAD Software

$V_R = 1.835 \times 10^5$ Litres

(1000 liters = $1m^3$)

Therefore:

$$\frac{1.835 \times 10^5}{1000} = \frac{1,83500.00}{1000}$$

$$= 183.50 \text{ m}^3$$

Volume of Anaerobic Reactor = 183.50 m^3

Optimization

Coulson & Richardson (2009) give equation for purchased equipment cost.

$PEC = a + b\ s\hat{}n \quad \times$ MF

Where:

PEC is the purchased equipment cost a & b, cost constants peculiar to the equipment.

s ,the characteristics size parameter

$n,$ the index characteristic of equipment size

$a = 28{,}000$ in 2010

That is, *28,000* mutiplied by *1.96* in 2018 is equal to *54,880*

Range for b: 0 to 104,000

s is same for 2018 as it was in 2010

$$s = 0.5$$

n is same for 2018 as it was in 2010.

$$n = 0.8$$

MF, materials factor for stainless steel $=$ *1.3* multiplied by 1.*96* in 2018 is equal to *2.548*

≈ *2.55* in 2018

The Volume of the Anaerobic Reactor gave 183.50 m^3; The Diameter obtained by interpolation at £148,906.4103 the purchased equipment cost of the Anaerobic Reactor gave 3.83 meters and the height of the Anaerobic Reactor calculated from appropriate design equation gave 15.93 meters.

Discussion

From Table 1 to Table 11, the result of Mass balances and Energy balances across each process equipment show a confirmation of the laws of conservation of mass and energy as materials in equals materials out and energy in equals energy out. Moreover, From Table 10, Koop's rule is being confirmed as the specific heat capacity of the mixture is the average sum of the contribution of each individual constituent.

Table 20 show that a reasonable volume of biogas can be produced in substantial amount from anaerobic digestion of the sludge as 200 g of sludge yielded 10,500 m^3/d biogas for a solids retention time of 16 days. 1 g Sludge would yield 10,500/200 = 52.5 m^3/d biogas for 16 days. 52.5 × 16 = 840 m^3 biogas from 1 g of sludge.

British pounds is used for costing and economic analysis of the project because of instability of the naira. However, conversion to naira can be made based on the exchange rate at the time of conversion.

Table 17 show that the total cost of the anaerobic reactor process for the treatment of 5 Tons per day of petroleum sludge gave a total cost of £14,861,000.00 Despite this, high profitability rate is expected as sales of product £ 18,112,500.00 is higher than £ 14,861,000.00 the total cost of the plant.

Table 18 show that the net present value minus the total investment is higher than zero. This is an indication that the project is economically viable. The net annual profit of £ 4,937.767.42 is quite high showing that high profit could be made from the project. A Pay-back period of 2 years is low enough. This shows that the loan could be repaid within a short period of 2 years. The anaerobic reactor process is considered economically viable considering the low pay-back period and reasonable rate of return of 47 % .

The high rate of profitability expected, the reasonable rate of return and low pay- back period show that an anaerobic reactor process plant for the treatment of sludge if well managed could be economically viable in Nigeria. Private investors and government are therefore encouraged to source for capital and set- up the plant. The plant should be located as a process unit in every Nigerian process industry, Waste water treatment plant and sites where sludge is dumped.

Conclusion

Anaerobic digestion helps transform the toxic petroleum sludge to harmless bio solids useful as fertilizer of higher quality than petrochemical based fertilizers. Biogas, being a renewable energy source and environmentally friendly is a better substitute for natural gas. Besides enhancing sustainable development and increasing the Nigerian gross domestic product, anaerobic digestion of petroleum sludge could optimize petroleum oil and gas production in Nigeria. With anaerobic digestion of petroleum sludge, Nigeria oil and gas reserves and net petroleum exports will increase as 1 gram of sludge was found to yield 840 m^3 biogas for a solids retention time of sixteen days. With anaerobic digestion plant as a process unit in every Nigerian process industry and waste water treatment plant, the problem of sludge treatment and disposal according to Environmental Protection Agency (EPA) standards and regulations will be solved. Economic analysis of the anaerobic reactor process with 5 Tons per day plant capacity gave a total cost of £ 14,861,000.00, a payback period of 2 years and a rate of return of 47 %. This shows that an anaerobic reactor process for the treatment of sludge if well managed could be economically viable in Nigeria. The plant should be located as a process unit of every Nigerian process industry, Waste Water Treatment Plant (WWTP) and sites where sludge is dumped.

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APPENDIX

NOMENCLATURE

Symbol	Definition	Unit
B	Mass of wet Biosolid	kg
C_i	Inlet concentration	kmol/m^3
$C_{i,o}$	Initial concentration of component	kmol/m^3
C_o	Outlet concentration	kmol/m^3
C_p	Specific heat capacity at constant pressure	kJ/kg K
CP_{cw}	Specific heat capacity of the cooling water	kJ/kg K
CP_s	Specific heat capacity of the wet bio solid	kJ/kg K
CP_w	Specific heat capacity of moisture	kJ/kg K
CP_{wv}	Specific heat capacity of water vapour	kJ/kg K
C_v	Specific heat capacity at constant volume	kJ/kg K
C_w	Cooling water	
D_i	Impeller diameter	m
E	Efficiency of sludge utilization	*0.6 – 0.9*
F_{AO}	Molar feed rate	mols^{-1}
$G'G_s$	Mass transfer rate of air	kg/hr
H	Height of the bioreactor	m
H_1	Enthalpy of inlet Stream	kJ/kg K
H_2	Enthalpy of outlet Stream	kJ/kg K
H_G	Enthalpy of gas read from the Psychrometric chart	kJ/kg
ΔH	Change in enthalpy	kJ/kg K
$\Delta H_{products}$	Enthalpy change to bring products to reaction	kJ/kg K

	temperature t	
$\Delta H_{reactant}$	Enthalpy change to bring reactants to standard temperature	kJ/kg K
$\Delta H^{o}r$	Enthalpy change, negative for exothermic reaction and positive for endothermic reaction	kJ/kg K
$\Delta Hr,t$	Heat of reaction at temperature t	kJ
K	Rate constant	
K_1	Inhibition constant	
K_d	Endogenous respiration coefficient or specific maintenance rate	(d^{-1})
Δ KE	Change in kinetic energy	kJ
ΔKP	Change in potential energy	kJ
M	Mass flow rate of the cooling water	kg/hr
M_m	Mass of water evaporated	kg/hr
M_s	Mass rate of wet bio solid	kg/hr
M_w	Mass rate of moisture	kg/hr
m_o	Mass of dry solids	kg
N_{A0}	Number of moles	mols/day
n	Project life	Years
P_1	Initial pressure	bar
P_2	Final pressure	bar
P_s	Percent solids expressed as decimal	
P_x	Net mass of cell tissue produced per day	kg
Q	Flow rate of methane	m^3
Q_1	Heat required to raise product to a discharge temperature	kJ/kg

Q_2	Heat required to remove moisture	kJ/kg
$Q_{air\ in}$	Enthalpy of air	kJ/kg K
Q_{cw}	Heat removed by the cooling water	kJ/kg
Q_T	Total heat supplied	kJ/kg
Q_S	Heat generated in the system	kJ/kg
q	Volume of sludge	m^3
R	Gas constant	kJ/kmol K
r	Increase in productivity per year	%
r_A	Rate of reaction	$mgl^{-1}s^{-1}$
r_{fi}	Rate of reaction of component i	mgl^{-1}
S	Biological carbonaceous oxygen demand (BCOD) in the effluent bio solids	mg/l
SRT	Solids retention time	days
S_D	Side depth of bioreactor	m
S_0	Biological carbonaceous oxygen demand (BCOD) in the influent sludge	mg/l
T_1	Initial temperature	K
T_2w	Final temperature of moisture	K
ΔT	Temperature difference	K
ΔT_{cw}	Change in temperature of the cooling water	K
t	Time	days
t_G	Temperature of air	K
tG_1	Inlet temperature hot air.	K
tG_2	Outlet temperature of the hot air	K
t_W	Temperature of water	K
U	Overall heat transfer Coefficient	W/m^2 K

V_d	Volatile solids destroyed	%
V_R	Volume of Bioreactor	m^3
V_{RC}	Culture Volume, a function of time	m^3
V(t)	Volumetric Feed rate at time t	m^3/d
V_{CH4}	Volume of methane produced	m^3/d
W	Water evaporated	Kg
W_G	Weight of gas	$kghr^{-1}$
W_s	shaft work	kJ/Kg
W_w	Weight of water	$kghr^{-1}$
X_A	Conversion	
X_B	Composition of wet Bio solid	Kg
X_D	Composition of dried Bio solid	Kg
X_W	Composition of water in water vapour	
Y	Yield coefficient	
$\frac{1}{\tau}$	Space velocity	hr^{-1}
θ_c	Mean cell residence time	Days
μ_m	Maximum specific growth rate or half minimal velocity concentration	hr^1
ρ	Density	kg/m^3
ρ_W	Specific weight of water	kg/m^3
λ_w	Latent heat of vaporization	kJ/kg

ABBREVIATIONS

Abbreviation	Definition
BCOD	Biological Carbonaceous Oxygen Demand
BSRT	Biomass Solids Retention Time
CFU	Colony Forming Unit
CSTAR	Continous Stirred Tank Anaerobic Reactor
CWM	Chemical Warfare Material
DF	Dilution Factor.
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agricultural Organization
FC	Fixed Capital
GDP	Gross Domestic Product
HRT	Hydraulic Retention Time
MF	Materials Factor
NAP	Net Annual Profit
NPV	Net Present Value
OP	Operating Cost
PAHs	Polycyclic Aromatic Hydrocarbons
PBP	Pay-back Period
PEC	Purchased Equipment Cost
PPC	Physical Plant Cost
PPM	Parts Per Million
ROI	Rate of Return on Investment

SRT	Solids Retention Time
TABC	Total Anaerobic Bacterial Count
TC	Total Cost
THC	Total Hydrocarbon Content
TI	Total Investment
USEPA	United States Environmental Protection Agency
VC	Variable Cost
VSS	Volatile Suspended Solids
WC	Working Capital
WWTP	Waste Water Treatment Plant