Wastes Converter Reactor Plant Design for Synthesis of Bio-fuels, Minerals and Petrochemicals

Fredrick U. B; Wordu, A. A; Ehirim, E. O; Ugi, B. U

Chemical Petrochemical Engineering Department
Rrivers State University, Nkpolu-oro-worukwo,
Port Harcourt, Rivers State-Nigeria

University of Calabar
Pure and Industrial Chemistry Department
Calabar - Nigeria

Correspondence Author: E-mail: wordu.animia@ust.edu.ng
E-mail: ugifredrick@gmail.com
E-mail:ugibenedict@gmail.com

ABSTRACT

The environmental pollution facilitated by wastes disposal have been the greatest challenge to man for decades. Several technological research efforts have been on the increase to tackle its menace to humanity. This present research thrives to design a waste converter reactor plant (WCRP) with which waste from various sources was subjected to combustion cum distillation process to generate bio-fuels, solid minerals and petrochemical feed stocks for further applications. Reactor performance equations for the reactor and major equipment were developed from first principle by the application of the principles of conservation of mass and energy to determine the dimensional and functional parameters of the waste converter reactor plant (WCRP). The results obtained for the dimensional and functional parameters at fractional conversion of 90% are: volume = $1.8m^3$, length = 1.0m, space time = 16.6hrs, space velocity = 0.06hr^{-1}, heat load = $5.55 * 10^5 J$. The results detailed parameters required for the design and development of a waste converter reactor plant.

Keywords: *Waste-converter-reactor-plant, municipal wastes, kinetic balances, rate law, Heat balance, petrochemicals*

1. INTRODUCTION

The increase in population and industrial activities has led to an exponential rise in environmental pollution which has been a problem for many decades. The need to urgently tackle this problem is increasing as the effect of environmental pollution is becoming more devastating. Many professionals in various fields of studies especially in engineering and environmental management have proposed methods for effective waste management without due attention given to design and development of equipment for waste disposal which this present research has addressed by considering the design of a waste converter reactor plant for synthesis of biofuel and petrochemicals from both domestic and industrial wastes. Energy has been one of the most important things needed by man and other environmental constituents to execute their various daily activities, and till date it is one of the requirements our daily activities.

Energy tends to exist in different forms with unique source and strengths such as: chemical energy present in organic matters, used in yielding energy for our body when gotten from food that we daily eat, fuel for cars obtained from the distillation of crude oil, electrical energy obtained from charged bodies and been used as source of electricity for homes and offices, thermal energy to generate thermal heat used for cooking, solar energy sourced from the sun and used by plants for photosynthesis (Perry & Green, 2000). The daily energy requirement cannot be over emphasized; its availability is an important factor for the development of our economy. Some of these energies mentioned earlier can be synthesized from organic/environmental waste through recycling to obtain compounds such as methane (CH_4) gas, which is a colorless, odorless, flammable gaseous petroleum product ie hydrocarbon that is a product of biological decomposition of organic matters and of the carbonization of coal, of which can be used as fuel and as a starting material in chemical synthetic processes. Bio-energy production from biomass and biodegradable waste has received increasing focus, due to depletion of fossil fuels. The portion of renewable energies accounted only 11% of total energy consumption while 74% is fossil energy (Ria & Mohammad, 2019). Igoni et al. 2007 researched on production of biogas from municipal solid waste in Port Harcourt, Rivers State - Nigeria. A good quantity of biogas was achieved, but the research was experimental and no design was done. Bio-energy and bio-fuel production from biomass and biodegradable waste is the most reliable renewable energy resource, which occupies the predominant hare of today's market places (Fredrick & Wordu, 2021).

2. Materials

2.1 Wastes Converter Reactor Plant Design Interconnections

2.1.1 Plant overview

Figure 1 represent the Waste Converter Reactor Plant (WCRP) process design units' interconnections for the synthesis of environmental wastes into Bio-fuels, Solid Minerals and Petrochemicals.

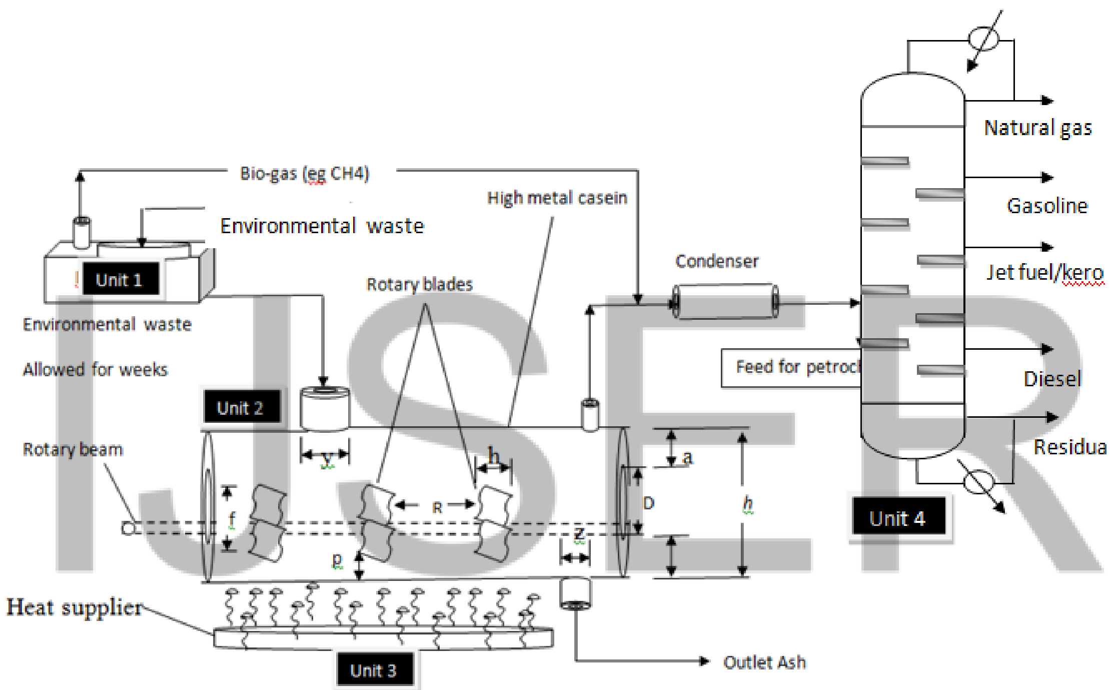

Figure 1: Prototype of Waste Converter Reactor Plant Design Interconnections

3. Methods

3.1 Design Model and Kinetic Expressions

3.1.1 Converter Reactor Configuration (Rectangular)

This unit is mainly the fermenter meant to keep the mixed environmental waste over some period of time before transfer into the waste converter reactor (WCR).

3.1.2 Fermenter's Volume

$$V_F = \frac{mass\ of\ feed}{feed\ density} + vessel\ allowance\,(\mathrm{m}^3) \quad \textbf{(1)}$$

3.1.3 Fermenter's Length

Considering the fermenter to be Figure 2;

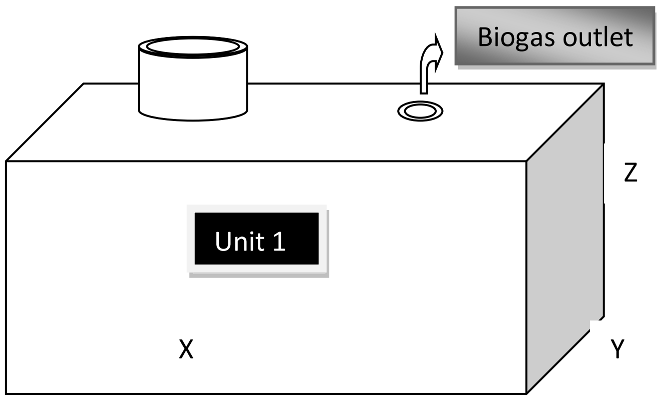

Figure 2: Waste Fermenter

$$\text{Length } (X) = \frac{YZ(\rho_{feed})}{M_{feed} + vessel\ allowance(\rho_{feed})} \quad \textbf{(2)}$$

Equation (2) is developed considering the chemical characteristics of a fermenter such as feed properties, vessel allowance, and vessel thickness

Where, M_{feed} = Mass of feed, ρ_{feed} = Density of feed

$Y\ and\ Z$ = Are the two functional dimensions of the fermenter

3.1.4 Material Balance

3.1.5 Kinetic Model Schemes

The kinetic study of this research considers the rate expression of principle of material balance, which will predict the production of bio-distillates and solid minerals from environmental wastes. Generally, one of the bio-distillates considered here is biogas such as methane (CH_4) which is one of the highest distillate due to the organic waste used, which are obtained from agricultural sector and domestic daily activities. This is because it is a predominant compound produced from the decomposition of organic wastes. Studies shows that organic waste contains 68.14% CH_4, 27.71% CO_2, 2.17% H_2, 1.09% H_2S and 0.89% N_2 present (Igoni et al. 2007).

Thus; environmental waste which is a mixture of both biodegradable and non-biodegradable materials, we can write out the reaction schematic or stoichiometry as follows;

This yields equations of the form;

Environmental waste → Crude distillates + Petrochemicals feed

The equation (3) becomes equation (4) properly couched as follows;

$$A + B \overset{k_1}{\rightarrow} biogas\ (P) + biomass\ (C) \overset{k_2}{\rightarrow} Petrochemicalfeed\ stock\ (R) \tag{3}$$

From the above stoichiometric equation (3), we can adequately predict that the process can be operating in an irreversible second order fashion kinetics,

Taking a material balance for 1 kg mole of the waste as stated below:

$$\left\{\begin{array}{c} Rate\ of \\ accumulation \\ of \\ Environmental \\ waste\ in \\ the\ reactor \end{array}\right\} = \left\{\begin{array}{c} Rate\ of\ inflow \\ of \\ environmental \\ wastes \\ into\ the\ reactor \end{array}\right\} - \left\{\begin{array}{c} Rate\ of\ outflow \\ of \\ products \\ obtain\ from \\ environmental \\ wastes \\ from\ reactor \end{array}\right\} + \left\{\begin{array}{c} Rate\ of \\ deplation \\ due\ to \\ reaction \\ in\ the\ reactor \end{array}\right\} \tag{5}$$

Hence, the general rate models to satisfy the equation [3] above are derived with respect to reactions process

$$\frac{dC_A}{dt} = -k_1 {C_A}^{n_1} {C_B}^{n_2} = -k_1 C_A C_B \tag{6}$$

$$-\frac{dC_{(biomass)}}{dt} = k_2 {C_C}^{n_3} {C_P}^{n_4} - k_1 {C_A}^{n_1} {C_B}^{n_2} = k_2 C_C C_P - k_1 C_A C_B = -\frac{dC_P}{dt} \tag{7}$$

$$\frac{dC_R}{dt} = k_2 C_C C_P \tag{8}$$

Neglecting the biogas which is an off gas deviated from entering the second unit where heat reaction process act on the biomass, we now have the following rate equations;

Considering; $n_1, n_2, n_3, n_4 = 1$

Hence the Bio-gas which is the P will move off first through the condenser inlet line leaving mainly the Bio-mass in the famenter to undergo non-Isothermal chemical reaction in the tubular reactor to yield the petrochemical feed stocks.

Hence; the actual rate equations becomes;

$$\frac{dC_A}{dt} = -k_1 C_A C_B = r_1 \tag{9}$$

$$-\frac{dC_{(biomass)}}{dt} = k_2 C_c - k_1 C_A C_B = r_{net} \quad (10)$$

3.1.6 Reactor Space Time (τ_{WCR})

So now from equation [36] we now have the reaction space time to be

$$t = \tau_{wcr} = \frac{\ln\left[\frac{C_c C_{B,o}\{k_2 + k_1(C_{B,o} - C_{A,o})\}}{k_1 {C_B}^2 C_{A,o}}\right]}{[k_1(C_{A,o} - C_{B,o}) + k_2]} = \frac{1}{[k_1(C_{A,o} - C_{B,o}) - k_2]} \ln\left[\frac{C_c C_{B,o}\{k_2 + k_1(C_{B,o} - C_{A,o})\}}{k_1 {C_B}^2 C_{A,o}}\right] \quad (11)$$

3.1.7 Volume of the WCRP (V_{WCRP})

The reactor volume considering a tubular reactor is given as;

$$\tau_P = \frac{v}{v_o} \quad (12)$$

$$V_{WCR} = \frac{v_o}{[k_1(C_{A,o} - C_{B,o}) + k_2] v_o} \ln\left[\frac{C_c C_{B,o}\{k_2 + k_1(C_{B,o} - C_{A,o})\}}{k_1 {C_B}^2 C_{A,o}}\right] \quad (13)$$

3.1.8 Area of the WCR

Considering an a waste Conversion Tubular Reactor taking a cylindrical form, will be having its area as;

$$A_{WCR} = \pi D_{WCR}(L_{WCR} + D_{WCR}) \quad (14)$$

3.1.9 Height of the WCRP

With respect to the Fred-Ugi's Model which states that the perfect height of the reactor with A, B,……i- feed is the ratio of the sum of the reactor feed to their respective densities entering the unit vessel, hence can mathematically be considered as;

$$h_R = \frac{V_R \times \rho_{feed}}{M_{o,feed} \times \tau} \quad (15)$$

3.1.10 Space Velocity of the WCRP

The space velocity of a reactor is generally the inverse of space time or is the ratio of the volumetric flow rate to the volume of the reactor.

$$S_v = {}^{1}/{\tau_{WCTR}} \quad (16)$$

3.1.11 Energy Balance Models

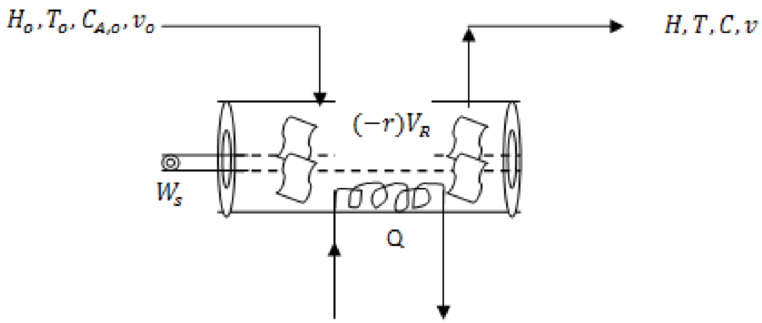

Figure 3: WCRP Process Temperature Operation with Heat Effect

Taking Energy Balance for the Non-isothermal (WCRP) using the general principle of conservation of energy which is given as:

$$\left\{\begin{matrix} Rate\ of\ accumulation \\ of\ Heat\ within\ the \\ Elemental\ Volum \end{matrix}\right\} = \left\{\begin{matrix} Rate\ of\ Input\ of \\ Heat\ into \\ Elemental\ Volume \end{matrix}\right\} - \left\{\begin{matrix} Rate\ of\ output\ of \\ Heat\ into \\ Elemental\ Volume \end{matrix}\right\} -$$

$$\left\{\begin{matrix} Rate\ of\ Depletion \\ of\ \ Heat\ due\ to \\ Chemical\ Reaction \end{matrix}\right\} - \left\{\begin{matrix} Rate\ of\ Heat \\ Removed\ to\ the \\ Surrounding \end{matrix}\right\} + \left\{\begin{matrix} Shaft\ Work \\ done\ by\ the \\ Stirrer \end{matrix}\right\} \quad (17)$$

Hence substituting all the evaluated into the energy equation above, we can now have;

$$\rho v C_p \frac{dT}{d\tau} = \rho v_o C_{p,o} T_o - \rho v C_p T - (-r_A) V_R (\Delta H_R) - U_v A_C (T_{v2} - T_{v1}) + W_s \quad (18)$$

Hence the **process temperature to** ascertain the safe reaction execution is given as;

$$T = \tau \frac{(r_{net})(\Delta H_R)}{C_p} + \frac{U_v A_C (T_{v2} - T_{v1})}{v_o C_p} + T_o \quad (19)$$

Where: U_v is the overall heat coefficient of the material used to notion the reactor walls.

3.1.12 Determining Heat Flow Rate in the System

Heat generated by the reactor:

$$\therefore\ Q_{PFTR} = m \left(\tau \frac{(r_{net})(\Delta H_R)}{1} + \frac{U_v A_C (T_{v2} - T_{v1})}{v_o} \right) \quad (20)$$

Where; $k_2 C_c - k_1 C_A C_B = -\frac{dC_c}{dt} = r_{net}$

3.1.13 Mechanical Design

Focusing on some other mechanical design of the **unit 2** of the WCRP, as follows; Considering the following parameters;

3.1.14 Stirrer Design

Usually, a clearance is allowed between the stirrer blade and the reactor sides

The length of the stirrer can be obtained as follows

$$L_{St} = L_R - C \qquad (21)$$

Where: L_R = Length of reactor=L_{WCPP}, C = Clearance or the blade-wall distance { $C = \frac{D_{WCTR} - D_{st}}{2}$ }, L_{st} = Length of Stirrer [blade]

3.1.15 Blades Width/Diameter of the stirrer (D_{st})

The diameter of the stirrer [blade] can be obtained from the equation

$$D_{st} = D_R - 2C \qquad (22)$$

where: D_R = Diameter of the Reactor, D_{st} = Diameter of the Stirrer [blade]

3.1.16 Blades Spacing (R)

This can be determined using;

$$R = \frac{Lenght\ of\ reactor}{\text{Diameter of the Stirrer [blade]}} \times \text{Diameter of the Reactor}$$

$$R = \frac{L_{WCTR}}{D_{st}} D_{WCTR} \qquad (23)$$

3.1.17 Number of Stirrers Blades (n)

$$n = \frac{L_R}{R \times f} \qquad (24)$$

Where;

f = Pair blade distance

3.1.18 Cylindrical section

$$\mathrm{e} = \frac{\mathrm{P_i D_i}}{\mathrm{2SE - P_i}} \qquad (25)$$

Thickness (t) = e + Corrosion Allowance

Where;

$$\text{Thickness (t)} = \frac{\mathrm{P_i D_i}}{\mathrm{2SE - P_i}} + \text{Corrosion Allowance} \qquad (26)$$

We should note that when Welds are fully graphed: E will be = 1

3.1.19 Doomed Head

Try a Standard Dish-Head (Torispherical)

$$\mathrm{e} = \frac{\mathrm{P_i R_i C_i}}{\mathrm{2SE_h - P_i(C_i - 0.2)}} \qquad (27)$$

Where: R_s = D_i, C_s = Stress Concentration Factor

$$C_s = \frac{1}{4}\left[3 + \sqrt{\frac{R_c}{R_k}}\right] \qquad (28)$$

Where R_k = knuckle radius = 6% R_c

$$\text{Thickness (t)} = \frac{\mathrm{P_i R_i C_i}}{\mathrm{2SE_h - P_i(C_i - 0.2)}} + \text{corrosion allowance} \qquad (29)$$

Table 1: Input Parameters

S/N	Parameters	Values	References
1	Heat Capacity, Cp	1.394KJ/Kgk	Average of the analyzed C_p
2	Rate constant, k_1	$0.043hr^{-1}$	Perrys, et al., 2008
3	Rate constant, k_2	$0.27hr^{-1}$	Perrys, et al., 2008
4	Volumetric flow rate	0.1066 m^3/hr	Calculated
5	Inlet temperature	303K	Perrys, et al., 2008
6	$C_{A,O}$	1.1356 mol/dm^3	Calculated
7	$C_{B,O}$	0.8747 mol/dm^3	Calculated
8	$C_{C,O}$	2.0103 mol/dm^3	Calculated
9	Heat of reaction	353kJ/kmol	Perrys, et al., 2008
11	Stirred Clearance	0.52m	Perrys, et al., 2008
12	T_{v1}	298k	Estimated
13	T_{v2}	975k	Estimated
14	H	8.5m	Perrys, et al., 2008
15	U	3.5Cp	Estimated
16	M	232kg	Calculated

4. Results and Discussions

Models developed were simultaneously simulated using matlab to check is the models are progressive or regressive and of which when progressive they tends to sure that the models developed are in coherency to the aim of this research. Hence, the production of crude distillates and petrochemicals from environmental waste tends to be source-able and economical, also helps in eliminating environmental pollution released due to wastes deposited by residential, industrial and agricultural practices in the ecosystem.

Table 2: Summary of Mechanical Design Results

	Cylinder head	Ellipsoidal head
Thickness(t) (mm)	53.23	52.1
Corrosion allowance(e) (mm)	1.2	1.2

$\varepsilon =$ Using the reactor operating frequency of 60%

$h_{WCTR} = \frac{L_{WCTR}}{2}$= 1.5m and using stainless steel as the design material due to its good heat conductivity capacity, also taken the cost of feed to be 100 pounds.

Hence using the above information, we get the tabulated values;

Table 3: Summary of Cost of Reactor

Cost ($pound$)	**Time**
250166	Daily
1250833.33	Weekly
5003333.333	Monthly
75050000	Yearly

4.1 Variation of Volume of Reactor with Fractional Conversion

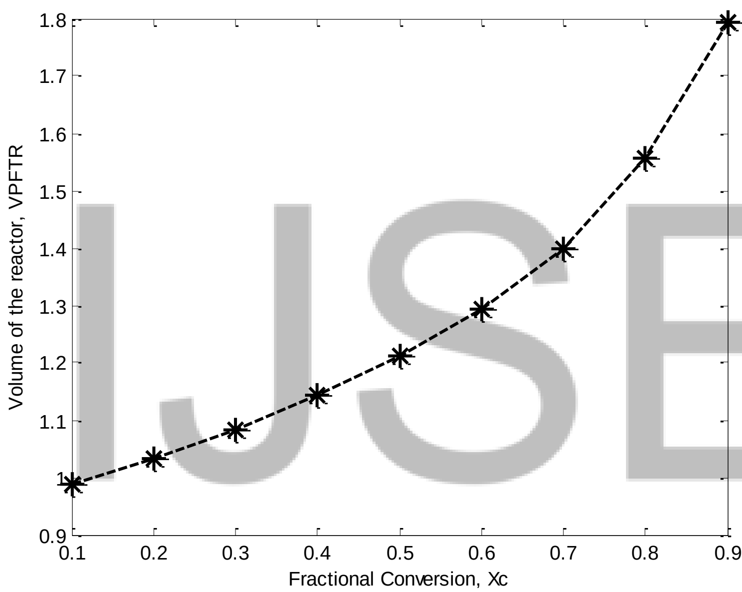

Figure 4: Variation of Volume of Reactor with Fractional Conversion

Figure 4 shows exponential increase in volume of WCPP with fractional conversion from point $V_{WCPP} = 1m^3$ / Xc = 0.1 to the Xc = 0.9 level of conversion.

4.2 Length of WCRP with Fractional Conversion

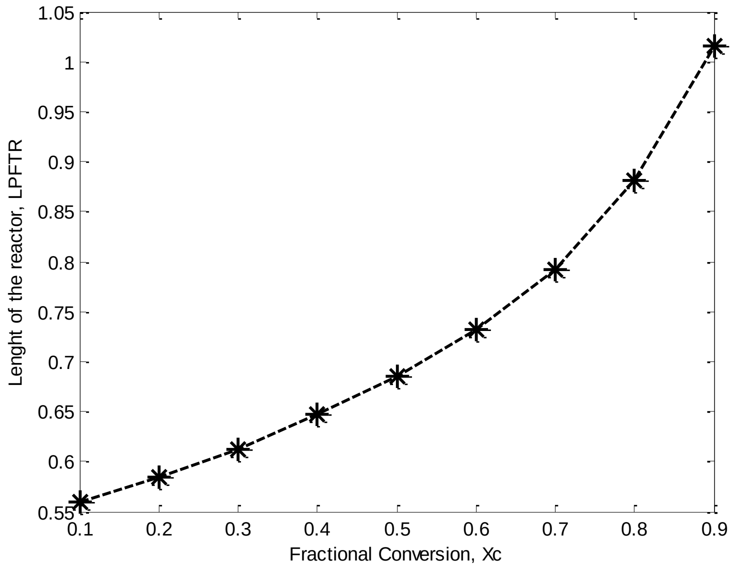

Figure 5: Variation of Length of Reactor with Fractional Conversion

Figure 5 depicts variation of length with fractional conversion. From the plot, it is seen that the length of WCPP increase proportionally as X_c increase, and of cause it can be easily known that at normal bases the reactors length is affected by the change in volume.

4.3 Space time (τ) with fractional conversion

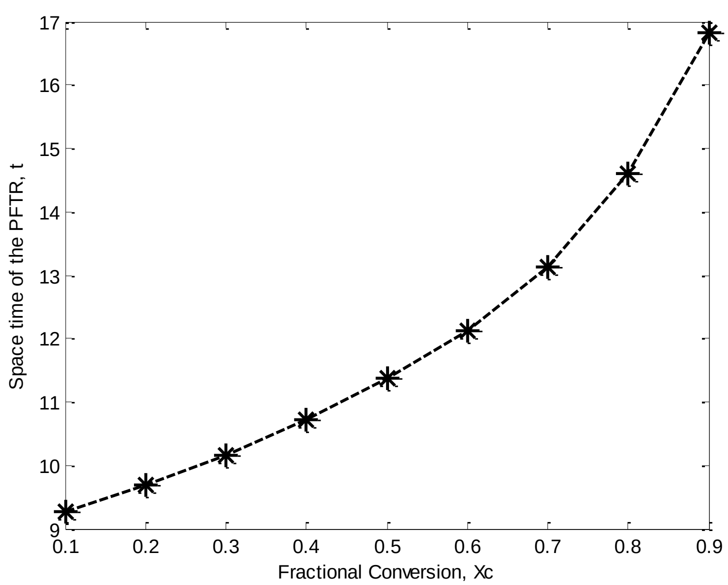

Figure 6: Plot of Space time versus conversion

Figure 6 shows variation of space time with fractional conversion (X_A) which is exponentially increasing as space time "X_A" increases. At maximum value of space time ranging from $\tau = 9\ hour$ and $\tau = 14.5\ hour$ the exponent level of the reaction tends to grow smoothly while after then there is a vast growth in the conversion process.

4.4 Heat generated per unit volume with X_A

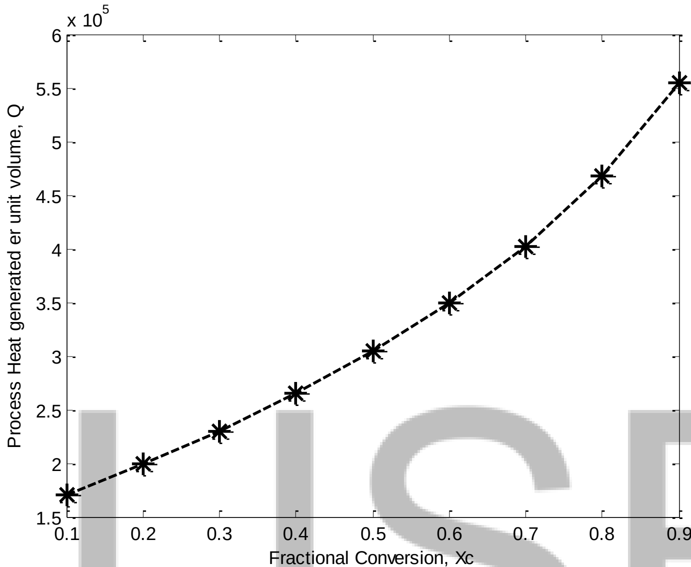

Figure 7: Plot of heat generated per unit volume versus XA

Figure 7 shows a proportional exponential increase in the fraction of feed materials converted into product under temperature bases as the heat of formation increase vastly along the process conditions showing a great impact of heat towards the conversion of environmental heat as a process of pyrolyses into reasonable derivatives which are so much useful for petrochemical distillates production and biogas generation over time.

4.5 Space time with Volume of the reactor

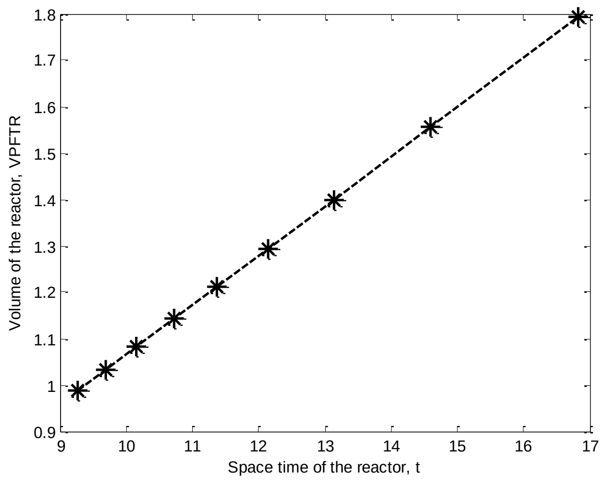

Figure 8 Plot of Space time with Volume of the Reactor V_{WCPP}

Figure 8 shows a directly proportionality between the reactors space time with the volume of reactor, hence an increase of the reactors space time leads to a directly proportional increase in the amount or number of reactors volume of feeds converted or treated in a volume element under specific reactors operating conditions at time t.

4.6 Process temperature T versus the Rate of reaction r_2

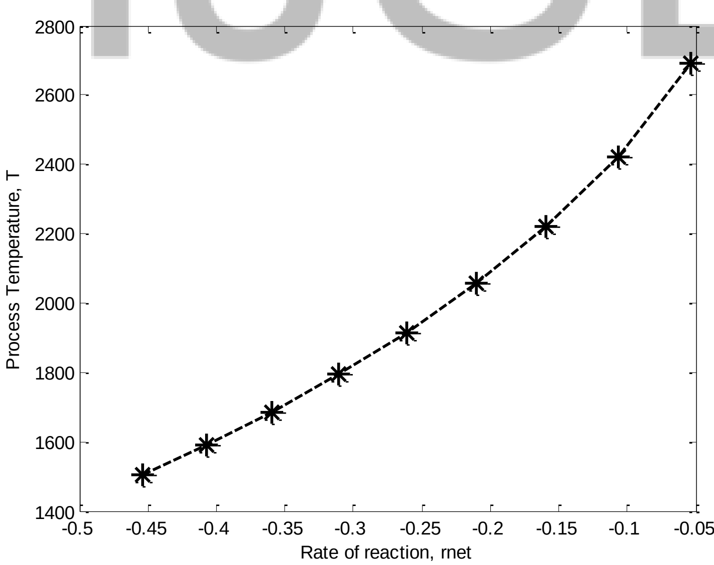

Figure 9: Plot of temperature versus the Rate of reaction r_2

Figure 9 shows a plot investigating the relationship between the reaction rate with the process temperature, of with it shows that the process temperature tends to increase proportionally to the increase in the reaction net rate.

4.7 Space time versus the Product concentration C_R

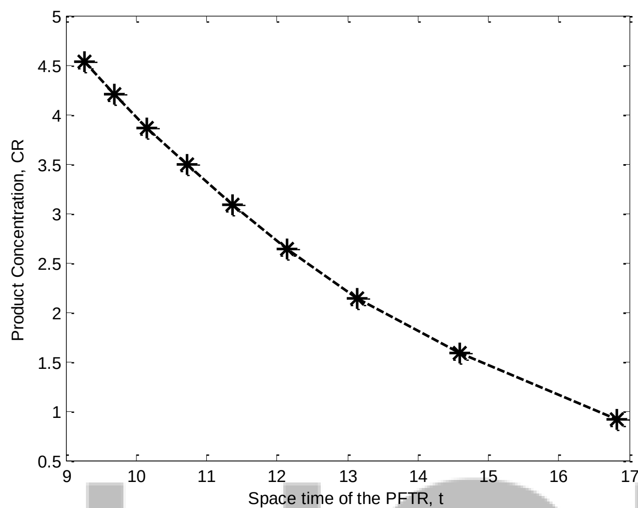

Figure 10 Plot of Space time t versus the Product concentration C_R

Figure 10 shows the plot of the concentration of the product which will be obtained from the reactor as a yield of the environmental waste aiming to be further used as a petrochemical and bio-fuel generator, hence one can see that the product concentration plot shows a logarithmic falling correspondently to the increase in the reactor space time, Hence, it is seen that at a maximum space time of t> 50 hrs under same operating reactor conditions will yield a zero concentrated output.

5. Conclusion

This work is based on the design of WCRP used for the production of crude distillates and petrochemicals useful for the production of gasoline and order useful and economically friendly products from industrial, environmental and agricultural waste. Material and energy balance principles were applied incorporating some principles of thermodynamics, mathematics, economics and applied sciences to obtain the design models for the volume and functional parameters such as length, space time and space velocity, diameter of the stirrer and length of the stirrer and also heat generated per unit volume and temperature of the WCPP. Data were adopted via calculations and used for the MATLAB simulation of the design models.

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