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Design, Simulation Analysis and Performance Evaluation of aFluidized Bed Reactor for the Pyrolysis of Biomass

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ABSTRACT: *Pyrolysis is a preliminary method to other thermochemical energy conversion of biomass which is known to be economical and convenient to carry out. This paper addresses the design of a typical electrically operated pyrolysis reactor that comprises a furnace with temperature controller, condensate receiver with pressure sensor, gas collection unit and a gas cylinder. Detailed analysis of the design was carryout and verified by simulation using Finite Element Method (FEM). The design was fabricated and performance evaluation of the reactor was carryout using 500g sample of cassava peels of 10.01 % moisture as biomass feedstock at pyrolysis temperatures of*$673\ K, 773\ K,\ 873\ K,\ 973\ K$*and* $1073\ K$*. A high energy ratio of 0.955 was obtained and the overall system efficiency was estimated to be 54 %. The furnace was designed to withstand a maximum temperature of* $1273\ K$ *with* $0.0132\ m^3$ *retort capacity which accommodates biomass feedstock.*

KEYWORDS:*Bio fuel, Biomass,Calorific value,Cassava peels,Char, Energy content, Energy efficiency, Energy Ratio, Finite Element Method,Furnace, Heat transfer,Pyrolysis, Pyrolysis reactor, Pyrolysis temperature, Pyrometer, Syngas, Tar.*

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I. INTRODUCTION

One of the most common methods of thermo-chemical conversion of biomass is pyrolysis. It is a process which involves of thermal decomposition of biomass in the absence of oxygen in a furnace at temperature between $673\ K$ and $1173\ K$ [1]. Various types of reactor (furnace) exist but each is designed to carry out a specific function. There are parameters to be considered during the pyrolysis in which temperature is the most paramount. Various scholars have researched into the process and reactors have been developed based on the required product and biomass type. Most of the developed reactors did not show explicit method of their design and numerical analysis. Musale*et al.* [2] designed pyrolysis reactor with generalized considerations using thermocouple to measure the range of the pyrolysis temperature. The reactor is designed to carry out both the slow pyrolysis and fast pyrolysis.

Sinha*et al.* [3] described heat transfer as one of the mechanism that affect the process of pyrolysis. The effect of the heat loss to the surrounding affects the stability of a required pyrolysis temperature and this has to be minimized. This paper addresses a design, numerical and simulation analysis, construction and performance evaluation of a small scale fluidized bed reactor plant for the pyrolysis of biomass. The reactor is developed to operate at a required specific pyrolysis temperature up to a maximum temperature of $1273\ K$.

II. MATERIALS AND METHOD

2.1 DESIGN

The components of fluidized bed pyrolysis equipment include the retort, furnace, condensate receiver, gas collection unit. The design consideration parameters considered are interdependent and are as follows:

- feedstock particle size;
- heat transfer and rate of heat loss;
- pyrolysis temperature;
- heating time;

- reaction pressure;
- capacity and melting point of retort;
- thickness and type of insulating materials;
- heating rate of the heater; and
- temperature control and sensing device.

2.1.1 Retort

The retort used is a heat sealable container that is thermally processed like a vessel. It was fabricated vented in order to allow the escape of vapourised mixture during pyrolysis process. Mild steel of 2.0 mm thickness was selected as the materials because of it mechanical properties such as, high thermal conductivity, machinability as well as resistance to corrosion.

The capacity by volume, V, of the retort is determined using equation (1).

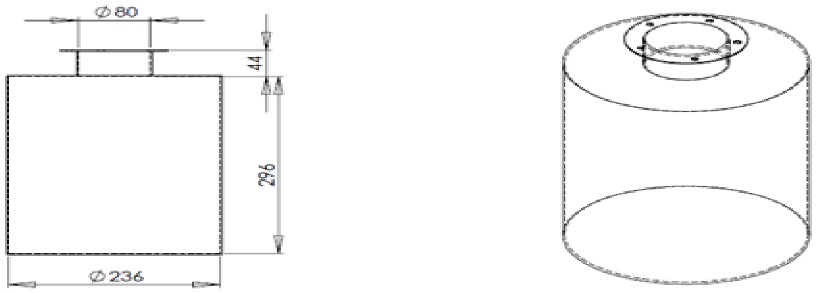
$$V = \pi(R^2H + r^2h) \qquad \ldots \qquad (1)$$

Where R= radius of the cylinder, H= height of the cylinder, r= neck radius and h= neck height

From Fig. 1 (a and b), $R = 0.118\ m$,$H = 0.296\ m$,$r = 0.040\ m$, $h = 0.044\ m$, taking$\pi = 3.142$. Hence,

$V = 0.0132\ m^3$

The details of the design work are shown in Fig. 1.



(a) (b)

Figure 1: Retort

2.1.2 Analysis of Metal Furnace

The furnace fabricated is cuboidal in shape, electrically operated with glass fiber placed in – between the inner and outer wall of the furnace as a lagging material. A reinforced fired-clay of about 6.35 mm (2.5 inches) thickness was molded and introduced into the furnace to prevent heat loss as well as direct contact of heat from the heater to the inner surface of the furnace. The inner and outer surface was made up of galvanized sheet metal. The lagging materials prevent heat lost by conduction. The arrangement of the furnace with the lagging materials is as shown in Fig. 2. The accessories incorporated are heating element, pyrometer-sensor (thermocouple) and the pyrometer.

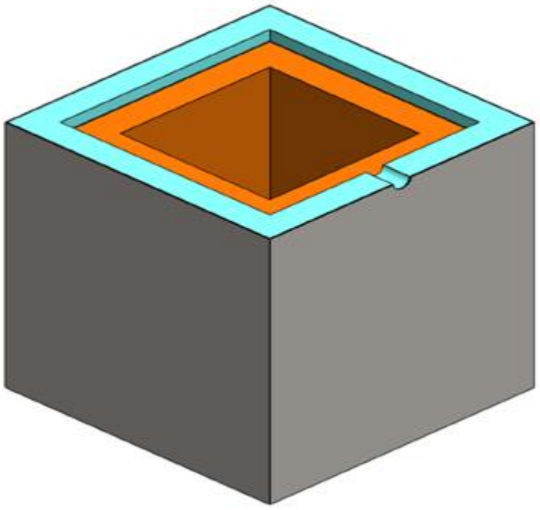


Figure 2: Model Lagging Arrangement

The heat transfer rate, q_x, between the system and the environment is determined by equation (2) with one – dimensional heat equation for the composite bodies as stated by [4].

$$q_x = \frac{T_1 - T_\infty}{R_t} \qquad \dots \qquad (2)$$

Where $T_1$and T_∞ are maximum and minimum temperatures respectively and R_t is the total thermal resistance. The equivalent thermal resistance, R_t, for the lagging of the composite materials as shown in Fig. 3 is determined by equation (3) as adapted from [4].

$$R_t = \frac{L_c}{K_c A} + \frac{L_m}{K_m A} + \frac{L_f}{K_f A} + \frac{L_m}{K_m A} + \frac{1}{h_a A} \qquad \dots \qquad (3)$$

Where L is the thickness of each material, K is the thermal conductivity of each material, h_a is the convective heat transfer coefficient of air and A is the cross-sectional area of the face transferring the heat energy.

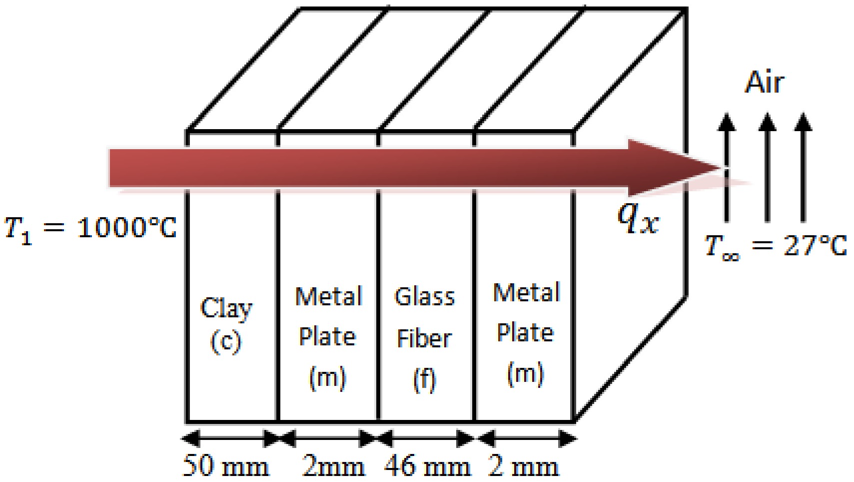


Figure 3: Equivalent thermal circuit for a series composite wall

From the design (Fig. 3) $L_c = 0.05\, m, L_m = 0.002\, mandL_f = 0.046\, m$. According to Bergmanet *al.* [4] thermal conductivities of each of the materials are given as follows:$K_c = 1.1\, W/mK(operatingat\ 1073K), K_m = 18\, W/mK, K_f = 0.036\, W/mK$.At a moderate flow of air over a surface, h_a is assumed to be$100 W/m^2K$.

From the design, the area, A, of the contacting surfaces of the composites from the inner surface of the clay is $0.1152\, m^2$.

Hence, the thermal resistance,

$R_t = 11.56\, K/W$

The furnace is designed to work with a maximum temperature, T_1 of 1273 K and the minimum temperature of the outer surface (i.e. room temperature of the air), T_∞ of 298 K. Therefore, the heat transfer, $q_x$from the inner to the outer surface of the furnace is,

$q_x = 86.51\, W$and the heat flux,

$\ddot{q_x} = 750.95\, W/m^2$

Since a specific temperature has to be maintained at the inner part of the furnace, it is necessary to determine the percentage heat loss during the process to the surroundings. The percentage heat loss, q_{loss}, is determined mathematically by equation (4).

$$q_{loss} = \frac{Quantityof\ \ heattransfer\ \ (W)}{Powerratingoft\ \ heheater\ \ (W)} \times 100 \qquad \dots \qquad (4)$$

The designated heater is rated 2800 W. If the furnace is operating at the maximum designated temperature of 1273K, therefore maximum the percentage heat loss to the surrounding would be

$q_{loss} = 3.09\, \%$.

2.1.3 Condensate Receiver

Condensate receiver is a cylinder which received the mixture of both syngas and vapourized liquid fuel (tar) from the retort. It was fabricated with a galvanized sheet metal. The galvanized sheet was selected because is a good material for heat exchanger. Fig. 4 shows how the condensate receiver is connected to the reactor assembly.

2.1.4 Gas-collection Unit

It was also fabricated using galvanized steel. The galvanized steel metal was selected because of machinability, heat resistance, weld-ability, as well as its corrosion resistance properties which prevent any reaction. It consists of three openings as shown in Fig. 4.

2.2 ACCESSORIES

The accessories used include the heating element, pyrometer otherwise known as temperature controller, ice bath, measuring cylinders, weighing machine, among others. Their functions are discussed as follows:

2.2.1 Heating Element

The element has a rated power of 2.8KW. It uses 220V – 240V alternating current power source. The power generated is sufficient enough to pyrolyse the feedstock (residues) effectively. The input energy in Joules of the heater is determined using equation (5).

$$InputEnergy_{Heater} = RatedPoweroftheHeater \times time \quad \ldots \quad (5)$$

The type of heater selected adapts the shape of the retort as shown in Plate 1.

Plate 1: Heating element

2.2.2 Pyrometer

It comprises the thermocouple wire with a sensor which was introduced into the furnace and controlled by relay-switch known as contactor (Plate 2). It is used to regulate and control the inner temperature of the furnace at a given period. The pyrometer can be adjusted to determine the type of pyrolysis over a given range of temperature i.e. fast, intermediate or slow pyrolysis.

Plate 2: Pyrometer

2.2.3 Ice bath

The bath contains the mixture of both ice and water to cool the hot gases coming from the retort and are placed at the base of the condensate receiver.

Other accessories used include clips, valves, pressure gauge, rubber gaskets, measuring cylinder, flange couplings, galvanized iron pipes and rubber holes. Fig. 4 shows the isometric view of the plant assembly with part list.

Part No	Part Name	Part No	Part Name
1	Furnace cover	8	Pressure gauge
2	Fired clay cover	9, 14	Non-return valves
3	Glass fibre	10	Condensate receiver
4	Retort	11	Gas collection unit
5	Fired clay	12	Gas cylinder
6	Metal housing	13	Water flow pipe
7	Ice bath	15	Ordinary valve

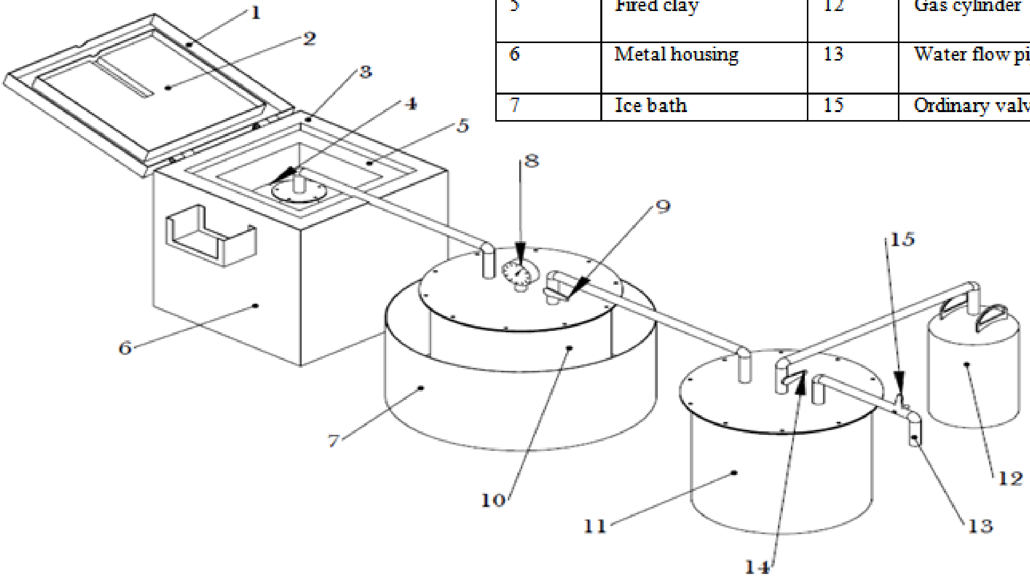


Figure 4: Isometric View of Reactor Assembly

2.3 ENERGY EVALUATION

2.3.1 Biomass Energy Content and Energy Output

The biomass energy content, E_C and biomass energy output, E_P are the values of energies in Joules (J) which could be generated from the biomass and its products respectively. It is the product of the mass and the calorific value of the residue/product as shown in equations (6) and (7).

Mathematically;

$$E_C = massofbiomasssupplied \times CalorivicValue \qquad (6)$$

$$E_P = massofproductobtained \times CalorivicValue \qquad (7)$$

2.3.2 Biomass Energy Ratio

This is the ratio of the energy output of the products (for instance char, tar and syngas) to that of the energy content of the biomass. It could be calculated using equation (8).

$$E_R = \frac{E_P}{E_C} \qquad \ldots \qquad (8)$$

2.3.3 System Energy Efficiency (η_{system})

This is the ratio of the total output energy of the product to that of the total energy supplied. It is derived using equations (5), (6) and (7). The energy efficiency of the whole system is determined using equation (9).

$$\eta_{system} = \frac{Average\ E_P of the product}{BiomassEnergyContent\ \ (E_C) + InputEnergy\ \ _{Heater}} \times 100 \qquad \ldots \qquad (9)$$

III. RESULTS AND DISCUSSION

3.1 Simulation Results

The model of the metal furnace heat transfer analysis was simulated using Finite Element Method (FEM). A temperature of 1273 K and 298 K is subjected at both the inner and outer parts of the model respectively with a heat source of 2.8 kW at the inner surface and an equivalent thermal resistance of $11.56\ K/W$ as initially determined. Fig. 5, 6 and 7 show the schematic diagrams of the results obtained.

The distribution of the temperature in the model of the designed furnace (Fig. 5) shows clearly that the temperature of the lagging material, glass fiber, is least across the whole thickness as result of the low thermal conductivity of the material. This accounts for the low heat transfer obtained from analytical method. The interpretation of this analysis corresponds to displacement in structural analysis.

The result of temperature gradient (K/m), of the model shown in Fig. 6 and the interpretation is similar to that of strain in structural analysis. The maximum temperature gradient occurs at the corner of the clay at the inner part of the furnace while other parts maintain uniform distribution. This shows that there would be surface cracks along the vertical edges of the clay from the inner part of the furnace when first subjected to heat supply as a result of binding strength of clay particles.

Fig. 7 shows resultant heat flux of the model and the explanation of the result is the same to that of stress in structural analysis hence, also known as thermal stress. It can be seen that the thermal stress distribution is minimal across the whole model due to appropriate material selection for the design. Therefore, the design was acceptable for the intended purpose.

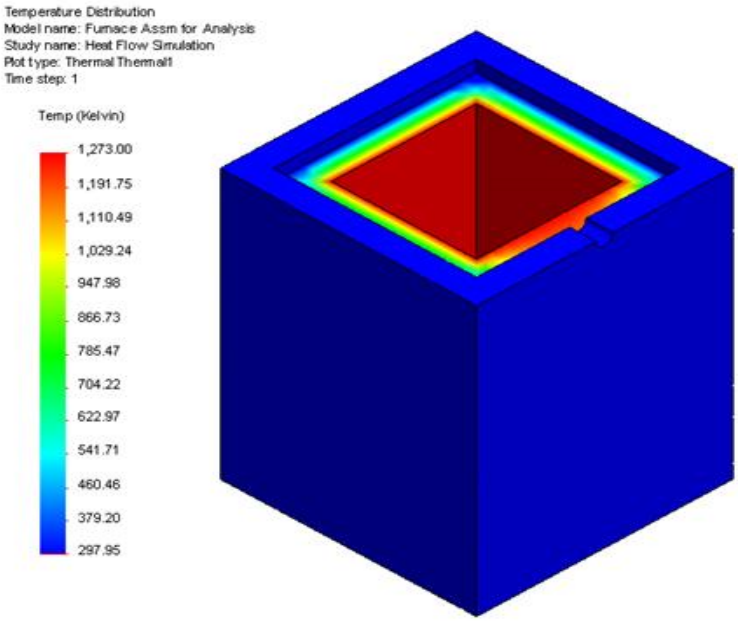


Figure 5: Schematic Diagram of Furnace Model Temperature Distribution

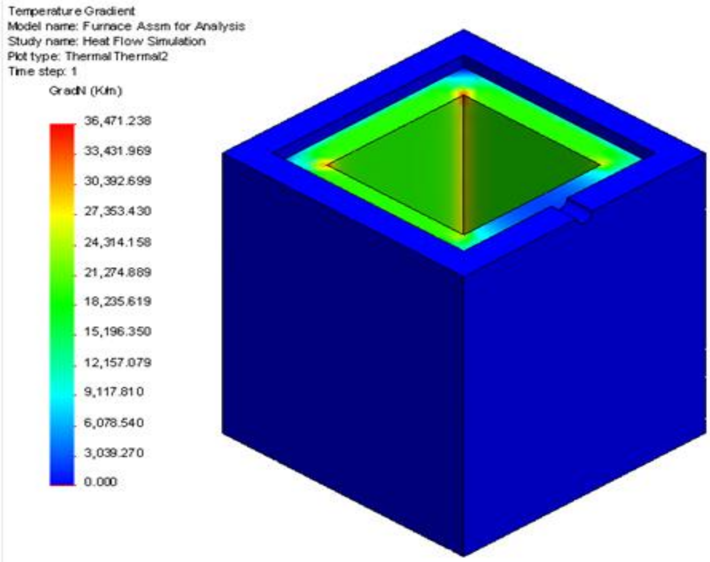


Figure 6: Schematic Diagram of Furnace Model Temperature Gradient

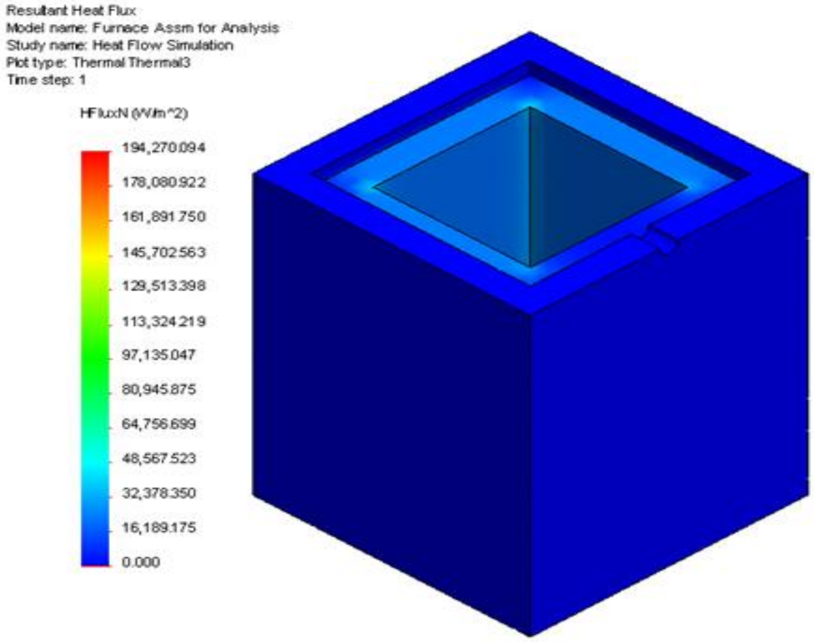


Figure 7: Schematic Diagram of Furnace Model Heat Flux

3.2 Experimental Results

Cassava peels were the residue used to perform the evaluation of the developed furnace and the products yields were as determined by Adeleke*et al.* [5]. It was stated that 500 g of dry sample of cassava peels at 10.01 % moisture content were subjected into the furnace between the pyrolysis temperature of 400 ^{0}C and 800 ^{0}C for 40 minutes. The results obtained from the yields of the char, tar and syngas were used to determine energy content in the biomass and are summarized in Table 1.

Table 1: Experimental Results

S/No	Description of Parameter	Value	Unit	Remark
01	Energy content of dry cassava peels (E_C) for 450 grams	8748.0	KJ	As calculated
02	Average output Energy of the Product (E_P)	8330.7	KJ	As calculated
03	Input Energy from the Heater	6720.0	KJ	As calculated
04	Pyrolysis product energy content (Char)	27.5	MJ/Kg	[6]
05	Pyrolysis product energy content (Tar)	16.0	MJ/Kg	[6]
06	Pyrolysis product energy content (Syngas)	10.44	MJ/Kg	[7]
07	Heating Value of cassava peels	19.40	MJ/Kg	[8]
08	Energy ratio of the Process	0.952	-	As calculated
09	Efficiency of the whole Plant	53.86	%	As calculated

3.3 Performance Evaluation

The energy ratio of the process is 0.952 and indicates high products yield during the process due to low production loss. The efficiency of the plant is $53.86\,\%$ because at higher temperatures pyrolysis process had ended before the end of 40 minutes which amounts to waste of energy. Fig. 8 depicts the energy yields of the product with increase in temperature. Between temperatures of $700\ ℃ and\ 800\ ℃$, there is little difference in the energy yield and it shows the process has ended before$800\ ℃$. This agrees with the results obtained by Adeleke *et al*. [5] as it also accounts for the drop in the plant efficiency.

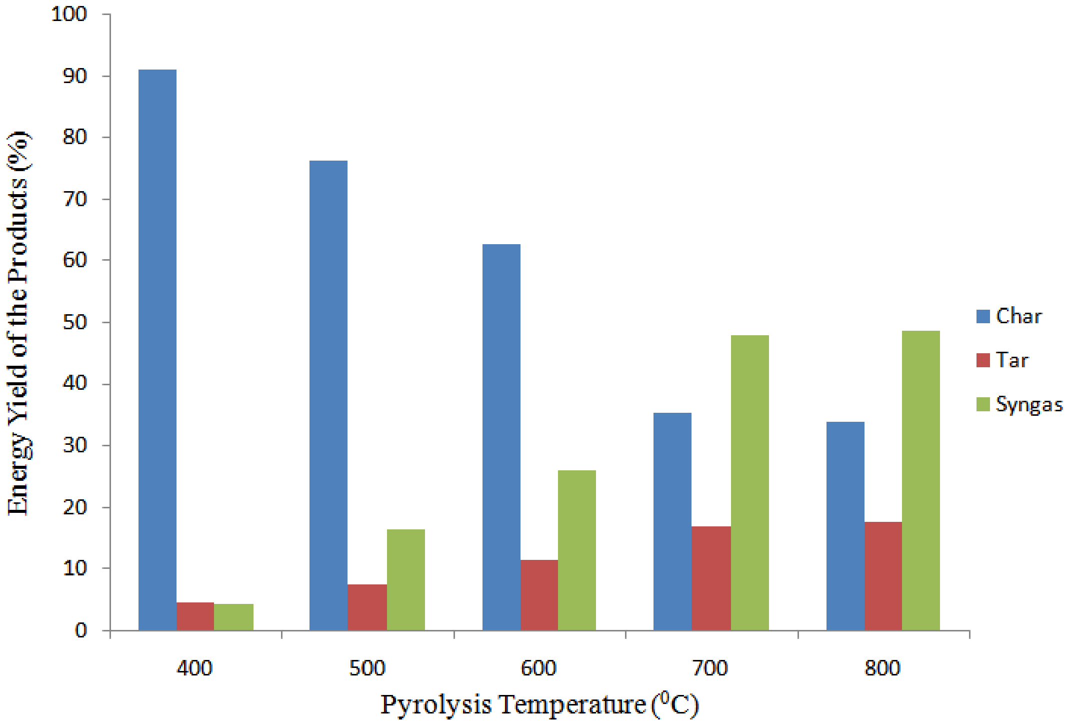


Figure 8: Comparison of the Energy yield of the Products at various Temperatures.

IV. CONCLUSION

An electrically operated pyrolysis furnace was designed, simulated and implemented. The model was simulated using FEM and the results obtained were verified and these commensurate to that obtained from design analysis. The developed furnace was tested using cassava peels. The energy ratio of the process was determined as 0.952 and the efficiency of the system was estimated as54 %. The developed furnace can be used to determine suitable initial operating parameters for a particular biomass feedstock to give desired output yield.

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