EVALUATION OF THE EFFICIENCY OF A THERMOCHEMICAL REACTOR FOR WOOD PYROLYSIS

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ABSTRACT

The evaluation of the efficiency of a thermochemical reactor for wood pyrolysis is presented in this paper. Biomass from seven tropical wood species; Obeche (*Triplochiton scleroxylon*); Iroko (*Melicia excelsa*); Danta (*Nesogordonia papaverifera*); Mahogany (*Khaya ivorensis*); Omo (*Cordia platythyrsa*); Mansonia (*Mansonia altissima*) and Afara (*Terminalia superba*) retrieved from sawmills were pyrolysed in a fixed-bed batch thermal reactor. Thermodynamic principles were used to obtain the reactor efficiency at varying temperatures. Linear regression analysis was done and regression trend equations were written, with which the reactor temperatures were calculated. There were highly significant linear correlation between the pyrolysis experimental temperatures and the calculated temperatures. The correlation coefficients of 95.50% for Product Temperature, 91.00% for the Reactor Efficiency at generating gas, and 71.60% for the Reactor Thermal Efficiency. These give an overall average of 86.00% for the reactor. It was concluded that the thermochemical reactor is highly efficient.

Keywords: Thermochemical, pyrolysis, reactor, efficiency, fixed-bed.

INTRODUCTION

Biomass is the renewable, biodegradable or combustible organic matter generated through life processes, which are themselves dependent upon solar energy, including cow dung cakes, agricultural residues and firewood. "It is defined as non-fossil, energy-containing forms of carbon and includes all land- and water-based vegetation such materials as municipal solid wastes, forestry and agricultural residues, municipal bio-solids, and some industrial wastes." In other words, biomass is all non-fossil organic matters that have intrinsic chemical energy content or heating value. It refers to living and recently dead biological material that can be used as fuel or for use as biofuel, but it also includes plant or animal matter used for production of fibres, chemicals or heat. Biomass may also include biodegradable wastes that can be burnt as fuel. It excludes organic material which has been transformed by geological processes into substances such as coal or petroleum. (Rajendra, 1991; Klass, 1998; Akinola, 2012).

Biomass is organic material made from plants and animals. Biomass contains stored energy from the sun. Plants absorb the sun's energy in a process called photosynthesis. The chemical energy in plants gets passed on to animals and people that eat them. Biomass is a renewable energy source because we can always grow more trees and crops, and waste will always exist. Some examples of biomass fuels are wood, crops, manure, and some garbage. (Carneige and Pohl, 1980).

LITERATURE REVIEW

Pyrolysis has been defined as 'the incomplete thermal decomposition of biomass, generally in the production char, condensable liquids (tar oils and acids) and non-condensable gaseous products (Fapetu, 1994). In wood pyrolysis, the process is referred to as carbonization if the char is the principal product of interest or wood distillation if the primary product is the liquid. The process is called destructive distillation if the products of interest are the char and the liquid. Generally, it is a well-known method of extracting valuable products from feedstock, especially plant-based biomass.

Pyrolysis (also known as carbonization, destructive distillation, dry distillation, or retorting) is the chemical decomposition induced in organic materials by heat in the absence of oxygen. In practice, it is not possible to achieve a completely oxygen-free atmosphere; pyrolytic systems are operated with less than stoichiometric quantities of oxygen. Because some oxygen will be present in any pyrolytic system, nominal oxidation does occur. If volatile or semi-volatile materials are present, thermal desorption (changing from an adsorbed state on a surface to a gaseous or liquid state) will also occur. Pyrolysis processes produce an array of solid and liquid derivatives, and fuel gases depending on the process conditions and the organic material content of the feedstock.

Pyrolysis is thermal degradation either in the complete absence of oxidizing agent, or with such a limited supply that gasification does not occur to an appreciable extent or may be described as partial gasification. Relatively low temperatures are employed of 500 to 800 °C, compared to 800 to 1000 °C in gasification. Three products are usually produced: gas, pyrolysis oil and charcoal, the relative proportions of which depend very much on the pyrolysis method, the characteristics of the biomass and the reaction parameters. Fast or flash pyrolysis is used to maximize either gas or liquid products according to the temperature employed.

Pyrolysis is the thermal decomposition of materials in the absence of oxygen or when significantly less oxygen is present than required for complete combustion. It is important to differentiate pyrolysis from gasification. Gasification decomposes biomass to syngas by carefully controlling the amount of oxygen present. Pyrolysis is difficult to precisely define, especially when applied to biomass. The older literature generally equates pyrolysis to carbonization, in which the principal product is a solid char. Today, the term pyrolysis often describes processes in which oils are preferred products. The time frame for pyrolysis is much faster for the latter process.

The general changes that occur during pyrolysis are enumerated by Sinha *et al*., (2000) as
(1) Heat transfer from a heat source, to increase the temperature inside the fuel; (2) The initiation of primary pyrolysis reactions at this higher temperature releases volatiles and forms char; (3) The flow of hot volatiles toward cooler solids results in heat transfer between hot volatiles and cooler unpyrolyzed fuel; (4) Condensation of some of the volatiles in the cooler parts of the fuel, followed by secondary reactions, can produce tar; (5) Autocatalytic secondary pyrolysis reactions proceed while primary pyrolytic reactions (item 2, above) simultaneously occur in competition; and (6) Further thermal decomposition, reforming, water gas shift reactions, radicals' recombination, and dehydrations can also occur, which are a function of the process's residence time/ temperature/pressure profile.

For some time now, fundamental research on fast or flash pyrolysis has shown that high yields of primary, non-equilibrium liquids and gases, including valuable chemicals, chemical intermediates, petrochemicals, and fuels, could be obtained from carbonaceous feedstocks. Thus, the lower value solid char from traditional slow pyrolysis can be replaced by higher-value fuel gas, fuel oil, or chemicals from fast pyrolysis. (Diebold and Bridgwater, 1997)
However, the efficiency of the thermal plant is very important for high yield of the desired product. Therefore, this work is to evaluate the efficiency of a developed thermochemical plant, and therefore determine its suitability for application in the thermal conversion of biomass. The results would be a readily useable tool for the prediction of reactor temperature for different efficiencies.

METHODOLOGY

A thermochemical plant of 17.4 litre capacity was developed. The plant is made up of the Furnace; the Thermal Reactor; The Electronic Control Unit; and the Condensing Unit. It can withstand a temperature of $1,200^oC$ and a pressure of 2.3 MN/m^2. The materials used for the furnace were evaluated for their Chemical Properties, Porosity, Bulk Density, Shrinkage, Thermal Shock Resistance, Slag Resistance and Cold Crushing Strength (Akinola, 2012; Akinola, *et al.*, 2013).

Biomass from seven tropical wood species were retrieved from sawmills across Akure, Nigeria. The wood species were: Obeche (*Triplochiton scleroxylon*); Iroko (*Melicia excelsa*); Danta (*Nesogordonia papaverifera*); Mahogany (*Khaya ivorensis*); Omo (*Cordia platythyrsa*); Mansonia (*Mansonia altissima*); and Afara (*Terminalia superba*). The actual volume converted to planks and the volumes of wastes (sawdust and slabs) were determined from the volume of wood processed in the sawmills.

The woods collected were prepared into 50 x 20 x 20 mm sizes and oven dried to 18% Moisture Content at 100^oC for 24 hours per batch. The dried samples were kept in polythene bags to prevent them from excessive humidity. Samples were withdrawn and tested for Volatile Matter, Ash Content, Fixed Carbon, Heating Values, Moisture Content, and Specific Gravity. The tests were conducted using the American Society for Testing and Materials Standards (ASTM 1993). Known densities of the wood species were used to calculate the mass of the wastes, and hence the energy content of the wastes. (Akinola, 2012; Akinola and Fapetu, 2015)
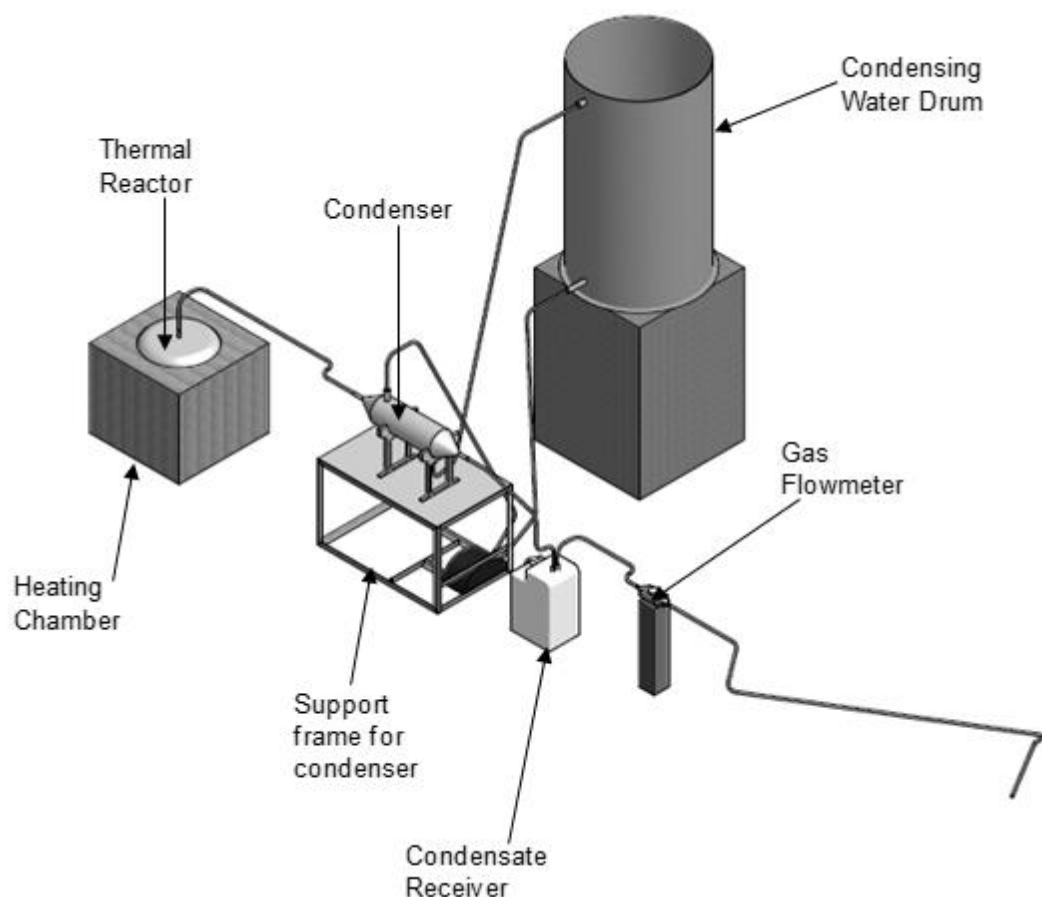
Fig. 1: Fixed-Bed Batch Pyrolysis Plant

RESULTS AND DISCUSSION
Reactor Efficiency Measurement

In the reactor, chemical-bound energy in the wood (fuel) is converted to thermal energy which becomes available in the form of hot flue gas. The reactor efficiency was calculated using the relation, (Ince, 1979; Quaak *et al*., 1999)

$$\eta_R = \frac{Calorific\ Value\ of\ gas\ /\ kg\ of\ fuel}{Average\ Calorific\ Value\ of\ 1\ kg\ of\ fuel} \times 100 \qquad (1)$$

where;

η_R is the Reactor Efficiency

With an average calorific value of 15.69 MJ/m^3 for the woods used (Akinola, 2012), the reactor efficiency was calculated for the varying reactor temperatures at which the reactor was tested. Results are as presented in Table 1.

Table 1: Reactor Efficiency (%) at generating Gas

Reactor Temperature ^{o}C	Volume of Gas (m^3)	Reactor Efficiency %
200	0.06	4.32
300	0.08	5.76
400	0.13	9.36
500	0.18	12.96
600	0.39	28.08
700	0.53	38.16
800	0.64	46.08
Average	**0.29**	**20.67**

A graph of the reactor efficiency was plotted against the varying reactor temperatures (Fig. 2). The graph shows that the efficiency of the reactor at generating gas increases with temperature, just as the volume of gas generated increases. (Fig. 3)

However, the efficiency was very low initially at temperatures between 200°C and 400 $^{\circ}$C because the volume of gas generated at these temperatures was low.
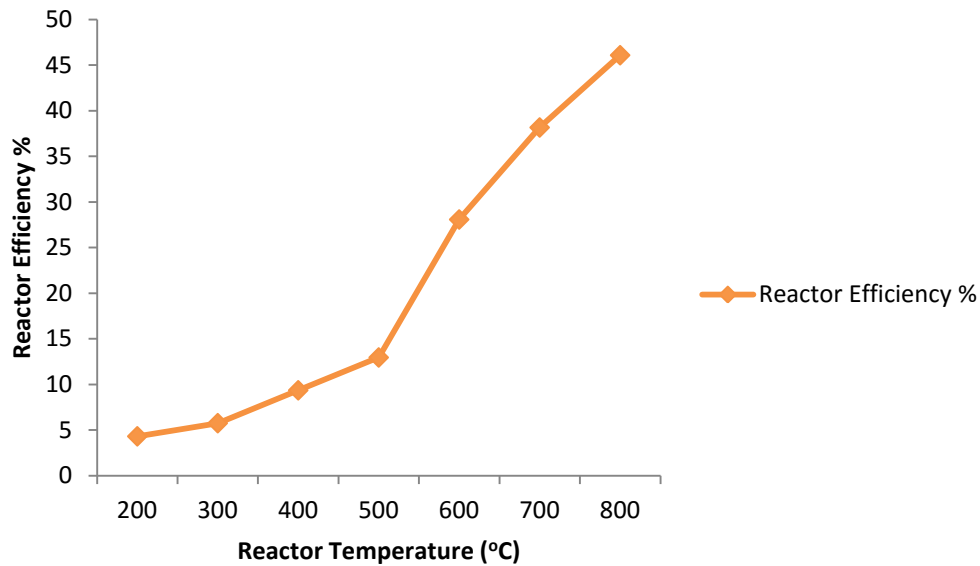

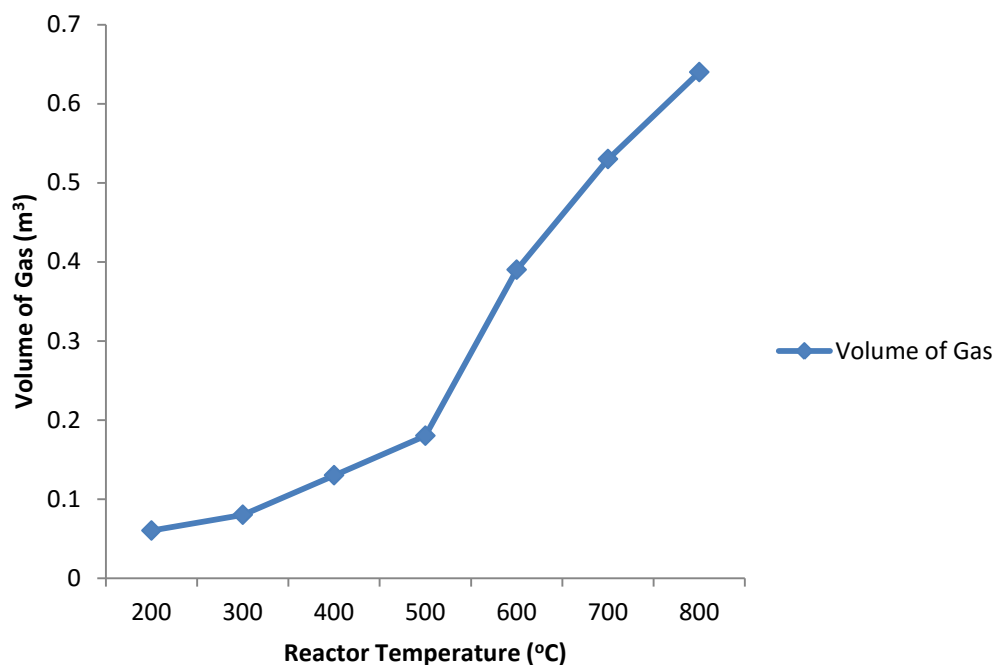**Fig. 2: Reactor Efficiency against Reactor Temperature**

Fig. 3: Volume of Gas against Reactor

Reactor Thermal Efficiency

The effectiveness of the reactor is governed by thermodynamic law. The law states that it is impossible to convert all heat completely into power. The limitations are quantified by Carnot efficiency, related to a theoretical cycle producing power from heat. When the heat is supplied at a constant high temperature (Reactor Temperature, θ_R), and released at a constant low temperature (Product Temperature θ_P), the thermal efficiency is given by as (Metcafe, 1972);

$$\eta_{R_{th}} = 1 - \frac{\theta_P}{\theta_R} \times 100 \qquad\qquad (2)$$

where $\eta_{R_{th}}$ is the Reactor Thermal Efficiency
        θ_P is the Product Temperature
        θ_R is the Reactor Temperature

The reactor's thermal efficiency was calculated using equation (1) and results are presented in Table 2.

Table 2: Reactor Thermal Efficiency

Reactor Temperature ^{o}C	Product Temperature ^{o}C	Reactor Thermal Efficiency %
200	30	85.0
300	30	90.0
400	33	92.0
500	36	92.8
600	39	93.5
700	42	94.0
800	47	94.1
	36.71	**91.6**

Fig. 3 shows the Reactor Thermal Efficiency plotted against the Reactor Temperature
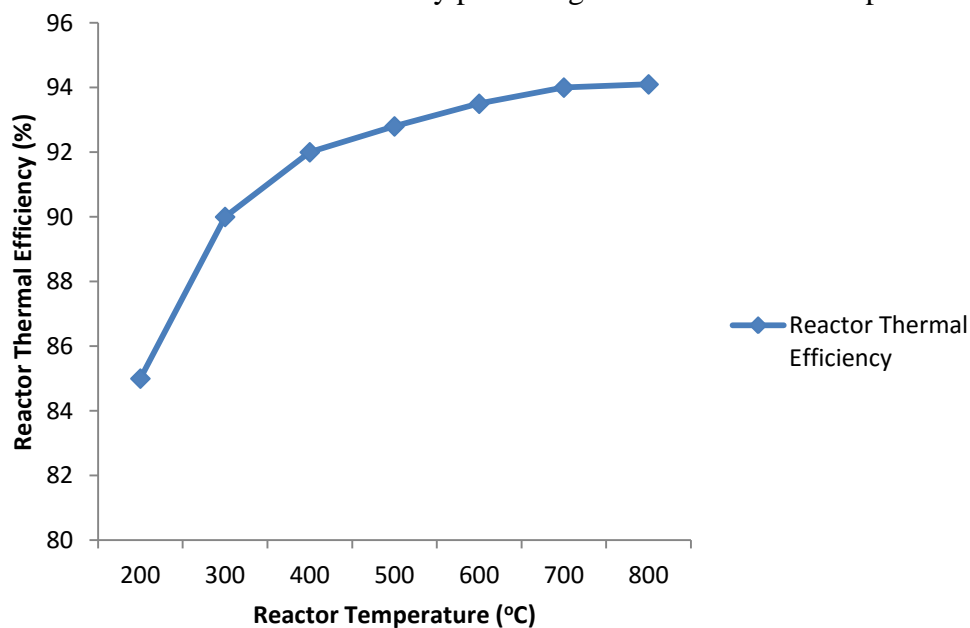

Fig. 3: Reactor Thermal Efficiency against Reactor Temperature

It was observed from the plots that the thermal efficiency increases rapidly with temperature up to about 600 ^{o}C when it became almost constant. This confirms the thermodynamic law upon which the effectiveness was based. The system has an average thermal efficiency of 91.6%.

Regression analysis using the least square method was carried out for three sets of data. These set of data are:

- (i)   The Reactor Temperature and Product Temperature
- (ii)   The Reactor Temperature and Reactor Efficiency
- (iii) The Reactor Temperature and Reactor Thermal Efficiency

In all cases, the reactor temperature was made the independent factor, and equations of the form below were used (Aderoba, 1995).

$$\theta_R = a + b\theta_P \qquad (3)$$
$$\theta_R = a + b\eta_R \qquad (4)$$
$$\theta_R = a + b\eta_{R_{th}} \qquad (5)$$

where

θ_R is the Reactor Temperature (^{o}C)

θ_P is the Product Temperature (^{o}C)

η_R is the Reactor Efficiency (%)

η_{Rth} is the Reactor Thermal Efficiency (%)

a & b are the parameters of regression equation.

The regression analysis results are summarized in Table 3. It shows the values of 'a' and 'b', as well as 'R', the coefficient of correlation for the three sets of data used.

Table 3: Results of Regression Analysis

Dependent	a	b	R
Product Temperature	-721.655	33.275	0.955
Reactor Efficiency	243.577	12.403	0.910
Reactor Thermal Efficiency	-4824.022	58.104	0.716

The analysis gives an 'R' value of 95.50% for Product Temperature, 91.00% for the Reactor Efficiency at generating gas, and 71.60% for the Reactor Thermal Efficiency. These give an overall average of 86.00% for the reactor.

The following trend equations were written;

$$\theta_{R_C} = -721.655 + 33.275\theta_P \qquad (6)$$
$$\theta_{R_C} = 243.577 + 12.403\eta_R \qquad (7)$$
$$\theta_{R_C} = -4824.022 + 58.104\eta_{R_{th}} \qquad (8)$$

These equations (6), (7) and (8) were used to calculate new reactor temperatures. Results obtained are presented alongside their corresponding experimental values in Table 4.

Table 4: Experimental 'θ_{REx}' and Calculated 'θ_{Rc}' Reactor Temperatures

Experimental Reactor Temperature 'θ_{Rex} ^{o}C'	Calculated Reactor Temperature 'θ_{Rc} ^{o}C'		
	Product	**Reactor Efficiency**	**Thermal Efficiency**
200.00	282.18	297.16	250.50
300.00	282.18	315.12	439.52
400.00	379.69	359.67	515.12
500.00	476.86	404.32	545.36
600.00	574.03	591.85	571.82
700.00	671.20	716.88	590.72
800.00	833.15	815.11	594.50

The calculated values follow the same trend as the experimental values. With this analysis, it is possible to predict at what reactor temperature a particular value of the product temperature, reactor efficiency at generating gas or thermal efficiency would be obtained using the relevant trend equations.
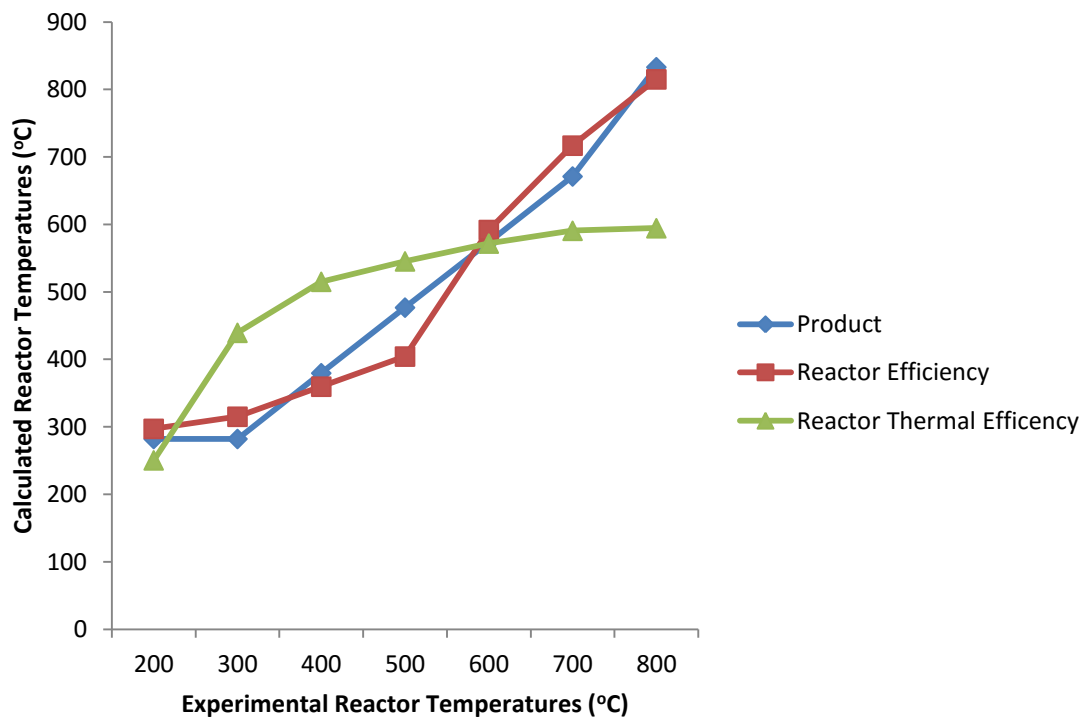
Fig. 4: Calculated Reactor Temperatures against Experimental Reactor

As shown in Fig. 4, the trend shows that the product temperature kept on increasing with increasing experimental temperatures. So also is the Reactor efficiency at generating gas. The higher the reactor temperature, the higher the reactor's efficiency to generate gas from samples.

CONCLUSIONS

The efficiency of a thermochemical plant was evaluated. There were highly significant linear correlation between the pyrolysis experimental temperatures and the calculated temperatures. The correlation coefficients of 95.50% for Product Temperature, 91.00% for the Reactor

Efficiency at generating gas, and 71.60% for the Reactor Thermal Efficiency. These give an overall average of 86.00% for the reactor. It can thus be concluded that the thermochemical reactor is highly efficient.

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