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OPTIMIZATION OF BIOCHAR PRODUCTION FROM BEECH WOOD PYROLYSIS

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Abstract: Application of biochar to soil is considered as a means of carbon sequestration which also enhances soil productivity by improving its nutrients. The process of production of biochar from forest wastes and residues on a large scale via pyrolysis requires some important variables to be optimized for overall process efficiency. In this work, beech wood pyrolysis model was developed, sensitivity analysis revealed that temperature and nitrogen flow has much effect on the yield while on particles size distribution has less effect. Then, optimization of the process was carried out. The model was developed in Aspen Plus software using user defined approach. The wood was defined as a non-conventional component using attributes from its proximate and ultimate analyses. The biochar was considered as a solid mainly made up of carbon. The optimization was carried out considering model constraints and maximization of biochar yield as objective function, while pyrolysis temperature and nitrogen flow rate were manipulated variables. Both lower and upper bound constraints were imposed on the optimizing variables. The results revealed that biochar yield increases with temperature decrease but increases along with nitrogen flow rate. The joint effect of both conditions give the highest biochar as 33.04 %wt. at temperature of 405.32^{o}C and nitrogen flow rate of 2968.83 kg/hr respectively.

Keywords: Aspen plus, Beech wood, Biochar, Objective function and Pattern search

1. Introduction

Biocharis a highly porous charcoal which consists of mainly carbon and ash obtained from vegetation substances by applying heat to remove the volatile constituents including water. Usually, biomass resources with little or no value such as bagasse, sawdust, wood, palm fronds, coconut shells and corn cobs, are used to produce biochar. In olden days, biochar has been used for many purposes including art, filtration and as fuel for heating homes and cooking. Biochar was also used in glass production and metal smelting for heating [1]. Coke has been employed as reducing agent in steel industry until recently replaced by fossil fuel resulting in emission of greenhouse gases [2] which causes increase in global warming. The use of biochar for heating and cooking is still practiced in developing countries, Nigeria inclusive. Biochar is also applied in the field of agriculture for various reasons. Biochar, when added to soil increases its fertility, displace certain amount of conventional fossil fuel

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based fertilizers and sequester carbon which may otherwise pollute our environment [3]. High surface area of biochar along its negative surface charge and charge density enhances the biochar nutrients holding capacity and became more stable compared to most fertilizers and other organic matters in soil [4]. It is relatively simple but powerful material to mitigate climate change by its application in agriculture for soil amendment [5].

So the use of sustainable and green form of fuel like biochar for heating in industries and its application in agriculture for soil enhancement will be helpful in curtailing the release of greenhouse gases contributing to global warming. This requires increase in production of biochar. In ancient times biochar was produced traditionally by burning wood logs in an uneconomical way. With the advent of technology various thermochemical processes such as pyrolysis and carbonization have taken over the traditional ways of producing biochar. Pyrolysis is the thermochemical breakdown of carbonaceous material in an oxygen deficient environment which leads to subsequent release of volatiles and formation of solid residue known as biochar. The yield of biochar depends on pyrolysis conditions and characteristics of feedstock.

Noumi *et al.* [2] carried out optimization of charcoal production from Eucalyptus wood using experimental results from pyrolysis of the wood. They used General linear model (GLM) for the study and reported that high temperature above 550°C, high pressure and low heating rate gives higher charcoal yield. Abid *et al.* [6] carried out optimization of biofuels from pyrolysis of Paper Mulberry and reported that the highest yield of biochar was obtained at 350ºC and 3 mm particle size. Ren *et al*. [7] reported optimization of bark pyrolysis to produce phenol-rich bio-oil using response surface methodology. They were able to find temperature of 485 ^{o}C and particle size of 0.35 mm as the optimum conditions. Wretborn [8] carried out an experimental optimization of charcoal yield from pyrolysis of fir wood chips and concluded that the optimum temperature that yielded higher charcoal (32 %) was 340 ^{o}C. Work on optimization of biochar production from beech wood is still unavailable. The objectives of this work are to model and simulate the pyrolysis of beech wood, and to determine those parameters that affect the yield of the process and their optimum values through numerical optimization.

2. Methodology

The study was carried out in three sequence. Beech wood pyrolysis model was developed and simulated, followed by sensitivity analysis and char yield optimization.

2.1 Model Development

Beech wood attributes (proximate and ultimate analysis), presented in Table 1 was used in this work. The components of the product stream are substances on the right hand side of Equation 1. Development of the process model was carried out using Aspen Plus software, version 8.4. Aspen Plus has no in-built pyrolysis reactor, so a make-shift reactor termed R Yield was designed to handle the process of pyrolysis. This was modelled as a non-stoichiometric reactor based on known yield distribution that decomposes the wood into various products as contained in Equation 1.

Table 1: Beech Wood Attributes

Ultimate analysis(%wt)		**Proximate analysis(% wt)**	
Carbon	49.2	Volatile matter	85.3
Hydrogen	6	Fixed carbon	14.3
Oxygen	44.1	Moisture	0
Nitrogen	0.5	Ash	0.4
Sulphur	0.02		

Source: Rabaçal *et al.*, 2014

$$Wood \xrightarrow[heat]{} Char(carbon)_{solid} + (C_6H_6, CH_3OH, CH_3COOH, \ldots)_{liquid} + (CO_2, CO, CH_4, C_2H_{6,} \ldots)_{gas} \quad 1$$

Model Assumptions

- Steady state operation was considered
- The temperature in each block was considered uniform with negligible heat losses
- The char is virtually made up of carbon

Beech wood does not exist in the software's library, so it was considered non-conventional component using its proximate and ultimate analysis as presented in Table 1 to define its properties, while the rest of the components were defined as conventional compounds from the software's library. In choosing the property package, RK-Soave equation of state was used to correlates the properties of the model components. This equation of state is used when a process contains real gases. R Yield was used to represents the pyrolysis reactor which allows the decomposition of the beech wood into elemental components that is; C, H, N, S, O and Ash. The elemental components were recombined to form char, liquid and gases in RGIBBS reactor fed with nitrogen to aid volatiles separation from char and prevent combustion reaction as well. Table 2 presents the operating parameters of the R Yield. Pyrolysis product separator was modeled as CYCLONE (SEP) to separate the product from the RGIBBS reactor into volatiles and char. GASCOOL, modeled as condenser quenches the condensables into liquid (bio-oil). GASSEP was used to separate bio-oil from the non-condensable gases. The complete pyrolysis model built in the simulation environment is depicted in Figure 1.

Table 2: PYRO-RE Inputs

Operating Conditions	
Feed flow rate	100 kg/hr.
Pyrolysis temperature	450 °C
Pyrolysis Pressure	1 atm
Nitrogen gas flow rate	500 kg/hr

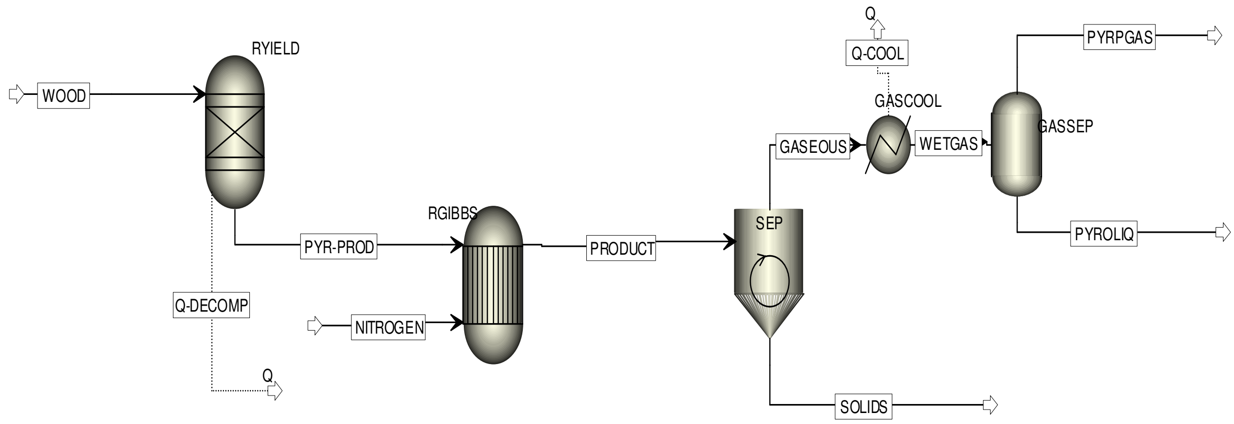

Figure1: Flowsheet of Beech Wood Pyrolysis

2.2 Sensitivity Analysis

Sensitivity analysis was performed on the model to check the influence of temperature and nitrogen flow on biochar yield. Pyrolysis temperature was chosen as a block variable which was varied from 400 °C to 700 °C based on Wretborn, (2016) which reported that wood pyrolysis normally happens within a temperature range of 400 °C – 650 °C and PYRO-RE was selected as the block.

2.3 Optimization

The optimization approach used in this work is outlined here. Complex method was used for convergence, which uses the well-known Complex algorithm, a feasible path "black-box" pattern search. The method can handle inequality constraints and bounds on decision variable. It frequently takes many iterations to converge, but does not require numerical derivatives which is a hiccup to optimizing many complex processes.

Pattern search

Pattern search, also known as direct or Blackbox search, is a numerical optimization method that does not require derivative of the problem. As such it can be applied on functions that are not continuous or differentiable. It utilizes the theory of positive bases for convergence (Yu, 1979).

The method makes use of values of the objective function $F(x), x \in R_n$without derivatives, and they are designed to have the following convergence property. If all level sets of the form $\{x: F(x) \leq F(x_j)\}$ are bounded, and if F has a continuous first derivative, then, assuming exact arithmetic and an infinite number of iterations, the condition:

$$\lim\inf\{\| \{\nabla F(x_j)\|: j = 1, 2, 3, \ldots\} = 0 \quad (2)$$

is achieved, where $\{x_j: j = 1, 2, 3, \ldots\}$is the set of points at which F is calculated.

The method is suitable for this optimization problem as the model contain bounds on the manipulated variables and inequality constraints.

The Optimization Equations

$$\max_{T,F_N} \ bCYield = f(T, F_N) \quad (3)$$

$$g(W, T, F_N) = 0$$

s.t. $400 \leq T \leq 650$

$$500 \leq F_N \leq 3000$$

$$bCYield = \frac{char\ flow}{Wood\ flow} * 100 \quad (4)$$

where *bCYield* which represents biochar Yield is the objective function and is a function of temperature, T in degree celcius, and nitrogen flow, F_N in kg/hr which are linked through the model equations in (3), W is the wood flow rate in kg/hr, C_F is the biochar flow and is a function of wood in kg/hr. The model equations which are equality constraints are represented by a vector of functions, **g**.

3. Results and Discussion

The results of the simulation shows that the biochar yield from the wood pyrolysis was 33.04 % at 400 ^{o}C and 550 kg/hr nitrogen flow. Sensitivity analysis carried out on the model revealed that pyrolysis temperature and nitrogen flow influence the biochar yield. The biochar flow decreases with increase in temperature at constant nitrogen flow as depicted in

Figure2. Three regions are distinguishable from this Figure: First region (200 – 375 ^{o}C), the decrease is fast, this might be due to the escape of the entrapped volatile within the char. Between 375 – 400 ^{o}C a more or less steady region is observed as the remaining content are mostly solid biochar and finally a very fast decreasing region (400 – beyond) may be resulted from further burning of the char which is mainly Ash and carbon to produce carbon dioxide. Variation of char yield with nitrogen flow is shown in Figure 3.

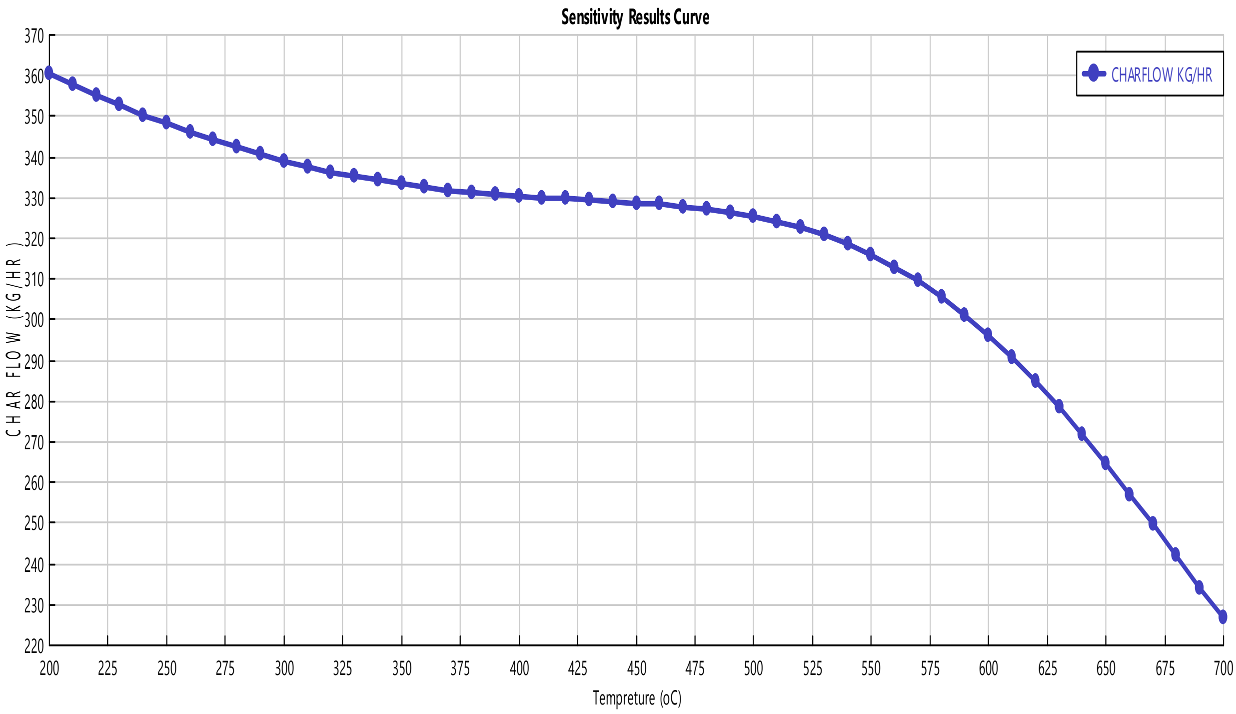

Figure 2: Char yield at different temperatures

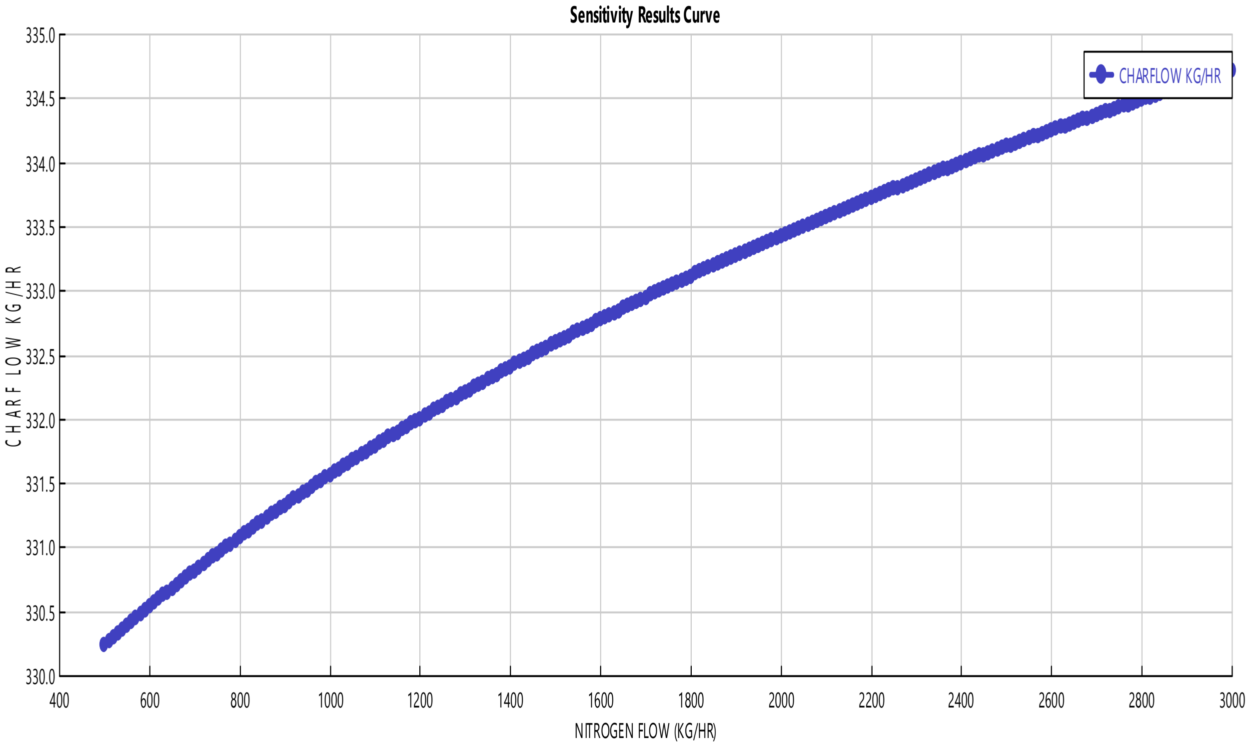

Figure 3: Char yield at different nitrogen flow

Varying the nitrogen flow while keeping temperature constant indicated increase in char yield with nitrogen flow which shows that nitrogen help in preventing combustion of the char. Optimization of the model shows that 33.4 %wt. highest yield of biochar was obtained at a temperature of 405.318^{o}C and nitrogen flow rate of 2968.831 kg/hr respectively. This shows that the optimum yield was just 1.12 % above the nominal yield, 33.03%.

4. Conclusion

Beech wood pyrolysis has been modelled and simulated. The effects of temperature and nitrogen flow were studied and optimization carried out. It can be concluded that: Biochar yield decreases with temperature increase but increases with increase in nitrogen flow, highest biochar yield was obtained at temperature of 405.318 ^{o}C and nitrogen flow rate of 2968.831 kg/hr respectively where 33.4 % of the feed wood was converted to biochar. This shows that the combined influence of pyrolysis temperature and nitrogen flow has relatively little effect on the char yield.

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