

Conversion of Mixed Waste of Wood and Plastic to Clean Fuels Using Pyrolysis in Nigeria – Numerical Study

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Abstract - Waste management is a major challenge in Nigeria, where around 32 million tons of waste is generated annually including 13 million tonnes of agricultural waste and 2.5 million tons of plastic waste. Currently, the waste management system is very inefficient where almost 70% of the waste ends up in landfills, sewers, beaches and water bodies causing serious environmental and health problems. This work numerically investigates the conversion of mixed wastes (wood and plastics) to produce clean and affordable solid, liquid and gaseous fuels that can be used for cooking, heating and electricity generation.

Pyrolysis process which involves heating the waste at different rates in the absence of Oxygen has received significant research interest since it can convert various types of waste to clean fuels thus reducing fossil fuel consumption and CO₂ emission. For example, wood waste can be converted to high-quality syngas, oil, and char while plastic waste can be converted to high-quality syngas, oil, light and heavy waxes. Also, it generates lower emissions compared to other waste conversion processes such as combustion, gasification, and plasma treatment.

In this study, a numerical model is developed to simulate the pyrolysis process of mixed wood and plastic waste materials to predict the outputs in terms of char, syngas, oil and wax production. The model is based on the kinetics of the reactions associated with wood and plastic when subjected to different heating rates from 320 to 923 Kelvin for 20 minutes. Results showed that for 1kg of mixed waste (30% plastic and 70% wood) and after 20 minutes of heating, the output consists of 50.13% syngas, 8.35% oil, 9.5% char, 10.8% light Wax and 8.33% heavy wax. This modelling allows for controlling the output composition based on varying the input waste constituents which can optimize the waste conversion process.

Keywords: Pyrolysis, Mixed Waste, Modelling, Clean energy.

1. Introduction

Nigeria is a developing agricultural country which generates huge amount of agricultural waste reaching 13 million tonnes per year where significant amounts of this waste are either left to rot or burned in open fields causing significant air pollution [1]. The most common agricultural wastes are maize cobs, husks, and stalks (62.5 percent) and cassava stalks and peels 60 percent[2]. Also, in urban cities there is an increasing amount of waste with heavy plastic of around 2.5 tons of plastic waste per year [3]. Currently, the waste management system is very inefficient where almost 70% of the waste ends up in landfills, sewers, beaches and water bodies causing serious environmental and health problems[4].

Pyrolysis has been developed since the 1970s [5] which is an advanced thermochemical conversion process of carbonic feedstock in the absence of oxygen to produce bio-fuel (oil, char, and fuel gases) [6]. This process can reduce greenhouse gas emissions and contribute to energy security. There are three types of pyrolysis [7]. Slow pyrolysis: this is the slow heating rate process between (5–7 K/min) which mainly produce char and low liquid and gaseous products. Fast pyrolysis: in this process, the material heating rate is high 650 K for 5 s and it produces mainly liquid fuel. In the flash process, the material is briskly heated for few seconds or even less produce pyrolysis oil. The quality and the stability of the generated oil are influenced by the char or ash content of bio-oil. Various studies have been conducted to model the slow process of various wastes. Koufopoulos et al. [8] established the kinetic model of the pyrolysis of biomass and its constituents to develop an

efficient pyrolyzer. Koufopoulos and Papayannakos [9] studied the kinetics coupled with thermal and heat transfer effects and concluded that the pyrolysis can be applied for a wide range of heating rates 573 K to 873 K and particle sizes from 1mm to 20 mm. Kabir et al. [6] presented a numerical and experimental analysis about the pyrolysis of green waste process showing that around 19.972 % bio-oil, 40.83 % bio-char, and 29.77 % syn-gas can be generated.. Miljković et. al [10] built a mathematical model of single-particle biomass under the pyrolysis process and compared the results with experimental measurements and other different types of wood samples, the ultimate analyses for the composition have been reported. Dubdub and Al-Yaari [11] investigated the kinetics of mixed plastic waste. Their results showed that using a single thermal degradation stage, the pyrolysis of pure polymer samples happens in the following order: PS, PP, LDPE, and HDPE. Andersen et al. [12] simulated the pyrolysis process of plastic waste to produce environmentally friendly fuel. The above literature indicates that most of the research was conducted on wood samples or plastic samples separately. Therefore, there is a need to develop models to simulate the pyrolysis process for converting mixed wastes to clean fuels. In this study, a numerical model for simulating the pyrolysis of mixed waste consisting of wood and plastic using the Ordinary Differential Equations (ODEs) solver in MATLAB to predict the outputs in terms of syngas, char, oil, light and heavy waxes.

2. Model Description

This model aims to simulate the pyrolysis process for converting heavy plastics and wood to clean fuels including syngas, oil and charcoal. It uses the kinetic equations of heavy plastic and wood subjected to different heating rates from 320 K to 923K. Eq. 1 to Eq. 8 represents the kinetic reactions for wood where Eq. 1 describes the initial concentration of wood. After applying the heat, the gas starts to be produced as shown in Eq. 2. At the same heating rate Eq. 3 reveals the amount of char produced from the same sample. Then during the second phase reaction, the same outputs occur as in Eq. 4 and Eq. 5. The auxiliary equations 6-8 are used to determine the values of the reaction constants related to the wood sample with Table 1 listing the required input parameters.

$$\frac{\partial C_w}{\partial t} = -k_{w1} \cdot (C_w)^{n1} - k_{w2} \cdot (C_w)^{n1} \quad (1)$$

$$\frac{\partial C_{gas1}}{\partial t} = k_{w1} \cdot (C_w)^{n1} - k_{w3} \cdot (C_{gas1})^{n2} \cdot (C_{char1})^{n3} \quad (2)$$

$$\frac{\partial C_{char1}}{\partial t} = k_{w2} \cdot (C_w)^{n1} - k_{w3} \cdot (C_{gas1})^{n2} \cdot (C_{char1})^{n3} \quad (3)$$

$$\frac{\partial C_{gas2}}{\partial t} = k_{w3} \cdot (C_{gas1})^{n2} \cdot (C_{char1})^{n3} \quad (4)$$

$$\frac{\partial C_{char1}}{\partial t} = k_{w3} \cdot (C_{gas1})^{n2} \cdot (C_{char1})^{n3} \quad (5)$$

$$k_{w1} = A_{w1} \cdot e^{\left(\frac{D_1}{T} + \frac{L_1}{T^2}\right)} \quad (6)$$

$$k_{w2} = A_{w2} \cdot e^{\left(\frac{D_2}{T} + \frac{L_2}{T^2}\right)} \quad (7)$$

$$k_{w3} = A_{w3} \cdot e^{\left(\frac{-E_3}{T \cdot R_c}\right)} \quad (8)$$

Where C_w, C_{gas}, C_{char} are concentrations for Wood, gas, char respectively.

Eq. 9 to Eq. 13 represents the kinetic reactions for heavy plastics, where Eq. 9 represents the initial plastic concentration. After applying the heat, the light wax starts to form first which is represented in Eq. 10. At the same heating rate, Eq. 11 determines the amount of heavy wax produced from the same sample. Then, Eq.12 gives the oil production while Eq.13 determines the amount of the produced gas. The values of the reaction constants related to the plastic sample at 713 Kelvin plastic are shown in table 2.

$$\frac{\partial C_p}{\partial t} = -k_{p1} \cdot C_p - k_{p2} \cdot C_p - k_{p3} \cdot C_p - k_{p4} \cdot C_p \quad (9)$$

$$\frac{\partial C_{LW}}{\partial t} = k_{p1} \cdot C_p - k_{p6} \cdot C_{LW} - k_{p5} \cdot C_{LW} \quad (10)$$

$$\frac{\partial C_{HW}}{\partial t} = k_{p4} \cdot C_p - k_{p8} \cdot C_{HW} - k_{p9} \cdot C_{HW} \quad (11)$$

$$\frac{\partial C_{oil}}{\partial t} = k_{p2} \cdot C_p - k_{p5} \cdot C_{HW} - k_{p9} \cdot C_{HW} - k_{p7} \cdot C_{oil} \quad (12)$$

$$\frac{\partial C_{pgas}}{\partial t} = k_{p3} \cdot C_p - k_{p6} \cdot C_{LW} - k_{p7} \cdot C_{oil} - k_{p8} \cdot C_{HW} \quad (13)$$

Table 1: Model inputs for wood.

Parameter name	value
Wood density (ρ_0)	650 [kg/m ³]
Reaction constant(A_1)	9.973×10^{-5} [1/s]
Reaction constant(A_2)	1.068×10^{-3} [1/s]
Reaction constant(A_3)	5.7×10^5 [1/s]
Reaction constant(L_1)	-9061227 K ²
Reaction constant(L_2)	-6123081 K ²
Activation energy(E_3)	81000 J/mol
Reaction order (n_1)	1
Reaction order(n_2)	1.5
Reaction order(n_3)	1.5
Applied Temperature range(T)	[320:923] [Kalvin]

Table 2: Estimated rate constants at 713 Kelvin for plastic [13].

Parameter name (The rate constants of the reactions)	value
k_{p1}	0.170488
k_{p2}	2.43E-08
k_{p3}	0.0301269
k_{p4}	0.206132
k_{p5}	0.0146288
k_{p6}	0.0103907
k_{p7}	2.25E-14
k_{p8}	0.0204982
k_{p9}	3.48E-10

Figure 1 illustrates the structure of the pyrolysis for the mixed waste of heavy plastic and wood, while figure 2 shows the applied heat rates for this process.

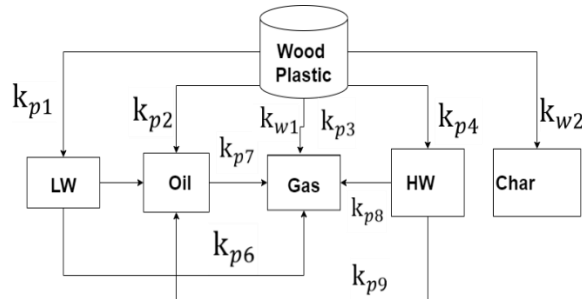


Fig. 1: Model structure.

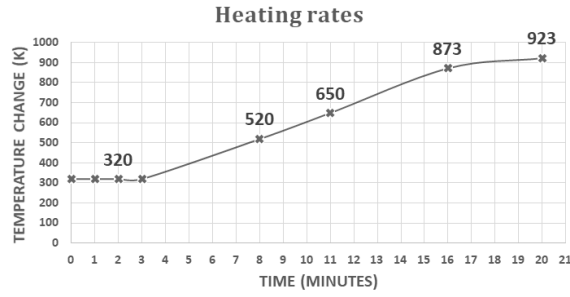


Fig. 2: Applied heating rates.

The total volume of gas generated from the pyrolysis of wood and heavy plastics by combining Eq. 2, Eq. 4, and Eq. 13 as shown in Eq. 14:

$$\frac{\partial C_{Wpgas}}{\partial t} = k_{w1} \cdot (C_w)^{n1} + k_{p3} \cdot C_p - k_{p6} \cdot C_{LW} - k_{p7} \cdot C_{oil} - k_{p8} \cdot C_{HW} \quad (14)$$

Fig. 3 shows the model output in terms of the wood sample mass change with time as subjected the heating rate shown in Fig. 2 compared to the results of Miljkovi et. al. [10]. It can be seen that the model predicted the published experimental results with maximum error of 13.5%.

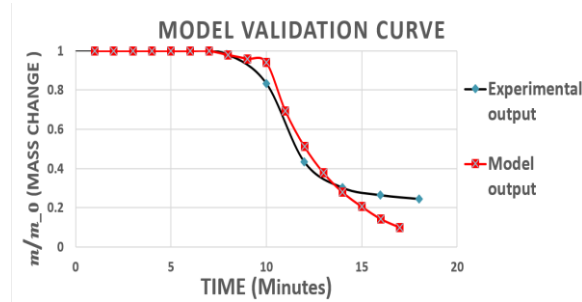


Fig. 3: Model validation with published experimental data.

3. Results And Discussion

Fig. 4 shows the percentage yield of the pyrolysis process of a mixed waste consisting of 300 grams of plastic and 700 grams wood using the heating rates shown in Fig. 2 for a period of 20 minutes. It can be seen that during the first 11 minutes, the wood showed no change in its behaviour, while the plastic started to degrade. Table 4 shows that using one kg of mixed waste composed of 300 grams plastic and 700 grams wood will produce 50.13% syngas, 8.35% oil, 9.5% char, 10.8% light Wax, and 8.33% heavy wax. Although light and heavy waxes are not fuels but they have other useful applications like their significance stems from the distinct properties that they impart to these formulations. Waxes, for example, can minimize the viscosity of a hot melt adhesive, add lustre to an ink or fruit coating emulsion, serve as a lubricant through the fabrication of PVC pipes, or impart desirable buff ability, gloss, and toughness properties to emulsion paste polish or a solvent., G. Webber[14].

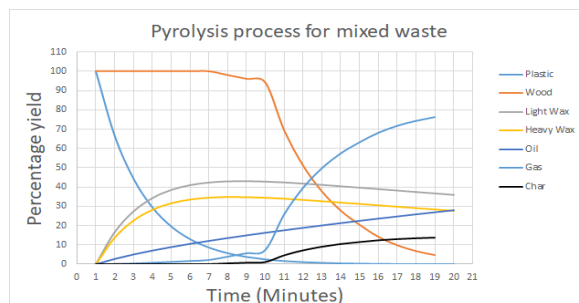


Fig. 4: Model output Time vs percentage yield.

Plastic 300 grams	Plastic outputs grams	Wood 700 grams	Wood outputs in grams	1000 grams (Mixed waste)
LW=36.15%	108			10.8%
HW=27.75%	83.25			8.33%
Oil =27.82%	83.46			8.35%
Gas=8.25%	24	Gas=68.19%	477.33	50.13%
		Char=13.55%	94.85	9.5 %

Conclusion

Nigeria is an agricultural developing country with huge amount of waste including 13 million tonnes per year of agricultural waste where significant amounts of this waste are either left to rot or burned in open fields causing significant environmental damage. Also, in urban cities there is an increasing amount of waste where heavy plastic represents a significant amount. In this work, a numerical model for the pyrolysis process of mixed waste consisting of heavy plastic and wood was developed using MATLAB software and the built-in solver for ODEs to predict the amount of clean fuel produced in terms of syngas, oil and char. The results of the model using wood were compared to published results showing good agreement with maximum deviation of 13.5%. Using one kg of mixed waste composed of 300 grams plastic and 700 grams wood, the model shows that 50.13% syngas, 8.35% oil, 9.5% char, 10.8% light Wax, and 8.33% heavy wax can be produced. Results also shows that mixed waste pyrolysis has the potential to manage the wood and plastic waste in Nigeria, improve the environment and generate clean fuels like syngas, oil and charcoal.

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