CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791

A publication of

AIDIC

The Italian Association of Chemical Engineering

Online at: www.aidic.it/cet

DOI: 10.3303/CET1229117

Kinetic Modelling and Analysis of Waste Bamboo Pyrolysis

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In Asia, bamboo is mostly used for scaffolding because of its versatility, durability and being eco-friendly. About 50,000 t of bamboo waste are generated annually in Hong Kong. The abundance of bamboo in Asia and other parts of the world as well as its fast rate of replenishment have resulted in a global interest in bamboo as a wood substitute. To further utilise the growing waste, pyrolysis which is a promising technology for tackling waste disposal can be employed. To fully design a pyrolysis process for waste bamboo, the mass loss and heat flow kinetics as well as the effect of the various operating parameters must be known. The objective of this work therefore is to model the pyrolysis of waste bamboo and to study experimentally the effect of different operating strategies during the pyrolysis process. The influence of feed particle size, mixed – size, heating rate and target temperature on the processing time and energy usage are discussed in the study. The detailed results and analysis are presented including the overall energy usage and the processing rates.

1. Introduction

Large quantities of construction wastes are generated annually in Hong Kong and due to the foreseen expansion in the construction industry, the amount are expected to increase in the future. One of the components of construction waste is bamboo waste. Bamboo is majorly used for scaffolding in Hong Kong because of its versatility, durability and being eco-friendly. Bamboo is known as a cheap and fast grown resource which offers great potential as an alternative to wood. About 50,000 t of waste bamboo are deposited in landfill site in Hong Kong annually (Choy et al., 2005) and due to the limited landfill site in the City, alternative ways of utilizing the wastes are necessary.

Pyrolysis, a thermo-chemical process is an efficient means with less emission to produce valuable products from waste bamboo. In the literature, most emphasis has been on the production of activated carbon from waste bamboo and very few emphasized its use in producing valuable liquid fuel or used as feedstock in gasification for energy generation. Pyrolysis can be a pre-cursor for gasification or other thermo-chemical processes. In order to design a pyrolysis process for waste bamboo, it is highly essential to understand how the processing conditions and feedstock characteristics influence the process and this can in turn help to optimize the thermal conversion of the feedstock.

The objective of this study is to model the pyrolysis of waste bamboo and to study experimentally the effect of different operating strategies during the pyrolysis process. The influence of feed particle size, mixed – size, heating rate and target temperature on the processing time, energy usage and product quality are discussed.

Please cite this article as: Oyedun A. O., Lam K.-L., Gebreegziabher T., Lee H. K. M. and Hui C.-W., (2012), Kinetic modelling and analysis of waste bamboo pyrolysis, Chemical Engineering Transactions, 29, 697-702

2. Methodology

2.1 Experimental Study

Waste bamboo samples were collected from a construction site inside the campus of Hong Kong University of Science and Technology. The samples were washed and dried in an electric oven at 110 ^oC for one week. The dried samples were crushed and sieved to powder form of size less than 600μm. Thermogravimetric and differential thermal analysis (TGA/DTA) were performed on the samples using the machine TGA/DTA 92 Setaram II. The experiment was carried out in an isothermal condition and four heating rates of 5, 10, 20 and 30 ^oC/min were employed. The samples were heated from room temperature to 800 ^oC in a nitrogen-purge environment; the purity of the flowing gas is UHP grade 99.99 %. Different samples weights were employed for the experiment ranging from 2 mg – 8 mg.
The result from the TGA analysis was used to study the effect of process parameters (heating rate, sample weight and final target temperature) on the performance of the waste bamboo pyrolysis.

2.2 Modelling Study

A pyrolysis model for waste bamboo was developed to simulate the pyrolysis progress of a bulk particle. The model is an upgrade of the pyrolysis model in our earlier works (Cheung et al., 2011; Lam et al., 2011; Oyedun et al., 2012) with the addition of a particle shrinking model and a simple reactor model. The following assumptions were made when constructing the model:

1. The shape of the pyrolysis waste bamboo is spherical.
2. Volatiles leaving the particle do not interfere directly with the pyrolysis gas.
3. Temperature gradients are along the radial position only.
4. Conduction is the only mode of heat transfer within the particle.
5. The only form of inter-particle interaction is heat transfer.

Table 1: Pyrolysis model equations

Equations	Numbers
$\frac{d\alpha_i}{dt} = A_i \exp\left(-\frac{E_i}{RT}\right)(1-\alpha_i)^{n_i}$	(1)
$\frac{d\gamma_j}{dt} = A_j \exp\left(-\frac{E_j}{RT}\right)(1-\gamma_j)^{n_j}$	(2)
$\alpha_T = \sum_i \omega_i \alpha_i$	(3)
$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial t^2} + \frac{2}{r}\frac{\lambda}{\rho C_p}\frac{\partial T}{\partial r} + \frac{1}{C_p}\sum_i\left(H_i \frac{\partial \alpha_i}{\partial t}\omega_i\right) + \frac{1}{C_p}\sum_j\left(H_j \frac{\partial \gamma_j}{\partial t}\right)$	(4)
$C_{p,p} = \frac{(\alpha_{T,f} - \alpha_T)}{\alpha_{T,f}} C_{p,f} + \frac{\alpha_T}{\alpha_{T,f}} C_{p,c}$	(5)
$\lambda = \frac{(\alpha_{T,f} - \alpha_T)}{\alpha_{T,f}} \lambda_f + \frac{\alpha_T}{\alpha_{T,f}} \lambda_c$	(6)
B.C. 1: $-\lambda \frac{\partial T}{\partial r} = h(T_R - T_{bulk})$	(7)
B.C. 2: $\frac{\partial T}{\partial r}\Big\|_{r=0} = 0$	(8)
$\frac{dV}{dt} = -V_0 \frac{d\alpha_T}{dt}(1-\delta)$	(9)
$m_{bulk} = \rho_g \left[\bar{V}_0\left(\frac{\nu}{1-\nu}\right) + (\bar{V}_0 - \bar{V})\right]$	(10)
$m_{bulk} C_{\rho,g} \frac{\partial T_{bulk}}{\partial t} = C_{\rho,g} \frac{\partial m_{inlet}}{\partial t}(T_{inlet} - T_{outlet}) + \frac{\partial Q_p}{\partial t}$	(11)
$Q_T = m t_T C_{\rho,g}(T_{inlet} - T_{ambient})$	(12)

The pyrolysis model equations are presented in Table 1. Eqs. 1 – 3 represent the kinetic model, the heat transfer model is represented by Eqs. (4) – (8) and the particle shrinkage as well as the reactor model equations are presented in Eqs. (9), and (10) – (12) respectively.

The pyrolysis model describes transiently the pyrolysis progress of particles within the reactor and subjected to certain pyrolysis condition. In the pyrolysis reactor, heating gas flows in and contact with the particle feedstock thereby operating like a batch reactor.

3. Results and Discussions

3.1 Experimental and process parameters study

Thermogravimetric analysis (TGA) is known as a high-precision method usually used for the study of pyrolysis at low-heating rates, under well-defined conditions. A study of feedstock composition can be beneficial in order to understand the variations in the TG profile. In the study of Bamboo composition by Scurlock et al. (Scurlock et al., 2000), bamboo contains cellulose (43.3 %), hemicellulose (24.6 %) and lignin (26.2 %) The decomposition temperature is given as 200 – 260 ^{o}C for hemicellulose, 240 - 350 ^{o}C for cellulose and 280 - 900 ^{o}C for lignin (Park et al., 2010). In waste bamboo pyrolysis, there exists a pre-pyrolysis phase between 80 – 160 ^{o}C and this phase is responsible for the removal of moisture and volatile extractives. The process parameters such as sample weight, heating rate and final pyrolysis temperature can affect the condition and quality of the pyrolysis products.

3.1.1 Effect of sample weight

The effect of sample weight on waste bamboo pyrolysis was studied at low heating rate of 10 ^{o}C/min. Figure 1 shows the TG profiles at different initial sample weight. The result shows that mass residue increases as the sample weight increases. All the sample weight showed the same trend for temperature below 380 ^{o}C but changes significantly as the temperature increases above 380 ^{o}C. This result further shows the importance of sample weight during the pyrolysis of waste bamboo and it can be concluded that the mass transfer barrier becomes more significant as sample weight increases.

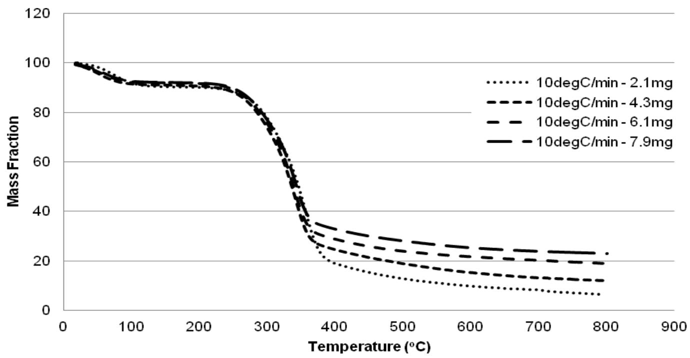

Figure 1: TG profiles of bamboo with different sample masses at heating rate of 10 °C/min.

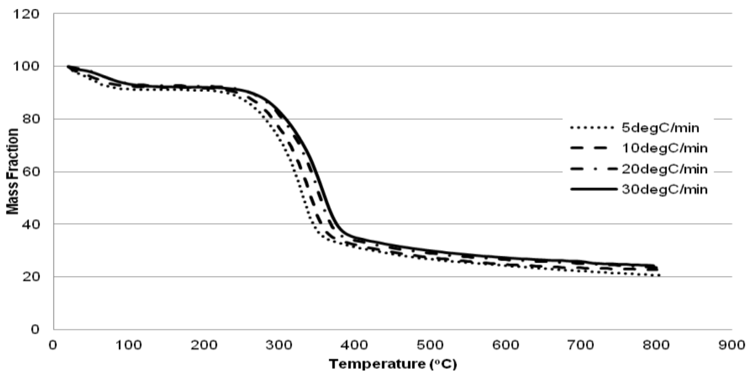

Figure 2: TG profiles of bamboo at different heating rates

Table 2: Mass Residue at different heating rates and different target temperatures

Heating rates	Final Target Temperature		
	400 ^{0}C	600 ^{0}C	800 ^{0}C
5 ^{0}C/min	0.31332	0.24272	0.20608
10 ^{0}C/min	0.32356	0.24721	0.22692
20 ^{0}C/min	0.33870	0.26572	0.23647
30 ^{0}C/min	0.34932	0.27304	0.24280

3.1.2 Effect of heating rates and final pyrolysis temperature

A slow heating rate is usually employed for biomass particles to avoid the problem of thermal lag or temperature gradient occurring between sample and the heating device which is one of the main problems of the combined effect of the chemical reactions and transport phenomena in kinetic analysis (Weerachanchai et al., 2010). The effect of heating rates and final pyrolysis temperature was studied at different heating rates and at same sample weight of 8 mg. As expected, the mass loss curve shifts towards the right (higher temperature) as the heating rate increases from 5 ^{o}C/min to 30 ^{o}C/min which is also observed in other biomass (Williams and Besler, 1996).

The residue fraction of the waste bamboo at different heating rates and target temperatures is presented in Table 2. The result shows a trade-off between the mass residue and the target temperature. More devolatilization takes place as the target temperature increases and can still increase more than 800 ^{o}C though at a lower rate but it is expected to consume more energy and subsequently increase the processing time of the pyrolysis.

3.2 Modelling and Operating strategy study

The particle model equations in Table 1 were built on MATLAB® platform using the finite difference method (FDM). The energy equation, equation (4) was solved numerically using the Crank–Nicolson implicit scheme (Crank and Nicolson, 1996). The model parameters are summarized in Table 3, though the value for wood were used in some cases because of unavailability of data for waste bamboo and the shrinking factor (δ) for the waste bamboo was estimated from the laboratory-scale pyrolysis of waste bamboo particle.

Table 3: Model Parameters

Model Parameters	Value	Ref.
Initial density of bamboo, ρ (kg/m^3)	800	(Jain et al., 1992)
Specific heat capacity of heating gas, $C_{p,g}$ (J/kg-K)	2400	(Yang et al., 1995)
Thermal conductivity of wood, λ_f (W/m-K)	2380	(Ahuja et al., 1996)
Thermal conductivity of char, λ_c (W/m-K)	1600	(Ahuja et al., 1996)
Specific heat capacity of wood, $C_{p,f}$ (J/kg-K)	0.158	(Ahuja et al., 1996)
Specific heat capacity of char, $C_{p,c}$ (J/kg-K)	0.107	(Ahuja et al., 1996)
Convective heat transfer coefficient, h (W/m^2-K)	5.69 + 0.0098T	(Ahuja et al., 1996)
Reactor void space factor, ν	0.8	-
Shrinking factor for bamboo pyrolysis, δ	0.859	-

3.2.1 Particle size study

Processing time and energy usage during the pyrolysis of waste bamboo can vary a lot with different particle size because of the low thermal conductivity of biomass. In this study, 1 tonne of waste bamboo particles containing 50 % by mass each of smaller particles with radius of 1cm and larger particles with radius of 2.5 cm were pyrolysed with 800 ^{o}C heating gas at the rate of 1 kg/s. In the first scenario, the two particles were pyrolysed individually using 50 % of the heating gas each and in the second scenario, the two particles were pyrolysed together. The simulation results are presented in Table 4 and the mass loss fraction of the two types of waste bamboo particles as the pyrolysis progress is shown in Figure 3.

Mixed-size particle pyrolysis is a strategy that can be applied in pyrolysis because of the difficulty in sorting waste into different sizes. Based on the result in Table 4, the energy usage for mixed-size strategy is lower than that of the individual pyrolysis though have to be compensated by low processing rate since for the individual pyrolysis case, smaller particles would finish the pyrolysis faster than larger particles. So in operating a waste bamboo pyrolysis process, feedstock with broad size range can be used but processing rate might be lower than expected.

Table 4: Simulation results for particle size study

Strategy	Energy Usage (MJ/kg)	Processing time (h)	Processing rate (kg/h)
Individual pyrolysis	6.85	1.045(average)	988
mixed-size pyrolysis	6.52	1.031	970

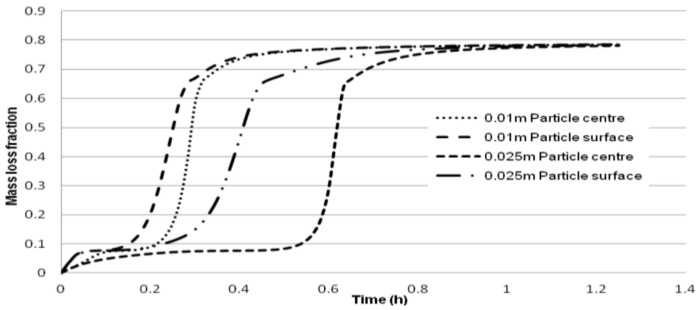

Figure 3: Mass loss fraction of smaller and larger particles in mixed-size pyrolysis.

3.2.2 Effect of heating gas temperature on Processing time and Energy Usage

The inlet heating gas temperature can greatly determine the extent of pyrolysis process since this process is governed by heat transfer. The effect of the heating gas temperature on the energy usage and processing time is studied in this section. 1 tonne of waste bamboo particles with particle size radius of 2.5cm are pyrolysed with heating gas temperature varying from 600 ^{o}C to 1000 ^{o}C at a rate of 1 kg/s. Based on the mass fraction profile in Figure 1 and 2, considerable amount of mass are lost at temperature below 600 ^{o}C during the pyrolysis of waste bamboo. Therefore it is advisable to carry out the pyrolysis of waste bamboo at a temperature of 600 ^{o}C and above.

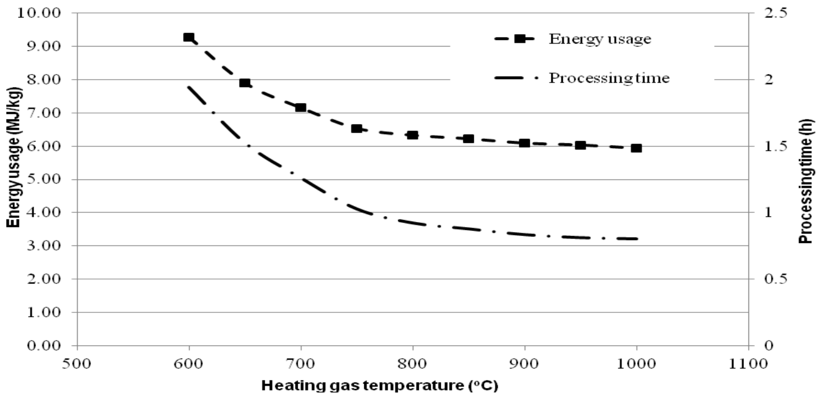

Figure 4: Effect of heating gas temperature on processing time and energy usage

Figure 4 shows the effect of the heating gas temperature on the processing time and the energy usage. The energy usage and the processing time both reduces as the heating gas temperature increases from 600 – 1000 ^{o}C but the changes becomes insignificant from 800 ^{o}C and beyond. Therefore the ideal heating gas temperature for the waste bamboo pyrolysis can be 800 ^{o}C. The heat loss from the flue gas has not been accounted for in this work and will be explored in our future work.

4. Conclusion

The pyrolysis behaviour of waste bamboo particles under different conditions of heating rate, sample weight and final target temperature was studied experimentally by TGA. The results show that the mass loss is greatly influenced by the sample weight and the final target temperature. A mathematical model was also developed to simulate the pyrolysis progress of waste bamboo in a reactor. The effects of particle size and heating gas temperature on the energy usage and processing time have been discussed extensively. Mixed-size particle pyrolysis results shows that it can achieve a lower energy usage than the individual pyrolysis though have to be compensated with a lower processing rate. The result of the heating gas temperature shows that the ideal temperature for the waste bamboo pyrolysis is 800 ^{o}C.

Nomenclature

α, γ	extent of reaction	α_T	overall mass loss fraction
$\alpha_{T,f}$	final total mass loss fraction	*t*	reaction time (s)
T	temperature (K)	*n*	order of reaction
A	pre-exponential factor (s^{-1})	R	universal gas constant (J/mol-K)
E	activation energy (J/mol)	H	heat of reaction (J/kg)
ω	mass loss contribution	*r*	radius of a discrete layer (m)
T_R	particle surface temperature (K)	T_{bulk}	bulk temperature (K)
V	particle volume (m^3)		
i	mass loss reaction *i*	*j*	non-mass loss reaction *j*
f	feedstock	*c*	char

Acknowledgement

The authors gratefully acknowledge the support from Hong Kong RGC in form of PhD Fellowship to Oyedun Adetoyese Olajire (PF09-05997) and RGC research grant (No. 613808, 614307).

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