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Energy recovery from biomass by fast pyrolysis

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Abstract

Bioenergy is now accepted as having the potential to provide the major part of the projected renewable energy provisions of the future. It has been ascertained that the biomass is a common form of renewable energy and widely used in the world. The use of biomass to provide energy has been identified as a fundamental to the development of civilization. There are different types of thermo-chemical conversion technologies available for converting biomass into energy which stretches from direct burning to more complex processes including gasification or pyrolysis. Among these processes, pyrolysis has become increasingly popular because it gives products of better quality compared to any other thermo-chemical conversion processes for biomass. A computational fluid dynamics (CFD) model is developed using Advanced System for Process Engineering (ASPEN) PLUS which is a computer assisted energy simulation tool to analyse and optimize the performance of pyrolysis process i.e., to maximize the yields of pyrolysis products such as bio-oil, biochar and syngas as a function of pyrolysis temperature, operating conditions, and physical and chemical properties of biomass. The simulation was done for four types of biomass, namely shredded green waste, pine chips, wood and birch. The results show that the shredded green waste is the best for bio-oil production which possesses high cellulose and low moisture content. The bio-oil of up to 58% can be produced from this material.

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1. Introduction

Renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage and its contribution to the greenhouse effect. Biomass is one of the main renewable energy resources that are available and

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provide the only source of renewable liquid, gaseous and solid fuels. In addition, biomass is a promising eco-friendly alternative source of renewable energy in the context of current energy scenarios. However, in today's society, biomass energy is beginning to play an integral part in both economic development and in protecting the environment. Biomass is swiftly becoming one of the most widely utilized sources of energy, with many developing countries with large agriculture sectors producing up to 40-50% of their total energy from biomass [1]. It can be used in many different ways, including electricity generation, household heating as well as industrial needs such as process heating. Essentially, biomass can be defined as non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms, mainly composed of carbon, hydrogen, oxygen and nitrogen. Biomass can be used directly (e.g., burning wood for heating and cooking) or indirectly by converting it into a liquid or gaseous fuel (e.g., alcohol from sugar crops or biogas from animal waste) [2].

There are several methods available for energy production from biomass which stretches from direct burning to more complex processes including gasification or pyrolysis. Among the thermo-chemical conversion processes, pyrolysis has become increasingly popular due to the fact it gives products of better quality compared to any other thermo-chemical processes for biomass conversion. There are different types of pyrolysis process but in this study the focus is on fast pyrolysis which utilizes very high heating rates and short residence time to produce bio-oil, bio-gas and char. Fast pyrolysis is of rapidly growing interest in the world as it is perceived to offer significant logistical and hence economic advantages over other thermal conversion processes [3]. Fast pyrolysis is one of the three main thermal routes, with gasification and combustion, to providing a useful and valuable biofuel. However, it is one of the most recent renewable energy processes to have been introduced and offers the advantages of a liquid product bio-oil that can be readily stored and transported, and used as a fuel, an energy carrier and a source of chemicals. It has now achieved commercial success for production of some chemicals, liquid fuel and electricity [4, 5].

Unlike most other renewable energy sources, biomass can be converted into solid, liquid and gas fuel forms [6]. A low temperature, high heating rate, short gas residence time process would be required for the purpose of maximizing the yield of liquid products whereas a high temperature, low heating rate, long gas residence time process would be preferred for the purpose of maximizing the yield of fuel gas resulting from biomass pyrolysis [7]. Pyrolysis oil is made up of 300-400 compounds and studies have found that the reactions and aging occur faster at higher temperatures but can be reduced if the oil is stored in a cool place [8, 9]. The process yields, quality and stability can be altered by process variables such as heating rate, pyrolysis temperature, residence and quenching times etc. Biomass differs from fossil fuels like coal and oil in that wood and other plant biomass are composed of oxygen-containing organic polymers [10]. Dobele et al. [11] investigated the effects of drying biomass and duration on the properties, composition and yields. The wood was dried at a temperature between 200-240°C with a holding time between 45-90 minutes. It was concluded that the increased drying temperature changed the yield whereas the time has no effect. The biomass was grounded down to 2-6 mm particle size for a rapid reaction inside a pyrolysis reactor. The bio-oil produced improves with the drying process due to the decrease of waters and acids.

The decomposition of wood and woody material through pyrolysis process involves with a complex series of reactions and consequently changes with experimental heating conditions, method of sample preparation, temperature, thermodynamic properties, particle physical properties and moisture content. After considering all of these factors it is necessary to do more research for further improvement and enrichment in the modelling and simulation in this area. The modelling of pyrolysis has a wide range of approach with varying complexity. Wood and woody material have compounded chemical composition, structural variation, heating rate effect, residence time effect which results in secondary reactions [12]. The ASPEN PLUS based simulation model has been developed for a low temperature pyrolysis process, incorporating triple fluidized bed and with solid circulation, for both valuable fuel oil production and power generation from low-rank coal [13]. The simulation results indicated that for the coal modelled combustion of char and remaining volatiles after pyrolysis not only provided enough energy required for the endothermic pyrolysis reactions and the wet coal drying but also can supply extra energy for power generation. Luo et al. [14] developed a model of wood pyrolysis in a fluidized bed reactor in which the effect of main operation parameters on wood pyrolysis product distribution was well simulated. The model showed that the reaction temperature played a major role in wood pyrolysis. However, CFD is gaining more attention to use as virtual process engineering and identifying the most promising design of pyrolysis process as well as chemical reaction industries. The ASPEN PLUS can easily calculate the pyrolysis yield and optimize the operating conditions by getting chemical properties from ultimate analysis test values. However, modelling and simulation could be the best possible option for understanding the thermochemical reaction mechanism, and also optimizing economic and efficient pyrolysis process design instead of having costly and time consuming experimental study [15]. In addition, due to the unavailability of experimental pyrolysis process facilities, computer simulation have been adopted which is a recognized and acceptable tool for process engineering applications. It is expected that this study will bring green waste pyrolysis technologies to the forefront of improved performance and will provide a sustainable solution for green waste management for the future. Therefore, the main focus of this study was to enhance the performance of the fast pyrolysis process with municipal green waste as a function of operating conditions. In order to satisfying the purpose, a CFD model was developed using ASPEN PLUS for predicting and optimizing the performance using mass and energy balance calculations.

2. Principles of Fast Pyrolysis Process

Fast pyrolysis is a high temperature process in which the feedstock is rapidly heated in the absence of air, vaporizes and condenses to dark brown mobile liquid which has a heating value of about half that of conventional fuel oil. While it is related to the traditional pyrolysis processes used for making charcoal, fast pyrolysis is a more advanced process that can be carefully controlled to give high yields of liquid. It has been observed that maximum liquid yields are obtained with high heating rates, at reaction temperatures around 500^0C and with short vapor residence times to minimize secondary reactions. Fast pyrolysis processes have been developed for production of food flavors (to replace traditional slow pyrolysis processes which had much lower yields), specialty chemicals and fuels. These utilize very short vapor residence times of between 30 and 1500 ms and reactor temperatures around 500^0C [3, 16]. Both residence time and temperature control is important to “freeze” the intermediates of most chemical interest in conjunction with moderate gas/vapor phase temperatures of 400-500^0C before recovery of the product to maximize organic liquid yields. The main product, bio-oil, is obtained in yields of up to 75 wt.% on a dry-feed basis, together with by-product char and gas which can be used within the process to provide the process heat requirements so there are no waste streams other than flue gas and ash [4, 17]. Liquid yield depends on biomass type, temperature, hot vapour residence time, char separation, and biomass ash content. The process includes drying the feed typically less than 10% water in order to minimize the water in the product liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, rapid and efficient separation of solid (char), and rapid quenching and collection of the liquid product.

3. Modeling and Simulation

The software package known as ASPEN PLUS was utilized for modeling and simulation purposes. ASPEN PLUS is a complete integrated solution for process engineering including reactor as well. It has no built in models and instead consists of several unit operation blocks which represents specific process operations. The ASPEN PLUS is easily able to model fast pyrolysis and predict the output of bio-oil, gas and char. The feedstocks chosen for the simulation are shredded green waste, pine chips, wood and birch. The fuel properties are an integral part of the model and therefore, data needed to be as accurate to a real world situation as possible. The physical and chemical properties that were run through the pyrolysis simulation have been obtained by CSIRO and BEST Energy Pty Ltd [18] at their respective facilities. These properties are shown in Tables 1 and 2.

Table 1. Different feedstocks proximate analysis data [18]

Sample	Air Dried Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)	Gross Calorific Value (%)
Shredded Green waste	6.1	1.0	77.6	15.3	18.12
Pine Chips	4.4	13.8	16.0	65.80	26.59
Wood	20	0.4	82	17	-
Birch	18.9	0.004	-	20	-

The development of a model in ASPEN PLUS involves the following steps: (1) Identifying the process stages; (2) Selecting the model blocks to represent each stage; (3) Creating the flow diagram for process identification and linking streams; (4) Placing the model blocks: (5) Setting the model parameters; (6) Defining the calculations for sensitivity; (7) Running the simulation; (8) Making any corrections required and repeating the steps for the remaining feedstocks. However, there are eight stages need to be incorporated into the model for the conversion process of biomass to bio-oil which is shown in Table 3 along with the necessary assumptions made.

Table 2. Different feedstocks ultimate analysis data [18]

Sample	Carbon	Hydrogen	Oxygen	Nitrogen	Total Sulphur
Shredded Green waste	47.2	5.66	45.91	0.20	0.03
Pine Chips	69.2	2.30	13.53	1.04	0.13
Wood	51.6	6.3	41.5	0.1	-
Birch	44	6.9	49	0.1	-

Table 3. Design stages

Sections	Section Description	Key assumptions
Chopping	Particle size reduction to 5 mm	Incoming Biomass has an average size of 25 mm and fed at 6 kg/hr
Drying	Biomass drying up to 10% moisture content	Steam drying at 200°C
Grinding	Particle size reduction to 1 mm	Incoming biomass maximum size of <5 mm
Pyrolysis	Biomass conversion to pyrolysis products	500°C and 1 atm, Incoming air at 9.22 kg/hr
Solids Removal	Removal of solid particles	Approximately 90% particle removal
Bio-Oil Recovery	Collections of condensing vapour	Rapid condensation to about 50°C and 95% collections
Combustion	Provides process heat and steam generation	Adequate air combustion, Adequate gas temperature, 200°C steam generation
Storage	Stainless steel material to prevent corrosion from bio-oil acids	Storage of 4 weeks product capacity

ASPEN PLUS is made up of several unit operation blocks which are capable to model specific parts of an operation reactors, cyclone, heater and pump. However, the properties need to be put into the flowchart with specifications in regards to the feedstock and energy streams. In addition, the following conditions need to be determined: (1) system component specification from ASPEN PLUS database; (2) process flow diagram; (3) feed conditions-flow rate compositions, thermodynamics properties etc. The ASPEN PLUS unit blocks was used for this model and shown in Table 4 with a short description. The ASPEN PLUS does not come with a built in pyrolysis model, however, a number of reactor types are defined.

It has been seen from the investigation and reading of the ASPEN PLUS user guide that for pyrolysis process which involves solid, liquid and gas phases, the RYIELD reactor block is the best suited for reactor modeling. Atnaw et al. [19] reported that this model calculates the yield distribution of the products without the need to specify reaction stoichiometry and reaction kinetics. A flow sheet of model was made by using ASPEN PLUS for pyrolysis to replicate and run smoothly which is shown in Fig. 1. Defining the stream properties was the most important part for the simulating process as they would determine the output results and how the system reacts as a whole. These properties include temperature, pressure, chemical composition and particle size. To correctly model a chemical process in ASPEN PLUS a great deal of attention was paid towards the blocks in regards to setting properties and internal processes. In addition, to ensure better performance proper attention was given by employing individual settings in each block.

Creating the sensitivity analysis in ASPEN PLUS is a complicated process requiring each variable to be defined. Variables could be pointed to any block or stream property to be used in the calculations. Once identified, the sensitivity analysis used numerical methods to predict the balance conditions for the defined conditions. The ASPEN PLUS simulation was run after putting all the required data. In order to get the accurate results from the model, the model was reviewed and changed the model input data whenever necessary.

Table 4. ASPEN PLUS unit blocks

Reactor Name = ASPEN Block	Description
RYIELD = DECOMP	Simulating decomposition of fuels into components for reaction (components and energy output).
RGIBBS = PYROREAC	Only block capable of calculating the reactions within the kiln. Used to calculate the reactions of the fuels and the resultant temperatures of the products.
CYCLONE	Model the cyclones used to withdraw solids.
HEATER	Simulates the temperature of the unreacted carbon to the reactor temperature. Simulates syngas cooling to a gas clean up temperature
CRUSHER = CRUSHER and GRINDER	Used to reduce particle size of the biomass
RSTOIC = DRYER	Simulates a dryer after particle size reduction. Removes a % of moisture before combustion.
SEP = OILSEP and SEP	Simulates an oil separation system. Separates the syngas and bio-oil. Also simulates the removal of moisture in the dryer.

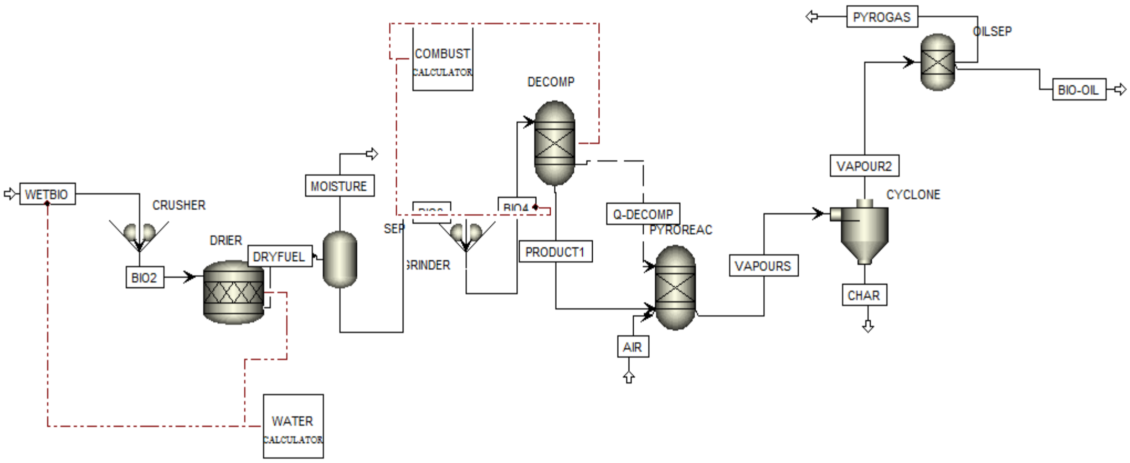

Fig. 1. ASPEN PLUS model flow sheet for biomass pyrolysis

4. Results and Discussion

ASPEN PLUS was able to create intricate breakdowns for each biomass fuel input which in turn would be valuable for making predictions in real world application. Replicating the fast pyrolysis process was proving to be quite difficult in regards to recycling the char and bio-gas and so, it was decided to simply change block settings to suit and record their outputs, assuming that this would have no effect on the bio-oil output. Upon inspection of the results, it was found that the OILSEP block was not completing its task of separating the bio-oil (BIO-OIL) and bio-gas (PYROGAS) entirely and was instead feeding the majority of PYROGAS out of the wrong stream. This could be evidenced by the presence of vapor in the BIO-OIL column and that it has been marked as a 'mixed' phase. After much deliberation and alteration of the model, separation was partially possible to be completed. Hence, to obtain more accurate results the manual calculation was used using the vapor and liquid fractions, equations 1 and 2, against BIO-OIL flow rate where, the CHAR stream was unaffected.

$$Vapour\ fraction \times Total\ B10-OIL\ flowrate = real\ syngas\ flowrate \quad (1)$$

$$Liquid\ fraction \times Total\ B10-OIL\ flowrate = real\ bio-oil\ flowrate \quad (2)$$

Using these two Equations (1) and (2), the results became a great deal more accurate which is shown in Table below.

Flow rate (kg/hr.)	Shredded Green waste	Pine Chips	Birch	Wood
Bio-oil	8.83 (58.01%)	6.51(42.77%)	6.56 (43.10%)	6.54 (42.97%)
Syngas	3.79 (24.90%)	3.32 (21.81%)	3.33 (21.88%)	3.33 (21.88%)
Char	2.60 (17.08%)	5.39 (35.41%)	5.33 (35.02%)	5.35 (35.15%)
Input	15.22	15.22	15.22	15.22

The results from the simulation showed that out of the four feedstocks listed in Table 5, the shredded green waste produced the highest yield of the prioritised product, bio-oil. It can be concluded that the shredded green waste is the best fuel for production of bio-oil which can produce up to 58% of the total yield. It was also observed from examining the simulation results that the presence of hydrogen in the BIO-OIL stream was to a much extent. Around 0.17 kg/hr of hydrogen was produced in case of shredded green waste in comparison to 0.002-0.004 kg/hr for the other samples run through the simulation. Apart from the high level of hydrogen present, the other chemical components were very similar and showed little to no effect. However, in regards to char and syngas production, it seemed that a high level of hydrogen significantly reduced their production levels in favour of the bio-oil.

5. Conclusion

A computational model was developed using ASPEN PLUS software and utilised to analyse the performance of the fast pyrolysis process using municipal waste as fuels as a function of operating conditions and physical and chemical properties. Four different biomass feedstocks, namely shredded green waste, pine chips, birch and wood, which are readily available were identified and run through the ASPEN PLUS separately to determine the respective yields of bio-oil, char and bio-gas. It was found from the simulation results that out of the four feed stocks mentioned above the shredded green waste produced the highest yield of the prioritised product, bio-oil. Therefore, it would be recommended the use of shredded green waste as a potential biomass fuel for converting it into energy through fast pyrolysis process.

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