

Lappeenranta University of Technology
Faculty of Technology
Department of Bioenergy Technology

Master's Thesis

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Comparison of energy balances of steam explosion and torrefaction technologies

Examiner: Prof. Tapio Ranta

Supervisor: Dr. Jussi Heinimö

ABSTRACT

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The present study introduces two pretreatment technologies which are torrefaction and steam explosion, and compares energy balance for both technologies to investigate and compare the use of these technologies to improve pelletization. In this research, torrefaction and steam explosion pretreatments were accomplished on the mixed small diameter wood (70%) with moisture content of 40 %, and logging residues (30%) with moisture content of 45 % at temperature 230 °C, and treatment duration 10 min.

Competing methods were evaluated, and the results showed higher volumetric energy for steam explosion pellet than torrefied pellet.

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LIST OF ACRONYMS AND ABBREVIATIONS

GHG	Greenhouse Gas
ILs	Ionic Liquids
AWL	Anhydrous Weight Loss
MEC	Minimum Explosivity Concentration
SE	Steam Explosion
HMF	Hydroxymethylfurfural

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1. INTRODUCTION

The use of fossil fuels which has been on the increase has led to an increase in the level of awareness of environment. Wide utilization of fossil fuels lead to rising greenhouse gas emission and make worry over climate change, which has led to introduction of incentives to lower the level of greenhouse gas effect. Currently, the world is challenged to reduce its fossil fuel dependence, therefore developed industries have encouraged looking for clean energy methods for their sustainable development. Increased use of biomass energy reduces the emission of greenhouse gas (GHG) in accordance with targets set under the Kyoto Protocol. Biomass energy can be produced through different thermo-chemical, biological, and chemical processes; these process utilize direct combustion to produce energy solution on short-term basis. As a solid fuel, biomass is grown in usage. It is used as combustion fuel to generate steam for domestic and commercial electricity production, gasification for combustible gas which is known as producer gas; that is large partial pressure of nitrogen and CO₂, and syngas which is carbon monoxide and hydrogen with low amounts of nitrogen and CO₂. Biomass can be used as a reliable source of energy to the society and at the same time as the most effective to avoid the environmental pollution. Nature has offered a wide range of biomasses and man also has contributed to formation and modification to suite his domestic and industrial use. [1]

Lignocellulosic feedstock biomasses such as wood have some unattractive properties in their structure and characteristic, and need to be rationalized in order to make biomass as a reliable and efficient source of fuel. The main problems with most of the raw biomass materials is that, compared to fossil fuels, they are bulky, of low calorific value, high content of moisture, easily decays, hydrophilic in nature and high amount of fuel required to ignite its usage. This renders biomass challenging for large scale electricity production. These limitations have created great logistical problems and also reduced energy production efficiency. Due to biomass' low energy density over fossil fuels, large volumes of biomass are required to produce equal units of power. These problems are compounded by transportation, storage, and feedstock handling at co-generation, thermo-chemical, and bio-chemical conversion plants. The fact that raw biomass is high in moisture presents a primary challenges. The moisture reduces production efficiency and this translates into higher production costs. It also leads to natural decomposition, loss of quality, and storage complications, such as, off-gas emissions. Additionally, undesirable moisture content

distorts the physical, chemical, and micro-biological properties of the biomass fuel. Furthermore, irregular biomass materials shapes also present difficulties in feeding the co-firing or gasification system. It is also worth noting that biomass has more oxygen content compare to carbon and hydrogen. This makes it lesser appropriate for thermo-chemical conversion processes. Generally, the above listed limitations render biomass materials as inefficient and cumbersome sources of energy fuel.

A high moisture content level can also result in inconsistent reaction, reduced efficiency, and also increase the conversion process costs. Additionally, the apparent high level of raw biomass moisture content contributes to the biomass's thermal instability. High moisture content causes low calorific values and uneven particle-size distribution during thermo-chemical processes. This can lead to irregular output, formation of condensable tars, and consequently to the development of gas-line blockage problems.

Notwithstanding, the foregoing challenges can be remedied by re-processing the biomass material to make the biomass fuel more suitable for energy purposes. The other viable option is to pre-treat the biomass material before use. The process alters the biomass' physical and chemical composition thus making the material suitable for conversion. The pretreatment can either be a chemical, such as ammonia fiber explosion, thermal for example torrefaction, or hydro-thermal like steam explosion process. These processes alter the amorphous and crystalline properties of the biomass and further cause significant changes to its structural and chemical composition. Notably, torrefaction is a thermal pretreatment process. This technological process significantly alters the biomass' physical and chemical composition. The other pre-treatment process is known as steam explosion. It entails treating biomass with high pressure steam under optimal conditions – these conditions entail production of the best hydrolysis substrate with minimal material loss due to ancillary reactions like dehydration. This is followed by quenching the reactor content through a pressure vessel by adiabatic expansion. Steam explosion has been credited with several advantages. It is used to fractionate wood into three major components and also enhances cellulose's the susceptibility to enzymatic attack. [2] [3]

The structure and characteristic of woody biomass can be improved by utilizing pretreatment technologies, make it environmentally friendly fuel in co-combustion process in existing coal

plants, in addition it is applicable in producing chemicals such as ethanol as a result of steam explosion treatment.

Although there are several options available in pre-treatment technologies, nevertheless this study attempts initially to introduce two technologies; torrefaction and steam explosion, which can apply for treatment of woody biomass, and study the effects of so pretreatment technologies on woody biomass as well as the application of treated fuel. Furthermore, in order to compare both technologies wood biomasses with different moisture contents are selected to conduct energy balance calculations for both technologies.

The main contents of the study is as follows. Following the introduction and introduce of woody biomasses in the first chapter, torrefaction technology and its associated topics are reviewed in the second chapter. The focus is merely given to the topics related to woody biomass rather than other biomasses. In chapter three, steam explosion will be discussed. Chapter four is calculation part following by Discussion in chapter five and Conclusions in chapter six.

This study is fulfilled according to the Miktech company plan, which can be used later to compare with similar cases.

1.1 Solid Woody Biomass Fuels

Woody biomass refers to the manner in which material gain from products or trees is stored in sufficient quantities which have difficulties with disposal as well as from trees particularly used for the market of biomass. Woody biomass is usually used in research and development communities for waste wood materials that do not have a prevailing local market. The definition of biomass derived from the forest is as components of wood residues gotten either indirectly from wood manufacturing and processing facilities or directly from the forest itself.

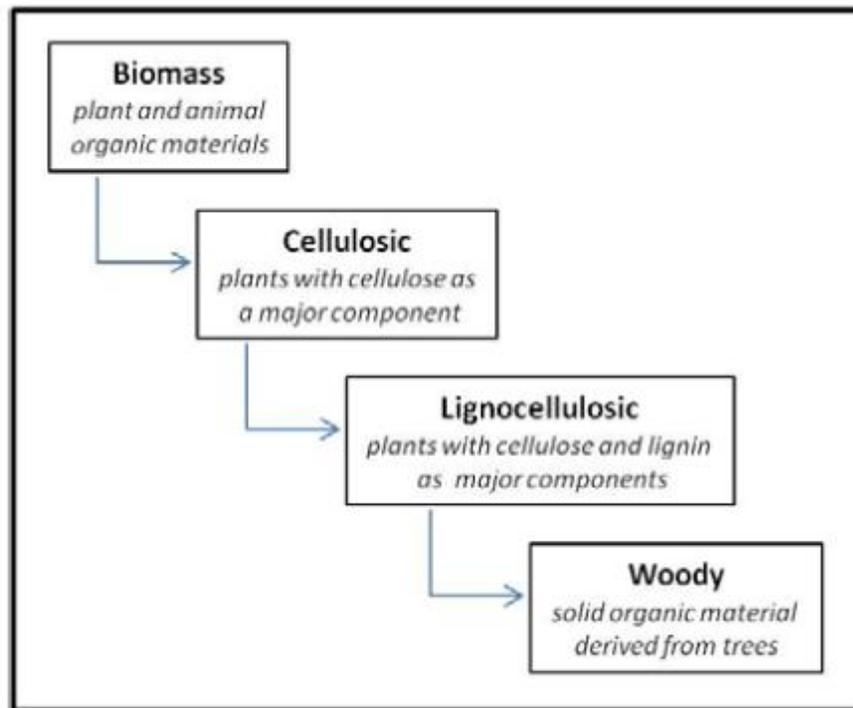


Figure 1: structure of biomass [4]

Woody biomass can be used as a feedstock or source to produce energy in the form of electricity or heat, in fact there is the potential of woody biomass to be used as feedstock to generate energy and elevated value manufactured merchandise, although its value and quality is low.

1.2 Sources of Woody Biomass

Woody biomass can originate from a variety of sources, including:

- Sawmill and other wood production residues contains bark or defective wood pieces, Sawdust, and other wood waste,
- timber harvesting and logging residues,
- Non-timber tree removal , dying trees, urban waste wood,
- Dedicated forests, fast growing trees grown particularly for biomass markets, energy, fuel wood, and forest thinning that reduce damage from fires and pests. [4]

1.3 Pretreated Woody Biomass

Woody biomass can be applied in different types of product, such as pellets, torrefied or steam explosion pretreated pellets. Pellets are being produced from the following materials:

- Whitewood species (saw dust and planer shavings)

- Hardwood species (saw dust and planer shavings)
- Bark from whitewood (smaller volumes)

White wood is useful in making most of these pellets since it has less ash that leaves fewer residues in the stove after combustion. [5]

The frequently use of white pellets today, have numerous operational and safety issues. However, they are fragile, potentially explosive, sensitive, and if they are exposed to either snow or rain, they crumble. Thus, loading or unloading should occur in adequate weather conditions and transportation and facilities should be addressed. Moreover, due to the fragility of white pellets they should be handled with care when they are moved during shipment since they can easily breakdown into potentially harmful dust. The white pellet dust is just risky identical to grain or sugar dust, when it explodes. White pellets can be expensive to use and transport due the costs associated with protecting them from water and waste of product. [6]

The pre-treatment of biomass raises its fuel properties. Wood pellets have better energy and bulk densities compared to solid wood. However, the fuel properties are enhanced even before pelletizing, when wood chips are first torrefied. The allocations of different woody biomasses are founded on both their bulk- and energy density, and are depicted in figure 2. Currently, torrefaction addresses a number of woody sources as feedstock: woody biomass from mills, from urban waste, from forests, and from plantations. [7] [8]

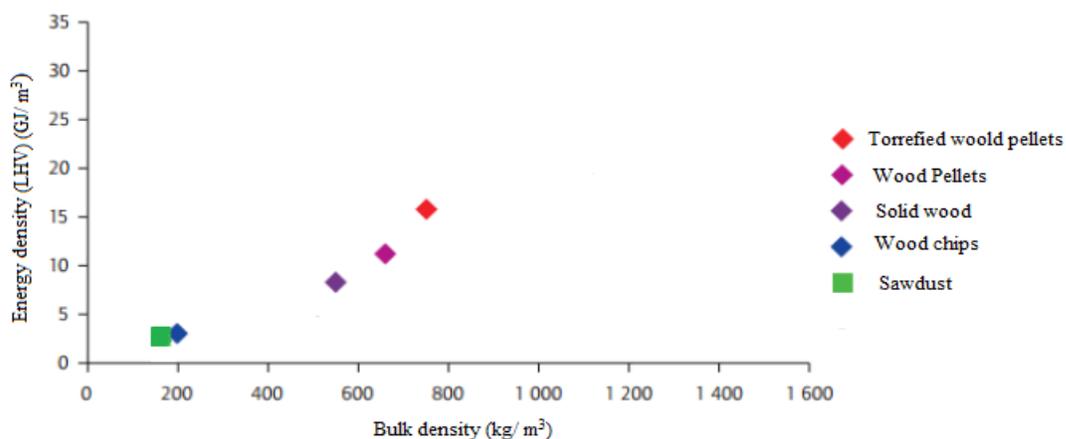


Figure 2: evaluation of bulk density and energy density of different woody biomass [7]

The properties of coal are almost the same as chemical and physical features of torrefied material. As a result, using the conventional (coal-fired) power plants for combustion or co-combustion of torrefied pellets can be conducted. This cuts the additional costs on the technology of incineration. [7]

When the torrefied material co-firing is compared to sole coal utilization, one of its most evident benefits is the reduction of total Carbon dioxide (CO_2) and sulphur oxides (SO_x) emissions. As a result, the incentives and the net profit of having CO_2 certificates are attained. In addition, by developing renewable energy sources, the basis of the fuel is more varied and realization of the goal of producing green energy goals is approached. In comparison to non-torrefied woody biomass and coal, torrefied wood fuel has better combustion behavior, low sulphur and ash content. [7]

Wood subject to steam explosion exhibits an alteration in the chemical property, hygroscopicity, color, rigidity, texture, value of calorie and thermal performance when comparing with raw wood. Typically, the pretreatment technologies reduce the bulk, drive away most of the water, elevate energy content as well as increasing in calorific value. Besides, so technologies make a fuel which can burn similar to coal, in addition the sulfur and ash content of wood reduce significantly compare to coal, lead to possessing an environmentally friendly fuel.

2. TORREFACTION

2.1 Introduction

Charcoal produced from burning of wood is an old method to enhance the combustion properties of wood, because of its higher burning temperature, easier storage in order to better moisture resistance and simpler to ignite attributes. However, if the procedure performs well, then charcoal includes 20 to 55 percentages of the whole energy content of raw materials.

Progressive way of this procedure is called torrefaction which wood under controlled condition and in the absence of oxygen roasts result in substance with high heating value and energy content whilst there is reduction in size and moisture content. [9]

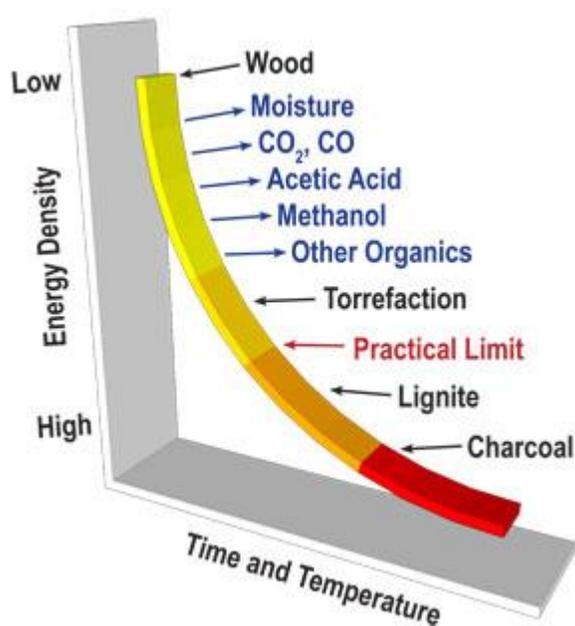


Figure 3: Energy density of wood improves by means of Torrefaction [10]

However, studies on torrefaction was done in France in the 1930's but there is no substantial reports available. The procedure was opened up by Bourgois and Doat in 1980's. They tried torrefaction process on two tropical wood samples with two temperate and then published the results. Eucalyptus and a mixture of chestnut and oak as the deciduous wood types and maritime and Caribbean pine as coniferous wood types were examined by torrefaction process. For the deciduous wood types, torrefaction at 270–275 °C increased the lower heating value of the wood from 18.6 to 22.7 MJ/kg and 17.9 to 21.5 MJ/ kg, respectively, while maintaining over 90 % of

the energy. The coniferous wood types, maritime and Caribbean pine, required a higher temperature of 280–285 °C, while the increase in energy density was somehow less. Based on this result continuous wood torrefaction plant was built in 1987, where wood torrefied to apply as reducer in the production of silicon metal. Two batch plants were also built in order to produce barbecue fuel and firelighters. [11]

Typically torrefaction is done between 200 °C and 300 °C to remove moisture, carbon dioxide and volatiles from the wood. During the dehydration and decarboxylation reactions of the long polysaccharide chains some volatiles like hydroxymethylfurfural, furfural and aldehydes are formed. The energy density of wood is increased, but the O/C and H/C ratio is reduced because of removal of water and carbon dioxide. Reduction in oxygen content makes wood an ideal fuel for gasification processes. [9]

Figure 4 briefly introduces the whole treatment process on wood.

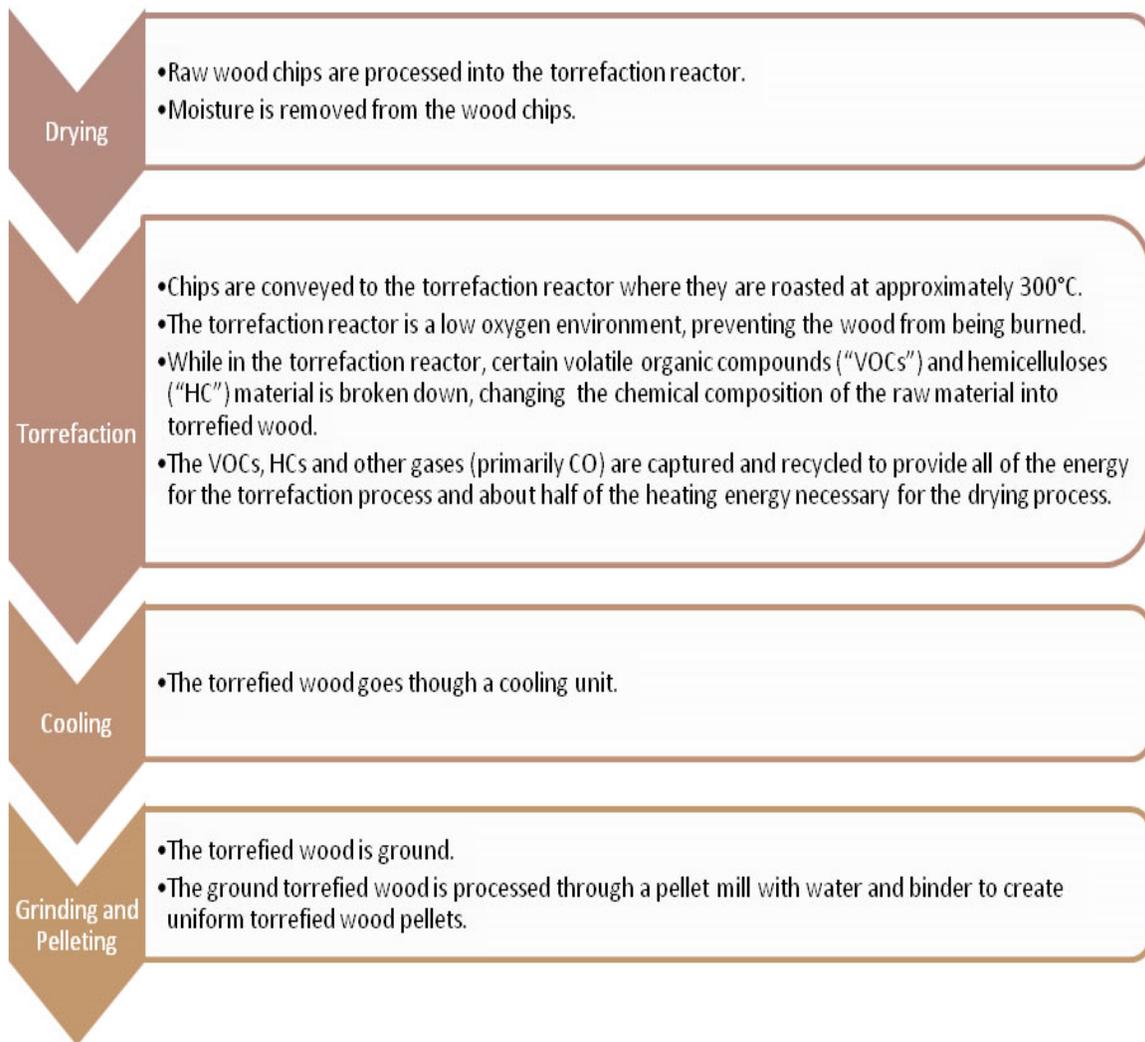


Figure 4 [12]

Figure 5 exposes the torrefaction process more accurately.

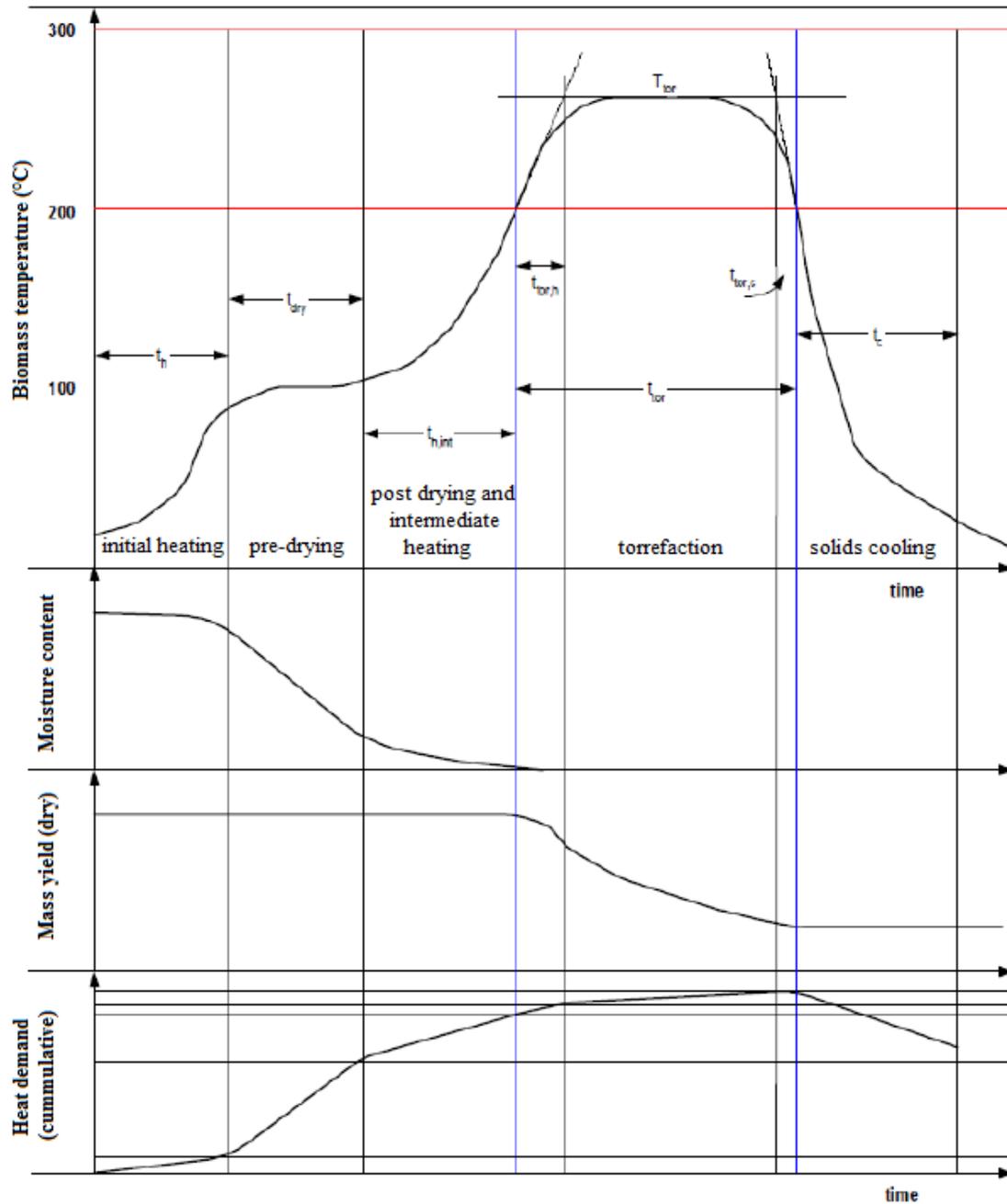


Figure 5: Steps of torrefaction [7]

The sum of the time of initial heating (t_h), drying time (t_{dry}), intermediate heating time ($t_{h, int}$), reaction time at desired torrefaction temperature (t_{tor}) and cooling time (t_c) to ambient temperature altogether make the process time. Reaction time includes of three items: time of heating from 200°C to desired temperature (T_{tor}), the desired duration time in that temperature, and cooling time from the desired T_{tor} to 200°C. This point is where considered that the torrefaction process ends and the final cooling phase starts. Based on the above diagram, during

the first three stages, the moisture content becomes zero, then after generation of torrefaction gases and the volatile compounds throw off, the mass yield becomes lower. 60 % of torrefaction gases are fire-resistant substances consist of about 50 % water and 10 % CO₂. Process properties and, the humidity of the raw material determine the actual amount. The end product which can be easily handled and transported is fuel with high amount of energy. [7]

Considering to the fact that hydrocarbons, such as CH₄ and C₂H₆, are diffused only at higher temperature than those used in the torrefaction process, result in utilizing torrefacted woody biomass as a practical subject for co-gasification or co-combustion with coal. [13]

More practical CO and H₂ are produced through gasification of torrefied woody biomass compare to raw wood. [14]

In torrefied wood there is more char produced which contains greater residual carbon and less as compared to the gasification process of fresh wood. Char obtained from torrefied wood also is less reactive compared to that from wood.

Torrefaction can be done under various gaseous atmospheres. Most of the time, Nitrogen or hot gases which are diffused during the thermal treatment are utilized. There is a possibility to happen exothermic reaction in the presence of Oxygen. Preventing for increase is done through a rapid and uncontrolled increase in temperature of the material. Nevertheless, temperature of the wood highly effects on chemical reactions implicated during torrefaction, along with final characteristics of the material. [15]

Pre-treatment of untreated woody biomass is recommended because of some characteristics of untreated woody biomass such as: relatively low energy density, high moisture content and difficult decomposition into small particles. These features lead to somehow expensive transport cost of wood. Pre-treatment helps to improve mentioned characteristics, meanwhile consider to the fact that a large amount of wood is needed to replace the same amount of coal in purposes like combustion and gasification. [11]

2.2 Torrefaction Procedure

Being that wood contains different fractions makes the topic of thermal degradation in it quite a complex topic of research. Under when observed under the microscope, the wood cells are seen to be made up of bundles of cellulose molecules called microfibrils which are also seen to covered with hemicellulose. The microfibrils usually have lignin deposits in between then and occasionally such deposits are also found within the amorphous parts of the microfibrils. The

compartments within the wood cells are referred to as the wood fractions and they actually exhibit variations in terms of their heat properties hence distinguishable in wood's weight loss curve. Hemicellulose, cellulose and lignin undergo thermal decomposition at the temperature ranges of 225-325 °C, 305-375 °C and 250-500 °C respectively which implies that the most reactive wood fraction is the hemicellulose. Thermal decomposition of these fractions results into a solid torrefied product which is widely applicable as a barbecue firelighter. [15] [16]

Chemically, the wood structure is constituted by the following components: up a percentage range of between 35-40% by weight is made up of cellulose, 20-30% being hemicellulose while lignin constituting between 20-30% of the total weight of wood. It should be noted that extractive compounds also constitute 1-4% of the total weight of wood. There is also a larger hemicellulose content in deciduous trees (hardwood) than coniferous trees (softwood); 37-40% against 25-28% while the coniferous trees contain higher lignin than deciduous as indicated by 24-33% against 16-25%. Lignin has a high carbon, hydrogen, ergo and heat producing cells hence is used to consolidate the wood fibre making wood mechanically strong. Other important components of wood are in the forms of terpenes, lipids and phenols whose percentage compositions in dry wood and bark are 5 % and 30-40% respectively. Wood burns with long flames in large combustion chambers due to the presence in their structure of 80-90% of very volatile compounds. [7]

The first stage of torrefaction is characterized by decomposition of hemicellulose and this process usually occur at a temperature of around 250-260 °C. The process of hemicellulose degradation is divided into two steps. During the initial step is concerned with the formation of monosaccharide, polysaccharides and dehydrosugars while the second and the final step involves the decomposition of these sugars into CO and CO₂, a process that is catalysed by mineral matter. The carbon bonds of carboxylic groups undergo thermal cleavage leading to the formation of acids. These acids are used as catalysts in thermal cleavage reactions leading to the formation of carbon dioxide and carbonyls such as hydroxy acetone, methanol, and propanol most of which consist of 1-3 carbon atoms and 1-2 oxygen atoms in their structures. Lignin and cellulose are different from hemicellulose in that their decompositions do not occur at such low temperatures hence the overall loss is quite minor. [17] [11]

Hemicellulose being one of the major is considered as the most reactive component of wood during the torrefaction process. Previous research that was carried out on the process of

torrefaction concentrated on the analysis of three lignocellulosic materials using a thermogravimetry. It was observed that when temperatures were increased and the weight losses observed, it was recorded that there were effective degradation in hemicellulose even when the temperatures were kept as low as 230°C. The reason behind this phenomenon is the fact that there is decomposition of several saccharides and branches in the hemicellulose which are more easily extractable from the major backbone which is then proceed by the decomposition of cellulose which can finally occur at higher temperatures. Cellulose is composed of non-branched glucose polymers making it possess a higher thermal stability. Lignin does not have any noticeable impact on the process of torrefaction and it decomposes into three items which are a char solid, tar and gases that are highly volatile with the last two constituting the highest mass degradation during high temperature torrefaction. [18]

The second stage of torrefaction is characterized by the decomposition cellulose whose reactivity is lower than that of the hemicellulose and has a rate controlling of below 300°C. Water, Carbone monoxide and carbon dioxide are given out from the disintegration of hydrogen bonds that occur within or between cellulose molecules. This normally causes a change in the super-molecular structure of cellulose and reduces its length down to ca.200 all the way from 104. Raising the temperature to above 270°C has positive effects on rate of cellulose decomposition by intensifying the reaction making the use of torrefied wood as fuel much dependent on lignin than any other fractional component. [17] [19]

When torrefaction is in progress the amount of hydroxyl groups are greatly falls due to the decomposition of hemicelluloses and lignin. As this occurs, the products resulting from the degradation of hemicelluloses and lignin, which constitutes acids, sugars and charcoal, gets evolved or deposited on the surfaces found in between the wood particles making the plasticity to fall. The consequence of reduced plasticity is that the extraction process will be characterized by increased energy consumption. [20]

Lignin gets depolymerized; majorly β -aryl-ether bonds alongside re-condensation reactions are responsible for the reduction in its average molecular weight. Some carbohydrate fractions become volatilized and some acid-insoluble degradation components are created out of such carbohydrates increasing the fraction of acid-insoluble components. For instance, cellulose can form an insoluble acid after undergoing scission reactions with aromatization and cross-linking. [9]

Bound water in wood is of three main kinds which are freezing and Non-freezing bound water. Non-freezing bound water particularly bound to the hydroxyl part of the wood polymers, mostly the hemicelluloses. Freezing bound water on the other hand has a loose bond with hydroxyl components arranged in clusters and can be obtained at high humidity areas of nanovoids as well as on the linings of macro- and microvoids' walls. Micro and macro voids are characterized by free water that is trapped here and strongly held in position by forces of capillarity even though it does not get to certain sorption sites. The fact that hemicelluloses get decomposed when wood gets thermally treated and many hydroxyl groups are lost makes the water in torrefied wood intact and retained as free water among macroscopic and microscopic voids where capillary forces holds it in place. Torrefied wood attains equilibrium as far as moisture content is concerned much quicker than those that are not torrefied. The role of the water is to make the wood polymers plastic thereby reducing their softening temperature. Naturally, hemicellulose combines cellulose and lignin fibrils making the cell wall of plant more flexible. When wood gets decomposed, it becomes increasingly brittle and hence easier to disintegrate into small pieces. The decomposition process undergone by the hemicelluloses, cellulose and the lignin have effects on the pelletizing properties like the friction coefficient and Poisson ratio. It is very likely that extractive components are lost when the woods are exposed to torrefaction process. [9] Solvents of different classes such as mineral acids and ionic solvents have been found to have the capacity to disrupt with hydrogen bonds between polysaccharide chains. When such chains are exposed to solvents, they become less materially compact and increasingly sensitive to hydrolysis. Doping cellulose with mineral acids such as H_2SO_4 , HCl and HNO_3 considerably increases the rate with which it decomposes while also lowering the temperature required for decomposition. However, corrosive property possessed by most acids alongside their volatility, results in poisonous radiations at high temperatures, makes them unsuitable for use in biomass torrefaction. Unlike mineral acids, ionic liquids (ILs) at room-temperature possess very low vapour pressures, are less flammable and highly thermally stabile. [17]

The torrefaction reaction kinetics at temperature ranges of between 230-300°C can be accurately explained using a two-step model. The first step is more rapid than the second so that time demarcation of the two steps can be achieved. During the first step, hemicellulose decomposition mainly occurs while cellulose decomposition occurs in the second step. The first step has a solid yield of between 70-88% while the second step yields a relatively lower solid material of

approximately 41% with the solid yield in the first step being experiencing a decrease with temperature. The difference in solid yield is so because hardwoods have less xylan content which is also the most reactive part of hemicellulose as compared to cellulose component. On the other hand when torrefaction is taking place, there is tendency of pyrolysis to occur lowering the rate of thermal wood decomposition. The decomposition process causes Anhydrous Weight Loss of wood abbreviated as AWL and which represents the process of physical-chemical transformation in wood. AWL is usually flexible making it match the progress in the torrefaction reaction. The AWL of wood can be controlled by controlling its torrefaction process and the corresponding AWL can be estimated from the temperature records can be achieved using a model. Special types of hemicellulose known as the xylan decompose much slower than other forms of hemicelluloses. [20] [15]

The mass loss of wood during torrefaction is usually as a result of dehydration and decarboxylation which leads to the disintegration of hemicellulose. Hemicellulose usually does not have crystallinity making it less thermally stable as compared to cellulose. Hemicellulose decomposes quite rapidly and its process of decomposition is usually complete within the initial 30 minutes which makes its weight loss quite rapid as well. On the other hand, lignin and cellulose decompose at a much slower rate hence the explanation for a gradual steady weight loss after 30 minutes of combustion. [20]

The data obtained from the kinetics may be applied in making recommendations for industrial torrefaction process conditions and for process scale up. During torrefaction, the rapid first reaction involving the decomposition of the highly reactive hemicellulose is vital and it is recommended that this stage should proceed all the way to completion. The following stage of reaction, which is characterized by the decomposition of cellulose and secondary charring reactions of products from cellulose reactions takes much more time to come to a completion and hence may cause to uneconomically large equipment. Figure 6 illustrates the time required to obtain the maximum yield of intermediate product B. This time reduces from over 3 h at 230°C to 10 min at 300°C. The latter reaction time is apparently short enough for commercially viable processes, since the estimated reactor volume may be fitted into a single reactor even at large capacity up to 10 kg s⁻¹. [21]

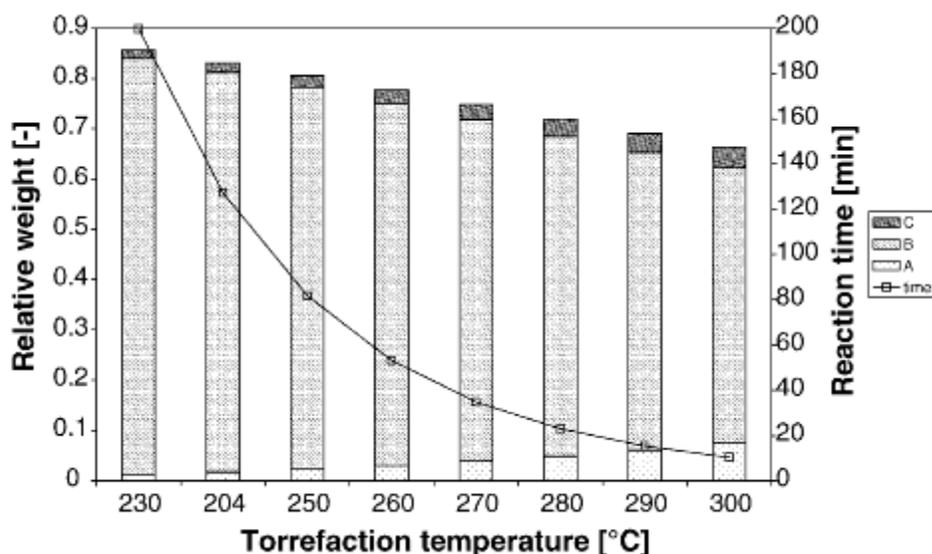


Figure 6: Time needed for maximum output of intermediate product B and corresponding yields of A, B and C at different temperatures [21]

The maximum output of B as illustrated by the diagram assumes a downward trend alongside temperature due to the fact that volatility is increased with increasing temperatures. This may be desirable if the so formed volatiles are made up of species that contain small energy amounts. Such species include water vapour or carbon dioxide. However at temperatures above 300–320 °C, cellulose undergoes rapid thermal cracking which may result into the formation of tar hence it is recommended that the operation be maintained at temperatures below 300 °C. Operation under such temperature conditions also leads to a considerable selectivity to the intermediate product; the selectivity to B decreases with temperature since the secondary reaction has a higher activation energy than the primary reaction. Besides temperature and residence time, torrefaction is also dependent on another important process parameter which is the size of the particles. In order to minimize residence time, it is vital that the rate at which heat is transferred to and within the particle is quicker than the overall rate of reaction. The implication of this requirement is that the solid temperature will be essentially the similar to that of the surrounding temperature, and the overall controlling factor is the intrinsic kinetics. [21]

2.3 Torrefaction Product Distribution and Structure

During the torrefaction process, hemicellulose which is the most reactive fraction of woody biomass undergoes decomposition leading to the formation of torrefied wood and volatiles. The solid product, which can be recovered and weighed accurately, is the largest component of the

product obtained. The quantity of the material that is lost increases with temperature and the product of torrefaction process are usually brown-black in colour with low volatile content and high energy density. The products obtained, are usually of three types which are in the forms of a solid product with a dark colour, an acidic aqueous phase which is yellowish in colour and permanent gases like carbon monoxide and carbon dioxide. The solid product is always characterized by impressive fuel characteristics like a high heating value, low humidity and simplicity in reducing the size into smaller particles. Generally, up to 70 % of the mass is conserved in the solid form and this usually contains approximately 90 % of the wood's original energy content. The remaining 30 % of the mass is transformed into torrefaction gases which contribute only up to 10 % of the total energy content in the wood. [11] [10]

As wood torrefaction progresses the high temperatures surrounding the torrefaction environment initiates the production of certain light volatiles. The high-temperature environment also results into the thermal decomposition of the three cell wall polymers leading significant changes in the properties of wood. For instance, biomass is transformed from being hygroscopic to hydrophobic. In fact, when wood gets torrefied, all the products of the reaction are manifested in three ways which include a partially carbonized solid component also called charcoal or bio-char, a condensed liquid and a permanent gas mixture of carbon monoxide, carbon dioxide and traces of hydrogen and methane. [19]

When temperatures are kept below 300°C, the major products of wood disintegration include water, carbon dioxide, carbon monoxide, formic acid, acetic acid and furfural. A lot of researches studies have indicated that these products are mainly correspondent to the disintegration of hemicelluloses. Similarly, when the temperatures are raised beyond 250°C, lignin and cellulose become decomposed to some extent [15]. However, the most conspicuous product obtained from torrefaction process is water. This water is lost in two mechanisms which include the drying period, prior to torrefaction, and dehydration reactions that occur among organic components during torrefaction process. Besides the torrefied wood, torrefaction process normally yields several other products from the reactions occurring here. The production of such products and their corresponding quality are dependent on the under which the process occurs. The solid products are in the form of sugars, newly synthesized polymers alongside certain amounts of aromatic compounds, char structures that are rich in carbon, and ash. Most of the liquid compounds produced and that would exist in liquid states at room temperature are

observed to be in gaseous state during the torrefaction process. The typical gaseous compounds and include only permanent gases like as carbon monoxide and carbon dioxide, methane, hydrogen gas as well as some aromatic compounds like toluene and benzene. The non-permanent gaseous components produced are those that exist as liquids at room temperature and they include water, organic compounds and lipids. [18] [7]

The volatiles come in the forms of condensable and noncondensable fractions. In both cases the quantity yielded increases alongside the temperature of torrefaction. There is a tendency of reduction in volatile matter together with progressive increment in fixed carbon content as the torrefaction conditions become more extreme. The increasing mass loss among the organic matter during the process also leads to a substantial increment in the ash content. [18] The energy efficiency of torrefaction process can be as high as above 90 % due to the fact that the gaseous products produced by the process undergo combustion and the heat produced is reabsorbed into the process. [18] [7]

2.4 Boosting Torrefaction Procedure Efficiency

Temperature has the key factor in torrefaction therefore in order to obtain an acceptable energy yield, selecting an ideal condition is essential. In fact, lower temperature and shorter residence time are ideal conditions in treatment process to attain good physical features with a reasonably high energy yield. [18]

On the other hand Volatiles generated in the process possess relatively low calorific values; however the gas still is flammable. In case the gases generated are flammable, then they can be burnt and used in heating the reactor in a recycle loop, the gas has to be examined further to determine if it can burn, if there is a possible auto thermal operation of the reactor, If additional fuel is needed, and also the temperature and time generate flammable gases and required efficiencies. Gas chromatography is used to quantify and identify flammable components of the gas and the flame temperature needed to ignite, thus, the possible use of the gases as sources of heat for the reactor can be evaluated further. If the gases produced during torrefaction are flammable, they may be combusted and used to heat the torrefaction reactor in a recycle loop.

The condensable fraction can also be used in the production of other chemicals such as concentrated acetic acid, methanol, furfural and formic acid.

In an examination of torrefaction of willow, 5 % of the total yield was found to be acetic acid. Methanol was 1 % while furfural and formic acid were 4 %. [22]

Acetic acid is used to obtain specialized compounds. It is of great use in generation of vinyl acetate monomer that is used in production of adhesives, paints, paper coatings and such like. Also it is used in generation of ethylene vinyl alcohol polymers, used in films for vehicle petrol tanks, plastic bottles among others. Also, Acetic acid is used in creation of purified Terephthalic acid, used in making polyester fibre and bottle resins. Ethyl acetate, another derivative is used as a solvent especially in enamels and oil-based lacquers. Lastly, acetic acid is used in deriving acetate esters, used in inks, paints and dyes. Formic acid has a number of uses such as generation of pharmaceuticals and other chemicals. Furfural and also its derivatives can be made use of as substitutes for crude oil organics that are used in the industry. [22]

2.5 Modelling Torrefaction

The heat degradation for wood represents a chain of chemical reactions involving several distinct chemical compounds. The building units of wood are quite complex and usually give out many products after torrefaction process. Torrefaction models are simplified simulations that can be used to approximate the actual activities that take place during the actual process and are usually necessary requirements in the control of torrefaction process. Kinetic control of torrefaction process is achievable due to the fact that the transfer phenomena are negligible. Kinetic models under the focus of this paper are three in number and they include simple model, Di Blasi-Lanzetta and Rousset models. All the three models work under the assumption that the kinetics of all reactions taking place are in accordance with Arrhenius law and are characterized by two main properties which are the activation energy and kinetic constant. These models have been referred to as the simple models. [15]

2.5.1 Simple Model

This is a single equation universal model of wood disintegration and its relevance is much realizable when the decomposition is occurring at low temperatures. The chemical reactions that occur when wood gets decomposed at low temperature include decarboxylation, decomposition of O-methyl groups, and hydrolysis of O-acetyl groups. Since volatiles are characterized by low molecular weights and the molecules of char are polymer chains with high molecular weights, the value of f is anticipated to be less than one.



Equation 1

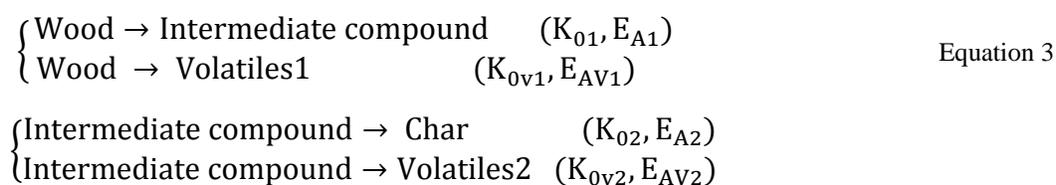
The so called simple model is defined by mainly two parameters which are the k_{0M1} and E_{AM1} as wood, char and volatiles are not well defined chemical compounds. Equation 3.1 employs these compounds as ‘pseudo’ chemical compounds whose corresponding ‘pseudo’ molar masses (M_V) and (M_C) representing volatiles and char respectively are unknown. It is important that the products obtained from experiments involving volatiles and char be factored in. This creates the need to incorporate an extra parameter, f , which is the ratio of pseudo molar mass of volatiles to that of char. This parameter should not only be introduced but also optimized. Its expression in accordance with the above definition is given by equation 3.2.

$$f = \frac{M_V}{M_C} \quad \text{Equation 2}$$

As wood gets thermally decomposed at low temperature, the reactions that take place include decarboxylation, decomposition of O-methyl groups, and hydrolysis of O-acetyl groups. As volatiles are of low molecular weight, and char molecules are polymer chains of high molecular weight, f is expected to be lower than one. Despite being useful in estimating the AWL, This model does not factor in the many reactions that occur during heat treatment at low temperature. [15]

2.5.2 Di Blazi-Lanzetta Model

The equation explaining this model was suggested by two scholars named Di Blazi and Lanzetta.

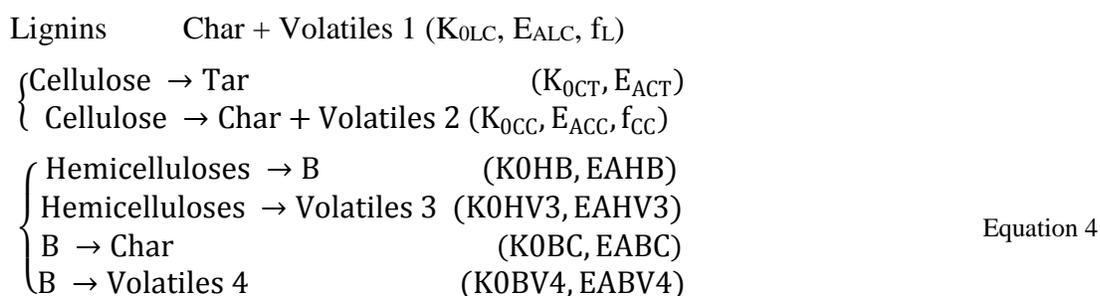


The initial intention behind the design of this model was to explain the thermal degradation of xylan. When exposed to temperatures capable of initiating torrefaction, the wood component that undergo the most pronounced decomposition are the hemicelluloses. Xylan is the hemicellulose that undergoes the most thermal decomposition. The thermal degradation of xylan takes place in the same temperature ranges that cause torrefaction to occur. Di Blazi Lanzetta model works under the assumption that the first step of wood decomposition results into the production of volatiles and intermediate compounds while the second step is involved with decomposition of the intermediate compound into volatiles and char. This model is explained using four distinct and independent reactions. The exposure of the intermediate compounds to high temperatures

leads to the production of char as suggested by this model. This concept is experimentally justifiable by knowing the fact that an increase in torrefaction temperature leads to corresponding increase in carbon content making wood to become char like. It is a fact that it becomes a little difficult to physically interpret this models specifically, the difficulties in justifying how wood is directly and independently transformed into intermediate compounds and char. For example, hydrolysis of O-acetyl groups of xylan (main hemicellulose of hardwood) produces acetic acid and a remaining polymer chain. These two products are not formed independently. The same remark applies to the transformation of the intermediate product into volatiles and char. [15]

2.5.3 Rousset Model

This model comes in the form of an equation that was pioneered by Rousset et al. The basic assumption under which the model achieves its relevance is that thermal degradation of wood is a superposition of the thermal degradation of its major components and is proportional to their quantitative composition in wood. The decomposition of lignin to give char and volatiles assumes a simple degradation path. In accordance with the Broido-Shafizadeh model the decomposition of cellulose to give in tar, char is an independent process and leads to the production of an intermediate product labelled 'B' according to the following equations.



For the purpose of optimizing short time torrefaction, the models employed should have the capability to estimate the AWL curve. The models used here are universal since thermal degradation of wood occurs in many reactions. These models better the kinetic models in terms of being phenomenological. [15]

It has been proven that torrefaction has no effect on the thermal degradation reactivity of the partly torrefied particles but just the quantities of volatiles yielded on extensive heating. An increased rate of heating in thermogravimetry is known to cause substantially varying activation energies, particularly amongst the hemicellulose and lignin pseudo-components, whether the wood under consideration is torrefied or not. Torrefaction has no effects on the reactivity of

wood fractions that are decomposed by oxidation. It however has noticeable effects on the reactivity of char under high temperatures and activation energies. The variations are minor and the kinetic properties still conform to the ranges observed among lignocellulosic chars. The reactivity of char is substantially influenced by the conditions of formation which include rate of heating, temperature and pyrolysis pressure, and the nature of lignocellulosic precursor. The fact that there are variations in heat conditions during torrefaction has a consequence of leading to production of char that show variations in characteristics, hence may have effect on the universal characteristics of char as well as its combustibility. Nevertheless broad studies about the reactivity of chars produced from hemicellulose, cellulose and lignin do not exist. [23]

2.6 Advantages of Torrefaction

2.6.1 Grindability

It may be a requirement that wood is reduced to smaller particles so that gasification can be achieved at high yields. The process wood grinding needs large amounts of energy to compensate for that dissipated before failure but the grindability can still be boosted through torrefaction. After undergoing torrefaction process, wood becomes more brittle and its physical strength decreases hence less energy used to grind it is lowered. For example, compare to untreated woody biomass, specific energy consumption for grinding torrefied logging residues and torrefied wood chips can be decreased up to 6 and 10 times, respectively. In comparison with the original biomass of wood, the process of milling a torrefied wood using a hammer mill required as less energy consumption as by 85 percent. This results to an increase in the throughput by well about 2 percent to 6.5 percent. It is worth noting that there are no results from full scale torrefaction grinding have been published, whether with hammer mills or the pulverizer. The grindability is also subject to the technology of torrefaction, in addition to the conditions of milling, the feed-in arrangement and type of milling. [24] [15]

characterized by high inert contents. Pellets formed from woody biomass remain the recommended feedstock for the bioenergy industries that deal on solid biomass. They are compact in nature as well as being regularly shaped hence easier to handle, store and transport in bulk. Energy pellets that are specifically made of wood have high feedstock quality, high ash melting temperature and low ash contents that do not trouble users. Their combustion is friendly to both the user and to the environment as well. [8]

Pelletization is simply a commercial technology; during industrial production of Pellets dies are used to obtain the required cylindrical shapes of the pellets by forcefully passing sawdust through them. Due to the pressing involved and the corresponding friction that results when the particles are pressed against each other and against the wall, sawdust experiences a temperature increase to between 70 and 100 °C, then the lignin component which then acts as a natural binder. The process of mechanical densification is achieved by further subjecting the material to 150 °C. They are cooled down making them hard and remains cylindrically shaped. The ability of the saw dust to form pellets as well as the corresponding rigidity of the so formed pellets is determined by the pelletization temperature and moisture content. At high pelletization temperature and moisture contents during pelletization, less energy is required to drive the process to completion. Raising the pelletization temperature leads to the production of more rigid pellets while increased moisture content lowers the friction between the particles and against the walls during torrefaction, hence may lead to the production of pellets with reduced strength. There is usually major decomposition among unstable hemicelluloses and slight losses in lignin. The plasticity of wood decreases as hemicelluloses and lignin gets decomposed and as a result, the energy required by compression and extrusion increases significantly. Hydroxyl groups functionally contribute towards the binding of particles in the absence of adhesive forces. In order to make the pellets denser, the torrefaction temperature should be kept relatively low since mass loss is directly proportional to the density reduction among the pellets. Increasing the torrefaction temperature also leads to a significant increase in the amount of energy consumed during the manufacture of the pellets. When the pellets are deeply torrefied, the heating value and the hygroscopicity are increased, but the energy yield and the hardness of torrefied pellets are decreased. [20] [27] [28]

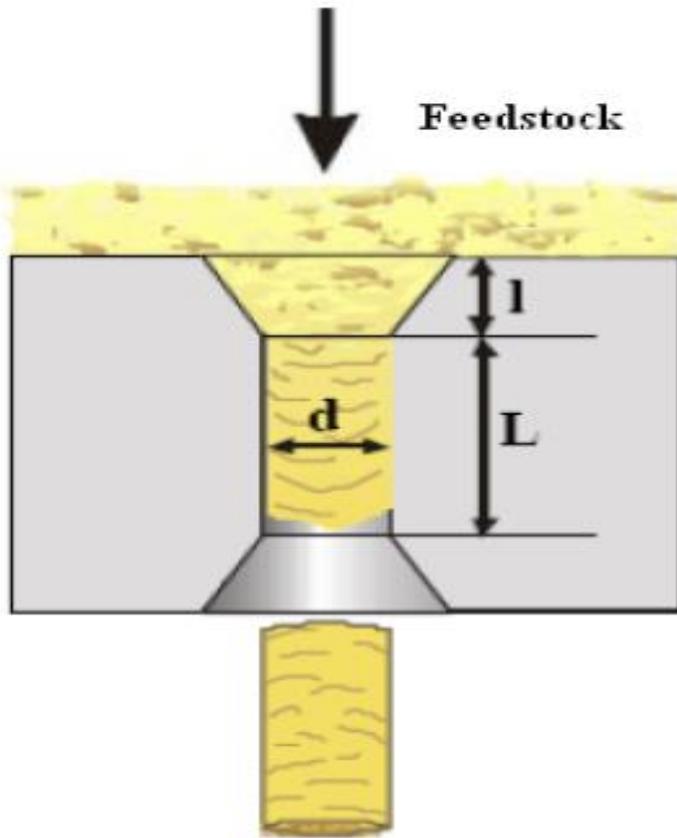


Figure 8: The press of pellet [27]

The produced pellets consist of lower heating value ranging from 16 to 18 MJ/Kg. The thermal efficiencies of the process averaged 94 percent, but the efficiency reduces slightly to 87 percent when the utility fuel is included. The cost of investment lies in the range of 0.15-0.25 M€/MW, while the production cost varies depending upon the scale of production, as presented in figure 4.4. [27]

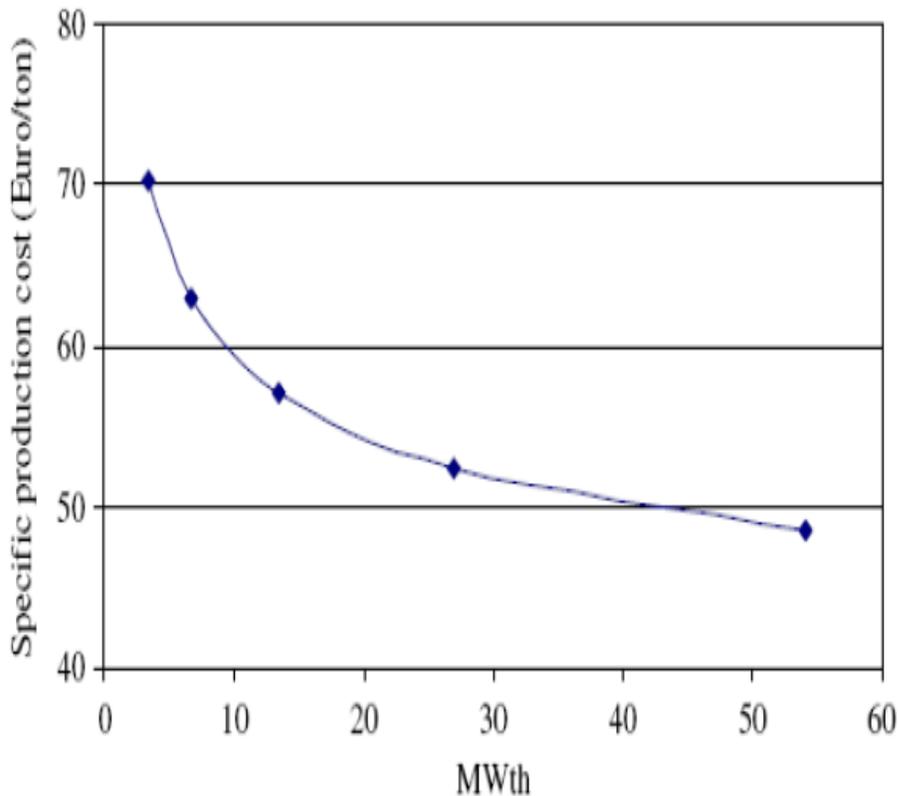


Figure 9: Scaled effect of the cost of Pelletisation [27]

The resultant mechanical strength of torrefied pellets may, in some cases, equal the normal pellets of wood. This is in consideration to the fact that lignin plays a crucial role in the binding the particles of the pellets. It is the same role that is carried out by the existent moisture contents. The process of torrefaction is often accompanied by degradation of lignin and this is dependent upon the conditions of the processes. In this regard, the processes of preparing strong pellets are subject to optimal conditions such as temperature and pressure. Whereas the volumetric energy density of torrefied chips is almost equal to the original material, the step of compression creates the advantage difference. The products that have been subjected to the pelletisation process result in less dust emissions, implying that they can be easily moved for immediate storage, yet they are less vulnerable to the effect of moisture and degradation, compared to pulverized chips and fuels. The energy consumed in the process of pelletisation of a ton of woody biomass is higher than wood pellets. However, there are currently a number of researches that are being conducted to reduce this. High amounts of friction in the pellet press channels result in the generation of heat, which is associated with the risks of fire and dust explosion [24].

Figure 9 illustrates some wood biomass in its different stages. The ordinary wood chips (background) are first torrefied (on the centre, left hand side) and then pelletized on the centre, right hand side). All these steps are indicated in the following picture. [7]



Figure 10: Untreated wood chips, torrefied chips and torrefied wood pellets [7]

2.6.2.1 Pellet Density

The density of the pellets is a very important aspect of the fuel since it dictates the energy density in a unit volume of the fuel as well as the corresponding rigidity of the pellets. This parameter measure how intense or thorough torrefaction has been done on the fuel. The degree of torrefaction is observed to be inversely proportional to the density. This implies that the density of a pellet is bound to decrease as the torrefaction becomes more intense. This is attributed to the fact that chemically bonded water which is responsible for the compactness of the materials is lost during torrefaction especially when softening is done at a temperature of about 100°C. The torrefied pellets' density can be increased by compacting them at very high pressures while increasing the temperatures in the die. The best quality of pellets can be obtained by increasing the temperature of reaction and shortening residence time. [20]

2.6.2.2 Fuel Properties

One of the most fascinating talking points as far as concerned to this fuel is its calorific value.

The net calorific value of torrefied wood is as high as 20 - 22 MJ/kg while the energy density is as high as $>14 \text{ GJ/ m}^3$. This is far better than the untreated wood pellets whose energy density is merely 10 - 12 GJ/m^3 . It can therefore be seen that treated wood pellets have higher energy density than untreated ones whose energy content per volume are 20 % lower as compared to the torrefied ones. Pelleting is known to have no effect on the calorific value of an object; all it does is just changing the physical state of the material, increasing its density as well as boosting its characteristics, in which it can be handled, storage and transport easily. However, due to the fact that the calorific value is directly proportional to the moisture content of the material, front end stock preparation improves the calorific value of the pellets since it involves the removal of moisture through the use of dryers. The torrefied wood fuel is better than coal in many ways such as possession of low sulphur and ash components. It also burns with better characteristics than non-torrefied biomass. Torrefied fuel is quite similar to coal in terms of its physical and chemical properties. In fact, the chemical and physical properties of torrefied material are so close to properties of coal; therefore torrefied pellets can be combusted or co-combusted in power plants that are fire by coal, thereby reducing the extra cost incurred in installing incineration equipment, and power plants' capacity constraints than as compared to wood pellets that are not torrefied. [26] [7]

2.6.2.3 Torrefied Wood vs. Wood Pellets vs. Coal

Torrefaction eliminates moisture and volatiles characterized by low energy from the roasted woodchips. This produces a product that has a higher energy density (more energy per unit of weight) as compared to wood. The density of the product is almost the same as that of coal and is more easily grindable quite a number of other desirable properties. The importance of the high energy density and the rest of the advantages are shown in the following charts which try to create a comparison between torrefied wood and wood pellets and coal. [12]

The complete set of comparison between Torrefied Wood vs. Wood Pellets vs. Coal in different Characteristics are presented in Appendix 1.

2.6.2.4 Use of Torrefied Wood Pellets

The rapid growth that has recently been witnessed in wood pellet industry is mainly attributed to the urge to eradicate the emission greenhouse gases especially in Europe as well as price hikes in oil and natural gas. Due to the fact that torrefied pellets energy dense and possess high hygroscopicity characteristics, torrefied pellets are recommended for use in thermal power plants to substitute coal as well as for long distance transportation for instance from North America to Europe for export purposes. Across the world today, many plants dealing with torrefaction have been constructed, are under construction or have officially been launched. For instance, two main jointly operating programs have been established in Europe and Canada with the aim of conducting demonstrations on pellet torrefaction. One of these plants is to be situated in BC Canada with an anticipated annual yield of 30000 tons of torrefied pellets by the year 2015. [28]

The treated wood is produced particularly for the purpose of co-firing purposes in the already established power plants that use coal as the main firing fuel. The use of wood in ordinary power plants has promising results due to the fact that the established power plants have sufficient infrastructure and market volume and the fuel properties are close to similar, hence a likely occurrence of avoiding unnecessary expenditure is expectable. Torrefied wood and coal fuels exhibit similarities in the way they are handled and stored, hence can lead to a reduction in costs of investment and transportation from one plant to another one. Mixing coal with torrefied pellets leads to a remarkable reduction in the CO₂ and SO_x emissions when comparing the torrefied material co-firing to pure coal utilisation, hence the achievement of the net profits of carbon dioxide certificates. The diversity of the fuel basis is also as well as the objective of green energy production handled through developing renewable energy sources. The gas evolved during the torrefaction of wood biomass is purified to remove the dust and any other foreign materials before being passed through the incinerator for combustion. After they have been incinerated the gases attain temperature of 1000 °C, and this amount of heat is sufficient for maintaining the temperature of the rotary furnace high enough as torrefaction progresses. The flue gases discharged into the atmosphere are still hot enough with temperatures as high as 200 °C, and can be passed through the belt drier since this heat may be employed to dry the untreated wood chips reducing their moisture content down to below 10 %. The gases used as drying agents alongside the steam are discharged into the atmosphere with less than 20 mg/Nm³

of dust content. The level of the contaminants in the flue gas is substantially low, and so is the load to the environment. [7]

2.6.2.5 Rationale and Objectives

The mechanical characteristics exhibited by the pellets are dependent on both the biomass composition and the processing conditions. Due to the fact that hemicelluloses and lignin are all exposed to thermal decomposition during thermal treatment, and the quantity of the hydrogen bonding sites is reduced, the strength of the pellets made from torrefied materials can be expected to be lower than those made from non-torrefied wood. The low moisture content of the torrefied wood causes increased glass transformation temperatures of the rest of the hemicelluloses and lignin, and can result in the reduction of interdiffusion of the wood polymers between adjacent particles. This can consequently form solid bridges between these particles. The pellets formed under such conditions show undesirable properties, such as brittleness and low stability as compared to those made from non-torrefied wood. The only way of improving the physical characteristics of the pellets is by ensuring that the particles are effectively bonded. Short chained fatty acids or mono glycerides should be added to the wood to substitute the bonding sites that are lost and hold together the hydrophobic surfaces of the wood and remaining polar groups on the wood polymer. This is a technique used in ensuring appropriate bonding between the particles. Another way of achieving this is by adjusting the conditions of torrefaction, so that only few wood polymers are decomposed to ensure that there are enough hydroxyl groups on the wood polymer chains to make the particle strongly bonded. This is done by reducing treatment time, torrefaction temperature, and varying the torrefaction medium. [9]

The pellet durability is one of the crucial characteristics that aimed at minimizing their breakage on course of handling and use. Moreover, pellets are also hygroscopic and breakdown when subjected to moist environments. In this regard, increasing their resistance is one of the important properties for handling and storage. Pelletized properties are described based on the cylindrical dens that are achieved through compaction of loose fuel, which can be automatically directed into boilers because they have desirable flow ability [29] . Pellets have widely attracted a commercial interest because they can be used for the generation of electricity, as well as for heating purposes. Pellets find application in the grate firing systems, which are often preferred for power and heat production. The durability of pellets is dependent on the moisture content,

size of particle distribution, conditions of densification, content of moisture, size of particle and length to diameter ratio. Despite the fact that the area has attracted a lot of research, aiming to improve the durability of the pellets, most of the pellets in the market are still sensitive to moisture. Exposure to snow or rain results in the disintegration of the pellets. In this regard, there is always the need to exercise caution to the weather when transporting, loading and even storing. [29]

2.6.3 Torrefied Wood Briquettes

Another product, which can come from torrefaction of wood, and is environmentally friendly energy sources, is Briquettes. To upgrade the fuel and raise its standards to the required levels, most power generating companies have considered the use of pellets and briquettes. However, most power generators that are fired by coal pulverize coal in the ball mills and scatter the ground fuel into the combustion chambers. This leads to the formation of thread like mats and fibres that causes system clogging and hence inefficiency especially if long term use is to be considered. Roasting wood makes it brittle if the temperature reaches a certain level making it easily breakable into tiny crystals using a hammer. The manufactured chunks from torrefaction resemble coal and share certain properties with coal such as burning, and physical properties with the only difference being the fact that they have much greater heat energy by weight and are sustainably renewable, meeting the mandated criteria.



Figure 11: Torrefied wood briquettes [10]

As an alternative fuel to coal torrefied wood briquettes are now being used globally. The main reason which makes such fuels desirable for co-firing in existing coal-fired power stations is its improved grindability in comparison with untreated or clean wood. [10]

2.6.4 Transportation

Consisting high amount of energy per cubic meter in torrefied wood makes it more cost-effective to dispatch compare to wood pellets. During the torrefaction process, the density decreases following a decrease in mass, but the volume may remain the same. Pelletisation decreases the volume, result in transportation makes easy. On the other hand, it makes increasing in the energy density of torrefied biomass and decreasing the risk of dust emission, which makes by non-densified material, also degradation has less effect on torrefied pellets compare to wood pellet.

Untreated biomass has logistic problems. This problem can be solved by torrefaction and pelletisation, simultaneously. The process makes high energy content. Compare to wood pellets by having 8 to 11 GJ/m³ energy density; these pellets include 15 to 18.5 GJ/m³, result in decreasing costs in long- distance transportation in the comparison with wood pellets. [24]

Considering the regular wood pellet trade, the additional costs of pelletisation are often compensated by the fact that pelletisation reduces the cost of transport. Transportation of pellets

over the ocean is subject to approval based on se regulation. The same applies for the transport of the pellets by train.

2.6.5 Management and Storage Characteristics

The volume to be handled and stored is reduced significantly due to pelletized torrefied material. In comparison with wood pellets, the required mass is less for the same production of energy because of the torrefied pellets' higher energy density. The outcome at the power plant is the significant savings in the process of handling and storage, especially if there is no need for weather protected storage. Another vital aspect is the torrefied material's hydrophobic character. Unsaturated non-polar groups substitute OH-groups, leading to a significant loss in the capacity to absorb water. The torrefied materials' hydrophobic characteristic makes the fuel to be less sensitive towards degradation, moisture uptake and self- heating. After torrefaction, moisture and water absorption decreases based on the level of torrefaction. For example, time and relative humidity at a given ambient temperature dictates certain torrefied pellets' hygroscopic characteristic. The use of other feedstock types, binder or additive may show varied outcomes.

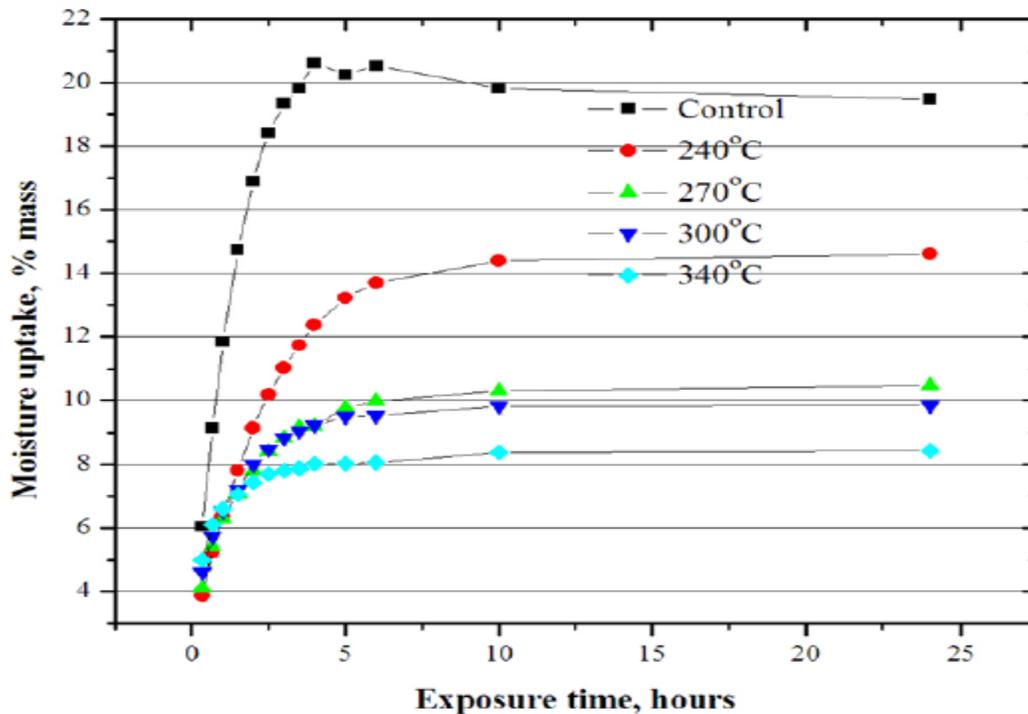


Figure 12: Hygroscopicity of 6 mm pellets made [24]

Apart from hygroscopic absorption, water absorption is also experienced upon exposure to such liquid forms of moisture as rain. This absorption of water has indicated leaching that is of unknown composition. In large power plants, the main concern is the risk of generating dust in the storage and handling, rather than the hydrophobic characteristics. This is so because the dust has the ability to explode highly.

Both White Wood pellets and Bark Pellets produce dust when being handled. If the dust is of sufficiently high concentration and is exposed to oxygen and a source of ignition, it can explode; this will also happen in case the dust is in exposure to temperatures high enough to explode it. After conducting standards tests on Dust Clouds and Dust Layers the corresponding results can be used to classify the dust, a process called dust classification that can be utilized to give directions regarding the precautionary measures that can be considered when handling the substances that produce these dust as well as the mode of design of the facilities used in handling them. Coal and the dust obtained from wood pellets are similar in terms of their minimum explosivity concentration (MEC). Incidences of explosions of coal dust can be alleviated to some extent by injecting incombustible mineral dust, such as limestone at air intakes, so as to maintain the dust level below critical 65 % which is the critical level beyond which explosions can occur for the case of coal dust; even though this method is not applicable in the case of activities handling the wood pellets. [5]

While wood pellets call for silo during storage, torrefied pellets can be stored by means of coverage storage. In conclusion therefore, the self-heating risk is not sufficiently addressed. This is as a result of insufficient torrefied biomass quantity availability for practical testing. Small scale research results indicate that torrefied pellets show off-gassing at a slower rate in the storage stage. The pellets also indicate a varying carbon-monoxide-carbon dioxide ratio, in comparison with regular wood pellets. However, the resultant release of off-gas is equal to the released gas from regular pellets.

Torrefied pellets are ideal for long-term storage; meanwhile the management and transportation costs are lesser than wood pellets, because of the lower water content. [7]

3. STEAM EXPLOSION

3.1 Introduction

For the first time, steam explosion was introduced in 1928 and 1932 in two patents.

The first patent, explained the results of steam explosion on the pine by applying saturated steam at 218°C to 262°C for 0.5 to 5 seconds, which was quickly released, then the pine affected by aqueous extraction and fermentation. The second patent represented tools, which can apply to utilize steam explosion on an industrial scale. Masonite boards have been produced based on this patent.

Steam explosion has been recommended for enzyme treatment or production of chemicals such as ethanol through pre-treatment of woody biomass. Fermentation is needed to produce ethanol. Earlier to fermentation, lignocellulosic materials need to be pre-treated and/or hydrolysed with acids and/or enzymes in order to obtain carbohydrates, which are needed for microorganisms fermenting. [30]

Whenever fermentation process is required, this pre-treatment procedure is mainly used resulting in fuel increase and fermentability of chemicals of lignocellulosic hydrolysates. [29] Steam explosion leads to changes in the chemical composition as well as particle size enhance the process of hydrolysis and increase the output of ethanol. [31]

In fact, this method applies to pre-treat lignocelluloses to separate the characteristics of wood in the primary components; cellulose, lignin and hemicelluloses. This process employs the application of steam that is saturated. After the steam is transferred out, the product is subjected to a faster depressurisation that occurred after inducing change in the properties of the plant cell wall, and making wood to be reached easily as illustrated in Fig. 14 [29]

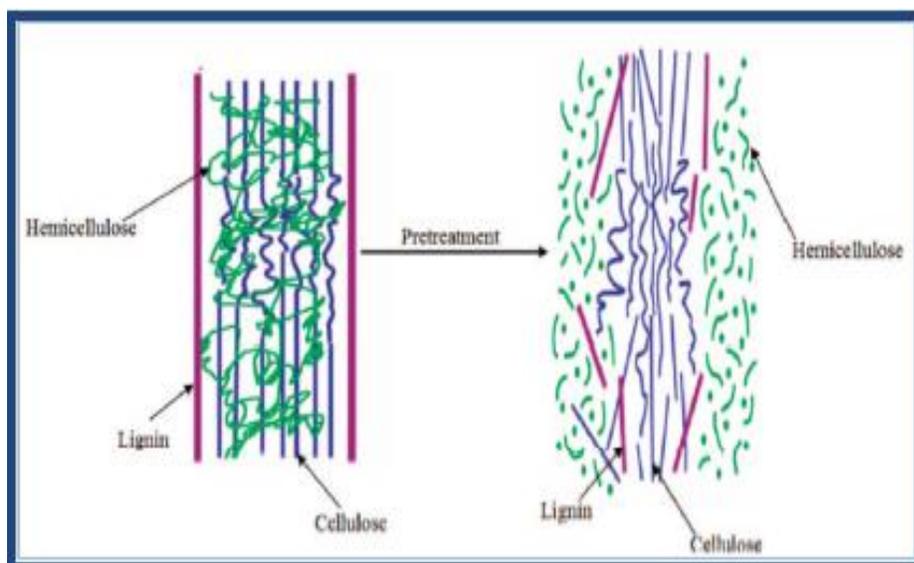


Figure 13: lignocellulosic materials to be changed by steam explosion [29]

In comparison with raw wood the steam-exploded wood shows a change in the chemical characteristics, hygroscopicity, colour, hardness, texture, value of calorie and thermal conduct. Incomplete hydrolysis of cellulose is the outcome of steam explosion with the inclusion of volatile characteristics, lignin plus other carbohydrates. There is the potentiality of other accessible links of glycosidic, lignin β -ether and complex bonds of lignin-carbohydrate to be discovered. Extraction of better chemical components is aided through this fraction to be applied in the paper and pulp, composites of biofuel industry or textile. For example, elements that are soluble in water (hemicelluloses) and alkali (lignin) may be separated with alkali removal and wastes. [29]

Bundle fibres play the foundation role for wood. This is because the fibres of cellular structures that are typically bonded together are usually generated wholly. Possessing bigger mechanical weights and to repel enzymatic and chemical breakdown via microorganisms represents their natural role. The main technical hindrance for many processes of bio-refinery is the overall property of fibres of plants. [31]

Defibrillation of the bundle of cellulose is facilitated by instant pressure. The end result of this is the access of fermentative enzymes to the fibres is enhanced thus facilitating the processes of fermentation by enzymes as well as hydrolysis. In relation to the temperature and residence time, any substance from the fissures to finished defibrillation in the structure of wood can be the

outcome of the process of SE. When acetic acid is released from the wood, the components of the cell become partly hydrated. [31]

Overall, the treatment affects significantly on the lignocellulosic structure, hydrolysis of the hemicellulosic fraction, depolymerization of the lignin components and defibration. Therefore, cellulose components availability to degrade by enzymes is substantially increased. [32]

3.2 Procedure of Steam Explosion of Wood

Steam explosion method has been considered as one of the best handling methods for removing lignin from wood biomass. The method works best in hardwoods but not in softwoods due to the fact that the latter contain high quantities of lignin in condensed form. According to the method, wood chips are treated with steam at high pressure before the pressure is lowered through quick release. The wood structure ruptures due to rapid expansion of the liquid its chips. This process releases acetic acid which hydrolyses the cell components. [33] The cell walls of woody biomass are majorly made of polysaccharides and aromatic polymers called lignin. During the steam explosion (SE) process, woody biomass is exposed to saturated steam whose temperature ranges between 180 °C and 240 °C with a wide range of residence time. This causes changes in the wood structure both morphologically and chemically. SE pre-treatment normally disrupts the carbohydrate bonds through introduction hemicelluloses into solution. It also causes significant changes in the structures of both cellulose and lignin based on the severity of the process. [34]

The steam explosion can be explained using two types of reactions related to lignin decomposition and structure alteration. The first reaction is rather a rapid one and involves the depolymerisation of long chained lignin and hemicelluloses by acidic hydrolysis. The second is as a result of continued heating and it involves the condensation and repolymerization leading to increased acid insoluble residue which is called klason lignin. [35]

The percentage of lignin is usually observed to slightly increase after SE pre-treatment probably due to condensation and repolymerization reaction between degrading materials of hemicellulose and lignin. Some hemicellulose components with high reactivity like furfural may react with lignin and cause an increase in portion of acid insoluble lignin. Severe modification of the structure of lignin can also result into increased apparent production of lignin. [36]

Wood combustion also occurs in two steps where the first one is as a result of cellulose and hemicellulose while the second is in due to the loss of lignin with the aromatic structure. [35] The decomposition of hemicelluloses starts nearly instantly when the treatment is in progress and

the fact that it is not recommendable that the hemicelluloses and fibres be destroyed, suggests that the conditions should be kept as gentle as possible. These conditions are also required to be optimum, so that the useful chemicals and enzymes can gain full access to the structure of the wood. [33]

The residues exposed to steam explosion are more thermally stable than the initial cellulosic portion due to the fact that the native residue have higher hemicellulose content. The structures of hemicelluloses are made up of many saccharide groups and apparently assume random amorphous form. It has a lot of branches that are easily separable from the main chain before decomposing it into volatiles under low temperature conditions. The explosion of steam can open up the structure of wood unless it occurs under extremely harsh conditions in which it will substantially decompose the wood polymers, mainly the hemicelluloses, leading to the formation of a residue that is quite difficult to manage and handle. [35] [33]

Despite the fact that SE pre-treatment significantly contributed towards altering the hemicelluloses, its impacts do not depend on the thermal degradation of cellulose under the examined conditions. The stability of cellulose is due to the intra-molecular and intermolecular hydrogen bonds that occur repeatedly along cellulose chains. Thermal destructing the cellulose structure using heat creates cavities inside the microfibrils. [36] [35]

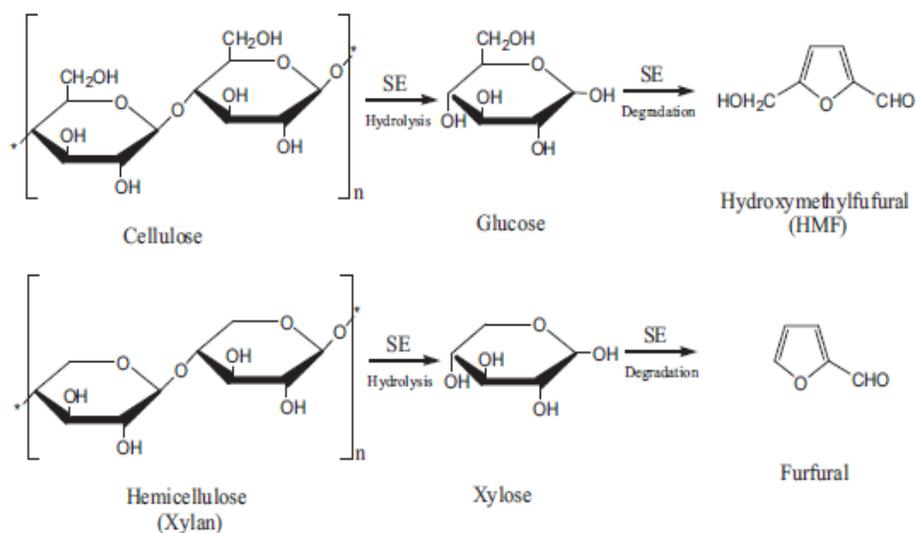


Figure 14: Reaction collocations for sequential disintegration and degradation reaction of cellulose and hemicellulose (xylan) during steam explosion [36]

Microfibrils are rooted in a hemicelluloses matrix and lignin with the polar surfaces of the cellulose fibrils linked to by hydrophilic hemicelluloses. This forms in the neighbourhood a gel-like matrix. Wood cells that are hollow tend to be wrapped by cellulose micro fibrils that are semi crystalline bundles of molecules of cellulose held to each other by hydrogen bonds. Figure 5.5 illustrates the way the plant cell is arranged into separate layers. Micro fibrils that appear to be loosely attached and not structured according following any pattern form the primary cell wall. This permits stretching of the cell as it grows. In the event of growth of cells, the secondary wall is formed on the inside of the primary wall and possesses three layers S₁, S₂ and S₃. S₁ and S₃ represent the outer layers and are 0.2 and 0.3 μm respectively and thickness is 0.1 μm . The S₂ layer is stronger and is almost 1-5 μm in thickness.

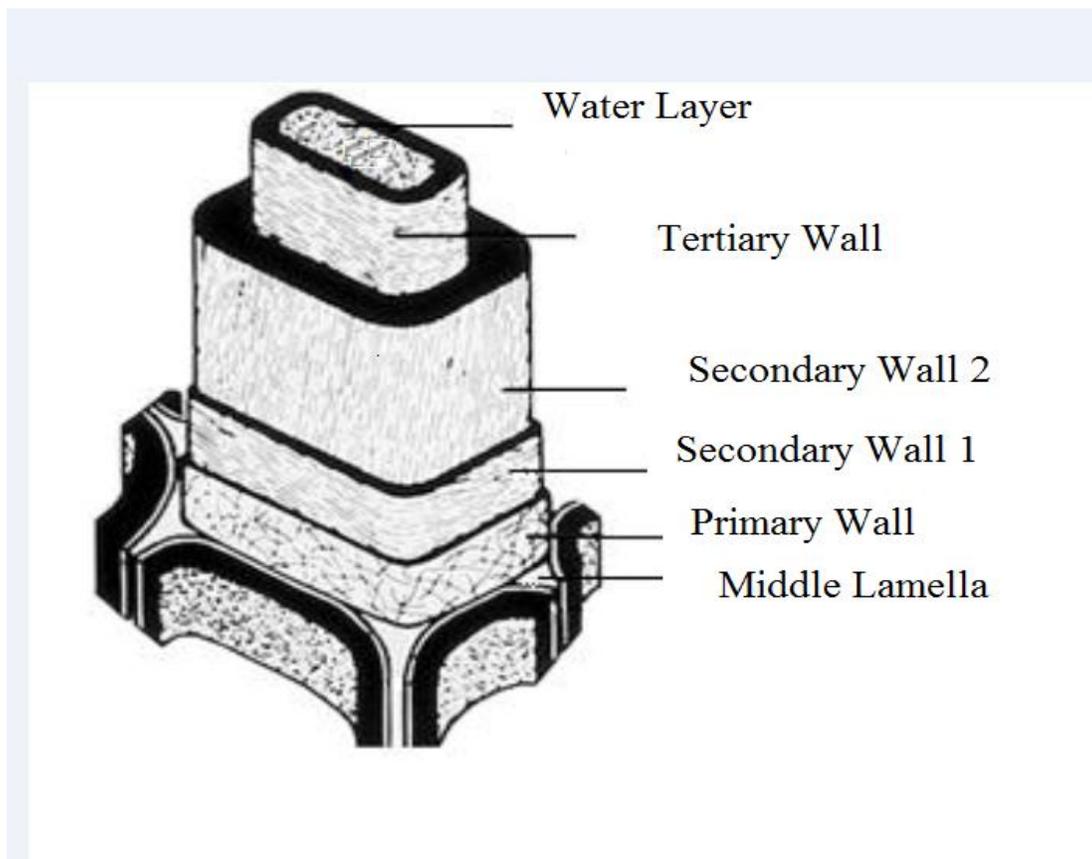


Figure 15: represents structure of cell wall of softwood tracheid and fibers of hardwood in a simple form [31]

As temperature increases hydrogen bonds in cellulose gradually collapse and the microfibrils become softer. The cavities gradually consolidate forming a net of pores and the gases

responsible for degradation exits the cellulose matrix, leading to significant loss of mass. When the surrounding atmosphere is inert, cellulose decomposes into carbonaceous residues, a combination of polycyclic aromatic compounds. The lignin splinters separate from the dioxin extract are transform into carbon fibre and adhesives. When the lignin of secondary wall (s_2) middle layer exposes to steam, it decomposes and becomes more extractable as compared to the rest of the parts. The enzymatic susceptibility increases as the remaining quantity of lignin diminishes. The ease of extraction of secondary wall lignin of ray and axial parenchyma cells becomes higher as compared to fibres and vessels. [35] [37]

The steam explosion has three basic influences which include hydrolysing the hemicellulose fraction, inverting the lignin structure and the reduction the alkali ion content of the samples. This effectiveness of this method of pre-treatment can be achieved by adding sulphuric acid or sulphur dioxide to catalyse the involved reactions. Impregnation additives should be introduced into the process for the purpose of reducing the duration, temperature and formation of inhibitors before the enzymatic steps since impregnation additives such as sulphuric acid or sulphur dioxide is known to significantly boost the enzymatic digestibility of softwood. [38] In the recent times, there have been attempts to raise the delignification effect of softwood biomass by carrying out pre-treatment using steam explosion that is catalysed by sulphur dioxide. In this reaction, SO_2 is used as a catalyst and it improves the productivity of the pre-treatment through the shortening of the required residence time and/or the temperature of the process. Steam treatment catalysed by sulphur dioxide leads to severer degradation to the structure of lignocellulosic softwood. It has found most of its long time applications, in the efficient pre-treatment softwoods waiting for bioconversion. It causes efficient solubilization of the hemicellulosic component as well as producing water insoluble cellulose with high amenability to enzymatic hydrolysis. The use of SO_2 makes it to be uniformly distributed in the wood chips and the unabsorbed, remaining SO_2 is recycled for utilization in subsequent processes, thereby economizing the catalyst. [39] [40]

The end products of this pre-treatment technique include a solid fraction that is made up of lignin and cellulose to a larger extent. It also produces a prehydrolysate; a compound of hemicellulose-derived monomeric sugars, little carbohydrates, products of sugar and lignin decomposition, acetic acid, and some other products. It is important to note that the so formed products can inhibit hydrolysis and fermentation processes. Despite the fact that SO_2 -catalyzed steam

explosion is an important pre-treatment technique for softwood its effects on the environment are quite devastating, due to the fact that it uses sulphur dioxide; a well-known environmental pollutant. For the purpose of protecting the environment, it is recommended that environmentally friendly ways of converting cellulose and lignin contained in wood biomass into their useful forms should be devised. [39] [41]

3.3 Pelletization

Steam explosion has been considered a very promising technology as far as improving the quality of wood pellet is concerned. There are recent ideas to involve this concept in ensuring that the produced wood pellets are of higher quality than ever before. It is characterized by the separation of major woody biomass components such as lignin, cellulose and hemicelluloses through a combination of both chemical decomposition and physical deformation. The sub-processes occurring during steam explosion include adiabatic expansion of water inside the pore of wood tissue and auto hydrolysis of cell components. As pelletizing process occurs there is melting of lignin on the pellet surface leading to the formation of hard layer around it. Steam treatment leads to the production of highly durable pellets. That is the pellets produced from steam treatment are up to 100 % durable and hence much better than the conventional ones as far as durability is concerned. [42]

The colour of pellets are generated from the process of steam explosion tends to be dark brown. These pellets are also stiffer as compared to traditional wood pellets. They fail to be abrasive and are stabilized greatly towards moisture similar to the typical wood pellets. The pellets that have gone through steam pre-treatment have a significantly greater bulk density with different values relative to traditional wood pellets. [31]

It is hypothetical that the use of SO₂ catalysed steam treatment can be used to produce wood pellets with impressive quality besides employing the so produced pellets as a feedstock for bio-ethanol production. SO₂-catalyzed steam pre-treatment drastically disrupts the rigid structure of wood. Steam treatment greatly boosts the physical properties of corresponding pellets. Another important characteristic of pellets that steam treatment catalysed by sulphur dioxide improves is the density of the pellets which increases and betters that of conventional pellets. The mechanical properties of pellets made of steam treated material improve. The pellets that pass through the steam treatment are on average denser than the conventional ones for obvious reasons. The production of particles with finer texture as a result of SO₂ catalysed steam treatment enhances

the achievement of desirable compactness when the materials are being densified. This process also leads to the increment in the levels of lignin and sugar contents which in turn introduce more binding effects thereby making the pellets relatively stronger mechanically.

The steam treatment of wood using Sulphur dioxide catalysed substantially reduced the particle sizes, thereby making the pelletization process easier and less involving as there is no need for further reduction of the particle sizes before subjecting them to pelletization. This also results into time saving during the process. When particles are first treated using the sulphur dioxide catalysed steam method, the so formed pellets show significant improvements in terms of their physical strengths as well as being economical in terms of the energy used in their densification. Such pellets are unaffected even under high humid conditions, a property that makes them ideal for prolonged storage and transportation. The treated pellets possess qualities, such as high calorific value coupled with low ash content value and high recovery of the original carbohydrates which make them suitable feedstock for both thermochemical and biochemical conversions, respectively. The resulting pellets are twice as dense as the conventional one, resistant to moist conditions, high calorific values alongside low ash content, high resistivity to breakage, with unchanged carbohydrate contents. Nevertheless, grinding the wood chips followed by steaming, and a pursuing densification operation required elevated amounts of energy, therefore constraining the economic attractiveness of the entire process. [40]

3.4 Significant Process Parameters

Temperature and residence time are two main factors which control steam explosion effect.

Nevertheless, there are other factors which affect the results and must be considered during enhancing the steam explosion process. These factors include: wood source, chip size, and moisture content. [33]

The initial content of moisture largely affects lignin recovery, hemicelluloses, and cellulose sugars in the resulting processes [43]. Based on the theory, a substrate that is hydrated and hydrolysed easily is formed generated from a perfect process of pre-treatment. Nevertheless, it fails to allow for the formation of inhibitors of fermentation and products of sugar degradation. The parameter known as “severity factor” determines the assessment of the pre-treatment process. This parameter is a product of the effects of acidity, temperature and pre-treatment length put together. The severity factor has been used in researches pertaining to the pre-treatment of biomass when the pre-treatment outcomes require to be combined; however the

severity value that comes up is fails to be accurate. Therefore, it can be mentioned that this parameter is applied to attain approximate values alone. [44]

Standardization of the parameters is necessary to enhance comparison of process parameters. For example, the reduction of the degeneration of products is among the main issues currently being studied. As such, it is quite imperative relating the overall production to pre-treatment severity. [45]

Studies of the past, which focused on pulping industry, have encountered this while investigating the effect of steam processes on parameters like accessibility of pulp enzyme, temperatures and time for treatment cannot be replaced [46]

Regarding this observation, a simulation to describe the severity of SE during pre-treatment relative to the temperature and residence time effect when put together has been done. [47]

Hence, it results in the aspect of persistent severity for any temperature and residence time sets. The model is based on the assumption of process kinetics is in the first place, and follows the law of Arrhenius.

$$K = A e^{-E_a/RT} \quad \text{Equation 5}$$

Where, k represents rate constant

A represents Arrhenius frequency factor

E_a represents activation energy (kJ / kg mol)

R represents universal gas constant (8.314 kJ / kg mol K)

T represents absolute temperature (K)

$$R_0 = \int_0^t \exp [(T_r - T_b)/14.75] dt \quad \text{Equation 6}$$

Where, Reaction Ordinate is represented by R_0

Residence time (min) represented by t

Reaction temperature (°C) is represented by T_r .

Base Temperature at 100 °C is represented by T_b .

(14.75 is the traditional energy of activation assuming that the whole treatment is hydrolytic and the whole change is first order).

The factor of severity is provided by the reaction ordinate's log value; it is thereafter used to determine the effect of SE during the process of treatment.

$$\text{Severity} = \log_{10} (R_0) \quad \text{Equation 7}$$

Where severity stands for the severity factor and R_0 represents the Reaction Ordinate. There is deficit of content of moisture of feedstock and size of particle which are disadvantages of this model. These bear a powerful effect on the kinetics of SE process, including physical and chemical changes. When extremely higher contents of moisture are present in feedstock, the kinetics slows down as the void spaces and wood get filled with the condensate before reaching the temperature of the steam. [31]. The aim of SE prior to treatment decides choosing of parameters and severity index of the process. Wood destruction starts at around two, and at a greater severity ($R_0 > 4$), the reactions of dehydration and condensation occur, leading to sugar degradation. Woody biomass R_0 must be in the range of 2-4 to facilitate conversion, nevertheless, it can be larger when the aim is to improve the hydrophobicity and heating value, that is, formation of pellet. [31]

The effects of steam explosion can be modified by varying the temperature and residence time resulting into effects such as causing cracks in the structure of wood and complete defibrillation. This makes the process applicable in achieving many other functions in or outside the energy industries. [33]

3.5 Advantages and Disadvantages of Steam Explosion

The application of SE in wood treatment has gained substantial popularity in the recent past especially through the previous decade since it has been seen as a promising technique capable of chemically and structurally transforming the lignocellulosic biomass. This has an implication that appropriate exploitation of steam explosion could result into positive industrial revolution as far as energy and environmental protection are concerned. [36]

Steam explosion also finds its importance in the preparation of cellulosic feedstocks prior to enzyme catalysed hydrolysis and sugar fermentation. Recent developments in the cellulose technology have resulted into the attractiveness of enzymatic saccharification of wood waste. Steam explosion has been proven to be a factor that facilitates the enzymatic actions of certain enzymes on certain wood species. Xylose and xyloosigosaccharides can be obtained from the water extracts and as a sweetener and/or food additive. The extent to which these alternatives are economically feasible is dependent on the possibility of developing a technique that can be used to simultaneously produce desirable quantities of pure hemicelluloses, lignin, and cellulose components. Fractionation processes occur in accordance with the pre-treatment which makes the lignocellulosic structure more reactive as well as the subsequent treatments that makes the

hemicelluloses and the middle lamella and the fibres' cell walls to dissolve. It is hence of great importance to note that the cellulosic residual also very useful as it is isolated and subjected to further hydrolysis producing bio-ethanol. [35] The process of biological conversion to obtain ethanol from the lignocellulosic woody biomass occurs in three major steps which include the following: the first stage is pre-treatment whose main objective is to make the substrate more accessible. This is then followed by the enzyme catalysed hydrolysis of the carbohydrate fractions into simple sugars and then the final step which involves the fermentation of so formed monomeric sugars into ethanol. It has been evidently proven that pre-treatment is a very instrumental step in the conversion of wood to ethanol particularly in cases where recalcitrant substrates such as softwoods are used. It mainly affects the entire conversion process as seen in the facilitating enzymatic hydrolysis as well as the fermentation of the resulting substrate. It is advisable that the process of converting celluloses and lignin components of wood biomass into materials and products of much usefulness without generating pollutants such as waste gas, wastewater, and solid waste materials should be achieved using newly designed environmentally friendly techniques. This is of course for the purpose of protecting the environment at global levels. [48] [41]

A positive effect attached to the processes of steam pre-treatment is a result removal of a large part of the hemicelluloses. The consequence of this is that the cellulose fibre reactivity increases. This may be due to the fact that enzymes have the ability to access cellulose with ease. [49] Hemicelluloses and lignin on the other hand are used in the industrial production of more useful chemical products such as medical ingredients, food additives and other important industrial chemicals. [35]

When we compare the process of steam with other mechanisms of pre-treatment, the SE process is very unique. For example, the environment is less affected, reduced capitals costs and less hazardous process chemicals are incurred, there is improved effectiveness towards energy production, chemicals for the process as well as conditions are less damaging and sugar can be retrieved completely. The process of SE can employ lagers sized chips, unnecessary addition of acid catalyst with the exception of softwoods and facilitate sugar recovery to the highest degree. This represents the major vital benefits of the process of steam explosion. The products which result from the process of hydrolysis are adequate and can be applied in industrial development of a large scale. More credit is awarded on the fact that energy employed to small sized chips

prior to pre-treatment can make up for a third of the energy that is required to bring the process to the end. Discussions have also been raised regarding the prevention of catalysis by use of acids, and the based on the notion that this is advantageous. However, when there is inclusion of acid catalysis, the digestibility of cellulose can be improved, the hydrolysis of hemicelluloses can also be improved and the production of degraded compounds is also reduced with respect to temperature ranges. A pre-treatment procedure that is a success required low costs and reduced energy use, therefore, it would be appropriate to have particles with large sizes and without use of acid for the optimization of the influence of the process. [44] [35]

The following list is the advantages of SE when compared to other pre-treatment techniques for application of lignocelluloses chemically: [50].

- 1) There is enough yielding of hemicelluloses with reduced number of by-products that have been broken down.
- 2) The corrosion of equipment is reduced because of mild pH of the reaction material in relation the processes of acid hydrolysis.
- 3) There is prevention of handling of acid and the stages of recycling.
- 4) The effect of explosion results in the breakage of the solid material ranging from bundles to fibre pieces. [50]
- 5) The fact that SE process employs a restricted chemical application, does not result in excess sugar dilution and requires input of low energy that does not involves any costs of recycling makes the process unique. [44]
- 6) SE is appropriate for hardwoods; besides, it may not be efficient for softwoods whose pre-treatment critically demand application of an acid catalyst. [44]

In case of disadvantages can mention to defective break down of the matrix of lignin and carbohydrates. The consequence of this is the condensation as well as precipitation of the soluble elements of lignin and hence rendering the wood digestible to a reduced degree. A part of xylan is destructed in hemicelluloses. There is also the probability of generation of inhibitors of fermentation at higher temperatures. Lastly, it leads to the necessitation of washing the hydrolysate that may facilitate a reduction in the generation of saccharification by 20-25% of the original dry matter due to the removal of sugars which are soluble. [44] Nevertheless, sugars and

lignin make degradation products which need to be considered on the way to lessen the possible negative outcome on upcoming steps. [32]

There are a few limitations encountered by the process of SE when an acid is introduced. Besides, there are a number of pre-treatment procedures such as SO₂-explosion which have adopted the use of external incorporation of acid (H₂SO₄) to act as a catalyst for the hemicelluloses solubilisation, thus lowering the temperatures required for pre-treatment and also offer partial cellulose hydrolysis. The fundamental limitations related to the inclusion of acids pertain to equipment needed and an enhanced generation of the compounds that have been broken down. The process of steam explosion that is under catalysis SO₂ is usually regarded to be among the excellent pre-treatment methods for softwoods. [44]

Steam Pre-treatment process entails risks during production of compounds like HMF, phenolic which are soluble and furfural. These compounds limit ethanol fermentation as well as methane production. Bacteria that are able to generate methane, however, have the ability of adaptation to a certain degree and produce methane in the presence of these compounds. Besides, there are no facts to proof that greater ethanol or methane generate compensates which are costly regarding the step of the second pre-treatment. [49]

The most crucial limitation of the process of steam explosion pre-treatment is the breakdown of hemicellulose that has taken place to a certain degree and the generation of compounds that are toxic which could bear some effects on hydrolysis and fermentation processes that are bound to occur thereafter. The quantity of the toxic compounds that have been generated is determined by the raw materials as well as the pre-treatment intensity. This is the reason it is imperative to apply robust pressure in the fermentation process that proceeds. The most crucial inhibitory substances include phenolic compounds, weak acids and derivatives of furan. The most fundamental furan derivatives include Furfural and 5- hydroxymethyl furfural which are produces from the breakdown of pentose and hexoses respectively. Regarding the process of batch fermentation, they are also both categorized as inhibitory substances where there is over extension of the lag phase. [44]

4. CASE STUDY AND CALCULATIONS

Final fuel for both technologies is Pellet. The objectives of this chapter is to quantify and compare energy pellet from treated materials of torrefaction and steam explosion technologies as well as energy balance in both technologies discuss toward pelletization, final results established in tables 1,2,3,4, and 5.

The feedstock considered in the review is the mixture of 70 % small diameter wood with moisture content of 40 %, and 30 % logging residues with moisture content of 45 %. Energy balance and energy pellet calculations start first on torrefaction plant followed by Steam explosion next.

4.1 Torrefaction

Calculations to find energy balance and energy pellet in torrefaction process accomplish based on some approaches and assumptions. The following data have extracted based on previous investigations on torrefied fuels. [51] [52]

These following approaches and assumption are used in the calculations:

- Biomass and air enter in the unit at ambient temperature of ($T_0 = 0^\circ\text{C}$)
- Torrefaction ultimate temperature and residence time for the process is 230°C (T_{ut}) and 10 minutes, respectively.
- During the torrefaction process 15 % of the dry biomass is converted into volatiles and volatiles carrying 5 % of the thermal energy.
- Moisture in torrefied biomass is 6 %.
- Capacity of the torrefier is 600 Kg/h produces torrefied dry ash free biomass from raw biomass.
- C_{pw} , specific heat of raw biomass, is 1.46 KJ/Kg $^\circ\text{C}$
- C_{pd} , specific heat of dry or torrefied biomass, is 0.269 KJ/Kg $^\circ\text{C}$
- T_{st} , torrefaction starting temperature, is 200°C
- L , latent heat of vaporization at 100°C ($L= 2260$ KJ/kg)
- C_g , specific heat of flue gas, is 1.13 KJ/ Kg $^\circ\text{C}$.
- C_v , specific heat of steam, is 1.89 KJ/ Kg $^\circ\text{C}$.
- T_{gi} , temperature of gas at inlet of torrefier plant

- T_{go} , temperature of gas at exit of torrefier plant

Numerous items such as biomass handling, preparation, dryer, torrefier, and product cooler make a common torrefaction plant to carry out biomass handling and pre-treatment like chipping, grinding of the biomass if fine particles are needed, its drying, and finally torrefaction.

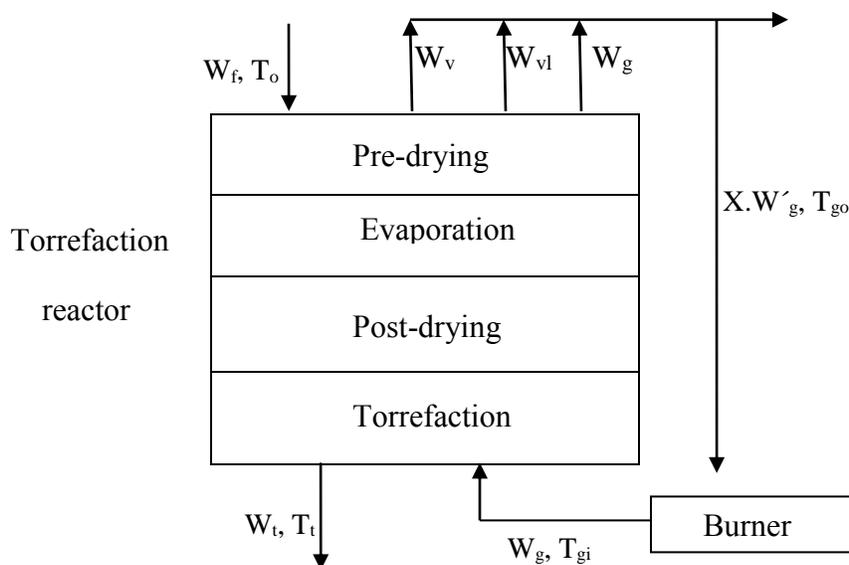


Figure 16: torrefaction unit [51]

In torrefaction reactor, the feed is heated to the torrefaction at starting temperature, T_{st} , in the steps of Pre-drying, Evaporation, Post-drying, and finally Torrefaction. The first three stages are called drying. Calculation on each stages is accomplished, separately.

4.1.1 Pre-drying

This is the first step in the process. When the biomass is heated from room to the drying temperature around $100\text{ }^\circ\text{C}$, its temperature rises gradually receiving tangible heat from the reactor or the heating medium.

Q_{ph} which is indicated by 'equation 1' is needed for preheating feed from room temperature to the drying temperature, taken as $100\text{ }^\circ\text{C}$.

$$Q_{ph} = W_f C_{pw} (100 - T_0) \quad \text{Equation 8}$$

Where, C_{pw} is the specific heat of wet or as-received biomass, W_f is feed rate of raw biomass, and T_0 is feed temperature. (Table 1).

Feed rate of wet biomass (W_f) is:

$$W_f = W_t (1 - w' - \text{ASH}') / (\text{MY}_{daf} (1 - w - \text{ASH})) \quad \text{Equation 9}$$

Where, W_t refers to production rate of torrefied biomass which its value is 600 kg/h (assumption), w' is moisture content in torrefied biomass assumed 6 %, ASH' is the amount of ash in torrefied mixture, MY_{daf} refers to mass yield of dry ash free material, and w is moisture content (Table 1).

To find feed rate of biomass we need to know the amounts of W_t , w' , MY_{daf} , and ASH' .

The solid yield of the torrefaction process can be measured by mass yield. It determines what fraction of the original mass of biomass would stay in the torrefied product. Torrefaction concerns the change in the hydrocarbon content of the biomass.

During torrefaction the mixture loses 15 % of its dry mass, so the mass yield on dry biomass is:

$$\text{MY}_{db} = 1 - \text{dry mass loss}, \text{ on the other hand } \text{MY}_{ar} = \text{MY}_{db} * (1 - M) \quad \text{Equation 10}$$

And,

$$\text{MY}_{daf} = \text{MY}_{db} - \text{ASH}_{db} / (1 - \text{ASH}_{db}) \quad \text{(Table 1)} \quad \text{Equation 11}$$

The ash of the biomass is not lost during torrefaction, although the overall mass of the biomass is reduced. Torrefaction does not change the absolute amount of ash in the biomass.

Ash on wet basis or as received:

$$\text{ASH}_{ar} = \text{ASH}_{db} * (1 - w) \quad \text{Equation 12}$$

$$\text{ASH}_t = (\text{ASH}_{ar}) / \text{MY}_{ar} \quad \text{Equation 13}$$

$$\text{ASH}_{daf} = \text{ASH}_{db} / (1 - w - \text{ASH}_{ar}) \quad \text{(Table 1)} \quad \text{Equation 14}$$

By applying (Eq.1) energy required for increasing specified amount of raw biomass to 100°C in preheater is determined (Table 1).

4.1.2 Drying (Evaporation)

Drying is the most energy-intensive step of torrefaction. It is so applicable for high-moisture biomass since the moisture in biomass is evaporated throughout this stage. There is minimal

change in biomass temperature when evaporation happens at constant temperature until all the surface moisture or free water is run off.

Q_{dr} is needed for complete evaporation of moisture in biomass. Due to this reason, there is extremely little change in the temperature in this zone. The heat duty of this stage is usually highest particularly for a high-moisture feed. Q_{dr} could be calculated by employing Equation 8.

$$Q_{dr} = W_f w L \quad \text{Equation 15}$$

Here, L indicates the heat of vaporization at 100°C. So, it is taken as 2260 kJ/kg (Table 1).

4.1.3 Post-drying Heating

After the biomass is dried, it needs to be heated. During this stage, all physically bound moisture together with some light organic compounds escape from the biomass. Q_{pd} is needed for post drying heating of the dry feed.

$$Q_{pd} = W_d C_{pd} (T_{st} - 100) \quad \text{Equation 16}$$

Where C_{pd} is the specific heat of dry biomass and W_d is flow- rate of dry biomass and can be defined by equation 10. (Table 1).

$$W_d = (1-w) * W_f \quad \text{Equation 17}$$

Total energy required or heat load, Q_d , for drying biomass to the torrefaction temperature, T_t , is the sum of the mentioned energies (Table 1).

$$Q_d = Q_{ph} + Q_{dr} + Q_{pd} \quad \text{Equation 18}$$

4.1.4 Torrefier

Torrefaction stage is key to the entire process as the majority of depolymerization of the biomass occurs in this stage.

In this step, biomass gets more heat in order to reach the designed torrefaction temperature, T_{ut} . (Table 1).

Energy required for this stage can be determined by Equation 12.

$$Q_t = W_d C_{pd} (T_{ut} - 200) \quad \text{Equation 19}$$

4.1.5 Cooling

Biomass leaves the torrefier at the torrefaction temperature that is the highest temperature in the whole system. Furthermore, handling of such a hot product is dangerous and unsafe. So, the

torrefied product need to be cooled off from the torrefaction temperature (T_{ut}), to appropriate final temperature (T_c) of the product for further processing or storage. By extracting the energy, Q_{cool} , available as either hot air or vaporized liquid, the product is cooled.

The cooling section cools the torrefied product from the torrefaction temperature to a secure temperature ($T_c \sim 50\text{ }^\circ\text{C}$), that is adjacent to that of the atmospheric temperature. Consequently heat obtained from the torrefied product is:

$$Q_c = W_t C_{pd} (T_{ut} - T_c) \text{ (Table 1).}$$

Equation 20

Table 1: Torrefaction Calculations

production rate of torrefied biomass (W_t)	Kg/s	0.167
(ASH_{ar})	%	1.3
($MY_{ar, total}$)	%	49.3
(ASH_t)	%	0.03
($MY_{daf, total}$)	%	84.6
feed rate of raw biomass (W_f)	Kg/s	0.341
Energy needed for preheating feed from room temperature (Q_{ph})	kw	49.8
Energy required for complete evaporation of moisture in biomass (Q_{dr})	kw	323.7
Flow- rate of dry biomass (W_d)	Kg/s	0.2
Energy needed for post drying heating of the dry feed (Q_{pd})	kw	5.4
Total energy required for drying biomass to the torrefaction temperature (Q_d)	kw	378.9
Energy required in torrefaction stage(Q_t)	kw	1.6
Energy required for cooling (Q_c)	kw	8.1

4.1.6 Mass Balance Calculation for Torrefier

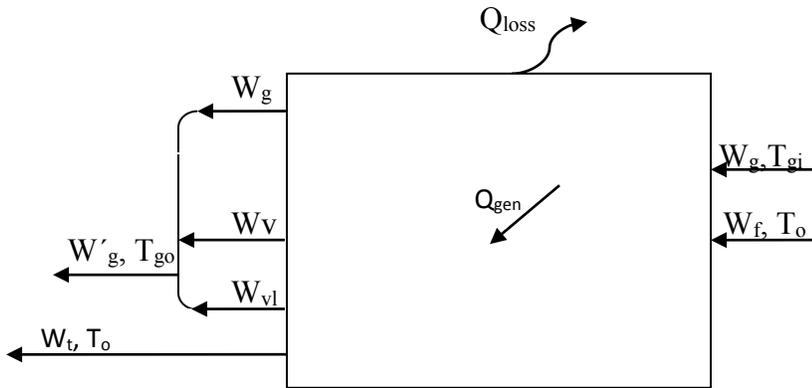


Figure 17: Torrefier control volume [51]

From 18:

$$W_t + W'_g = W_f + W_g \quad \xrightarrow{W'_g = W_g + W_v + W_{vl}} \quad W_t + W_v + W_{vl} = W_f \quad \text{Equation 21}$$

$$\text{Moisture in Fuel } (W_v = wW_f) \quad \xrightarrow{\text{Substituting in Eq. 14}} \quad W_{vl} = W_f - W_t - MW_f \quad \text{Equation 22}$$

The following equation can be resulted from the mass balance around the torrefier (Figure 18).

Enthalpy in+ energy generated by mild exothermic process= enthalpy out+ energy loss through reactor+ latent heat carried away by the moisture content

Assuming that heat losses and heat generated by mild exothermic reaction minimal, then we have:

$$W_g C_g T_{gi} + W_f C_{pd} T_o + Q_{gen} = (W_g C_g + W_v C_v + W_{vl} C_g) T_{go} + W_t C_{pd} T_t + Q_{loss} + W_v L = 0$$

$$W_g = (W_v C_v + W_{vl} C_g) T_{go} + W_t C_{pd} T_t - W_f C_{pw} T_o + W_v L / C_g (T_{gi} - T_{go}) \quad \text{Equation 23}$$

The flue gas, W'_g , leaves the drier carrying with it moisture and product gases from the torrefaction. So, the total flow-rate of product gas is:

$$W'_g = W_g + W_v + W_{vl}$$

4.1.7 High Heating Value of Torrefied Biomass

Calculation of high heating value and energy yield of dry ash free (daf) is needed to find the amount of high heating value of torrefied biomass. The determination of the calorific value normally results in a value for the HHV. For comparison, HHV is also calculated from the elemental composition using the Milne formula:

$$\text{HHV}_{\text{Milne}} = 0.341 \cdot \text{C} + 1.322 \cdot \text{H} - 0.12 \cdot \text{O} - 0.12 \cdot \text{N} + 0.0686 \cdot \text{S} - 0.0153 \cdot \text{ash} \quad \text{Equation 24}$$

$$\text{HHV}_{\text{f, daf}} = \text{HHV}_{\text{db}} (1/(1-w\text{-Ash})) \quad \text{Equation 25}$$

Energy yield provides the portion of the original energy in the biomass maintained after torrefaction. After torrefaction, energy-rich components stay in the biomass, but some energy lean components are lost. Base on the assumptions energy yield is specified as:

$$\text{Energy Yield (EY): } 1 - \text{energy lost through volatiles} = (1 - 0,08) = 92 \%$$

Energy yield is independent of the mass, so $\text{EY}_{\text{db}} = \text{EY}_{\text{daf}}$

On the other hand,

$$\text{EY}_{\text{daf}} = \text{MY}_{\text{daf}} * (\text{HHV}_{\text{product}} / \text{HHV}_{\text{feed}})_{\text{daf}}$$

Then we have:

$$\text{HHV}_{\text{tor, daf}} = \text{HHV}_{\text{f, daf}} * \text{EY}_{\text{daf}} / \text{MY}_{\text{daf}} \quad \text{Equation 26}$$

After the amount of $\text{HHV}_{\text{tor, daf}}$ calculated, it is the time to calculate the amount of the volumetric energy of torrefied pellet. This can be calculated by applying the following equation:

$$\text{EV}_{\text{p, t}} = \text{HHV}_{\text{tor}} * \rho_{\text{p}} \quad \text{Equation 27}$$

Which, ρ_{p} , (kg/m^3); refers to biomass mass density of pelletized raw wood.(Table 2)

Table 2: Mass Balance Calculation for Torrefier

(W _v)	Kg/s	0.143
(W _{vl})	Kg/s	0.031
(W _g)	Kg/s	2.231
(W' _g)	Kg/s	2.405
(HHV _{f, ar})	MJ/kg	11.3
(HHV _{f, db})	MJ/kg	20
(HHV _{f, daf})	MJ/kg	20.8
(EY _{daf})	%	90
(HHV _{tor, daf})	MJ/kg	21.52
(EV _{p, t})	GJ/m ³	12.9

4.2 Steam Explosion Pre-treatment

In this section, SE residues is analyzed for fuel properties. The detailed description of the procedure are shown in Tables 3,4, and 5. The steam used is in saturated condition. Sampled wood chips had a moisture content of roughly 42 % (w.b.).

Energy required during steam explosion process can be calculated by provided model in Figure 19. The effect can be assessed by some critical limit of moisture content, M_c , at which the energy spent on heating the waterless part of the biomass to the required temperature is equal to the energy spent on elevating the temperature of the moisture.

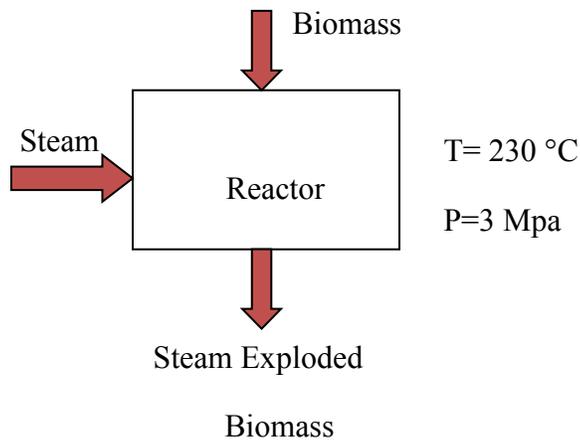


Figure 18: Block diagram of steam explosion model used for energy calculations [53]

In order to find the total amount of energy required during steam explosion process (E_t), following calculation must be done. From thermodynamic tables of saturated steam, the value of enthalpy difference (Δh), evaporation energy (E_{evap}), and specific volume (v) at pressure of 3 Mpa can be founded. These amounts are 2803 KJ/Kg, 1813 KJ/Kg, and 0,071 m³/Kg, respectively.

The enthalpies of saturated vapour (h_g) and enthalpies of latent heat of vaporization (h_{fg}) at reaction temperature are used to calculate the energy input for steam generation in the boiler. The results are listed in Table 3.

Mass of moisture in biomass (m_w) can be calculate by the following equation:

$$w = \frac{m C_{pd}(\Delta T)}{m C_{pd}(\Delta T) + (\Delta h) m_w} \quad \text{Equation 28}$$

Where Δh equals to 2803 KJ/Kg, $\Delta T=230^\circ\text{C}$, and $m=100\text{Kg}$. Then m_w can be found. (Table 3)

Energy consumed to heat the biomass up to the operation temperature (E_b) can be calculated by the following equation. (Table 3)

$$E_b = mC_{pd} (\Delta T) + m_w (\Delta h) \quad \text{Equation 29}$$

Mass of condensed saturated steam (m_{cs}) calculates as follow (Table 3).

$$m_{cs} E_{evap} = E_b \quad \text{Equation 30}$$

Amount of steam essential to preserve the pressure in the reactor calculates as:

$m_0 = V / v$; where V is the reactor occupied volume by the biomass for treatment, m^3 ; v is the specific volume of saturated steam under operation pressure and temperature, m^3/Kg ; Then, Total amount of steam can be calculate as:

$$m_s = m_{cs} + m_0 \quad \text{Equation 31}$$

Thereafter, energy to generate the total amount of steam calculates as:

$$E_s = m_s (\Delta h) \quad \text{Equation 32}$$

Table 3 shows all analysis results.

Table 3: Energy required for steam generation in SE pre-treatment

Mass of moisture (m_w)	Kg	3.05
Energy consumed to heat the biomass up to the operation temperature (E_b)	KJ	14.7
mass of condensed saturated steam (m_{cs})	Kg	8.13
Amount of steam necessary to maintain the pressure in the reactor (m_0)	Kg	7.46
Total amount of steam (m_s)	Kg	15.59
Energy to generate the total amount of steam (E_s)	MJ	44

4.2.1 Drying of Wet Biomass after SE

Over the steam explosion process the moisture content of feedstock raises and grows to about 75 %, which means wet feedstock need to be dried to 12 % before storing and densification into pellet. So, the energy required for evaporates water depends to drying temperature [53].

The wet wood chips are dried from 45 % to 10 % moisture in a rotary drum dryer.

The heat energy required to vaporize water can be calculated by the following equation:

Heat energy (KJ) required for 1 Kg biomass = heat energy to raise temperature of biomass to drying temperature + latent heat to remove water

Heat energy to raise temperature of biomass to 140 °C equals to $mC_{pd}(\Delta T)$, and, latent heat to remove water equals to m_wL . Latent heat of vaporization of water, at 140 °C is 2144 kJ/kg. Total energy required for drying is the sum of heat energy to raise temperature of biomass to 140 °C and latent heat to remove water. The results are shown in table 4.

Table 4: Energy required for drying steam exploded feedstock

Heat energy to raise temperature of biomass	MJ	1.076
latent heat to remove water	MJ	6.54
Total energy required for drying	MJ	7.62

4.2.2 Energy Analysis of Steam Explosion Process

The steam explosion system largely comprises of a steam explosion reactor, a release valve and a buffer tank. While in the pressure increases, materials are heated from the adjacent temperature (T_0) to the holding temperature (T_e). Energy input is given by high-pressure saturated steam produced by the steam generator. During the pressure increases the steam is to fill the reactor and pass through into materials' porous structure to build the holding pressure in gas state which affiliated consumed energy is heating steam energy (Q_1), as well as heats the air which equivalent consumed energy is heating air energy (Q_2), heats wet materials and the reactor up to the setting temperature which related consumed energies are (Q_3), and (Q_4), respectively, during

this high-pressure saturated steam is condensed into water considering the amount of ml. The calculates are followed as:

1) Heating steam energy:

$$Q_1 = m_s(h_{ge} - h_{f0}); \quad \text{Equation 33}$$

Where m_s is the amount of steam in the reactor for establishing the holding pressure. h_{ge} is the enthalpy of steam at T_e , kJ kg^{-1} ; h_{f0} indicates the enthalpy of water at T_0 , kJ kg^{-1} ; and steam in the reactor for generating the holding pressure.(Table 5)

2) Heating air energy:

For air in the reactor, in considering of the equation of ideal gas we will have:

$P_a = P_0 T_e / T_0$, where T_0 and P_0 are the initial surrounding temperature and pressure, respectively; T_e is the holding temperature (K).(Table 5)

$n = m_a / M$; where m_a donates to amount of air in the reactor kg

$$PV = nRT \rightarrow m_a = MP_a V / RT_e$$

$$Q_2 = C_v m_a (T_e - T_0); \quad \text{Equation 34}$$

Where C_v is the specific heat of air at constant volume, $\text{kJ kg}^{-1} \text{K}^{-1}$

3) Heating materials energy

Q_3 is the sum of two energy where are used for heating the dry solid materials (Q_{3m}) and the moisture in materials (Q_{3w}), respectively. (Table 5)

$$Q_3 = Q_{3m} + Q_{3w} = (C_{pd} m (1 - w) + C_w m w) (T_e - T_0) \quad \text{Equation 35}$$

4) Heating reactor energy

$$Q_4 = C_r M_r (T_e - T_0); \quad \text{Equation 36}$$

Where M_r is the weight of the steam explosion reactor, and C_r is the specific heat of reactor's material, $\text{kJ kg}^{-1} \text{K}^{-1}$. (Table 5)

Thus the sum of above steps is total energy consumption of the steam explosion process (Q_t) and stated as:

$$Q_t = Q_1 + Q_2 + Q_3 + Q_4 \quad \text{Equation 37}$$

After running pressurized steam for a short time, materials are instantly exploded into the buffer tank together with internal superheated water flashing into steam, which yields the expansion work. The expansion work ends in steam energy loss (Q_5); liquid water energy loss (Q_6); air energy loss (Q_7); and dry materials energy loss(Q_8).

Now I intend to formulate each of these losses, respectively.

5) Steam energy loss

$$Q_5 = (m_s + m_2) (h_{ge} - h_{gt}); \quad \text{Equation 38}$$

Where m_2 is the amount of flash water, h_{gt} is the enthalpy of steam at temperature after decompression T_t , kJ kg^{-1} . (Table 5)

$m_2 = (m_w + m_1) (h_{fe} - h_{ft}) / (h_{gt} - h_{ft})$; where m_2 , h_{fe} and h_{ft} stand for the amount of flash water in immediate decompression stage, enthalpy of water at T_e and T_t .

m_1 identifies as: $m_1 = (C_{pd} m (1 - w) + C_w m_w + C_r M_r + C_v m_a) (T_e - T_0) / h_{fg}$; which is the amount of condensed water provided when pressure increases includes water condensed from heating solid materials, steam explosion reactor and air, C_w donates to specific heat of water equals to $4,18 \text{ kJ kg}^{-1} \text{ K}^{-1}$, and h_{fg} is evaporation enthalpy of steam at T_e .

6) Liquid water energy loss

$$Q_6 = (m_w + m_1 - m_2) (h_{fe} - h_{ft}) \quad \text{Equation 39}$$

Where h_{fe} and h_{ft} symbolize the enthalpy of water at T_e and T_t , kJ kg^{-1} .

7) Air energy loss

$$Q_7 = m_a (h_2 - h_1) \quad \text{Equation 40}$$

Where h_1 and h_2 are the enthalpies of air at T_t and T_e , kJ kg^{-1} .

8) Dry materials energy loss

$$Q_8 = C_{pd} m (1 - w) (T_e - T_t) \quad \text{Equation 41}$$

Consequently, Q_L is the total energy loss for immediate decompression equals the sum of Q_5 , Q_6 , Q_7 , and Q_8 .

$$Q_L = Q_5 + Q_6 + Q_7 + Q_8 \quad \text{Equation 42}$$

All results are shown in table 5.

Table 5: Energy analysis of steam explosion process

Heating steam energy (Q_1)	MJ	42.4
Initial surrounding pressure (P_a)	MP	0.18

Amount of air in the reactor (m_a)	Kg	3.87
Heating air energy (Q_2)	MJ	1.7
Heating materials energy (Q_3)	MJ	44
Heating reactor energy (Q_4)	MJ	7.4
Total energy consumption of the steam explosion process (Q_t)	MJ	95.5
Amount of flash water in instantaneous decompression stage (m_2)	Kg	18.83
Amount of condensed water (m_1)	Kg	29.2
steam energy loss (Q_5)	MJ	4.4
Liquid water energy loss (Q_6)	MJ	29.9
Air energy loss (Q_7)	MJ	0.51
Dry materials energy loss (Q_8)	MJ	2.03
Total energy loss for instantaneous decompression (Q_L)	MJ	36.8
$HHV_{SE, daf}$	MJ/kg	23.5
$EV_{p, t}$	GJ/m ³	14.1

Assumptions:

- The digester was operated at 230 °C (steam pressure of 3 MPa) for 10 min to perform steam explosion of the agricultural biomass.
- Mass of biomass is 100 Kg
- Temperature of solid materials and air after decompression is equal to steam temperature (T_i)
- Moisture content of steam exploded feedstock is about 75 %
- Drying process diminish moisture content to about 12 %
- Drying inlet temperature 140 °C
- Temperature of feedstock at reactor outlet is 100 °C
- M_r , the weight of the steam explosion reactor is 70 Kg
- C_r , the specific heat of reactor's material, is 0.46 kJ kg⁻¹ K⁻¹.

SYMBOLS AND NOMENCLATURE

- Q_c energy content of cooling section, KJ
- $Q_{d \text{ total}}$ energy required or heat load for drying biomass to the torrefaction starting temperature, KJ
- W_t production rate of torrefied biomass, Kg/s
- W_f feed rate of raw biomass, Kg/s
- W_v moisture in biomass, Kg/s
- W_g flow rate of diluted hot gas entering the torrefier, Kg/s
- W_{vl} flow rate of volatiles, Kg/s
- ΔT difference between the operation temperature and the initial temperature, °C
- Δh enthalpy difference of water content of the biomass with respect to ΔT , kJ/kg
- m_w mass of moisture in biomass, kg
- E_b Energy consumed to heat the biomass up to the operation temperature, KJ
- m_{cs} mass of condensed saturated steam, Kg
- E_{evap} the heat of evaporation at the operating temperature, kJ/kg
- m_0 amount of steam necessary to maintain the pressure in the reactor, Kg

- V volume of the reactor occupied by the biomass containing one mass unit of the dry substance to be treated, m^3
- v specific volume of saturated steam under operation pressure and temperature, m^3/Kg
- m_s total amount of steam, Kg
- E_s energy to generate the total amount of steam, KJ
- E_t total amount of energy required during steam explosion process, KJ
- Q_1 energy consumed when pressure increases for heating steam, KJ
- Q_2 energy consumed when pressure increases for heating air, KJ
- Q_3 energy consumed when pressure increases for heating materials, KJ
- Q_4 energy consumed when pressure increases for heating reactor, KJ
- Q_5 energy losses of steam in prompt decompression, KJ
- Q_6 energy losses of liquid water in prompt decompression, KJ
- Q_7 energy losses of air in prompt decompression, KJ
- Q_8 energy losses of dry material in prompt decompression, KJ
- T_0 ambient temperature, $^{\circ}C$
- T_e holding temperature, $^{\circ}C$
- h_{se} enthalpy of steam at T_e , KJ/Kg
- h_{f0} enthalpy of water at T_0 , KJ/Kg
- C_v specific heat capacity of air at constant volume, $KJ/Kg^{\circ}C$
- m_a amount of air in reactor, Kg
- m , amount of material, Kg
- C_w specific heat capacity of water, $KJ/Kg^{\circ}C$
- w , moisture content of materials
- C_r specific heat capacity of reactor's material $KJ/Kg^{\circ}C$
- M_r Weight of reactor, Kg
- m_1 amount of condensed water, Kg
- m_2 amount of flash water, Kg
- h_{st} enthalpy of steam at T_t , KJ/Kg
- h_{fe} enthalpy of water at T_e , KJ/Kg
- h_{ft} enthalpy of water at T_t , KJ/Kg

- h_1 enthalpy of air at T_t , KJ/Kg
- h_2 enthalpy of air at T_e , KJ/Kg

5. DISCUSSION

The effects of torrefaction and steam explosion processing on physical and chemical properties of wood pellet could be derived the following results from the literature.

Based on the previous studies on both technologies, results indicate that the density increased in initial of pellets made from torrefied woody biomass, but increasing in torrefaction temperature has negative impact on the unit density, and exhibits reduction in the unit density. This attribute is a sign of poor adhesion between the particles in elevated temperatures.

The initial density of pellets made from steam exploded biomass increases for the samples treated, but with increasing the severity of the treatment, the initial pellet density start to reduction. The decrease in pellet density with increasing severity treatment is due to the volatile loss of the feedstock after steam treatment.

On the other hand volumetric contraction of the steam exploded pellets have increment after relaxation with increasing treatment severity by considering to the fact that steam exploded biomass can increase the compressibility of wood particles prior to compression. This makes drastically reduction in the expansion of internal stresses during compression.

Carbon content in torrefied pellets demonstrate an increasing tendency, despite the fact that the oxygen and hydrogen contents decrease, associated with the reduction in the hydroxyl groups and formation of water vapour lead to notable losses. CHO content changing result in increase in higher heating values. The high heating value of torrefied pellets increased from 20.8 MJ/kg for pellets made from untreated feedstock to 21.52 MJ/kg for pellets made from treated feedstock. In steam exploded pellets demonstrate increasing in carbon content and reduction in hydrogen content which is due to the removal of the – OH group of hemicelluloses after the hydrothermal treatment. The high heating value of the steam exploded pellets increased to 23.5 MJ/kg for pellets made from the steam treated feedstock.

Water adsorption capacity of wood decreased considerably after torrefaction. When the torrefaction temperature increases water uptake rate decreases due to the slight difference in the structure and composition of the torrefied wood; in fact two reasons for decreased water uptake

rate, based on the previous studies, are the decomposition of hydroxyl groups and lignin coating on particles.

The pellets that are made from untreated feedstock exhibits the most hygroscopic behaviour that steam treated feedstock, and the value of equilibrium moisture content (M_e) for pellets made from steam treated biomass has notable reduction compare to untreated steam exploded pellets, however it needs to be considering that the moisture adsorption resistance of the steam treated samples increased with the treatment severity.

6. CONCLUSIONS

Two pre-treatment technologies introduced separately, and the effects of processes on physical and chemical properties of woody biomass were studied, then the energy and mass analysis of a woody biomass densification with torrefaction and steam explosion pre-treatment's was conducted. Based on mass and energy balance of unit operations the energy inputs to torrefaction and steam explosion, energy required for each steps of pre-treatment's and the pelletization were calculated. The results show that pellets treated with steam explosion have higher high heating value (HHV) than the pellets made from untreated feedstock as well as torrefied feedstock. On the other hand steam exploded pellets demonstrate higher volumetric energy than torrefied. In addition results indicate that initial moisture content is an important factor that effects on energy required during the process result in improving energy efficiency.

This study was conducted based on the mixed woods with specific chemical composition and water content at constant temperature and residence time. Other woods have different chemical composition and water content, therefore more focused studies on different mixed woods at different temperatures and residence time to understand the effects on formation of pellets as well as studying on some subjects like energy yield, process economies and potential benefits are recommended to carry out in the future.

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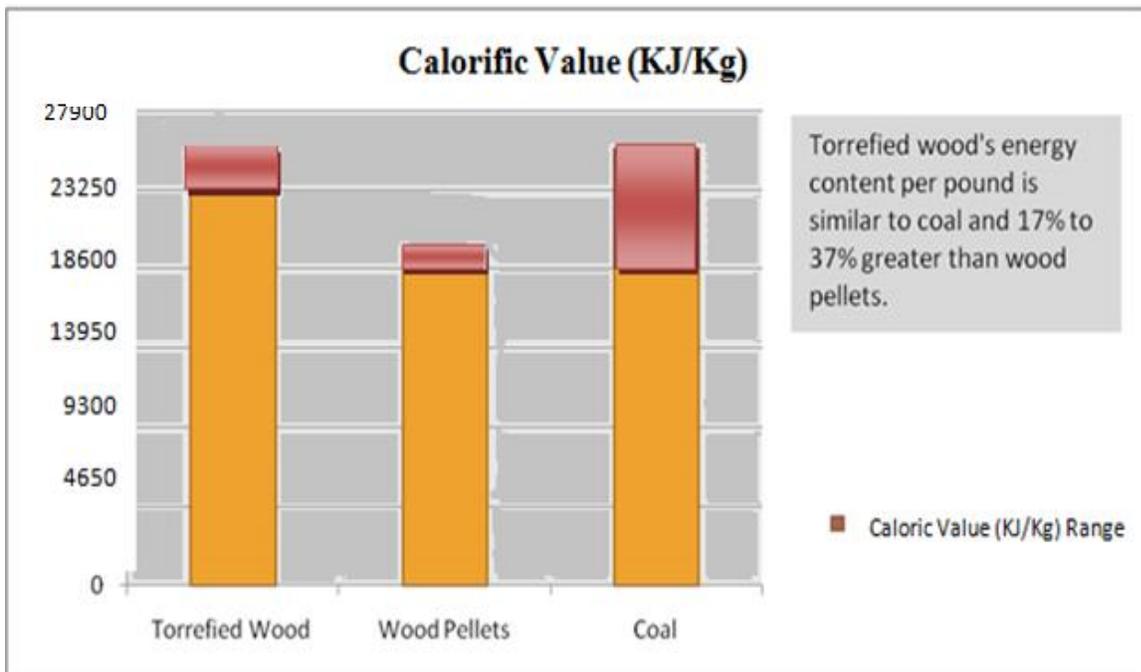
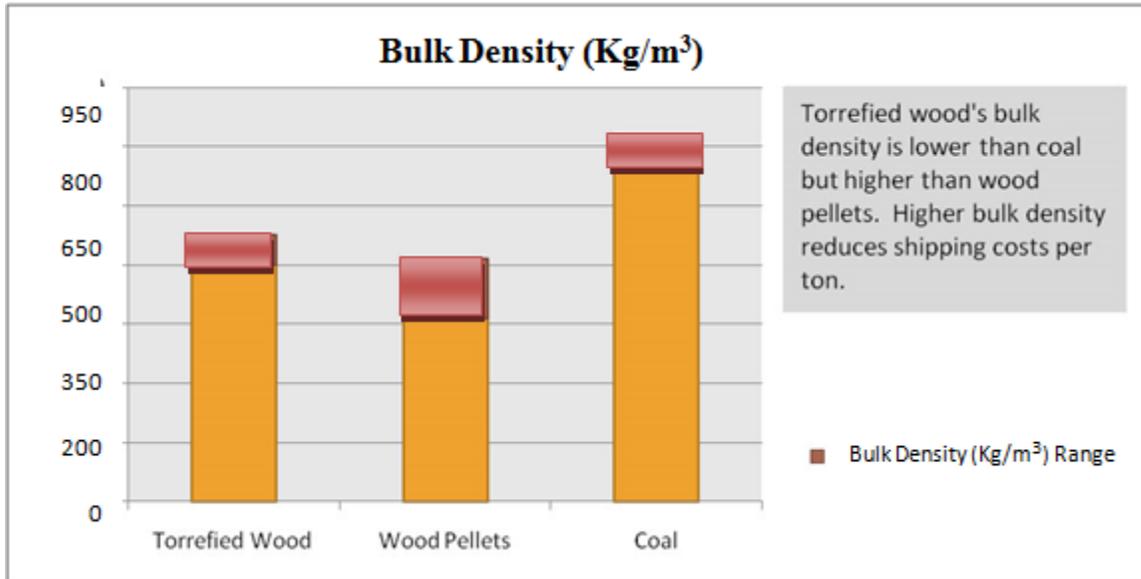
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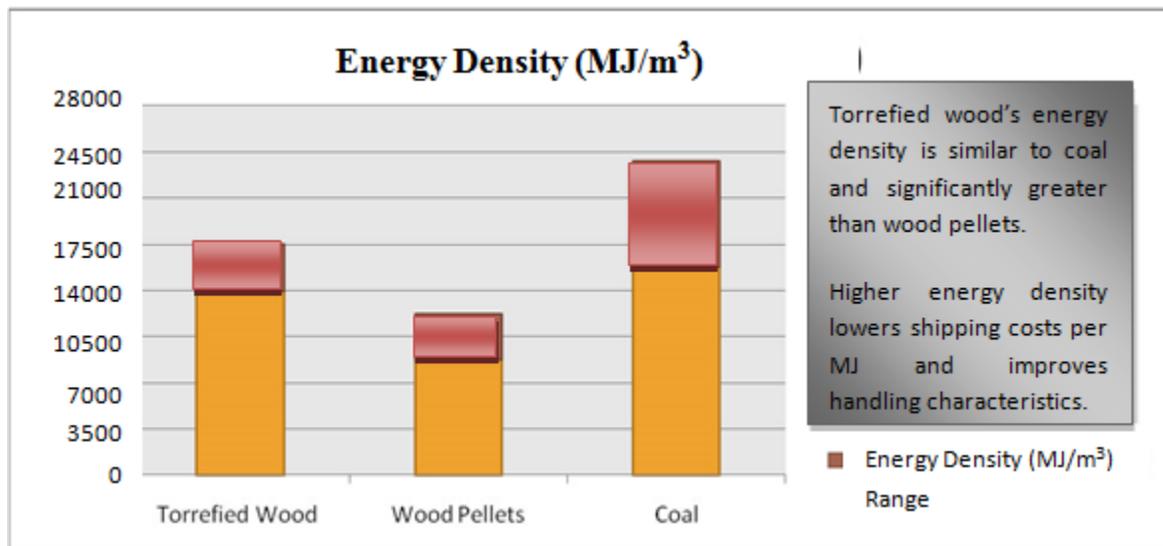
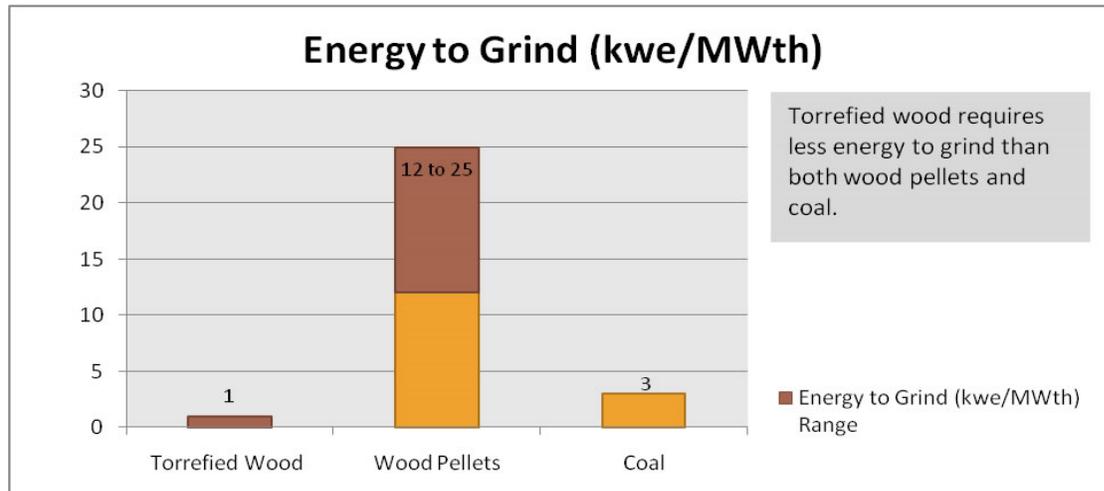
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APPENDICES

Appendix 1: Comparison between Torrefied Wood vs. Wood Pellets vs. Coal in different Characteristics



Appendix 1. (Continued)



Appendix 1. (Continued)

