UNIVERSITY OF TECHNOLOGY, SYDNEY

PAM Review

Subject 68412

www.uts.edu.au

Analysis of Industrial Syngas Production from Biomass

Minh Nguyen [1],*, Gabriella Duddy [2] and Camila Karam [3]

[1]Faculty of Science, UTS, P.O. Box 123, Australia ;minh.a.nguyen@student.uts.edu.au

[2] Faculty of Science, UTS, P.O. Box 123, Australia ;gabriella.duddy@student.uts.edu.au

[3]Faculty of Science, UTS, P.O. Box 123, Australia ;camila.karam@student.uts.edu.au

***** Author to whom correspondence should be addressed; E-Mail: author@email

Received: 25/5/2015 / Accepted: 29/5/2015 / 1/6/2015:

Abstract: This meta-study provides a comparison across various gasification systems on the production of syngas from biomass as feedstock. The gasifier configuration systems analysed included; fixed-bed, fluidized, plasma, and entrained, and the effect of operational parameters on the syngas volume and composition were obtained and analysed across a number of studies. The relationships between efficiency, temperatures within the system, equivalence ratio, fuel quality, and biomass fuel types were investigated and it was shown that ER was the most influential operating parameter. A small generalised comparison between existing competing energy sources was also performed with respect to biofuels.

Keywords: Biofuel; Biomass; Gasification; Gasifier; Syngas; Thermodynamics; Meta-study

DOI: http://dx.doi.org/10.5130/pamr.v2i0.1396

PAM Review **is a Student Journal from UTS ePRESS showcasing outstanding UTS student works**

Nomenclature

BFB	Bubbling Fluidized Bed
C	Carbon
CFB	Circulating Fluidized Bed
DFB	Downdraft Fixed Bed
DLF	Dual Fluidized
EF	Entrained Flow Gasifier
ER	Equivalence ratio
FLB	Fluidised Bed Gasifier
FXB	Fixed Bed Gasifier
H	Hydrogen
LHV	Low heating value
MC	Moisture content
O	Oxygen
PG	Plasma Gasifier
S	Sulphur
UFB	Updraft Fixed Bed

1. Introduction

Biofuels are defined as a fuel derived from organic matter or biomass, with its constituents consisting mainly of renewable resources and biological materials such as plants and animals [1]. Biomass is an abundant and carbon-neutral resource, currently representing 13% of the world's source for renewable energy, and is continuing its growth. Biofuels are in no way an emerging technology, with the usage of vegetable oils and ethanol fuelling lamps dating back to the late 1800s- long before the introduction of combustion engines. Henry Ford, the founder of the Ford motor company, said that "there is fuel in every bit of vegetable matter than can be fermented" demonstrating the huge potential of biomass in the fuel industry [2].

Today, the need for biofuels is readily apparent, with a decline in the finite reserves of fossil fuels and crude oils. The global population consumes over 11 billion tonnes of oil and fossil fuels annually, resulting in a sharp decrease in the total fuel reserves available [3]. The constant availability that biofuels can bring can help to mitigate this drop in fuel reserves and extend the period of which energy can be available. The onset of climate change is also a prevalent issue, with the sheer amount of greenhouse gas, with 24% of the total amount of emissions produced due to combustion of coal, oil, and natural gas during energy production alone. It is with the boost to biofuel production with appropriate production methods, that the reduction in greenhouse gas emissions can be observed [4, 5].

During this meta-study, a thermodynamic analysis will be provided primarily on the production systems on the biofuel syngas with a comparison between the systems as well as a general comparison with existing systems from competing energy systems such as coal, wind, biodiesel, and nuclear energy

2. Methods

Our meta-study compares a variety of gasification systems on their production of syngas using biomass as feedstock. We noticed there was limited analysis reported in literature that directly compared more than two gasification systems at once, so our Meta study aims to provide a comparison across a number of systems. Various gasification systems were compared on parameters including, efficiency, and temperatures within the system, air equivalence ratios (ER), fuel quality and the biomass fuel types. Data was collated across each system studied to compare various parameters of the biofuel such as syngas composition, efficiency of carbon conversion (the amount of carbon converted to useable syngas [6]) and lower heating value as function of ER. Our Meta study was conducted using internet websites from verified sources as well as scientific databases including UTS Library as well as NREL (National Renewable Energy Laboratory) with search parameters restricted to scholarly articles and journals published between 1995 and 2015.

3. Results and Discussion

3.1. Fundamentals of Syngas production via Gasification

Commercial production of syngas from coal, biomass, petroleum coke and various other feedstock is capable of generating power in order to produce hydrogen and other liquid fuels or chemicals, including liquid and gaseous transport fuels [7]. Historically, the relatively low-price and high abundance of coal made it an ideal choice for production of electric power, but for environmental and economic reasons there is now a growing interest in the development of technologies to exploit renewable energy sources such as biomass [8]. Production of high quality syngas requires a high concentration of H_2+CO and high ratio of H_2 to CO and low tar content for the sufficient use within various energy systems.

3.1.1. Gasification

Gasification is a thermo-chemical process which transforms biomass into a mixture of combustible gases, called synthesis gas (syngas), containing 20-40% hydrogen (H_2), 35-40% carbon monoxide (CO), 0-15% methane (CH_4) and 25-35% carbon dioxide (CO_2) [9],[10]. During the process, biomass is heated at a high temperature of approximately 850 C with a controlled amount of oxygen, air and/or steam (gasifying agent) and limited combustion to provide thermal energy and sustain the reaction [11]. The equivalence ratio (ER) is defined by the ratio of the biomass and gasifying agent feed rates [9]. There are four primary stages during the process of gasification of carbon materials; drying, devolatilisation or pyrolysis, combustion, and reduction [12].

1. Drying - moisture is removed from the mass material from heating
2. Pyrolysis - continued heating is performed to remove all volatile matter and react with oxygen

3. Combustion - an exothermic process where carbon dioxide and carbon monoxide are formed from carbon and oxygen
4. Gasification - the final stage consisting of a series of reduction reactions

The process of gasification can be summarised with the following set of chemical equations:

Table 1. Reactions which occur within the gasification phase of the overall gasification process

Reaction Name	Chemical Formula	Thermodynamic process
Water Gas	$C + H_2O \rightarrow CO + H_2$	Endothermic
Boudouard	$C + CO_2 \rightarrow 2CO$	Endothermic
Water-Gas-Shift	$CO + H_2O \rightarrow CO_2 + H_2$	Exothermic
Methanation	$CO + 3H_2 \rightarrow CH_4 + H_2O$	Exothermic

The biomass fuels used in gasifiers vary widely from wood, straw and charcoal to maize, bagasse and coconut shells, and hence include many reactions and reaction paths [13]. In Figure 1., we present fuel characteristics of different biomass fuel types presently used commercially for energy generation which shows the relationship between net heating value and moisture content percentage of each fuel. As moisture content (MC) decreases, the net heating value, or lower heating value (LHV) increases.

The heating value of a fuel, or calorific value, is indicative of energy chemically bound in the fuel with reference to a standardized environment [13]. For LHV, the gaseous state of water is the reference state; for high heating value (HHV) the liquid state of water is the reference state. The linear relationship in Figure 1. suggests that at a wet basis moisture content of approximately 80%, the LHV would be zero. Literature states that for the ignition of fuel and extraction of energy, the maximum allowable moisture content must be 55% [13]. Charcoal has the highest LHV range of 25,000-32,000kJ/kg, with the lowest moisture content at 5.5%.

The different gasification systems can be classified by the gasifier, which include Updraft Fixed Bed (UFB), Downdraft Fixed Bed (DFB), Bubbling Fluidized Bed (BFB), Circulating Fluidized Bed (CFB) and Entrained flow Gasifiers (EF) [14]. Classification also varies upon pressure conditions and the oxidant used. In this paper, the lower heating value (LHV) of the syngas produced from the 7 listed gasification systems is reported and compared as an indicator of the gas quality. One application of syngas, with a high HHV and containing negligible contents of tar and ash, is as fuel for the direct generation of power in syngas engines . Therefore, gas contaminants in syngas such as tar and humidity, are key technical challenges to the use of synthesis gases in gas engines [10]. Gasification is performed within a variety of gasifier configurations. Syngas quality from varied production systems are discussed below.

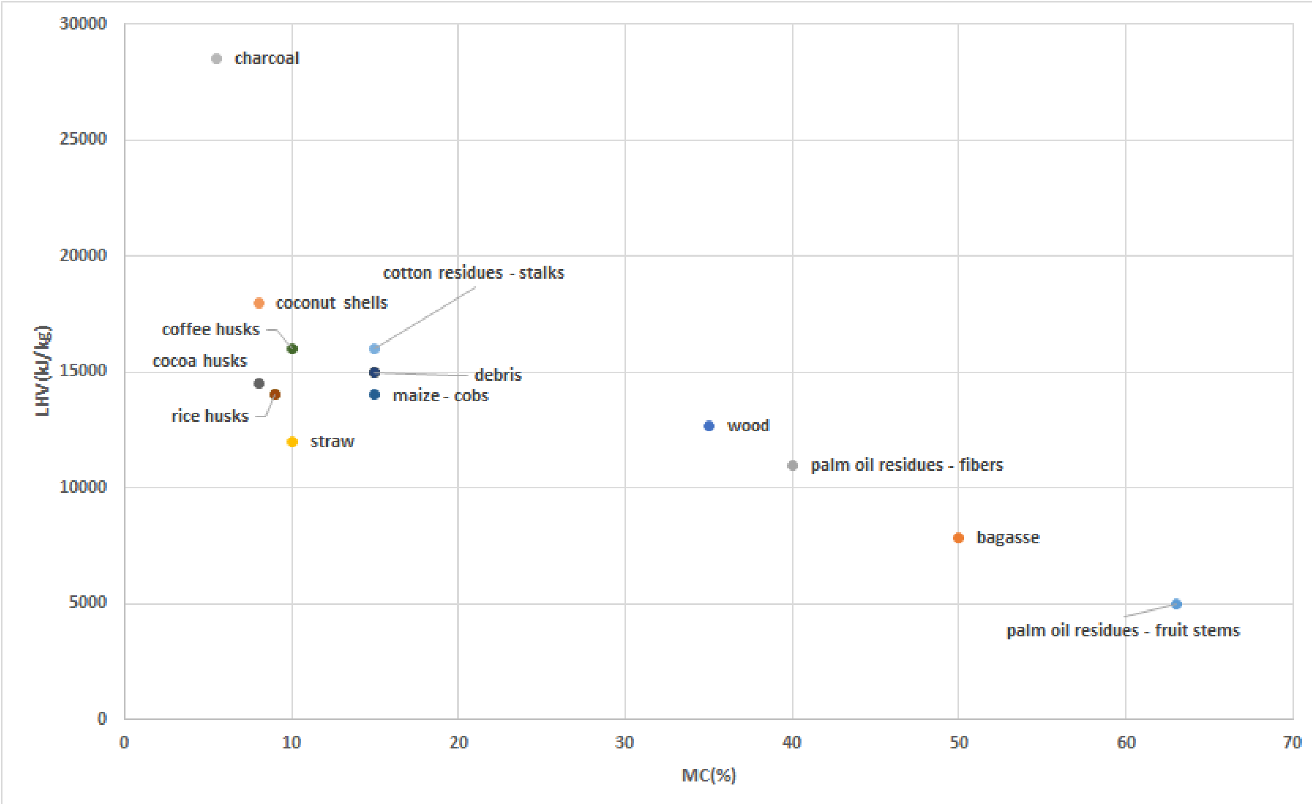

Figure 1. Comparison of natural moisture content MC_w(%) and net heating value LHV (kJ/kg) of different biomass fuel types presently used commercially for energy generation. Data source [13].

Fixed bed gasifiers are one of the two most used reactors for industrial gasification of biomass. These gasifiers exhibit either cocurrent (feedstock and gasifying agent flow in opposite directions) or countercurrent (feedstock and gasifying agent will flow in same direction). They can also be classified by the direction in which the reactive material is travelling, with updraft and downdraft configurations for feeding from the top of the reactor or feeding from the bottom respectively [15].

The FXB system consists of a reactor/gasifier with a gas cooling and cleaning system that converts biomass into useful fuel sources such as syngas. The simple structure of this gasifier typically consists of a cylindrical space for the fuel feeding unit, an unit to remove ash, a gas exit and a bed of solid particles that the gasifying agent and resultant syngas move either up or down. The system operates at high carbon conversion, long solid residence time, low gas velocity and low ash carry over[15].

Our research focused on two systems of FXB's - updraft gasifiers (UFB) and downdraft gasifiers (DFB). Both of these gasifiers are composed of four zones: drying zone, pyrolysis zone, oxidation zone and reduction zone [16]. Figure 2. highlights the different order of gasification zones between UFB and DFB.

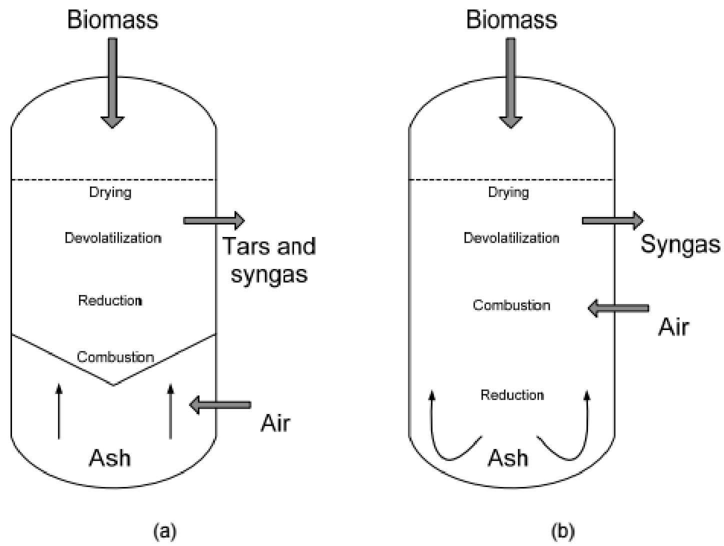

Figure 2. Zone comparison of (a) UFB and (b) DFB. Figure source [12]

The syngas produced by the fixed bed gasifier must pass through a cleaning process, as it is loaded with particulates, condensate and pyrolytic products. The cooling and cleaning units are designed depending on the future use of the gas [16].

3.3. Downdraft Fixed Bed Gasifiers (DFB)

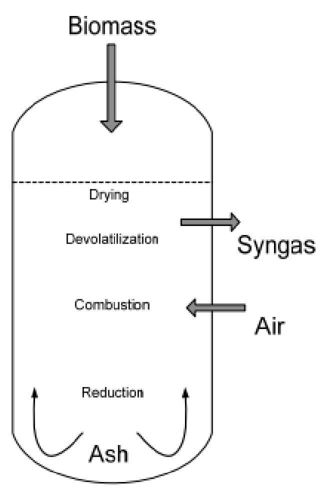

Figure 3. Downdraft fixed bed gasifier: gasifying agent intake at top or side. Biomass and gases move in same direction [12]

Similar to UFB, the biomass is fed in at the top, however, the gasifying agent intake is also at the top or from the sides, and the gas is drawn from the bottom of the reactor. Therefore, the biomass and gases move in the same direction. Air contacts the pyrolysing biomass before it contacts the char and supports a flame. The heat that maintains the pyrolysis is from the burning of volatiles. As pyrolysis continues, limited air is consumed rapidly resulting in a rich flame and gas composed of almost equal parts of CO_2, H_2O, CO and H_2. This flame in limited air supply is known as 'flaming pyrolysis'[16], and produces most of the combustible gases and consumes, at the same time, 99% of the tars. Since FXBs typically produces vapours less than 1% condensable tar-oils, they are widely used for engine operations [17]. Syngas quality and composition is affected by the operating temperature. Higher temperatures favour syngas production and decreases char and tar, however syngas composition decreases with increasing temperature [17]. For olive tree cuttings and olive kernels gasification, raising the temperature from 750 °C to 950 °C, while the air equivalence ratio (ER) is kept at 0.42, increases gas production by at least, 10%. This increase in temperature also affects the concentrations of CO_2, CH_4, CO and H_2. Since higher temperatures favour reactants in exothermic reactions, and products on endothermic reactions (outlined in table 1.), the CO_2 concentration decreases, while CH_4, CO and H_2 concentrations increase [19].

The LHV of gas from olive kernels increased as temperature increases in the 750-850 °C region, but above this temperature, changes are minimal as the heating value is maximized and has its peak (8.60MJ/Nm^3) at 950 °C. In the case of olive tree cuttings, a sharp rise trend was observed between the temperature range of 750 and 950 °C, with a maximum LHV value of 9.41 MJ/Nm^3 at 850 °C.

Variations of ER have a huge impact on biogas production. By varying the air supply during gasification, the process approaches two extreme operating conditions: complete combustion towards CO_2 and the complete gasification towards CO, making ER a crucial operating parameter. ER influences the gas composition, syngas production on gas mixture, LHV, and H_2 /CO molar ratio. Increasing ER results in a decrease in overall syngas production, as gasification requires less air for decomposition of carbon materials and must avoid oxidation (combustion), the systems are optimised at lower ERs. Increasing ER increases the CO_2 concentration and lowers H_2 and CO. The higher LHV value (10.40 MJ/Nm^3) is obtained for olive kernels at an ER of 0.21. For the olive tree cuttings higher LHV (11.33MJ/Nm^3) is reached at an ER of 0.14. Both occur at a temperature of 950 C. When the ER value raises to 0.4 the LHV value presents a huge decrease due to combustible gas consumption [19].

H_2/CO molar ratio has its higher value (which is desirable) when the equivalence ratio is around 0.27, as shown in Figure 4.

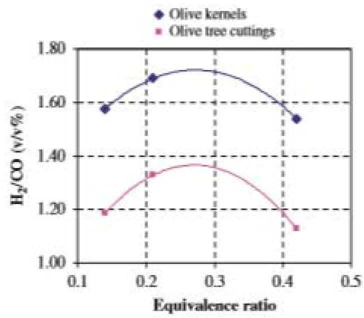

Figure 4. Effect of Equivalence Ratio in H_2/CO molar ratio [19]

Higher ER reduces gas quality due to further oxidation reactions that results on more CO_2 being produced and less combustible gases. Conversely, increasing ER favours exothermic oxidation reactions, giving more heat to the system and optimizing gas quality due to tar destruction.

3.4 Updraft Fixed Bed Gasifier (UFB)

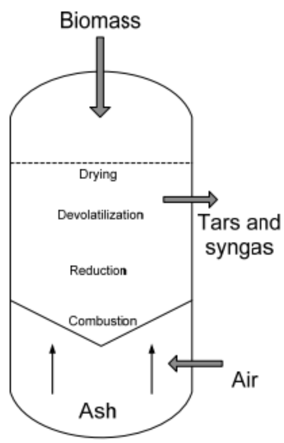

Figure 5. Simple diagram of an updraft fixed bed gasifier. Biomass and gases move in opposite direction [12].

In a UFB the biomass is inserted via the top of the gasifier while the gasifying agent (usually air, oxygen or steam) intake resides at the bottom (gasifying agent moves 'updraft'), this results in the biomass and gasses moving in opposite directions, as illustrated in Figure 5. As the produced gas passes through the fuel bed, it picks-up volatile matter including tars and moisture from the feedstock fuel. Syngas exits the UFB at around 200-400°C temperature, at which most of the volatile hydrocarbons are in vapour form, adding to the energy content of the gas [17]. Fuel flexibility is the main feature of UFBs since they can operate on either coal or biomass without any changes in the reactor required. UFBs tolerate higher ash content, higher moisture content and greater size variation in fuel compared to DFBs [18].

A study on the gasification of wood sticks [20] compared the syngas output in an ER range of 0.26-0.43. For full combustion the ER was optimum at 1.3, and for gasification it is 0.3 It was found that decreasing the particle size of the feedstock increased HHV and gasifier efficiency

[20]. When mesquite and juniper are used as biomass, the equivalence ratio on gasifier vary between 0.27-0.42, and the HHV for these ER values for juniper ranges from 3900-3700 kJ/Nm³, and for mesquite from 3500-2400 kJ/Nm³. As ER increases, HHV of the product gas decreases [21].

The maximum temperature in the combustion zone can rise depending upon HHV and oxygen concentration. Above the combustion zone, O_2 concentration decreases, and most reactions are endothermic, which decreases the temperature. Increasing ER also decreases the temperature, as shown in Figure 6.

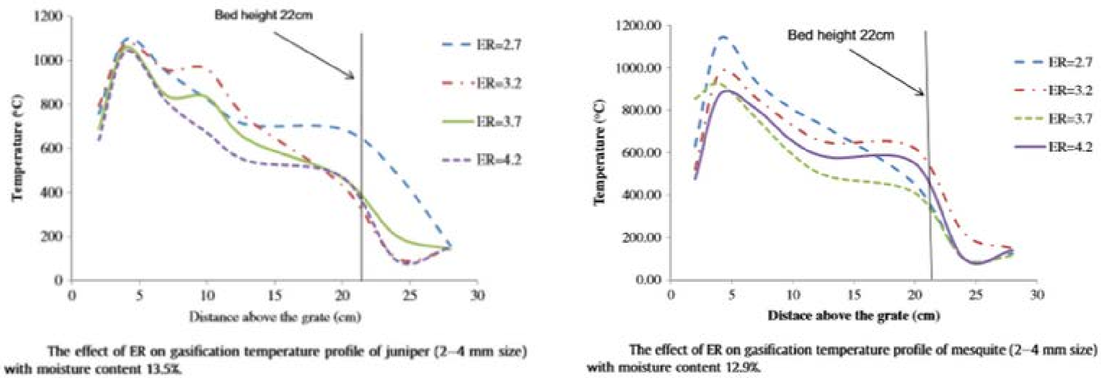

Figure 6. Effect of ER on gasification temperature of juniper and mesquite moistures [21].

We plotted data from the study to illustrate how ER affects the composition of the producer gas, as shown in Figure 7., As the ER increases, the molar composition of CO% and H_2 % decreases, while the CO_2 and N_2 percentage increases.

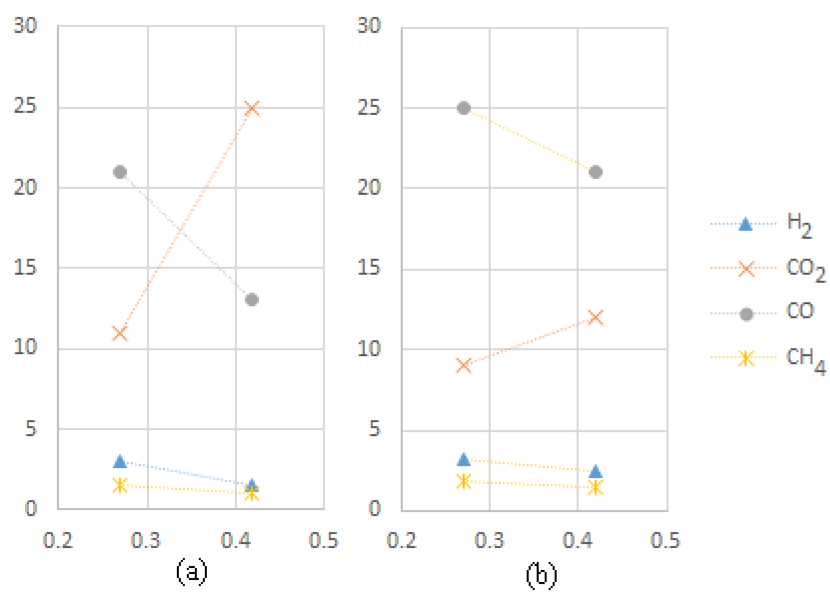

Figure 7. Effect of ER on product gas composition for (a) Mesquite and (b) Juniper. Data source [21].

Syngas HHV percentages and gas yield are negatively influenced by ER. The max juniper HHV of 4000kJ/Nm^3 was obtained at the lowest ER of 0.27.

3.5. Fluidized Bed Gasifier

There are several problems with the operation of fixed bed gasifiers including lack of bunker flow, slagging and extreme pressure drop over the gasifier since operation is influenced by the morphological, physical and chemical properties of the fuel [22]. Originally developed to increase efficiency of gasification of fixed bed gasifier [23], fluidized bed gasifiers can achieve a high heating rate, uniform heating and high productivity[24]. Gasification temperature is relatively low at around 750°C to 900°C (compared to fixed bed operating from 800°C-1400°C) to avoid ash melting and sticking [25]. Biomass feedstock is fed as fuel into a suspended (bubbling fluidized bed (BFB)) or circulating (circulating fluidized bed (CFB)) hot sand bed so the resulting bed within the gasifier acts as a fluid and is characterised by high turbulence. These gasifiers employ back-mixing to efficiently mix the fuel particles in oxygen-rich gas, resulting in rapid pyrolysis and low tar-conversion rates as the temperatures are relatively low. Unlike FXB, relatively fine particle sizes of 0-20mm are preferred, while FXB can take 10-100mm biomass particle sizes.

3.5.1. Bubbling Fluidized Bed Gasifier (BFB)

Figure 8. shows a simplified schematic diagram of a BFB system. Feedstock is fed through the top/sides while the gasifying agent (air, steam or oxygen) is blown upwards through the bed at 1-3m/s to agitate the inert bed material at the gasifier bottom. The feedstock mixes and combusts or forms syngas which leaves upwards. The composition of syngas is varied by feed rates of biomass and gasifying agent while temperature distribution in the gasifier and the composition of syngas is monitored. The biomass undergoes successive reaction processes such as drying, pyrolysis, gasification and combustion.

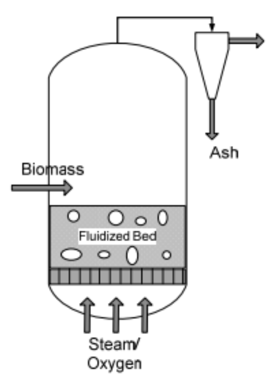

Figure 8. BFB gasification system. Image source [12]

The thermo-chemical conversion of biomass is strongly related to dimensions and shapes of the feedstock. In Figure 9., we presented data collected from the fast pyrolysis of apricot stone which indicates that the smaller particle size favours the yield of hydrogen rich gas (total concentration of $CO+H_2$ exceeds 60% and the H_2/CO ratio is greatly increased to 0.57 when the particle size is 0.20-0.30mm).

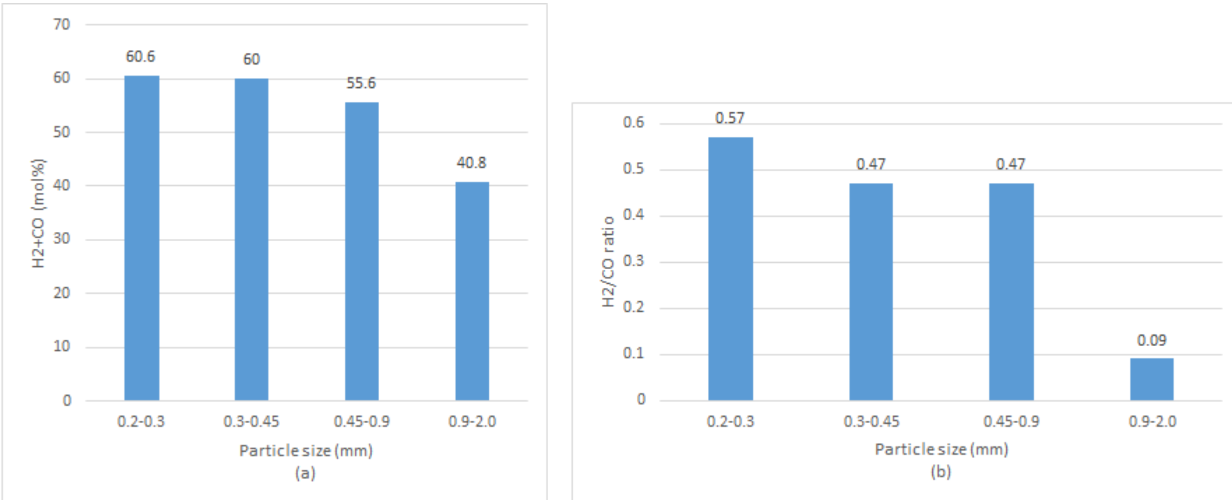

Figure 9. Effect of sample particle size on (a) H_2 + CO (mol%) and (b) H_2/CO ratio in gaseous product from fast pyrolysis of apricot stone. Data source [26].

The feeder continuously feeds a uniform amount of feedstock to the gasifier at a feed rate controlled by revolutions per minute, RPM. The preheat chamber located at the bottom of the gasifier is equipped with an LPG gas burner which supplies air to the gasifier. The feed rate and air-flow rate control the vertical temperature and hence the syngas composition and tar content of syngas [9].

Young et al [9] investigated the air-blown gasification of woody biomass in a BFB gasifier. using silica sand as the bed material, and the optimum gasifier performance occurred at an ER of 0.19, with an LHV of 5.7Mj/Nm^3 and H_2/CO ratio of 1. Figure 10. illustrates the concentration of syngas composition and LHV as a function of ER that we plotted from the study.

Evident is the concentration of syngas tending to increase as ER was at at its lowest value at 0.19. At this ER, H_2/CO ratio was greatest and the LHV was highest. The H_2 concentration, which is important for combustion of CO in syngas engines, increased from 13.8% to 16.1% as ER was reduced. The total volume of the product gas, however, decreased as ER decreased.

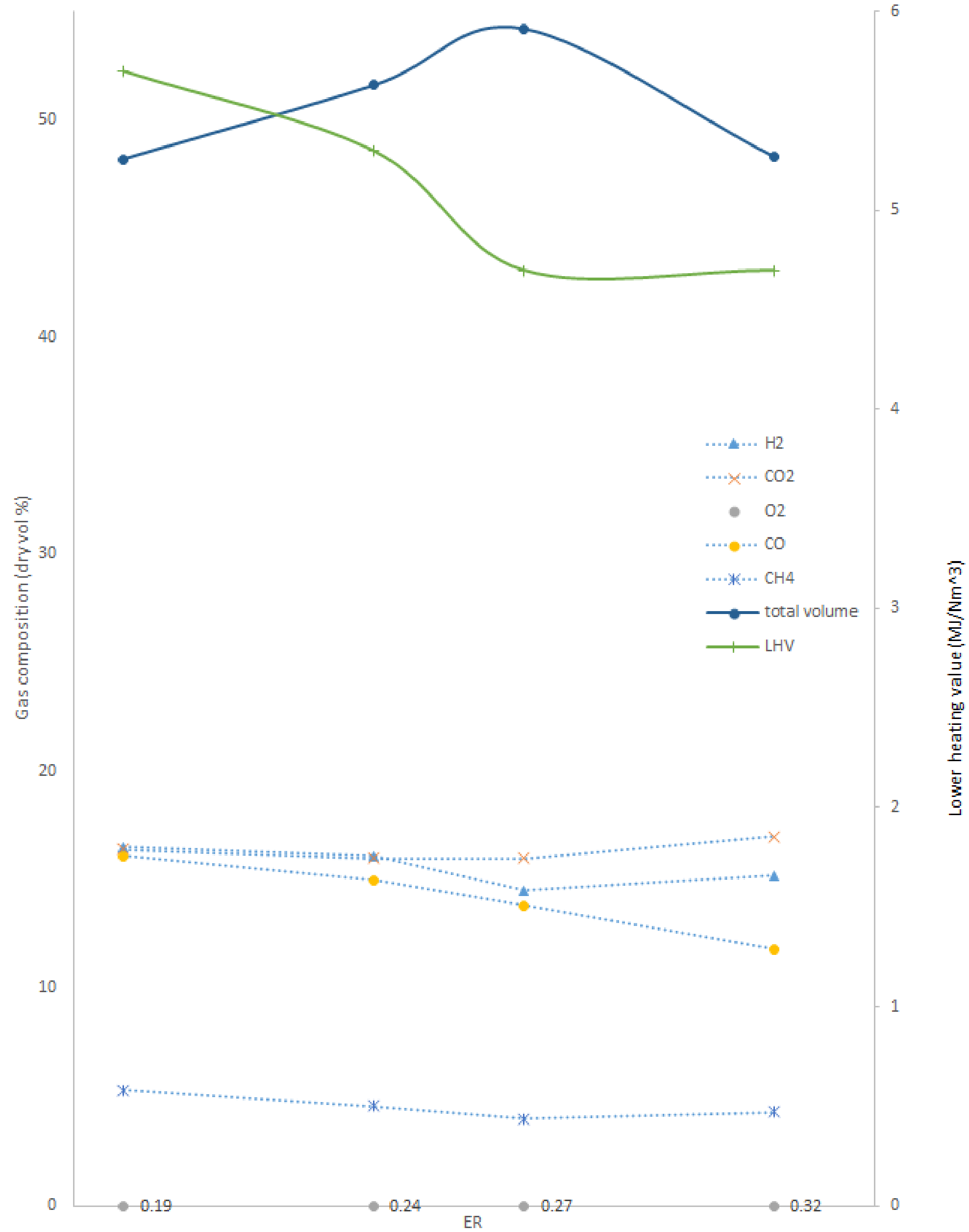

Figure 10. Syngas composition, and LHV as function of ER for BFB. Data source [9].

Beheshti et al [27] also demonstrated that ER was the most important factor in the process: increasing the ER from 0.3 to 0.7 increased carbon conversion, gas yield and tar reforming. Since the average tar content of producer gas must be around 10g/Nm^3[28] in order to use in internal combustion engine, it is essential to minimize the tar formation by performing the gasification at higher ER's (at 0.3, tar content is about 12.57g/Nm^3 which exceeds the standard for use in internal combustion engines). However, higher ER lowered gas calorific value from over 10MJ/Nm^3 at 0.3 ER to around 3MJ/Nm^3 at 0.7 ER and also lowered cold gas efficiency.

3.5.2. Circulating Fluidized Bed Gasifier (CFB)

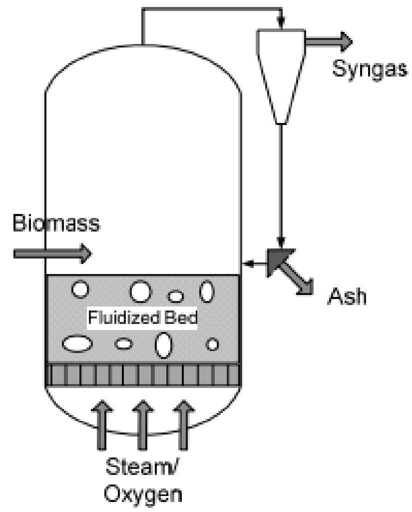

Figure 11. Circulating Fluidized gasifier. Figure source [12]

The CFB has a similar setup and operation to the BFB but with one major variation. The gasifier vessel is equipped with a cyclone and particle recirculation system so the gasifying agent has a higher velocity allowing greater mixing between the fluid and particles in the bed and the fast fluidization enhances the heat and mass transfer, speeding up the gasification process and improving carbon conversion efficiencies [29]. Most of the solid and non gasified particles are moved to the attached recirculation system where the solids are recirculated to the gasifier bed. Circulation also increases the residence time of char, reducing reaction time and decreasing syngas composition loss due to char[30]. The CFB gasifier is designed to produce 10-150MW combustible fuel gas [31]. CFB and BFB follow the same trends for effect of operating conditions on syngas. Figure 12 from Miao et al's model of CFB's [32] summarises the effect of operating conditions on syngas LHV. The LHV doubled from 3.79MJ/m^3 to 7.63 MJ/m^3 when ER decreased from 0.35 to 0.15. Varying the airflow rate, ER, controls the degree of combustion, affecting the gasification temperature. Higher airflow leads to higher temps which allows greater biomass conversion and quality of syngas. Excess combustion, however, decreases the calorific value, LHV, since some of the biomass energy is used during combustion. Higher ER can also reduce the residence time which leads to greater syngas composition loss due to char. Although increasing the bed temperature has a positive effect on LHV, compromise has to be made between low operating temperature (giving higher % combustible gases as well as % of tar and char) and high temperatures that lead to less char and tar but low % of combustible gases [32]. Biomass feed rate had the smallest effect.

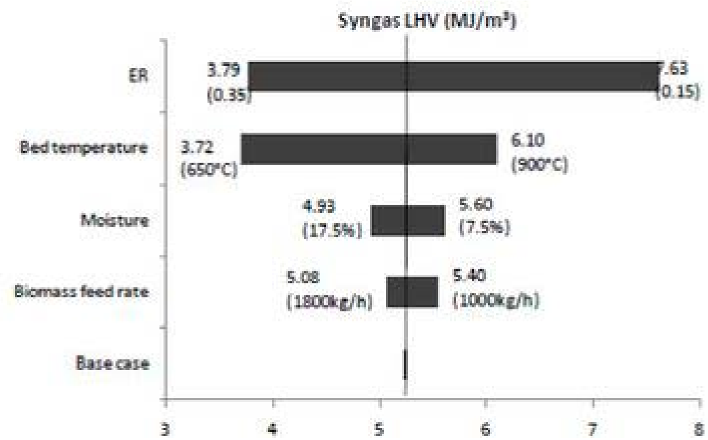

Figure 12. Effect of operating conditions in CFB on syngas LHV. Data source [32]

3.5.3. Dual Fluidized (DLF)

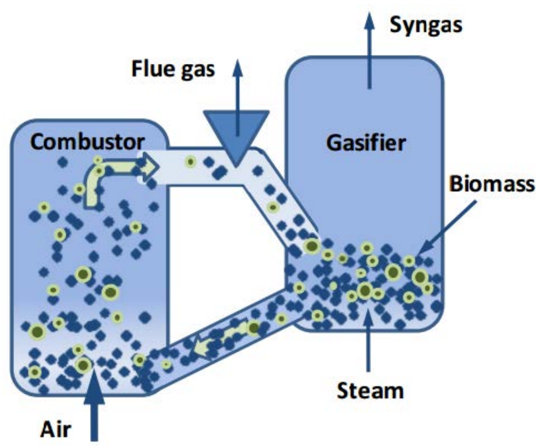

Figure 13. Dual fluidized gasifier. Figure source [25]

As shown in Figure 13. a DLF gasifier consists of two reactors: steam gasifier and a combustor. The steam gasifier performs the conversion of feedstock into syngas at 700-900°C as the bed is blown with steam to gasify the biomass, while the combustor is blown with air to oxidise residual char to provide heat to gasify the feedstock and flue gas. The bed material circulates between the two acting as a heat carrier and maintain temperature along with the char combustion. A DLF is typically a combination of a BFB and CFB[33] and Xu et al [34] found the optimal design has gasification in the BFB and char combustion in a CFB due to particle circulation, fuel conversion and tar production. In Figure 15. we have presented the composition of syngas from a DLF[33] compared with the syngas compositions and LHV across BFB, CFB and DLF discussed in our paper at each optimum LHV. Figure 14. illustrates how the presence of steam in the gasification reaction of a DLF promotes the production of H_2% to a level considerably higher than both BFB and CFB, but also promotes CH_4 (which in DLF's can reach 10% or higher[25]). The high gas syngas composition is due to the bed material in DLFs that renders in situ gas conditioning [33] so less composition is lost to char. But since CH_4 is stable at lower temperatures once formed, the high CH_4% detracts from the high H_2% and CO% in syngas produced in DLF's.

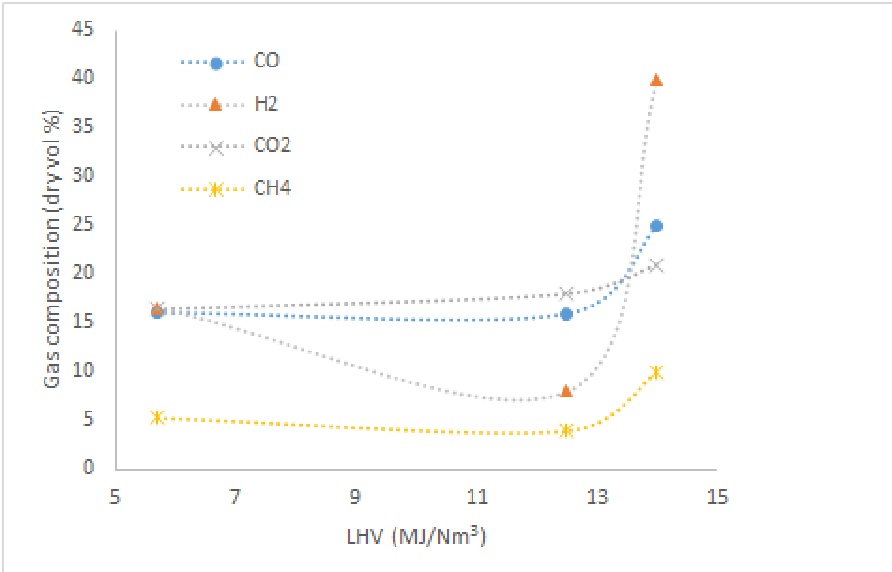

Figure 14. Our comparison of gas composition at optimum LHV for each BFB, CFB and DLF discussed.

3.6. Entrained-Flow Gasifier (EFG)

Syngas can also be synthesised within an entrained-flow gasifier. They consist of 4 main components, a gasification main body, a fuel feeding system, a system for the supplement of gas, and analytical systems such as a temperature measurement and sampling apparatus [35]. These gasifiers are typically operated at inflated pressures of almost 50 atmospheres. To ensure that gasification goes to completion, fuel is required to be atomised within the time it resides within the reactor. Fuel particles, smaller than 1 mm at an operating temperature of 1100 C - 1500 C are required for successful gasification. Entrained-flow gasifiers mix fuel with a steam/oxygen steam to form a turbulent flow within the gasifier. Liquid slag forms at the bottom of the reactor from melting ash-forming components, effectively creating a wall on the sides of the gasifier, protecting the gasifier walls. As slag forms at the bottom of the reactor, it is processed and cleaned, then extracted as syngas. Due to the complete gasification of the char, tar and methane content due to incomplete combustion are negligible and thus, carbon conversion rate is resultantly higher [12].

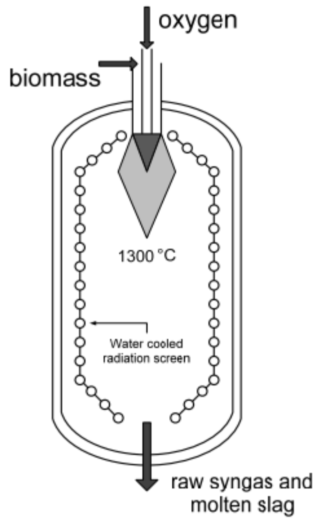

Figure 15. Simple model of an Entrained Flow Gasifier. Figure source [12]

When overviewing the process by which this gasifier operates, there are important factors which affect the efficiency equivalence ratio and heating value of the resultant syngas. The most apparent factor which affects the aforementioned properties was found to be the feedstock used. Blended fuels along with different forms of organic matter such as torrefied wood, ash deposits, coal and petroleum coke blends are examples of the various feedstock which can be used for synthesis, also showing the fuel flexibility that entrained gasifiers are capable of [36, 37].

A study performed by Jinsong Zhou et. al. sought to determine the influence of some key parameters such as reaction temperature, reaction time, equivalence ratios, and feedstock composition. Rice husk, sawdust, and camphor wood were used as feedstocks for gasification.

Table 3. Our proximate analysis of the main feedstocks used in the investigation by Jinsong Zhou et. al. Data source [36]

	Proximate analysis (air-dried weight %)		**Heating value (kJ/kg)**
Material	**Moisture**	**Ash**	**LHV**
Rice husk	9.23	17.21	15,039
Sawdust	4.79	4.69	18,313
Camphor wood	12.29	0.49	17,482

The residence time of the fuel droplets were also shown to be crucial for the gasification process. Maximum carbon conversion efficiency was obtained at a very particular time, as a short residence time would result in incomplete gasification which leads to overall less. Temperature was also shown to affect the overall biomass gasification process, as high temperatures are a key component in the operation of entrained gasifiers. According to Le Chatelier's principle, high temperatures tend to favour reactants in an exothermic reaction and products in endothermic reactions. For the chemical reactions undertaken within the gasification process can be summarised in Table 1.

Therefore from this principle, with an increase in temperature, endothermic reactions are strengthened which results in an increase of hydrogen and carbon monoxide contents (H_2 and CO respectively), whilst decreasing methane and carbon dioxide contents (CH_4 and CO_2 respectively). H_2 and CO are arguably the most important gas components, as they determine the quality of the syngas. Consistent with Le Chatelier's principle are the results of an increase to temperature, showing a rise in H_2 and CO contents for both rice husk and sawdust, which can be displayed in Figure 16. [36].

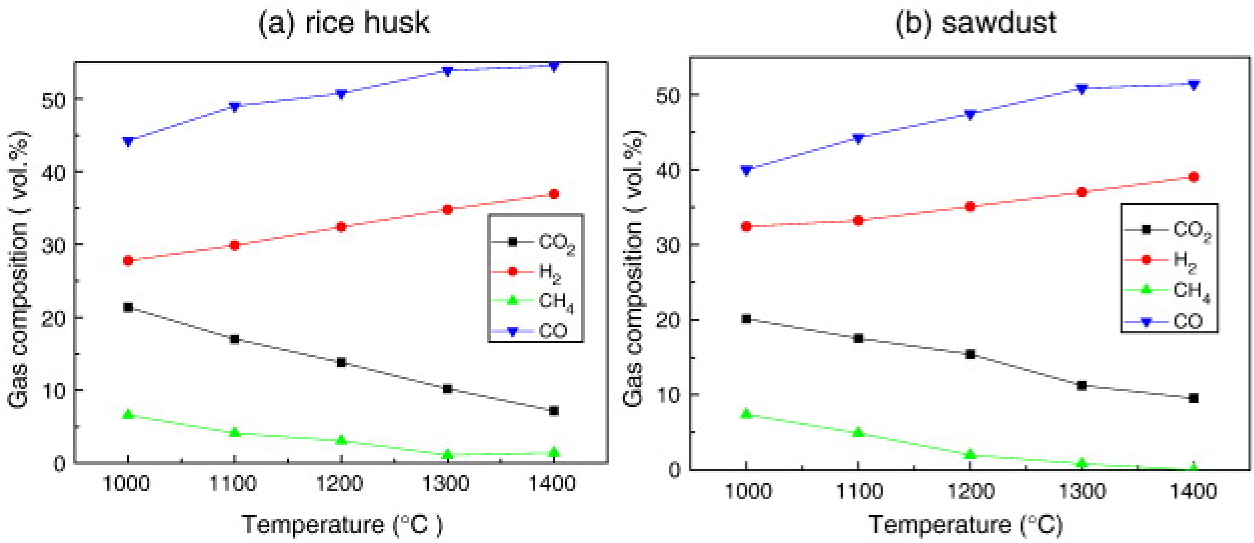

Figure 16. The effect of reaction temperature on the gas composition of syngas for both rice husk and sawdust feedstock. Figure source [36].

This was also confirmed with similar study by Aaron W. Palumbo et. al, investigating high temperature steam gasification of biomass within an entrained flow reactor, which also verified the statement that an increase of heat resulted in an increase in H_2 and CO concentrations [37].

Cold gas efficiency was also shown to increase as a result of the increase of CO and H_2, as the temperature was raised from 1000 C to 1400 C, with an increase of 16% and 11% for sawdust and rice husk respectively. It can then be said that operation at higher temperatures improve syngas quality.

The time in which the fuel is retained within the gasifier, or residence time, was shown to be a factor which determined the carbon conversion efficiency. Residence time is typically 1-2 seconds during an entrained flow gasifier, where they are decomposed with temperature and gasified. It was shown that with increasing residence time, carbon conversion efficiency as a whole increased, due to the increase of CO concentration as well as the temporary increase of CO_2, the sharp temporary decrease in H_2 and the negligible methane content concentrations. Figure 17. shows the overall efficiency with respect to residence time for both rice husk and camphor wood feedstocks.

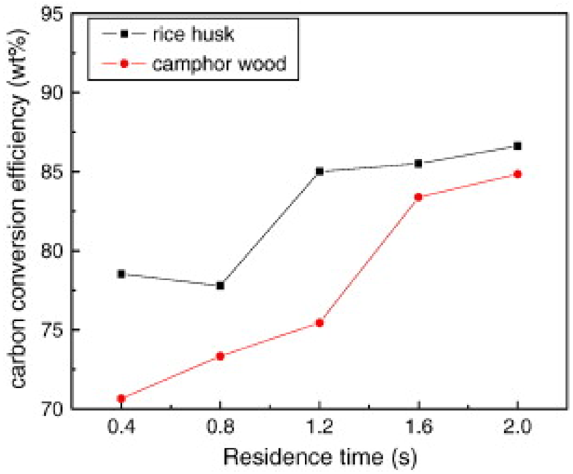

Figure 17. The effect of residence time on carbon conversion efficiency on both rice husk and camphor wood feedstocks. Figure source [36]

The equivalence ratio is also an important parameter which has been shown to affect the carbon conversion of the syngas. The ratio of O_2 to biomass, where O_2 is the gasifying agent, when varied was shown to affect both the gas composition and resultantly, the the carbon conversion efficiency. The efficiency of the conversion was shown to increase with an increasing O_2/Biomass ratio which is indicative of more carbon from the biomass burning due to the influence of O_2. The optimal O_2/Biomass ratio was shown to be 0.4 [36].

3.7. Plasma Gasifier (PG)

Plasma gasifiers utilize plasma torches placed next to air nozzles in order to heat incoming moving air to extremely high temperatures of approximately 1500-5000°C at 1 atmosphere. The system is used almost entirely on waste feedstock, organic plant matter, and ash or coal. External electric energy sources are used to produce the plasma flames which then gasify the crude reactants such as coal or various biomasses [12].

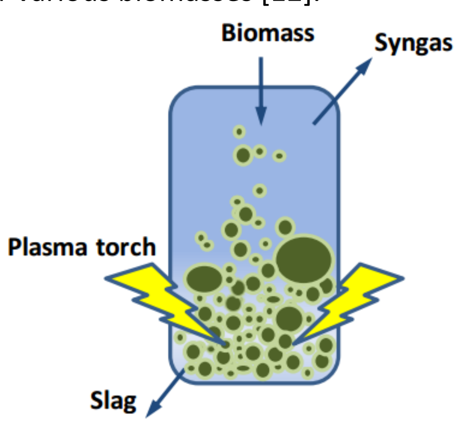

Figure 18. Simplified model of a Plasma Gasifier. Untreated biomass is dropped into the gasifier where the organic matter is converted into high quality syngas when the biomass comes in contact with the plasma, with any inorganic matter vitrified into inert slag. Figure source [25].

Plasma gasifiers can be used in a multitude of different ways, utilising a variety of different processes between them in order to maximise the yield and efficiency in the production of syngas.

One such example of this was from Sang Jun Yoon et. al.'s investigation into the production of hydrogen and syngas from glycerol through microwave plasma gasification, whereby the use of a microwave generator was also implemented into the plasma gasification process. During their investigation, experimental results displayed that efficiency of gasification along with the heating value of the syngas, increased with a supply of microwave power, while the increase of oxygen and steam in the system resulted in an overall lower performance in gasification [13]. This generalised statement can be further explained by understanding the factors which affect this result.

The equivalence ratio, which in this case includes the comparison of the composition of oxygen O_2 to the composition of fuel when glycerol was supplied through a tube. Their investigation demonstrated that with an increasing O_2/fuel ratio, the carbon conversion increased, while the heating value of the syngas as well as cold gas efficiency was shown to decrease.

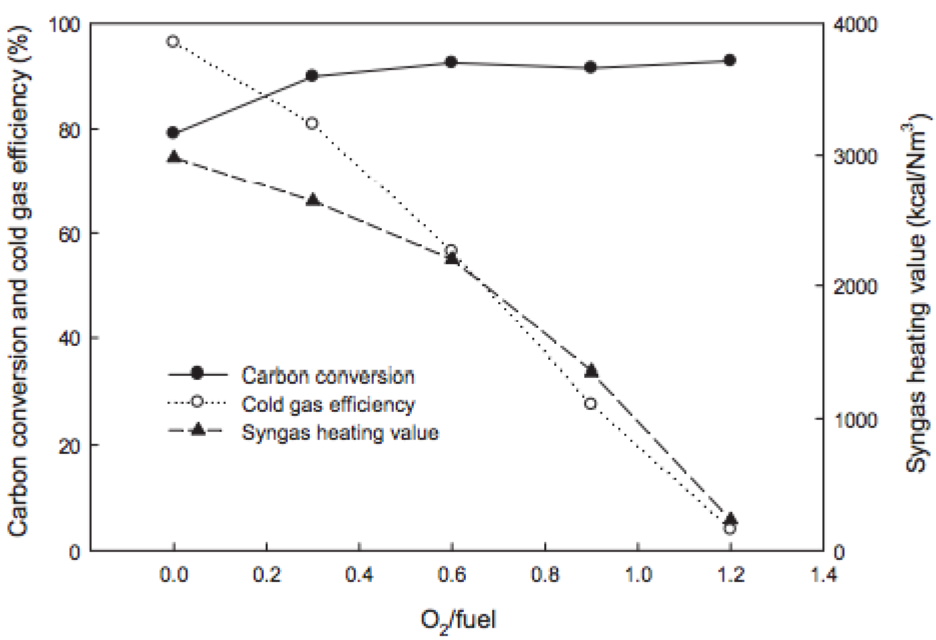

Figure 19. The effect of the O_2/fuel ratio on the heating value (right y-axis), carbon conversion as well as cold gas efficiency (left y-axis)

The microwave power is a major factor which affects the performance of the plasma gasification. The microwave power is associated with gasifier temperature, in this case the size of the flame and the plasma density are affected with changes in the power of the microwave. Studies show that an increase in microwave power results in an increase of reactor temperature, plasma density, and plasma flame diameter and length [43].

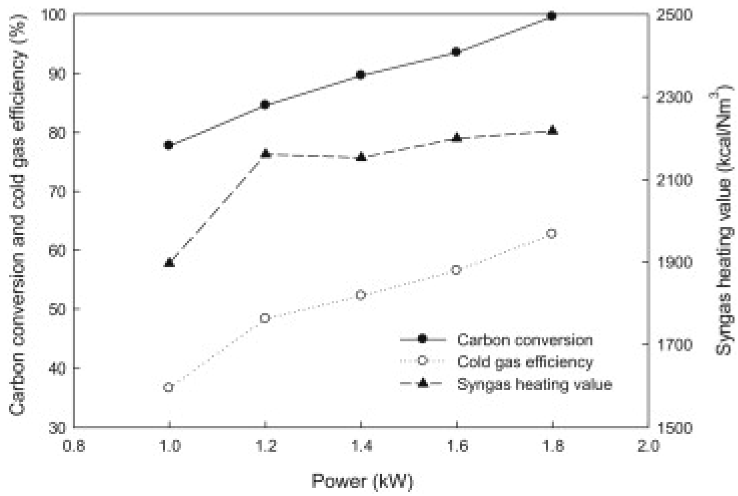

Figure 20. (a) The effect of microwave power on the composition of syngas

As seen in Figure 20., as microwave power is increased from 1 to 1.8kW, carbon conversion and cold gas efficiency increased by a factor of over 20%, with the carbon conversion almost going to completion and over 62% of cold gas efficiency. It can then be stated from this that with an increased volume of high temperature flames, the fuel retention time within the plasma flame along with reaction temperature were also increased, thus improving gasification efficiency [12].

The rate at which the glycerol was sprayed into the chamber for plasma gasification also affected the gasification reaction and efficiency. It was determined that as the nozzle spray flow rate increased at a constant glycerol feed rate, the glycerol atomized into fine droplets and hence increased reaction surface area, effectively increasing the thermochemical conversion of the glycerol. However, an excessive spray rate lowers reactor temperature and thus decreasing the heating value and resultantly, the production yield of the syngas. The optimal spray rate of 3L/min was shown to be the most efficient spray of glycerol supplied at 3 g/min [12].

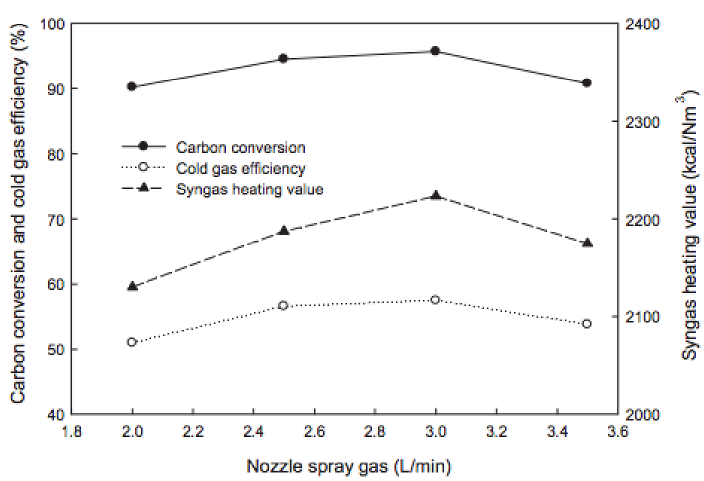

Figure 21. (a) The effect of nozzle spray rate upon syngas heating value as well as carbon conversion and cold gas efficiency.

3.8. Existing Energy System Competitors

There are numerous other energy sources available in the world today, with many of them still in use and occupying a larger space in the world's total energy supply. As of 2013, biofuels rank 5th out of 7 in the world for total energy consumption worldwide at 5.3% of the total energy supply with oil and natural gas still the primary energy supplies at 25.8% and 25.8% respectively. We presented the data from the U.S. Energy Information Administration (EIA)[38] in Figure 24.

We performed a comparison of the energy production and consumption growth from 2008 to 2012 between biomass, natural gas and two major fossil fuels -petroleum and coal, as shown in Figure 23 from data collected from the Energy Information Administration [39].

Both the production and consumption of biofuel exhibits the largest growth percentage as of 2008-2012, at 22.3% and 27.7% respectively. Although coal, a fossil fuel which has provided the world with energy since the late 1700s, is the most abundant and widely distributed energy source to date [40, 41], in comparison to the biofuel syngas, it's growth in both production and consumption is almost half as much as that of biofuel. The same can be said for the two other energy sources, with petroleum production growth as the lowest at 4.3% due to the onset of increasing oil prices [42].

The increase in growth in production as well as consumption of biofuels is consistent with our aforementioned statement on climate change, with the world striving to achieve greener energy production.

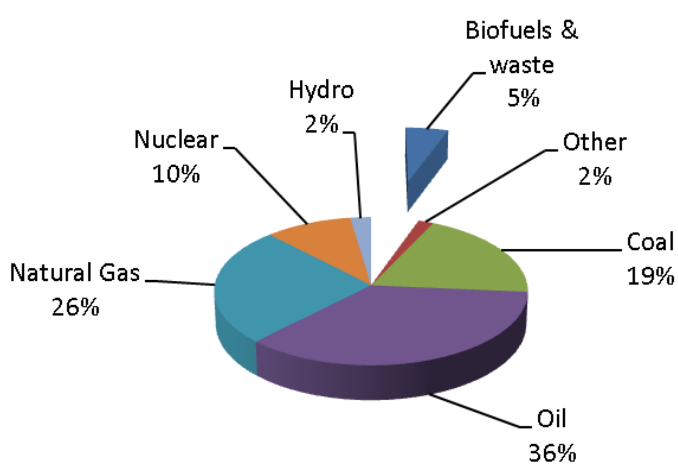

Figure 22. The statistical comparison of the world's energy supply as of 2013, with emphasis on biofuels. Data source [38].

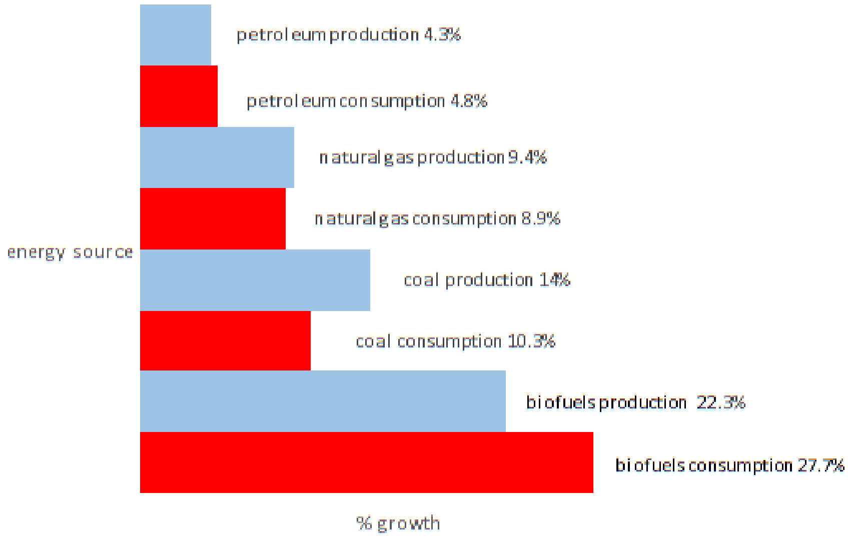

Figure 23. Percentage growth of both energy production and consumption from 2008 to 2012 for various energy sources. Data source [39]

4. Conclusions

Gasification systems used industrially for the preparation and synthesis of syngas vary in terms of design and operation. From this study, we have analysed and compared the thermodynamic parameters of seven different systems which are involved in the production of syngas; fixed-bed updraft and downdraft gasifiers, fluidized bubbling, circulating and dual gasifiers, entrained gasifiers, and plasma gasifiers. The quality of syngas from each system was dependent on a number of operating parameters and requirement of different gasifier types including ER, operating temperature, particle size and MC of the feedstock. General trends highlighted across the various gasifiers from our study included the following; ER was shown to be the most important factor during the gasification process: increasing ER, causes an increase in carbon conversion, gas yield and tar reformation, but a lowered gas calorific value and cold gas efficiency. For the both fluidized and fixed bed gasifiers, a compromise was needed between low operating temperature (which gives higher percentage of combustible gases, but also a higher percentage of char and tar) and high operating temperatures, which leads to a lower percentage of char and tar, but a resultantly lower percentage of combustible gases. Our study, through the comparison of each gasification system, emphasised the complex relationship between the operating parameters and the quality of the resultant syngas.

A smaller more general comparison was made to highlight biomass's position against competing energy sources such as coal, petroleum and natural gas. Although biofuels and waste currently make up only 5% of the world's total energy supply, its production growth over the last few years is at a healthy 27%- more than double that of coal, the world's current leading source of energy supply.

5. Acknowledgments

The authors would like to acknowledge Dr. Jurgen Schulte for his guidance and constructive criticism during the course of this meta-study, as well as the Energy Science & Technology class of 2015 for peer-reviewing this work.

6. References

1. Biofuel.org.uk, (2015). *Biofuels - Biofuel Information - Guide to Biofuels*. [online] Available at: http://biofuel.org.uk/ [Accessed 24 May 2015].
2. Katarina Eklöf, J., Ekerholm, H. and Mårald, E. (2012). Promoting Ethanol in the Shadow of Oil Dependence: 100 years of arguments and frictions in Swedish politics. *Scandinavian Journal of History*, 37(5), pp.621-645.
3. Ecotricity.co.uk, (2015). *The End Of Fossil Fuels - Our Green Energy - Ecotricity*. [online] Available
4. Kumari, A., Mahapatra, P., Garlapati, V. and Banerjee, R. (2009). Enzymatic transesterification of Jatropha oil. *Biotechnol Biofuels*, 2(1), p.1.
5. BODEN,, T., MARLAND,, G. and ANDRES,, R. (2010). GLOBAL, REGIONAL, AND NATIONAL FOSSIL-FUEL CO2 EMISSIONS. *Carbon Dioxide Information Analysis Center (CDIAC) Datasets*.
6. Nuffield Bioethics, (2015). *Why do we need biofuels? - Nuffield Bioethics*. [online] Available at: http://nuffieldbioethics.org/report/biofuels-2/biofuels/ [Accessed 24 May 2015].
7. Harris Group Inc., (2012). *Biomass Gasification Technology Assessment Consolidated Report*. [online] Atlanta, Georgia: NREL, p.4. Available at: http://www.nrel.gov/docs/fy13osti/57085.pdf [Accessed 22 May 2015].
8. Liu, K., Song, C. and Subramani, V. (2010). *Hydrogen and syngas production and purification technologies*. Hoboken, N.J.: Wiley.
9. Baratieri, M., Baggio, P., Fiori, L. and Grigiante, M. (2008). Biomass as an energy source: Thermodynamic constraints on the performance of the conversion process. *Bioresource Technology*, 99(15), pp.7063-7073.
10. Kim, Y., Yang, C., Kim, B., Kim, K., Lee, J., Moon, J., Yang, W., Yu, T. and Lee, U. (2013). Air-blown gasification of woody biomass in a bubbling fluidized bed gasifier. *Applied Energy*, 112, pp.414-420.
11. Clarke Energy, (2015). *Synthesis gas, (syngas), producer gas use in gas engines*. [online] Available at: https://www.clarke-energy.com/synthesis-gas-syngas/ [Accessed 24 May 2015].
12. Alternative Technologies to Transform Biomass into Energy. (2012). 1st ed. [ebook] Western Sarnia-Lambton Research Park. Available at: http://www.ofa.on.ca/uploads/userfiles/files/alternative%20technologies%20to%20transform%20biomass%20into%20energy%20jan%202013.pdf [Accessed 6 May 2015].
13. Yoon, S., Yun, Y., Seo, M., Kim, Y., Ra, H. and Lee, J. (2013). Hydrogen and syngas production from glycerol through microwave plasma gasification. *International Journal of Hydrogen Energy*, 38(34), pp.14559-14567.
14. Quaak, P., Knoef, H. and Stassen, H. (1999). *Energy from biomass*. Washington, D.C.: The World Bank.

15. Dogru, M. (2013). EXPERIMENTAL RESULTS OF OLIVE PITS GASIFICATION IN A FIXED BED DOWNDRAFT GASIFIER SYSTEM. *International Journal of Green Energy*, 10(4), pp.348-361.
16. Handbook of Biomass Downdraft Gasifier Engine Systems. (1988). 1st ed. [ebook] Golden: Solar Energy Research Institute, p.27. Available at: http://www.nrel.gov/docs/legosti/old/3022.pdf [Accessed 24 May 2015].
17. Eai.in, (2015). *Fixed-bed gasifiers for Biomass Gasification - EAI.in*. [online] Available at: http://www.eai.in/ref/ae/bio/bgt/type/fixed_bed_gasifier.html [Accessed 1 May 2015].
18. Seggiani, M., Puccini, M., Raggio, G. and Vitolo, S. (2012). Effect of sewage sludge content on gas quality and solid residues produced by cogasification in an updraft gasifier. *Waste Management*, 32(10), pp.1826-1834.
19. Skoulou, V. ; Zabaniotou, A. ; Stavropoulos, G. ; Sakelaropoulos, G. *`Syngas production from olive tree cuttings and olive kernels in a downdraft fixed-bed gasifier`* – Published in: International Journal of Hydrogen Energy, 2008, Vol.33(4), pp.1185-1194
20. Saravanakumar, A. ; Haridasan, T.M. ; Reed, Thomas B. ; Bai, R. Kasturi. *`Experimental investigation and modelling study of long stick wood gasification in a top lit updraft fixed bed gasifier`* Published in: Fuel, 2007, Vol.86(17), pp.2846-2856
21. Chen, Wei ; Annamalai, Kalyan ; Ansley, R. James ; Mirik, Mustafa. *`Updraft fixed bed gasification of mesquite and juniper wood samples`* Published in: Energy, 2012, Vol.41(1), pp.454-461
22. Fao.org, (2015). *2.3 Types of gasifiers*. [online] Available at: http://www.fao.org/docrep/t0512e/T0512e0a.htm#2.3.4 [Accessed 24 Apr. 2015].
23. Tasma, D. and Panait, T. (2015). *THE QUALITY OF SYNGAS PRODUCED BY FLUIDISED BED GASIFICATION USING SUNFLOWER HUSK*. Galati, Romania: Thermal Systems and Environmental Engineering Department.
24. Wang, L., Weller, C., Jones, D. and Hanna, M. (2008). Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. *Biomass and Bioenergy*, 32(7), pp.573-581.
25. E4TECH, (2009). *Review of Technologies for Gasification of Biomass and Wastes*. [online] E4TECH, pp.4-5, 25-30. Available at: http://www.ecolateral.org/review-of-technologies-for-gasification-of-biomass-and-wastes/ [Accessed 17 Apr. 2015].

26. Li, S., Xu, S., Liu, S., Yang, C. and Lu, Q. (2004). Fast pyrolysis of biomass in free-fall reactor for hydrogen-rich gas. *Fuel Processing Technology*, 85(8-10), pp.1201-1211.
27. Beheshti, S., Ghassemi, H. and Shahsavan-Markadeh, R. (2015). Process simulation of biomass gasification in a bubbling fluidized bed reactor. *Energy Conversion and Management*, 94, pp.345-352.
28. Bhattacharya, S., Mizanur Rahman Siddique, A. and Pham, H. (1999). A study on wood gasification for low-tar gas production. *Energy*, 24(4), pp.285-296.
29. Latif, A. (1999). *A STUDY OF THE DESIGN OF FLUIDIZED BED REACTORS FOR BIOMASS GAS IFICATION*. [online] London: University of London, p.28. Available at: http://discovery.ucl.ac.uk/1349342/1/341355.pdf [Accessed 20 Jun. 2015].
30. Biofuelsacademy.org, (2015). Circulating Fluidized Bed Gasifier | Biofuels Academy. [online] Available at: http://biofuelsacademy.org/web-modules/equipment/gasifier/circulating-fluidized-bed-gassifier/ [Accessed 1 Apr. 2015].

31. Andritz.com, (2015). *Circulating fluidized bed (CFB) gasifiers - ANDRITZ GROUP*. [online] Available at: http://www.andritz.com/products-and-services/pf-detail.htm?productid=13863 [Accessed 8 May 2015].
32. Miao, Q., Zhu, J., Barghi, S., Wu, C., Yin, X. and Zhou, Z. (2013). ChemInform Abstract: Modeling Biomass Gasification in Circulating Fluidized Beds. *ChemInform*, 44(18), p.no-no.
33. Göransson, K., Söderlind, U., He, J. and Zhang, W. (2011). Review of syngas production via biomass DFBGs. *Renewable and Sustainable Energy Reviews*, 15(1), pp.482-492.
34. Xu, G., Murakami, T., Suda, T., Matsuzawa, Y. and Tani, H. (2006). The Superior Technical Choice for Dual Fluidized Bed Gasification. *Industrial & Engineering Chemistry Research*, 45(7), pp.2281-2286.
35. Zhang, Y., Zhao, Y., Gao, X., Li, B. and Huang, J. (2015). Energy and exergy analyses of syngas produced from rice husk gasification in an entrained flow reactor. *Journal of Cleaner Production*, 95, pp.273-280.
36. Zhou, J., Chen, Q., Zhao, H., Cao, X., Mei, Q., Luo, Z. and Cen, K. (2009). Biomass–oxygen gasification in a high-temperature entrained-flow gasifier. *Biotechnology Advances*, 27(5), pp.606-611.
37. Shen, C., Chen, W., Hsu, H., Sheu, J. and Hsieh, T. (2011). Co-gasification performance of coal and petroleum coke blends in a pilot-scale pressurized entrained-flow gasifier. *International Journal of Energy Research*, 36(4), pp.499-508.
38. *Key World Energy Statistics. (2014). 1st ed. [ebook] France: IEA, p.6. Available at: http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf [Accessed 24 May 2015]*.
39. Eia.gov, (2015). *International Energy Statistics - EIA*. [online] Available at: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=1# [Accessed 24 May 2015].
40. Power Generation from Coal Measuring and Reporting Efficiency Performance and CO2 Emissions. (2015). 1st ed. [ebook] France: Coal Industry Agency Board, p.15. Available at: http://www.biotechnologyforbiofuels.com/content/2/1/1 [Accessed 24 May 2015].
41. Fe.doe.gov, (2015). *DOE - Fossil Energy: A Brief History of Coal Use in the United States*. [online] Available at: http://www.fe.doe.gov/education/energylessons/coal/coal_history.html [Accessed 24 May 2015]. at: https://www.ecotricity.co.uk/our-green-energy/energy-independence/the-end-of-fossil-fuels [Accessed 24 May 2015].
42. Energy Trends in Selected Manufacturing Sectors: Opportunities and Challenges for Environmentally Preferable Energy Outcomes. (2015). 1st ed. [ebook] Fairfax: ICF International, p.89. Available at: http://www.epa.gov/sectors/pdf/energy/ch3-11.pdf [Accessed 24 May 2015].
43. Du, C., Li, H., Zhang, L., Wang, J., Huang, D., Xiao, M., Cai, J., Chen, Y., Yan, H., Xiong, Y. and Xiong, Y. (2012). Hydrogen production by steam-oxidative reforming of bio-ethanol assisted by Laval nozzle arc discharge. *International Journal of Hydrogen Energy*, 37(10), pp.8318-8329.