CHAPTER I
INTRODUCTION

1.1. Rationale/Problem Statement

Following the Energy Efficiency Action Planning of ASEAN, 4 of the ASEAN member states will be able to reduce primary energy consumption Indonesia (25%), Thailand (22%), Malaysia (21%), Brunei (20%), consecutively [1]. Each member state has their own action plan for the development of renewable energy as part of their current energy mix for the matter of energy security. For example, Thailand’s government assigned the Ministry of Energy to establish Renewable and Alternative Energy Plant for 25% in 10 years, so called “AEDP (2012-2021)”, to identify the framework and direction of Thailand renewable energy development [2].

Since an energy mix can be the best alternative to reduce primary energy consumption, the world is looking for new alternative energy resources, such as renewable energy. The prices of petrol, natural gas or other fuels will increase over time unless people have moved to alternatives to fossil fuels. Increased use of renewable energy such as wind, hydro, geothermal, solar and biomass will extend the lifetime of crude oil supplies.

Biomass is the oldest and most common type of renewable energy. Biomass energy can be in the forms of bio-gas, bio-liquid and bio-solid fuels. Some scientists even foresee that bio-gas and bio-liquid significantly replacing fossil fuels in power and transportation. It is a renewable energy source not only because the energy mainly comes from the sun, but also because biomass can re-grow over a relatively short period of time. Thailand as an agricultural country that produces a huge agricultural residues such as rice husk, cane trash, bagasse, grass, cassava trash, empty brunch, etc. are abundant renewable energy resources. Therefore Thailand has potential for using agricultural residues for energy production.

More effective, clean and controllable energy production can be obtained by converting raw biomass into a more concentrated and compact fuel with a higher heating value and controllable fuel characteristics by converting the biomass into a liquid or a gaseous fuel under preliminary defined process conditions. A well-developed technology of biomass conversion into a gaseous fuel is the biomass gasification, i.e. an incomplete combustion with thermal decomposition of the biomass resulting in the production of combustible volatiles (CO, H_2, CH_4, C_xH_y) and solid residues (char) [3].

Higher amounts of tar concentration in the producer gas is identified as one of major problems in biomass gasification. It is normally reduced by employing elaborate gas cleaning or scrubbing system, but the problems are its expensive and bulky. The gas cleaning system produces waste water which contain carcinogenic substances and may need further treatment before disposal [4].

Researchers have carried out extensive research on tar reduction using multi-air-stage gasification. The supply of secondary air between the two stages (i.e. pyrolysis zone and gasification zone) of the reactor generates a high temperature zone in the gasification zone of the reactor which creates a favourable environment for tar cracking. The two stage gasifier developed in some countries has been successfully demonstrated the advantages of multi-stage approach of wood gasification by reducing the tar content of the producer gas.

Theoretically, almost all kinds of biomass with moisture content of 5-30% can be gasified. However, not every biomass fuel can lead to successful gasification, because most biomass feedstocks are inconsistent in moisture, density, size and thermal energy or carbon content. It must be either handled in bales or must be chopped or pelletized to enable mechanical or pneumatic handling [5].

According to the rationale above, biomass gasification still requires much research in the development of reactor design to improve producer gas quality in terms of higher HHV and lower tar contents and conditioning of the raw materials before being processed in gasifier. Further development is still needed to ensure that the efficiency of the process is maximized and that the environmental impact is minimized

1.2. Literature Review

1.2.1. Biomass Gasification

Son et al, [6] studied a downdraft gasifier that was combined with a small engine system for power generation. Wood chips sorted into sizes ranging from 3 to 5 cm for the experiment were used as fuel. The feeding rate of wood chip is 40-45 kg h^{-1}, and the temperature was maintained at 1000 ^{o}C on the basis of the combustion part. The optimum air ratio for gasification was 0.3-0.35, and the result showed a low heating value of 1100-1200 kcal $Nm^{-}3$ and a cold gas efficiency of 69-72%. Tar concentration in raw syngas was around 3.9-4.4 g $Nm^{-}3$. Syngas combustion in the gas engine after purification showed that HC emissions were below 200 ppm, and NOx emissions were below 40 ppm in the exhaust gas. It was confirmed that stable power generation was possible.

Chang et al, [7] studied a new route for dimethyl ether production from biomass gasification. A Cu-Zn-Al/HZSM-5 (16.7 wt%) was developed for DME synthesis from the biomass-derived syngas. Using atmospheric pressure at temperature 1113 K, the feed rate of 0.6 kg biomass/h, ER of 0.28, and CO_2/biomass ratio of 0.327, 1.4 Nm^3 of raw gas kg^{-1} biomass with LHV of 8.36 MJ m^{-3} was produced. Gasification with CO_2 agent and sequent co-reforming with biogas supplies great potential for high efficient production of DME from biomass.

Virginie et al, [8] investigated the effect of Fe-olivine on the tar content during biomass gasification in a dual fluidized bed. The use of Fe/olivine instead of olivine leads to an important decrease in the amount of producer gas, which was reduced by up to 65% at 850 ^{o}C. It has been found that Fe/olivine can act as catalyst for tar and hydrocarbon reforming and also as an oxygen carrier that transfers oxygen from the combustor to the gasifier. The result showed an inexpensive and non-toxic Fe/olivine catalyst was a material suitable for used as a primary catalyst in a fluidized bed gasification of biomass and improved the commonly used olivine catalytic activity.

Bhattacharya and Duta [4] examined the results of an experimental study on two-stage gasification of wood chips with a preheated air supply. It used wood chip of cubic shape with sides in the range 10-15 mm. The gasifier was tested for different pairs of primary and secondary air flow rates. The result showed a clear increase in temperature throughout the gasifier and tar in the producer gas was found to be significantly low due to preheating of air. The measured tar content was below 10 mg/Nm^3 and it should be possible to use gas of such low tar content for trouble free operation of engines directly after filtering and cooling to remove particles and condensable vapours. Increasing in the secondary airflow rate of the two-stage gasifier resulted not only a decrease in tar content, but also concentration of CO_2 while the concentration of CO and H_2 increased.

1.2.2. Biomass Gasifier

Bhattacharya et al, [9] studied multi-stage hybrid biomass-charcoal gasification using coconut shell as fuel. It produced low tar content gas for engine application and achieved 11.44 kW at a maximum electrical power output. By supplying additional air, igniting the charcoal fuel from the bottom of charcoal hopper, charcoal consumption could be increased significantly and it helped to create a local high temperature zone. Consequently, it increased the heating value of the producer gas and reduced the tar content of the final raw gas. The lowest tar content found in hybrid coconut shell-charcoal gasification was 28 mg/Nm^3. Raw producer gas then cooled down to 40^{o}C using a spray tower and almost tar-free was obtained.

Jaojaruek et al, [10] conducted experiments on three different wood downdraft gasification approaches: single stage, conventional two-stage, and an innovative two-stage air and premixed air/gas supply approach. The feedstock was eucalyptus wood cut into 2 cm cubes approximately and had a bulk density of around 285 kg/m^3. The result showed that producer gas quality generated by the innovative two-stage approach improved as compared to conventional two-stage. The higher heating value (HHV) increased from 5.4 to 6.5 MJ/Nm^3. Tar content in producer gas reduced to less than 45 mg/Nm^3. The gasification thermal efficiency also improved by approximately 14%. The approach gave both benefits on gas qualities and energy savings. So the producer gas itself could be fed directly to internal combustion engine.

Martinez et al, [11] studied the gasification of wood biomass in a moving bed downdraft reactor with two-air supply stages. The biomass used in this study is residual eucalyptus wood with a relative heterogeneity in size. The gasifier produced a combustible gas with a CO, CH_4 and H_2 concentrations of 19.04, 0.89 and 16.78% respectively. This type of gasifier gave advantages for the biomass devolatilization in the pyrolysis zone resulting in much lighter compounds that are more easily cracked when the gas stream passes through the combustion zone. The effect of the secondary stage resulted the reduction of CH_4 concentration which is associated with the decreased of the tar content in the producer gas.

Wang et al, [12] studied a comparison of biomass gasification and pyrolysis in three kinds of reactors using corn stalk pellets. It compared the conversion behaviour during downdraft gasification in air environment, bubbling reactor in an oxygen-rich environment, and slow pyrolysis reactor in an oxygen-free environment. The three reactors were connected in parallel with a common control system, condenser, root blower, gas tank, and gas chromatography (GC) system. LHVs of the gas formed in the downdraft reactor, the bubbling reactor, and the pyrolysis reactor were 3.91–4.44, 8.48–9.38, and 14.51–16.49 MJ/Nm^3, respectively. Pellets charcoal and bio-oil were formed in the pyrolysis reactor as gas-assisted products. All reactors consumed some energy, although of the three systems, the downdraft reactor consumed the least.

Campitelli et al, [13] analyzed in a systematic and wide process, the integration of a biomass gasifier with Solid Oxide Fuel Cells (SOFCs). The results showed how a variation of the SOFC H_2 utilization, a parameter whose effects are also correlated with the gasifier air requirement, affects electrical power output also depending on the biomass moisture content.

1.2.3. Gasifying Medium

Nipattummakul et al [14] studied hydrogen and syngas production from sewage sludge by using steam as a gasifying agent. Steam was effective in tar reforming and char gasification at temperatures of 800, 900 and 1000^{o}C. Steam as the gasifying agent increased the hydrogen yield three times as compared to air gasification. Compared to air gasification of sewage sludge, steam gasification resulted in about 40% higher mole fraction of hydrogen. This showed the direct benefit of using steam as a gasifying agent as compared to air assisted gasification or merely pyrolysis.

Ahmed et al, [15] investigated the kinetics of woodchips char gasification with steam and carbon dioxide as the gasifying agents. The reactor temperature were maintained at 900 ^{o}C. Partial pressure of gasifying agents varied from 1.5 bars to 0.6 bars in intervals of 0.3 bars. Steam and CO_2 flow rates were chosen so that both gasifying agents had equal amount of oxygen content. Changing the partial pressure of the gasifying agent did not affect the reaction rate of both steam and CO_2 gasification, which indicates that the process is not controlled by the adsorption step. The process is controlled by either the surface reaction step or the desorption step. The results showed an average reaction rate for steam gasification was almost twice that of CO_2.

Martinez et al, [16] reviewed a downdraft biomass gasifiers, coupled with reciprocating internal combustion engines (RICEs) for small-scale heat and power generation. The influence of gasifier design features were analyzed, such as the biomass particle size (which usually should be less than 5 cm), the moisture content (which should be less than 25%) and the effects of the equivalence ratio (which should be kept between 0.2 and 0.4). The average temperature in the combustion zone was about 1000 ^{o}C with the low heating value and the process cold efficiency for a downdraft type reactor were around 4 - 6 MJ/Nm^3 and 50 - 70%, respectively. The low energy density of the producer gas/air mixture and the engine's volumetric efficiency were the main factors causing the power de-rating of engines. The use of air as an oxidizing agent in the biomass gasification process leads to high concentrations of nitrogen (between 40 and 50%) in the fuel/air mixture and the nitrogen acts as a knock suppressor, which was beneficial in cases when engines with the high compression ratio were employed.

Gai et al, [17] studied the gasification of corn straw carried out in a downdraft fixed-bed gasifier under atmospheric pressure, using air as an oxidizer. The operating conditions had a great influence on the temperature profiles of the gasifier and the composition distribution of the product gas. The ratios of CO/CO_2 and H_2/CO_2 both increased first with the equivalence ratio (the ratio of the actual fuel-air ratio to the theoretical fuel-air ratio) increasing from 0.18 to 0.32, then decreased gradually under the effect of higher equivalence ratio. However, the ratio of H_2/CO showed a narrower fluctuation with different equivalence ratio. It can be concluded that the ER obviously affects the chemical processes in the gasifier.

Mastellone et al, [18] investigated the effect of a gasifying stream composed by air enriched with pure oxygen on the performance of the co-gasification process of coal, plastics and wood fed as a mixture in the bubbling fluidized bed gasifier. The experiments were carried out by keeping the fluidization velocity almost fixed, bed temperature and equivalence ratio (defined as the ratio between the oxygen content of oxidant supply and that required for complete stoichiometric combustion) as much as it was possible by tuning the fluidizing gas pre-heating and by varying the molar oxygen fraction in the fluidizing and oxidizing stream from 21% (air) to 26% and 35%. It is confirmed that the main advantage of an O_2 -enriched air is the possibility to increase the bed temperature, or if a relatively low temperature of the reactor is desired (for instance, to prevent particles sintering), to reduce the size of the transversal cross section and the total cost of pre-heating.

Huynh et al, [19] investigated the characteristics of a biomass gasification system using mixtures of ‘‘oxygen-enriched air’’ and steam as the gasifying agent for increasing the syngas heating value and combustible gas constituents, and also aimed to characterize the effects of oxygen and steam gasification on ammonia concentration, which could lead to significant NOx emissions from syngas combustion. The results indicated that oxygen-enriched air and steam gasification favors the production of combustible gas components, including hydrogen, carbon monoxide, methane, and lighter hydrocarbons. Overall, it was found that oxygen and steam gasification was most effective for feedstock with low nitrogen and moisture contents. The results also showed that ammonia and NOx concentrations in syngas increase as oxygen enrichment increases.

1.2.4. Gasification of Pelletized Biomass

Erlich et al, [20] studied the pyrolysis and gasification of pellets from sugar cane bagasse and stem wood. The bagasse was represented in pellet form, with diameter 6 mm for Cuban bagasse and 12 mm Brazilian bagasse, as well as in shredded form. Some experiments were also performed with 6 mm diameter pellets of Brazilian bagasse prepared in Sweden. The wood was studied both in pellet and chip forms. Wood pellets with diameter 6 mm and 8 mm. The primary interest in this study were physical parameters such as decrease of volume and mass during treatment, as well as pyrolysis and gasification rates. The result showed for pellets the char density decreased during pyrolysis to a minimum around 450 ^{o}C, but thereafter increased with continued heating. The wood chips behaved differently with a continuous char density decrease during pyrolysis. The larger the pellet, the slower the gasification. The smaller the pellet, the smaller was the relative volume decrease of char during gasification. The size of the pellet had larger impact on the shrinkage behaviour throughout the conversion than the raw material, which the pellet was made of.

Lickrastina et al, [3] studied the gasification of pelletized renewable fuels (wood sawdust and wheat straw) for clean energy production. Biomass was pelletized (180 g) using a laboratory pellet mill KAHL 14-175. The water and ash content were determined according to CEN/TS 14774-1 and CEN/TS 14775, correspondingly. For wood pellets, the maximum rate of the volatile production with the peak value of CO and H_2 in the produced fuel gas has been observed at the stage of wood pyrolysis/gasification, while for wheat straw pellets, the maximum rate of the CO and H_2 production has been detected at the final stage of char gasification. With the constant rate of additional heat energy supply and the sub-stoichiometric combustion conditions in the flaming pyrolysis zone ($\alpha \approx 0.17 - 0.30$), a faster thermal decomposition of the pelletized biomass and a larger average amount of the produced volatiles (CO,H_2) can be obtained by increasing the air supply rate from 0.27 g/s to 0.43 g/s, determining the air–fuel ratio 1.3–1.6, which gradually approaches the optimum conditions of air supply for the biomass gasification. The results indicated that the process of biomass gasification was strongly influenced by the amount of additional heat energy and air supply into the biomass.

Erlich et al, [21] studied the downdraft gasification of pellets made of wood, palm-oil residues (EFB) respective bagasse. The pellets differ in chemical composition, but had similar form and densities. The diameter of EFB pellets were 6 mm with length 36 mm. EFB pellets were also produced in 8 mm diameter with an efficient press length of 50 mm. While the diameter for wood and bagasse only 6 mm pellets were available. For gasification of pellets in the studied load interval there seem to be an almost linear relation between air–fuel ratio and cold gas efficiency: The higher the air–fuel ratio, the higher was the efficiency. The results showed that one and the same reactor can be used for a variety of fuels in pellet form, but at varying air–fuel ratios, temperature levels, gas compositions and lower heating values.

Yoon et al, [22] studied the gasification and power generation characteristics of rice husk and rice husk pellets using a downdraft fixed-bed gasifier. Gasification was conducted within a temperature range of 600 - 850 ^oC , and an excess air ratio of 0.45 - 0.6 for rice husk and 0.2 - 0.32 for rice husk pellet gasification. In the case of rice husk gasification, synthetic gas composition shows about 13.6%, 14.9%, 12.9%, and 2.3% for H_2, CO, CO_2, and CH_4. The heating value of the synthetic gas was moderate at 1084 kcal/Nm^3. For rice husk pellet gasification, synthetic gas composition shows about 18.6%, 20.2%, 8.1%, and 1.5% for H_2, CO, CO_2, and CH_4. The heating value of the synthetic gas shows higher value of 1314 kcal/Nm^3 than the synthetic gas produced from rice husk gasification. It was found that the optimum excess air ratio for gasification of rice husk and rice husk pellet is about 0.6 and 0.3. Compared to the rice husk, the synthetic gas generated from rice husk pellet gasification showed higher stability without critical variation depending on time, because the rice husk pellet yielded improved energy density per unit volume, uniformity, and defined form of fuels. It was confirmed that stable power generation about 8 - 10 kW was achieved.

Simone et al, [23] performed a pilot-scale investigation aimed at assessing the feasibility and reliability of biomass pellet gasification. Two pelletized materials were used as feedstock: wood sawdust pellets (WSP) supplied by a local producer and pelletized meal produced from sunflower seed pressings (SMP). The size distribution of WSP and SMP were very homogeneous. WSP and SMP had both cylindrical shape, with a diameter of 6 mm and 10 mm, respectively. The length range was 10–30 mm for WSP and 30–60 mm for SMP. The results proved that pelletized biomass was not an ideal feedstock for downdraft gasifiers, due to high pressure drops, difficult gasifier control and fragmentation of the gasification residues. However, the good syngas compositions (H_2 17.2%, N_2 46.0%, CH_4 2.5%, CO 21.2%, CO_2 12.6%, and C_2H_4 0.4%), cold gas efficiency (67.7–70.0%) and global performance indicators were quite satisfactory, therefore the pelletized biomass might be used as complementary feedstock to increase the energy content per volume and reduce the moisture effects.

Kallis et al, [24] studied a 50 kWth pilot scale of a downdraft gasifier with the equivalence ratio varied in the range 0.2 – 0.3. The feedstock were pellets of two types of Miscanthus (Types 1 and 2) and a bioethanol production reside (distiller's dried grains with solubles (DDGS)). The pellets were made of similar size (6–8 mm). The paper focused on durability of pellets, ash content and gasification parameters, expressed through the equivalence ratio. The result showed type 1 Miscanthus pellets got highest efficiencies. 30% of cold gas efficiency, 47 % of carbon conversion, high durability (96.5%), low K/Ca ratio (0.35) and adequate level of equivalence ratio (0.28). It can be concluded that durability and ash content played a role in the performance of these fuels in the downdraft gasifier. It was also concluded that higher temperatures in combination with better heat distribution resulted in an increase in syngas quantity.

Garg and Sharma [25] evaluated the performance of the gasifier engine system using different feed stocks. Biomass feed stocks such as sawdust, pine wood, sal wood, eucalyptus and popular wood the form of pellets were used for the operation of 5 kW biomass gasifier for electricity generation. It was found that cold gas efficiency (50-70%) and overall efficiency of the system were in the acceptable. It is concluded that gasifier engine system has performed satisfactorily except some problems related to discharging of battery due to low quality gas.

1.3. Objectives

1. To study the effect of the equivalence ratio (ER) on HHV and the tar content of producer gas produced from eucalyptus wood pellet gasification.
2. To examine the producer gas compositions, tar quantity and heating value of producer gas from eucalyptus wood pellet gasification.

1.4. Scope of Research Work

The raw materials for this study were eucalyptus wood pellets. They were cylindrical shapes of diameter 6 – 10 mm and length range 30 – 70 mm. Downdraft gasifier type was used. It was designed by Andini [26] and supported by Thai Steam Service & Supply Company. The gasifying medium was air.

This study investigated the effects of equivalence ratio (ER) on the producer gas composition quality, tar quantity and heating value of the producer gas. As well as measuring the temperature profiles along the gasifier height.

CHAPTER 2
THEORIES

2.1. Gasification

Gasification is a process that uses heat, pressure, and steam to convert materials directly into a gas composed primarily of carbon monoxide and hydrogen. Heat itself is produced in the gasification process, which is provided by oxygen as a gasifying medium. The feedstock is prepared and fed, in either dry or slurried form, into a reactor chamber called a gasifier. The feedstock is subjected to heat, pressure, and either an oxygen-rich or oxygen-starved environment within the gasifier [27]. Gasification processes convert the biomass into combustible gases that ideally contain all the energy originally present in the biomass. In practice, gasification can convert 60% to 90% of the energy in the biomass into energy in the gas. The gas can be burned to produce industrial or residential heat, to run engines for mechanical or electrical power, or to make synthetic fuels [28]. There are three primary products from gasification [27]:

- Hydrocarbon gases (also called syngas)
- Hydrocarbon liquids (oils)
- Char (carbon black and ash)

Gasification is also called “staged combustion”, since usually the gas is produced with the intent to burn it later. This raises the question why first gasifying and then burning the gas over direct combustion of the biomass. There are several essential advantages [29]:

- Possibility to transport in pipelines;
- Ease of control and continuous operation;
- Clean combustion of produced gas since impurities can be removed from the producer gas, and the volume of producer gas is much smaller compared to flue gas;
- Efficient and clean combustion since the exact required air can be mixed for optimum combustion;
- Producer gas can be used in IC engines or turbines with higher efficiencies over steam devices;
- Producer gas, syngas, in particularly can be used for chemical synthesis to produce fertilizers and transportation fuels.

Gasification adds value to low- or negative-value feedstock by converting them to marketable fuels and products. From a chemical point of view, the process of biomass gasification is quite complex. It includes a number of steps, such as [30]:

- Thermal decomposition to gas, condensable vapors and char (pyrolysis);
- Subsequent thermal cracking of vapors to gas and char;
- Gasification of char by steam or carbon dioxide;
- Partial oxidation of combustible gas, vapors and char.

In complete combustion, carbon dioxide is obtained from the carbon and water from hydrogen. Oxygen from the fuel will of course be incorporated into the combustion products, thereby decreasing the amount of combustion air needed [31].

Combustion, occurring in the oxidation zone, is described by the following heterogeneous chemical reactions [30]:

Complete oxidation of solid carbon $C + O_2 \rightarrow CO_2$ $\Delta H = -394$ kJ/mol (1)

Partial oxidation of solid carbon $C + \frac{1}{2} O_2 \rightarrow CO$ $\Delta H = -111$ kJ/mol (2)

These reactions are exothermic and can provide by autothermal gasification the heat necessary for the endothermic reaction in the drying, pyrolysis and reduction zones. [32].

The devolatilisation step (pyrolysis) is slightly endothermic, and for temperatures above 500^{o}C, 75 to 90 wt % volatile matter is produced in the form of steam plus gaseous and condensable hydrocarbon. The water vapour is introduced with the air and produced by drying and pyrolysis of the biomass that reacts with the hot carbon according to the following heterogeneous reactions [30]:

Water gas reaction $C + H_2O \rightarrow CO + H_2$ $\Delta H = +131$ kJ/mol (3)

The most important reduction reactions are the water gas reaction (3) and the following Boudouard Reaction [30]:

Boudouard Reaction $C + CO_2 \rightarrow 2\ CO$ $\Delta H = +172$ kJ/mol (4)

These heterogeneous endothermic reactions increase the gas volume of CO and H_2 at higher temperatures and low pressures. Besides these reactions, several other reduction reactions take place, of which the most important ones worth mentioning are the water gas shift reaction (5) and the methanation reaction (6):

Water gas shift reaction $CO + H_2O \rightarrow CO_2 + H_2$ $\Delta H = -41$ kJ/mol (5)
Methanation reaction $C + 2\,H_2 \rightarrow CH_4$ $\Delta H = -75$ kJ/mol (6)

Although Reaction (7) and (8) produce heat, which is beneficial to the gasification process, they are not desirable because they reduce the heating value of syngas.

Oxidation of hydrogen $H_2 + \frac{1}{2}\,O_2 \rightarrow H_2O$ $\Delta H = -242$ kJ/mol (7)
Oxidation of carbon monoxide $CO + \frac{1}{2}\,O_2 \rightarrow CO_2$ $\Delta H = -283$ kJ/mol (8)

The final product gas contains carbon monoxide, hydrogen and methane as the desired components, next to steam and carbon dioxide. Its precise composition is determined by the water gas shift equilibrium, a homogeneous gas phase reaction between steam plus carbon monoxide (7).

Other homogeneous gas reactions also take place to the heterogeneous reactions in the following way [33-34]:

Steam methane reforming $CH_4 + H_2O \rightarrow CO + 3\,H_2$ $\Delta H = +206$ kJ/mol (9)
CO_2 reforming reaction $CH_4 + CO_2 \rightarrow 2\,CO + 2\,H_2$ $\Delta H = +247$ kJ/mol (10)

Despite a favorable equilibrium constant at $900^{o}C$, methane reformation to CO and H_2 does not occur at atmospheric pressure due to the slow rate of reaction.

2.2. Downdraft Gasifier

There are five major types of gasifier classification such as fixed-bed updraft, fixed-bed downdraft, fixed-bed cross draft, bubbling fluidized bed, and circulating fluidized bed gasifiers. Differentiation is based on the means of supporting the biomass in the reactor vessel, the direction of the flow of both the biomass and oxidant, and the way heat is supplied to the reactor. Fixed bed gasifiers are typically simpler, less expensive, and have a lower heat content - producer gas [5]. Gasifiers can also be classified according to the gasification agent. There are air-blown, oxygen, and steam gasifiers. According to the heat source, there are autothermal or direct gasifiers (heat is provided by the partial combustion of the biomass) and allothermal or indirect gasifiers (heat is supplied from external source through heat exchanger or indirect process). According to the pressure in the gasifier, there are atmospheric and pressurized. According to the design of the reactor, there are fixed bed, fluidized bed, entrained flow, and twin-bed [35].

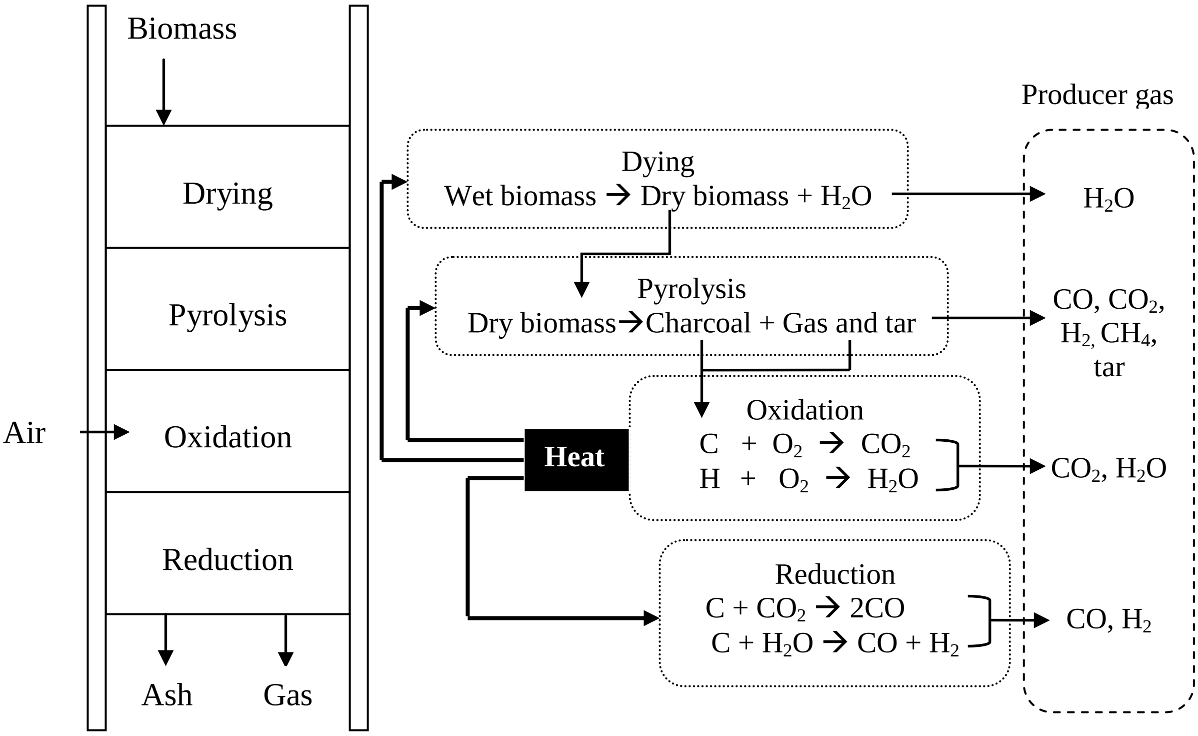


Figure 2.1 Gasification process in a downdraft gasifier

In a downdraft reactor, biomass is fed in the top and the air intake is also at the top or from the sides. The gas leaves at the bottom of the reactor, so the fuel and the gas move in the same direction. Figure 2.1 presents the overall gasification process in a downdraft gasifier [36]. The same zones can be distinguished as in the updraft gasifier, although the order is somewhat different. Adding air to the char zone is an excellent approach for achieving low tar gas (<100 mg tar/ Nm^3). In effect, this is a twin-zone or double-fire gasifier with a plug flow reactor configuration, which is why tar production is often very low. The main advantage of a downdraft gasifier is the production of a gas with a low tar content, which is nearly suitable for engine application. Tars released in the pyrolysis zone go through the oxidation/combustion zone, where they can be oxidized at least partially, and then through the reduction zone, where they come in contact with chars, and can crack to form gases or undergo condensation reactions to form chars. Downdraft gasifiers produce the lowest level of tar, and are therefore, the best option for engine applications [30].

2.3. Multi-Air-Stage Gasifier

The basic idea of multi-air-stage gasification is to decrease the tar production by the combustion of the pyrolysis gases, since combusting a gas-gas mixture is more effective than combusting a gas-solid one. Tar is organic compounds of molecular weight greater than benzene. Tar itself is a complex mixture of condensable hydrocarbons. It is a product of highly irreversible process taking place in the pyrolysis zone. Pyrolysis process occurs in the pyrolysis zone where volatile components of the fuels with boiling temperatures below 600^{o}C evaporate. As a result, the pyrolysis process produces fixed carbon (charcoal), tars (organic volatiles) and mixture of gases [36]. Tar will impose serious limitations in the use of producer gas due to fouling of the downstream process equipment, engine wear and high maintenance costs. By far, tar removal is the most problematic.

Tar removal technologies can be divided into two broad approaches; hot gas cleaning after the gasifier (secondary methods), and treatments inside the gasifier (primary methods). Although secondary methods are proven to be effective, treatments inside the gasifier are gaining much attention as these may eliminate the need for downstream cleanup. In primary treatment, the gasifier is optimized to produce a fuel gas with minimum tar concentration. The different approaches of primary treatment are gasifier modifications, proper selection of operating parameters, and use of bed additive/catalyst [37].

The design of a multi-air-stage reactor was developed in order to separate the flaming-pyrolysis zone from the reduction zone. Tar vapors generated in the first zone are burned or cracked to simple molecules by high temperature in the second zone due to the addition of a secondary air. Most of results showed double-stage reactor has improved gas quality and conversion efficiency. The tar content of the gas dozen times less than that obtained with a single-stage reactor under similar operating conditions.

Described in the journal of Martinez [11], two-air supply stages were considered as primary method for improving the quality of the producer gas regarding its tar reduction. The second stage of air supply was meant to reduce the tar present in the produced gas (cracking) to minimum levels, as well as to encourage the oxidation and reduction phases. A useful gas power of 40 kW was produced with cold gas efficiency around 68%. An innovative two-stage air and premixed air/gas supply gasification has also been studied by Jaojaruek [10]. The first air supply was located at combustion zone and the other located at the pyrolysis zone for supplying the premixed gas (air and producer gas). The producer gas was partially bypassed to mix with air and supplied to burn at the pyrolysis zone. This method was expected to create higher temperature profile and better stability of the flame location. It was proved by a low tar content around 45 mg/Nm^3 with HHV of producer gas of 6.5 MJ/Nm^3.

2.4. Biomass

Biomass can be defined as organic materials from various natural sources of energy, e.g. agricultural crops and residues, wood and its residues and industrial wastes, as follows [38]:

- Agricultural crops, such as sugarcane, cassava, corn, etc. which are sources of carbohydrates, starch and sugar, including oil-containing plants.
- Agricultural residues, such as rice straw from rice fields, cassava rhizome from tapioca fields, corncobs from cornfields, etc.
- Wood and wood residues such as fast-growing trees, wood wastes from wood mills, waste from pulp and paper mills, etc.
- Waste streams such as bagasse from sugar refineries, rice husk from rice mills, residue from palm oil extraction plants, municipal solid waste, etc.

Biomass and waste needing disposal can be burned directly or converted into intermediate solid, liquid or gaseous fuels to produce heat, electricity and transport fuels. A number of biomass conversion technologies are currently commercially available. In addition, there is a potential for technological advances and commercialization of more efficient technologies for production of electricity and transport fuels in a rather near future [39]. The main technology options are summarized in Table 2.1 [40].

Biomass is a very versatile feedstock in its morphology and physical characteristics. It can be quite wet or dry, very dense or fluffy, high or low ash containing, small in shape or large, homogeneous or inhomogeneous, etc. This makes the use of biomass fuels in dedicated gasifier reactors quite difficult, and in most cases, some pretreatment of the biomass is needed [30]. For example, pelletized fuel instead of fine light biomass will operate best in a downdraft gasifier type [41].

Table 2.1 Summary of the main characteristics of technologies under consideration

No.	**Conversion technology**	**Biomass Type**	**Example of fuel used**	**Main product**	**End-use**	**Technology status**	**Remarks**
1.	Combustion	Dry biomass	Wood logs, chips and pellets, other solid biomass, chicken litter	Heat	Heat and electricity (steam turbine)	Commercial	Efficiencies vary, e.g. > 15-40% electrical; >80% thermal
2.	Co-firing	Dry biomass (woody and herbaceous)	Agro-forestry residues (straw, waste)	Heat/ electricity	Electricity and heat (steam turbines)	Commercial (direct combustion). Demonstration stage (gasification and pyrolysis)	Large potential for use of various types of biomass; reduced pollution, lower investment cost. Some technical, supply and quality problems
3.	Gasification	Dry biomass	Wood chips, pellets and solid waste	Syngas	Heat (boiler), electricity (engine, gas turbine, fuel cell, combined cycles, transport fuels (methanol, hydrogen)	Demonstration to early commercial stage	Advanced gasification technologies offer very good opportunities for using a range of biomass sources for different end-uses
4.	Pyrolysis	Dry biomass	Wood chips, pellets and solid waste	Pyrolysis oil and by-products	Heat (boiler), electricity (engine)	Demonstration to early commercial stage	Issues remain with quality of pyrolysis oil and suitable end-uses
5.	CHP	Dry biomass, biogas	Straw, forest residues, wastes, biogas	Heat and electricity	Combined use of heat and electric power (combustion and gasification processes)	Commercial (medium to large scale) Commercial demonstration (small scale)	Political priority in the UK, high efficiency, e.g. c.90%; potential for fuel cell application (small plants)
6.	Etherification/ pressing	Oleaginous crops	Oilseed rape	Biodiesel	Heat (boiler), electricity (engine), transport fuel	Commercial	High cost
7.	Fermentation/ hydrolysisi	Sugar and starches, cellulosic material	Sugarcane, corn, woody biomass	Ethanol	Liquid fuels (e.g. transport) and chemical feedstock	Commercial. Under development for cellulosic biomass	Cellulosic, 5-10 year for commercialization
8.	Anaerobic digestion	Wet biomass	Manure, sewage sludge, vegetable waste	Biogas and by-products	Heat (boiler), electricity (engine, gas turbine, fuel cells)	Commercial, excepts for fuel cells	Localized use

Source: Rosillo-Calle [42]

Two types of analysis for any biomass are the proximate analysis and the ultimate analysis. It is useful for defining the physical, chemical, and fuel properties of a particular biomass feedstock. The proximate analysis determines the moisture, volatile matter, fixed carbon, and ash in the biomass. The analysis is an essentially practical tool providing an initial indication of the biomass' quality. The methods for performing these analyses have been standardized by all the major standards institutions (e.g. ASTM, ISO, DIN, BS, and others). These standards, though similar in nature, are different from one another in, for example, the temperature specified for determining the volatiles content, so it is important when providing data to specify the method used. For the ultimate analysis the percentages of carbon, hydrogen, oxygen, sulfur, and nitrogen are determined.

2.4.1. Eucalyptus

Eucalypts have been grown in Thailand for 100 years, but only after 1970 on plantation scale. Eucalypt advantages are: easy grown, good survival, tolerant to various climates and soil types; no proven negative effects on soil, environment, human and wildlife; positive support to farm income; withstands long dry seasons, pathogen resistant; has wide domestic and industrial use [43].

Exactly when eucalypts were introduced to Thailand is not clearly recorded. The memories of Sathean Gost, a senior and famous author of Thailand, mentions that when he moved to his new residence near the corner of Chareong Krung and Suravong road in 1905, he saw some unfamiliar tall trees, with smooth and reddish bark, thick and long narrow leaves with a strong smell. They were exotic trees and known later as *Eucalyptus*. He assumed that these trees had been introduced by foreigners who lived in that region around 1900-03.

Although many species of eucalypts were introduced into Thailand, only a few species and provenances show promising survival and growth. *E. camaldulensis* seems to be the first choice, as far as survival and growth rate is concerned. It is adaptable to saline soils in the north-east of Thailand, and tolerates a variety of climatic conditions.

2.5. Densified Biomass: Pellet

The term pellet stands for “a small round mass of substance”. A pellet is thus normally a small round mass, mostly made of compressed material, of a spherical or cylindrical shape. Pellets are a solid biofuel with consistent quality – low moisture content, high energy density and homogenous size and shape. Various products and materials can be pelletised to be used thermally or still as a material as shown by the following list [44]:

- Pellets made of iron ore are preliminary products in iron production.
- Animal feed pellets are produced for easier handling of animal food (e.g. fish feed pellets, horse feed pellets, etc.).
- Catalyst pellets are used as a carrier of the actual catalyst in heterogenous catalytic chemical reactions.
- Pellets are also used in anaerobic digestion. In this sense, pellets are 2 to 3 mm granular aggregations of anaerobic bacteria.
- Pellets made of sawdust, wood shaving, straw, hay or hemp are also used as animal bedding in stalls, cages and the like.
- Pellets for energetic utilization can be made of wood, peat, herbaceous biomass or waste.

The list makes no claim to be complete and it is probable the pellets of different kinds and applications are used in many other areas too.

Biomass densification appears to have the greatest use for upgrading agricultural and forestry residues that might otherwise be lost or that require disposal at additional cost [45]. The main advantages of densified fuels, compared to non-densified ones are the following [46]:

- An increased bulk density (from 80-150 to 600-700 kg/m^3), resulting in lower transportation costs.
- Reduced storage volume and easier handling.
- A lower moisture content (lower than 10%), favouring a long conservation and less loss of product during storage.
- An increased energy density and more homogeneous composition, resulting in better control possibilities and thereby higher energy efficiency with lower emissions during combustion.

Many countries have different pellet standards. The different national standards and quality regulations attempt to control pellet quality in ways that, in part, differ greatly from another. Above all standards, the Pellet Fuel Institute (PFI) standards in the U.S.A. combined standards from various European countries such as Austria, Sweden, United

Kingdom, France, and Denmark. They have an International standards for densified solid fuels, as shown in Table 2.2 [47]:

Table 2.2 Pellet Fuel Institute (PFI) standard specifications for residential/ commercial densified fuel

Fuel Property	Residential/Commercial Densified Fuel Standard		
	PFI Premium	PFI Standard	PFI Utility
Normative Information – Mandatory			
Bulk Density, lb./cubic foot	40.0 – 46.0	38.0 – 46.0	38.0 – 46.0
Diameter, inches	0.230 – 0.285	0.230 – 0.285	0.230 – 0.285
Diameter, mm		5.84 – 7.25	5.84 – 7.25
Pellet Durability Index	≥ 96.5	≥ 95.0	≥ 95.0
Fines, % (at the mill gate)	≤ 0.50	≤ 1.0	≤ 1.0
Inorganic Ash, %	≤ 1.0	≤ 2.0	≤ 6.0
Length, % greater than 1.50 inches	≤ 1.0	≤ 1.0	≤ 1.0
Moisture, %	≤ 8.0	≤ 10.0	≤ 10.0
Chloride, ppm	≤ 300	≤ 300	≤ 300
Heating Value	NA	NA	NA
Informative Only – Not Mandatory			
Ash Fusion	NA	NA	NA

Densified biomass is acquiring increasing importance because of the growing domestic and industrial applications for heating, CHP and electricity generation in many countries. In countries such as Austria, Denmark, the Netherlands and Sweden, for example, it is becoming a major industry with pellets traded internationally. It is expected that the pellet market will expand rapidly, and even become an international widely traded commodity despite the growing importance of wood chips due to their lower cost [40].

Transforming biomass resources into pellets would bring several advantages for biomass gasification, especially for fixed bed gasifiers. It answers the feedstock quality criteria needed and suitable to downdraft gasifier design. Pellets allow for a variety of fuels to be used in one and the same gasifier since the anisotropic characteristics for each biomass type is removed during pelletizing. Also, possible for very wet and bulky forms of biomass residues, such as sugarcane residues, can be utilized if pelletized. Higher density fuels should give fewer operational problems, such as bridging and channelling.

CHAPTER 3
METHODOLOGY

3.1. Raw Material

The raw materials initially selected for this experiment were pellets made of eucalyptus wood. Each pellet had a diameter range 6 – 10 mm and length range 30 – 70 mm, approximately. Proximate and ultimate analyses were done as the analytical investigation of eucalyptus pellet properties.

Figure 3.1 Eucalyptus wood pellet

3.1.1. Proximate Analysis

A thermal gravimetric analyzer (PerkinElmer, TGA Pyris 1) as shown in Figure 3.2 was used to perform a proximate analysis of the pellets in terms of volatile matter, ash content and fixed carbon, while the moisture content was determined by a drying oven (Memmert, VO500).

The test method is an empirical technique using thermo-gravimetry in which the mass of a substance, heated at a controlled rate in an appropriate environment, is recorded as a function of time or temperature. The loss of mass over specific temperature ranges and in a specific atmosphere provided a compositional analysis of that substance.

After the eucalyptus wood pellets were dried in an oven, they were mashed into small particles smaller than 75 μm. Approximately 5 mg of pellet particles were weighed and heated from room temperature to 900^{o}C in a nitrogen stream in order to quantify moisture and volatile matter. As the temperature reached 900^{o}C, an oxygen or air atmosphere was used in order to quantify the fixed carbon from weight loss in the oxygen atmosphere and ash from the remaining solid.

Figure 3.2 Thermal Gravimetric Analyzer

3.1.2. Ultimate Analysis

The Organic Elemental Analysis (OEA analysis) model Flash EA 1112 (Thermo Finnigan) was used for analyzing the percentage of biomass chemical elements, as shown in Figure 3.3. Chemical elements, namely C, H, N, O, S, were analyzed. The oxygen content was determined by subtracting the sum amounts of the other chemical elements, which were determined by the analyzer, from 100.

Figure 3.3 Organic Analysis (Thermo Finnigan model Flash EA 1112)

The percentages of C, H, N, O, S are important for determining the theoretical air required for completing the combustion and the amount of air required for gasification. The ultimate and proximate analyses were measured by ASTM standards as shown in Table 3.1.

Table 3.1 Standard method for biomass compositional analysis

Biomass Constituent	Standard Methods
Proximate Analysis	
Volatile matter	ASTM E-872
Ash	ASTM D-1102
Moisture	ASTM E-871
Fixed carbon	By difference
Ultimate Analysis	
Carbon	ASTM E-777
Hydrogen	ASTM E-777
Nitrogen	ASTM E-778
Oxygen	By difference
Sulphur	ASTM E-775

3.1.3. Calorific Value Analysis

The bomb calorimeter (LECO AC-350) as shown in Figure 3.4 was used to analyze the calorific value of the eucalyptus wood pellets.

Figure 3.4 Bomb Calorimeter (LECO AC-350)

This apparatus determines the calorific value of a sample by burning it in a controlled environment, and measuring the heat released by combustion as the calorific value of the substance. The sample was analyzed in a high pressure oxygen environment, known as bomb. The sample is ignited while the bomb is in condition surrounded by water. During the analysis, the temperature of the water is measured by an electronic thermometer and the stirrer is used to make a uniform temperature.

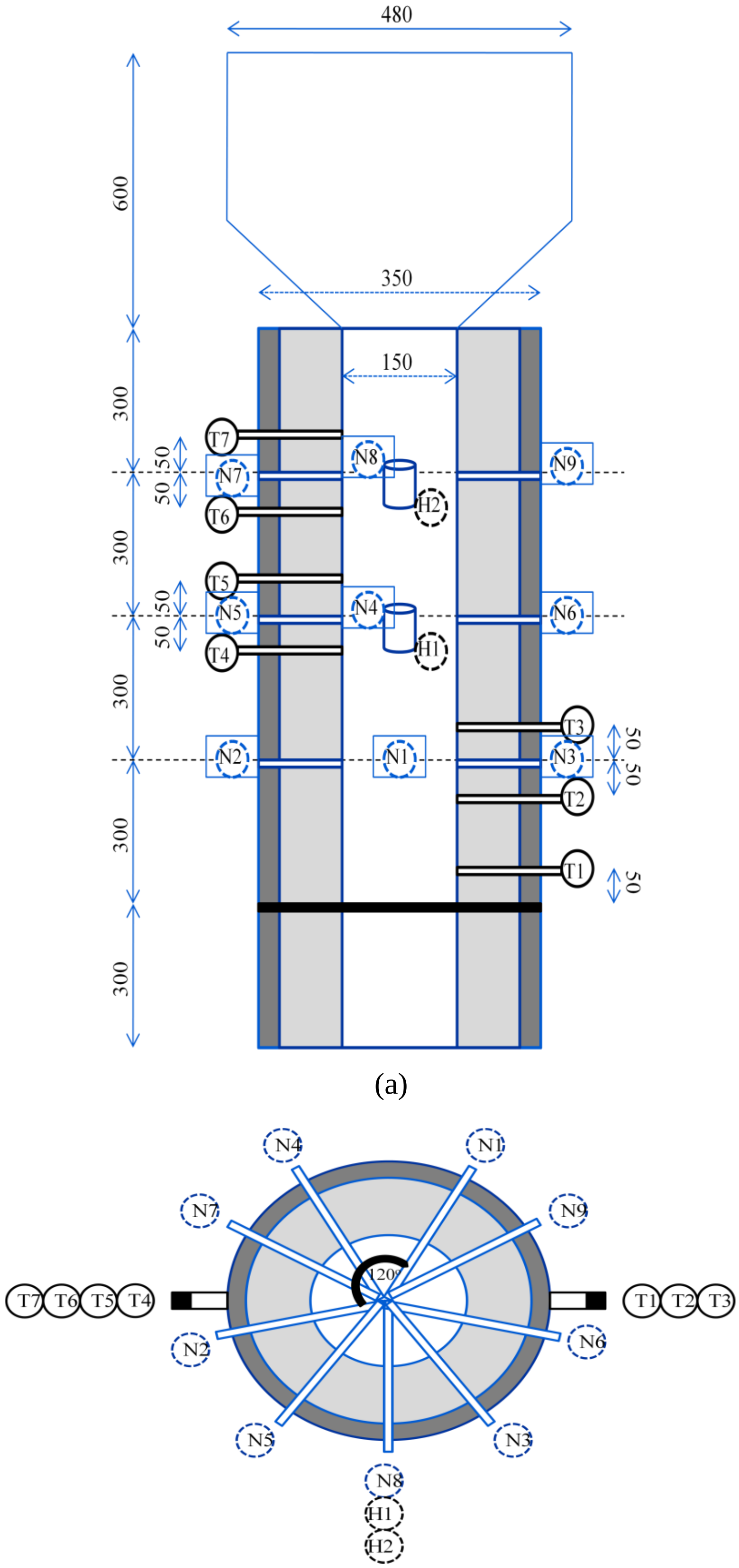
3.2. Gasification Equipment

3.2.1. Triple Air Stage Downdraft Gasifier

The reactor used in this experiment was a triple air stage downdraft gasifier (Figure 3.5a). The gasifier was designed for atmospheric pressure operation and to maintain biomass material. Air was used as a gasifying medium, because of its low capital and operating costs.

The gasifier has an internal diameter of 150 mm and a total height of 2100 mm. It is built with an internal coating of refractory material. 300 mm from the bottom is an ash chamber zone with a grate used as the ash separator. 1200 mm from the ash chamber zone is a gasification zone. Here, they are separated into 3 stages for air injection and located at a distance 300 mm for each stage. Each stage has 3 nozzles that put in around 120^o angle (Figure 3.5b). This position of each nozzle would help to give a better air distribution along the gasifier. Two ignition ports are also located in gasification zone which are placed around the second and the third air supply stages area (600 mm and 900 mm above the grate). The top zone of the gasifier is a fuel hopper with a height of 600 mm.

The purpose of the triple air stage supply is considered to be a primary method to improve the producer gas quality and reduce the tar content in the producer gas. This is located in the oxidation and reduction zones. Biomass is fed from the top of the gasifier and dried in the drying process. Then it comes to pyrolysis zone, where the dried biomass is burned with limited oxygen and produce charcoal and pyrolytic gases. Followed by oxidation zone, assisted by triple air stage supply to produce more producer gas with less tar. Oxidation zone has byproduct which is ash that collected at the bottom of the gasifier while the main product, producer gas, flow and pass through cleaning process. The ash chamber is separated by the grate as a bed to support the raw material.



(a)

(b)

Figure 3.5 Gasifier details: **(a)** The side view. **(b)** The position of thermocouples and air nozzles (H: Ignition port; N: Air nozzle; T: Thermocouple)

3.2.2. Cyclone

A cyclone is a tool for initial gas treatment using centrifugal force. It is the first step in this gasification cleaning system, where impurities, such as fly ash and particles, are removed from the producer gas using the cyclone.

3.2.3. Heat Exchanger

Shell and tube heat exchanger is used to cool down the producer gas temperature. The inlet temperature is estimated to be 600 ^oC, which was nearly same as the temperature of the gasifier output. The ambient temperature is assumed to be that of the input of air temperature.

3.2.4. Bag House Filter

A bag house filter was used to remove fine particles and was suitable only for removing dry particulates, sticky or tacky material is not release from filter bag. Therefore, special provisions and precautions are required to maintain the bag filter temperature in order to prevent water vapor or tars from condensing on the filter bag. It is placed after heat exchanger and before the blower to avoid problems in blower due to particles.

3.2.5. Blower

A blower is used to supply air as the gasifying medium and also to suck the producer gas up. Here, ring blower and suction blower are operated to give the required air supply. The suction blower is used due to the suction of the engine generally use to move air through the gasifier and clean up train.

3.2.6 Air Flow Controller

A flow meter is used to control the air flow rates of the gasifying medium and adjust for the equivalence ratio. The flow rates are measured before entering the gasifier. There are three air flow meter placed in each three air stages pipe.

3.2.7. Temperature Monitoring System

The temperature of the system was measured using K–type thermocouples installed at 9 positions. 7 of them were placed along the height of gasifier to obtain continuous temperature data, 2 of them were used to obtain the producer gas temperature after the exit of the cyclone and before the tar sampling equipment.

3.2.8. Tar Sampling Equipment

The tar sampling process takes place after the cyclone and heat exchanger at which most of the entrained solid particles were already been removed from the syngas as lower temperatures. A series of impinge bottles consisted of 6 impinger bottles were used.

The first impinger bottle acted as a moisture collector, then the gas was passed through a series of four impingers with isopropanol used as solvent and 1 final impinger which was emptied to trap moisture. Cooling liquid was made of mixture of ice cubes, salt and water. Glass impingers of 250 ml volume, with an inner tube diameter of 4 mm was used. The producer gas at around 40-50^{o}C passed through a particle filter and then flowed to series of impinger bottles. The first until the fifth bottle was filled with 70 ml isopropanol while the last bottle was empty. The vacuum pump of 4 L/min for 10 minutes was generated to maintain the gas flow.

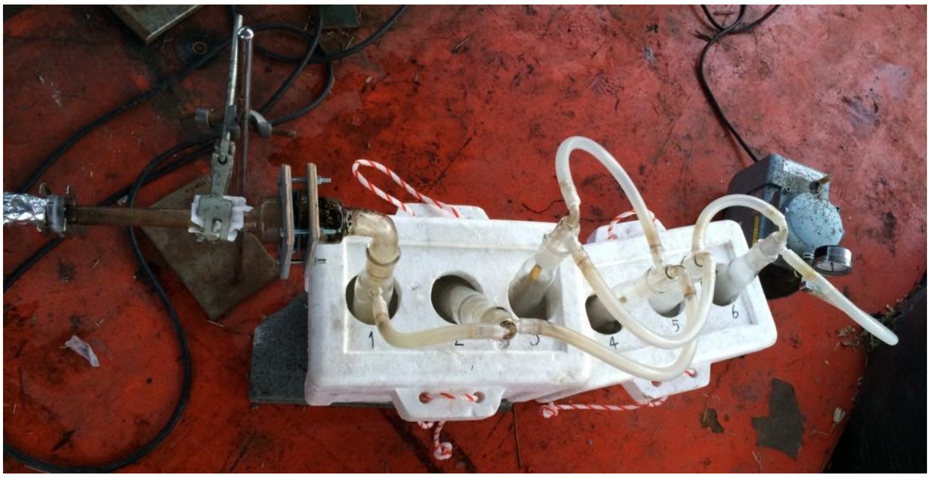


Figure 3.6 Tar sampling equipment

3.3. Operating Conditions

The controllable variables studied for the assessment of the gasification process were the total air flow and variation stages between the single, double and triple air supply stages. This downdraft gasifier was operated at an atmospheric pressure using air as the gasifying medium. The temperature along the height of gasifier would be recorded every minute. A batch of 19 kg eucalyptus wood pellet was loaded into the gasifier in each experiment. Tar sampling equipment was prepared and to start the system, a suction blower was used to suck in a flame torch. Gasoline was used to help the ignition. When combustion developed well inside the gasifier, suction port was closed and air supply was set. Steady state condition was assumed when the temperatures in oxidation zone and reduction zone became almost constant or it seen from the fire that could be ignited in flare tower. In this study the equivalence ratio was used always simultaneously with the total air flow values. The calculated values of ER can be used as reference.

Technical problems, such as fuel flowing problems, pipe leakage, or problems caused by human error, could occur. After all the tests were done, the obtained data were screened, and the doubtful ones, showing non-logical or out-of-tendency values, were repeated. Repetitions 2 or 3 times during all the trials were done.

The experimental tests considered a total of 10 tests for the total air flow and the three different stage combinations as shown in Table 3.2.

Table 3.2 Experimental set up for eucalyptus wood pellet gasification tests.

Stage	**Total Air Flow (L/min)**	**Air Flow (L/min)**			**ER**
		First Stage	Second Stage	Third Stage	
1	179	179			0.27
	208	208			0.14
2	283	132	151		0.19
	354	165	189		0.24
	420	193	227		0.29
3	293	85	113	95	0.20
	401	127	142	132	0.26
	467	151	179	137	0.30
	543	170	194	179	0.36
	580	179	212	189	0.39

3.4 Experimental Procedure

The experimental procedure comprised a series of gasification tests carried out in the multi-air-stage downdraft gasification unit. A schematic diagram of the gasification can be seen in Figure 3.7. The main reactor has a total height of 2100 mm and an internal diameter of 150 mm.

At the beginning of the first run, the triple air stage downdraft gasifier was filled with eucalyptus wood pellets from the top of gasifier R-01 in line 1. After loading, it was ignited with gasoline, suction blower B-02 was operated to help the ignition. When it burned well, the ignition port was closed and ring blower B-01 was operated. The air was flowed through pipe 2 and 3. For single air stage gasification, only valve v-2 in pipe 4 would be opened, for double air stage gasification both valve in pipe 4 and 6 would be opened, while for triple air stage, all valve in pipe 4, 6 and 8 were opened. Each pipe had valve and flow meter to control the air flow and measure the value of air feed rate.

The pellets become charcoal, syngas and ash at the end of the process as they pass through the drying, pyrolysis, oxidation and reduction stages. During the series of stages, the temperature was measured with some thermocouples T1, T2, T3, T4, T5, T6 and T7. The temperature would be recorded every minute. The thermocouples were set up only until the inner gasifier wall. Due to this limitation of the thermocouples, it would not show reliable temperature but it prevented biomass flowing problems, chanelling and bridging. The temperature would show lower value than it should be. The main product, syngas, would exit from reactor through line 11 to cyclone C-01 to be separated from the impurities, then exited at line 13 while the impurities discharged at line 12. The ash and slag as the byproduct were removed through line 10. Between cyclone and heat exchanger HE-01, there was a thermocouple T8 where the temperature of producer gas was measured here. Then syngas at line 13 would pass heat exchanger to cool down the temperature and came out at line 15. At the outlet of heat exchanger, there was also a tar sampling point. An amount of syngas would be taken at line 14 to measure the tar quantity. It was then filtered in bag house filter BF-01 before sucked out by blower B-02. The clean syngas was released at line 16. An amount of syngas would be taken for sampling and analyzing process at line 17 while the rest was burned by the flare F-01 at line 18.

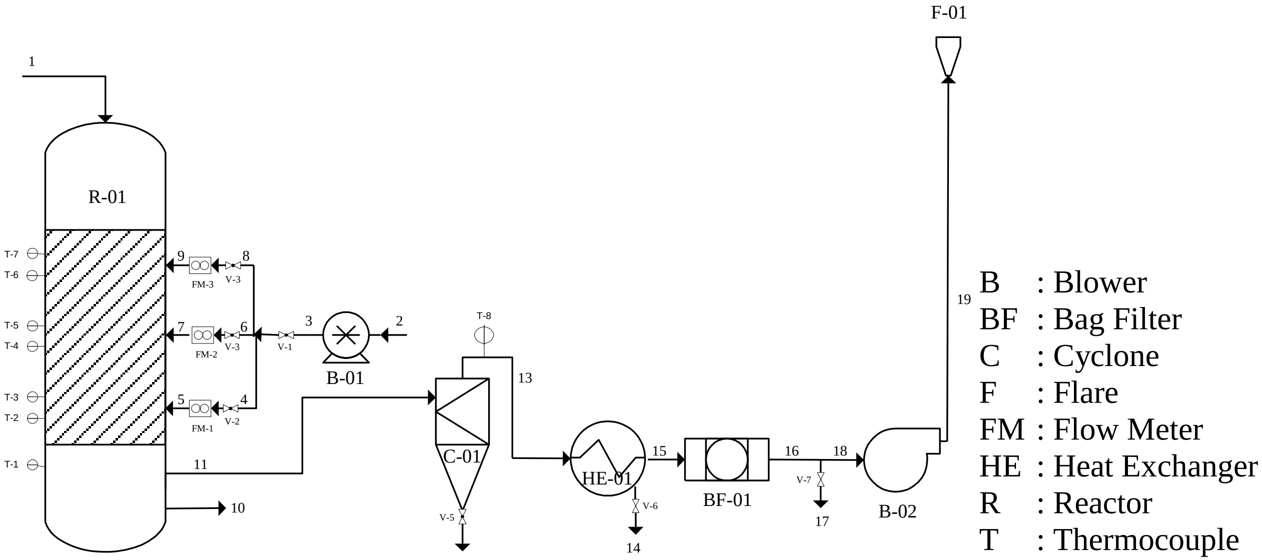


Figure 3.7 Schematic diagram of multi-air-stage downdraft gasification

3.5. Analysis

3.5.1. Producer Gas Analysis

Micro-gas chromatography (Micro GC, Agilent 490) was used to measure the composition of the syngas. The concentration of CO, H_2, CO_2, and CH_4 were measured. Figure 3.8 shows the micro-gas chromatography measurement apparatus.

Figure 3.8 Micro GC Agilent 490

3.5.2. Tar Analysis

Gravimetric tar was determined by the evaporation process. A rotary evaporator (Figure 3.9) was used to evaporate isopropanol solvent from tar sample solution. The gravimetric or total tar was the residual of rotary evaporation.

The tar sample solution of 350 ml was prepared for evaporation. A series of evaporation apparatus such as cooler at 20^{o}C, water bath at 55^{o}C and vacuum level of the empty flask at 130 mbar were set. For about 150 ml of tar sample solution was poured into a 250 ml round bottle flask. Then it was connected to rotary evaporator before started the evaporation. It was set at 180 rpm and a few minutes later, drops started to fall from the cold finger. When the tar solution reduced until a few left, the evaporation was stopped for a while to add the remained tar sample solution. It was repeated until no sample left. Evaporation continued until no drop fell from the cold finger. Then the rotation of the flask was stopped and the flask bottle was removed from water bath. The outer surface of flask bottle was cleaned for next dried in the oven of 105^{o}C for 2 hours. Finally, the flask bottle was left at least 5 minutes at room temperature before weighing. The weight difference between the empty flask bottle and after evaporation contained tar residue, also called gravimetric tar.

Figure 3.9 Rotary evaporator

Figure 3.10 Multi-air-stage downdraft gasification system

CHAPTER 4
RESULTS AND DISCUSSION

4.1. Eucalyptus Wood Pellet Analysis

The eucalyptus wood pellets were bought from Sira Intertrade. Co., Ltd., Chonburi, Thailand. The ultimate and proximate analysis were done as raw material preparation. It is important in order to know the quality of raw material. Table 4.1 shows the result of eucalyptus wood pellet properties.

Table 4.1 Properties of eucalyptus wood pellet

Ultimate Analysis (wt. % d.a.f)		Method
Carbon	48.17	ASTM E-777
Hydrogen	6.02	ASTM E-777
Oxygen	45.15	By difference
Nitrogen	0.66	ASTM E-778
Proximate Analysis (wt. % dry)		
Volatile matter	66.37	ASTM E-872
Fixed Carbon	12.07	By difference
Ash	21.56	ASTM D-1102
Moisture Content (wt. % as received)	10.07	
HHV (MJ/kg)	14.42	
LHV (MJ/kg)	13.46	

4.2. Experimental Results

The study was done for 3 different air supply stages from total 10 experiments. Each experiment was repeated two or three times. Two air flow rates of 179 and 208 L/min were tested for single air stage gasification. Three air flow rates of 283, 354 and 420 L/min were tested for double air supply stages. Five different air flow rates of 293, 401, 467, 543 and 580 were also tested for triple air supply stages. Temperature profile was observed for each experiment. Producer gas quality was analyzed by using Micro – GC and tar quantity was found out by using rotary evaporator.

4.2.1. Temperature Profile

The temperature in the gasifier was recorded via the data logger during the experiments. There were 7 thermocouples type – K which connected to the data logger and installed along the gasifier height, allow for registering the temperatures at different gasifier points. Thermocouples are projected up to the internal gasifier wall to avoid biomass flowing problems as it is consumed. This adjustment may not show reliable temperature readings, but it avoids of biomass flowing problems in the moving bed gasification which are bridging and chanelling [11, 48]. Due to this limitation of the equipment, the temperature which read during the gasification process was lower than it should be.

All thermocouples were set to record every minute during each experiment. T1, T2, T3, T4, T5, T6 and T7 were placed at 5 cm, 25 cm, 35 cm, 55 cm, 65 cm, 85 cm and 95 cm above the grate respectively. The other thermocouples which are T8 was placed in the output pipe of the cyclone in order to obtain the producer gas outlet temperature and T9 was placed before tar sampling equipment to measure the producer gas temperature before the tar sampling time.

4.2.1.1. Single Air Supply Stage

There were two different air flow feeds set for the single air supply stage, namely 179 L/min and 208 L/min. The air flow feeds were equal to ER of 0.27 and 0.14. Figure 4.1 shows gasification temperature profile of 179 L/min. Figure 4.2 shows the gasification temperature profile at 208 L/min.

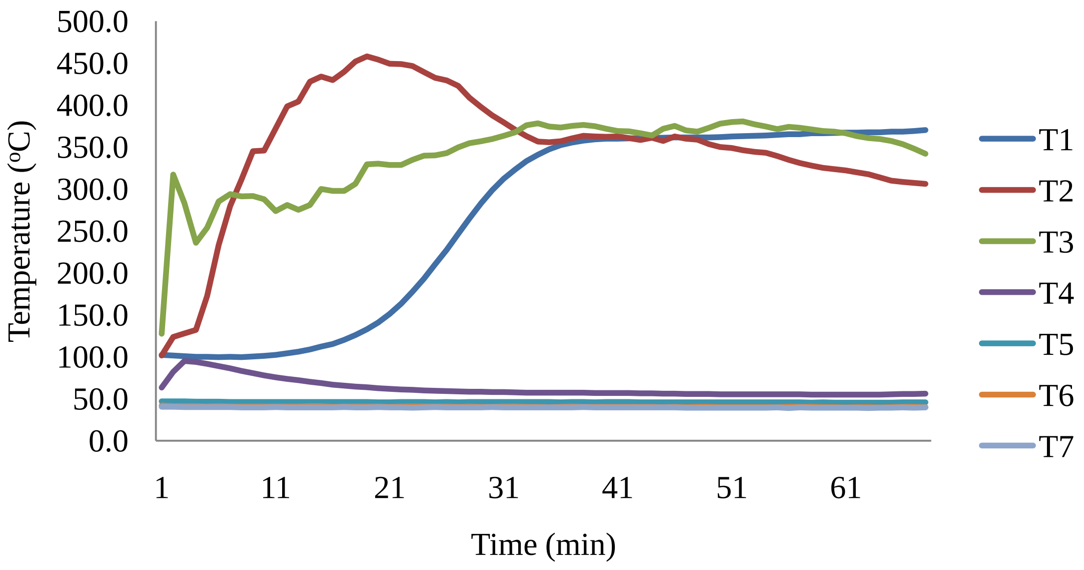


Figure 4.1 Gasification temperature profile at 179 L/min

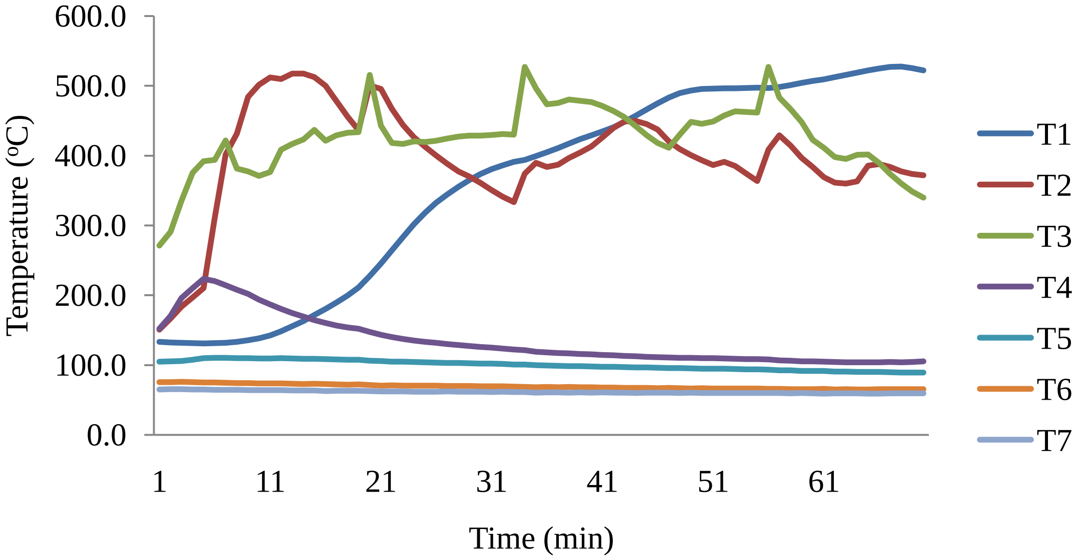


Figure 4.2 Gasification temperature profile at 208 L/min

Figures 4.1 and 4.2, it was shown a quite stable temperatures of Thermocouple 1, 2 and 3. Those areas were the oxidation zone and reduction zone took place. From this observation, it can be explained that in single air supply stage has poor heat distribution within the gasifier. The highest temperature of 179 L/min was only around 450 ^{o}C and mostly stabled at 350 ^{o}C (temperature at the oxidation zone in the inner wall of the gasifier). during the gasification process. The highest temperature of 208 L/min was a little bit higher than 179 L/min which reached 500 ^{o}C and stabled at 400 ^{o}C. This better result was caused by a higher air flow rate, even this was not work well yet for a common gasification system where drying, pyrolysis, oxidation and reduction zone can be seen clearly from the temperature difference. The other possibility of why this gasification only showed a low temperature was because the thermocouple could not read the real gasification temperature which held in the center of gasifier. The thermocouple only read the inner wall temperature due to avoid the bridging problem when the biomass flow downward. In point of fact, the temperature should be higher than it was read.

In most commercial gasifiers, oxidation reactions give it thermal energy for the drying, pyrolysis and endothermic reactions. Though these typical processes are frequently modeled, there is no sharp boundary between them, so they often overlap [41].

4.2.1.2. Double Air Supply Stage

Temperature profiles for the double air supply stage are presented in Figures 4.3, 4.4 and 4.5. Three different air flow rates were tested: 283, 354 and 420 L/min, which are equal to ER of 0.19, 0.24 and 0.29 respectively.

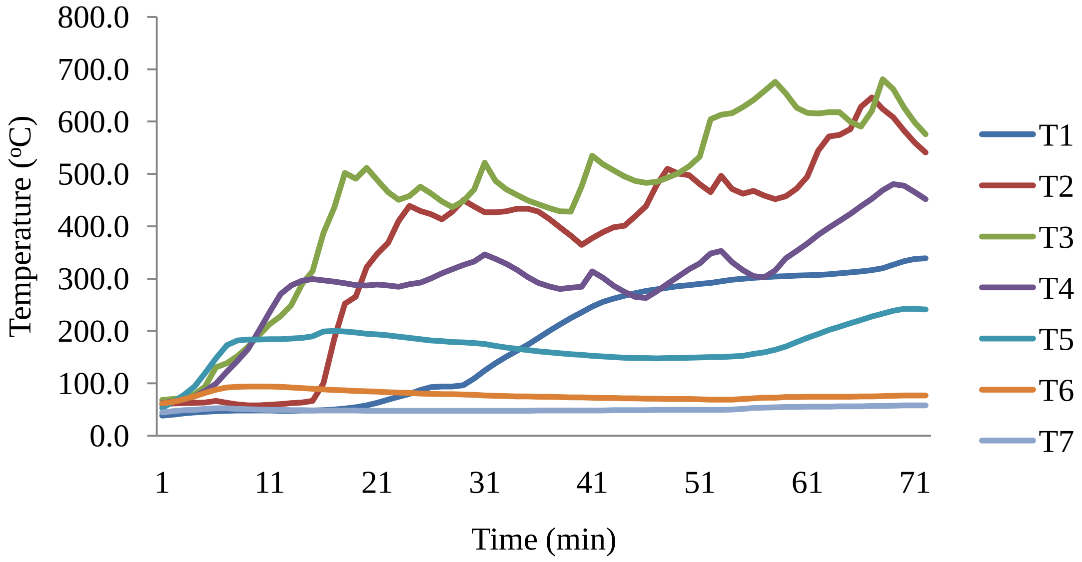


Figure 4.3 Gasification temperature profile at 283 L/min

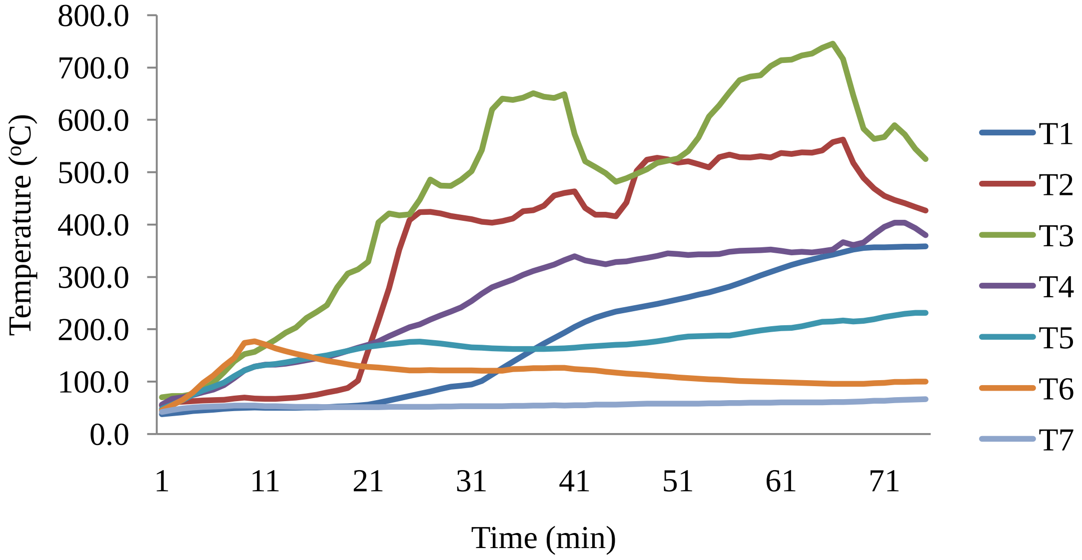


Figure 4.4 Gasification temperature profile at 354 L/min

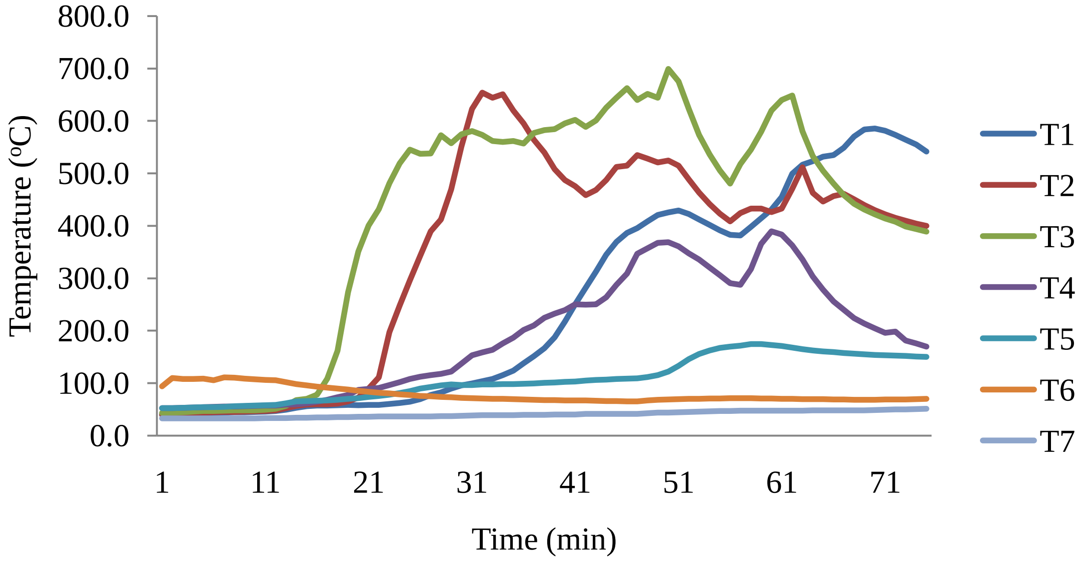


Figure 4.5 Gasification temperature profile at 420 L/min

As can be seen in the figures above, the same case with single air supply stage was found that the maximum temperature had occurred above the grate. In the single air supply stage, ignition was held in the first ignition port (55 cm above the grate or in parallel with T4) while in double and triple air supply stages, the ignition was held in the second ignition port (85 cm above the grate or in parallel with T6). Even the air supply came from 2 different pipes, the maximum temperature occurred in the same area with single air supply stage. This could be assumed as an effect from using of suction blower that made downward movement of hot fuel faster than flame propagation (upward) and also its nature of downdraft gasification. This is in agreement with the studies of Phuphuakrat et al and Kallis at al [24, 49]. The considerable time needed for heat to propagate upwards while the biomass was burning has made the highest temperature section moved downwards to the bottom of the gasifier and finally made the biomass was combusted to create a bed of char above the grate.

In the double air supply stage, the gasifying medium enters the gasifier from two different pipes. As each pipe has three nozzles placed at different angles, causing the double air supply stage gasification to provide a better air supply distribution. A high temperature which read in the inner wall of gasifier was given a good gasification result. A higher percentage of gas compositions and lower tar concentration were achieved. However, slag started to occur in this stage. The presence of slag proved that actually temperature inside the gasifier was very high, even much higher than shown in the data logger.

4.2.1.3. Triple Air Supply Stage

Figures 4.6 to 4.10 show the gasification temperature profiles of the triple air supply stage. Five variant of flow rates of 293, 401, 467, 543 and 580 L/min were tested.

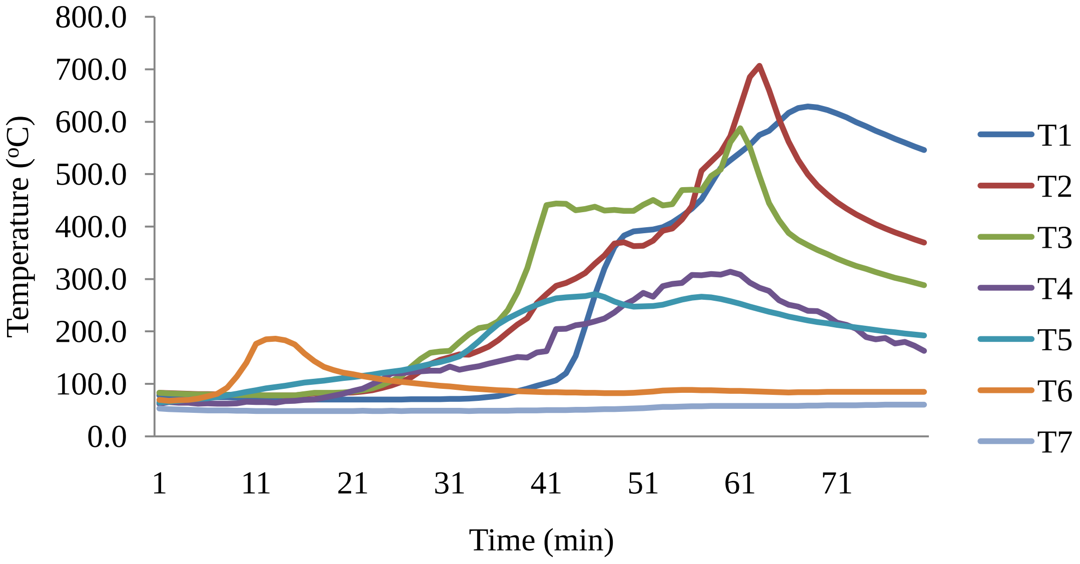


Figure 4.6 Gasification temperature profile at 292 L/min

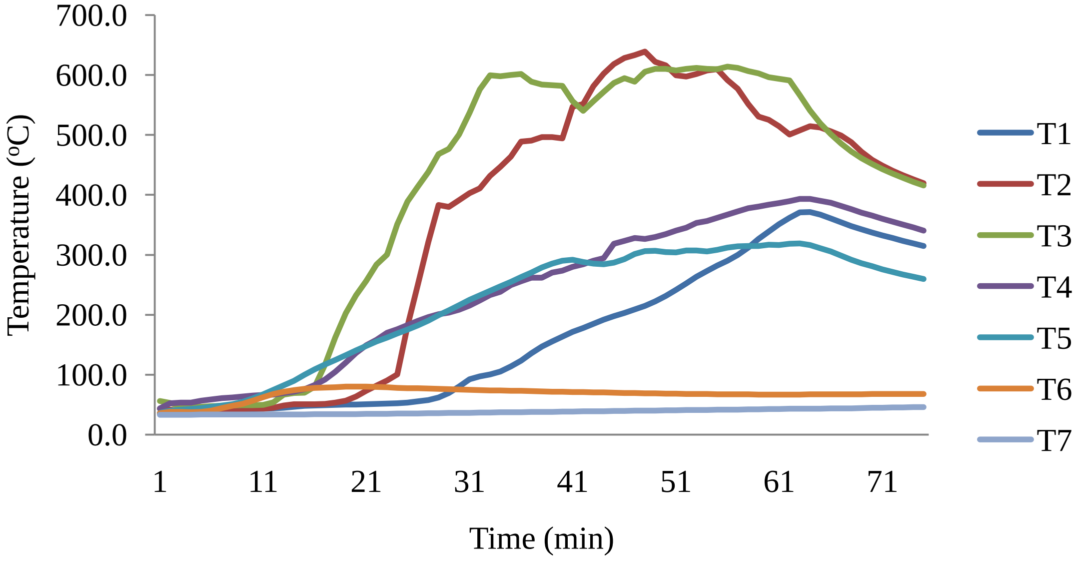


Figure 4.7 Gasification temperature profile at 401 L/min

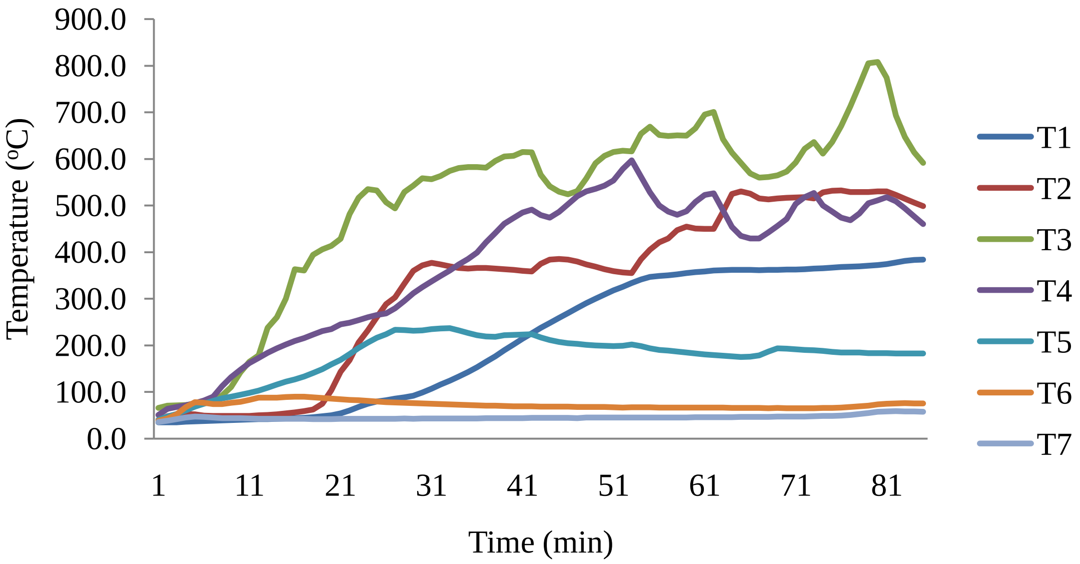


Figure 4.8 Gasification temperature profile at 467 L/min

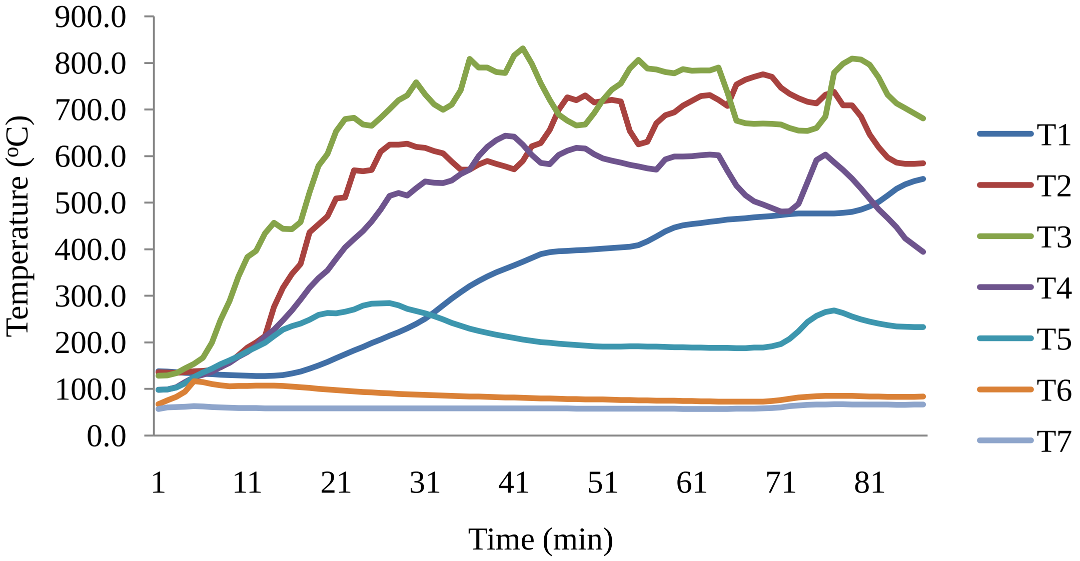


Figure 4.9 Gasification temperature profile at 543 L/min

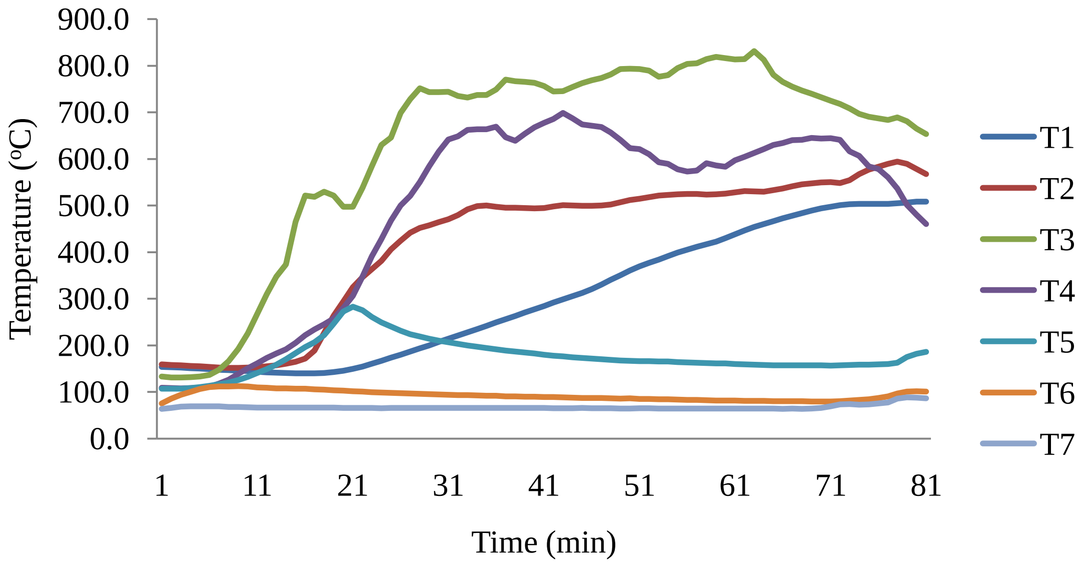
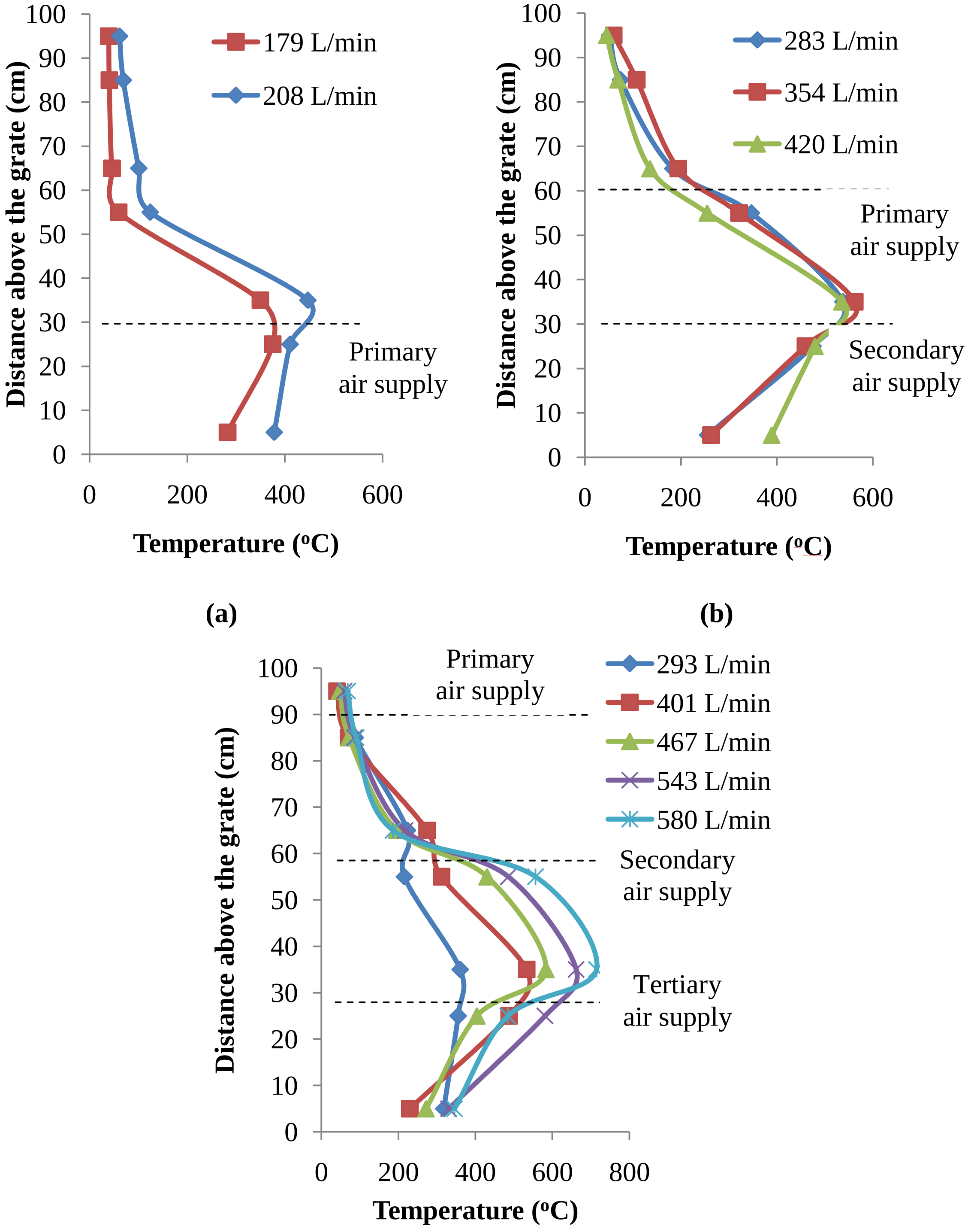


Figure 4.10 Gasification temperature profile at 580 L/min

The main aim for designing the triple air supply stage gasifier was to have more oxidation and reduction zones to hopefully burn the fuel completely, obtain higher gasification temperatures and produce lower tar quantity. When there are more oxidation and reduction zones, there will be more chance for incombustible gases produced in partial oxidation to turn into combustible gases in reduction zone. In line with the tar quantity, hopefully there will more chance for tar cracking and reduce its quantity.

In the triple air supply stage, there were three different pipes for the air supply inlet, which means that there were twelve nozzles of air supply for this stage. The highest gasification temperature was showed by experiments 543 L/min and 580 L/min. The oxidation temperature was about 800^{o}C. This value was a representation from the actual oxidation temperature considering that the limitation of thermocouple which only projected up in the inner wall of the gasifier. From the figure above, it showed that the gasification temperature will be increase by the increasing of air flow rate. Even if in the similar air flow between double and triple air flow rate showed almost the same gasification temperature, triple air supply stage gave a better result on gas composition and produced less tar due to its better air distribution in all parts of the gasifier.

Figure 4.11 shows the temperature profiles along the height of the gasifier for each stage. The highest temperature occurred around 25 – 40 cm above the grate. Even the main aim of the newly designed downdraft gasifier could not be seen yet, but in the experiment of the triple air supply stage, it can be assumed that there were two combustion zones. It was took place around the primary and secondary air supplies.



(a)

(b)

(c)

Figure 4.11 Temperature profiles along the height of the gasifier. (a) Single air supply stage, (b) Double air supply stage, (c) Triple air supply stage

4.2.2. Effect of Equivalence Ratio on Producer Gas Composition

The ratio of the actual air supply to the stoichiometric air required is known as the equivalence ratio (ER). ER indicates the oxygen feed in the gasification experiments and it is a crucial factor that affects the performance of the gasification process. ER was changed by adjusting the air supply rate during the experiments. Ten experiments were formed by changing only air flow rate to contribute a parametric study of the effect of ER.

The experimental conditions observed during the gasification are presented in Table 4.2.

Table 4.2 Experimental conditions during gasification

	Air Flow (L/min)	ER	Producer Gas Composition (%v)			
			H_2	CH_4	CO	CO_2
1S	179	0.27	3.10	0.01	6.00	11.4
	208	0.14	5.22	1.13	7.37	9.23
2S	283	0.19	4.52	0.19	7.63	11.2
	354	0.24	5.08	0.75	6.91	9.34
	420	0.29	8.78	0.88	12.64	12.0
3S	293	0.20	4.47	0.24	8.40	6.40
	401	0.26	7.96	0.63	11.10	12.2
	467	0.30	7.79	0.49	10.44	11.8
	543	0.36	9.35	0.92	12.56	12.7
	580	0.39	8.22	0.49	11.5	10.4

Table 4.2 shows that the equivalence ratio rises in line with increases in air flow feed. Each single air supply stage (1S), double air supply stage (2S) or triple air supply stage (3S) has attempted to operate according to its maximum ability. The ER varied from 0.14 until 0.39. Except of ER 0.30, 0.36 and 0.39, eucalyptus wood pellet of 24 kg was fed. It was because of the burning rate in higher air flow rate made the pellet burned faster, by added the amount of pellet could keep the level of pellet stayed above the third air supply pipe longer during the experiment.

Two experimental conditions of ERs 0.27 and 0.14 were tested for the single air supply stage. The air flow rates were 179 L/min and 208 L/min. Due to a small amount of air supply has made least eucalyptus wood pellet burnt which also resulted in a little biomass consumption. This impacted the calculation of ER. As shown in Figure 4.11, CO and H_2 produced in single air supply stage was 6 – 7% and 3 – 5%, respectively. During of all experiments, ER 0.27 showed the lowest gas quality result. It can be showed that ER 0.27 was not suitable for this gasification system. While ER 0.14 showed a better result than ER 0.27. Higher producer gas quality was achieved, even the oxygen required still insufficient yet. A low air flow rate resulted to a low gasification temperature that made an amount of pellet un-burnt or even has left a lot of char, this also the reason why the lowest air flow rate resulted a high ER.

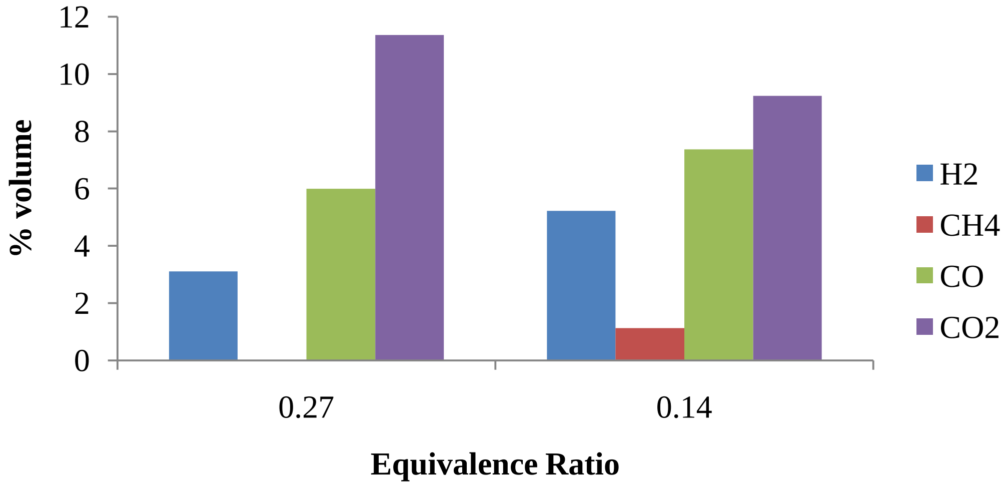


Figure 4.12 Effect of ER on producer gas composition of single air supply stage

In the double air supply stage, the ER varied from 0.19, 0.24 and 0.29. Two pipes of air supply were operated in 30 cm different height in aimed to get a better air supply distribution. Due to a bad quality of the raw material, double and triple air supply stage gave benefit to the experiments. Started the ignition from the second port which is farther than gasifier grate made more raw material could be burnt. A high ash content (21,56 %) of eucalyptus wood pellet effected on slag formation in high temperature of gasification. A fixed grate with small holes in it was not suitable for this kind of raw material, the slag was restrained above the grate and made the raw material could not flow down smoothly. In Figure 4.12 can be seen the effect of ER on producer gas composition. ER 0.19 and 0.24 gave a slightly different of its gas composition, while ER 0.29 showed two times better result compared to ER 0.19. The trend of H_2 increased along with the increasing of equivalence ratio. As the temperature increased, CO and H_2 could have been expected as dominant products and the trend of CO_2 will almost opposite to CO [21, 48], however this case was not appear here. Nevertheless changes in ER cannot be the only explanation for changes in this gasification performance.

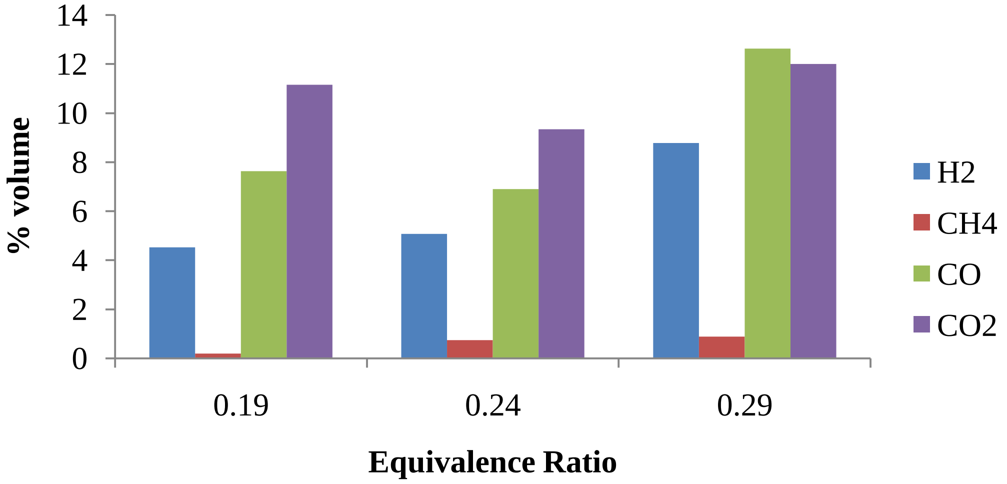


Figure 4.13 Effect of ER on producer gas composition of double air supply stage

Figure 4.13 shows the effect of ER on producer gas composition of the triple air supply stage. There were five ER of 0.20, 0.26, 0.30, 0.36 and 0.39 tested in this stage. The best producer gas composition (CO and H_2) was showed at ER 0.36. While the highest ER showed the decreasing of its quality. The eucalyptus wood pellet gasification results were comparable with the data found in literature [24] that investigated miscanthus and bioethanol waste pellets. The low temperatures and product gas compositions occurred due to the physical characteristics of the fuel and the chemical composition of the ash.

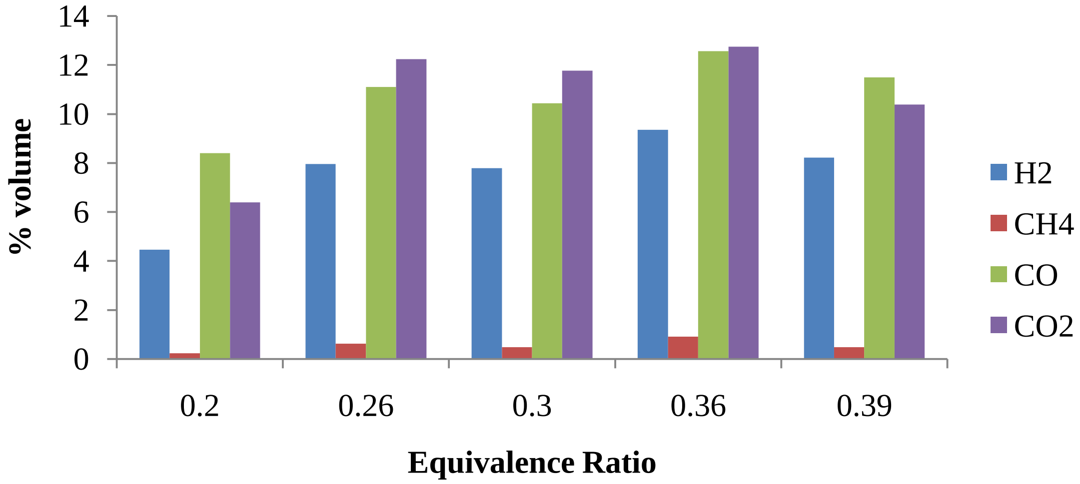
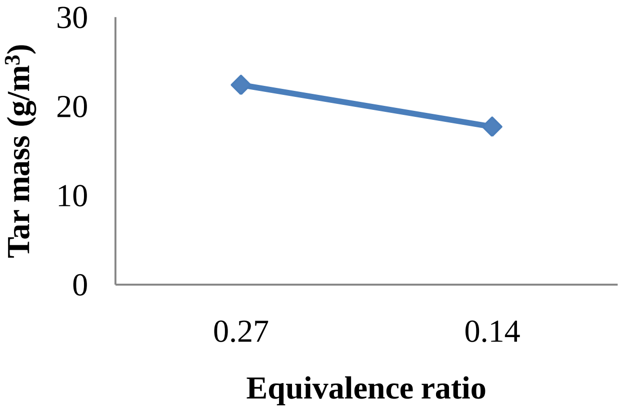


Figure 4.14 Effect of ER on producer gas composition of triple air supply stage

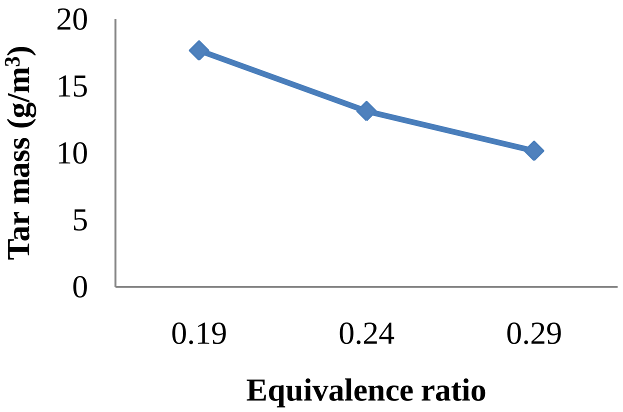
From the ten experiments, it was found that the producer gas composition was better at higher ER. The increased of flow rate along with the increasing of ER gave a significant impact to producer gas composition. Except the highest ER of 0.39 that start to decrease its quality. The ER range which worked well was 0.29 – 0.36 with CO and H_2 of 12.64%, and 9.35%. H2O and CO2 formed during partial oxidation reactions reacted with the charcoal bed, was favored the Shift and Boudard endothermic reaction. $C + H_2O \leftrightarrow CO + H_2$ and $C + CO_2 \leftrightarrow 2CO$. More than half of producer gas volume was N_2, i.e. 60 – 70%, and CO2 slightly more than CO. The presence of these incombustible gases dilute the producer gas and lower its combustible gases quality along with its heating value considerably.

4.2.3. Effect of Equivalence Ratio on Tar Quantity

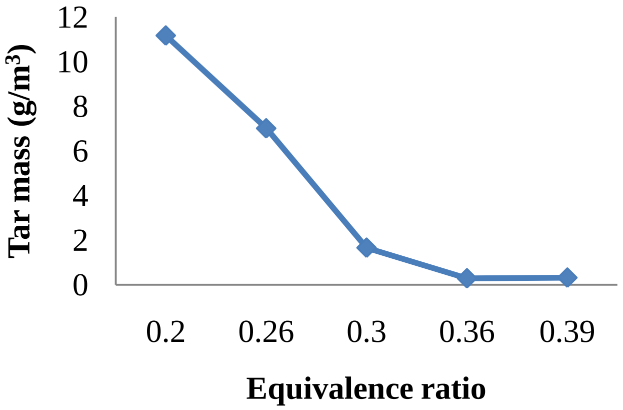
Tar formation is one of the major problems when dealing with the biomass gasification. Tar is a complex mixture of condensable hydrocarbons, which block and foul gasification facilities and requiring complex cleaning inside the gasifier [3]. Figure 4.14 shows the effect of equivalence ratio on gravimetric tar.



(a) Gravimetric tar in single air supply stage



(b) Gravimetric tar in double air supply stage



(c) Gravimetric tar in triple air supply stage

Figure 4.15 Effect of equivalence ratio on gravimetric tar

The results of the gravimetric tar mass as a function of equivalence ratio is shown in Figure 4.14. Of all single, double and triple air supply stage presented the decreasing of tar along with the increasing of ER. The tar mass was 22.4 gr/m^3 and it reduced to 0.31 gr/m^3 of ER 0.39. The decreasing of tar mass not only because of higher gasification temperature during the experiment but also the air supply nozzles in each pipe which arranged in different angle position helped to get a good process of gasification and created a uniform air supply distribution inside the gasifier. This affected to a more chance for tar to be cracked. The tar concentration in the producer gas obtained in this study was considered to be high, which is unexpected for gasification system. Nevertheless, the results also clearly pointed that the yield of tar concentration in producer gas could be significantly reduced by controlling the ER. Rise in temperature as a result of higher ER has made considerable tar reduction by way of decomposed into CO, H_2, CH_4 and light hydrocarbons. Reduction in the gravimetric tar was corresponded to the increase of the oxidation temperature and the increase of the reduction temperature.

Tar aerosols formed in the pyrolysis zone are effectively decomposed or combusted in the oxidation zone under the influence of high temperature and the oxidation reaction, as its nature of downdraft type gasifier [49]. Therefore, less tar mass was obtained with higher ER. In the same type of throatless type downdraft gasifier, Dogru et al. reported that 13.0 g/m^3 reduced to 6.37 g/m^3 in sewage sludge gasification, whereas the high tar concentration was due to gasifier design and experiment conditions [50]. Phuphuakrat et al., reported that tar produced from dried sewage sludge in a downdraft fixed bed gasifier was significantly decreased under the gasification temperature between 980^oC – 1180^oC of 13 – 3 g/m^3 when the ER increase from 0.29 to 0.36 [49]. Kaewluan reported the drop of tar concentration from 5.6 to 0.85 g/m^3 when the ER was increased from 0.32 to 0.43 in bubbling fluidized bed bed reactor [51]. Bhattacharya developed a two stage gasification of wood with preheated air supply and got a cleaned gas of tar content about 10 mg/m^3 [4].

4.2.4. Effect of Equivalence Ratio on Cold Gas Efficiency and Higher Heating Value

The effect of ER on variation of cold gas efficiency and carbon conversion efficiency is plotted in Figure 4.15. Both cold gas efficiency and carbon conversion efficiency are increased with the increasing of equivalence ratio. The cold gas efficiency and heating value of producer gas are varied from 9.7 – 44.5 % and 1.2 – 3.1 MJ/m^3. Since the gas heating value was determined by the concentrations of gases, the result was quite low which influenced by the gasifying agent. The nitrogen in air greatly dilutes the product gas.

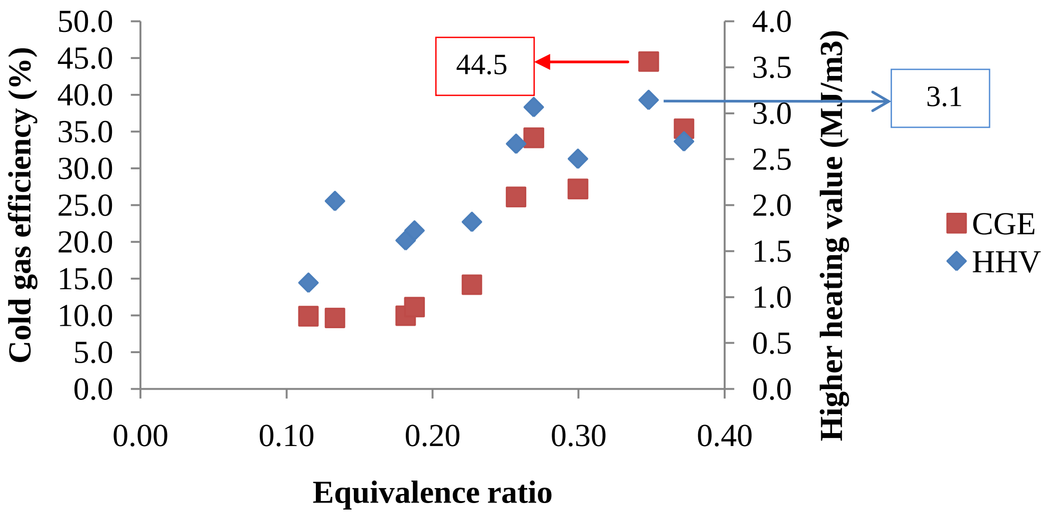


Figure 4.16 Effect of equivalence ratio on cold gas efficiency and higher heating value

4.2.5. Ash and Slag Analysis

Ash is the inorganic solid residue left after the fuel is completely burned which ingredients are silica, aluminum, iron, and calcium; small amounts of magnesium, titanium, sodium, and potassium [41]. The ash content of most biomass is typically much less than that of coals (<3%), but some forms have a high as content [50]. Proximate analysis of eucalyptus wood pellet showed that the amount of ash was quite high (21.56 % dry basis).

The high ash content can affect both the quality and quantity of producer gas. High temperature that occurs in oxidation and reduction zone can make the ash melting and form slag. Slagging is a complex phenomenon which is influenced by many factors and which can be a cause of operability problems. Pelletizing of eucalyptus wood pellet that might use bark or additional binders or lubricants has made its quality become lower. In this gasification case, the formation of significant amounts of slag can cause blockage of the grate in the gasifier. Blockage of this grate will increase the pressure and have an adverse effect on the fuel flow distribution. Figure 4.16 shows the slag occurred in gasifier.

Figure 4.17 The slag in gasifier

The slagging problems definitely disserve the gasification process. Due to this slag, the experiment could not run continuously. As the slag was collected above the grate which means that it is also close to the reduction area. When an amount of slag formed, the producer gas quality will decrease. X-ray diffraction and X-ray fluorescence spectrometry analysis were done to investigate the components of eucalyptus wood pellet slag. The crystal structure in slag was measured and found that it contained 60% of silicate mineral, 22.5% of Iron mineral, 6.68% of Calcium mineral and the other elements, such as aluminium, potassium, magnesium, manganese, titanium, etc.

Out of the total 18 components found, silicate mineral is dominated. So, it can be assumed that sand and soil can be added and mixed with the eucalyptus wood in the making of the pellet. Result from the experiments showed that the slag start occur at double air supply stage experiments and the highest yield of slag was 18% at the triple air supply stage.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

5.1 Conclusions

This work presents the test results of the eucalyptus wood pellets in the multi-air-stage downdraft gasifier. Of the total ten experiments, consisting of two experiments of the single air supply stage, three experiments of the double air supply stage and the five experiments of the triple air supply stage were investigated.

The suitable ERs that gave good gas composition results were 0.29 – 0.36 with CO and H_2 of 12.64%, and 9.35% with higher heating value around 3.1 MJ/m^3. The chart trend showed that CO and H_2 tend to increase along with the increasing of ER, but the highest ER of 0.39 showed it decreasing. Thus it can be concluded that ER itself cannot explain the trend of producer gas compositions as raw material quality, equipments condition and environment should be taken into account.

The tar mass was significantly reduced by controlling the equivalence ratio. The tar mass was 22.4 gr/m^3 and it reduced to 0.31 gr/m^3 of ER 0.39. However, a cleaning system is still necessary to remove tar because the result showed that it cannot be completely eliminated by gasifier design and influence of equivalence ratio. It still cannot be used directly to the engine.

Eucalyptus wood pellets used in this study had only 10% of moisture content and did not show any trouble in the gasifier, except its high ash content (21.56% dry basis). It affects the formation of slag when the ash melts at high gasification temperature. Slag be accumulated and blockage the gasifier grate which finally give trouble to the fuel flow distribution. Not only disrupt the fuel flow distribution but the slag also give a low quality and quantity of producer gas. XRF analysis investigated that slag of eucalyptus wood pellets contents of 60% of silicate mineral, 22% iron mineral, 6.68% of calcium mineral, 5.17% aluminium mineral, etc.

5.2. Recommendations for Future Studies

1. The fact that the single air supply stage was not able to reach flow rate as high as double or triple air supply stage made that they could not be compared due to the design of same size of all air supply stage pipe that generate high pressure drop when just want to operate single air supply stage. So, an adjustable pipe with different sizes could help to reach the same air flow rate when run only single stage, double stage or even triple air supply stage.
2. The air flow in each air supply pipe can be varied in order to study the effect of the air distribution along the gasifier. The balance between downward fuel movement and upward flame propagation is very important. If the fuel moves downward faster than upward flame propagation, it will enable the whole system to act like single air stage gasifier.
3. Modification of tar sampling equipment, such as an additional particle filter, can bring down the contamination of solid particles in tar. Tar quality analysis may be required to investigate tar components at each air supply stage.
4. New design of grate and ash removal system might help the ash problem to all kinds of biomass, such as type of rotary grate.
5. Considering that the lab is in the outdoor, keeping the quality and moisture content of raw material is a must, especially during the rainy season. Some problems with the gasifier such as ash gate that usually get curved when gasifier reach a very high temperature and possibility of gas leakage along the gasifier must be solved. A routine cleaning after finish the experiment and monthly cleaning of whole gasification system can keep the whole gasification efficiency well.

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APPENDIX A

FUEL FEED RATE

$$M_f = \frac{Q}{LHV_{bm}\eta_{gef}}$$

Which, M_f = Biomass feed rate (kg/s)

Q = Gasifier required power output (MWth)

LHV_{bm} = Lower heating value of biomass (MJ/kg)

η_{gef} = Gasifier efficiency

LHV_{bm} = 13456 kJ/kg

= 13.46 MJ/kg

η_{gef} = 70 % (Ciferno & Marano, 2002)

= 0.7

Q = 50 kWth

= 50 kJ/s

= 0.05 MJ/s

$$M_f = \frac{Q}{LHV_{bm}\eta_{gef}}$$

$$M_f = \frac{0.05\ \frac{MJ}{s}}{13.46\ \frac{MJ}{kg}\ x\ 0\ .7}$$

M_f = 0.0053 kg/s

= 19.11 kg/h

APPENDIX B

FLOW RATE OF GASIFYING MEDIUM

Table B.1 Proximate and ultimate analyses of eucalyptus wood pellets

Proximate analysis	
Moisture content (wt. % as recieved)	10.07
Volatile matter (wt. % dry basis)	66.37
Ash content (wt. % dry basis)	21.56
Fixed carbon (wt. % dry basis)	12.07
Ultimate analysis	
Carbon (wt. % d.a.f)	48.17
Oxygen (wt. % d.a.f)	45.15
Nitrogen (wt. % d.a.f)	0.66
Hydrogen (wt. % d.a.f)	6.02
HHV (MJ/kg)	14.42
LHV (MJ/kg)	13.46

Table B.2 Oxygen calculations

Element	**wt**	**kmol**	**Rx**	**O_2 Required**
C	48.17	4.01	$C + O_2 \rightarrow CO_2$	4.01
H	6.02	3.01	$H_2 + ½ O_2 \rightarrow H_2O$	1.51
O	45.15	1.41	$O_2 \rightarrow O_2$	-1.41
N	0.65	0.04	$½ N_2 + O_2 \rightarrow NO_2$	0.04
Total				4.15

Stoichiometric O_2 required is 4.15 kmol

Stoichiometric air required :

$m_{\text{dry air}}$ = wt O_2 + wt N_2

= (4.15 kmol x 32 kg O_2/kmol) + (4.15 kmol x 3.76 x 28 kg N_2/kmol)

= 132.99 kg O_2 + 437.56 kg N_2

= 570.56 kg air / 100 kg biomass

= 5.70 kg air / kg biomass

The best results were given by the air flow rate of 543 L/min.

So, wt of $\text{air}_{(\text{actual})}$ $= \dfrac{543\ L/min\ x\ 1000m^3\ /L}{60\ min\ /hr}$

$= 32.56\ m^3/hr$

The wt of $\text{fuel}_{(\text{actual})}$ when air flow rate of 543 L/min is 18.46 kg/hr

Where, ρ_{air} = Air density (kg/m^3)

$= 1.165\ kg/m^3$ at 30^oC

So, wt of $\text{fuel}_{(\text{actual})}$ $= \dfrac{18.46\ \text{kg}/\text{hr}}{1.165\ kg/m^3}$

$= 15.85\ m^3/hr$

$$ER = \frac{(wt\ of\ air/wt\ of\ fuel)_{actual}}{(wt\ of\ air/wt\ of\ fuel)_{stoiciometri}}$$

$$ER = \frac{\left(32.56\frac{m^3}{hr}\Big/15.85\frac{m^3}{hr}\right)}{5.70}$$

$ER = 0.36$

APPENDIX C
GASIFICATION EFFICIENCY

C.1. Cold-Gas Efficiency

Cold-gas efficiency is the energy input over the potential energy output. If M_f kg of solid fuel is gasified to produce M_g kg of product gas with an $LHV_{solid\ fuel}$ of Q_g, the efficiency is expressed as

$$\eta_{cg} = \frac{Q_g M_g}{LHV_f M_f}$$

C.1.1. Raw Material and Producer Gas Composition

Table C.1 Raw Material and Producer Gas Composition

Eucalyptus Wood Pellet Composition	
Carbon (wt. %)	48.17
Oxygen (wt. %)	45.15
Nitrogen (wt. %)	0.66
Hydrogen (wt. %)	6.02
Ash (wt. %)	21.56
HHV (MJ/kg)	14.42
LHV (MJ/kg)	13.46
Producer Gas Composition (%)	
CO	12.56
CO_2	12.74
CH_4	0.92
H_2	9.35
N_2	64.42

C.1.2. The Dry Air Supply Rate

Air supply volume : 543 L/min

: 32580 L/h

: 32.58 m^3/h

Air Density (ρ) : 1.165 kg/m^3 at 30°C

m_{air} $= V_{air}\ x\ \rho$

$= 32.58\ m^3/h\ x\ 1.165\ kg/m^3$

$= 37.956\ kg/h$

Air Humidity (ω) : 0.016 kg/kg for Thailand

$$m_{air} = m_{dry\ air} + m_{moisture}$$

$$= m_{dry\ air} + (m_{dry\ air}\ x\ \omega)$$

$$= m_{dry\ air} + 0.016\ m_{dry\ air}\ {}^{kg}/_{kg}$$

$$= 1.016\ m_{dry\ air}\ {}^{kg}/_{kg}$$

$$m_{dry\ air} = \frac{m_{air}}{1.1016\ {}^{kg}/_{kg}}$$

$$m_{dry\ air} = \frac{37.956\ {}^{kg}/_{h}}{1.016\ {}^{kg}/_{kg}}$$

$$= 37.358\ kg/h$$

$m_{dry\ air}$ for each kg of biomass $= \dfrac{37.358\ kg/h}{18.461\ kg/h}$

= 2.024 kg dry air/kg biomass

C.1.3. Nitrogen Flow

The mass fractions of N_2 and O_2 in air is 0.7547 and 0.232

The N_2 supply from air = Mass fraction of N_2 x $m_{dry\ air}$

= 0.7547 x 2.024 kg dry air/kg biomass

= 1.527 kg N_2/kg biomass

The total N_2 supplied by the feed air and the fuel feed, which carry 0.66% N_2 is

= 1.527 kg N_2/kg biomass + 0.0066 kg N_2/kg biomass

= 1.534 kg N_2/kg biomass

= 0.055 kmol N_2/kg biomass

The volume % = molar % in a gas mixture

The producer gas contains 64.42 % by volume of nitrogen, the amount of producer gas per kg of fuel feed is

= 0.055 kmol N_2/kg biomass / 0.6442

= 0.085 kmol gas/kg biomass

C.1.4. Oxygen Flow

The O_2 supply from the air = Mass fraction of O_2 x $m_{dry\ air}$

= 0.232 x 2.024 kg dry air/kg biomass

= 0.469 kg O_2/kg biomass

The O_2 supply from the moisture air feed is

= $m_{moisture\ air}$

= $m_{dry\ air}$ x ω

= ((37.358 kg dry air/h x 0.016 kg/kg)/ 18.46 kg biomass/h) x (16/18)

= 0.029 kg O_2/ kg biomass

The total O_2 supply from air, moisture and include 45.15% O_2 from biomass is

= 0.469 kg O_2/kg biomass + 0.029 kg O_2/kg biomass + 0.451 kg O_2/kg biomass

= 0.950 kg O_2/kg biomass

C.1.5. Hydrogen Balance

The total H_2 inflow to the gasifier from fuel feed and moisture in the air is

= 0.06025 kg H_2/kg biomass

+ ((37.358 kg dry air/h x 0.016 kg/kg)/ 18.46 kg biomass/h) x (2/18)

= 0.064 kg H_2/kg biomass

The H_2 leaving with H_2 and CH_4 in the producer gas, noting that 1 mole CH_4 contributes 2 mols of H_2, is

= (0.093 + (2 x 0.009)) x 0.085 kmol gas/kg biomass

= 0.009 kmol/kg biomass x 2 kg H_2/kmol

= 0.019 kg H_2/kg biomass

The H_2 in producer gas is

= H_2 in – H_2 out

= 0.064 kg H_2/kg biomass – 0.019 kg H_2/kg biomass

= 0.045 kg H_2/kg biomass

The $H_2O_{(l)}$ in producer gas associated with this hydrogen is

= 0.045 kg H_2/kg biomass x (18/2) kg moisture/kg H_2

= 0.403 kg moisture/kg biomass

C.1.6. Carbon Balance

The total Carbon output-CO, CO_2 and CH_4- in the producer gas contains each 1 mol of C. So the total Carbon in 0.085 kmol gas/kg biomass is :

= (0.1256 + 0.1274 + 0.0092) x 0.085 kmol gas/kg biomass x 12 kg C/kmol

= 0.268 kg C/kg biomass

The C input found from Eucalyptus wood pellets is 0.4817 kg C/kg biomass

The Carbon conversion efficiency = (The C output / The C input) x 100%

= (0.268 / 0.4817) x 100%

= 55.55 %

C.1.7. Energy Balance

The Higher Heating Values for different gas constituents are :

CO	: 12.63 MJ/nm^3
H_2	: 12.74 MJ/nm^3
CH_4	: 39.82 MJ/nm^3

Note that: The volume of 1 kmol of any gas is 22.4 nm^3.

Total heating value of product gas is

= (12.63 x 0.1256 + 12.74 x 0.0935 + 39.82 x 0.009) MJ/nm^3

= 3.14 MJ/m^3

= 3.14 MJ/m^3 x 0.024 kmol gas/kg biomass x 22.4 nm^3/kmol

= 5.987 MJ/kg biomass

Total energy input = The heating value of biomass

= 13.455 MJ/kg

So, the Cold Gas Efficiency is

$$\eta_{cg} = \frac{Q_g M_g}{LHV_f M_f}$$

$$= \frac{Total\ Energy\ Output}{Total\ Energy\ Input}\ x\ 100\%$$

$$= \frac{5.987\ MJ/kg}{13.455\ MJ/kg}$$

$$= 44.499\ \%$$

C.2. Hot-Gas Efficiency

When gas is burned in a furnace or boiler without being cooled, it will create a greater utilization of the energy. Hence, by taking the sensible heat of hot gas into account, the hot gas efficiency can be defined as:

$$\eta_{hg} = \frac{Q_g M_g + M_g C_p \left(T_f - T_0\right)}{LHV_f M_f}$$

C.2.1. Enthalpy

The producer gas exit the gasifier at 500^{o}C (773 K). The enthalpy of the producer gas is the total enthalpy of its components.

Table C.2. Specific Heat of Gases [41]

Gases	Specific Heat Relation at Temperature T (K)	Specific Heat (kJ/kmol.K)
CO	27.62 + 0.005T	31.485
CO_2	43.28 + 0.0114T – 818363/T^2	50.723
H_2	27.71 + 0.0034T	30.338
N_2	27.21 + 0.0042T	30.457
CH_4	22.35 + 0.048T	59.454

The enthalpy of CO in the product gas that contains 12.56% CO above the ambient temperature, 30^{o}C or 303^{o}K, is

Q = n.Cp.ΔT

= (0.085 x 0.1256 kmol gas/kg biomass) x 31.485 kJ/kmol.K x (773-303) K x 10^{-3} MJ/kJ

= 0.1597 MJ/kg biomass

Table C.3. Enthalpy Calculation

Component	Vol%	Enthalpy (MJ/kg)
CO	12.56	0.1597
CO_2	12.75	0.2611
H_2	9.35	0.1146
N_2	64.42	0.7924
CH_4	0.92	0.0221

The amount of steam in the producer gas was calculated as 0.403 kg moisture/kg biomass. The steam enthalpies at 773K and 303 K are 3488.7 kJ/kg and 125.76 kJ/kg, respectively, so the enthalpy in water is

= 0.403 kg moisture/kg biomass x (3488.7 – 125.76 kJ/kg) x 0.001 MJ/kJ
= 1.356 MJ/kg biomass

The total enthalpy of producer gas at 773 K is,

= (0.1597 + 0.2611 + 0.1146 + 0.7924 + 0.0221 + 1.356) MJ/kg biomass
= 2.706 MJ/kg biomass

The total thermal energy = Heating Value + Enthalpy
= 5.987 MJ/kg biomass + 2.706 MJ/kg biomass
= 8.694 MJ/kg biomass

So the Hot Gas Efficiency (Net Gasification Efficiency) is

$$\eta_{hg} = \frac{Q_g M_g + M_g C_p (T_f - T_o)}{LHV_f M_f}$$

$$= \frac{\text{Total Thermal Energy}}{\text{Total Energy Input}} \, x \, 100\%$$

$$= \frac{8.694 \, MJ/kg}{13.455 \, MJ/kg} \, x \, 100\%$$

$$= 64.61 \, \%$$