EXPERIMENTAL TESTING OF PALM KERNEL SHELL IN MULTI-STAGE AIR GASIFICATION

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A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS
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ABSTRACT

This work discusses the experimental testing of palm kernel shells in multi-stage air gasification. The gasification of palm kernel shells was operated under atmospheric pressure, using air as the gasifying agent. The research focused on the effect of multi-air-stage supply and equivalence ratio (ER) on heating value of producer gas, gas composition, and tar content. The configuration was regarded as first stage, second stage and third stage air supply to enrich the producer gas. With increasing ER from 0.25 to 0.30 presented the good results of gas compositions. The results showed that CO (15.31 vol.%) and H_2 (10.33 vol%) gas concentrations had the highest values in this range of ER. The gas composition of gasification attained a good condition with higher heating value and lower heating value were 3.90 MJ/m^3 and 3.6 MJ/m^3, respectively. The result of tar content in producer gas was lowest at ER of 0.3 as low as to 2.01 g/Nm^3. In terms of gasification efficiency, the cold and hot gas efficiencies were employed in which they were 45% and 58%, respectively.

Keyword: Multi-stage downdraft air gasification, Tar, Palm kernel shell.

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CHAPTER 1

INTRODUCTION

1.1 Rationale/Problem statement

Currently, the main energy resources in the world are fossil fuels. In the near future, these energy resources will be exhausted. Therefore, the discovery of renewable energy sources is highly significant. Figure 1.1 presents the world's total primary energy consumption that the utilization of biomass is consumed about 12%. It is evaluated that biomass consumption will be enhanced up to 15% by future closely (Han and Kim, 2008).

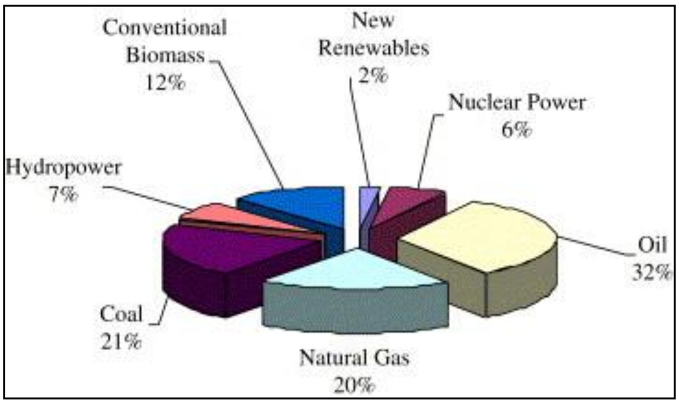

Figure 1.1 The shares of current world's primary energy consumption (Han and Kim, 2008)

Thailand is one of the developing countries whose have been rapidly continuous increasing energy demand, as well as electricity generation. Over the past decade, the fossil fuel demand is used for industrial section, transport section, and electricity generation. The data from the department of alternative energy development and efficiency in ministry of energy displayed information of energy demand of Thailand. It reports the total energy used 2.56 million barrels per day (Haema, S. 2012). In present day, Thailand has to face with crisis of increasing fossil fuel prices such as oil, coal, and natural gas, as well as effect of fossil fuels to environment for instance surface or ground water contamination, air pollution problems with the release of a greenhouse gas (CH_4) which causes the global warming, NH_3, H_2S, amides, volatile organic acids, and other compounds (Xianbin Xiao, 2010). Therefore, Thai government has become interested biomass as a renewable energy resource due to Thailand can produce large amounts of agricultural crop residues that able to be utilized as renewable energy resource. Residues of palm oil which generated by the palm oil industries are also attractive crop residues to be used as renewable energy fuel in Thailand. According to Thailand published by Energy Research Institute was showed the production of renewable energy of biomass energy in 2014. There were residues of palm oil around 2,315 kg/Rai that produced showed in Table 1.1

Table 1.1 Potential biomass of Thailand in 2014. (Puttichartet al., 2014)

Type of Agricultural crop	**Products Kg/Rai**	**Biomass types**	**Biomass/ Product (Kg/Kg)**	**Calorific Value (MJ/kg)**
Bagasse	10,905	Sugar cane	0.303	7.53
		Top leave bagasse	0.204	16.15
Corn	650	Corncob	0.189	16.78
		Corn stem	0.892	16.01
Palm oil	2,315	Empty Fruit Brach	0.215	16.32
		Fiber	0.149	17.25
		Kernel Shell	0.130	18.53
		Palm fronds	0.272	16.03

Biomass refers to all organic matter derived from plants and animals, which includes algae, trees, wood from forest, agricultural crops, seaweed, domestic human wastes and animal wastes (Saidur et al., 2011). Biomass uses the sunlight converting energy in chemical bonds into plant material by the photosynthesis process. When the bonds between adjacent carbon, hydrogen and oxygen molecules are broken by digestion, combustion, ordecomposition, these elements release their stored chemical energy (McKendry, 2002a). Biomass is also known as the important primary and renewable energy source as well as clean energy. It is possible to be a more potential energy to substitute conventional fossil fuels in the energy market (Balat et al., 2009).

The potential conversion technology of biomass converts biomass in to bio-fuels. Bio-fuel is an efficient production of energy organic matter, prevents environmental pollution, and reduces greenhouse gases. Bio-fuels can be subdivided into two types “first generation bio-fuels” and “second generation bio-fuels”. First generation bio-fuels are converted from sugar, starch, or vegetable oil into bio ethanol, biodiesel, bio-ethers, and biogas. Second generation bio fuels are converted from sustainable feedstock such as algae, wood or grass into cellulosic ethanol, algae-based bio-fuels, bio hydrogen, methanol, etc. (Yılmaz and Selim, 2013). However, in order to compete with fossil energy resources.Therefore, biomass needs to utilize efficient conversion technologies. Biomass has mainly two routes to be converted: one is the biochemical route and another is the thermo-chemical route (Jaojaruek et al., 2011). Biochemical conversion includes fermentation and digestion and thermo-chemical conversion consists of combustion, pyrolysis, gasification, and liquefaction (McKendry, 2002a).

Gasification is a well-known type of thermo-chemical conversion for converting of carbonaceous materials (coal, petroleum coke, biomass, etc.) mainly consisting of CO, H_2, CO_2, CH_4, and N_2 (using gasification agent as air) into producer gas or syngas. The sufficient quantity of syngas can be used as fuel for internal combustion engine and in boiler (Jaojarueket et al., 2011). Although, biomass has several advantages, the major problems of biomass are tar and soot that generated as impurities during synthesis of syngas by gasification process (Son et al., 2011).

Tar formation which is a product from decomposition organic compounds in biomass is a biggest problem during biomass gasification Tar contains single-ring to 5-ring aromatic compounds along with other oxygen-containing hydrocarbons and complex PAH (McKendry, 2002a). Furthermore, it condenses when decreasing temperature as well as its properties is thick, black highly viscous liquid that lead to block the gas passage and operating system (Lopamudra et al., 2011). Therefore, this study provides downdraft gasification technology that can be used to covert biomass as a potential bio-fuel and reduce tar in the product gas. The treatment of tar formation can be carried out inside the gasifier (primary process) and in the hot cleanings of the gas generation (secondary process) (McKendry, 2002b). The tarformation depends on various factors, such as temperature, gasifying agent, equivalent ratio, etc. In order to tar reduction in product gas that there are many works study about multistage biomass gasification, which reduced the tar content in product gas by using downdraft gasifier (Martínez et al., 2011).

Palm kernel shell is a residue from crushing in palm oil mill and is used as a solid fuel for steam boilers. There are many reasons for use palm oil shell as fuel due to lower the moisture content than the other biomass residues and can be easily handled. Moreover, its higher heating value is also high. At local area in southern Thailand has many residues from palm oil that produces in the small factory. Therefore, it is suitable as a solid fuel to generate renewable energy in local area of Thailand. This work focused to study gasification from palmkernel shell. Downdraft gasification is an attractive technology to generate electricity, energy, and chemicals. This conversion technology is proper toproduce gaseous fuel by reaction with air. Three-stage of air supply downdraft gasifier used for improving quality of gas and reduce tar content in producer gas in different operating conditions.

1.2 Literature review

Biomass gasification has been studied for a long time due to its potential as a thermo-chemical process that results in the high production of a gaseous mixture and small amounts of tar content and ash. Consequently, there are several studies to investigate biomass gasification by using downdraft gasifier followed by.

1.2.1 Downdraft gasification

Biomass gasification is one kind of thermo-chemical conversion technology that converts carbonaceous materials (woody, non-woody, etc.) into producer gas or syngas. Producer gas mainly includes a mixture of carbon monoxide, hydrogen, small amount methane, with carbon dioxide and nitrogen. Biomass gasification did not only generate producer gas but also generated by products from thermal decomposition, tars, char inorganic compounds, ash, and other gaseous hydrocarbon (Balat et al., 2009).

Son Yoon et al. (2011) studied gasification of woody biomass in a downdraft gasifier by using air as the gasifying agent. From the experimental condition, the feeding rate of wood chip was 40-45 kg h-1 and syngas having flow of around 80-100 Nm3 h-1. The results showed the optimal operation was possible at a gasifier temperature of around 1000°C. As the gasification air ratio was increased up to 0.35, the low heating value increased of 1200 kcal Nm-3 and the cold gas efficiency of 69-72% can be achieved. The average concentration of generated syngas is H_2:16.5%, CO: 15.9%, CH_4:2.1% and CO_2:15.3%. In addition, tar component contained in the producer gas was a level of 3.9-4.4 Nm-^{3}, which is much lower than the level of 10-30%, in the case of the other fixed-bed of gasifier process. Moreover, the generated power using the syngas can be used as fuel fed in to a gas engine (CD800L reciprocation engine) that was better than using LPG fuel. The observation of exhaust pollutant emission from syngas combustion had proved that the NO_x emission was less than using LPG fuel. The NO_x emission of syngas and LNG was 30-40 ppm and 250 ppm, respectively.

Martínez et al. (2011) studied the gasification of wood biomass in a moving bed downdraft of reactor with double air supply stages. This experiment developed the quality of producer gas which produced from residual eucalyptus wood and considering tar reduction by varying the air flows fed in gasifier (AR=0%, 40%, 80%). The gasifier produced the must combustible gas with CO, CH4, and H2 concentrations of 19.04, 0.89, and 16.78% v respectively, and 20 Nm3 h-^{1} of total air flow for AR equaled to 80%. In these conditions, the lower heating value of producer gas was around 4539 kJ Nm-^{3}and the cold efficiency was around 68%. From the calculation model presented a useful gas power around 40kW.

Gai et al. (2012) studied the gasification of corn straw which was implemented in a downdraft gasifier under atmospheric pressure and using air as a gasifying agent. The influents of the operating condition affected the gasification performance in terms of temperature profiles of the reactor, the producer gas composition, and the discharge of sulfur and chlorine compounds during the gasification of corn straw. As the results, the optimum value of equivalent ratio (ER) was 0.28-0.32 that decreased the mole fraction of CO_2 from 23.93 to 11.58%, while CO rose to 19.81% from 11.35%,and H_2 concentration was increased from 6.91 to 13.51%. Besides, the optimal low heating value of producer gas was 5.39 MJ/Nm^3, gas yield of 2.86.Nm^3/kg, gasification efficiency of 73.61% and tar concentration of 4617 mg/Nm^3 was obtained at different ER.

Zainal et al. (2002) studied the furniture wood and wood chips in the downdraft biomass gasifier by using an air supply system. The average gas composition is 1.69% O_2, 43.62% N_2, 14.05% H_2, 24.04%CO, 14.66% CO_2, 2.02% CH_4 and C_2H_6.The formation of CH4 was unstable as it separated into CO and H_2 in the reduction zone. The optimum operation of equivalence ratio was around 0.388. This equivalence ratio produced the calorific value was 5.62 MJ/m3. Moreover, the overall efficiency was found to be a maximum of 15.46%, as well as the cold gas efficiency of the gasifier was around 80%.

Péreza et al. (2012) studied the effects of pine bark and sewage sludge used as biomass on the performance of the gasification/combustion process of waste biomass in fixed bed downdraft reactors and using air as a gasifying agent. As the results, they found that the optimal fuel air equivalence ratio was 3.2. The quality of lower heating value of producer gas was 2965.6kJ/Nm^3, tar concentration was 7.73g/Nm^3 and proportion of syngas of 8.0% H_2, 13.0% CO, 1.4% CH_4, 14.9% CO_2, and 62.7% N_2.

Erlich et al. (2010) studied the downdraft gasification of pellets made of wood, palm oil residues and bagasse. They were generally focused on the development of performance and the optimizing of gasifiers on testing difference fuels. The main objective in this works was to study the impact of char bed properties bed porosity and pressure drop on gasifier. In addition, the impact of fuel particle size and composition on the gasification performance were investigated into pellet form. The results showed that the same reactor can be used for several fuels in pellet form but varying air fuel ratios, temperature, gas composition, lower heating values. For producer gas of wood pellet was better than bagasse pellet and empty fruit brunch (EFB) which gave a lower one. In term of higher air fuel ratios resulted in a greater gasification efficiency. However, high pressure drop in char bed was also higher for more reactive fuels which in turn are a reason to be low porosity char beds.

1.2.2 Effect of moisture content

The moisture content of biomass affected gasifier performance and composition of producer gas. Biomass contains moisture as high as 90% (dry basis). The moisture indicated that high energy was desired to evaporate water and was not recoverable. For operating conditions in the downdraft gasifier was determined to be less than 25% wet basis (Basu, 2013).

Kramreiter et al. (2008) studied the effects of moisture content in a downdraft gasifier. The two types of wood chipsused were experimental Type 1 and Type 2. Both types had different moisture contents. The study showed that the average product gas and heating value decreased with high moisture of the wood chips relative with the increasing combustion, the CO_2 amount was also increased and the H_2 and CO amounts in the product gas were decreased. These results show that the moisture content was higher than 25 wt% (wet basis) in the downdraft gasifier and could not be operated efficiently. Therefore, the feedstock was necessary dry biomass before feeding it to gasifier.

Kallis, K.X. et al. (2013) investigated the influence of initial moisture content on biomass pellet gasification in fixed bed gasifier. They found that the result in the moisture content in fuel largely affected on the operating factors of gasifier and syngas composition while the high moisture content of biomass fed to gasifier, which affected the temperature drop inside gasifier. Besides the temperature decreased, the main differences in syngas composition produced the molar of CO was decreased from 23.9% to 10.9%while the amount of CO_2 was raised from 8.5% to 18% with high moisture content. LHV of syngas was also declined in this case. However, the molar fraction of H_2 was increased with the high moisture content from 16% to 20.5%.

1.2.3 Effect of temperature in gasifier

During biomass gasification, various parameters have effect of the product yields and syngas composition. The gasification temperature is one of significant parameter which is investigated.

Son Yoon et al. (2011) investigated the effect of temperature on syngas composition. The temperature was calibrated at 700-850 °C in the gasification part and at 800-1000 °C in the combustion part. The results showed that the temperature had increased, the H_2 concentration had also increased with increasing CO concentration, while CH_4 concentration trend to decrease. Meanwhile, the temperature was increased up to 700 °C that presented the CO_2 concentration trend to decrease.

Lv et al. (2004) demonstrated the effect of reactor temperature on biomass gasification. In their experiment, reactor temperature was varied from 700-900 °C in 50 °C increments. The results showed that H_2 and CO concentrations increased with raising temperature and a decrease in CH_4 concentration. However, high temperature was not favorable CO production. As illustrated in Figure 1.2, CO content was higher than H_2 content below the temperature of around 830 °C.

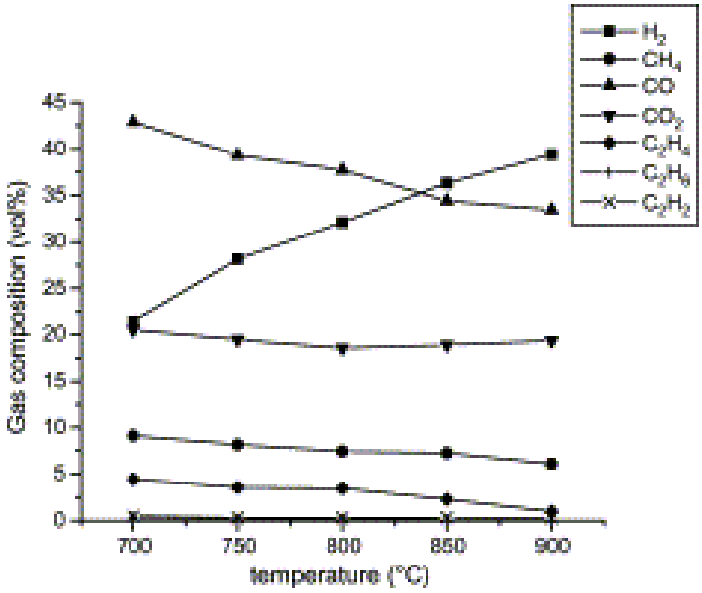

Figure 1.2 Effect of temperature on gas composition biomass feed rate: 0.445 kg/h; air: 0.5 Nm^3/h; steam rate: 1.2 kg/h

The gas yield and the carbon conversion efficiency have a tendency to increase when the reactor temperature increased as show in Table 1.2. Due to thermal cracking was more favorable conditions in high temperature.

Table 1.2 Experimental results of different reactor temperature.

Reactor temperature (°C)	700	750	800	850	900
Gas yield (N m^3/kg biomass)	1.43	1.51	2.23	2.45	2.53
Carbon conversion efficiency (%)	78.17	80.66	85.90	92.35	92.59

1.2.4 Effect of gasifying agent

The gasifying agent is used to react with solid carbon in biomass to convert it into light hydrocarbon gases, such as CO and H_2. The main gasifying agents are oxygen, steam, and air, which was the cheapest option.

Garcia et al. (2000) studied CO_2 as a gasifying agent for gas production from pine sawdust using a Ni/Al co-precipitated catalyst. The CO_2 gasifying agent was converted into valuable gases in catalytic biomass gasification at 700°C and atmospheric pressure compare with steam gasification. As the result, Steam gasification produced higher H_2 yield than CO_2 gasification. The change of the CO yields was highest in the CO_2 gasification with values rising to 1.4g CO/g sawdust.

Karatas H et al. (2012) studied and quality of producer gas depended on difference of the gasifying agent (air and CO_2, air and steam, and steam). In accord with the experimental results, the maximum LHV was 9.59 MJ/Nm^{3}of the CO_2 to air ratio at 0.207, which was varied between 0.095-0.229 in air/CO_2 gasification tests. In addition, the steam to air ratio was varied between 0.204 and 0.269. The maximum LHV was 7.34 MJ/Nm3 at 0.237. For the steam gasification, the maximum LHV was 15.21 MJ/Nm^3 at 0.378, as in shown Fig.1.3, comparison of each gasifying agent. The composition of producer gas with comparison of each gasifying showed on Table 1.3.

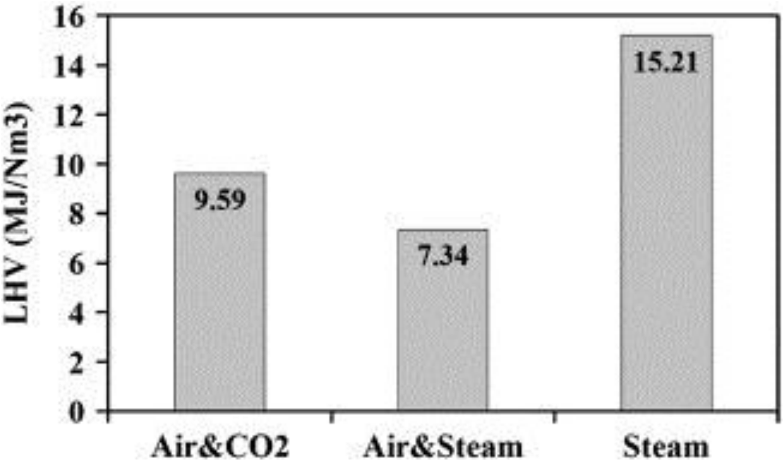

Figure 1.3 Comparison of air and CO_2, air and steam, steam, and gasification result

Table 1.3 Comparison of air and CO_2, air and steam, and steam gasification results.

Property	Air and CO_2	Air and steam	Steam
CO_2/air [kg/h]/ [kg/h]	0.218	n/a	n/a
Steam/air [kg/h]/ [kg/h]	n/a	0.237	n/a
Steam/fuel [kg/h]/ [kg/h]	n/a	n/a	0.378
CO [% v/v]	5.48	4.88	3.89
CO_2 [% v/v]	12.76	9.58	3.30
CH_4 [% v/v]	15.58	11.94	26.37
H_2 [% v/v]	30.71	22.63	48.81
O_2 [% v/v]	0.57	0.44	0.49

Gila et al. (1999) studied the effects of the type of gasifying agent on the product distribution in atmospheric and bubbling fluidized bed. Comparison of air, pure steam, and steam-O_2 mixtures as the gasifying agent was investigated in the experiment. As the result, the lower heating value (LHV) of the producer gas was high closely between pure steam and steam-O_2 gasifying agent around 12-13 MJ/m3at 0.9 pure steam S/B ratios and 0.90 gasifying ratio H2O/O_2=3 as well as H_2 content in the gas was maximum (around 55% vol.). On the other hand, pure steam gasification enhanced tar content around 30-80 g/m3. Furthermore, using air ER=0.3 as gasifying agent produced lowest tar content in the producer gas around 2-20 g/m^3.

Zhao et al. (2010) studied sawdust air gasification in an entrained-flow reactor by using air as a gasifying agent. Estimation of the equivalence ratios was between 0.22 and 0.34. The optimal equivalence ratio was 0.28, while the optimal reaction temperature was 800^{o}C for highest the LHV of the produce gas was6.0 MJ/Nm3, carbon conversion was 92.8%, and cold gas efficiency was 66.7%.

1.2.5 Stage of Gasifier

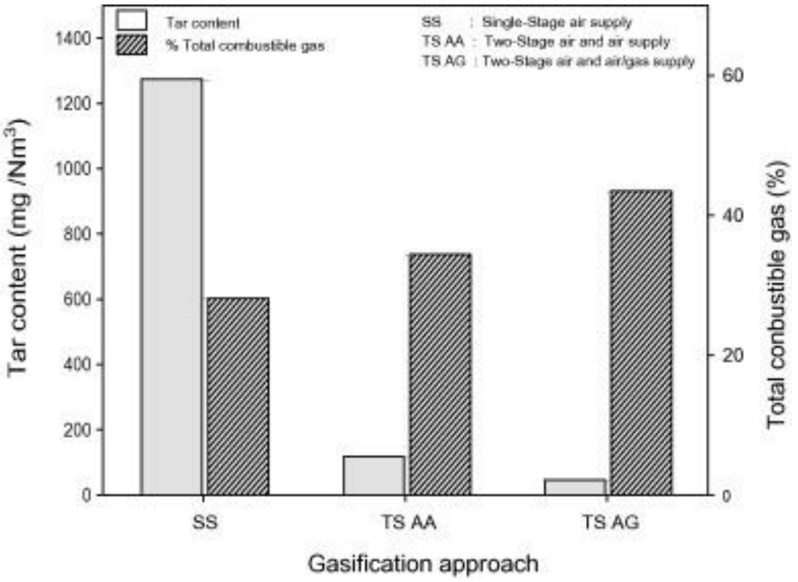

Figure 1.4 Comparison of the gas quality from three approaches in terms of tar content and total percentage of combustible gas.

Jaojaruek et al. (2011) studied on the two-stage air and premixed air/gas supply methods. A reactor was designed to have two stage of air supply nozzles located at combustion and pyrolysis zone. In this experiment, considering single-stage with air supply, two-stage air supply and two-stage air with gas supply. As the result, comparison of the producer gas qualities from three methods was presented in Figure 1.4. A two-stage air and premixed gas produced the tar content of 43.2 mg/Nm^3 which was lower than single-stage air supply. Meanwhile, the total combustible gas (CO, CH_4, and H_2) of two-stage air and gas was 43.9% as well as the HHV of producer gas was improved by as high as 6.47 MJ/Nm^3. From the experiment, the thermal capacity of two-stage air and gas supply was 27.5 kW higher than 25% and 40% compared to single-stage and two-stage air supply, respectively the in Table 1.4.

Table 1.4 Percentage of combustible gas of each gasification approach.

Gasification approach	Air or premixed gas supply at pyrolysis (l pm)	Air supply at combustion (l pm)	Tar content (mg/Nm^3)	Gas thermal capacity (kW)	%CO	%H_2	%CH_4
SS	–	160	1270	19.5	14.3	11.1	2.9
TS AA	80	80	114.4	22.0	17.1	15.7	2.7
TS AG	80	80	43.2	27.5	20.2	20.9	2.8

SS: Single-stage air supply.

TS AA: Two-stage air and air supply.

TS AG: Two-stage air and premixed air/gas supply.

Bhattacharya et al. (2001) studied the multistage air supply with hybrid biomass-charcoal in a gasifier-engine system. This research, regards the three stage air injection in order to investigate the tar content in the producer gas from hybrid coconut shell-charcoal gasification as well as the performance of a gas cleaning system. As the result, tar content was the lowest of 28 mg Nm3 at primary air flow of 200 l min^{-1}, secondary air flow of 140 l min^{-1}, and tertiary air flow of 160 l min^{-1}. The effect of multistage air supply resulted in reduction of tar content, increasing a local temperature zone, and increasing heating value of producer gas. In addition, the efficiency of engine-generator was 14.7% which obtained a maximum electrical power output of 11.44 kWe.

Guo et al. (2014) studied the effects of design and operating parameters. The configuration of downdraft gasifiers in their work was three air stages supply in order to distribute air in the oxidation zone and reduction zone. A special rotating grate was used to remove ash continuously. Corn straw was a feedstock in this the experiment. The results showed the three air stage supply obtained a high and uniform temperature in combustion and reduction zone for better tar cracking. The experimental results of hydrogen concentration (12.89%) was highest when increase at ER=0.25 and CO concentration (19.41%) was highest at ER= 0.27.The product gas achieved a good condition with lower heating value about 5400kJ/m^3.

1.2.6 Biomass gasification

Normally, biomass has low energy density. The natural unsteadiness of biomass leads to problems in terms of collection and transport cost. In order to solve this problem many papers were studied.

Simone et al. (2012) investigated the pelletized biomass in a pilot scale downdraft gasifier. Using wood sawdust and sunflower seeds pellet as raw materials that were experimented in 200 kW downdrafts gasifier operating with air as gasifying agent. The result showed that good syngas composition was obtained H2 17.2%, N2 46.0%, CH4 2.5%, CO 21.2%, CO_2 12.6%, and C_2H_4 0.4%, specific gas production (2.2–2.4 Nm^3kg^{-1}) and cold gas efficiency (67.7–70.0%) were achieved.

Yoon et al. (2012) conducted the experimental research on the gasification of rice husk and rice husk pellets in a bench-scale downdraft gasification fixed-bed gasifier. The temperature range was varied around 600-850°C. From the result, the heating value of synthetic gas and cold gas efficiency from rice husk pellet gasification showed higher values than rice husk gasification. Moreover, the compositions of syngas from rice husk pellet were better than rice husk particle is shown in Table 1.5. The heating value of synthetic gas calculate from these compositions showed about 1084 kcal/ Nm3 for rice husk gasification and 1314 kcal/Nm3 for rice husk pellet gasification.

Table 1.5 Composition of synthetic gas produced from rice husk gasification and rice husk pellet gasification

Syngas composition (vol.%)	Rice husk gasification	Rice husk pellet gasification
H_2	13.6	18.6
CO	14.9	20.2
CO_2	12.9	8.1
CH_4	2.3	1.5
Heating value of syngas (kcal/ Nm^3)	1084	1314

1.3 Objectives

1. To study the effects of ER on higher heating value and the tar content of the producer gas produced from the gasification of palm kernel shell.

2. To study the performance of a multi-stage air downdraft gasifier pertaining to gas composition, heating value, and gasification efficiency.

1.4 Scopes of work

The downdraft gasifier was designed in a previous study and built by the Thai Steam Service and Supply. Co. Ltd. (Bangkok, Thailand).

The scope of this study is described below.

1. Palm kernel shell was used as feed stock in this experiment and supported by Hybrid Energy Co., Ltd. The characteristics of the palm kernel shells such as proximate analysis, ultimate analysis, and higher heating value were analyzed.

2. A multi-stage air, including primary air, secondary air and tertiary air stages were used for air distribution. The air flow rate was varied for one stage, two stages, and three stages.

3. Some modifications of the system were changing in the air inlet pipe to reduce a press drop along the pipe, changing the rotating grate, installing the rotameter at each air stage and by-pass inlet air feeding.

4. Nine experiments were carried out by varying the air flow rate at different air injection stages.

5. The tar content in the producer gas was collected by impinge bottles and using the isopropanol as a solvent and the gravimetric method analyzed the amount of tar.

CHAPTER 2

THEORIES

2.1 Biomass

Biomass is a renewable energy source and biological material from various sources, such as residues from agriculture, forestry and relative industries, as well as the non-fossil, biodegradable parts of industry and municipal solid waste (MSW) (Long et al., 2013). Biomass as a sustainable energy when compared with fossil fuels which are caused environment problems such as surface or ground water contamination, air pollution problems with the release of CH4(greenhouse gas), NH3, H2S, amides, volatile organic acids, ether and other compounds (Xianbin Xiao et al., 2010). It contains energy stored in organic compounds which are converted into the potential bioenergy by biomass conversion processes. Both biochemical conversion and thermo-chemical conversion are utilized to transform biomass in to biofuel. The components of biomass are cellulose, hemicellulose and lignin and extractives are found to be the major components of biomass (Kirubakaranet al., 2009)

Generally, oil palm plantations in Thailand have many applications, such as cooking oil, crude oil palm, etc. Palm oil is an interesting biomass to utilize in biofuel products. It is production of the major industries in the south of Thailand. Oil from palm oil can be mixed with diesel oil become to biodiesel. When oil was extracted from the fruits, it also produced the large amount of residues. The palm oil mill industries can produce the residues around 663310 tons/yr (Prasertsan and Prasertsan, 1996). The byproduct generation in the palm oil industries is shown in Figure 2.1 (Hosseini and Wahid, 2014). Empty fruit bunches and shells are the residues from palm oil mil industry. In the industry section, it is used for solid fuel in some factories to burn in furnaces

Figure 2.1 The residues of palm oil mill industries.

2.2 Composition of Biomass

2.2.1 Structure of biomass

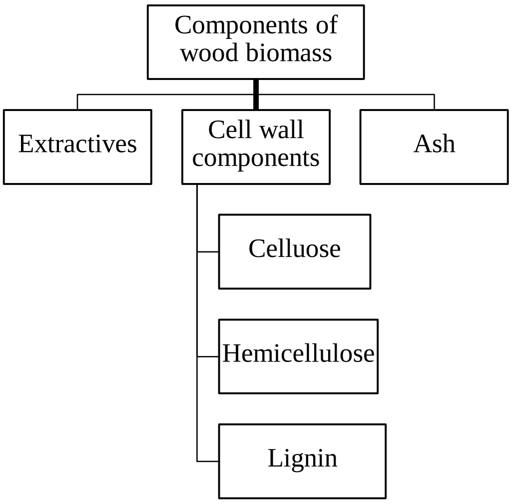

Figure 2.2 Major constituents of a woody biomass(Basu, 2013)

Biomass is a complex mixture of organic materials, such as carbohydrates, fats, and proteins, covering small amounts of minerals, for instance, sodium, phosphorus, and iron (Basu, 2013). Biomass contains various amounts of cellulose, hemicellulose, lignin which the combination of these is called lignocellulose and small amounts of other organics (Abbasi and Abbasi, 2010). In Figure 2.1 showed the major constituents of woody biomass. Cellulose is the major component of lignocellulose materials which is crystalline structure and non-starch, fibrous part of plant materials. It amount varies from 33% for most plant and 90wt % in cotton. Cellulose is a long chain polymer with a high degree of polymerization around 10000. This structure is high strength and is highly insoluble (Basu P., 2010) Followed by hemicelluloses have a random, amorphous structure with slight strength. It is branch chain structure and lower degree of polymerization around 100-200. Hemicellulose leads to yield more gases and small of tar than cellulose(Milne, T.A. and Evans R.J., 1998). Ligninis an aromatic polymer synthesized from phenylporopaniod precursors (Saidur et al., 2011). It is an integral part of the secondary cell walls of plants. Moreover, lignin is the cementing agent for cellulose fibers holding adjacent cells together. It is highly insoluble (Klass, 1998)

2.2.2 Moisture Content

Moisture is the amount of water in the biomass represented as a percentage of the material’s weight, for instance, the moisture content of green wood chip about 40-50%, moisture content of green sawdust about 40-50%, and moisture content of coal for comparison about 6-10% (Sims, R. EH., 2002). When considering thermo-chemical conversion to the biofuel such as combustion, pyrolysis, or gasification, the moisture content of the lignocellulose biomass is an important concern (Gray et al., 1985). The influence of moisture was investigated by pyrolyzing ground samples in a batch fluid bed reactor show the result to increase yield of char, however, in the case of tar formation had been either suppressing or enhancing depend on the pyrolysis temperature and ash content (Acharjee et al., 2011). In case of gasification, a limit amount of moisture there is useful because of the steam generation can enrich the hydrogen content of the product by water gas shift reaction. In spite of advantage in gasification, too much moisture increases the thermo-chemical conversion cost (Singh, 2004). In addition, the losing energy efficiency,take place in combustion zone, is negative impacts of moisture to thermo-chemical process (Fagernäs et al., 2010).

2.2.3 Volatile Matter Content

The volatile matter of a fuel is a condensable and non-condensable vapor released when the fuel is heated at low temperatures. Amounts of volatile elements depend on the heating rate and the temperature which is heated (Basu, 2013). The volatile matter content in biomass varies in the interval of 48-86% and normally the order: HAG > WWB > HAB > HAS > HAR > CB > AB. In addition, the extremely high volatile matter value is characteristic of some WWB, sugar cane bagasse, and paper waste. It may contribute to either air pollution or eutrophication (Vassilev et al., 2014).

2.2.4 Fixed Carbon

Fixed carbon represents the solid carbon in the biomass that remains in the char in the pyrolysis process after devolatilization. Fixed carbon comprises elemental carbon in the original fuel, any carbonaceous residue formed while heating. As FC depends on the amount of VM, it is not determined directly. Fixedcarbon in a fuel is determined from the following equation, where M, VM, and ASH represent for moisture, volatile matter and ash, respectively.

$$FC=1-M-VM-ASH \qquad (2.1)$$

For gasification analysis, FC is a significant parameter, because in gasifiers, the conversion of fixed carbon into gases determines the rate gasification and its yield. This conversion reaction, being the slowest, is used to determine the size of the gasifier (Basu, 2013).

2.2.5 Ash Content

Ash, the solid residue, is the chemical breakdown of biomass fuel produced by complete combustion in air. Ash, includes amount of inorganic material (0.1–46wt%, mean 7%, on dry basis), which consists of various minor and accessory mineral species and poorly crystallized mineralogist from various mineral groups and classes, such as silica, aluminum, iron, and small calcium(Basu, 2013), as well as some amorphous inorganic phases. The ash content of biomass affects both the handling and processing costs of the overall, biomass energy conversion cost. In a thermo-chemical conversion process, the chemical composition of the ash can present significant operational problems. This is especially true for combustion processes, where the ash can react to form a slag, a liquid phase formed at elevated temperatures, which can reduce plant throughput and result in increased operating costs (Vassilev et al., 2013).

2.3 Conversion Technologies of Biomass

Biomass has a great potential as a renewable feedstock for producing various energy forms. Moreover, efficient conversion technologies need to be utilized to convert biomass feedstock into biofuels in order to compete with fossil energy sources. Therefore, selecting suitable approach leads to optimal production (Yılmaz and Selim, 2013). Conversion of biomass can be divided into two main processes technologies (1) thermo-chemical process and (2) biochemical process.

In biochemical processes, biomass molecules are broken down into smaller molecules by bacteria or enzymes. In spite of this process is much slower than thermo-chemical process, it does not desire much external energy. The three principal routes for biochemical process are digestion (anaerobic and aerobic), fermentation, enzymatic or acid hydrolysis.

In thermo-chemical process, the biomass is converted into mixture gases, which are then synthesized into the desired chemicals or used directly. Production of thermal energy is the main driver for this conversion route that has four broad pathways are combustion, pyrolysis, gasification, liquefaction (Basu, 2013).

2.3.1 Gasification

Gasification is a technology normally used nowadays for extracting energy from biomass. Figure 2.2 shows that one of the most attractive features of gasification is it flexibility of application, including thermal power generation, hydrogen production, synthesis of fuels, and chemical feedstock. Many kinds of biomass gasification processes have been developed treating different materials and producing a mix of energy or chemical product (Brown R.C., 2011).

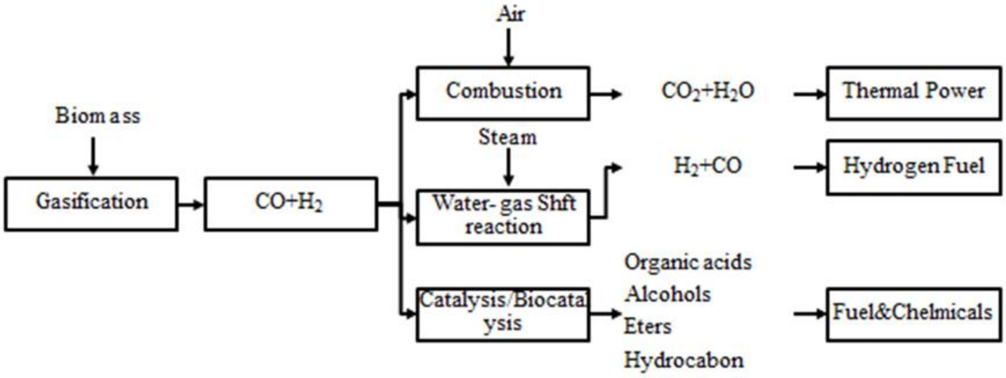

Figure 2.3 Gasification offers several options for processing biomass into power, chemicals, and fuels.

In addition, gasification is a process of the thermochemical transformation of carbonaceous solid or liquid fuels into a gaseous fuel or chemical feed stock through many chemical reactions listed in Table 2.1 with a controlled amount of air and high temperatures. The gaseous product is an energy rich mixture of H_2, CO, CO_2, and small amounts of CH_4, C_2H_4 and other impurities, such as nitrogen, sulfur, alkali compounds and tars. Air gasification results to a product with low to medium heating value (4–7 MJ/Nm^3), while gasification with oxygen or steam lends to a product with medium heating value (10–14 MJ/Nm^3). When steam is used, more hydrogen is produced from the reaction of methane reforming which leads to a product stream with higher heating value. Nevertheless, gasification with steam requires higher operating temperatures for the vaporization of water making it a more expensive alternative. Therefore, the use of a mixture of air/steam with a variable inlet ratio is useful in order to better exploit the benefits of each fluidizing gas (Skoulou et al., 2008).

Table 2.1 Main chemical reactions of biomass gasification (Sutton et al., 2001)

Reaction	Reaction	ΔH298, MJ mol−1
1. Partial oxidation of solid carbon	$C+0.5O_2=CO$	−111
2. Complete oxidation of solid carbon	$CO+O_2=CO_2$	+402
3. Oxidation of hydrogen	$H_2+0.5O_2=H_2O$	−242
4. Water gas reaction	$C+H_2O=CO+H_2$	+131
5. Boudouard reaction	$C+CO_2=2CO$	+172
6. Methanation reaction	$C+2H_2=CH_4$	−75
7. Methanation reaction	$CO+3H_2=CH_4+H_2O$	−206
8.Methanation reaction	$CO_2+4H_2=CH_4+2H_2O$	−165
9. Water gas shift reaction	$CO+H_2O=CO_2+H_2$	−41

2.3.2 Gasification principles

Although gasification and combustion are closely related thermo-chemical processes, there is an important difference between them. Gasification packs energy into chemical bonds in the product gas; combustion breaks those bond to release the energy.In combustion, excess air is supplied and fuel particles are retained in the reactor for sufficient residence time for complete oxidation to incombustible flue gases (H_2O and CO_2), while gasification, substoichiometric air just sufficient to gasify the feed into combustible gases issupplied (Natarajan et al., 1998). According to Basu(2013), the basic principles of biomass gasification processes, are comprised of the following steps:

- Preheating and Drying
- Thermal decomposition or pyrolysis
- Partial combustion of some gases, vapors, and char
- Gasification of decomposition products

Preheating and Drying

The heating rate and drying is the first step of gasification, that transforms biomass moisture content, which contains fresh wood in the range from 30-60%. The moisture content in biomass is reduced by energy from gasifier to vaporize water, and that is not recoverable. The process of heating and drying begins on the outside surface of the biomass particle and then progresses toward the center. Drying takes place at temperature around 100-200°C with decreasing the moisture content of the biomass to less than 10-15%.

Thermal decomposition or pyrolysis

In this step, the immediate thermal decomposition also known as pyrolysis of biomass is carried out in the absence of oxygen or air. It converts biomass to liquid tar, solid coal char, and hydrocarbon gas. Cellulose generally produces very little primary char, while lignin and hemicellulose components produce higher char yields (Reed T.B., 1981). Pyrolysis products can be condensed at sufficiently low temperature. This process becomes progressively more rapid and complete as temperature 400-500°C (Brown R.C., 2011).

Combustion of some gases, vapors, and chars

Most gasification reactions are endothermic. To provide the required heat of reaction as well as that required for heating, drying, and pyrolysis, a certain amount of exothermic combustion reaction is allow in a gasifier. When carbon comes in to contact with oxygen, their extent depends on the temperature. Combustion of biomass produces hot gas at temperature around 800-1000°C.

Gasification of decomposition products

The gasification step that follows pyrolysis relates to chemical reactions among the hydrocarbons in fuel, steam, carbon dioxide, oxygen, and hydrogen in the reactor. The char produced by the pyrolysis of biomass is not only carbon, but also hydrogen and oxygen. Gasification reaction involves several reactions between the char and gasifying agent.

2.3.3 Gasification Technology

The production of energy through biomass gasification has over 100 years of existence. After that the techniques for converting biomass gradually develops into fuel or into energy by means of direct combustion (Pereira, E.G. et al., 2012). In work, developing biomass as fuel, gasification is currently a very active area. Therefore, there are numerous kinds of gasification processes were developed to produced energy. The design of a gasification plant consists of gasifier reactor as well as auxiliary or support equipment. However, a gasifier is the main component of gasification plant owing to be responsible for keeping syngas production as stable as possible (Ruiz et al., 2013).

2.3.4 Types of Gasifier

Most gasifiers are designed as steady-flow processes rather than batch operations. The flow of feedstock through a reactor and mixing it with air and oxygen (for partial oxidation gasifiers), or with the heat carrier (for indirectly heated gasifiers), can be accomplished in many ways (Brown, R.C., 2011). Gasifiers are categorized mostly on the basis of their gas-solid contacting mode and gasifying medium. One gasifier type is not necessarily suitable for the full range of gasifier capacities, but there is an appropriate range of utilization for each. Figure 2.4 shows the classification of gasifiers.

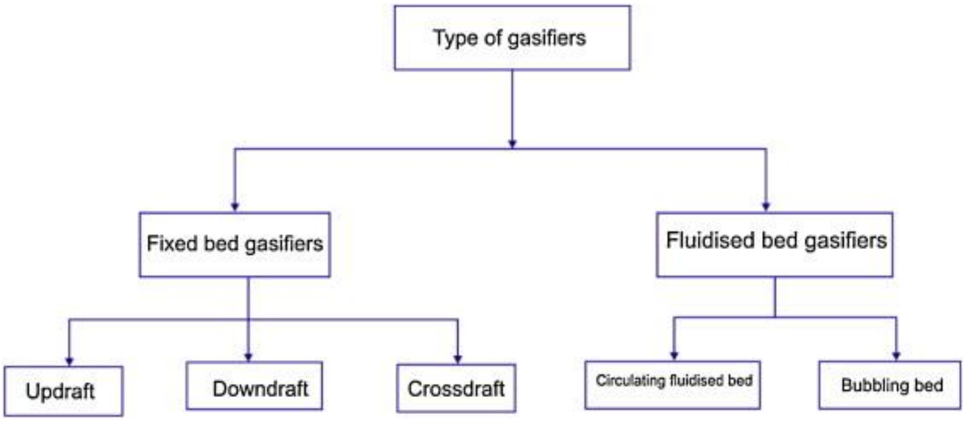

Figure 2.4 Classification of gasifiers

2.3.4.1 Fixed Bed Gasifiers

Fixed bed gasifiers are the oldest types of gasifier and have been developed for small scale application. Fixed bed gasifier also called Moving bed reactor because the fuel is support on the grate and moves down in the gasifier as a plug. There are three main types of fixed bed below that are shown in Figure 2.5.

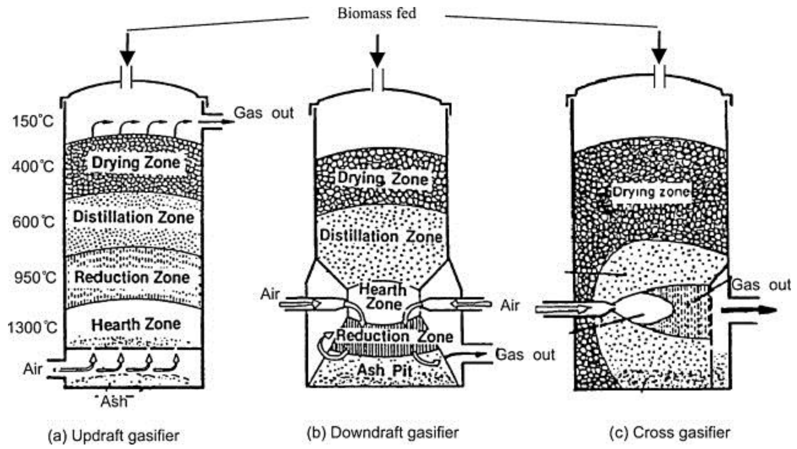

Figure 2.5 Fixed bed gasifiers (Panwar et al., 2012).

Updraft Gasifiers

Updraft gasifiers are the oldest and simplest of all designs. The biomass material slowly moves to enter the top of an updraft gasifier into the lock hopper. As it moves in counter flow to air or oxygen, it passes through stages of drying, devolatilizing, and char combustion. At the bottom of the gasifier, unburned char and ash exit a rotating grate at the bottom of the gasifier. Air or oxygen enter the bottom of the gasifier are reacted with char in the combustion zone to form CO, CO_2, and H2O at temperatures up to 1200^{o}C (Brown, R.C., 2011). The counter flow design of the updraft gasifier produced large amount of tars in the product gas, which are the big problem for sticking to pipes and to the heat exchanger, suspending continuous operation.

Downdraft Gasifiers

In a downdraft gasifier, the biomass material enters the top of the gasifier and flows downwards to the bottom. The reaction regions are different from those for updraft gasifiers. Steam and oxygen, or air is fed into a lower section of the gasifier with biomass. The pyrolysis and combustion products flow downward. From then on both gases and the solids (char and ash) move down in parallel streams though the reactor. Due to generated gas between pyrolysis may be burned in the gasification extent Therefore, the heat energy is provided by the combustion zone. The advantage of downdraft gasification is that volatiles released during gradual heating of the biomass must pass through at high temperature char combustion zone (800-1200^{o}C) where tars are rapidly and efficiently cracked. The moisture content of biomass for downdraft gasifier must be less than 20% in order to accomplish temperatures high enough to crack tars (Brown, R.C., 2011).

Cross draft Gasifier

Crossdraftgasifier, the load following the ability of the crossdraftgasifier is slightly good owing to the concentrated partial zone that operates at temperatures up to 2000°C. Begin up time (5-10 min) is much faster than that of this type of gasifier such as downdraft and updraft units. Crossdraftgasifier appropriates for low ash fuels such as wood, charcoal, and coke. The effect of higher temperature results in quality of producer gas which is increase amount of gas composition such as high carbon monoxide, and low hydrogen and methane content when dry fuel is investigated (Panwar, Kothari et al., 2012).

Multistage Gasifiers

The improvement of processes for the thermal gasification of biomass has been going on for many years already. One of the main problems has been the presence of tars in the produced gas. Tars damage internal combustion engines, gas turbines and other machinery. Consequently, technology of reduction of the produced tar has been investigated. In the nowadays, the technologies of biomass gasification are developed into increase the tar conversion. Due to the single stage of biomass gasification still produced large amount of tar in producer gas. Development of multistage gasifiers is investigated in (Jaojarueket al., 2011) the Viking gasifier, DTU, Denmark, (Figure 2.6) is the beginning construction of two stage gasification (fixed bed) which produced low tar and dust less than 5 mg/Nm3 and no waste. The principle of two-stage gasification, where the pyrolysis and gasification occurs in two separate reactors the 600°C hot pyrolysis products are partial oxidized by preheated air. As results in a temperature increase to around 1100°C at which the dominate part of the tar will decompose. The produced gas is cooled to 90°C by passing various heat exchangers, delivering heat for the process and district heating. At this temperature, the soot particles are eliminated dry in sample bag house filter (Knoef et al., 2012).

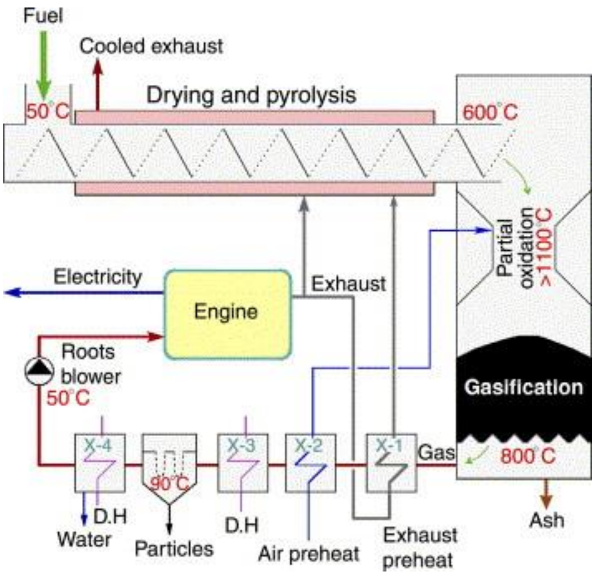

Figure 2.6 The Viking gasifier.

The single-stage gasifier is a down-fired system that contains a single injector concern about tar generation. Therefore, the two-stage gasifier which selected for study an up flow design with multiple air injection. The two-stage gasifier divides into two sections connected by a diffuser. Each section can have two or four feed injectors. The primary stage is supposed to be a slagging combustor used to remove a high fraction of the ash as slag and to provide hot gases to the second stage.

Typically, two-stage gasifiers are operated with the first stage as a combustion zone that provides the heat that was necessary to drive endothermic gasification reactions in the reducing second stage. The first stage is operated close to stoichiometry, while the remaining feedstock fuel is introduced in the second stage with very little or absent oxidant. In the two-stage model, staged fuel injection is easily controlled. Repetitions proceed in the first stage between the particle burnout, equilibrium, and heat transfer models until the exit temperature has converged (Figure 2.7).

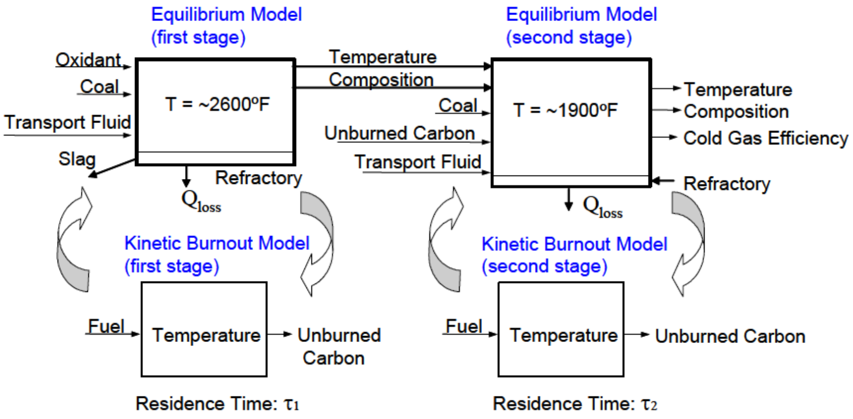

Figure 2.7 Schematic for the two-stage, process flow sheet gasifier model.

2.4 Tar removal technology

Tar is complex mixtures of condensable hydrocarbons that include single ring to 5-ring aromatic compounds along with other oxygen-containing hydrocarbons and complex PAH (McKendry, 2002b). Tar is a biggest problem in both gasification and pyrolysis. It is a thick, black, highly viscous liquid that condenses in the low temperature zone of the gasifier, blocking the gas passage and leading to system disruption. Tar is highly undesirable, as it can create the following problem.

- Condensation and subsequent plugging of downstream equipment
- Formation of tar aerosols
- Polymerization into more complex structures

There are two main methods for tar reduction depending on the location where the tar is removed. Primary process carries out inside the gasifier and secondary process carries out in the hot cleaning of the gas generated. The tar formation depends on several factors i.e. temperature, gasifying agent, Equivalent ratio etc. (Juárezet al., 2013)

CHAPTER 3

METHODOLOGY

This study focused on the air distribution in the gasification reaction in order to improve the quality of gas and tar reduction in the producer gas. Multi-stage air gasification was used in this experiment with palm kernel shell as the feedstock.

3.1 Raw material characterization and preparation

This experimental feedstock is palm kernel shell (Figure 3.1) which is supported by the Hybrid Energy Co., Ltd. The drying palm kernel shell is dried by sun light for controlling moisture content below than 15%. Its size is approximately 1-1.5 cm. The results of proximate, ultimate analysis and heating value of palm kernel shell are shown in Table 3.1.

Figure 3.1 Palm kernel shell

Table 3.1 Standard method for biomass compositional analysis

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

3.1.1 Moisture content

The oven-drying method following the ASTM standard D4442 – 07at temperature of 105°C for 24 hours is used to determine the moisture content in the palm kernel shells.

3.1.2 Ultimate analysis

Ultimate analysis is used to determine the elemental composition of the palm kernel shells. These are shown the percent weight of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) in the fuel while the oxygen content is calculated by difference. The percentages of element are significant to calculate the theoretical air requires for completed combustion. The OAE analyzer (Thermo Finnegan model Flash EA^{TM} 1112) is used to analyze the total organic carbon as shown in Figure 3.2.

Figure 3.2 OAE analyzer.

3.1.3 Proximate analysis

Figure 3.3 shows the proximate analysis for the total composition of the palm kernel shell in terms of moisture content (M), volatile matter (VM), fixed carbon (FC), and ash (ASH). This experiment used thermal gravimetric analysis (Perkin Elmer, Pylis 1 model) in order to measure the weight loss of a material as a function of temperature.

Figure 3.3 TGA analyzer.

3.1.4 Calorific value or High heating value.

The calorific value or energy content of palm kernel shells is defined as the heat released during combustion, as shown in Figure 3.4. In other word, the energy of chemical bond can be converted into heat energy. The calorific value of biomass can be measured by a bomb calorimeter as follow ASTM standard D-2015.

Figure 3.4 Bomb calorimeter.

3.2 Gasification system

3.2.1 Three stage downdraft air gasifier

The experiments were performed by a downdraft gasifier with three stages of air supply.The structure of the gasifier consisted of the downdraft gasifier was designed and constructed by the Thai Steam Service and Supply Co., Ltd. (Bangkok, Thailand). A schematic of the gasification system can be seen in Figure 3.4. The important parts of gasification system are the gasifier, the cleaning system (cyclone, bag house filter), heat exchanger, blower, suction blower, and flare. The gasifier was a cylindrical reactor with 100 mm refectory coating wall thickness and had an internal diameter of 150 mm. The total height of the gasifier was 2100 mm with divided into three parts; 600 for hopper, 1200 mm for gasification process and 300 mm for ash pit. In order to perform the uniform air distribution in the oxidation zone, so there are three-air stages supply entered from the side of the gasifier through different height of gasifier as showed in Figure 3.5. The distance from the grate to the first, second and third air stages are 300 mm, 600 mm and 900 mm, respectively. Each air stage supply included three nozzles are installed around gasifier. At the bottom of gasifier, the agitator grate was attached for the ash separator. Blower was used blown into gasifier as well as suction blower to drain flue gas to burn at the flare.

There are four zones in the gasifier. The drying zone is the first step of gasification that takes place in the upper part of the gasifier. The palm kernel shells are dried to reduce the moisture content (Basu P, 2010). Next zone, the devolatilized gases are partially produced by the thermal decomposition without oxygen that know as pyrolysis reaction. The temperature takes place at between 150 - 400°C and produces char and tar. In order to decrease the tar formation in the produced gas, the secondary and tertiary stages of air injection are supplied in gasifier. Reduction zone is below the combustion zone. Heat transfer from oxidation reaction will help reduction reaction can produce gas. The combustion zone generates the heat to transfer to the pyrolysis, drying and reduction zones.

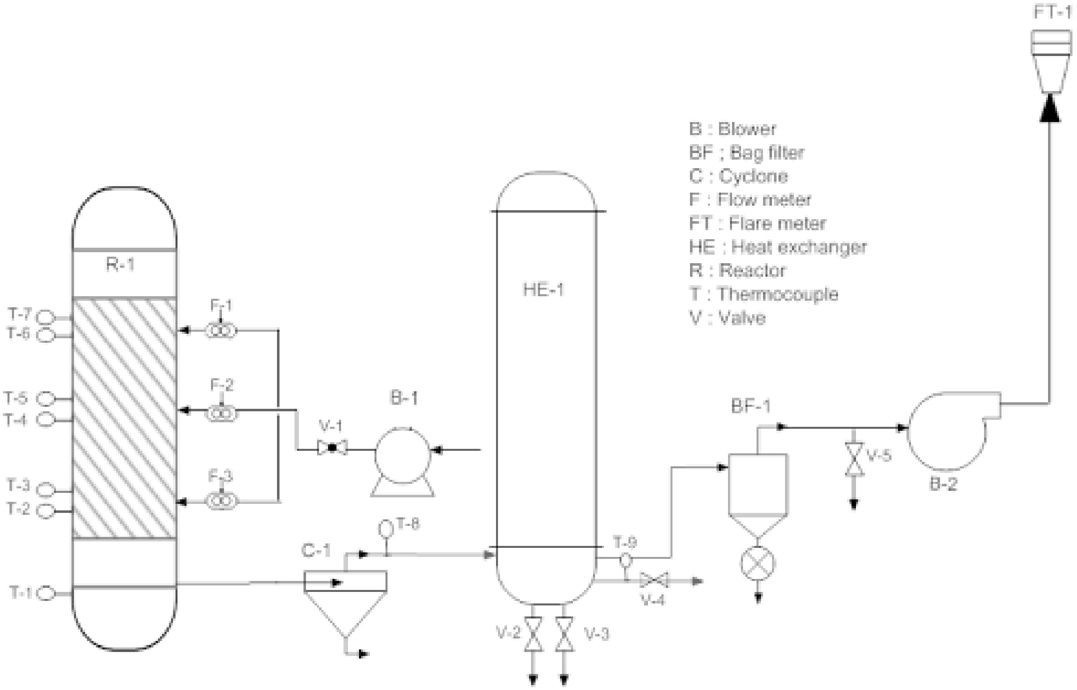

Figure 3.5 Schematic diagram of downdraft gasification system.

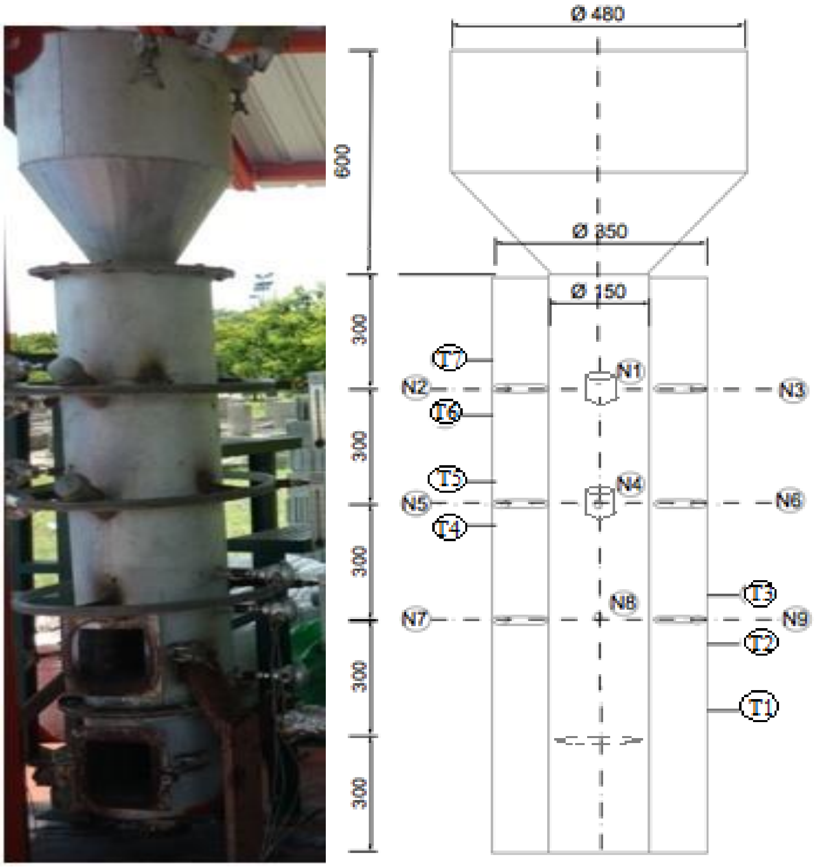

Figure 3.6 Thegasifier

3.2.2 Cleaning equipment

Cyclone: The cyclone was applied for cleaning purposes. It was designed based on the producer gas temperature and separated heavy dust from producer gas. The heavy dust flowed downward at the bottom for dust removal.

Bag house filler: To capture fine dust from the producer gas when it flowed out of the heat exchanger. The fiber glass was used as filter material and could resistant high temperature same as the outlet temperature of heat exchanger.

Heat exchanger: This heat exchanger was only used for producer gas to pass through in shell side. At the beginning, it was used to transfer fluid between ambient air and hot gas. But in order to reduce the pressure drop along pipe, the pipe was bypass air inlet directly to gasifier for reducing pressure drop.

3.2.3Measurement device

Thermocouples: The temperature along the gasifier was measured by K-thermocouples (T1-T7) installed at seven positions. They were projected up to the internal gasifier wall in order to avoid the problem of flowing of the biomass. This temperature reading was represented the actual temperature inside the gasifier. Thermocouple T-8 was installed above cyclone that measured the temperature of produce gas between cyclone and heat exchanger, T-9 measured temperature of produce gas before tar sampling port.

Flow meter: The air flow rateswere measured by three rotameters (F-01, F-02 and F-03).

Data acquisition (DAQ) device: The installed measurement system is shown in Figure 3.6. The data gathering system includes many measuring instruments, data acquisition devices (Yokogawa DC 100), communication devices, and computer. The DAQ program was set to record the temperature every minute thought out the experiment.

Figure 3.7 Data acquisition

Gas bag: The aluminum gas bag (SKC) was used for the collection of producer gas. It can contain 5 liters.

Figure3.8 Gas bag

Vacuum pump: The vacuum pump was used for suction of the producer gas and to collect the tar.

Figure 3.9 Vacuum pump

3.3 Experimental procedure

Figure 3.4 shows the schematic diagram of the gasification system in this experiment. The experimental conditions were operated at atmospheric pressure during all the experimentations. The palm kernel shell was weighted and loaded to the hopper. In each test, the eucalyptus pellet around 1.5 kg was put to burn palm kernel shell faster. After loading the fuels, the top cover was closed. To start up the experiment, gasifier was ignited by LPG burner at the port, while a suction blower was simultaneously started to suck a flame for helping to burn the raw material. Therefore, the flame went down the gasifier from top to bottom. Afterwards, a force draft blower introduced the ambient air into the gasifier. The total air flow values were obtained through flow measurement for each stage and controlled by valve before air inlet tube. The temperature was monitored by data logger which communicated to computer for recording. A steady-state has been reached in an experiment when the temperature in oxidation zone and reduction zone are constant. When the temperature in gasifier is steady-stage at each test, the gas sampling is collected in a gas bag and analyze by off-line micro-GC.

3.4 Experimental Conditions

In order to study the effect of the multi-stage air gasification on gas compositions and tar content in the producer gas, the experiment was set up as follows. Experiments were based on different air stages and different air flow rates. There were nine experiments performed in this work. In an experiments, the total air flow rate was adjust using ball valve which was installed at the inlet pipe; 142 and 198 L/min for single air stage, 293, 359 and 415 for double air stages and 359, 415, 453 and 562 L/min for triple air stages. In addition, air flow rate each stage was regulated by a using flow meter. Table 3.2 shows the operating conditions for the experiments.

Table 3.2 Gasification operating condition

Stage	No. Run	Air flow rate (L/min)				Feed (kg)
		$Q_{(1st)}$	$Q_{(2nd)}$	$Q_{(3rd)}$	Total air	
1	1	142	0	0	142	17
	2	198	0	0	198	17
2	3	132	151	0	293	22
	4	170	189	0	359	22
	5	189	226	0	415	22
3	6	142	113	104	359	23
	7	142	142	132	415	23
	8	142	170	141	453	23
	9	189	189	184	562	23

3.5 Gas analyses

The producer gas was collected by a vacuum pump that flowed into the gas bag. Afterwards, the gas sample was injected into the column of a micro-gas chromatography with helium as the carrier gas. A micro-GC is used to analyze the volume percentage of CO, CO_2, H_2, and CH_4 while tar sampling is caught by a series of impinger bottles installed at pipes between the cyclone and the heat exchanger. Tar is collected by a series of impinger bottles consisting of six impinger bottles which content isopropanol solvent. The solvent in tar solution has been removed by rotary evaporator. The gas composition was determined by using Agilent Micro-GC Agilent490, as shown in Figure 3.10.

Figure 3.10 Micro-GC Agilent 490

3.6 Tar sampling and equipment

Tar content in the produced gas is sampled by a tar collection unit. It had been applied for this experiment. The tar collection unit comprise of (1) ball valve, (2) impinger bottles, (3) flow meter, (4) vacuum pump, (5) glass connector and (6) filler, as shown in Figure 3.11.It installed after the heat exchanger at the bottom near the outlet pipe. There are two ice boxes which contain the six impinger bottles. Both of the boxes put the ice and salt to keep the temperature around 5˚C.The first five bottles content70 mL of isopropanol asa solvent to capture tar in produced gas but the last bottle is empty. The produced gas is sucked by vacuum pump though the silicon tubes and rotameter. Tar content in produced gas was analyzed by gravimetric method.

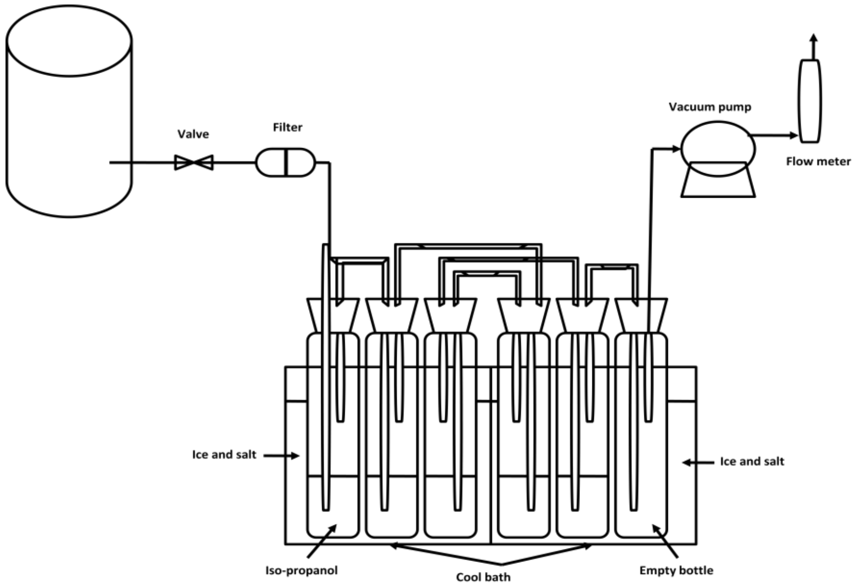

Figure 3.11 Schematic diagram of the tar collection unit.

3.7 Gravimetric tar analysis

The gravimetric analysis is based on the measurement of mass. The quantity of tar can be determined by this method. To determine amount of tar in gas, the isopropanol will be vaporized by the rotary evaporator as shown in Figure 3.12. Thermal energy was used to vaporize the solvent in the solution. The evaporation procedure is started by setting temperature of oil bath at 55˚C and vacuum pressure of 100mbar(Wongayara K., 2011).The flask was weight before pouring the solution. Afterwards, put solution in the flask and evaporated until the isopropanol removed from the solution. After the end of evaporation, the flask with tar was cleaned the outside and dried by oven. Then, the flask was left at room temperature and weight flask with residue for calculated the difference weight.

Figure 3.12 Rotary evaporator

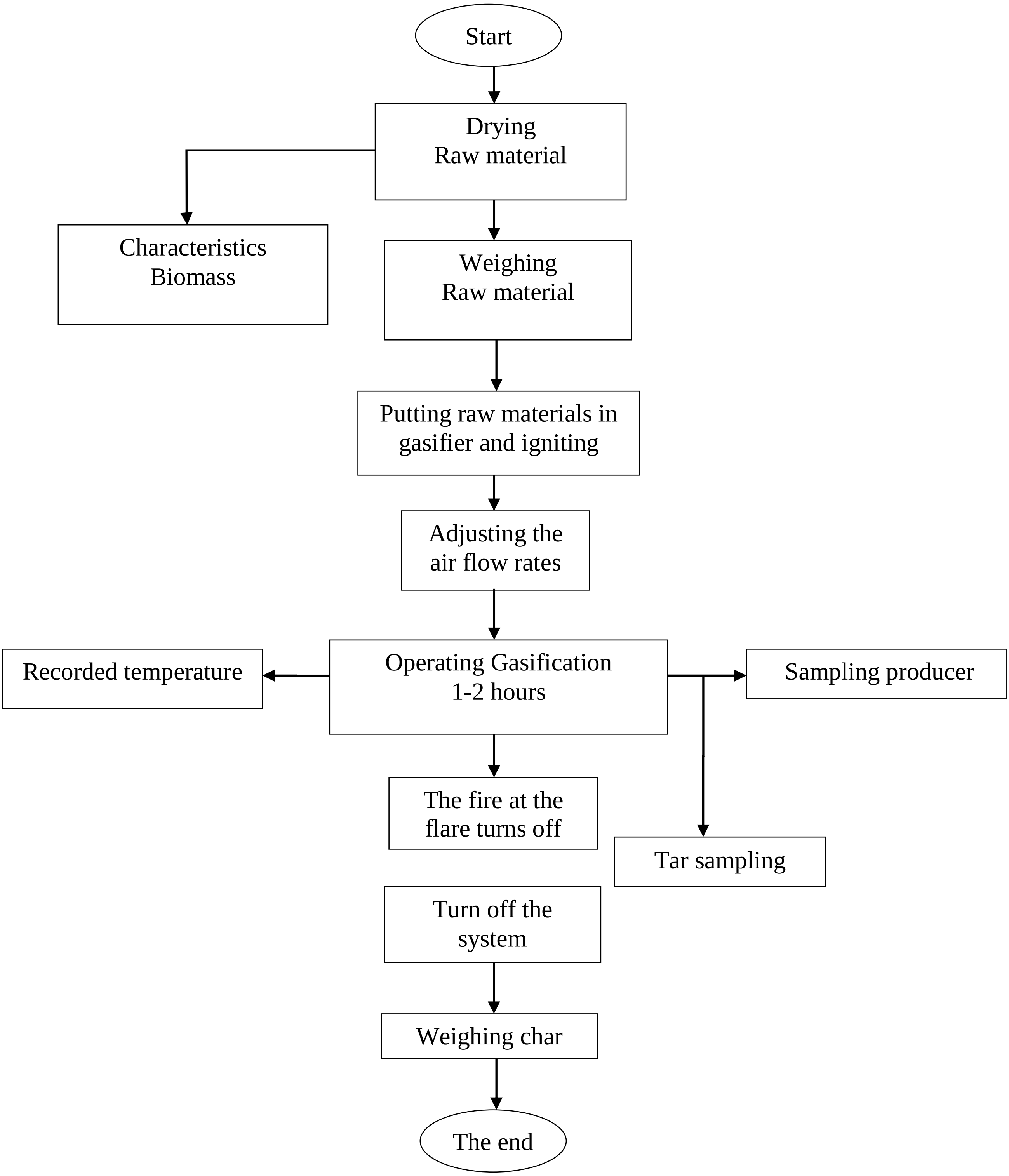

Figure 3.13 Flow chart of gasification procedure

CHAPTER 4

RESULT AND DISCUSSION

This chapter presents result obtained from the investigation of several parameters in multi-stage air gasification system based on 50 kW_{th} thermal that included temperature profile, gas composition, tar content, cold efficiency and hot efficacy. Nine experiments were tested and presented the effect of ER and a multi-stage air supply on gas composition and tar content**.**

4.1 Raw material characteristics

Palm kernel shells were used in this experiment and supplied from the Hybrid Energy Company. It obtained from south of Thailand, which is1-1.5 cm in size. The ultimate and proximate analysis of Palm kernel shell are shown in Table 4.1.The proximate analysis consisted of the percent weigh of fixed carbon, volatile matter, moisture content and ash content. The ultimate analysis consisted of the percent weigh of element such as carbon, hydrogen, nitrogen and oxygen. The high heating value can be measured by bomb calorimeter.

Table 4.1 Characteristics of palm kernel shell.

Proximate Analysis (as received)	
Volatile matter	74.8
Fixed carbon	13.5
Ash	5.0
Moisture	6.7
Ultimate Analysis (wt%, by daf.)	
C	51.79
H	5.68
N	0.42
O (diff.)	42.11
HHV (MJ/kg)	18.5
LHV (MJ/kg)	17.31

4.2 An overview of experimental results

The equivalence ratio (ER) is defined as the ratio of the actual air supply to the stoichiometric air required for complete combustion on a dry ash-free basis. The ER represents the oxygen quantity feed into the gasifier that resulted in the gasifier temperature and it also affects the gas compositions and tar cracking.ER was changed by variation of air flowrate during the experimental gasification The ER effect for several parameters was investigate. The air was introduced and varied into the gasifier. There are two air flow rates at single air stage, three air flow rates at double air stages and four air flow rates at triple air stages.Table 4.1presentsthe results from the calculation of the effect in terms of air flow rate on the equivalence ratio (ER).

Table 4.2 Equivalence ratio with the air flow rate

Stage	Air flow rate (L/min)	ER
1	**142**	**0.11**
	198	**0.15**
2	**293**	**0.19**
	359	**0.25**
	415	**0.27**
3	**359**	**0.26**
	415	**0.29**
	453	**0.32**
	562	**0.35**

4.3 Temperature Profile

Temperature is one significant factor on the gasification process, because the gasification reaction needs high temperatures to the produce producer gas. The high temperature can increase gas production and reduce tar content. At multi-air stage, we can get higher temperature at oxidation zone. To support energy necessary for drying, pyrolysis and reduction reactions, which is an endothermic reaction. Therefore, exothermic reaction is a significant reaction to provide and transfer heat to the upper part (pyrolysis zone and drying zone) and lower part (reduction zone) of the gasifier.

For the experimental testing, the temperature along the gasifier was investigated and measured at the internal wall of the gasifier using thermocouples. Thermocouples T1, T2 and

T3 were settledat third air stage; T4 and T5 were settled at secondary stageair and T6 and T7 were settledat first air stage. Thermocouple T8 was settled on the cyclone tomeasure the producer gas temperature and Thermocouple T9 was settled on the tar sampling pipe. In addition, temperature was monitored and recorded by data logger DC100. In fact, temperature value in this experiment showed a representative value of temperature inside gasifier because thermocouples (T1-T7) were installed at the internal gasifier wall, in order to avoid the problem of raw material flows downward to the bottom.Therefore, temperature profiles may beshowed lower than actual temperature. The main proposes of multi-air stage supply is to improve temperature at oxidation zone, reduction zoneand cracking tar contentin producer gas(Raman et al., 2013).

4.3.1 Temperature profile of the single air stage supply

This experiment investigated the effect of ER on the temperature profile inside the gasifier.ER atsingle stage can be varied into two values, 0.11 and 0.15. The temperature profilesof single air stage supply wereillustrated in Figure 4.1 and Figure 4.2. In single air stage, the air was supplied via three nozzleslocated30 cm above the grate. The result found that T2 can be indicated as the combustion zone due to the highest temperature at this zone. At ER0.11 and 0.15, the combustion temperatures are 437 °C and 551 °C, respectively. It can be explainedthat when ER was increased, the temperature also increased due to bigger amount of oxygen introduced into gasifier. The reduction zone, which is locatedbelow the combustion zone,can be seenatT1, because the temperature was lower than combustion temperature due to the endothermic reaction. In addition, the position at T3 should be pyrolysis zone and above pyrolysis zone was drying zone. The temperature dropped at T3 is causes by limitedair to generate oxidation reaction at start up process. The T3 temperature profile'swas high at the endbecause palm kernel shell still burnt with air supply at the bottom and then slight decrease due to depleted fuel (Bhattacharyaet al., 2001).

At the single air stage operation, the temperature of drying, pyrolysis and gasification zone were low because these temperatures depended on the heat from the combustion zone, which is not high due to insufficient air supply. It was due to the high pressure drop along pipe in single air stage, so the air flowrate was produced a maximum 200 L/min. However, temperature record was not actual value, it only represented the temperature inside gasifier because the thermocouples were measured on internal gasifier wall. Therefore, the measurements were used only to verify the moment when the gasifier temperature reached it steady stage operation.

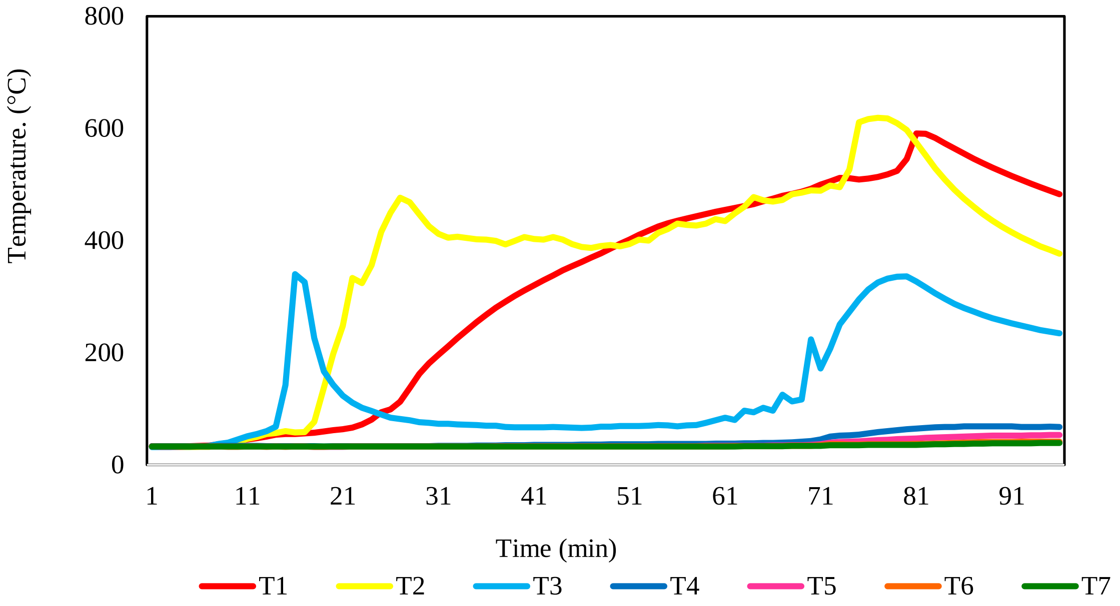

Figure 4.1 Temperature profiles during gasification of 1 stage air supply at ER 0.11

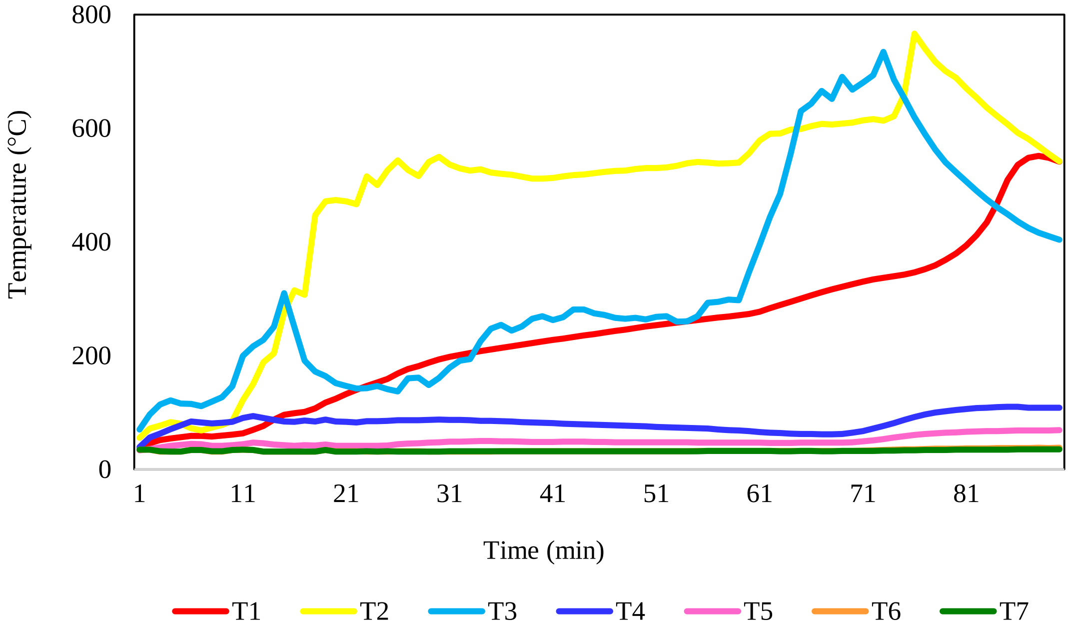

Figure 4.2 Temperature profiles during gasification of 1 stage air supply at ER 0.15

4.3.2 Temperature profile of double air stage supply

This study investigated the effect of the double stage air supply on the temperature profile of the gasifier. The purpose of the double supply air stage in the gasifier was to improve air distribution and temperature in the combustion zone. It has already studied at the Asian Institute of Technology, Thailand (Devi et al., 2003). The temperature profile at the ER 0.19, 0.25, and 0.27 are shown in Figures 4.3, 4.4 and 4.5, respectively. The first air stage and second air stage were located at 60 cm and 30 cm above the grate. Six nozzles were installed at different angles around gasifier for air distribution. Figures 4.3- 4.5 showed that when the first air stage was applied, the temperature profiles at T4 and T5 slightly increased. Due to the expanded flaming from the bottom gasifier to meet the air supply from the first air stage, then burn char at this zone and to release the heat. Hence, this position can become a new combustion zone.This behavior can reduce tar during the pyrolysis reaction and promote tar cracking in the first combustion zone and cracking again in the second combustion zone (T2 and T3). The pyrolysis zone (T5) produced char and devolatilized compound such as hydrogen (H_2), carbon monoxide (CO_2), methane (CH_4), light hydrocarbon and tar formation. This zone was located above the combustion zone. The location above the pyrolysis zone was the drying zone (T6 and T7). In addition, gasification temperature was also increased by heat from combustion zone when using first air stage and second air stage. Reduction zone may indicate below combustion zone.It can be observed that temperature was improvedin combustion zone at T2 with increasing the ER. At the lowest ER 0.19, the ignition took a long time; it indicated that lower heat transfer characteristics happened in the gasifier bed (Kalliset al., 2013). After 30 minutes, the temperature started to rise up 600°C in combustion zone. Results from this study are in agreement with the study of Galindo et al. which presented the two-stage air supply has directly effected on the performance of temperature in the gasifier.

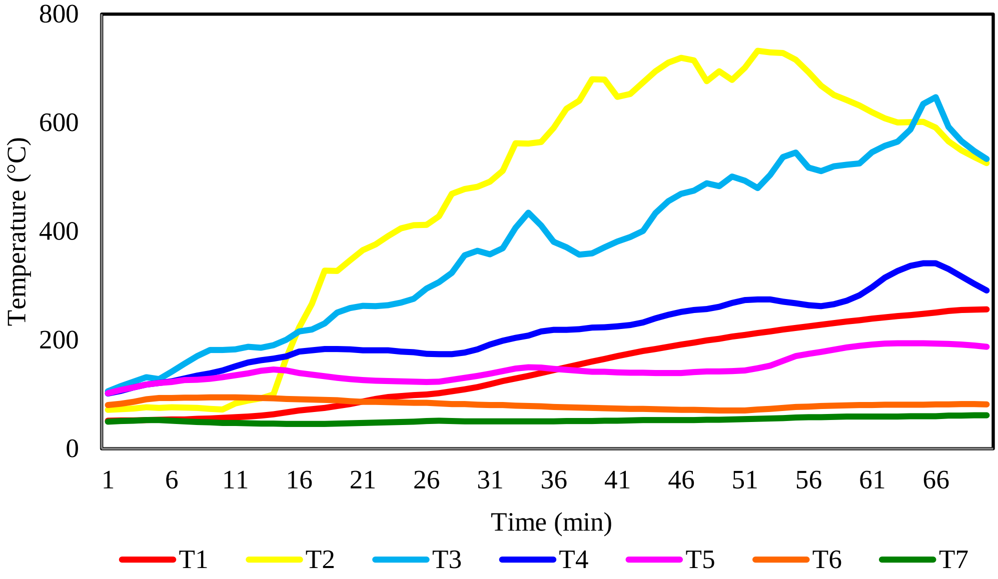

Figure 4.3 Temperature profiles during gasification of 2-stage air supply at ER 0.19

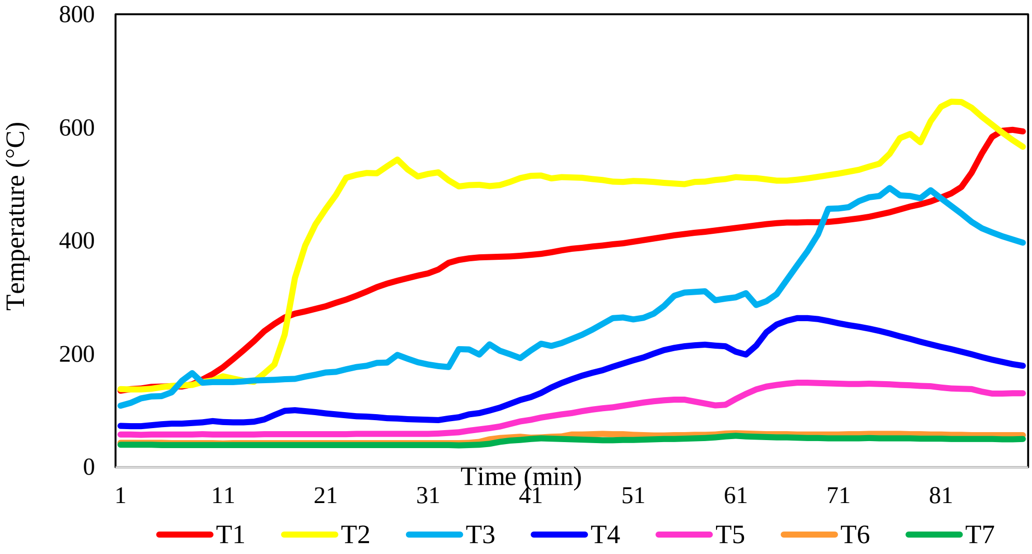

Figure 4.4 Temperature profiles during gasification of 2-stage air supply at ER 0.25

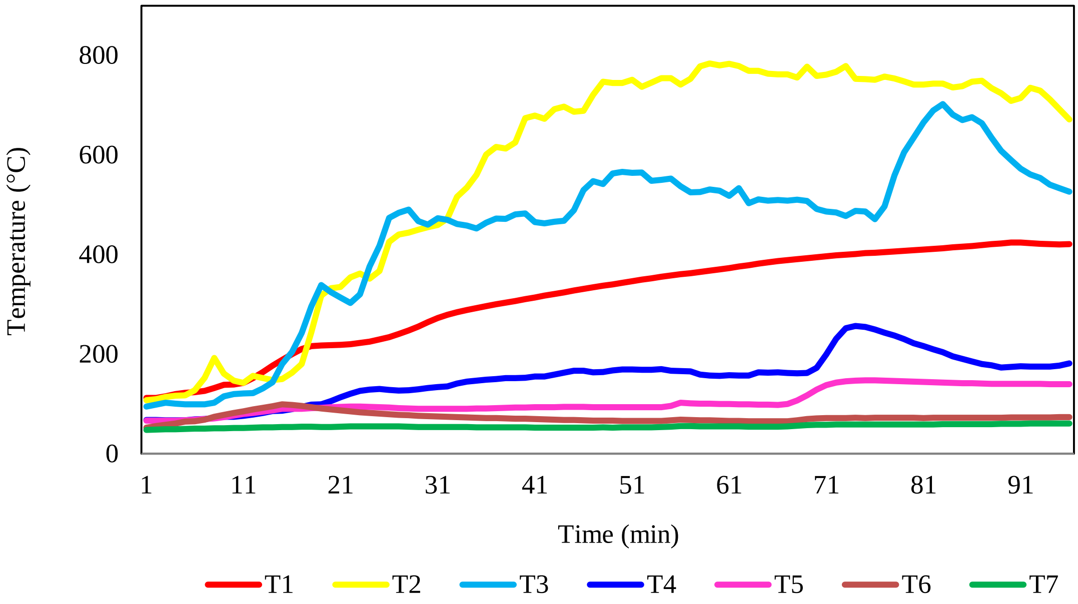

Figure 4.5 Temperature profiles during gasification of 2-stage air supply at ER 0.27

4.3.3 Temperature profile of triple air stage supply

In the case of triple stage air supply, the temperature profiles along gasifier are shown in Figures 4.6, 4.7, 4.8 and 4.9 at the ER 0.26, 0.29, 0.32 and 0.35, respectively. The position of air stage can be defined as first air stage, second air stage and third air stage whichlocated at 90 cm, 60 cm, and 30cm from the grate and also there are 9 nozzles for air distribution inside gasifier. It was found that the additional first air stage supply slightly increasesthe temperaturebelow the first air stage supply. High temperature of T4 can be assumed asthe first combustionzone. Thesecond air stage supplycan be indicated as the second combustion zone (T2) and so did thethird air stage supply. This result was in agreement with Galindo et al., they found that stage position where the air was supplied, the temperature increase in this position and become a new combustion zone (Galindo et al., 2012). Char, volatile gas and tar, produced in pyrolysis zone, were burnt at the first combustion (T4) to produce syngas. Afterward, the product gas, unburned char and tar which left from the first combustion reaction flowed downward contact with the third air stage supply and burntagain at the second combustion zone(T2). This situation could help to obtain a higher temperature inside gasifier. Above the combustion zone should be a pyrolysis zone wherecharcoal and volatile gas produced. The location below combustion zone was partial oxidationzone,the temperature was less than the temperature ofcombustion. Temperature of drying zone in this stage was below 100 °C and at location of T6 and T7.

However, all temperature profiles should show higher temperature values, because the temperature sensor equipments were read in the internal wall of the gasifier to avoid problems when the biomass flowed down to the bottom of gasifier.

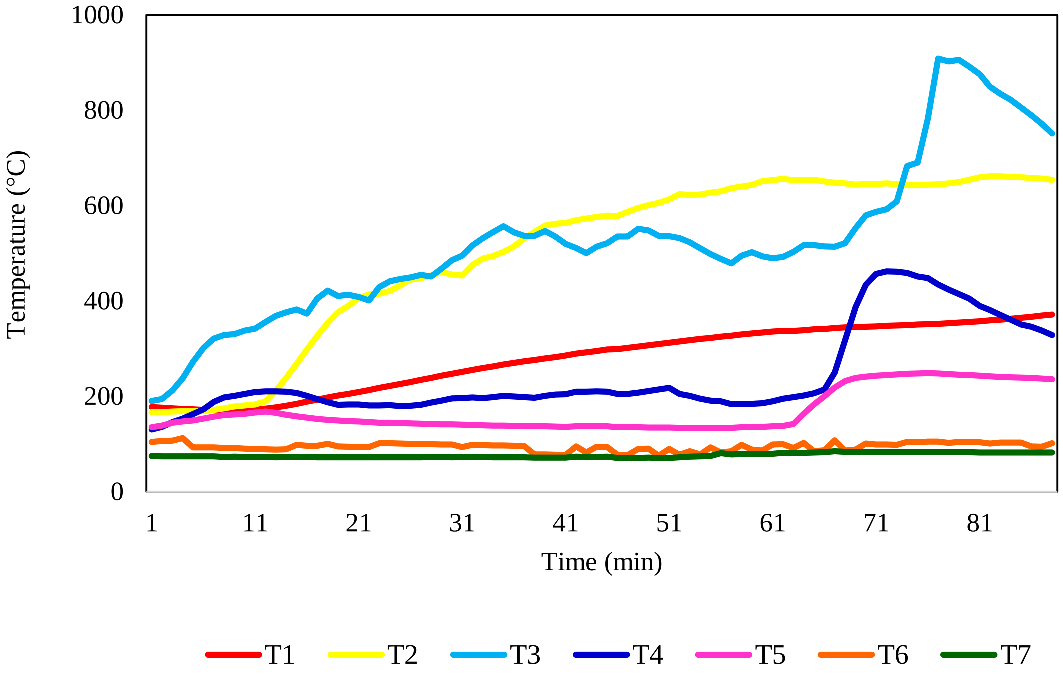

Figure 4.6 Temperature profiles during gasification of 3-stage air supply at ER 0.26

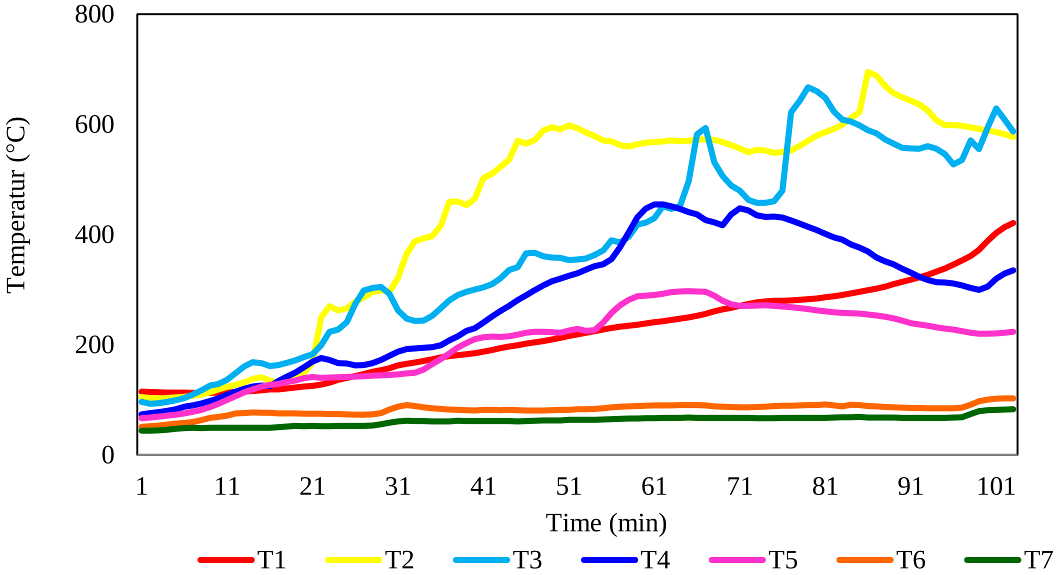

Figure 4.7 Temperature profiles during gasification of 3-stage air supply at ER 0.29

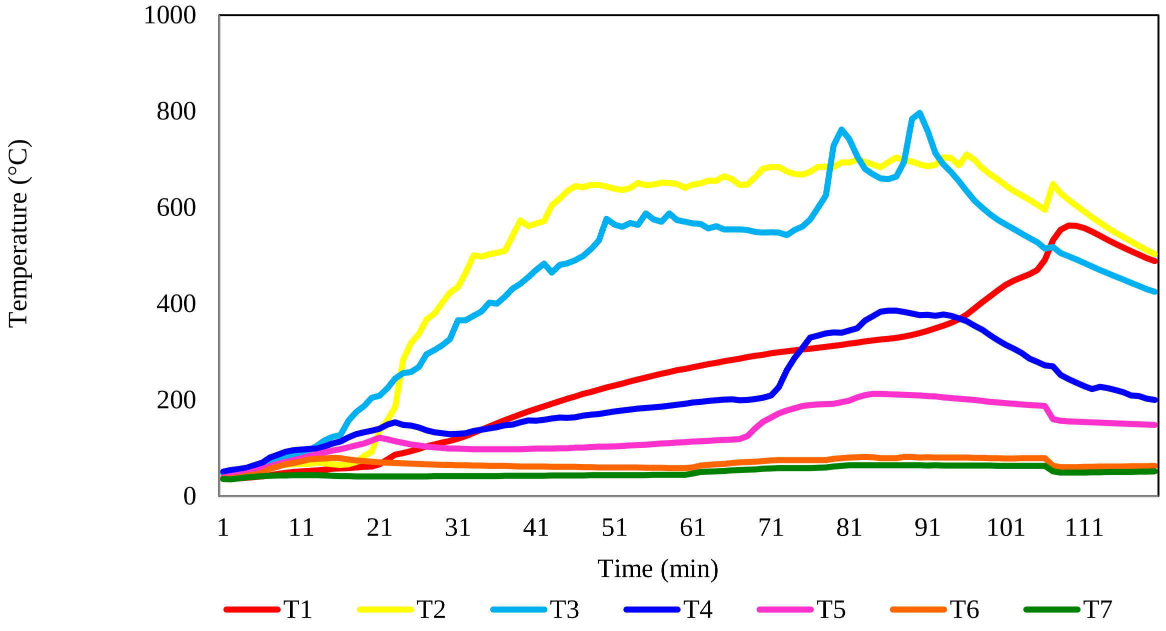

Figure 4.8 Temperature profiles during gasification of 3-stage air supply at ER 0.32

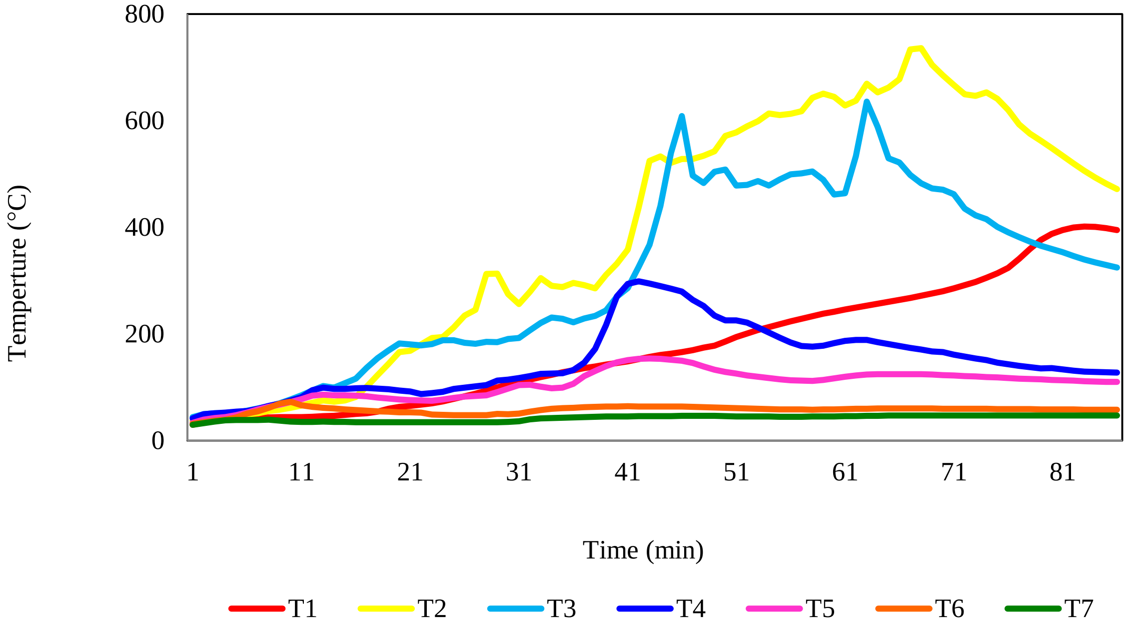

Figure 4.9 Temperature profiles during gasification of 3-stage air supply at ER 0.35

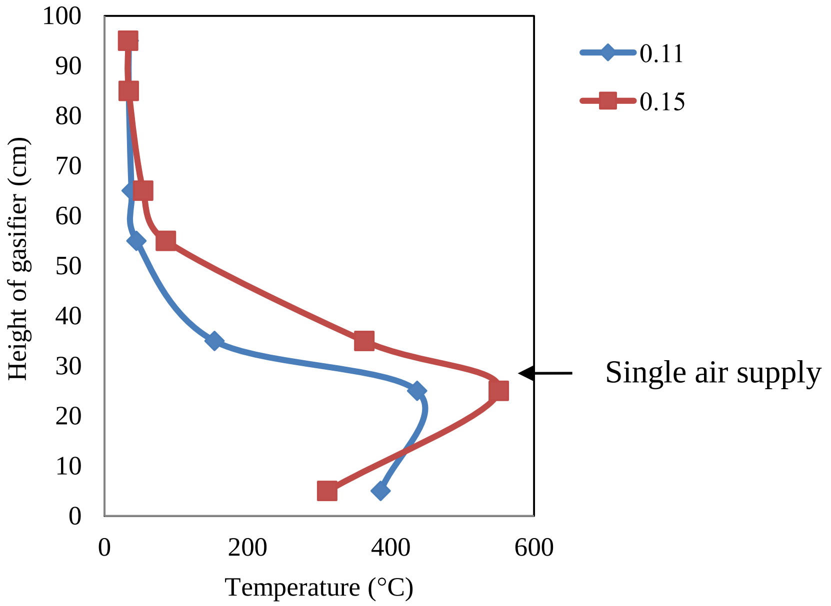

Figure 4.10 Temperature profiles along the height of the gasifier during single stage air supply

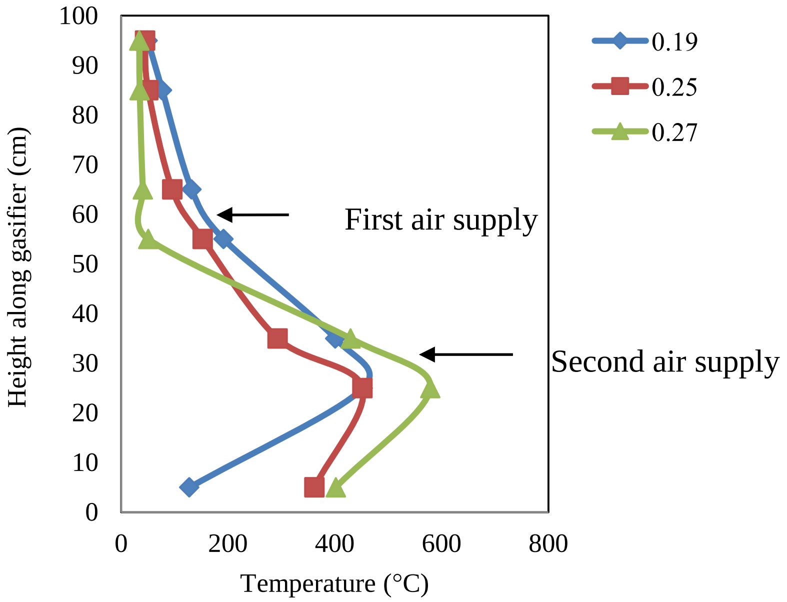

Figure 4.11 Temperature profiles along the height of the gasifier during first and second stage air supply

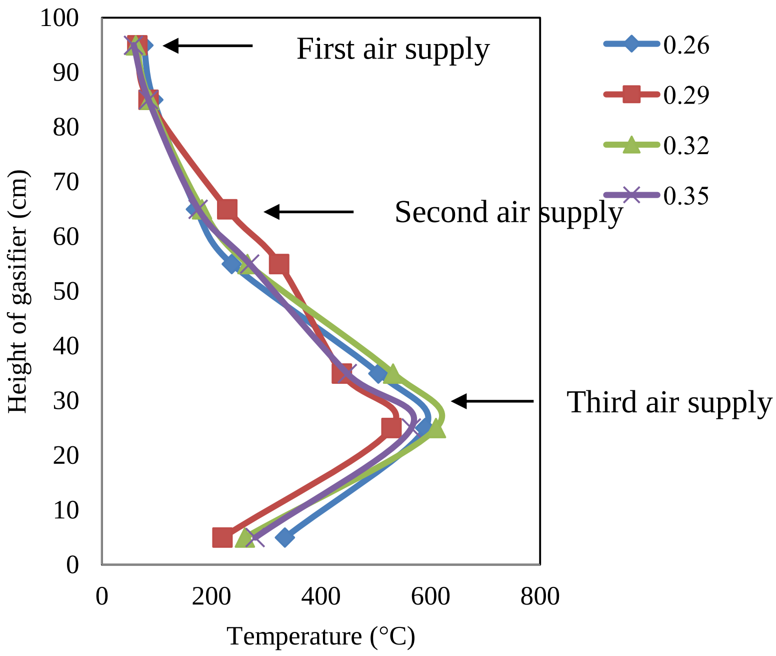

Figure 4.12 Temperature profiles along the height of gasifier (first, second and third stage air supply.

Figures 4.10, 4.11 and 4.12 show the temperature profiles along the height of gasifier in the single, double and triple stage air supply, respectively. These figures present temperature at any point in the gasifier which measured at height of5 cm, 25 cm, 35 cm, 55 cm, 65 cm, 85 cm and 95 cm above the agitator grate.ER of 0.11 and 0.15 were investigatedas single stage of air supply. It can be observed that Figure 4.10, both of the ERshowed that the highest temperature was at the height of 30 cm from grate. Temperature was around 400-550 °Cthat occurred in this zone was wherethe air supplied although the temperaturewas not high enough. It can be explained that the amount of air supplywas not enough for combustion reaction. In addition, the reduction zone was below the combustion zone, temperature in this zone was lower than combustion zone because of endothermic reaction. The location above combustion zone could be indicated as drying zone and pyrolysis zone at higher than 30 cm. Temperature in this zone was low because of low temperature of combustion zone, the driving force for drying, pyrolysis and reduction zone, which produced low heat to be transferred to the upper part.

In the case of double air stage supply were observed that two locations of air supply, ER of 0.19, 0.25 and 0.27 showed the highest temperature zone similar of single air stage. It is the location of 30 cm from the grate.The additional first air stage at location of 60 cm above the grate, it was expected that more air distribution could help increasing temperature of combustion zone in order to extend high temperature zone. According to Figure 4.11, three ER werevaried.The highest temperature of combustion zone was achieved at ER of 0.27. It can be explained thatthe increasing of ER resulted in higher temperature zone in gasifier. The result of temperature profile along the height of gasifier from triple air stage at difference ERs was presented in Figure 4.12.

For triple air stage supply including first air stage, second air stage and third air stage were used to investigate the effect of multi-air stage on temperature in gasifier. It can be observed that triple air stage could increase the temperatureat heightof 25–35 cm above the grate. This area can be indicated as combustion zone. It showed a wide combustion zone and increasesthe temperature of pyrolysis zone and drying zone which can be seen at height of 40 cm above the grate of gasifier. The reduction zone was below the combustion zone. In this zone, unconverted carbon was converted into syngas. Therefore, temperature decreases due to some endothermic reaction production. All the experiments showed that the highest temperature was at the bottom part of gasifier because of the burning biomass flowed downward to the grate.Table 4.2 showed the temperaturefor each stage and ER. Although the temperature measured along the gasifier cannot be considered as actual temperature (the values correspond to internal wall gasifier, it was only investigated the tendency of the temperature profile.

Table 4.3 Temperature for each stage air supply with gasifier

Thermo couple	ER								
	1 Stage		2 Stages			3 Stages			
	0.11	0.15	0.19	0.25	0.27	0.26	0.29	0.32	0.35
T1	386	311	128	362	402	334	220	261	280
T2	437	551	579	452	579	590	529	610	565
T3	154	363	401	0.19	430	505	438	532	448
T4	45	86	192	153	51	237	324	266	270
T5	38	54	132	96	41	172	229	183	176
T6	34	34	77	51	35	94	85	87	85
T7	34	33	50	45	34	76	65	62	58

4.4 Gascomposition

4.4.1 Effect of single stageair supply on gas compositions

Gas compositionof palm kernel shell gasification in three stages air supply were also studied in this experimental testing, the product gas mainly contained CO, H_2, CO_2, and smaller amounts of CH_4, C_2H_2, C_2H_4 and C_2H_6. Different ERs and different stage air supplies were varied. The single stage of air supply in this gasifier was presented by two ERs. Figure 4.13 presents the gas compositionplotwith each gas specieat various ERs of single air stage supply. The results obtained from varying ER between 0.11 and 0.15. It was found thatCO concentration and CH_4 in the product gas was increased from 10.8 vol.% to 12.73 vol.% of CO concentrationwhile CH_4 concentrationvary from 0.7 vol.% to 1.15 vol.%with the increasingof ER from 0.11 to 0.15. The increasing of ER resulted in the increasing of combustion rate which resulted in the decreasing of H_2 concentration from 7.74 vol.% to 6.35 vol.%. In addition, CO_2 concentration was decreased as ERincreased, the trend of CO and CO_2 represent the main carbon conversion during the gasification process. It can be said that the trend of CO_2 almost opposite to CO and obtained the minimum value of 8.38 vol.% at ER of 0.15. Single air stage does not showthe clear trend of gas composition due to there were only two ERs varied.

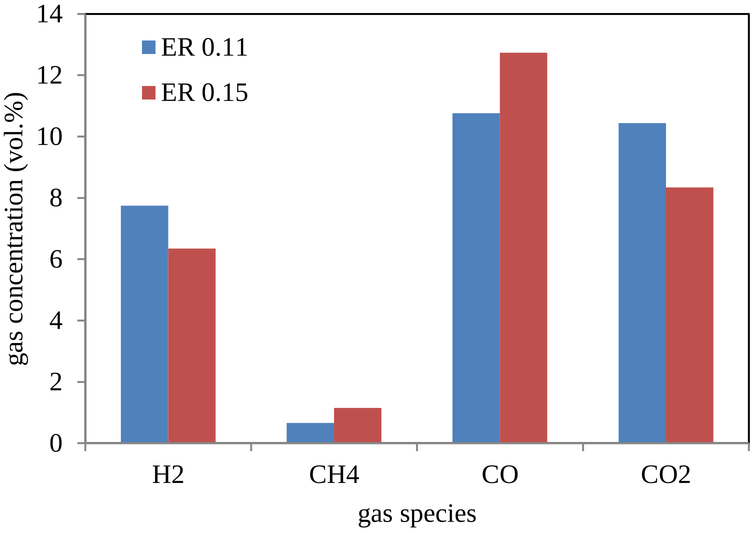

Figure 4.13 Thegas composition in various ERs at single stage air supply.

4.4.2 Effect of double air stage supply on gas compositions

The thermo-chemical reaction of downdraft gasification hadthree processes. The first process is the initial thermo-chemical decomposition of biomass which produced volatile gas, tar and charcoal. The next process involves oxidation reaction and the last process was reduction reaction. In order to improve gas composition therefore double air stage was investigated. According to Figure 4.14, it showed the gas composition of double air stage supplies as well as the effect of the ER on gas composition. There were three ERs which adjusted in this experiment. It comprises the ER of 0.19, 0.25 and 0.27. As the results of gas composition of double air stage, it can be observed that the increasing of ER from0.19 to 0.25, the CO concentration rises from 12.40 vol.% to 15.24 vol.% which was the highest concentration of alland H_2 concentration increase from 8.5 vol.% to 10.33 vol.%. While the increasing of ER from 0.25 to 0.27 resulted in the decreasing of COand H_2 concentration to 14.02 vol.% and 8.97 vol.%, respectively. The same trend also happened for CH_4 and CO_2 concentration.The gas composition of CH_4concentration was slightly increased from 1.3 vol.% to 1.38 vol.% at ER of 0.19 – 0.25 and then decrease to 1.08 vol.% at ER of 0.27. Besides, the CO_2 concentration was increased from 10.57 vol.% to 11.80 vol.% and then decreased to 10.44 vol.%

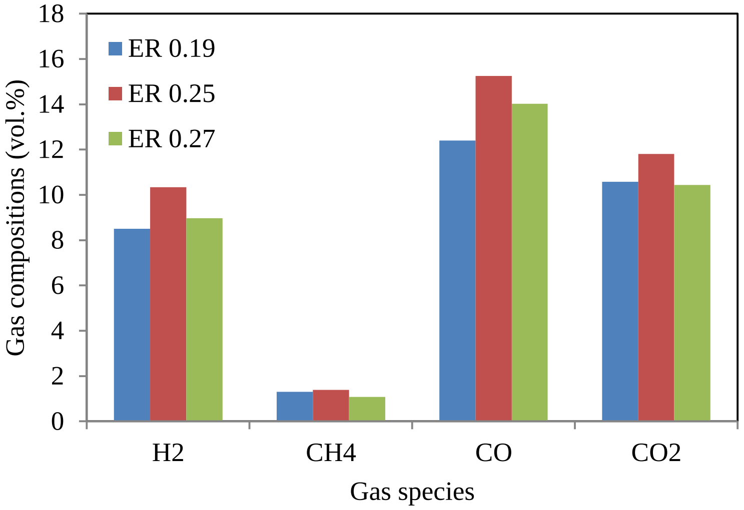

Figure 4.14 The gas composition in various ERs at double stage air supply

4.4.3 Effect of triple air stage supply on gas compositions

The experimental results of triple air stage supply on gas compositionwith the variation of ER are shown in Figure 4.15. Four ERs result in the gas composition shows in this figure. It can be found that at ER of 0.26, CO concentration was the highest concentration of 15.31 vol.% which according to favor the forward reaction of Boudouard reaction ($C+CO_2 \longrightarrow 2CO$). Higher temperature in combustion zone helps reduction reaction to improve gas composition, as suggested by Gou et al. And also highest CH_4 concentration (1.73 vol.%). Afterward, withthe increasing of ER to 0.29, CO concentration decreased to 12.33 vol.% and with the increasing of ER of 0.32 to 0.35, CO concentration decreased from 15.27 vol.% to 12.80 vol.%. The changing of H_2 concentration was similar with CO concentration. The rise in ER from 0.29 to 0.32 was found to increase the H_2 concentration from 6.01 vol.% to 10.14 vol.%. The highest H_2 concentration was 10.14 vol.% at ER of 0.32. The CH_4 concentration decreased from ER of 0.26 to 0.29 were 1.73 vol.% to 0.95 vol.%, respectively. Afterwards, the increasing of ER only gave a slight changing of CH_4 concentration.It was found that The highest valueof CO_2 concentrations of 12.61 vol.% at ERof 0.27. In addition, CO_2 concentration increased from 8.23 to 11.13 vol.% with a higher ER. The effect of triple air stage improved gas composition a little when it compared togas composition of double air stage due to the influence ofair distribution and ER.

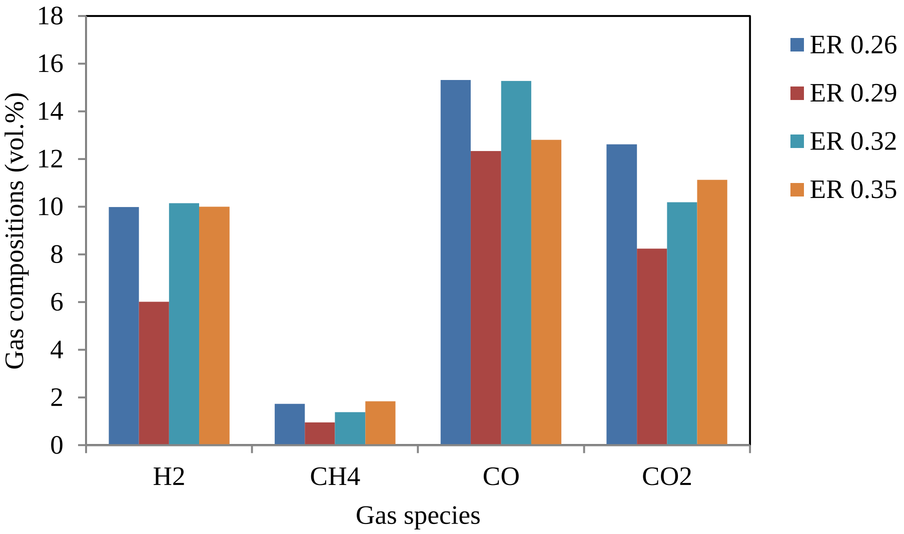

Figure 4.15 The gas composition in various ERs at three stage air supply

4.5 Heating value of producer gas

Higher heating values was depended on the amount of gas composition as seen in Table 4.3 that showed the higher heating value (HHV) of the producer gas and concentration (CO, H_2, CH_4) of gas composition in variation of ER andmulti-stages air. The result was found that the higher heating value of the producer gas from single air stage was 2.61 MJ/m^3 and 2.87 MJ/m^3. The double air stage of ER 0.25 corresponded to the highest level of CO, H_2, and CH_4 concentrations also obtained the highest HHV (3.79 MJ/m^3). In addition, the higher heating value of producer gas from tripleair stage supply was improved to 3.90 MJ/m^3 at the ER of 0.25. However, too high ER resulted in the decreasing in the gas composition which leaded to the decreasing of higher heating value. The more N_2 was supplied in gasifier with higher ER, the more diluted the gas composition (Guo et al., 2014). Hence, the higher heating value gradually decreases. Triple air stage was influent on gas composition (CO) which can be attributed to air distribution produced higher temperature in gasifier with favorite exothermic reaction and endothermic reaction (Jaojaruek et al., 2011).

Table 4.4 Gas compositions and heating value of producer gas

Stage	ER	Gas composition (vol.%)					HHV (MJ/m^3)
		CO	H_2	CH_4	CO_2	N_2	
1	0.11	10.8	7.74	0.7	10.44	70.40	2.61
	0.15	12.73	6.35	1.15	8.35	71.42	2.87
2	0.19	12.40	8.50	1.30	10.57	67.22	3.17
	0.25	15.24	10.33	1.38	11.80	61.24	3.79
	0.27	14.02	8.97	1.08	10.44	65.50	3.34
3	0.26	15.31	9.98	1.73	12.61	60.37	3.90
	0.29	12.33	6.01	0.95	8.23	72.47	2.70
	0.32	15.27	10.14	1.38	10.19	63.02	3.77
	0.35	12.80	10.00	1.85	11.13	64.23	3.63

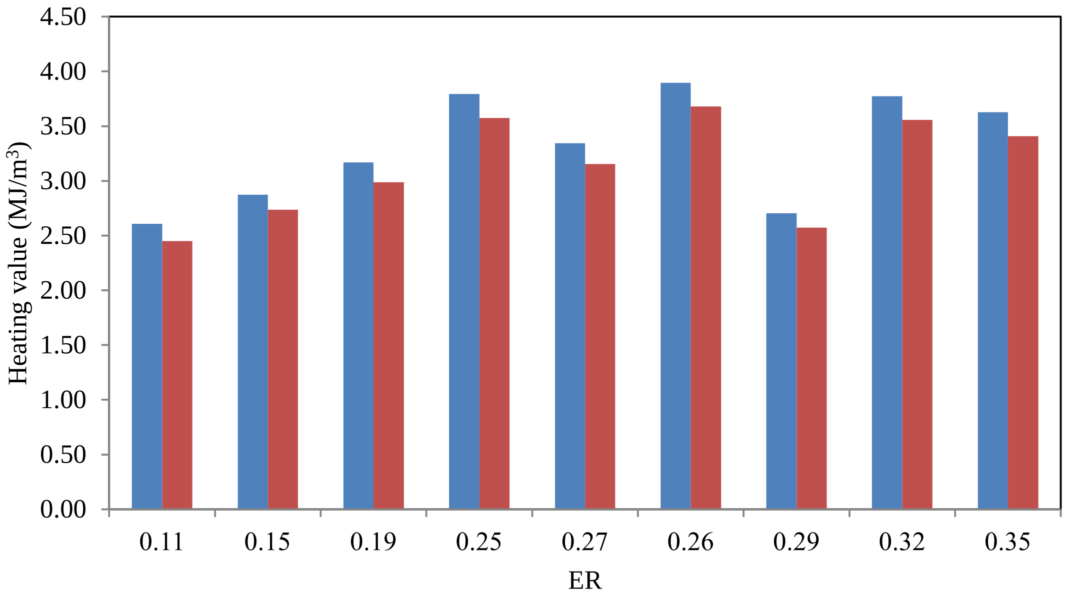

Figure 4.16 The higher heating value and Lower heating value when variation of ER

The gasification characteristics in terms of higher heating value (HHV) and lower heating value (LHV) when variations of ER were presented in Figure 4.16. Higher heating value and lower heating values were calculated from the equation below:

$$\mathbf{LHV} = \frac{\mathbf{107.98H_2+126.36CO+358.18CH_4}}{\mathbf{1000}}\ \mathbf{MJ/m^3} \qquad \text{Eq. 4.1}$$

$$\mathbf{HHV} = \frac{\mathbf{12.74H_2+12.63CO+39.82CH_4}}{\mathbf{100}}\ \mathbf{MJ/m^3} \qquad \text{Eq. 4.2}$$

where CO, H_2 and CH_4 are the gas concentrations of the product gas (Kallis et al., 2011). As listed in Table 4.3, the HHV and LHV of the gas are strongly affected by the concentration of combustible gases (CO, H_2 and CH_4). Therefore, the variation of HHV and LHV of the gas are depended on the variations of combustible gaseous concentration. According to the experimental results, the range of the operating parameter ERs was investigated. With the increasing ofER between 0.11 and 0.25, HHV of the gas increased from 2.61 to 3.79 MJ/m^3 and LHVof the gas from 2.45 to 3.57 MJ/m^3.The maximum of HHV and LHV were 3.9 MJ/m^3 and 3.6 MJ/m^3 respectivelyat ER = 0.26 in triple air stage. Afterward, the HHV and LHV values gradually decreased when ER rose up to 0.35. It can be explained that HHV and LHV of the gas were decreased when ERincreased because of the using air as gasifying agent,

N_2 was a main composition of air that could dilute combustible gases when ER increased (Galindo ,et al., 2014).

4.6Tar content in producer gas

This study investigated amount of tar content in producer gas using multi-stage air configuration that means the air feeding at three positions in the gasifier. The effect of air stage on tar content showed in Figures 4.17, 4.18 and 4.19. This method called a primary elimination which defined as tar removal during biomass gasification.The amount of tar content showed in unit volume of product gas compared with different air stage supplies. Tar content was measured when the gasification process steady stage.The highest amount of tar contentin product gas found in single air stage supply was 26.62 g/Nm^3, while the lowest amount of tar content found in double and triple air stage supply were11.48 g/m^{3}and 2.04 g/m^3, respectively.The tar formation tended to reduce when increasing the ER.

4.6.1 Effect of single stage supply air on tar content

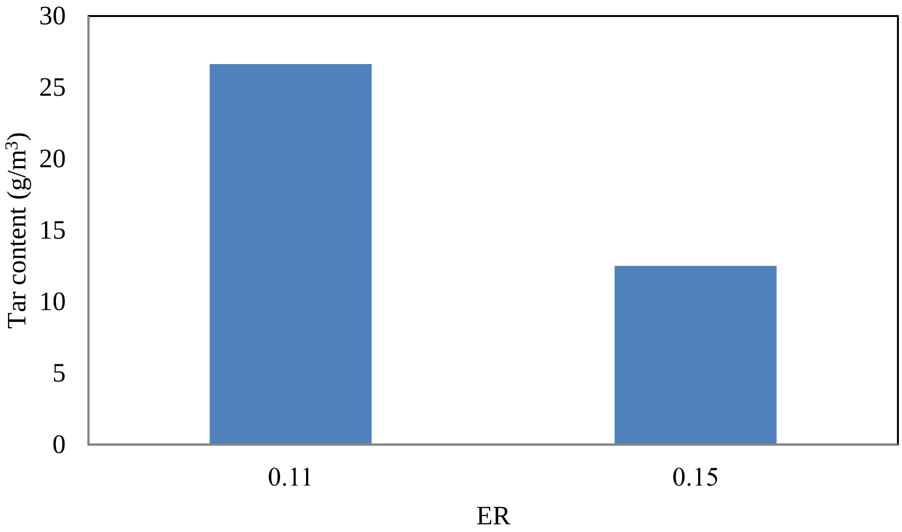

Figure 4.17 Effect of single air stage supply on tar content

The experiments were evaluated the effect of the single stage air supply on tar content in producer gases by varying the ER. At the single air stage, the amount of tar was producedfor the ERs of 0.11 and 0.15.It was observed, that the lower ER can produce highest tar content, 26.62 g/m^3 respectively. It may be related to the low temperature reached at the combustion zone. At the ER of 0.15, tar formation was decreased to 12.50 g/m^3. Therefore, resulting low temperature below than 500°C at combustion zone was not high enough to tar cracking in gasification process. According to Fagbemi et al., (2012) the amount of tar was produced a maximum at temperature of 500 °C in the pyrolysis zone. Single air stage presented the highest value of tar content because of the limitation of system, such as single air stage can be operated at low condition.The small tube of air feeding cause a pressure drop. Therefore, the amount of air was too low and cannot obtain a high operating temperature in single air stage gasifier.

4.6.2 Effect of double stage air supply on tar content

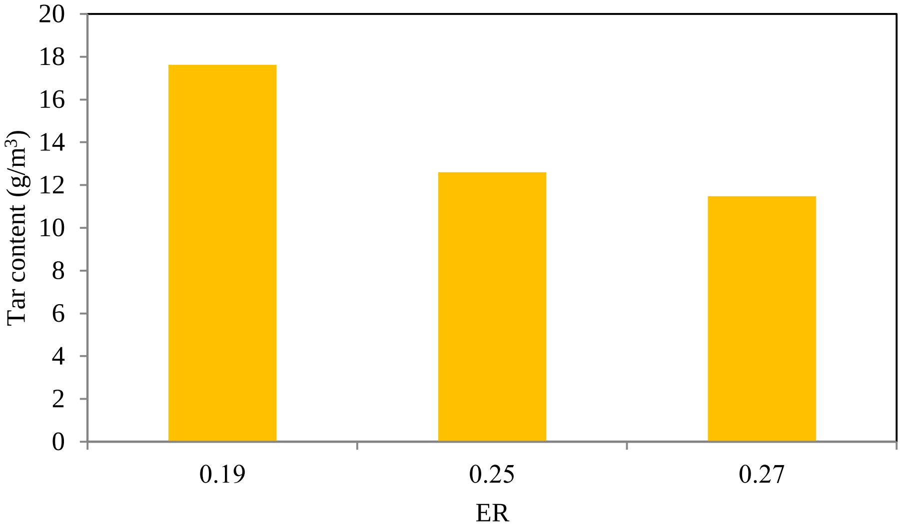

Figure 4.18 Effect of double air stage supply on tar content

The effect of double air stage supply on tar content is presented in Figure 4.18. The tar formation during gasification was investigated as a function of ER in the double air stage. It can be observed that tar formation with double air stage supply tends to decrease with the increase ER. In double stageair supply, the highest tar content (17.62 g/m^3) was obtained from ER of 0.19, while increase ER to 0.25, reduced tar formation to 12.6 g/m^3 (Reduction of 28 %). With further increase of ER to0.27, tar formationwas reduced to the lowest 11.48 g/Nm^3. It was corresponding to slightly decrease tar formation of 8%. The study of double stage air supply which has developed tar content of the gas around 40 times less than the single stage air supply was reported by Bui et al. (1994).

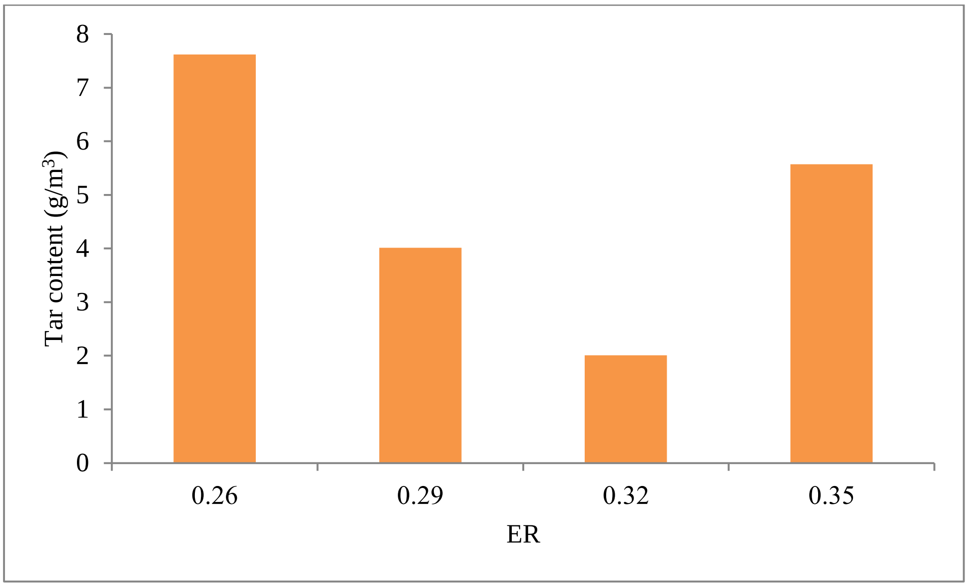

Figure 4.19 Effect of triple stage air supply on tar content

4.6.3 Effect of triple stage air supply on tar content

Figure 4.19 shows the effect of a triple stage air gasifier and variation of ER on tar formation. The different levels of air feeding were increasing air distribution and space of combustion zone. At triple air stage supply, the results foundthat tar formationin producer gas tend to decrease when ER increase. At ER of 0.29 tar formation was 7.6 g/m^3, while increasing ER continuously can drop the tar content to 4 g/m^3. With increasing the ER to 0.3, tar was reduced to 2.01 g/m^3. This corresponded to the tar reduction of 73 %. It means that the largest volume of air supplied prefers to increase the temperature inside gasifier and tar reduction by thermal cracking. However, when ER 0.35, tar content was a little increase around 5.57 g/m^3.Figure 4.20 showed tar color which collected in impinge bottle. They were shown the different color of solvent; Figure 4.20 (a) shows the tar content in triple air stages, Figure 4.20 (b) shows tar content in double air stage and Figure 4.20 (c) shows the tar content in single air stage.

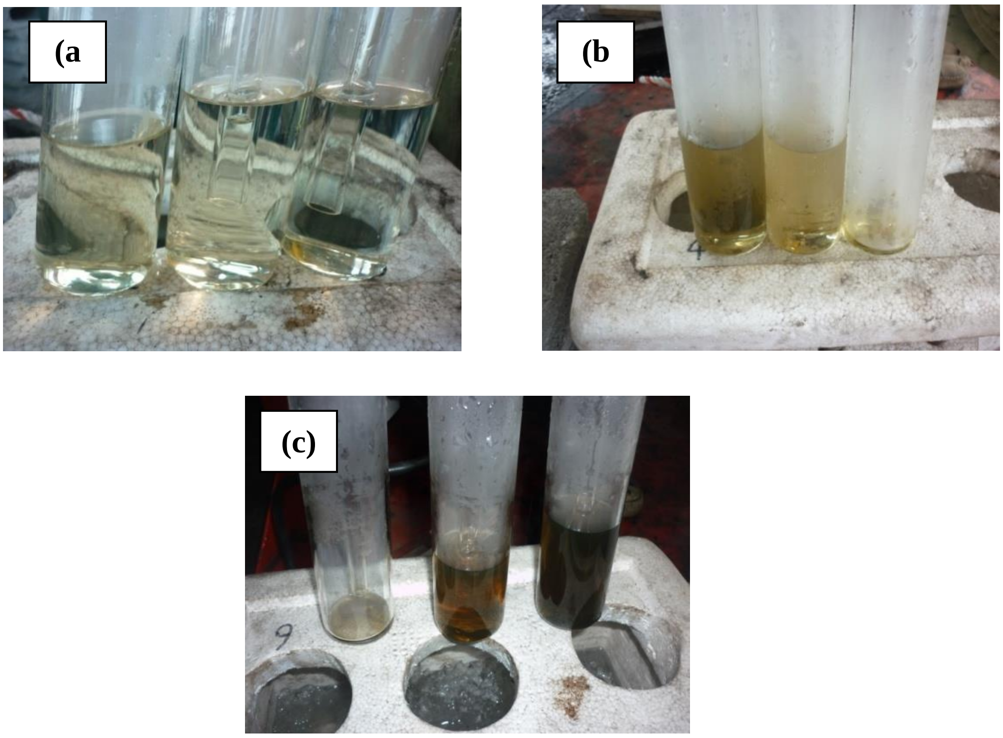

Figure 4.20 Tar content in the producer gas at each stage (a) Triple stage (b) Double stage (c) Single stage.

4.7 Gasification efficiency

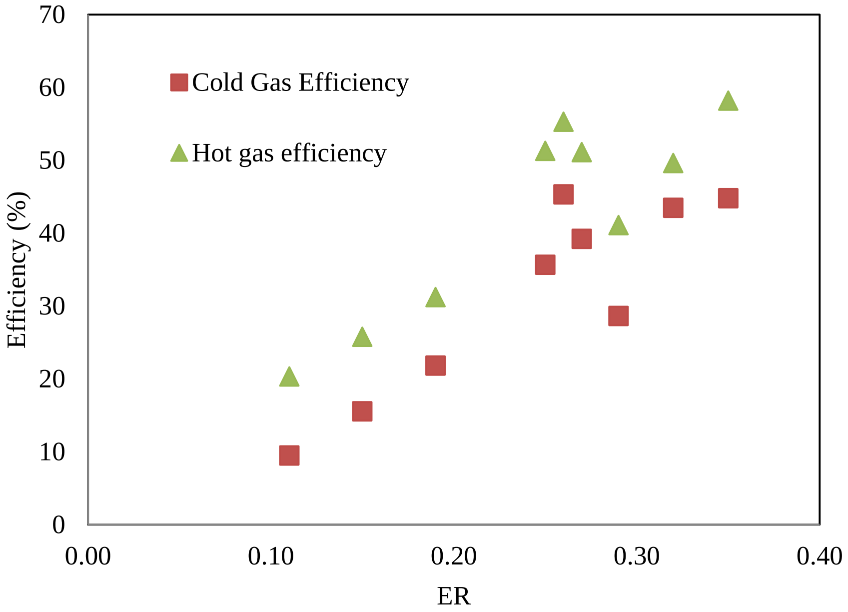

Figure 4.21 Effect of ER on hot gas and cold gas efficiency

The comparison of gas efficiency and ER variation from the experiment is shown in Figure 4.21. This figure shows the hot gas and cold gas efficiencies, of palm kernel shell. The highest hot gas efficiency 58.2% is at ER 0.35, while the highest cold gas efficiency 45.3% is at ER 0.25. The lowest hot and cold gas efficienciesfound at the ER0.11and 0.15 were 20.35% and 9.49%, respective. In fact, these results just showed the trend of gas efficiency of each ER. Cold gas efficiency is the percentage energy of palm kernel converted into cold producer gas. It is the ratio of total energy in producer gas and total energy in fuel. Therefore, the cold gas efficiency based on calorific value of palm kernel shell, consumption rate of fuel, calorific value of producer gas and ER (Centeno et al., 2012).

4.6 Carbon conversion into gas

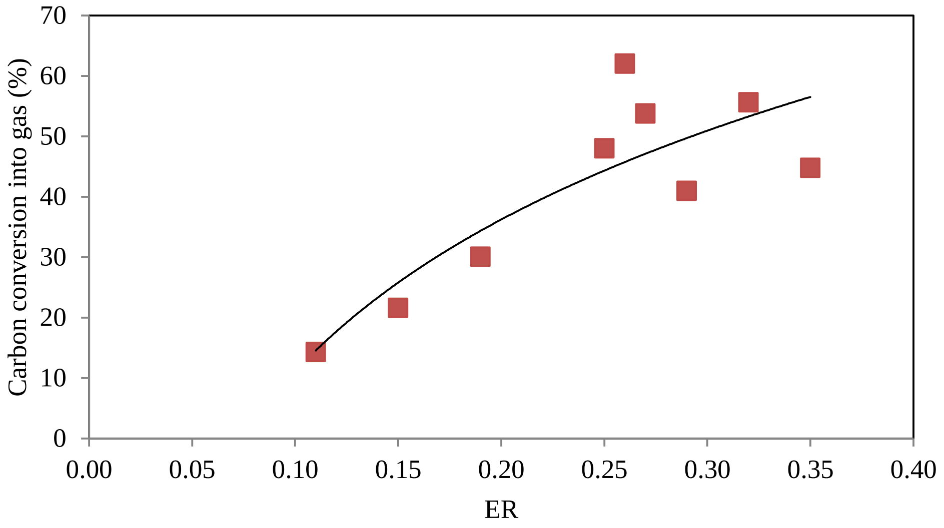

Figure 4.22 Effect of ERon carbon conversions into gas efficiency

The percentages of carbon conversion into gas for the total ER range are seen in Figure 4.22. The carbon conversion increase as well as with increasing ER and using single, double and triple stage air. The carbon conversions increased from 14 % to 21% on singleair stage supply at ER 0.11 to 0.15, 30% to 53.8 % on double air stage supply and the maximum carbon conversion was 62% at ER 0.26 in the triple stage air supply. Afterwards, it decreased when ER higher than 0.29. The carbon conversion is defined as the total carbon content of producer gas (CO, H_2, and CH_4) during the gasification to the total carbon content of the feedstock (Emami Taba ,et al., 2012). As a result, it can indicate that the higher ER affects the reaction of carbon in biomass that can be converted into gas.

CHAPTER 5

CONCLUSION AND RECOMMENDATION FOR FUTHURE STUDIES

5.1 Conclusion

Gasification experiments used multi-stage air gasifier that a potential production of producer gas from palm kernel shells. Base on design of this gasifier can produce energy 50 kWth which was designed by previous student and Thai Steam Company. Level of air injection is divided into three stages for air distribution. In order to improve the temperature reaction, quality of gas, tar information in producer gas. In this experiment was some modification in gasifier such as extending size of air inlet pipe, changing rotating great using with inverter. These modifications can solve the problem from pressure drop in pipe resulted in variation of the air flow rate can be varied but in single air stage supply still occurred the pressure drop only maximum air flow rate is 198 L/min. So, this experiment can show only two air flow rates of one stage air supply.

The results presented in this work showed that the main parameter was investigated included ER at multi-stage air that affected the temperature profile, gas composition and tar content. In only use single stage, the temperature was not high because it was low ER when feed into single stage was low. When using secondary air stage and tertiary air stage, the temperature slightly improved in combustion zone due to large air distribution came to inside. However, all of temperature profile was just the representative temperature due to thermocouples measured temperature only internal wall in order to avoid a problem biomass flowed down to the bottom. Therefore, temperature profile showed temperature lower than actual temperature.

The experiment result of multi-stage air gasification showed influence of air stage supplies in term of ER on gas product and tar content. By increasing ER from 0.11 to 0.35 were slightly increased gas compositions. In addition, the three air stage configuration affected on the tar content in the producer gas tends to decrease when increase the ER 0.32 which can obtain tar content as low as 2.01 g/m^3. The heating value of gas was achieved 3.90 MJ/m^3 which operating condition at ER 0.26. In calorific value of producer gas is showed in term of cold gas efficiency and hot gas efficiency, it presented the highest 58 % of hot gas efficiency and 45 % of cold gas efficiency in the three air stage supply. Finally, the carbon conversion into was obtained higher value of 62 % at ER 0.26.

5.2 Recommendation for future studies

1. The cleaning system should be improved for wet scrubbers, cooling towers, etc. In order to remove the tar condensate, in my case palm kernel shell produced high amount of tar condense on the floor. It should use more equipment for cleaning gas before leaving from gasifier. And about suction air blower must be fixed because when operating the experiment have a smoke leakage from suction blower. It is poison gas, it does not safe to people near this lab.

2. Palm kernel shells can operate in a continuous feed rate due to less slag production, but this gasifier should add a screw conveyer to be easy to handle. Due to when operation of palm kernel shell produced a lot of smoke backward to the feed tube while the gasifier was operating.

3. This gasifier is suitable for pellet biomass and high density. Biomass that has high ash content is not suitable. The grate should be changed into rotating grate that can help ash can fall in the ash pit.

4. Actually, a single stage air supply cannot compare with double and triple stage air supplies because the diameter of the nozzle is too small and produces the low air flow rate. The nozzle in the third air stage supply should be extended the diameter size to make it available variation of air flow rate.

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APPENDIX A

FEED RATE OF BIOMASS

For the design of 50 kWth, multi-stage air supply can calculate the feed rate of palm kernel shell with 70% gasification efficiency.

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

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} = 17310 kJ/kg (Calculation from Basu, P., 2010 P. 58)

= 17.310MJ/kg

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

= 0.7

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

$$M_f = \frac{0.05\ MJ/s}{17.310\frac{MJ}{kg}x\ 0.7}$$

M_f =0.004126422 kg/s

= 14.8 kg/h

APPENDIX B

FEED RATE OF AIR

Table A.1 Proximate and ultimate analyses of palm kernel shells

Property	Value
Proximate analysis (wt %)	74.8
Volatile	13.5
Ash	5.0
Fixed carbon	6.7
Elemental analysis (wt % d.a.f.)	
C	51.79
H	5.68
O	42.11
N	0.42
HHV(kJ/kg)	18500
LHV (kJ/kg)	17310

Flow rate of gasifying medium (Ma) of palm kernel shell

Table A.2 Oxygen Calculations

Element	wt	kmol	Rx	O_2 Required
C	51.79	4.31	$C + O_2 \rightarrow CO_2$	4.31
H	5.68	2.84	$H_2 + ½ O_2 \rightarrow H_2O$	1.42
O	42.11	2.63	$2O \rightarrow O_2$	-1.318
N	0.42	0.03	$½ N_2 + O_2 \rightarrow NO_2$	0.03
Total				4.442

Stoichiometric O_2 required is 4.442 kmol.

Stoichiometric air required:

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

= (4.442 kmol x 32 kg O_2/kmol) + (4.442 kmol x (79/21) x 28 kg N_2/kmol)

= 142.144 kg O_2 + 467.89 kg N_2

= 610 kg air / 100 kg biomass

= 6.1 kg air / kg biomass

wt of air $_{(actual)}$ = 142 ×1.165×60/1000 kg/h

= 9.925 kg/h

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

$$\boldsymbol{ER = \frac{(9.925kg/h/14.8kg/h)}{6.1\ kg\ air/kg\ biomass}}$$

= 0.11

wt of air $_{(actual)}$ = 9.925 kg/h dry air

$m_{moisture}$ = m_{dryair} x ω

where, $m_{moisture}$ = Mass of moisture (kg/h)

$m_{dry\ air}$ = Weight of air$_{(actual)}$ (kg/h)

ω = Humidity (kg/kg)

= 0.016 kg/kg for Thailand

$m_{moisture}$ = m_{dryair} x ω

= 9.925 kg/h x 0.016 kg/kg

= 0.1588 kg/h

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

= 9.925 kg/h + 0.1588 kg/h

= 10.084 kg/h

V air = m_{air} / ρ air

where, V air = Volume of air (m^3/h)

m_{air} = mass of air (kg/h)

ρ_{air} = Air density (kg/m^3)

= 1.165 kg/m^3 at 30°C

V air $= m_{air} / \rho$ air

$= 10.084$ kg/h / 1.165kg/m^3

$= 8.6$ m^3/h

APPENDIX C

GAS CONVERSION EFFICIENCY

Element	wt	Element	wt
C	**51.79**	**CO**	**10.7**
H	**5.68**	**CO_2**	**10.44**
O	**42.11**	**CH_4**	**0.7**
N	**0.42**	**H_2**	**7.74**
HHV (MJ/m^3)	**18.5**	**N_2**	**70.4**
LHV(MJ/m^3)	**17.31**		

The Dry Air supply

Air supply Volume = 142 L/min

= 8.52 m^3/h

Air density (ρ air) = 0.0165 kg/m^3 at 30 °C

Air density (ρ air) = 0.016 kg/kg

m_{air} = V air x ρ

= 8.52 m^3/h × 1.165 kg/m^3

= 9.9258 kg/h

$m_{air} = m_{dryair} + m_{moisture}$

$= m_{dryair\,+}\ (m_{dryair} x\ \omega)$

$= m_{dryair\,+}\ 1.016\ m_{dryair}$kg/kg

$= 1.016\ m_{dryair}$ kg/kg

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

$$m_{dry\ air} = \frac{\mathbf{9.9258\ kg/h}}{\mathbf{1.016\ kg/kg}}$$

= 9.769 kgdry air/h/13.4 kg/hAt 13.4 kg/h (actual feed rate)

$m_{dry\ air}$ for each kg of biomass = 0.729 kg dry air/kg biomass

Nitrogen balance

Mass fraction of N_2 and O_2 in air as 0.755 and 0.232

The N_2 supply from air = 0.755× 0.7291 kg dry air/kg biomass

= 0.5504 kgN_2/kg biomass

The total air supplied by the feed air and the fuel feed, 0.42 % of N_2 in fuel.

= 0.5504 kgN_2/kg biomass + 0.0042

= 0.5546 kgN_2/kg biomass/28

= 0.0198 kmol N2/kg biomass

The producer contains 70.4 % by volume of nitrogen

The amount of the product gas per kg of feed

= 0.0198 kmol N_2/kg biomass /0.704

= 0.0281 kmol gas/kg biomass

The oxygen from air flow in gasifier

= 0.232 × 0.7291kg dry air/kg biomass

= 0.1691 kg O_2/kg biomass

The oxygen supply from also moisture air feed

= $m_{moisture\ air}$

= 9.769 kgdry air/h ×0.016 kg/kg/13.4 kg biomass/h × 16/18

= 0.010 kg O_2 /kg biomass

The oxygen supply from air, moisture and 42.11 % from biomass is

= 0.1691+0.010+0.4211

= 0.601 kg O_2 /kg biomass

Hydrogen balance

The H_2 supply from biomass and moisture in the air is

= 0.0568 kg H_2 /kg biomass+9.769 kgdry air/h ×0.016 kg/kg/13.4 kg biomass/h × 2/18

= 0.058 kg H_2 /kg biomass

The hydrogen leaving with H_2 and CH_4 in the producer gas, that 1 mole of CH_4 contributes 2 moles of H_2

= (0.0774 + (2×0.007)) × 0.028 kmol gas/kg biomass × 2 kg H_2 /kmol

= 0.003 kgH_2 /kg biomass

H_2 in producer gas = H_2 in –H_2 out

= 0.058 - 0.003 kgH_2 /kg biomass

= 0.053 kgH_2 /kg biomass

The moisture associated with this hydrogen in the gas is

= 0.053 kgH_2 /kg biomass × 18/2 kg moisture /kg biomass

= 0.476 kg /kg biomass

Carbon balance

Carbon in dry gas (CO, CO2, CH4)

= (0.1075+0.1044+0.0065) × 0.028 kmol gas/kg biomass× 12 kgC/kmol

= 0.049 kg/kg biomass

The C input found from the combustion of feed 0.5179 kg/kg biomass

The carbon conversion into gas = 0.049 kg/kg biomass/0.5179 kg/kg biomass × 100

= 9.46 %

Heating value of gaseous constituents

CO	12.63	MJ/Nm^3
H_2	12.74	MJ/Nm^3
CH_4	39.82	MJ/Nm^3

Total Heating value of product gas is;

$$\boldsymbol{HHV = \frac{12.74H_2 + 12.63CO + 39.82CH_4}{100}}$$

= ((12.63 × 0.1075) + (12.75×0.0774) + (39.82× 0.00657)) × 0.028 kmol/kg mass ×22.4 m^3/kmol

= 1.64 MJ/kg biomass

Total energy input = heating value of feed

= 1.731 MJ/kg

Cold and hot gas efficiency

$$\boldsymbol{\eta_{cg} = \frac{QgMg}{LHVfMf}}$$

$= \frac{\boldsymbol{Total\ energy\ output}}{\boldsymbol{Total\ energy\ in\ put}} \times \mathbf{100\%}$

= 1.64×100 MJ/kg/17.31 MJ/kg

= 9.47%

Enthalpy

Temperature of gas outlet at 437 ℃ (710 K). To find the enthalpy of the producer gas, it is the enthalpies of its different components. Specific heats of individual components are calculate from

Gases	Specific heat at temp. (K)	Specific heat (kJ/kmol.K)
CO	27.62+0.005T	31.174
CO_2	$43.28+0.00114T+818363/T^2$	49.76389
H_2	27.71+0.0034T	30.126833
N_2	27.210.0042T	30.1955
CH_4	22.35+0.048T	56.47

The entralpy of CO in the product gas contains 10.75% CO at ambient temperature, 30 ℃ or 303 K

$\boldsymbol{Q = n.Cp.\Delta T}$

= (0.1075 × 0.028 kmol gas/kg biomass) × 31.174kJ/kmol.K × (710-303) K × 10^{-3} MJ/kJ

= 0.039 MJ/kg biomass

Gases	Entralpy (MJ/kg)
CO	0.0390
CO_2	0.0604
H_2	0.0271
N_2	0.2469
CH_4	0.0043

The amount of steam in the flue gas calculates as of feed 0.477 kg/kg biomass. The steam enthalpy at 710 K and 303 K are 3355.5477kJ/kg and 125.76 kJ/kg. The enthalpy in water is

= 0.477 kg/kg biomass × (3355.54 - 125.76) × 10^{-3} MJ/kJ

= 1.5405 kg/kg biomass

The total enthalpy of producer gas at 710 K

= (0.0390+0.0604+0.0271+0.2469+1.5405) MJ/kg biomass

= 1.9182 MJ/kg biomass

Total thermal energy = 1.643+1.9182 MJ/kg biomass

= 3.5613 MJ/kg biomass

Hot gas efficiency

$$\boldsymbol{\eta_{hg}} = \frac{\boldsymbol{Q_g M_g + M_g C_p (Tf - To)}}{\boldsymbol{LHVfMf}}$$

$$= \frac{\textbf{Total thermal energy}}{\textbf{Total Energy input}} \times \mathbf{100}$$

= (3.5613 MJ/kg biomass/17.31 MJ/kg biomass) × 100

= 20.57 %