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Article

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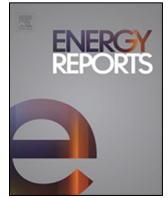
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Research paper

Fast pyrolysis from Napier grass for pyrolysis oil production by using circulating Fluidized Bed Reactor: Improvement of pyrolysis system and production cost



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HIGHLIGHTS

- The pyrolysis oil production from Napier grass was studied by using circulating fluidized bed reactor (CFBr).
- The new design of pyrolysis system was developed in order to reduce the pyrolysis oil production cost.
- The comparison between pyrolysis oil yield and optimization were discussed.
- Cold efficiency and energy conversion efficiency were shown in this work.
- Comparison of pyrolysis oil production cost was also shown.

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ABSTRACT

This article focused on production cost of pyrolysis oil production of Napier Grass in Circulating Fluidized Bed Reactor (CFBr) which sand was used as bed material. The Napier grass was converted to pyrolysis oil by using fast pyrolysis process. The reactor temperature, superficial velocity (U_f) and feed rate of feedstock were adjusted in order to find the best condition of this experiment, and the Quadratic Response Model was used to predict the yield of pyrolysis oil and the optimum condition coupled with the experiment. From a results of this experiment, it was found that the maximum pyrolysis oil production was 36.93 wt% at 480 °C of bed temperature, 7 m/s of superficial velocity and 60 kg/hr of feed rate, while the result from the Quadratic Response Model indicated that the maximum pyrolysis oil production was 32.97 wt%. From the analysis of properties of pyrolysis oil, results showed that heating value, density, viscosity, pH and water content were 19.79 MJ/kg, 1,274 kg/m³, 2.32 cSt, 2.3 and 48.15 wt%, respectively, and the ultimate analysis was also determined. From the analysis of the efficiency of energy conversion, it was concluded that the value of cold efficiency and total energy conversion to pyrolysis oil in this system were 24.88% and 19.77%, respectively. The greatest energy consumption in this system was made by the energy from the heating process. Furthermore, from the calculation result of production cost in this study, it was concluded that a production cost of pyrolysis oil was 0.481 \$/liter or 9.88 \$/GJ at the 75 kg/hr of feed rate.

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1. Introduction

Napier grass (*Pennisetum purpureum* Schumach) is a fast-growing vegetation with a harvesting round of 60 days. The grass is known for its high productivity (an average of 90–120 tons per hectare), weather endurance, and low producing cost. In addition to its productivity values, Napier grass holds high protein content and offers tasty flavor (Pincam et al., 2017). This is why the plant is suitable raw material for animal food product industry (Muia et al., 2001; Shem et al., 2003). Since Napier grass is a source of

high heat rate biomass, an average of 16.58 MJ/kg, it is widely used as a fuel source for industries and in electronic producing plants. Thailand is one of the countries interested in using the grass for electricity production. Based on the country's AED2013 plan, Thailand expects to produce about 3000 MW of electricity from Napier grass in the next 20 years (Waramit and Chaugool, 2014; Haegele and Arjarn, 2017).

There has been an amount of research into the exploitation of Napier grass as a substitutional energy in the productions of biogas (Sawasdee and Pisutpaisal, 2014; Janejadkarn and Chavalparit, 2014; Wilawan et al., 2014), bioethanol (Pensri et al., 2016; Ko et al., 2017; Liu et al., 2017), and pyrolysis oil (Strezov et al., 2008; Lee et al., 2010; Mohammed et al., 2017). Napier grass is more effective as a base material of the bioethanol and pyrolysis

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oil productions than it is for the biogas production since the first two energy products require simple storage and transportation, while they are applicable for more types of engines. Moreover, the heating value of bioethanol produced from Napier grass is almost two times higher than the heating value of the pyrolysis oil produced from the same grass. However, using Napier grass for bioethanol production yields less product exchange rate than what observed in the production of pyrolysis oil. The yield of bioethanol production in a study by Liu et al. (2017) was measured at 12.6 wt% while Mohammed et al. (2017) observed that the optimal production of pyrolysis oil was at 50.57 wt%. One of the primary factors for the energy production is the time it takes in the producing process. Bioethanol making process is based on fermentation, while the production of pyrolysis oil is based on a none-oxygen consumption burning, which takes as short as 0.5–2 s (Bridgewater and Peacocke, 2000). Obviously, producing bioethanol from Napier grass takes much more time than the production of pyrolysis oil. When the outcome and the production time are primary concerns in using Napier grass as an initial substance for the substitutional energy production, then Napier grass is more efficient as a base material for the production of pyrolysis oil than it is for bioethanol production.

This article has reviewed a number of studies into the production of pyrolysis oil from Napier grass. Strezov et al. (2008) investigated the production of pyrolysis oil from Napier grass by using Fixed Bed Reactor. In the experiment, the reactor temperature was ranged from 25 to 700 degrees centigrade, the heating accelerating rate was set at 10 °C/min and 50 °C/min. Fifty milligrams of the grass was used for each experiment. The maximum yield of pyrolysis oil production at the heating rate of 500 °C and 50 °C/min was 54.37 wt%. The experiment proved that high heat rate not only minimized the carbonization time, but it also helped diminish acid component and benzene compound in pyrolysis oil, the effects less observed in the low-temperature setting. A similar result was observed in a study by Lee et al. (2010) who conducted a research into the production of pyrolysis oil using Napier biomass and Fixed Bed Reactor. Maximum yield of pyrolysis oil product of 35.7 wt% was observed at the heating rate of 500 °C, 150 °C/min with the biomass size of 224 µm. This research showed that heating rate and size of biomass affected the acidity level in pyrolysis oil. However, the main objective of the study on pyrolysis production is finding the right factors and processes for maximizing the product. Mohammed et al. (2017) revealed that the reactor's temperature, the heating rate, the flow rate of moderating gas constituted the yield of pyrolysis oil made from Napier grass. This result is also articulated in a study by Bridgewater, who observed that the concentration of oxygen content in a reactor, a size and moisture content of biomass, feed-rate, time residence of reaction and characteristic of heat transferred to biomass have affected the quality and quantity of pyrolysis oil. The types of a reactor are crucial for the production of pyrolysis oil production. More specifically, the auger, bubbling fluidized bed reactor (BFB) and circulating fluidized bed reactor (CFBR) are highly efficient for the production of pyrolysis oil at a large commercial scale (Bridgewater and Peacocke, 2000; Bridgewater, 2003, 2004). The importance of the type of reactors in the production of pyrolysis oil has triggered more research into a different type of a reactor in addition to Fixed Bed Reactor. Conto et al. (2016) conducted a batch experiment (each batch used 75 g of biomass) using Rotary Kiln Reactor for the production of pyrolysis oil with Napier grass and a level of 52.99 wt% yield was measured in this study. SingBua et al. (2017) conducted an experiment that was similar to Conto's study but Singbua additionally installed automatic feeding system to consistently fill the biomass to the system at the rate of 22.5 kg per hour. This system leads to the maximum of pyrolysis oil production of 14.27 wt%. In order to promote the use of Napier grass as a raw material for pyrolysis oil

Table 1

The physical properties of the experimental materials.

Properties	Napier	Sand	Units
Mean diameter (the Sauter's mean diameter)	1–3	0.249	mm
Bulk density	137.8	1524	kg/m ³
Porosity	–	42.87	%
Heating value (ASTM D240)	15.23	–	MJ/kg
Proximate analysis (Shimadzu TGA 50)			
- Moisture	12.14	–	wt%
- Volatile matter	75.37	–	wt%
- Fixed Carbon ^a	7.33	–	wt%
- Ash	5.15	–	wt%
Elemental analysis (Perkin Elmer PE2400 Series II)			
- C	40.03	–	%
- H	6.02	–	%
- N	1.69	–	%
- S	1.08	–	%
- O ^a	51.18	–	%

^aFixed Carbon and Oxygen were calculated by difference.

production in a commercial scale, it is important for the production line to be developed in order that it can continuously feed the biomass into the system while the production process should work effectively. Sousa et al. (2016) investigate the efficiency of the production of pyrolysis oil using Napier grass and Fluidized Bed Reactor with the feeding rate of 40 kg per hour. In this experiment, a system to extract water from oil and a Non-Condensable Gas (NCG) cleaning system was installed to enable big scale production. The maximum of 28.2 wt% of oil product was observed in this study. Despite the fact that the cost is one of the major factors to help decide whether Napier grass is effective raw material for the production of pyrolysis oil to serve an industrial purpose, none of the above research has investigated into this matter. Moreover, the lab scale experiments merely dictate the pyrolysis oil production capacity without mentioning the energy consumption, which is the key indicator for capital measurement in pyrolysis oil production.

Based on the above limitations, this article proposes a system for the production of pyrolysis oil by using Napier grass with the feeding rate between 45 to 75 kg per hour. A Circulating Fluidized Bed reactor (CFBR) has been employed in this work because it offers more advantages than other reactors (Bridgewater, 2003). Liquid Petroleum Gas (LPG) and NCG were used as the fuels to produce heat into the reactor, and a cross flow heat exchanger was used to recover heat and to return it back into the process to save energy. The diagram showing device placement, system's outcome, product properties, energy consumption, efficiency of energy conversion and the production cost are presented in this work as a beneficial data for the development of future research.

2. Materials devices and methods

2.1. Experimental materials

Experimental materials included: (1) Napier grass and (2) sand, which was used as the bedding material in the CFBR. The Napier grass is shown in Table 1 showed the physical properties, such as density, porosity, mean diameters, and heating values of the Napier grass and the sand, and also presented the proximate analysis and ultimate analysis of the Napier grass.

2.2. Experimental devices

As shown in Fig. 1, the experimental devices consisted mainly of a circulating fluidized bed reactor (CFBR), gas combustion, a feeder system with pneumatic conveying, a hopper, two cyclones, a gas pre-heater, and a condenser. This pilot plant was designed to produce a low cost production for obtaining pyrolysis oil. The process

of production line was modified to a new schematic process from many previous literatures which it was not duplicate with other systems (Onay et al., 2001; Onay, 2007; Senoz and Angin, 2008; Jung et al., 2008; Duanguppama et al., 2016; Stamatov et al., 2006; Morales et al., 2014; Treedet and Suntiwarakorn, 2011; Asadullah et al., 2008; Cai and Liu, 2016; Cai et al., 2018; Akarregi et al., 2013; Boukis et al., 2001; Antonelli, 1989; Trebbi et al., 1997; Dai et al., 2001; Scott et al., 1985; McAllister, 1997; Lappas et al., 2002; Maniatis et al., 1993; Knight et al., 1982; Cuevas et al., 1994). The features of this particular pilot plant was that the CFB_r was heated using the exhaust gas from a can combustor and that LPG was used as the fuel to generate the heat. NCG was used in 2 parts: (1) as a conveying gas in the feeder system and (2) as fuel that was combined with LPG while the remainder was being re-circulated. In order to save energy, heat recovery was installed.

2.2.1. Circulating fluidized bed reactor (CFBr)

The main component of the plant was the CFB_r, which had a high heat transfer rate and good temperature control (Bridgwater, 2003). The components of CFB_r were comprised of a riser, a distributor plate, a riser exit, a cyclone (gas–solid separator), a down-comer, a solid feeder, and a butterfly valve. The riser had a internal diameter of 100 mm and height of 4.5 m. A perforated plate was used as distributor plate, which had a thickness of 2 mm and a percentage of open area of 7%. The C-shaped and L-shaped valves were applied at the riser exit and in the solid feeder of the CFB_r because it had a high solid-recirculating rate (Kim et al., 2008; Lacknermeier and Werther, 2002). The heat transfer rate of the CFB_r was directly affected by the solid-recirculating rate, the suspension density, and the bed inventory (Glicksman, 1984). A butterfly valve was used to control the solid-recirculating rate.

In order that the bed inventory of this CFB_r could be measured, a load-cell was installed at the down-comer so that the weight of the bed could be measured in the down-comer. To measure the bed inventory in the riser, the relationship between total weight of bed in the CFB_r and weight of bed in down-comer was used. The bed inventory in the riser was equal to the weight of bed in the CFB_r minus the weight of the bed in the down-comer. The solid-recirculating rate was measured by the weight of bed upon exiting the CFB_r per time per area of the riser.

2.2.2. Heat production by gas combustor

The gas combustor, which was used in this work, was a can combustor. A can combustor (or tubular combustor) is one type of continuous burning combustor that is used in gas turbines, ram jets, or scramjet engines. The purpose of the combustor in a gas turbine is to add energy, which can be used in the system of a power station. In addition, a can combustor can be used in a drying system or in a heat generator, etc. The suitability of any continuous combustor is based upon its size, thermal load, its flue gas temperatures, and the operating conditions, etc. (Cohen et al., 1996) However, the following requirements for accomplishing the design must be considered: (1) there must be a complete combustion between the fuel and the air; (2) in the combustor, there must be a drop in pressure; (3) the inside of the combustor must retain the flame; (4) in order to prevent damage or destruction of the devices by thermal cracking, there must be uniform exit temperatures from the combustor; and (5) finally, environmental pollution must be avoided (Rolls-Royce plc, 1996). Normally, the flow behavior of air in a continuous combustor has the characteristic of a toroidal reversal flow (or re-circulation) into a portion in which it can generate a Central Recirculation Zone (CRZ). The CRZ is helpful in mixing the fuel and air in order to increase the combustion time, which generates complete combustion (Lefebvre, 1983).

This can combustor was designed by utilizing information from the literature (Rolls-Royce plc, 1996; Lefebvre, 1983; Walsh and

Fletcher, 2004; Raj and Ganesan, 2008), and is comprised of a case, a diffuser, a liner, a snout, and a swirler, etc. The basic design for a can combustor must have the following specifications: (1) be easily build, (2) produce complete combustion, (3) have low emission levels, (4) produce a minimal loss of total pressure over a wide operating range, and (5) be durable (Mattingly, 1996). In general, can combustors have a cylindrical design. When the combustion begins, the pressure will be increased and a high pressure drop will be created within the combustion zone. For this reason, the traditional can combustor must be designed with a diffuser shape that reduces the air velocity (Lefebvre, 1983), and the frequency of the blower will be adjusted by inverter to increase the pressure for maintaining the volumetric flow rate in the system. The most important factor for accomplishing complete combustion is the creation of a swirling vortex inside the combustion chamber. The liner must divide the air into the combustion chamber in sufficient quantities. Furthermore, the temperature of the flue gas must be reduced before it reaches the turbine blade. The liner can be divided into 3 zones as follows: (Cohen et al., 1996; Rolls-Royce plc, 1996)

- **The primary zone:** This zone maintains the stability of the combustion. This zone will create a vortex of swirling air by using a swirler, which generates a CRZ to mix the fuel and the air. Moreover, it increases the residence time of the combustion process.
- **The secondary zone:** In this zone, air is induced to burn the unburned fuel from the primary zone in order to provide for complete combustion and for the cooling of the hot gas after it has been combusted.
- **The dilute zone:** In this zone, the total induced air is 20%–40%. The air is used to produce a uniform temperature profile which is desirable for the combustor.

The can combustor in this plant has been conducted at atmospheric pressure, and Liquefied Petroleum Gas (LPG) was used as the fuel. The operational temperature was 300 °K and the constant mass flow rate of the air was 0.0157 kg/s. It can be seen that the design of the can combustor consisted of an inlet diffuser, a liner, a swirler, and an outer case. The liner had a diameter of 250 mm and a length of 406 mm. The holes of the liner were divided into 3 zones: (1) primary holes (12 each with diameters of 6 mm), (2) secondary holes (12 each with diameters of 24 mm), and (3) dilute holes (12 each with diameters of 18 mm).

The air fractions into the swirler, and into the primary, secondary, and dilute zones were 18.29%, 9.15%, 40.24% and 32.32%, respectively. The air fraction is related to the flue gas temperature of the combustor, and it was found that the flue gas temperature of the combustor had increased due to the reduction of the air fraction in the dilute zone. This combustor focused on a constant flue gas exit temperature of 1300 °K. For this reason, the air fraction in the dilute zone was found to be less than in the secondary zone.

For this combustor, the swirler, that was utilized, was an annular swirler, as suggested in a study by Raj and Ganesan (2008). The given design details of the swirler vane geometry were 45° for a swirler having 8 vanes and a thickness of 2 mm. The vane angle indicated in the top view was 45° and the angle of overlap from the axial direction was 75°. Moreover, the design results of the other components consisted of a snout angle of 30°, a hub to tip ratio of 0.33, and auxiliary primary holes. These generated a maximum swirling number of 1.52 and the lowest Pressure Loss Factor (PLF) value of 2.28. This designed combustor was suitable as a heat generating device. Some advantages of using this combustor design are that it is simple to construct, is inexpensive, and has a good swirling flow.

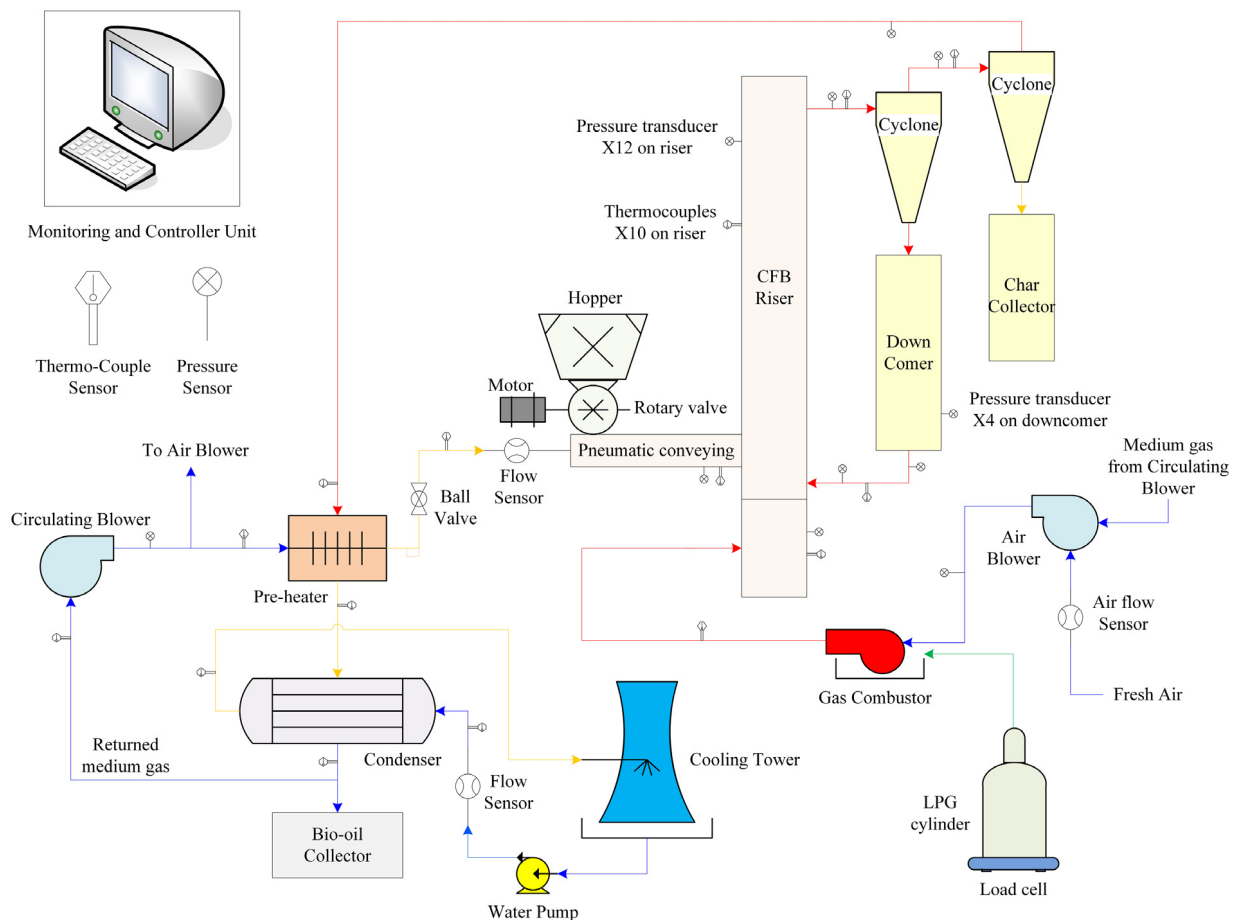


Fig. 1. A schematic diagram of the pyrolysis oil production system.

2.2.3. Feeder system with pneumatic conveying

Most pyrolysis reactors from biomass are operated under atmospheric pressure, which is an advantage for designing the feeder system. However, the fluidized bed reactor is conducted on positive pressure (approximate about 5–15 kPa of gauge pressure). For this reason, the pneumatic system (Scott and Piskorz, 1982; Berruti et al., 2009) and screw conveyor (Lu, 2007; Chen et al., 2011; Jung et al., 2008) are widely used in fluidized bed reactors to prevent the feeding system from becoming jammed. In this plant, the feeder system used a pneumatic conveying system, and a blow-through rotary valve was used to control the feed rate. NCG was used as the conveyor gas. The feeder system in this plant fed the Napier grass at a rate of 45–75 kg/h, and the rotational speed of the vane rotors of the rotary valve was between 0–10 rpm. The biomass is fed above the distributor plate to increase solid residence time in the dense phase (Rapagna and Celso, 2008).

The rotary valve used an electric motor as its power source, and the energy consumption of the feeder system was around 350 W. The overall pressure drop and the minimum velocity in this system were 437 Pa and 4.78 m/s, respectively.

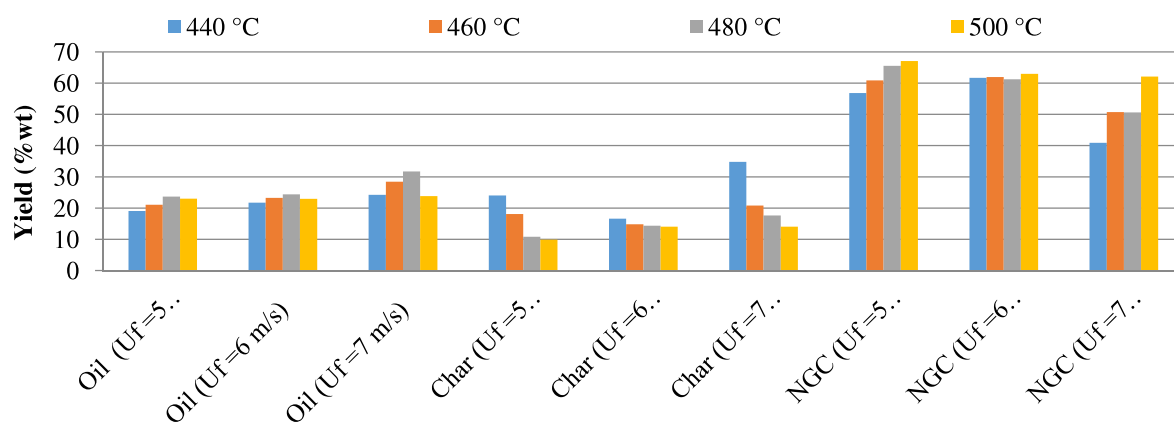
2.2.4. gas–solid separator system

The gas–solid separator in this plant used a cyclone. The cyclone design can be divided into 2 categories: general purpose cyclones and high-efficiency cyclones. The first cyclone or the general purpose cyclone was designed to filter large-sized particles of bed material, and this type of cyclone was installed between the riser and down-comer of the CFB. The second cyclone or the high-efficiency cyclone was designed to filter small-sized particles, such as charcoal powder. This cyclone was installed between the CFB

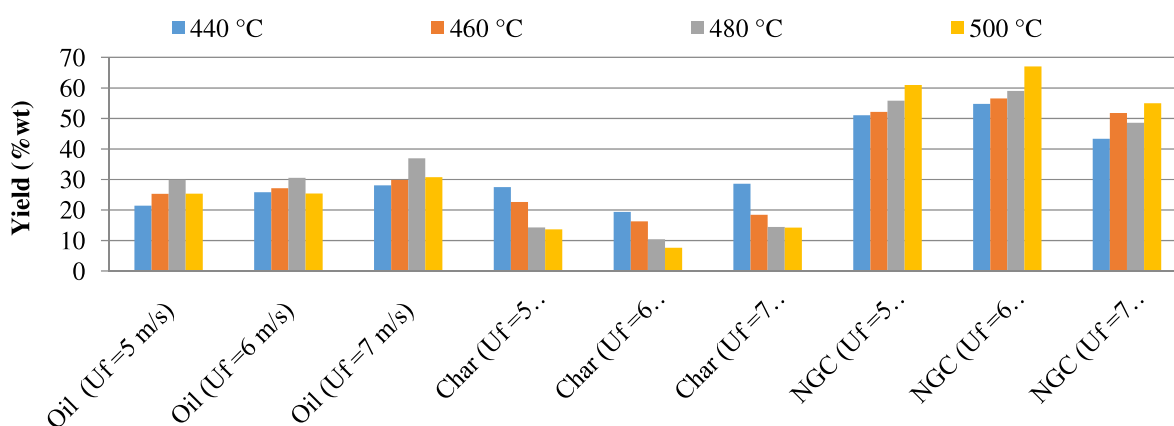
and the condensing unit. The design theory of the first cyclone used the principles of Sheoher and Lapple (1939), while the second cyclone used the principles of Stairman (1951).

2.2.5. Heat exchanger system

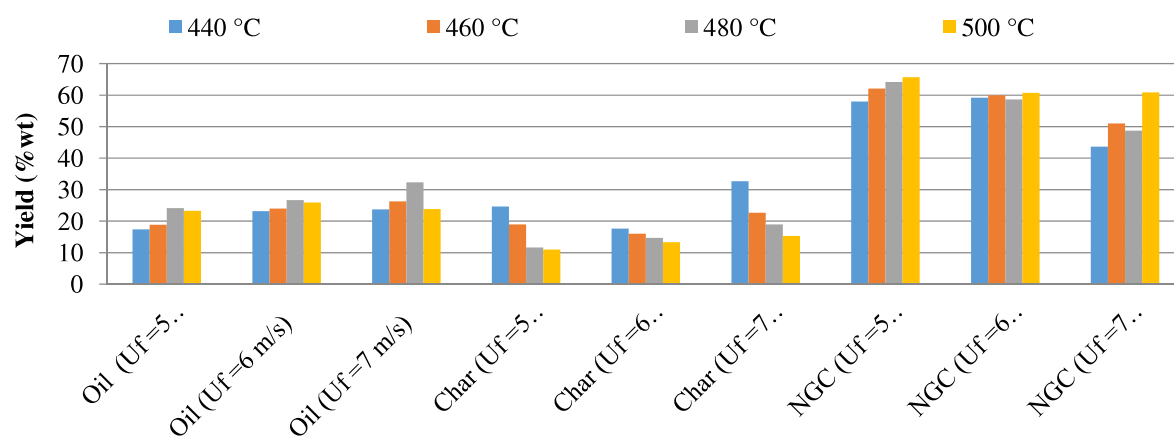
Pyrolysis vapors must be rapidly quenched in order to be converted as pyrolysis oil (Bridgwater et al., 1999), so a high-performance heat exchanger must be installed. This pyrolysis plant used 2 sets of shell and tube heat exchangers as gas pre-heaters and condensers. Gas pre-heaters were designed to decrease the temperature of hot vapors from processing before they entered the condenser unit, in which the cold fluid from this heat exchanger was the NCG from the condenser. The objective was to install a gas pre-heater, because they can reduce the heat load of the condenser. Moreover, it helped to increase the temperature of NCG before it entered the rotary valve and reduced the interruption of temperature between the conveying gas and reaction gas inside the reactor. The gas pre-heater had a heat capacity of 12 kW, which can decrease the temperature of the hot vapor from the process to about 250 °C and can increase the temperature of the NCG from the condenser exit to about 120 °C. The design of the 8 kW condenser, which has a role in condensing hot vapor to bio-oil, used a 10 RT cooling tower to reject the heat from the vapor. In addition, water was selected as the working fluid of this system and had a volumetric flow rate of 160 l/min. The operating procedure of the condensing unit was as follows: Firstly, hot vapor from the process of the secondary cyclone was conveyed to the gas pre-heater. In this step, the temperature of the hot vapor can be reduced from around 450 °C to 200 °C. Secondly, the hot vapor from the gas pre-heater exit was allowed to flow into the



a) Pyrolysis oil production at a feed rate of 45 kg/hr.



b) Pyrolysis oil production at a feed rate of 60 kg/hr.



c) Pyrolysis oil production at a feed rate of 75 kg/hr.

Fig. 2. Pyrolysis oil production at a feed rate between 45–75 kg/h.

condenser. In this step, the hot vapor was completely condensed as pyrolysis oil. Finally, the NCG from the condenser exit was sucked back to system and was recirculated.

2.2.6. Controller and data logging system

In this plant, Labview software was used to control and collect the data. The instruments, used in this system, consisted of 29

pressure sensors, 25 thermo-couples, 2 sets of strain gauges, 1 power analyzer, 1 gas component analyzer, and 1 liquid flow ultrasonic. The 25 sets of pressure sensors, which ranged from between 0–50 kPa, were installed at the riser, the down-comer, and the blower to measure the hydrodynamics, while the remaining high accuracy pressure sensors with a range from 0–2 kPa were used to measure the pressure differences of the pitot tube. All of pressure

sensors were calibrated and amplified along a linear scale from 0 to 5 VDC by using the IC code INA122. The 24 sets of thermo-couples (type K) with a range from 0 to 1000 °C were used to measure the temperature around the plant, and one ceramic probe of thermo-couple (type B) with a range from 0 to 1700 °C was installed on the can combustor to measure the exhaust gas temperature before it entered the CFBR. The 2 sets of strain gauges were installed at the down-comer and the LPG tank to measure the bed inventory and the fuel consumption, respectively. A Micronics PF330 ultrasonic flow meter was used to measure the volumetric flow rate of the cooling water of the condenser, and this instrument generated 0 to 20 mA output. The gas components of NCG and the exhaust gas of the can combustor were determined by using an Emission System, Inc. (Model 5002). Finally, a Chauvin Arnoux model (C.A.8332B) was installed to measure the electricity consumption of this plant. All signals for the instruments were transferred to Labview for control and for corrections, and the data was collected every second.

2.3. Experimental methods

The experimental device was originally set up at Khon Kaen University in 2016, and since then, has eventually been scaled up to maximum Napier grass feeding rates of 75 kg/h. Napier grass with a mean dimension of 1–3 mm was fed continuously into the reactor at rate of between 45–75 kg/h. The pyrolysis experiments using Napier grass were performed at the CFB reactor's superficial velocity (U_f) of between 5–7 m/s, while the bed temperature of the reactor was set at a range from 440 °C–500 °C and the bed inventory was set at 4.5 kg under atmospheric pressure. The yield of the pyrolysis oil was heavily impacted by the rate of cooling in the condenser. The cooling process had to be quick to prevent conversion of some condensable gases into NCG (Lu, 2007). Thus, in this experiment, a two stage heat exchanger, comprised of a gas-preheater and a condenser, was operated in cool water with a condensation temperature of 25 °C.

In addition to the pyrolysis oil, two by-products, namely charcoal and NCG, were also obtained when sugarcane bagasse was pyrolyzed. The yield of the pyrolysis oil was determined from the total weight of condensed liquid into the pyrolysis oil collector per total weight of feedstock, and the yield of the charcoal was determined from the total weight of char in char collector per total weight of feedstock. The yield of the NCG was determined from the fact that the sum of the three product yields should be equal to 100%.

3. Results and discussion

3.1. Product yields

Fig. 2 shows the actual production of pyrolysis oil from Napier grass at a feed rate between 45–75 kg/h, respectively. From these results, it was shown that this system has the ability to produce a maximum yield of pyrolysis oil at 36.93 wt% at 480 °C of bed temperature and at 7 m/s of superficial velocity (U_f). All of the test results regarding the bed temperatures revealed that the maximum pyrolysis oil production had been generated at 480 °C of bed temperature. Furthermore, it was found that: (1) the pyrolysis oil yields had first increased and then had decreased with the increases in reactor temperatures; (2) the Non Condensable Gas (NCG) yields had first decreased and then had increased with the increased reactor temperatures; and (3) the charcoal yields had steadily decreased with increases in the reactor temperatures. In regard to the influence of the pyrolysis temperatures and volumetric flow rate, these findings were consistent with results from studies by Lu (2007); Lu et al. (2008), Treedet and Suntivarakorn (2012) and Wang et al. (2005). The superficial velocity of carrier gas

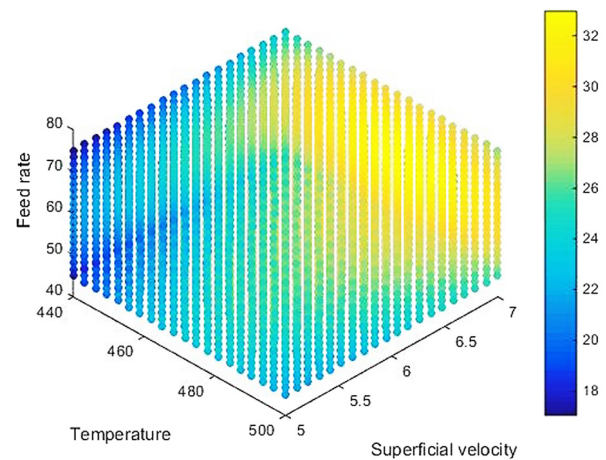


Fig. 3. The optimal quadratic response surface for pyrolysis oil production.

which can be calculated as volumetric flow rate had also affected the production yield at every temperature. A study of the relationship between the superficial velocity of the carrier gas and the production yield revealed the following that the yield of pyrolysis oil had always increased with increases in superficial velocity (U_f), and the highest yield for Napier grass had been generated at 7 m/s.

To find the best conditions to produce pyrolysis oil, mathematical modeling is a good choice to find the optimal conditions for pyrolysis oil production. By using multiple regression analysis, the optimal conditions for pyrolysis oil production were studied. The Quadratic Response Model was used to determine the yield of pyrolysis oil. Eq. (1) shows the model used to obtain the yield prediction.

$$y = (-953.828) + 9.31x_1 + 3.7707x_2 + 1.6141x_3 + 0.4275x_1x_2 - 0.0039x_1x_3 - 0.0178x_2x_3 - 0.0252x_1^2 + 0.0039x_2^2 + 0.0011x_3^2 \quad (1)$$

In which y , x_1 , x_2 and x_3 present the yield of pyrolysis oil prediction, the superficial velocity (U_f), the reaction temperature, and the feed rate, respectively.

The optimal quadratic response surface results are shown in Fig. 3. From the results, it was found that optimal conditions for pyrolysis oil production had been a superficial velocity of 7 m/s, a bed temperature of 473.68 °C, and a feed rate of 60.39 kg/h; and that these conditions had been able to produce a maximum yield of pyrolysis oil at 32.97 wt%. The percentage of error of yield of pyrolysis oil between the actual parameters and the quadratic response model was found to be 10.72%.

3.2. Product properties

Table 2 shows properties of the char and pyrolysis oil at a bed temperature of 480 °C, at a superficial velocity (U_f) of 7 m/s, at a feed rate of 60 kg/h. The results indicated that pyrolysis oil had a low viscosity. The low viscosity of the aqueous fraction makes it suitable for combustion in different types of equipment, such as boilers, turbines, and engines (Oasmaa et al., 2005). Moreover, the quality of feedstock has effected to quality of bio-oil. The high value of moisture content in feedstock was induced to increase an oxygen into the bio-oil directly, which it will create a lot of acid compound in bio-oil. However, the heating value of pyrolysis oil is low to be used in the engine when compared with the heating value of conventional fuel. This makes it difficult to directly use in engines. For this reason, crude pyrolysis-oil should be upgraded before it can be used in engines.

Table 2
The properties of char and pyrolysis oil.

Properties	Char	Pyrolysis oil	Units
Heating value (ASTM D240)	9810	19.79	MJ/kg
Density (ASTM D4502)	141.05	1274	kg/m ³
Viscosity (ASTM D445)	–	2.32	cSt
Acidity (pH meter)	–	2.3	–
Water content (ASTM E203)	–	48.15	wt%
Proximate analysis (Shimadzu TGA50)			
- Moisture	6.25	–	wt%
- Volatile matter	28.49	–	wt%
- Fixed carbon ^a	58.88	–	wt%
- Ash content (700 °C)	6.36	–	wt%
Ultimate analysis (Perkin Elmer PE2400 Series II)			
- C	25.23	56.41	%
- H	2.04	6.42	%
- N	0.93	2.16	%
- O ^a	65.70	71.28	%
- S	0.52	1.11	%

^aFixed Carbon and Oxygen were calculated by difference.

Moreover, the chemical components of pyrolysis oil were also tested by GS–MS. The gas chromatography/mass spectrometry analysis of pyrolysis oil were conducted by using Bruker model 450GC for gas chromatography and 320MS for mass spectrometry with Rtx-5MS capillary column, 30 m × 0.25 mm, film thickness 0.25 μm. The 50 μl of pyrolysis oil was diluted in 950 μl of Methyl Alcohol, and the samples were filtered through membrane with 0.45 μm pore size. Testing conditions were as following: injection volume 2 μl, temperature 300 °C, carrier gas Helium, gas flow rate 1.0 ml/min, identification NIST mass spectral library 2008. The chemical components of pyrolysis oil at 480 °C of bed temperature, 7 m/s of superficial velocity, and 60 kg/h of feed rate were reported in Table 3.

The gas components of NCG for each of feed rates at 480 °C of bed temperature, at 7 m/s of superficial velocity were investigated and are shown in Table 4.

The results from Table 4 found that the concentrations of CO, CO₂, and HC had increased due to that fact that the combustion of the feedstock was intense at the high feed rate. On the other hand, a decrease in the feed rate of the feedstock had a diluting effect on combustion, which had increased the conventional concentration of O₂.

3.3. Energy consumption and efficiency of energy conversion

An energy source in this plant used LPG to generate heat and electricity for any parts of the machine, such as the blower, feed motor, cooling tower, cooling pump, and the spark ignition. Table 5 shows the energy consumed in the process at 480 °C, at a superficial velocity of 7 m/s. It was these conditions that had created the maximum yield for pyrolysis oil production. Furthermore, this section showed an ability of cold efficiency and total energy conversion to pyrolysis oil, which both of relations can be expressed in Eqs. (2) and (3), respectively.

$$\text{Cold efficiency} = \frac{\text{Energy of pyrolysis oil}}{\text{Energy of feedstock}} \times 100\% \quad (2)$$

$$\text{Total energy conversion} = \frac{\text{Energy of pyrolysis oil}}{\text{Total energy input}} \times 100\% \quad (3)$$

Table 5 shows the cold efficiency and the total energy conversion to pyrolysis oil, in which cold efficiency represents the ratio of energy from the bio-oil per energy of feedstock, it was found that the feed rate of 60 kg/h had shown a value of cold energy and total energy conversion that had been greater than other feed rates because the maximum yield of pyrolysis oil can be

produced under this condition. Moreover, it was observed that the greatest energy consumption in this system was the energy from the heating process and this result was found to be similar to other research studies (Cai and Liu, 2016; Cai et al., 2018; Lu, 2007; Lu et al., 2008; Treedet and Suntivarakorn, 2012; Wang et al., 2005; Mei et al., 2016) which had used LPG as fuel in the system. For this reason, many studies, previously mentioned in the introduction, have re-used materials or waste from processes, such as feedstock, charcoal, or NCG, and have put them back into heating process in order to reduce this energy consumption. Thus, the method used to improve the pyrolysis system for pyrolysis oil production was to decrease the consumption of energy during the heating process. However, regarding the reuse of materials or waste products from the process, it should be considered as to whether or not they can generate a sufficient amount of heat to complete the pyrolysis process. Moreover, there should be concerns about the concentrations of oxygen from the combustion process, which can directly affect the quality of the pyrolysis oil.

Table 6 shows the energy conversion efficiency in the present study and compares it to the findings from the literature. The results indicated that the value of cold efficiency and total energy conversion to pyrolysis oil in this system were 24.88% and 19.77%, respectively. From the results of the study of pyrolysis oil production from rice husks (Lu, 2007) and cotton stalks (Lu et al., 2008) by Lu et al., it was found that the cold efficiency and total energy conversion to pyrolysis oil had higher values than those of the present study. This is due to the fact in the pyrolysis oil production carried out by Lu et al. nitrogen had been used as the medium to directly convey heat into the reactor, which means that the system could be completely controlled in the absence of oxygen. For this reason, the pyrolysis oil created in the study by Lu et al. had exhibited a low moisture content and a high heating value. When the pyrolysis oil production in present study was compared with the results from Cai et al. in which 3 tons of pyrolysis oil was produced per day from rice husks (Cai and Liu, 2016; Cai et al., 2018), it was found that the system of Cai et al. had reused NCG to recycle back into process in order to reduce the production costs, which was similar to the present study. Reusing NCG to recycle it back into process gives the pyrolysis oil a higher moisture content, which causes the pyrolysis oil to have a lower heating value.

Even though using inert gases to convey heat can create a pyrolysis oil with the quality of having high energy, production using this system will increase the production costs due to the medium of the gases. This is an important factor to take into consideration when constructing a pyrolysis oil plant on a commercial scale.

3.4. Production costs

From the data concerning the consumption of energy to produce pyrolysis oil and other costs, such as labor, raw material preparation, and transportation, it can be calculated the production cost of pyrolysis oil, which had a production cost of 0.481 \$/l or 9.88 \$/GJ at the 75 kg/h of feed rate. Even though the feed rate of 60 kg/h was determined as the best condition to produce the maximum pyrolysis oil of 36.93 wt%, this feed rate did not have the lowest production cost because the total pyrolysis oil that can be produced at a lower feed rate is lower than that which can be produced at a higher feed rate. Yet, the operating costs for each of the feed rates are close in value. The production cost data for pyrolysis oil production at each of the feed rates is shown in Table 5. In addition, Table 7 shows a comparison of the costs of pyrolysis oil production in the present study and in the literature. From the study results of Peacocke et al. (2004), Ringer et al. (2006), Dynamotive (2009), Badger et al. (2010), Wright et al. (2010) and Rogers and Brammer (2012) in Table 7, they conveyed NCG back to process for decreasing a production cost which was similar to this study, but the

Table 3

Chemical components of pyrolysis oil at 480 °C of bed temperature, 7 m/s of superficial velocity and 60 kg/h of feed rate.

Retention time (min)	Compound name	Formula	Chemical components (%)
2.69	Acetic acid	C2H4O2	34.98
2.97	2-Propanone, 1-hydroxy-	C3H6O2	3.08
3.69	1,2-Ethanediol	C2H6O2	12.62
4.10	o-Ethylhydroxylamine	C2H7NO	2.33
5.75	2-Furanol, tetrahydro-	C4H8O2	0.40
8.22	1,2-Ethanediol, monoacetate	C4H8O3	1.05
10.26	Butyrolactone	C4H6O2	1.00
13.26	Phenol	C6H5OH	0.83
13.50	Butanedial	C5H8O2	1.61
14.48	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	C6H8O2	2.82
16.42	Phenol, 2-methoxy-, acetate	C9H10O3	0.26
16.62	Cyclopropyl carbinol	C4H8O	6.08
17.43	2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	C7H10O2	0.40
20.01	(S)-(+)-2',3'-Dideoxyribonolactone	C5H8O3	2.27
20.28	1,4:3,6-Dianhydro- α -D-glucopyranos	C6H8O4	1.93
20.50	1,2-Benzenediol	C6H6O2	0.84
20.67	2,3-Dihydro-benzofuran	C8H8O	1.52
24.12	Phenol, 2,6-dimethoxy-	C8H10O3	3.16
25.44	Benzaldehyde, 4-hydroxy-3-methoxy-	C8H10N2O2	0.84
26.58	1,2,4-Trimethoxybenzene	C9H12O3	0.39
27.04	Decane, 1-Chloro-	C10H21Cl	0.56
27.15	1-Decanol	C10H22O	1.07
28.68	beta-D-Glucopyranose, 1,6-anhydro-	C6H10O5	16.40
30.33	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	C11H14O3	0.29
31.72	Benzaldehyde, 4-hydroxy-3,5-dimethoxy-	C9H10O4	0.26
32.74	Methoxyacetic acid, dodecyl ester	C15H30O3	0.80
33.30	Ethanone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-	C10H12O4	0.44
33.78	Isopropyl decanoate	C13H26O2	0.23
34.10	1-Butanone, 1-(2,4,6-trihydroxy-3-methylphenyl)-	C11H14O4	0.38
35.17	Eicosanoic acid, 2-hydroxyethyl ester	C22H44O3	0.17
38.38	Diethylene glycol monododecyl ether	C16H34O3	0.72
43.33	Pentaethylene glycol monododecyl ether	C22H46O6	0.48
Total (%)			100.00

Table 4

The gas components of NCG.

Type of gas	NCG at each of the feed rates (kg/h)			Unit
	45	60	75	
O ₂	0.2	0.1	0.1	% vol
CO	2.02	2.21	2.52	% vol
CO ₂	14.3	14.6	14.8	% vol
NO _x	0	0	0	ppm
HC	660	730	816	ppm

study of them produced a pyrolysis oil from wood and corn stove. Moreover, the utilization of LPG and NCG to produce a pyrolysis oil, SingBua et al. (2017) and Treedet and Suntivarakorn (2018) have studied a new method to produce a pyrolysis oil by using Napier grass and sugarcane bagasse, respectively. The data from the literature relates to pyrolysis oil production on a commercial scale, which has a feed capacity from 2.4 to 2000 tons per day. The data on pyrolysis oil production from many research studies has differed due to the efficiency of the processes used, the quality of the pyrolysis oil produced, and the global economic factors of the time period.

4. Conclusion

This research analyzes the production of pyrolysis oil from Napier grass using a fast pyrolysis system with the Circulating Fluidized Bed Reactor. The research aims to find the production cost yielded from producing pyrolysis oil from Napier grass in comparison with the costs resulted from using other forms of energy substitutes. LPG is applied via a can combustor, which is a heat generator for the system heating. Moreover, NCG circulation system and heat conversion device are installed to help save energy in the production system.

Table 5

The energy consumption and production cost of pyrolysis oil production system.

No.	Description	Feed rates (kg/h)		
		45	60	75
- Energy input to system (MJ)				
1	Feedstock	685.35	913.80	1142.25
2	Air blower 1	7.02	7.02	7.02
3	Air blower 2	6.30	6.30	6.30
4	Re-circulating blower	4.32	4.32	4.32
5	Feed motor	0.72	0.79	1.19
6	Water pump	5.22	5.22	5.22
7	Cooling tower motor	1.26	1.26	1.26
8	Spark ignition	0.05	0.05	0.05
9	LPG	198.91	211.34	222.39
- Energy from pyrolysis oil (MJ)				
10	Pyrolysis oil from Napier grass	146.51	227.37	248.58
Cold efficiency (%)		21.38	24.88	21.76
Total energy conversion (%)		16.12	19.77	17.88
Yield of pyrolysis oil (wt%)		31.73	36.93	32.3
Actual production of pyrolysis oil (kg/h)		14.28	22.16	24.23
Operating cost (\$/h)		4.32	4.53	4.74
Cost of pyrolysis oil production (\$/l)		0.743	0.503	0.481

Table 6

A comparison of energy conversion efficiency to the literature.

Pyrolysis oil production from the literature	Cold efficiency (%)	Total energy conversion to pyrolysis oil (%)
Present study	24.88	19.77
Lu (2007)	73.01	48.19
Lu et al. (2008)	61.12	42.00
Treedet and Suntivarakorn (2012)	27.05	3.77
Cai and Liu (2016) and Cai et al. (2018)	53.17	20.86
Mei et al. (2016)	46.70	-

Table 7
A comparison of costs for pyrolysis oil production as compared to the literature.

Study	Pyrolysis oil cost		Feed capacity (tons/day)	Year
	\$/l	\$/GJ		
Solantausta et al. (1992)	0.156	7.30	1000	1992
Cottam and Bridgwater (1994)	0.108	5.00	1000	1994
Gregoire and Bain (1994)	0.132	6.10	1000	1994
Islam and Ani (2000)	0.458	21.20	2.4	2000
Islam and Ani (2000)	0.217	10.10	2.4	2000
Mullaney et al. (2002)	0.320	14.50	100	2002
Mullaney et al. (2002)	0.235	10.60	400	2002
Peacocke, et al. (Wellman plant) Peacocke et al. (2004)	0.204	9.50	48	2004
Peacocke, et al. (BTG plant) Peacocke et al. (2004)	0.172	8.00	48	2004
Marker et al. (2005)	0.114	5.10	2000	2005
Marker et al. (2005)	0.146	6.77	500	2005
Ringer et al. (2006)	0.164	7.62	550	2006
Uslu et al. (2008)	0.177	6.00	132	2008
Velden et al. (2008)	0.241	11.63	–	2008
Dynamotive (2009)	0.196	4.04	200	2009
Badger et al. (2010)	0.249	11.54	100	2010
Czernik et al. (2010)	0.127	6.00	–	2010
Wright et al. (2010)	0.220	10.19	2000	2010
Rogers and Brammer (2012)	0.242	11.25	400	2012
Jones and Male (2012)	0.156	7.24	2000	2012
Brown et al. (2013)	0.466	21.73	15	2013
Czernik and French (2014)	0.206	9.57	–	2014
Mirkouei et al. (2016)	0.304	14.11	13.6	2016
SingBua et al. (2017)	2.357	146.54	0.54	2017
Treedet and Suntivarakorn (2018)	0.353	9.56	1.08	2018
The present study	0.481	9.88	1.8	2018

With regard to the production capacity, the system was able to reach the maximum of pyrolysis oil production at 36.93 wt% at 60 kg/h feeding rate, 480 °C bed temperature, 7 m/s of superficial velocity. The estimation of The Quadratic Response Model indicates that 60.39 kg/h feed rate, 473.68 °C bed temperature, and 7 m/s superficial velocity are the best condition for the production of pyrolysis oil. With regard to the property of the pyrolysis oil produced from the system, the heat and the density values were measured at 19.79 MJ/kg and 2.32 cSt, respectively. The quality of the oil at this level is applicable to steam engines and gas-turbine engines but not to the diesel ones. Since the pyrolysis oil produced by this system has rather a low pH value, it is important for the oil to undergo quality improvement to make it usable for other types of engines.

The result relating to the system's energy consumption, the maximum cold efficiency and total energy conversion to pyrolysis oil were gauged at 19.77% and 24.88%, respectively. As frequently reviewed in other research, it was observed in this study that the heat from LPG used for heating the system had consumed the highest energy. This is the reason why feedstock, NCG, and charcoal were used in place of LPG in many studies. However, when reusing the production materials, the operators have to consider whether the heating material can adequately heat the system or how it generates change in the quality of pyrolysis oil due to the contamination of oxygen in the system. The pyrolysis production cost resulted from energy consumption and other production costs was rated at 0.481 \$/l, which is compatible to the 9.88 \$/GJ of the energy capital.

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