Efficiency of Bio-oil Production from Napier Grass Using Circulating Fluidized Bed Reactor with Bio-oil Scrubber

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ABSTRACT

This work is to study the efficiency of bio-oil production with and without bio-oil scrubber in a circulating fluidized bed reactor. Napier grass was used to be a raw material for pyrolysis process. The experiment was performed at biomass feed rate of 45, 60, and 75 kg/h, the temperature from 440°C to 520°C and the superficial velocity of 7 m/s. The effect on temperature and feed rate of the pyrolysis process, bio-oil properties, cold efficiency and energy conversion were studied. The experimental results show that the maximum yield of pyrolysis oil with and without bio-oil scrubber were 44.60wt% and 43.73wt%, respectively. The properties of bio-oil were investigated and it was found that the Higher Heating Valuer (HHV), cold efficiency and energy conversion in this system were 12.29 MJ/kg, 29.94%, and 20.66%, respectively. The bio-oil scrubber can improve the bio-oil production with the increasing of bio-oil yield of 1.99% compared with the system without bio-oil scrubber and it can solve the problem in fluidized bed reactor.

Keywords: Bio-oil production, Fast pyrolysis, Napier grass

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Introduction

Nowadays, biomass is one of the abundant natural resource on this earth. Biomass also had advantages such as cheaper, environment friendly and available abundant from agriculture residues industry. Biomass can be converted into renewable energy through pyrolysis, gasification, liquefication, and combustion [1]. The pyrolysis process was very interest to produce bio-oil from biomass mainly into bio-oil, bio-char, and Non-condensable gas (NCG). The advantages of pyrolysis are directly produced liquid fuel to boilers, furnaces, engines, and turbines which the liquid fuel also can be readily stored and transported [2]. The relationship between slow pyrolysis and fast pyrolysis has reported by [4–7]. For this reason, fast pyrolysis process was better than that slow pyrolysis. In fast pyrolysis process, biomass was very fast heated in the absence of oxygen [1-2, 7] and fast pyrolysis had advantages such as very high heating transfer, short hot vapor residence, rapid removal of char and more bio-oil product.

Bio-oil is uncontributed to CO_2 emission and global warming as the environmental problems. Bio-oil can be generated from Napier grass as the raw material in this experiment. Napier grass is one kind of biomass that growing abundant in Thailand. The grass in Thailand is known high production (an average of 90-120 tons per hector), weather endurance, low production cost, protein content and offer tasty flavor [8]. The advantages of Napier grass are a source of high heat biomass with an average of 16.58 MJ/kg which it is widely used as an alternative energy for industries [9]. Napier grass as the raw material was used in this experiment with an estimated age of harvest around of 60 days.

Currently, a lot of experiments had conducted in the flied of the pyrolysis from Napier grass. Lee, et al. [10] performed that the pyrolysis from Napier grass using the induction-heating with pyrolysis conditions at pyrolysis temperature of 500°C, holding time of 3 min, heating rates of 150 $^{\circ}$C /min, and average grass size of 0.224 mm in triplicate. Yakub,et al. [11] conducted that the experiment on the pyrolysis oil derived from Napier grass at the pyrolysis temperature of 450-750°C. Singbua,et al. [12] reported that the pyrolysis oil from Napier grass on the feeding rates of 22.5 kg/h, superficial velocity of 8 m/s, and the reactor temperature was set at a range from 500°C to 520°C under atmospheric pressure. The temperature process had effect on the improvement of bio-oil production that the secondary cracking become in the higher temperature and it can produce more non condensable gases reported by Onay [13]. Pattiya and Suttibak [14] conducted research that the increasing of final pyrolysis temperature up to 700°C, the oil yield goes down to 31%. Asadullah *et al.*[15] reported that the results of bio-oil and gas increase when the temperature increases so that the yield of charcoal decreases. The most important to produce bio-oil is a condenser unit to condense the hot gas to a liquid.

However, the bio-oil yield is heavily influenced by the cooling in the condenser. The cooling should be fast; otherwise, some condensable gas will become into Non condensable gas. Based on the influence of condenser on the improvement of bio-oil production, some researchers have conducted experiment in this field. According to many researchers [11–15] reported that the improvement of bio-oil production is to modify the condenser.

Moreover, there was not a research about the pyrolysis from Napier grass using the scrub-condenser to improve the bio-oil yield. Hence, in this study the main objective is to study the bio-oil production from Napier grass using bio-oil scrubber unit to improve the bio-oil yield. The new system in this research was a condenser unit, in which a condenser unit in the system included a heat exchanger and a nozzle for bio-oil scrubber. An old condenser unit as the previous research [21] was performed to investigate the improvement of bio-oil yield and to compare the cold efficiency of this research. Furthermore, the bio-oil properties and energy consumption for bio-oil production was also analyzed.

Experimental materials, devices and methods

Experimental materials

The experiment materials in this work included Napier grass, sand, and LPG (Liquid Petroleum Gas). To make the uniform size and the consistent feeding, Napier grass was crushed with a crashing machine about 1-3 mm in particle size. (Table 1**)** shown the physical properties of Napier biomass such as bulk density, mean diameter, porosity and heating value, in which the heating value of Napier grass based on ASTM D240. The proximate analysis of Napier grass performed in the (Table 2) such as moisture water, volatile matter, fixed carbon and ash. The elemental analysis of Napier grass was listed in (Table 3) in which the elemental analysis of pyrolysis oil was showed using a Perkin Elmer PE 2400 series II.

Table 1 The physical properties of the experimental materials

Properties	Napier grass	Sand	Units
Mean diameter	1-2	0.249	Mm
Bulk density	137.8	1524	kg/m^3
Porosity	-	42.87	%
Heating value (ASTJ D240)	15.23	-	MJ/kg

Table 2 The proximate analysis of the experimental materials

Properties	Napier grass	Units
Moisture	12.14	wt%
Volatile matter	75.37	wt%
Fixed carbon[a]	7.33	wt%
Ash	5.15	wt%

Table 3 The elemental analysis (Perkin Elmer PE2400 Series II of Materials)

Properties	Napier grass	Units
C	40.03	%
H	6.02	%
N	1.69	%
S	1.08	%
O[a]	51.18	%

[a]Fixed carbon and Oxygen were calculated by difference

Experimental devices

(Figure 1) shows the system developed from previous research [21], in which the new system had a modification of condenser using scrubber in order to increase the ability of condenser to be fast cooling to avoid the secondary cracking and trap some bio-oils. The experimental devices mainly consisted of a Circulating Fluidized Bed Reactor (CFBr), gas combustion, a hopper, two cyclones, gas pre-heater, two condensers, some thermocouples and four pressure meters. The hopper was used to contain feedstock as Napier grass. The reactor had a height at 4.5 m and a diameter of 10 cm in which the Napier grass rapidly heated for pyrolysis. The two cyclones were used to separate solid particle such as charcoal and ash from the hot gas. The condenser unit was able to immediately cool the hot gas into a liquid (bio-oil). Some thermocouples and four pressure maters were used to monitor and control the pyrolysis system. The GC/MS analysis was used to test the chemical composition of pyrolysis oil. The gas chromatography/mass spectrometry analysis of pyrolysis oil were conducted by using Agilent 7890A for gas chromatography and Agilent 7000A for mass spectrometry with DB-wax capillary column, 60 m × 0.25 mm, film thickness 0.25 µm. The 200 µl of bio-oil was diluted in 1 ml of Methyl Alcohol, and the samples were filtered through membrane with 0.45 µm pore size. Testing conditions were as following: injection volume 1 µl, temperature 250 °C, carrier gas Helium, gas flow rate 1.0 ml/min, identification NIST mass spectral library 2008.

(Figure 2) shows the new condenser unit in the system. The new condenser unit was selected as a cross flow type (unmixed) in this system. The overall heat transfer coefficient (U) was determined from a function of the fluid flowing through the heat exchanger, outside diameter (D_o) and inside diameter (D_i). It can be described from:

$$U = \frac{1}{\frac{Do}{hi*Di}+\frac{Do}{Di}fi+\left[\frac{Do}{2K}\right]Ln\left(\frac{Do}{Di}\right)+fo+\frac{I}{ho}} \tag{1}$$

where h_i and h_o are convection heat transfer coefficients inside and outside, respectively. f_i, f_o are fouling factors at those surfaces. The *effectiveness-NTU* (ε) Method was used to find a hot temperature output ($T_{h,out}$), a cold temperature output ($T_{c,out}$) and a heat transfer rate (Q), respectively. It was determined from:

$$Q = \varepsilon * C_{\min} * (T_{h,in} - T_{c,in}) \tag{2}$$

where Q is heat transfer rate and C_{min} is minimal capacity ratio.

Finally, the characteristics of the new condenser unit are shown in (Table 4):

Table 4 The characteristics of the new condenser unit

No	Details	Values	Units
1	Diameter outside (D_o)	0.0334	m
2	Diameter inside (Di)	0.0302	m
3	Long pipe	0.75	m
4	Number row	6	-
5	Number tube	7	-
6	Temperature cold input ($T_{c,in}$)	25	$^{\circ}C$
7	Temperature cold output ($T_{c,out}$)	25.5	$^{\circ}C$
8	Temperature hot input ($T_{h,in}$)	100	$^{\circ}C$
9	Temperature hot output ($T_{h,out}$)	26	$^{\circ}C$
10	Overall heat transfer coefficient (U)	53.2	$W/m^2. ^{\circ}C$
11	Thermal Conductivity (K)	19	$W/m^2. ^{\circ}C$
12	Heat transfer outside (h_o)	56.4	$W/m^2. ^{\circ}C$
13	Heat transfer inside (h_i)	30363.6	$W/m^2. ^{\circ}C$
11	Heat transfer rate (Q)	3.1	kw

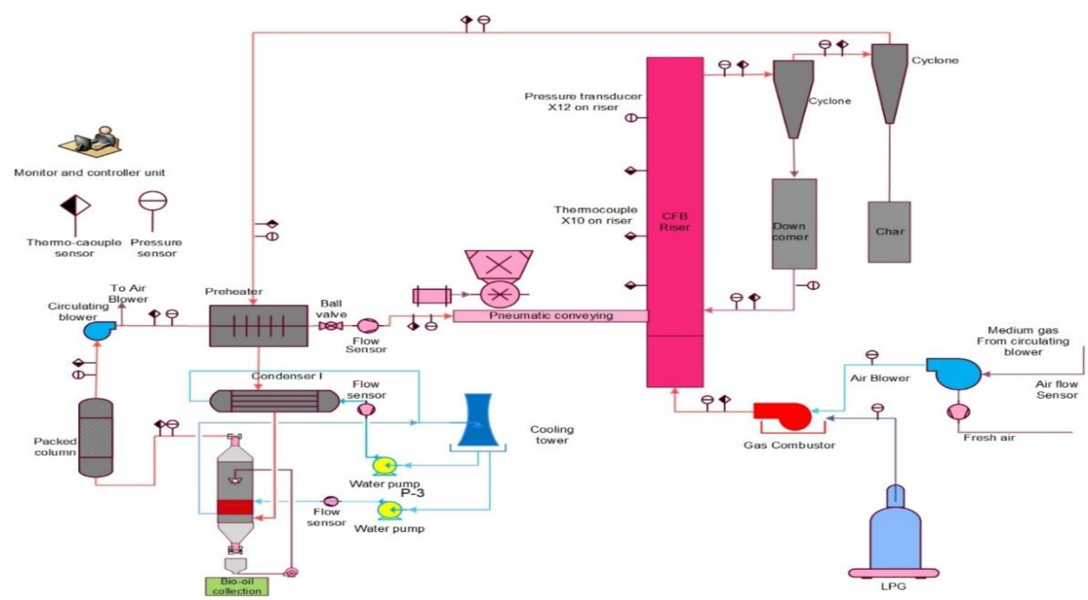


Figure 1 A schematic diagram of the pyrolysis of production system.

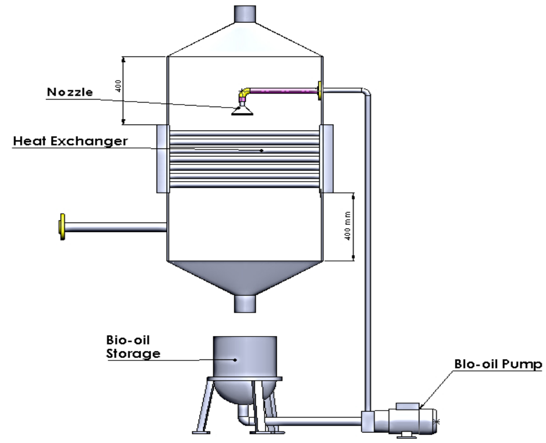


Figure 2 Schematic of bio-oil scrubber in the system

Experimental methods

The experimental methods had four parameters in the fast pyrolysis as follows pyrolysis temperature, feed rate of biomass, superficial velocity and the use of with and without bio-oil-scrubber. The pyrolysis process was performed at bed temperature ranging from 440°C to 520°C The superficial velocity was set at 7 m/s. The biomass type was Napier grass with the feed rate of 45 kg/h, 60 kg/h and 75 kg/h.

The experiment had two configurations as shown in (Figure 3); with and without bio-oil scrubber units. Firstly, consider a system without bio-oil scrubber, the pyrolysis vapor was input in a condenser unit and directly contact with the heat exchanger. The vapor was condensed and the bio-oil was collected in the storage of condenser unit. Secondly, consider a condenser system with bio-oil scrubber, two liters of bio-oil was installed at a storage tank under the condenser unit. The bio-oil pump was installed to pump the bio-oil from a storage tank to the top of condenser unit that called scrubber system. Therefore, the pyrolysis oil obtained from a storage tank actually consist of a mixture of two liters of bio-oil and pyrolysis oil from Napier grass. According to our experiment, the weigh instrument was used to calculate the yield of pyrolysis oil.

The experiment with varying the temperature from 440°C to 550°C, and the feed rate from 45 to 75 kg/h were conducted. The bio-oil yield, properties, energy conversion efficiency and energy consumption were studied.

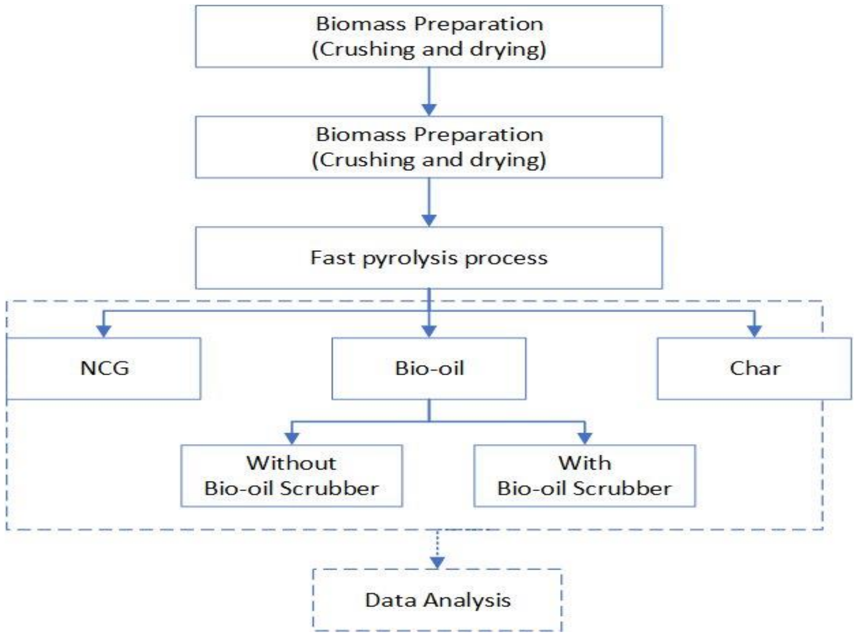


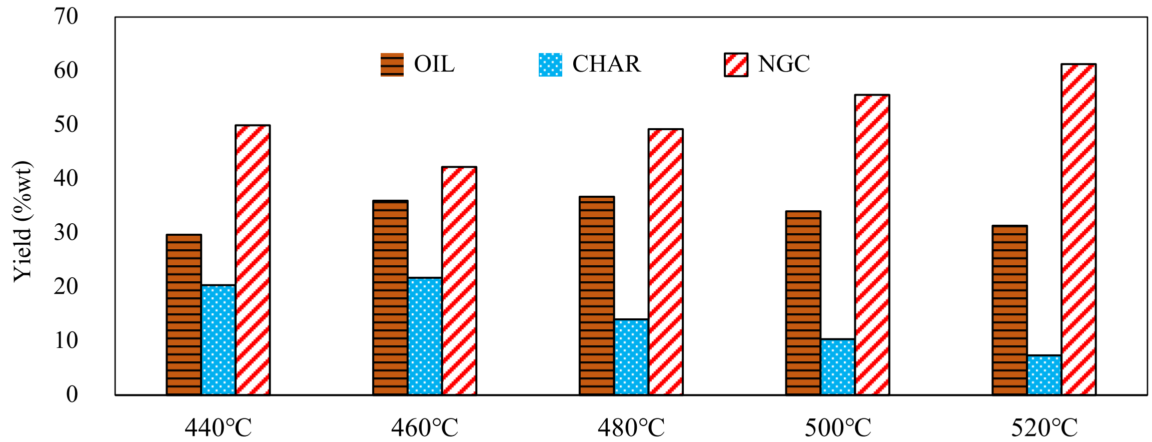
Figure 3 Research flow

Results and discussions

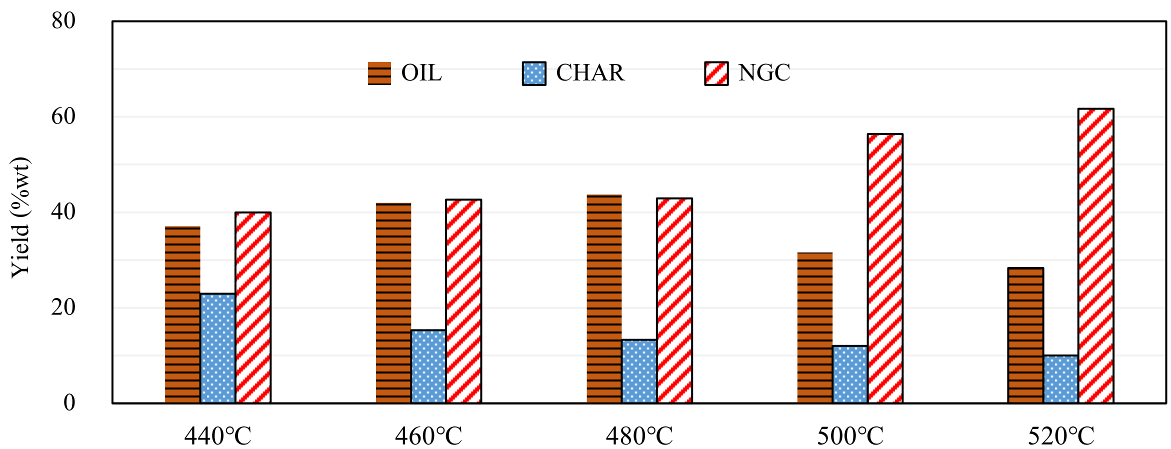
Temperature effect on bio-oil yield

(Figure 4**)** shows the temperature effect on bio-oil yield from Napier grass at a feed rate of 45-75 kg/h and a superficial velocity of 7 m/s. In all experiment, the bed temperature was installed at 440°C, 460°C, 480°C, 500°C, and 520°C. According to our experiment, Temperature has an influence on bio-oil products that the temperature below 440 °C can produce more charcoal and ash. In contrast, temperatures above 520°C are too high to reduce quickly the bio-oil yield.

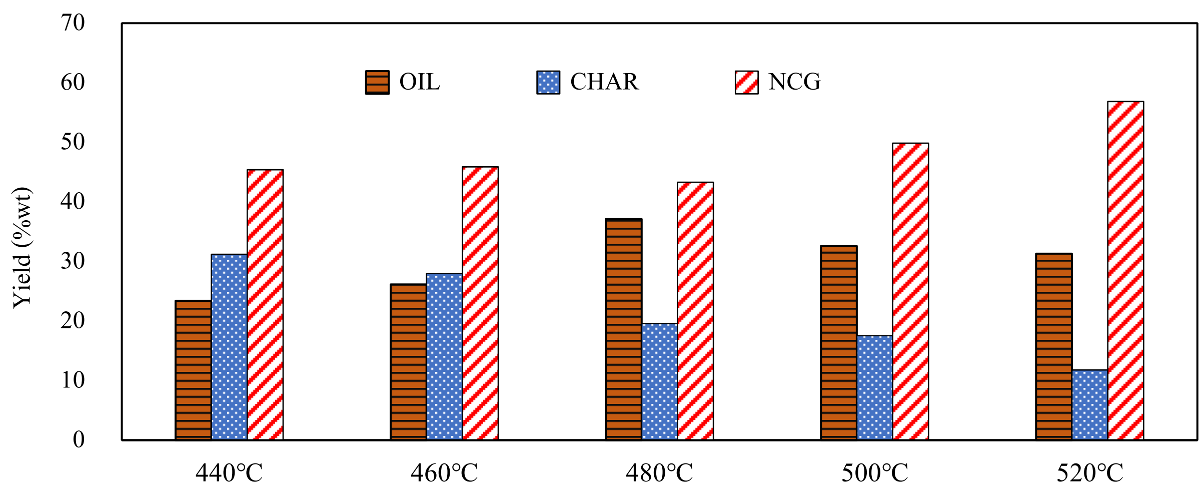
Therefore, the fast pyrolysis in this experiment was able to product the maximum yield oil at the bed temperature of 480°C in every feed rate conditions as shown in (Figure 3). The maximum yield is 43.7 % at the feed rate of 60 kg/h. For the result with bio-oil scrubber, the experiment was conducted with the condition as feed rate of 60 kg/h and temperature of 480°C that the maximum yield with scrubber was 44.60wt%. it was found that: (1) the bio-oil was increase and then it was suddenly decrease with the increase the bed temperature, (2) Charcoal yields was always decrease with the increase the bed temperature because; and (3) Non-condensable gas (NCG) was always increase with the varying temperature. The temperature effect on bio-oil yield can be explained that the high temperature in the system will continue to crack the vapour that called secondary cracking reaction. in this condition the good quenching was required to remove the secondary cracking reaction. The secondary cracking reaction also made break of the hydrocarbon chain while the char was increase at low temperature due to secondary cracking reaction was difficult to take place. Based on the temperature effect on pyrolysis oil, these result was similar with the previous result from Ji-lu, 2007 [22] and Lee, 2010 [10]. However, in our experiment, the maximum yield of pyrolysis oil is higher than that of the previous result.



a) Pyrolysis oil production from napier grass at a feed rate of 45 kg/h



b) Pyrolysis oil production from Napier grass at a feed rate of 60 kg/h



c) Pyrolysis oil production from napier gras at a feed rate of 75 kg/h

Figure 4 Pyrolysis oil at a feed rate between 45 kg/h-75 kg/h without bio-oil scrubber

In this experimental, testing without bio-oil scrubber is known that the maximum yield of bio-oil was at temperature of 480°C and at feed rate of 60 kg/h, then the testing with bio-oil scrubber was carried out at the same conditions which are 480°C of temperature and 60 kg/h of the feed rate in order to compare the performance of the system.

The results with and without bio-oil scrubber are compared with the previous results and shown in (Figure 5). It was found that the bio-oil production with bio-oil scrubber is higher than that without bio-oil scrubber, and both of the results are better than the previous results of Treedet (2018) [21] and Lee (2010) [10] because the bio-oil scrubber in our experiment can help to avoid the thermal cracking reaction and to rapidly cool the hot gas to a liquid. The additional of bio-oil scrubber in the condenser system is important to solve the dirty problem in the circulating blower because the problem can reduce the bio-oil yield and increase the electricity

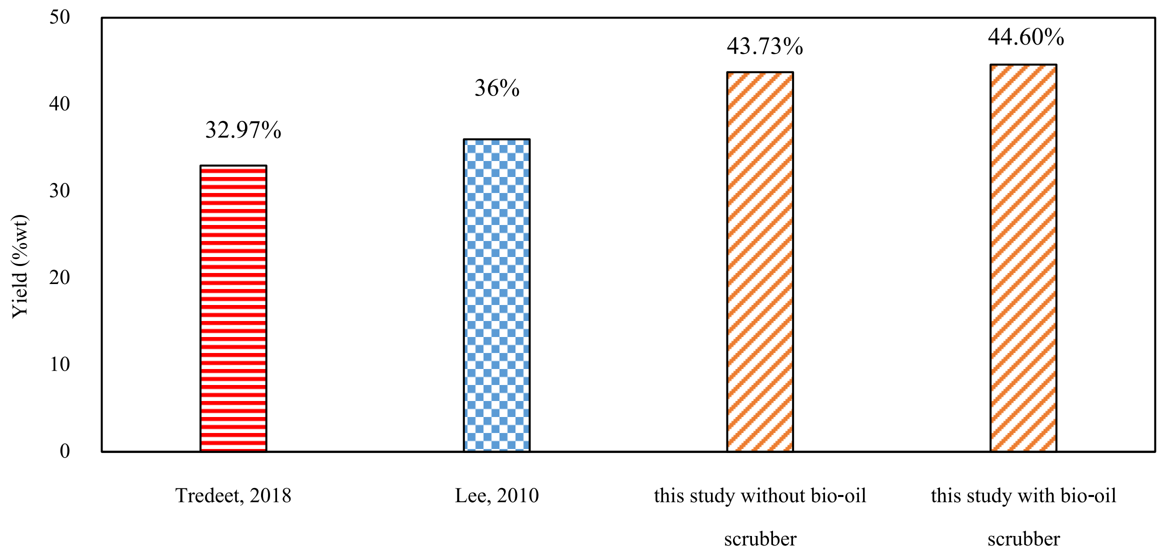


Figure 5 The comparison of bio-oil yield between a system with and without bio-oil scrubber

Influence of bio-oil scrubber on bio-oil yield

In the pyrolysis process, when the Non-condensable gas was sucked back into the system, it will flow through the circulating blower and makes the surface of blower dirty as shown in (Figure 6**).** In addition, the problem is that it reduced the amount of bio-oil and caused the increasing of electricity. The circulating blower had a black color on the surface before using bio-oil scrubber because a condenser unit was not fully function to condense a hot gas into liquid and not completely to avoid thermal cracking reaction. Therefore, Non-condensable gas was increased and condensed at a circulating blower. After using the bio-oil scrubber, the NCG will be condensed at the scrubber unit and it can reduce problem that occur. The surface of blower is cleaner and the scrubber can produce more pyrolysis oil. Moreover, the first condenser design is small size, it has been improved the capacity and also can be solve the dirty problem in the system.

a) Before using bio-oil scrubber   b) After using bio-oil scrubber

Figure 6 The condition of circulating blower before and after using bio-oil scrubber

The properties and compositions of bio-oil

(Table 5) shows the main properties of bio-oil in the pyrolysis process with bio-oil scrubber. The result indicated that the composition of bio-oil is oxygen, carbon, hydrogen, and nitrogen with the percentage of 54.38%, 36.57%, 7.40%, and 1.65%, respectively. The heating value is 17.29 MJ/kg. The pyrolysis oil was tested by GC/MS. From the testing, it was found that the compositions of bio-oil are organic compounds and hydrocarbon compounds. Hydrocarbon compounds make the bio oil be combustible. Most hydrocarbons are used as engine and industrial fuels. Moreover, an organic compound consists of water, acids and heterocyclic substances that can make the pyrolysis oil viscous and easily be polymerized. The result of GC/MS analysis shown in the (Table 6).

Table 5 Main properties of Bio-oil from Napier grass at a feed rate of 60 kg/h with bio-oil scrubber

Properties	Bio-oil
HHV (MJ/kg)	17.29
Carbon (%wt)	36.57
Hydrogen (%wt)	7.40
Nitrogen (%wt)	1.65
Oxygen (%wt)	54.38

Table 6 Chemical compositions of bio-oil from Napier grass at a feed rate of 60 kg/h with bio-oil scrubber

Compound Name	Area %
Acetic acid	15.56
Formic acid	2.59
Propanoic acid	0.96
4-Nitro-3-oxobutyric acid, methyl ester	1.10
2-Propenoic acid	0.37
Butanoic acid	1.21
Methane	0.30
2-cyclopenten-1-one	0.11
1-hydroxy-2-butanone	0.84
2,5-Hexanedione	0.22
2-cyclopenten-1-one.3-methyl	0.26
Benzaldehyde, 3-hydroxy	2.00
Phenol	1.88

Energy conversion and cold efficiency

Bio-oil production system in this study used the LPG as heat resource. The energy supply to start up the system was used electricity such as feed motor, three blowers, cooling tower, cooling pump and the spark ignition. The consumption of electricity to produce bio-oil at 480°C was measured by power analysis that can be show the result in (Table 7). Furthermore, the performance of system was known by calculate of cold efficiency. the cold efficiency can be expressed in Eqs (3). Cold efficiency (μ_c) is the ratio of the energy from pyrolysis oil (Q_b) per energy of feedstock (Q_f). The equation was displayed as bellow:

$$\mu c = \frac{\boldsymbol{Qb}}{\boldsymbol{Qf}}\ x\ 100\% \quad (3)$$

when $Q_b = m_b\ x$ HHV$_b$ and $Q_f = m_f$ x HHV$_f$. m_b and m_f are mass of bio-oil and feed stock, HHV$_b$ and HHV$_f$ are heating value of bio-oil and feed stock, respectively. The energy conversion efficiency is obtained from energy output (Q_b) divided by energy input (Q_t). The cold efficiency and total energy conversion of pyrolysis oil on the system with bio-oil scrubber at 480°C of bed temperature and the feed rate of 60 kg/h was shown in (Table 7). It was found that the cold efficiency and energy conversion efficiency were 29.94% and 20.66%, respectively.

Table 7 The cold efficiency and total energy conversion of pyrolysis from Napier grass with bio-oil scrubber.

No.	Description	Energy consumption at 60 kg/hr (MJ)
Energy input to system		
1	Energy from feedstock (Q_f)	913.80
2	Air blower 1	7.02
3	Air blower 2	6.30
4	Re-circulating blower	4.32
5	Feed motor	0.79
6	Water pump	5.22
7	Cooling tower motor	1.26
8	Spark ignition	0.05
9	LPG	211.34
Total Energy (Qt)		1150.10
Energy from pyrolysis oil		
10	Pyrolysis oil from Napier Grass (Q_b)	237.65
Cold efficiency (%) (Q_f / Q_b)		29.94 %
Total energy conversion to bio-oil (%) (Q_b / Q_t)		20.66%

Conclusions

In this study, the efficiency of bio-oil production from Napier grass was conducted with and without bio-oil scrubber. The experiment was performed on the temperature ranging from 440°C to 520°C, a feed rate of 45 kg/h-75 kg/h and a superficial velocity of 7 m/s. The system with bio-oil scrubber can solve a problem in the circulating blower and can produce the pyrolysis oil higher than that without bio-oil scrubber. The experimental result shows that the maximum yield of pyrolysis oil with and without bio-oil scrubber were 44.60wt% and 43.73wt%, respectively. The temperature had an effect on the pyrolysis oil. The pyrolysis oil was increase and then it was decreased with the increase of the bed temperature. The Higher Heating Value (HHV), cold efficiency and energy conversion of pyrolysis oil on the system with bio-oil scrubber at 480°C of bed temperature were 17.29 MJ/kg, 29.94% and 20.66%, respectively. These results show that using bio-oil scrubber can improve the bio-oil production system.

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