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Enhanced Utilization of Palm Oil Mill Wastes for Power Generation

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A massive amount of palm oil production has caused serious environmental problems, especially wastes. To minimize this negative impact as well as utilize optimally the produced wastes, an effective utilization of palm wastes, especially empty fruit bunch (EFB) and palm oil mill effluent (POME), for power generation is proposed and analysed in this study. The proposed integrated system consists of three units: EFB gasification, POME digestion and organic Rankine cycle (ORC). In addition, EFB gasification unit integrates EFB drying, gasification and power generation. POME digestion includes anaerobic treatment, power generation and aerobic treatment. The effects of EFB gasification temperature to the net generated power and remaining heat are evaluated. In case that there is remaining heat, it is utilized in ORC unit to generate additional power. Three working fluids for ORC are observed under different turbine inlet pressures. As the results, higher gasification temperature leads to larger net generated power and remaining heat due to high yield of syngas and calorific value. In addition, in ORC unit, cyclohexane showed the highest power generation efficiency than toluene and n-heptane. The highest total net generated power and generation efficiency are 8.5 MW and 30.4 %, respectively.

1. Introduction

High increase in demand for palm oil and its products has led to the massive cultivation of palm trees. Palm and palm kernel oils have become one of the largest revenue for some producing countries including Indonesia, Malaysia and Thailand (Aziz et al., 2015a). In Malaysia, at the end of 2014, palm plantation occupied about 14 % of the total land of the country (Tang et al., 2015). Unfortunately, large production of palm oil also causes some environmental problems, especially wastes. Only about 10 % of the whole palm tree is directly utilized for production of palm oil, while the rest has no significant utilization (Aziz et al., 2015b). Major wastes include EFB, fibre, palm kernel shell (PKS), and POME.

Recently, some efforts to convert the solid wastes into value-added products, such as pellet and bio-fertilizer, have received further attention (Ng et al., 2015). Unfortunately, these utilizations are still limited in a very small amount and the largest of the solid wastes (EFB) are still used for mulching which is disposed to the plantation for nutrients recycle. Unfortunately, this kind of tradition could increase the toxicity inside the soil and also lead to eutrophication. EFB is produced during threshing of fresh fruit bunch (FFB) in order to separate the palm fruit. EFB is considered to have the lowest economic value compared to other solid wastes, hence its further utilization becomes a difficult challenge. EFB has very high moisture content (up to 70 wt% wb), low density, and in bulky condition. Therefore, it demands further treatment such as cutting and drying if it will be utilized further.

On the other hand, POME is a liquid waste, containing water (95 %) and solid (5 %), and is the largest amount of waste having no specific commercial application. It is acidic and dangerous if it is discharged to the environment without any appropriate treatment due to high chemical and biological oxygen demands. At present, the major trend of POME treatment includes anaerobic and aerobic treatments for conversion to biogas and compost. The produced biogas contains about 40 – 60 % CH_4, but large part of it is only flared due to environmental concern without specific effort for further beneficial utilization.

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Therefore, from both economic and environmental concerns, an enhanced waste treatment in palm mill is urgently required. This utilization covers material conversion, energy harvesting and fertilizer. However, due to some barriers related to environmental issue, transportation and labour costs, energy harvesting is considered as the most efficient way to utilize effectively both EFB and POME. Hence, in this study, EFB and POME are utilized effectively as fuel for power generation with high energy efficiency.
Unfortunately, there is very few studies focusing on the effort for integrated utilization of EFB and POME for small-scale power generation with high energy efficiency. O-Thong et al. (2012) conducted co-digestion of EFB and POME with the aims of process simplification and cost reduction. However, lignocellulosic composition of EFB resulted in low biodegradability. In addition, Luk et al. (2013) proposed an integrated drying and power generation using boiler, but their system still showed large exergy loss resulting in lower energy efficiency. Therefore, with the objective of improving further efficient energy utilization from palm mill, in this study, an integrated system based on heat circulation technology was proposed and evaluated.

2. Integrated power generation

2.1 Overall integrated system

Figure 1 shows the schematic diagram of the proposed integrated-system for power generation from EFB and POME. The integrated system consist of three different units: EFB gasification, POME digestion and organic Rankine cycle (ORC) units. Solid, dotted and dashed lines represent material, electricity and heat flows, respectively. To achieve an optimum heat circulation, heat involved in each unit is basically circulated initially inside the same unit. In addition, if there is an unrecoverable heat in a certain unit, the heat will be utilized further in other units. Therefore, the exergy loss in the overall system can be minimized resulting in total high energy efficiency. The concept of heat circulation technology has been described well by Kansha et al. (2013).

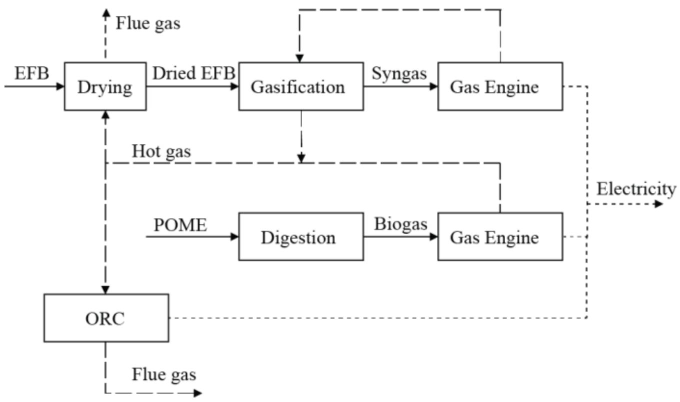

Figure 1: Schematic diagram of the integrated small-scale power generation utilizing EFB and POME.

2.2 EFB gasification unit

Figure 2 shows the process flow diagram of EFB gasification unit. Three continuous processes are involved: EFB drying, gasification, and power generation. Because of high moisture content (resulting in low calorific value and carbon conversion efficiency during gasification), EFB drying is performed initially before gasification. First, EFB from palm mill is collected and physically treated by cutting and shredding to achieve a uniform and small size particles. Next, these particles are fed to dryer for water removal. A rotary dryer is adopted as the evaporator in consideration of possible continuous operation, large heat and moisture transfers area, and easy drying control (Aziz et al., 2014). The rotary dryer is installed slantingly (the feeding inlet is higher than the discharging outlet), therefore EFB particles can move naturally due to gravitational force during drying. In addition, some peripheral blades are also installed inside with the objective of promoting uniform particle mixing and intimate contact between the particles and drying medium.
The energy required for drying is supplied by the exhausted gas from power generation. The dried EFB particles are then exhausted and fed to gasifier for conversion. Air-blown gasification is adopted to convert EFB particles to syngas, which is rich of H_2, CO, and CH_4. The produced syngas and excess air are exhausted from gasifier and their heat are recovered in the gas cooler to preheat the air for gasification. The syngas is then cleaned up to remove undesired matters including particulates, moisture, and H_2S. The cleaned syngas is then flowing to power generation as fuel.
For power generation, gas engine is adopted in this study due to its beneficial characteristics including suitability for small scale power generation, excellent control, familiar maintenance, and broad range of

operating rate. Gas engine utilizes both syngas and biogas produced from EFB gasification and POME digestion units. As the composition of produced gases from both units is different, different gas engines are employed for each unit. A part of the flue gas from gas engine in EFB gasification unit is flown to drying to cover up the required heat for drying (mixed with the flue gas from POME digestion module). In addition, the rest of the flue gas is flowing to ORC unit and utilized as heat source for additional power generation.

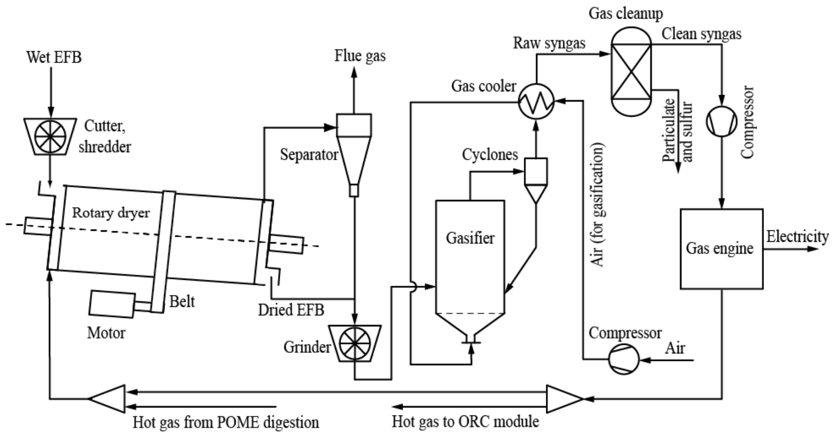

Figure 2: Process flow diagram of EFB gasification unit.

2.3 POME digestion unit

Figure 3(a) shows the process flow diagram of POME digestion unit. POME is discharged in hot condition (70 – 90 °C) from the mill and is flowing to acidification ponds for temperature and pH controls (retention time is about 2 days). It is then fed to anaerobic digestion ponds in where it is broken down by microorganism producing CH_4 rich biogas (retention time is about 60 days). Due to changes in composition and surrounding condition, the produced syngas is fluctuating in terms of CH_4 content and flow rate. Therefore, with the purpose of maintaining a constant flow rate of biogas flowing to gas engine, a flaring system is installed to burn the excess of biogas which is not utilized as fuel for gas engine. The biogas flowing to gas engine is firstly cleaned up and dried to remove H_2S and moisture. The flue gas exhausted from gas engine in POME digestion unit is basically used for EFB drying in EFB gasification unit due to its lesser amount of flue gas than the one exhausted from gas engine in EFB gasification unit (to facilitate easy control). The remained liquid goes to aerobic and maturation ponds for further treatment to reduce its organic content before it is permissible to be channelled to the river or plantation as liquid fertilizer (the retention time is about 2 weeks).

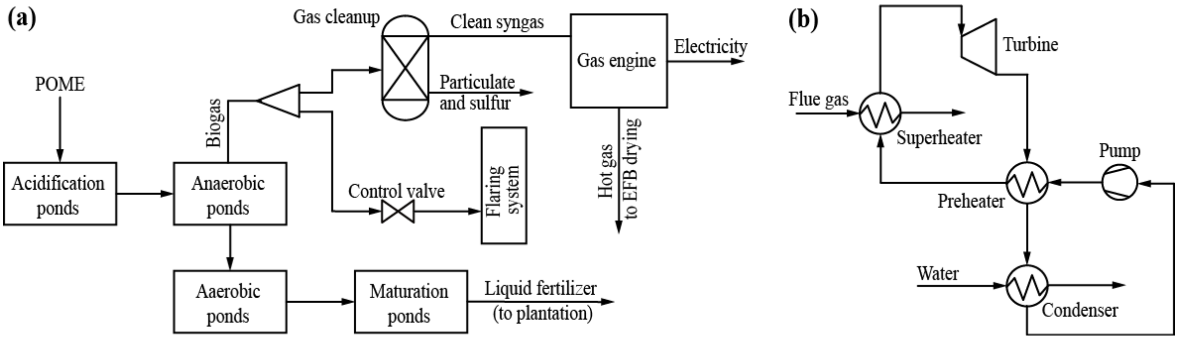

Figure 3: Process flow diagrams of: (a) POME digestion unit, (b) ORC unit.

2.4 ORC unit

In case there is a sufficient remaining heat from the gas engine in EFB gasification unit after a part of flue gas is fed to drying module to cover the required heat for drying, the remaining heat is further recovered for power generation in ORC unit. Figure 3(b) shows the process flow diagram of ORC unit. The flue gas is used to superheat the working fluid hence its phase changes from liquid to vapour and its pressure increases. Therefore, the working fluid expands in turbine to generate additional electricity. In this study, as the flue gas generally has temperature of about 350 – 500 °C, organic working fluids working on relatively high temperature are employed.

3. System analysis

In this study, the effect of EFB gasification temperature to the total net generated power and possible remaining heat is evaluated initially. In addition, in case the remaining heat exists, the effect of turbine inlet pressure to the generated power in ORC unit for each corresponding EFB gasification temperature is also evaluated.
Table 1 shows the assumed conditions of EFB gasification unit. The minimum temperature approach in all heat exchangers including dryer is 10 °C. The electricity consumed for the auxiliaries throughout the system, excluding motor for rotary dryer and compressor for fluidization, is 10 % to which is totally generated. The specifications of gas engine is based on the standard biogas engine manufactured by Yanmar Co., Ltd. (2016). Table 2 shows the compositions of produced syngas in each corresponding gasification temperature (Mohammed et al., 2011).

Table 1: The assumed conditions of EFB gasification unit.

Item	Component	Value
EFB analyses	Proximate (wt% wb)	Moisture 60; volatile 34.84; fixed carbon 3.71; Ash 1.46
	Elemental (wt% db)	C 46.62; H 6.45; N 1.21; S 0.035; O 45.66
EFB drying	Raw EFB flow rate (t/h)	10
	Target moisture content (wt% wb)	5
	Particle diameter (mm)	5
	Rotation speed (rpm)	10
EFB gasification	Temperature (°C)	800, 900, 1,000
	Fluidizing particle diameter (mm)	0.3
POME and its digestion	POME density (t/m^3)	0.98
	Produced biogas (Nm^3/t-POME)	25
	CH_4 concentration (%)	55
Gas engine	Power generation efficiency (%)	32
	Total efficiency (%)	84
	Flue gas temperature (°C)	450

Table 2: Syngas composition of EFB gasification under different gasification temperatures

Component	Temperature (°C)		
	800	900	1,000
Total yield (%)	68.24	80.05	91.7
LHV (MJ/m^3)	11.86	13.84	15.55
H_2 concentration (%)	17.23	27.42	38.02
CO concentration (%)	33.35	33.08	36.36
CH_4 concentration (%)	11.74	14.29	14.72
CO_2 concentration (%)	37.68	25.21	10.90

The energy balance during drying can be approximated as Eq(1).

$$m_g h_{g,in} + m_s h_{s,in} + \frac{m_s\, MC_i}{1 - MC_i}\, h_{w,in} = m_g h_{g,out} + m_s h_{s,out} + \frac{m_s\, MC_f}{1 - MC_f}\, h_{w,out} + m_{w,evp} h_v \qquad (1)$$

Therefore, the heat supplied by the flue gas can be expressed as Eq(2).

$$Q = \frac{m_s\, MC_f}{1 - MC_f}\, C_{p,w}\left(T_f - T_i\right) + m_s\, C_{p,EFB}\left(T_f - T_i\right) + m_{w,evp}\, C_{p,w}\left(T_f - T_i\right) + \Delta H_{evp} \qquad (2)$$

The pressure drop in the bed during gasification, ΔP_f, is approximated using Eqs(3, 4)

$$\Delta P_f = 1.4\, \Delta P_b \qquad (3)$$

$$\Delta P_b = \left(1 - \varepsilon_{mf}\right)\left(\rho_p - \rho_g\right) H\, {}^{g}/_{c} \qquad (4)$$

In ORC unit, three working fluids are observed: toluene, cyclohexane and n-heptane. These working fluids are considered stable (minimum degradation due to temperature and pressure), low cost, and broadly available.

Turbine inlet pressure is observed from 1 to 4 MPa with interval of 0.5 MPa. Turbine and pump efficiencies are set to 90 and 87 %, respectively. Power generation efficiency of ORC unit, η_{ORC}, is expressed as Eq(5).

$$h_{ORC} = \frac{W_t - W_p}{Q_{exh}} \quad (3)$$

4. Results and discussion

4.1 Power and remaining heat from EFB gasification and POME digestion units

Figure 4 shows the generated power (a) and remaining heat (b) from both EFB gasification and POME digestion units. The net generated power increases following the increase of EFB gasification temperature. Numerically it increases from 3.05 to 7.46 MW when EFB gasification temperature is increased from 800 to 1,000 °C. The power generation efficiencies are 11.2, 16.3 and 24.6 % for gasification temperatures of 800, 900 and 1,000 °C. In addition, the power generated from POME digestion unit is constant at 1.18 MW.

The energy for drying can be sufficiently supplied by the flue gas from gas engines without any additional heat from out of the system. Higher gasification temperature leads to larger remaining heat. Unfortunately, the amount of remaining heat in case of gasification temperature of 800 °C is relatively small, about 1 MW. This amount of heat significantly increases to about 8 MW when the gasification temperature is increased to 1,000 °C. Increasing the gasification temperature leads to higher yield of syngas as well as its calorific value. Therefore, larger amount of generated power and heat can be achieved.

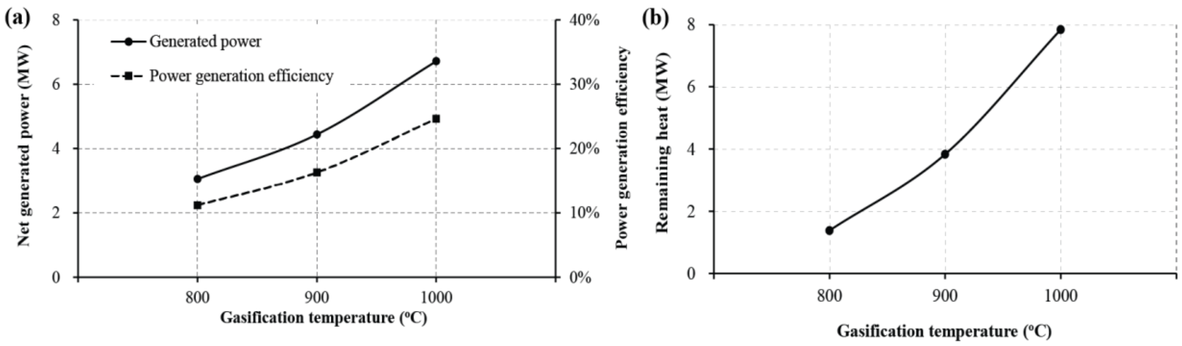

Figure 4: Performance of EFB gasification and POME digestion units: (a) power generation, (b) remaining heat.

A large amount of remaining heat can be utilized for other process creating a cogeneration. These include steam generation which can be supplied to the milling processes. Furthermore, this excess heat also can be utilized for additional power generation through ORC unit. On the other hand, the lower temperature of flue gas can be supplied to anaerobic digestion ponds to enhance digestion.

4.2 Generated power by ORC unit

Figure 5 shows the relationship among generated power, generation efficiency and turbine inlet pressure under different EFB gasification temperatures. As the amount of remaining heat in gasification temperature of 800 °C is very small, only two gasification temperatures are observed: 900 and 1,000 °C. In general, as the turbine inlet pressure increases, both generated power and generation efficiency in ORC unit increase accordingly. Furthermore, cyclohexane shows the highest value and is followed orderly by toluene and n-heptane.

EFB gasification temperature of 1,000 °C shows higher net generated power because of larger amount of remaining heat from EFB gasification unit. The achieved highest power generation efficiency is 15.5 % (1.23 MW) in case that cyclohexane is employed as working fluid with turbine inlet pressure and gasification temperature of 4 MPa and 1,000 °C, respectively. In addition, the highest efficiencies which can be achieved by toluene and n-heptane are 13.7 and 12.3 %, respectively.

Cyclohexane has higher specific heat capacity than other two fluids. In addition, cyclohexane and toluene are isentropic fluid which have a nearly vertical vapour saturation curve, hence the vapour at turbine outlet remains saturated throughout expansion without condensation. On the other hand, n-heptane is categorized as dry fluid which has positive slope on temperature-enthalpy diagram. Hence, the saturated vapour is superheated after isentropic expansion.

Finally, by adopting ORC unit, the total net generated power and power generation efficiency which can be achieved are 8.3 MW and 30.4 %, respectively, under gasification temperature of 1,000 °C and cyclohexane as working fluid in ORC unit.

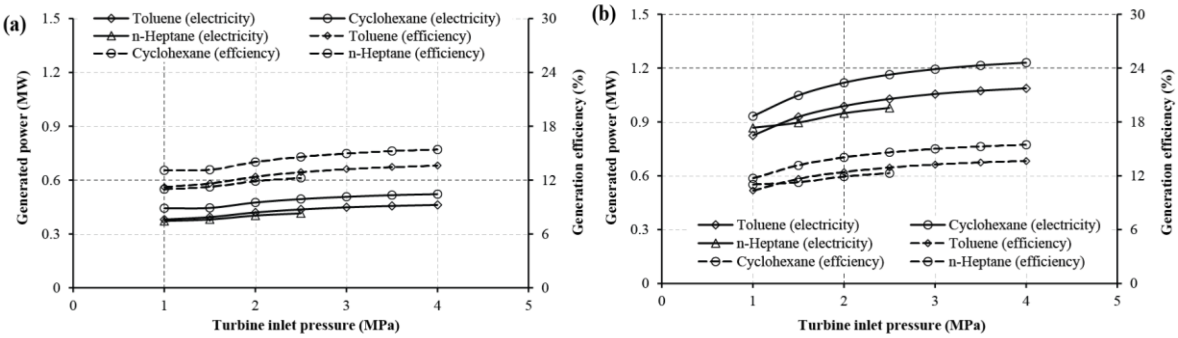

Figure 5: Relationship among net generated power, generation efficiency and turbine inlet pressure under different EFB gasification temperatures: (a) 900 °C, (b) 1,000 °C.

5. Conclusion

An advanced utilization of palm mill wastes including EFB and POME has been proposed and evaluated. The proposed system consists mainly of EFB gasification, POME digestion and ORC units. From process calculation, the proposed system is considered feasible and showing a relatively high total power generation efficiency. Higher EFB gasification temperature (1,000 °C) is recommended due to higher syngas yield and calorific value. Application of the proposed system is believed to be able to improve the economic performance of palm mills. In addition, as palm mills are commonly located in rural areas with poor access of electricity, this application can provide an additional supply of electricity in the needy area, hence increase the electrification across the country.

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