CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863043

Potential of Energy Recovery from an Integrated Palm Oil Mill with Biogas Power Plant

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The Malaysian palm oil industry has made significant contribution to the country's gross domestic product (GDP) due to the increasing global demand of palm oil over the past decades. However, it is undoubtedly a sector that consumes enormous energy and water. With the uprising concerns of the energy resource shortage and global warming, several green technology policies such as the feed-in-tariff policy have been implemented by government to accelerate the sustainable development of palm oil industry in Malaysia. The establishment of feed-in-tariff has successfully increased the number of palm oil mills that are completed with biogas facilities. Recent studies indicate that there are significant amounts of waste heat released from biogas power plant are utilisable as heat source for palm oil mill processes. As an initiative to develop the research of optimizing the energy efficiency of integrated palm oil mill with the biogas power plant, this study is directed toward the analysis of energy balance and material balance of an integrated palm oil mill with biogas power plant which covered both the palm oil milling process energy demand and the biogas power plant waste heat potential analysis. An integrated palm oil mill with biogas power plant running with 120 t/h fresh fruit bunches input was evaluated. The result indicates that there were a total of 3491.66 kW waste heat which corresponded to 46.82 % of the total biogas engine energy input could be recovered for process heating. By fully utilising the biogas plant waste heat as process heating for palm oil mill processes, it is estimated that up to 9.46 % of the total energy supplied could be saved.

1. Introduction

The palm oil industry stays as one of the fast-growing industry as Malaysian palm oil export has shown an uprising trend since 1980s due to the increasing global demands and it is now ranked at second of the largest world crude palm oil (CPO) producers after Indonesia (Chin et al., 2013). However, the palm oil industry has been confronted by several criticisms from the international non-government organisations on the environmental issues particularly the emission of greenhouse gas (CHG) and the excessive amount of palm oil mill effluent (POME) that produced from palm oil milling process (Jamaludin et al., 2016). The biogas generation from POME anaerobic digestion in palm oil mill could be effectively exploited to provide alternative source of energy for the rural electrification (Lee et al., 2017). With the establishment of feed-in tariff (Fit) rates by the government, there are 90 Malaysian mills are completed with biogas facilities which corresponded to 20 % of the nationwide palm oil mills in 2016 (Wan et al., 2016). The biogas from POME is utilised to produce electricity in internal combustion engine with the electrical efficiency from 35 % to 45 % (Loh et al., 2017). Recent studies indicate that more than 55 % of the energy input of the heat engine are converted to thermal energy which commonly released to environment has huge potential to be recovered (Booneimsri et al., 2016). By considering the increasing trend of the palm oil mills that completed with biogas facilities, analysis of material balance and energy balance of the conventional palm oil mill processes including the sterilisation, digestion, sludge separation and fibre-nut-kernel separation alone is not sufficient to provide information of actual heat demands and waste heat potential. A structured material balance and energy balance of an integrated palm oil mill with biogas power plant is presented and discussed in this study.

Please cite this article as: Boon Siang Tan, Haslenda Hashim, Zarina Ab Muis, Nor Alafiza Yunus, Wai Shin Ho, 2018, Potential of energy recovery from an integrated palm oil mill with biogas power plant, Chemical Engineering Transactions, 63, 253-258 DOI:10.3303/CET1863043

2. Methodology

2.1 Analysis of energy and material balance

The integrated material balance of this study was made based on the law of conservation of mass which states that mass can neither be created nor destroyed. The total mass of input ($\dot{m}_{in}$) must be equal to the total mass of output ($\dot{m}_{out}$).

$$\dot{m}_{in} = \dot{m}_{out} \tag{1}$$

Since the palm oil mill processes are nonreactive and mainly involve the separation process, the energy balance was made based on the equation below (Felder and Rousseau, 2005):

$$\dot{Q} = \sum_{out} \dot{m}_i \hat{H}_i - \sum_{in} \dot{m}_i \hat{H}_i \tag{2}$$

$$\dot{Q}_i = \dot{m}_i C_{pi} \Delta T \tag{3}$$

Where the $\dot{Q}$ represents the enthalpy change of the process, $\dot{m}_i$ is the mass flow rate (kg/h) of a species, $\hat{H}_i$ is the specific enthalpy of the species (kJ/kg), ΔT means the temperature difference (K or °C) whereas C_{pi} represents the specific heat capacity of the i-species (kJ/kg·K) which tabulated in Table 1.

Table 1: Specific heat capacity of the palm oil mill component

Species	C_{pi} (kJ/kg·K)	Species	C_{pi} (kJ/kg·K)
Fresh Fruit Bunch	3.231 (Ab Hadi et al., 2015)	Mesocarp Fibre	2.816 (Ab Hadi et al., 2015)
Empty Fruit Bunch	1.483 (Nyakuma et al., 2013)	Palm Shell	2.083 (Fono-Tamo and Koya, 2013)
Nuts	2.291 (Ab Hadi et al., 2015)	Palm Kernel	2.567 (Ab Hadi et al., 2015)

2.2 Percentage of energy saving by recovering biogas power plant waste heat

$$\text{\% of Energy Saving by Waste Heat Recovery} = \frac{\text{Total Recoverable Waste Heat from Biogas Power Plant}}{\sum \dot{Q}} \tag{4}$$

2.3 Case study and data collection

The material and energy balance were performed based on the raw data collected from a palm oil mill with capacity of 120 t/h FFB input in Malaysia. The values of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of the POME were obtained from the laboratory at the palm oil mill whereas the heat engines operating data were collected from the biogas power plant of this case study.

3. Findings

3.1 Palm oil mill material and energy balance

Figure 1 shows the process block diagram of integrated palm oil mill with biogas power plant based on 120,000 kg/h FFB input basis. The entire process flow is categorised into 3 main sections namely palm oil mill, POME effluent and biogas power plant. According to Figure 1, stream 1 to stream 49 covered the sterilisation, digestion, oil purification, sludge separation, fibre-nut and shell-kernel separation process whereas stream 20, 50 and 51 were about the POME released from the palm oil mill processes. Table 2, 3, 4, 5 and 6 show the material balance and energy balance for every stream from stream 1 to stream 49 while Table 7 presents the material flow for stream 50 to stream 56. Table 8 shows the biogas heat engine energy balance data that reveals the waste heat potential of the heat engines. Based on the basis of 120 t/h FFB, stream 7 highlighted that there were 80,400 fruitlets which is corresponded to 67 % of the FFB detached in the thresher. Stream 6 indicates that there were 27,720 kg/h of wet EFB (23.1 % to FFB) conveyed for pressing and thus sending back for mulching on oil palm plantation. Apart from EFB and fruitlets, the rest are losses such as the debris of fiber, silts, sands and other solids components. While the detached fruits were sent for digestion and the flesh fruits were then circulated into the pressing machine with hot water to be pressed (Kramanandita et al., 2014). By considering the palm oil flowrates in stream 10 and the flesh fruits flowrates of stream 9, the data shows that flesh fruits produce 33.4 % of palm oil through digestion. This finding is consistent with the values proposed by Subramaniam et al. (2013) in their study. The crude oil produced in pressing station was flowed into continuous clarification tank for separating the sludge from oil by gravity. The moisture of clarified palm oil was removed by vacuum dryer and the end products of the entire oil purification process are the CPO with less than 0.1 % of moisture content and 0.01 % of dust and solid impurities.

Stream 26 shows the press cake as by-product generated in the pressing station consisted of 16,818 kg/h wet fiber (with residual oil) and 14,386 kg/h nuts (dry basis) were separated through depericarper, nut cracker, hydro cyclone and clay bath. The separated mesocarp fibers contain about 5 % of residual oil undergo further oil extraction process by using solvent extraction technology and the products are palm fiber oil in red color nature due to the high content of carotene (1,500 – 2,000 ppm). Thus, the de-oiled dry fiber was mixed with shell and sent to boiler station for generating superheated steam at 2.5 MPa which is then used for driving the turbine and then generating electricity for the mill operation.

According to the energy data tabulated from stream 1 to stream 49, the total energy consumption of palm oil mill was determined by using Eq(2) and Eq(3) and the result indicates that up to 36,912 kW was needed for running a conventional palm oil milling process. The sterilisation is the major contributor to the total energy consumption due to the tremendous usage of 3 bar saturated steam (S4). The condensate from steriliser (S2), waste water with shells, fiber debris released from hydro cyclone (S35) and the clay bath (S37) were known as Palm Oil Mill Effluent (POME) were then undergo anaerobic digestion to reduce its COD and BOD values (Singh et al., 2010). Table 7 shows the stream summary from S50 to S56. With the ratio of 38.13 m^3 biogas/m^3 POME, 1,324 m^3 of biogas (1,523 kg/h) was generated and undergo a series of upgrading process to reduce its moisture content and H_2S concentration to prevent any possible damages to the biogas heat engine.

Based on the case study, there are 3 units of biogas spark-ignition heat engines running at 24 h to generate 2,779.98 kW electrical power where 1,967.54 kW was supplied to the nearby residential areas through national grid while the rest was used on site. However, typical heat engines can only run with maximum efficiency up to 45% while the rest lost in the form of thermal energy to the surrounding. According to Table 8, there were total 2,314.32 kW heat content in engine flue gas at 475 °C which released to the environment without heat recovery. The flue gas waste heat can only be utilised and recoverable from 475 °C to 150 °C to avoid the condensation of sulfuric acid (130°C) which might cause chemical corrosion (Booneimsri et al., 2016). The total jacket water heat loss of 1,908.18 kW is considered as low-grade heat loss as the temperature of hot jacket water is at around 88 °C before entering radiator. By fully utilising the waste heat of biogas power plant, it is expected to save up to 9.46 % of the total energy supplied for palm oil mill processes (Eq(4)).

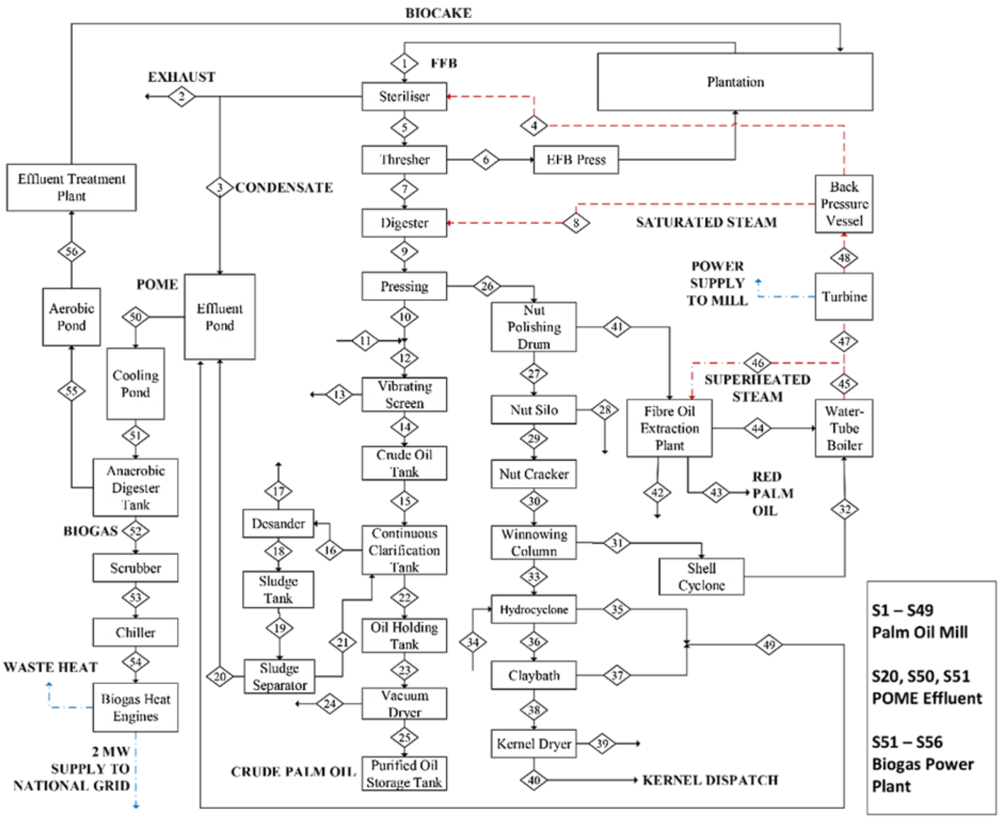

Figure 1: Process block diagram of palm oil mill with biogas power plant

Table 2: Energy and material balance summary from Stream 1 to 10

		Stream Number									
	Unit	1	2	3	4	5	6	7	8	9	10
Temperature	°C	30	110	90	144	100	90	90	144	95	90
FFB	kg/h	1.2×10^5	0	0	0	1.1×10^5	0	0	0	0	0
EFB	kg/h	0	0	0	0	0	9,367	0	0	0	0
Fruitlets	kg/h	0	0	0	0	0	0	8.0×10^4	0	0	0
Flesh Fruits	kg/h	0	0	0	0	0	0	0	0	8×10^4	0
Palm Oil	kg/h	0	0	120	0	0	624	0	0	0	2.7×10^4
Water, H_2O	kg/h	0	0	9,360	0	240	1.8×10^4	0	0	4,800	2.2×10^4
Steam, H_2O	kg/h	0	2.04×10^4	0	3×10^4	0	0	0	4,800	0	0
Solids	kg/h	0	0	1.2×10^4	0	0	0	0	0	0	4,800
Heat Flow	kW	3,231	1.52×10^4	1,464	2.3×10^4	9,710	2,234	5,462	3,651	6,295	3,916

Table 3: Energy and material balance summary from Stream 11 to 20

		Stream Number									
	Unit	11	12	13	14	15	16	17	18	19	20
Temperature	°C	50	80	70	70	90	95	90	90	80	90
FFB	kg/h	0	0	0	0	0	0	0	0	0	0
EFB	kg/h	0	0	0	0	0	0	0	0	0	0
Fruitlets	kg/h	0	0	0	0	0	0	0	0	0	0
Flesh Fruits	kg/h	0	0	0	0	0	0	0	0	0	0
Palm Oil	kg/h	0	2.7×10^4	50	2.7×10^4	2.7×10^4	940	0	940	940	800
Water, H_2O	kg/h	2.4×10^4	4.6×10^4	50	4.6×10^4	4.6×10^4	4.3×10^4	0	4.3×10^4	4.3×10^4	4.2×10^4
Steam, H_2O	kg/h	0	0	0	0	0	0	0	0	0	0
Solids	kg/h	0	4,800	53	4,747	4,747	5,088	200	4,888	4,888	4,544
Heat Flow	kW	1,398	5,717	8	4,995	6,422	4,970	8	4,701	4,179	4,664

Table 4: Energy and material balance summary from Stream 21 to 30

		Stream Number									
	Unit	21	22	23	24	25	26	27	28	29	30
Temperature	°C	90	95	85	85	85	50	50	70	60	60
Palm Oil	kg/h	140	2.6	2.6×10^4	0	2.6×10^4	750	0	0	0	0
Water, H_2O	kg/h	152	3,897	3,897	3,871	26	7,218	1,814	1,814	0	0
Steam, H_2O	kg/h	0	0	0	0	0	0	0	0	0	0
Solids	kg/h	344	3	3	0	3	0	0	0	0	0
Fibre	kg/h	0	0	0	0	0	8,850	0	0	0	0
Nuts	kg/h	0	0	0	0	0	1.4×10^4	1.4×10^4	0	1.4×10^4	1.4×10^4
Shell	kg/h	0	0	0	0	0	0	0	0	0	0
Kernel	kg/h	0	0	0	0	0	0	0	0	0	0
Heat Flow	kW	37	1,847	1,653	382	1,270	1,245	563	148	549	549

Table 5: Energy and material balance summary from Stream 31 to 40

	Stream Number										
	Unit	31	32	33	34	35	36	37	38	39	40
Temperature	°C	45	30	45	30	30	30	30	30	70	70
Palm Oil	kg/h	0	0	0	0	0	0	0	0	0	0
Water, H_2O	kg/h	0	0	0	6,500	5,000	1,500	400	1,100	1,088	12
Steam, H_2O	kg/h	0	0	0	0	0	0	0	0	0	0
Solids	kg/h	0	0	0	0	0	0	0	0	0	0
Fibre	kg/h	0	0	0	0	0	0	0	0	0	0
Nuts	kg/h	0	0	0	0	0	0	0	0	0	0
Shell	kg/h	7,242	7,242	958	0	670	287	287	0	0	0
Kernel	kg/h	0	0	6186	0	155	6,031	0	6,031	0	6,031
Heat Flow	kW	189	126	223	227	189	186	19	167	89	302

Table 6: Energy and material balance summary from Stream 41 to 49

	Stream Number									
	Unit	41	42	43	44	45	46	47	48	49
Temperature	°C	50	45	120	66	250	250	250	150	30
Palm Oil	kg/h	750	0	632	118	0	0	0	0	0
Water, H_2O	kg/h	5,404	5,404	0	0	0	0	0	0	5,400
Steam, H_2O	kg/h	0	0	0	0	54,000	7,000	47,000	47,000	0
Solids	kg/h	0	0	0	0	0	0	0	0	0
Fibre	kg/h	8,850	0	0	8,850	0	0	0	0	0
Nuts	kg/h	0	0	0	0	0	0	0	0	0
Shell	kg/h	0	0	0	0	0	0	0	0	958
Kernel	kg/h	0	0	0	0	0	0	0	0	155
Heat Flow	kW	681	283	43	461	43,212	5,602	37,610	35,938	208

Table 7: Energy and material balance summary from Stream 50 to 56

	Stream Number							
	Unit	50	51	52	53	54	55	56
Temperature	°C	60	46	30	28	28	37	36
Pressure	kPa	101	101	8	4	4	101	101
Palm Oil Mill Effluent (POME)	kg/h	75,792	30,424	0	0	0	0	0
Treated POME	kg/h	0	0	0	0	0	30,424	87,874
Biogas	kg/h	0	0	1,523	0	0	0	0
Upgraded Biogas	kg/h	0	0	0	1,523	1,523	0	0

Table 8: Biogas heat engine energy balance data

	Unit	Engine 1 (BG1)	Engine 2 (BG2)	Engine 3 (BG3)
Average Fuel Flow Rate	Nm^3/h	444.41	403.42	356.05
Energy Input (Q_{in})	kW	2,752.87	2,498.95	2,205.56
Electrical Output	kW	986.47	981.07	812.44
Engine Radiation Loss	kW	43.75	41.41	43.06
Generator Radiation Loss	kW	28.13	26.62	27.68
Jacket Water Heat Loss	kW	651.08	616.27	640.83
Lower Temperature Circuit Heat Loss	kW	83.34	78.88	82.03
Total Exhaust Gas Loss at 475 °C	kW	960.12	754.69	599.51
Total Exhaust Gas Loss from 475 °C to 150 °C	kW	656.92	516.37	410.19

4. Conclusions

An integrated material and energy balance of palm oil mills with biogas power plant was computed based on the data collected from a palm oil mill with the capacity of 120 t/h fresh fruit bunches. All the mass flow rates of streams were calculated based on the law of conservation of mass while the energy content of each stream was calculated based on the component specific heat capacity that were retrieved from literature reviews. The total heat flow of each stream was calculated from the summation of component energy flow, and it served as an important information in determining the actual energy requirement of each palm oil mill process. The energy data revealed that total energy amount of 36.912 kW was needed for running the palm oil mill processes including the process of sterilisation, digestion and other process heating usage. The energy balance of biogas heat engine shows that there were total 1,583.48 kW of heat engines flue gas waste heat were recoverable while the total jacket water heat loss of 1,908.18 kW has great potential to be recovered for lower temperature process heating. By fully utilising the biogas power plant waste heat, it is expected to save up to 9.46 % of the total energy required by the palm oil mill processes.

Acknowledgments

The authors would like to thank for the myriad support of mill senior managers and mill engineers who provided the advices and constructive comment throughout the data collection process. This study was supported by the Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia.

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