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THERMODYNAMIC ANALYSIS ON OIL PALM BIOMASS COGENERATION PLANT

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ABSTRACT

Growth in energy demand has become a major concern in the earth today. The shortage of main fuel derived from conventional fossil fuel has led to an increasing demand on new source of energy, the renewal energy. Renewal energy is the proven alternative to overcome these problems. For the case of palm oil mills, the palm fibre and shell are the main source of renewal energy and cogeneration are adopted in exploiting these renewal energy sources. For this case study, the potential of these renewal energy sources were being investigated using thermodynamic analysis. Sie-Manggaris Palm Oil Mill Cogeneration Plant has been selected as a case-study model. From the analysis, it was found that the available fuel, which was accounted only palm fiber and shell, was able to generate steam up to 45,000 kg h^{-1}. This would give the potential energy production of 157 GJ h^{-1} and easily able to fulfil the need of the utility requirement for the entire plant. Although, the current configuration of the existing cogeneration system would impose the deficit power of 4 kWh ton FFB^{-1} and has to be supported using diesel generator set at the diesel consumption rate of 0.8 L ton FFB^{-1}. The current boiler capable to convert 1 kg of fuel to 3.35 kg of steam with the turbine steam rate at 30 kg kWh^{-1}. Retrofit design of the existing plant is necessary in order to overcome the low energy efficiency. Substantial amount of power production could be generated if utilizing the high-energy efficient equipment.

Keywords: cogeneration, biomass, palm oil mill.

INTRODUCTION

The oil palm biomass, which contains high-energy value, is capable to substitute the fossil fuel especially on palm oil mill cogeneration plant. Many research and success stories have proven that the oil palm biomass is able to generate energy to meet the demand of the entire plant and in some cases capable to export the surplus energy to the national grid [1]

With abundance of oil palm biomass available, typical palm oil mill was previously designed for self-sufficient in energy to run only the plant nowadays has to meet the additional requirement of the bigger plant and as well as domestic consumption. Small Renewal Energy Program (SREP) has took placed in 8th Malaysia Plan on 2001 which was the tool to drive the fuel mix strategy and was the first introduced RE as a fifth fuel. On 2010 the National Renewal Energy Policy and Action Plan was designed and as well as Renewal Energy Act 2011 been regulated [2]. Thus, it should be no accuses for the palm oil mill player not to take the challenge in optimizing the use of renewal energy resources not only for energy self-sufficient but in addition the plant should also look into the possibility of generating additional energy.

Refer to National Renewal Energy Policy and Action Plan, 2010, the potential energy of 1340 MW from biomass connected to grid by 2030 is looking as a reliable target setting and feasible to achieve taking into consideration of the abundance oil palm biomass in Malaysia [2]. With this policy in place, many of existing palm oil mill cogeneration plant expanding their businesses into this feasible arena. It was also shown that the independence biomass plant has growing in utilizing this oil palm biomass becoming an independence power producer. Based on the REPPA application on year 2013, total amount of 118.693 MW capacities had been applied for biomass plant intended to supply the electricity to grid [3]. This was indicated extremely positive outcome from all the government efforts in promoting the RE as to meet the target of 5.5% from Malaysia total electricity generated by 2015 and biomass itself will carry 1.84% contribution equivalence to 330 MW [3].

Although there was a significant impact in promoting the RE, it has been disclosed that the Capacity Factor, CF of the biomass plant was very low up to 12.46% and 5.71% average in Selangor and Negeri Sembilan as for the example respectively [3]. There would be many factors contributing to low CF comprising fuel availability, transportation, marketability, design feasibility and etc. Therefore, this study is become important to determine the existing power production and any potential additional power could be produced.

COGENERATION SYSTEM IN PALM OIL MILL

The original palm oil mill cogeneration plant has been designed based on Dura palm as a main fuel which is well-known on its thick shell and yielded approximately 30% fuel [4]. With the abundant of fuel available, it is not the main concern to meet the motive and thermal energy required by the plant. However, as the technology is improved, the new planting material was introduced as to maximise the oil yeild. The original genome which are Dura and Pesifera are crossedbreed to produce a hybrid progeny that all modern planting currently cultivated. This hybrid planting material is known as Tenera, which all modern milling system is designed with [4]. This Tenera was reduced the fuel to 15% from the weight of FFB [5]. In other word, the fuel availability has reduced to about 50% from the initial design and energy efficient is becoming crucial in palm oil mill cogeneration plant. This is not only to meet the demand of the entire plant but also to become a major player in contributing to the renewal energy in general and to the national power generation as a whole.

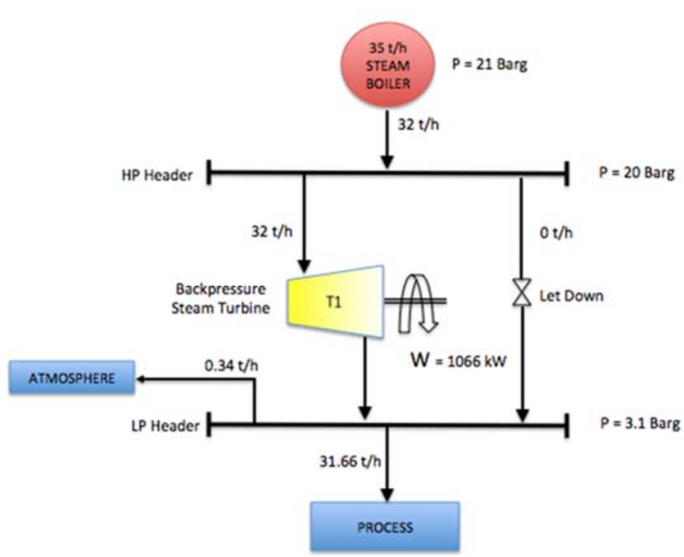

Figure-1. Sei-Manggaris palm oil mill cogeneration plant.

Figure-1 above shows the existing system of the Sei-Manggaris Palm Oil Mill Cogeneration Plant as a case study model. Steam turbine with design capacity of 1400 kW is received steam at 21 barg dry saturated through HP header from boiler with design capacity of 35 ton h^{-1}. One-unit backpressure steam turbine, which was running on part load, exhausted steam to LP Steam Main at 3.1 barg. Whenever the turbine is operated on part load and whenever there has any fluctuation on process demand, the let down will be regulated the steam as and when required.

METHODOLOGY

The study was divided into two analysis which were the fuel analyis and thermodynamic analysis.

Table-1. Symbols and description.

Symb	Definition	Unit
m_s	Steam flow rate produced	kg $h^{-1)}$
m_f	Fuel rate	kg h^{-1}
m_p	Steam flow rate consumed by process	kg h^{-1}
h_f	Enthalpy of feed water	kJ kg^{-1}
h_1	Enthalpy of steam produced	kJ kg^{-1}
h_2	Enthalpy of turbine exhaust	kJ kg^{-1}
h_{2s}	Enthalpy of turbine exhaust @ isentropic	kJ kg^{-1}
CV	Calorific value	kJ kg^{-1}
CV_{fs}	Calorific value mixture of fibre and shell	kJ kg^{-1}
P	Electrical power	kW
Q	Process heat rate	kJ s^{-1}

FUEL ANALYSIS

Both fibre and shell available in palm oil mill are the oil palm residue and are commercially used as a main fuel to the boiler. The study has to be carried out in order to determine the correct percentage of the fuel availability for the mill that receive the crop from difference estates which are contains Dura planting material .

i. Fuel availability

The fuel availability was calculated based on the data obtained from the assessment on site. Sei-Manggaris Palm Oil Mill received crop from own estates and also from smallholder surrounding the mill area. The Dura material was counted from the smallholder crop to be at 15%. In order to obtain the accurate figure in fuel analysis, the data was considered in the calculation and was calculated as below;

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$$fuel_{total} = \left[85\%_{own \quad estate}\right] \times \left[15\%_{smallholder}\right] \tag{1}$$

Table-2. Fuel fraction.

Description	Calculated	Literature
Fibre	15%	13% [6]
Shell	3.34%	7% [6]

ii. Calorific value

The calorific value is calculated based on the Dulong's equation obtained from T.M.I. Mahlia *et al*. [7].

$$H_u = 2.31\left[14093C + 61095\left(H - \frac{O}{8}\right)\right] \tag{2}$$

The lower heating value per kg of fuel mixed is calculated as below;

$$LHV_{fs} = 0.82LHV_f + 0.18LHV_s \tag{3}$$

where H_u is the gross calorific value and LHV_{fs} is the lower heating value for fibre and shell.

The chemical composition of palm fiber and shell that were tested in laboratory is tabled below;

Table-3. Chemical composition of palm fibre and shell.

Element	Fibre		Shell	
	Lab	Literature [7]	Lab	Literature [7]
Moisture, %	10.1	40	12.1	10
Ash, %	8.4	8.4	2.1	3.2
Sulphur, %	0.12	0.3	0.04	0.2
Carbon, %	45.2	47.2	46.8	52.4
Hydrogen, %	1.27	6	3.63	6.3
Oxygen, %	30.82	36.7	35.02	37.3

THERMODYNAMIC ANALYSIS

The monitoring and data collection of the existing cogeneration plant was carried out for two conditions, at the rated capacity and at the maximum capacity. The reason to relate with the milling throughput was because it is directly affected the plant performance especially on fuel availability and consumption. Data obtained from the analysis were compared to the industrial standard for baseline checking and further used to evaluate the maximum potential energy that could be produced by the existing plant.

Few assumptions have been made for this analysis;

- Maximum boiler load was 90% based on the actual practices.
- Boiler steam quality at 100% dryness fraction. [8]
- Turbine steam inlet at 20 bars dry saturated steam based on the average data.
- Turbine was expanding saturated steam at 0.9 dryness fraction indicated at turbine exhaust [8].
- LP Steam Header was at 0.9 dryness fraction supplied to the whole processing plant [8].
- Initial value for specific steam used to process 1 ton of FFB was at 600 kg tonFFB^{-1} [6].

i. Boiler fuel rate

The direct measurement of fuel consumed by the boiler was done at the fuel-feeding conveyor. The fuel feeding and fuel surplus were measured for the two conditions, which are at minimum and maximum milling throughput.

ii. Steam production

The steam production was measured using steam flow meter located at the outlet pipe of the boiler.

iii. Dryness fraction and steam parameter

The enthalpy of the steam production, steam inlet and outlet to the turbine were measured and estimated based on [8] as in the Table-4 below;

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Table-4. Steam condition at various study location.

Definition	Unit	Value
Boiler steam production @ 21 barg dry saturated steam	kJ kg^{-1}	2799.26 [measured]
Turbine steam inlet @ 20 barg dry saturated steam	kJ kg^{-1}	2798.29 [measured]
Specific steam to the process @ 3.1 barg, 0.9 dryness fraction	kJ kg^{-1}	2510.37 [8]
Isentropic expension is at 3.1 barg, 0.87 dryness fraction	kJ kg^{-1}	2462.85 [8]
Entropy across the turbine expansion	kJ kg^{-1}	6.33901 [8]

iv. Boiler efficiency

It was described as a ratio of energy content in a steam to the energy content in the fuel [8].

$$\eta_b = \frac{m_s\left(h_1 - h_f\right)}{m_f CV} \tag{4}$$

v. Maximum achievable boiler capacity

This was measured when the mill was running at highest throughput.

vi. Turbine isentropic efficiency

The formula used to calculate the isentropic turbine efficiency is defined by Equation (5) reported by [6];

$$\eta_s = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{5}$$

vii. Turbine thermal efficiency

The formula used to calculate the turbine thermal efficiency is defined by Equation (6) also reported by [6];

$$\eta_t = \frac{P}{m_s\left(h_1 - h_2\right)} \tag{6}$$

viii. Cogeneration efficiency

The formula used to calculate the cogeneration efficiency is defined by Equation (7) reported by [6];

$$\varepsilon_u = \frac{P + Q}{m_f CV} \tag{7}$$

RESULTS AND DISCUSSIONS

The result obtained for both fuel analysis and thermodynamic analysis is used to develop the databased for the case study cogeneration plant.

FUEL ANALYSIS

The results from the fuel analyis were compared to the others researcher for validation.

Table-5. Result from the analysis of fuel and energy availibility.

Item	45 ton h^{-1}	60 ton h^{-1}	Literature
Fuel availability [kg h^{-1}]	8,250	11,000	20% FFB [6]
Calorific value [kJ kg^{-1}]	11,572	11,572	14250 [8]
Energy availability [kJ h^{-1}]	95,945,400	127,360,000	-
Specific energy required to generate 1kg of steam [kJ kg $steam^{-1}$]	3449.5	3449.5	3466 [8]

THERMODYNAMIC ANALYSIS

The results from the thermodynamic analyis were compared to the others researcher for validation and for any gap analyis in the discussion.

i. Boiler fuel consumption and steam production

From the result obtained in the Table-5 above, it was shown that the fuel availability was huge. The calorific value for mixture of palm fibre and shell at 82:18 was comparatively low as compared to the value given by Z. Husain *et al*. [8]. The ratio of fuel mix seems to be far from the industrial standard of 70:30 and the calorific value was calculated using Dulong's equation based on the result obtained the laboratory shown very low. It might be an error in measuring the ratio of fuel mix and as well as on the sampling process. To avoid further error in the analysis, the value of 14250 kJ kg^{-1} quoted by Z. Husain *et al*. [8] is preferable and will be used in further calculation.

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And therefore the energy availability was adjusted to 156,750,000 GJ h^{-1} and able to generate steam up to 45,000 kg h^{-1} with the specific energy used to generate 1 kg of steam at 3449.5 kJ kg $steam^{-1}$.

Table-6. Result from the analysis of boiler fuel consumption and steam production.

Item	45 ton h^{-1}	60 ton h^{-1}	Literature
Boiler Fuel Rate [kg h^{-1}]	5820	7020	7000 [8]
Fuel Surplus [kg h^{-1}]	900	1200	-
Boiler Steam Production [kg h^{-1}]	25,000 (71%)	29,000 (83%)	70-74% [6]
Boiler Efficiency [%]	80.6	77.5	80 [9]
Evaporation Ratio	4.13	4.13	-
Maximum Potential Steam Production [kg h^{-1}]	34,081	45,441	-

From the measurement of the fuel rate directly on the fuel conveyor, the result shown that the fuel rate was directly correlated to the milling throughput and steam production. The result that was quoted by Z. Husain *et al*. [8] is comparatively similar to the fuel rate from the analysis. The excess fuel was at 10.9% from the available fuel regardless the milling throughput. The result is based on the steady state.

From fuel availability, the maximum potential steam that could be generated was 45,000 kg h^{-1}. The appropriate boiler capacity that could be installed in the plant in order to generate maximum steam was at 50 $tonh^{-1}$ with considering the 90% capacity factor. It could be understood that the current boiler capacity that was installed in the plant was lower than the maximum potential capacity. The actual steam that can be generated per unit fuel was 3.35 kg.

The initial design was based on the minimum throughput with self-sufficient power production with respect to the typical palm oil mill setup.

ii. Turbine steam rate and electricity generation

Table-7. Result from the analysis of turbine steam rate and electricity generation.

Item	Measured	Literature
Isentropic Efficiency [%]	85.8	70 [8]
Thermal Efficiency [%]	37.5	68.5 [8]
Turbine Steam Rate [kg kWh^{-1}]	30	27-30 [10]
Maximum Power Generation [kW]	1066.67	1620 [10]
Specific Power Generation [kWh $tonFFB^{-1}$]	18	18.3 ± 5.3 [11]

The isentropic efficiency of the existing turbine was on the higher side. This was due to the assumption of the steam expansion at 0.9 dryness fractions at exhaust [8] where in actual could be lower. No adequate equipment to measure the actual steam quality. Although, the thermal efficiency was lower than the published figure nearly 55%. This was due to the existing turbine performances, which lower than the design specification. The power output was less than the desired capacity.

Clearly understood that the steam rate of the existing steam turbine was higher when the thermal efficiency was low. However, the steam rate was still in between the value quoted by the F.R.P. Arrieta *et al* [10]. The existing turbine maximum power that could be generated was only 1066.67 kW which was lower than design capacity of 1400 kW. This was the main issue of the Sie-Manggaris Palm Oil Cogeneration Plant where insufficient power production. The problem encounted was validated by the value quoted by F.R.P. Arrieta *et al* [9] which is the 60 ton h^{-1} milling capacity was capable to generate up to 1600 kW.

iii. Process steam rate and electricity demand

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Table-8. Result from the analysis of process steam rate and electricity demand.

Item	45 ton h^{-1}	60 ton h^{-1}	Literature
Process steam rate [kg h^{-1}]	23,750	31,666	-
Specific steam used to process 1 ton of FFB [kg $tonFFB^{-1}$]	527.78	527.78	600 [6]
Process heat rate [kJ s^{-1}]	25,871.25	30,662.22	-
Specific power used to process 1 ton of FFB	22	22	20 [7,12,13]

The result was shown that the steam rate was lower than the potential maximum steam generation. No issue to meet the demand of process steam consumption. The figure shown to be at the lower rate as compared to the literature review figure quoted by A.B. Nasrin *et al*. [6]. This was indicating that the existing process steam requirement was at the optimum level as compared to the industrial standard. No heat integration analysis was required to the existing plant as to gain the maximum heat recovery.

Meanwhile, the specific power used to process 1 ton of FFB was at 22 kWh ton FFB^{-1} which was higher by 2 kWh ton FFB^{-1} against the industrial standard. This was due to the additional plant was integrated with the existing cogeneration plant and was increased the power demand of 323.4 kW.

iv. Energy surplus and deficit and cogeneration efficiency

Table-9. Result from the analysis of energy surplus and deficit and cogeneration efficiency.

Item	45 ton h^{-1}	60 ton h^{-1}	Literature
Thermal Efficiency [%]	57.5	55.3	62.7 [6]
Electrical Efficiency [%]	3.6	3.5	3.3 [6]
Cogeneration Efficiency [%]	61.1	58.8	66 [6]
Heat to Power Ratio	16	16	17.9 [8]
Energy Deficit [kWh $tonFFB^{-1}$]	-4	-4	5
Diesel Consumption [L $tonFFB^{-1}$]	0.76	0.8	0.44 ± 0.12

Thermal efficiency shown that the existing cogeneration plant heating energy was lower than the industrial standard quoted by A.B. Nasrin *et al*. [6], although the electrical efficiency was slightly higher than the industrial standard. This meant that the energy conversion process was efficient compared to heating process. Thus, was brought the overall cogeneration efficient to 60%, and its lower than the industrial standard quoted by A.B. Nasrin *et al*. [6] of 66%.

Energy analysis was shown that the plant was on 4 kWh deficits for every ton of FFB processed. This was contradicted against the value acquired from the literature review, which was surplus of 5 kWh for every ton of FFB processed. This was mainly due to the additional plant that was integrated with the existing cogeneration plant and was required additional power of 240 kW on the maximum throughput. This was resulted to the energy need to be supplied by the diesel generator set consumed at 0.8L ton FFB^{-1} of diesel. If the mill running at 60 $tonh^{-1}$, the diesel consumption would be at 48 L h^{-1}. The figure was on the higher side as compared to the industrial standard of 0.56 L ton FFB^{-1}

v. Databased development of the existing cogeneration plant

Table-10. Result from the analysis of databased development.

Definition	Unit	Sei-Manggaris plant
Specific Energy Consumption to Produce 1 kg of Steam	kJ kg^{-1} Steam	3449.5
Specific Steam Consumption to Generate 1 kWh of Power	kg kWh^{-1}	30
Specific Fuel Consumption to Generate 1 kWh of Power	kg kWh^{-1}	7.26
Specific Electricity Generated for 1 ton of FFB processed	kWh ton FFB^{-1}	18
Specific Steam Consumption to Process 1 ton of FFB	kg ton FFB^{-1}	527.78
Specific Electricity Consumption to Process 1 ton of FFB	kWh ton FFB^{-1}	22
Specific Electricity Deficit to Process 1 ton of FFB	kWh ton FFB^{-1}	-4
Specific Diesel Consumption to Process 1 ton of FFB	L ton FFB^{-1}	0.8

The database obtained was considered to be technically feasible baseline data that was developed and compared to the published data. All the data was reasonably acceptable except for electricity deficit. Initial design made based on the typical palm oil mill cogeneration plant setup and with regards to the design of energy self-sufficient. When additional plant was integrated with the existing plant, the mill was no more on the typical setup and running at the deficit power of 4 kWh ton FFB-1.

CONCLUSION AND RECOMMENDATION

The result from the analysis of the cogeneration plant performance shown that the fuel availability was sufficient to generate steam up to 45000 kg h^{-1} with the potential energy that could be generated was up to 157 GJ h-1. This was more than enough to meet the utility requirement for the whole processing plant either for heating utility or power utility.

With the current backpressure steam turbine ran at 30 kg kWh^{-1} steam rate, it was only able to generate electrical power up to 1066 kW with low thermal efficiency of 37.5%. This was insufficient to supply the power to the entire plant, as the whole plant power requirement was at 1300 kW. Low turbine performance and steam quality was the main factor contributed to the low efficiency. The current boiler is only able to generate power with 1 kg of fuel to 3.35 kg of steam. The energy deficit of 4 kWh $tonFFB^{-1}$ had to be supported by diesel generator set with diesel consumption of 0.8 L h^{-1}.

Retrofit design of the existing plant is necessary in order to overcome the low energy efficiency. The potential power production that could be generated using the high efficient backpressure steam turbine at the steam rate of 21.2 kg kWh^{-1} would be at 1500 kW. However, by utilising the Condensing Extraction Steam Turbine (CEST), it is estimated at 4600 kW of electrical energy could be generated as a potential power generation. The tremendously huge power production was creating the opportunity for power to be exported to the national grid.

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