Application of Biomass from Palm Oil Mill for Organic Rankine Cycle to Generate Power in North Sumatera Indonesia

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Abstract. Due to increasing oil and gas demand with the depletion of fossil resources in the current situation make efficient energy systems and alternative energy conversion processes are urgently needed. With the great potential of resources in Indonesia, make biomass has been considered as one of major potential fuel and renewable resource for the near future. In this paper, the potential of palm oil mill waste as a bioenergy source has been investigated. An organic Rankine cycle (ORC) small scale power plant has been preliminary designed to generate electricity. The working fluid candidates for the ORC plant based on the heat source temperature domains have been investigated. The ORC system with a regenerator has higher thermal efficiency than the basic ORC system. The study demonstrates the technical feasibility of ORC solutions in terms of resources optimizations and reducing of greenhouse gas emissions.

1. Introduction
Nowadays, fossil fuel has been used to supply 80% of total world energy consumption. This leads to fossil fuel depletion and increasing greenhouse gases (GHG) due to combustion of fossil fuel, causing global warming and acid rain [1]. Replacing the fossil fuel which leads to global problems and GHG emission by the hydrogen and biomass is essential [2,3]. In the context of climate change mitigation and energy security, biomass is the most promising renewable energy sources.

There is a wide range of processes available for converting biomass and wastes into more valuable fuels. These include biological processes to make ethanol or methane, and thermal processes to make heat, gaseous fuels, liquid fuels and solid fuels, from which electricity or power can be produced [4]. Power production from biomass can be carried out in several ways. The common way is by firing the biomass in a grate-fired or fluidized bed boiler to raise steam for Rankine cycle system in condensing or back-pressure of combined heat and power (CHP) mode. Such technology is limited in efficiency due to temperature restrictions in convective superheaters and in size of the plants [5]. One of technologies frequently used to increase the energetic effectiveness is cogeneration of heat and power with waste energy as a heat input of the cycle, mainly operated with organic fluids as working agents.
and called organic Rankine cycle (ORC) [610]. The function of organic agents corresponds with the function of water/steam in conventional heat cycles. However, ORC offers significant advantage over conventional Rankine cycle that uses water as the working fluid, which is efficiently producing power from medium temperature heat sources up to 370°C [11,12]. A basic ORC plant consists of thermal oil boiler, organic fluid evaporator with preheater unit, and condenser. Usually there are plants with heat regeneration, equipped with organic fluid regenerator and water economizer [6,13].

The palm oil mills (POM) accounts for the largest biomass production in North Sumatera Indonesia. Nowadays, all POMs have depended on their own biomass, such as shells and fibers, for fuel to generate the power. However, the empty fruit bunches (EFB) have not been optimally used because they are wet and bulky which are unfavorable properties for transportation and handling. Nevertheless, this biomass waste is needed to be utilized effectively to overcome its disposal problem in the field. This paper describes the potential of EFB to generate power by using ORC technology in North Sumatera. The aim was to introduce the use of ORC as a combined heat and power system in the POM field. Aspen Plus, which is widely used in industry, was used to model and analyze the biomass direct combustion and ORC part.

2. Technology Description
The layouts of the basic ORC system as a baseline and ORC system equipped with a regenerator are schematic in figure 1. The systems are based on EFB direct fired biomass thermal oil heater (TOH) unit in order to transfer heat from fuel to organic working fluid, and expander to utilize energy contained in the organic working fluid for power generation.

![Figure 1](image.png)

Figure 1. Schematic diagram of the ORC system, (a) Basic ORC, (b) ORC with regenerator.

The ORC operation principle is the same as the conventional Rankine cycle [14]. But, in this analysis, the working fluid is an organic compound of low boiling point instead of water, thus decreasing the temperature needed for evaporation. A basic ORC consists of four processes: increasing pressure of the working fluid through a pump, high temperature heat addition through an evaporator, expansion of high temperature as well as high pressure fluid through a turbine/expander, and low temperature heat rejection through a condenser.
3. Methodology

3.1. Aspen Plus flowsheet

Figure 2 depicts the Aspen Plus flowsheet of the ORC system with regenerator fuelled empty fruit bunches. The system consist of a TOH for recovering thermal energy from direct biomass combustion, ORC module to produce mechanical work through a Rankine cycle, and cooling circuit for condensation of the organic fluid. The modelling of the biomass thermal oil heater was based on the assumption that the gaseous products reach chemical equilibrium and the combustion process occurs near atmospheric conditions. The SYLThERM 800 heat transfer fluid was used for the TOH [15]. Six unit operation models (RYield, RGibbs, SSplit, Pump, Compr, Heater) have been used to simulate the TOH. The biomass is defined as an unconventional component (processes with solids). The biomass is first sent in a RYield reactor to decompose into its elements (C, H, O, N, S, etc.). RGibbs reactor is used to simulate combustion of biomass. The decomposed elements will react with the oxygen in the RGibbs reactor. RGibbs reactor models chemical equilibrium by minimizing Gibbs free energy.

![Figure 2. Aspen Plus simulation model for ORC plant with a regenerator unit.](image)

Referring to figure 2, hot oil leaving the TOH with temperature of 268°C then passes through evaporator to raise the temperature of ORC working fluid up to 130°C by means of the heat transfer medium. The hot working fluid of ORC is then expanded in the turbine/expander and at the same time producing power before entering regenerator. As the temperature of the vapor at the expander outlet is more than that of the liquid at the inlet of the evaporator, it is possible to enhance the efficiency of the system through a regenerator where the low pressure vapor from the expander (state 3) supplies heat to the stream of liquid working fluid entering regenerator at the other side (state 5). The heat of condensation is conducted away via cooling tower or used further as hot water for heating purposes. A pump re-increases the working fluid pressure before passing regenerator. After the working fluid was preheated in the regenerator, the working fluid is re-evaporated in the evaporator and superheated.
3.2. System performance
The total electrical efficiency of ORC power plant system can be calculated as follow:

\[
\eta_{\text{electrical}} = \frac{(W_{\text{expander}} - E_{\text{int.consumed}})}{m_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}
\]  

where \( W_{\text{expander}} \), \( E_{\text{int.consumed}} \), \( m_{\text{biomass}} \), \( \text{LHV}_{\text{biomass}} \) are the power produced by expander, internal energy consumed during processes, mass of biomass used per time, and heating value of biomass, respectively.

3.3. Input data
The biomass utilized in this study is EFB as waste from palm oil mill which are available much at North Sumatera province. The composition of the EFB is given in table 1. The operating parameters and other main assumptions for the plant calculation are summarized in table 2.

| Table 1. Composition of EBF [16]. |
|-----------------------------------|
| **EBF**                           |
| **Proximate analysis (wt.%)**      |
| Fixed carbon                      | 9.94 |
| Volatile matter                   | 42.20|
| Moisture content                  | 44.50|
| Ash content                       | 3.26 |
| **Ultimate analysis (wt.%)**       |
| Ash content                       | 3.26 |
| Carbon                            | 26.94|
| Hydrogen                          | 3.22 |
| Sulphur                           | 0.05 |
| Nitrogen                          | 0.35 |
| Oxygen                            | 21.58|
| **Heating values (kcal kg\(^{-1}\))** |
| Higher heating value              | 2450 |
| Lower heating value (calculated)  | 2337.1|

| Table 2. Main operational conditions and assumptions for plant calculation. |
|-----------------------------------|
| **EBF feed to boiler (kg hr\(^{-1}\))** | 100  |
| **Air feed to boiler (kg hr\(^{-1}\))** | 604  |
| **Flue gas temperature out boiler (°C)** | 90  |
| **Outlet temperature of oil heater from evaporator (°C)** | 115  |
| **Combustion temperature (°C)** | 300  |
| **Type of working fluid for ORC unit** | R245fa |
| **Mass flow rate of working fluid (kg hr\(^{-1}\))** | 750  |
| **Temperature of working fluid at the inlet evaporator (°C)** | 70  |
| **Outlet pressure of expander (bar)** | 2  |
| **Pressure losses during process (%)** | 0  |
| **Heat losses during process (%)** | 0  |
| **Electric generator efficiency (%)** | 98.7 |
4. Results and Discussion

4.1. Total system efficiency

The biomass fueled ORC system plant model shown in figure 1a was first analyzed. The simulation was done by Aspen Plus. The gross electrical power output produced by system via expander \(W_{\text{expander}}\) is 4.79 kW when the working fluid temperature and pressure out from evaporator of 104°C and 12 bar, respectively. The net internal energy consumption \(E_{\text{int,consumed}}\) by pumps and air blower is 1.46 kW. The net electrical power output of the plant is 3.33 kW giving an ORC system efficiency of 1.3% which due to low temperature adopted in this analysis. In the case of ORC system equipped with regenerator unit, net electrical power output of 4.24 kW was calculated which is about 0.91 kW higher than the ORC without regenerator unit. For a better description of ORC system with a regenerator unit, the characteristics of the main stream are shown in table 3. It can be seen that the regenerator contributes to higher energy thermal available during processes which can be used to increase the mass flow rate of ORC working fluid from 700 kg/hr (in the case of basic system) to 750 kg/hr (in the case of ORC equipped with regenerator).

| Point | % | T (°C) | P (bar) | m (kg hr⁻¹) | Molar composition (%) |
|-------|---|--------|--------|-------------|-----------------------|
| 1     |   | 70     | 12     | 750         | H₂O: R245fa: 100      |
| 2     |   | 133.4  | 12     | 750         | H₂: R245fa: 100       |
| 3     |   | 95.4   | 2      | 750         | O₂: R245fa: 100       |
| 4     |   | 45.3   | 2      | 740         | N₂: R245fa: 100       |
| 5     |   | 35.2   | 12     | 750         | CO: R245fa: 100       |
| 6     |   | 25     | 1.013  | 4000        | CO: 0                 |
| 7     |   | 25     | 1.2    | 4000        | O₂: 0                 |
| 8     |   | 33.2   | 1.2    | 4000        | N₂: 0                 |
| 9     |   | 25     | 1.013  | 100         | EFB, see table 1.      |
| 10    |   | 25     | 1.013  | 604         | 0                     |
| 11    |   | 115    | 1.5    | 1647.86     | 0                     |
| 12    |   | 267.9  | 2      | 1647.86     | 0                     |
| 13    |   | 115    | 2      | 1647.86     | 0                     |
| 14    |   | 90     | 1.04   | 700.74      | 0                     |

4.2. Effect of inlet pressure of expander

The ORC plant performance is estimated to improve with increase in working pressure of inlet expander as shown in figure 3. But, however, many tasks should be done in the near future by considering the sensitivity analysis to increase the total efficiency of the system.
5. Conclusions
We investigated the thermodynamic performance of small biomass fuelled ORC plant to generate power. The plant layout has been designed to utilize the energy from the EFB as fuel which are available from the waste of palm oil mill by using existing Aspen Plus unit operation block. From this preliminary design, 100 EFB per hour can generate 4.31 kW net electricity. Increasing inlet pressure of expander will increase the power output and total electrical efficiency. However, many tasks should be done to see the effect of changing design parameters on the net power output and total electrical efficiency. Plans for the future work to thoroughly analyse and describe the sensitivity analysis for total ORC with regenerator system performance including the effect of different biomass properties, working fluid ORC, and heat transfer fluid from heat source in the evaporator are underway.

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References
[1] Mohammed MAA, Salmiaton A, Wan Azlina WAKG, Mohammad Amran MS, Fakhru’l-Razi A, and Yap-Taufiq 2011, Hydrogen rich gas from oil palm biomass as a potential source of renewable energy in Malaysia, Renew. Sust. Energ. Rev. 15, 1258.
[2] Saidur R, Boroumandjazi G, Mekhilef S, and Mohammed HA 2012, A review on exergy analysis of biomass based fuels, Renew. Sust. Energ. Rev. 16, 1217-1222.
[3] Li G 2016, Organic Rankine cycle performance evaluation and thermoeconomic assessment with various applications part II: Economic assessment aspect. Renew. Sust. Energ. Rev. 64, 490-505.
[4] Bridgwater AV 1995, The technical and economic feasibility of biomass gasification for power generation, Fuel 74,631-653.
[5] Pihl E., Heyne S, Thunman H, and Johnsson F 2010, Highly efficiency electricity generation from biomass by integration and hybridization with combined cycle gas turbine (CCGT) plants for natural gas, Energy 35, 4042-4052.
[6] Tanczuk M, and Ulbrich R 2013, Implementation of a biomass-fired cogeneration plant supplied with an ORC (Organic Rankine Cycle) as a heat source for small scale heat
distribution system - A comparative analysis under Polish and German conditions, Energy 52, 132-141.

[7] Galloni E, Fontana G, Staccone S 2015, Design and experimental analysis of a mini ORC (organic Rankine cycle) power plant based on R245fa working fluid. Energy 90, 768-775.

[8] Li G 2016, Organic Rankine cycle performance evaluation and thermoeconomic assessment with various applications part I: Energy and exergy performance evaluation. Renew. Sust. Ener. Rev. 53, 477-499.

[9] Pezzuola A, Benato A, Stoppato A, Mirandola A 2016, The ORC-PD: A versatile tool for fluid selection and organic Rankine cycle unit design. Energy 102, 605-620.

[10] Pu W, Yue C, Han D, He W, Liu X, Zhang Q, Chen Y 2016, Experimental study on organic Rankine cycle for low grade thermal energy recovery. Appl. Therm. Eng. 94, 221-227.

[11] Desai NB, and Bandyopadhyay S 2009, Process integration of organic Rankine cycle, Energy 34, 1674-1686.

[12] Deethayat T, Asanakham A, Kiatsiriroat T 2016, Performance analysis of low temperature organic Rankine cycle with zeotropic refrigerant by Figure of Merit (FOM). Energy 96, 96102.

[13] de M Ventura CA, Rowlands AS 2015, Recuperated power cycle analysis model: Investigation and optimisation of low-to-moderate resource temperature organic Rankine cycles. Energy 93, 484-494.

[14] Velez F, Segovia JJ, Martin MC, Antolin G, Chejne F, and Quijano A 2012, A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation, Renew. Sust. Ener. Rev. 16, 4175-4189.

[15] http://www.dow.com/heattrans/products/synthetic/syltherm.htm (accessed: October 2016).

[16] Wijono A 2014, PLTU Biomassa tandan kosong kelapa sawit studi kelayakan dan dampak lingkungan. Proceeding Simposium Nasional RAPI XIII-2014 FT UMS (Indonesian Version).