Integrated biomass pyrolysis with organic Rankine cycle for power generation

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Abstract. The growing interest on Organic Rankine Cycle (ORC) application to produce electricity by utilizing biomass energy sources are increasingly due to its successfully used to generate power from waste heat available in industrial processes. Biomass pyrolysis is one of the thermochemical technologies for converting biomass into energy and chemical products consisting of liquid bio-oil, solid biochar, and pyrolytic gas. In the application, biomass pyrolysis can be divided into three main categories; slow, fast and flash pyrolysis mainly aiming at maximizing the products of bio-oil or biochar. The temperature of synthesis gas generated during processes can be used for Organic Rankine Cycle to generate power. The heat from synthesis gas during pyrolysis processes was transfer by thermal oil heater to evaporate ORC working fluid in the evaporator unit. In this study, the potential of the palm oil empty fruit bunch, palm oil shell, and tree bark have been used as fuel from biomass to generate electricity by integrated with ORC. The Syltherm-XLT thermal oil was used as the heat carrier from combustion burner, while R245fa was used as the working fluid for ORC system. Through Aspen Plus, this study analyses the influences on performance of main thermodynamic parameters, showing the possibilities of reaching an optimum performance for different working conditions that are characteristics of different design parameters.

1. Introduction
Fuel lately, is a hot topic to be discussed on various occasions. This is driven by increasing demand and fuel prices. In the meantime, the source of fuel oil and gas is decreasing. As a consequence, it is a necessity to seek other sources. One alternative is the utilization of renewable energy and used to replace the use of fuel oil and natural gas [1]. Biomass is the most widely used renewable energy source in the world today. It is used mostly in solid form and, to a lesser extent, in the form of liquid fuels and gas. The utilization of biomass for energy production has increased at only a modest rate in modern times [2].

Bioenergy can be produced from a variety of biomass feed stocks, including forest, agricultural and livestock residues; short-rotation forest plantations; energy crops; the organic component of municipal solid waste; and other organic waste streams. Through a variety of processes, these feed stocks can be directly used to produce electricity or heat, or can be used to create gaseous, liquid, or solid fuels [3-4].

Pyrolysis is a thermochemical decomposition process at elevated temperature in absence of oxygen. The pyrolysis gas contains mainly H2, CO, CO2, CH4, and others light hydrocarbons such as C2H6,
C₂H₄, C₃H₆, C₃H₆, C₃H₈. Pyrolysis of biomass yields gases, liquids (so-called bio-oils), and a carbonaceous residue (so-called bio-char). The obtained yields depend on the feedstock composition and pyrolysis conditions. There are three types of pyrolysis: fast pyrolysis with a typical maximum bio-oil yield of around 60-80 wt. % at very short residence times, convectional pyrolysis with equal yields of product at middle residence time (minutes), and as the last, slow pyrolysis with a maximum solid yield of around 60-80 wt. % at very long residence time (hours) [5].

2. Technology Description

Figure 1 illustrates an ORC system that utilizes heat from biomass pyrolysis. Biomass is heated to the working temperature. Then the pyrolysis gas heats the organic working fluid, and expander to utilize energy contained in the organic working fluid for power generation.

![Figure 1. Schematic diagram of the Basic ORC system](image)

The ORC operation principle is the same as the conventional Rankine cycle [6]. 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 with empty fruit bunches pyrolysis system. Seven unit operation models (RYield, RGibbs, SSplit, Flash2 Pump, Compr, HeatX) have been used to simulate the system. The biomass is defined as an unconventional component (processes with solids). The biomass is first sent in a RYield reactor to decompose into its elemets (C, H, O, N, S, etc.). RGibbs reactor is used to simulate pyrolysis of biomass. The decomposed elements will react 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.

Referring to Figure 2, flue gas leaving RGibbs reactor with temperature of 400 °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

Based on the energy equilibrium system, the mathematical model of ORC developed are given in Table 1.

| Component     | Mathematical Model |
|---------------|--------------------|
| Pump          | \( W_p = \dot{m} (h_2 - h_1) \) |
| Evaporator    | \( Q_{in} = \dot{m}(h_3 - h_2) \) |
| Expander      | \( W_{exp} = \dot{m} (h_3 - h_4) \) |
| Condenser     | \( Q_{out} = \dot{m} (h_4 - h_1) \) |

where \( W_p, Q_{in}, W_{exp}, Q_{out}, \dot{m}, \) and \( h \) are the power required by pump, heat transferred into system, the power produced by expander, heat transferred out from system, mass of biomass used per time, and enthalpy, respectively. The thermal efficiency of ORC power plant system can be calculated as follow:
\[ \eta_{therm} = \frac{W_{\text{expander}} - W_{\text{pump}}}{q_{in}} \] (1)

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 2. The operating parameters and other main assumptions for the plant calculation are summarized in Table 3.

Table 2. Composition of EBF [8].

| EBF               |               |
|-------------------|---------------|
| **Proximate analysis (wt.%)** |               |
| Fixed carbon      | 18.84         |
| Volatile matter   | 80            |
| Moisture content  | 20            |
| Ash content       | 5.89          |
| **Ultimate analysis (wt.%)** |               |
| Ash content       | 5.89          |
| Carbon            | 48.63         |
| Hydrogen          | 5.81          |
| Sulphur           | 0.09          |
| Nitrogen          | 0.63          |
| Oxygen            | 38.95         |
| **Heating values (MJ kg\(^{-1}\))** |               |
| Lower heating value | 18.5        |

Table 3. Main operational conditions and assumptions for plant calculation.

|                                      |               |
|--------------------------------------|---------------|
| Temperature EFB \( ^{\circ} \text{C} \) | 25            |
| Type of working fluid for ORC unit   | R245fa        |
| Mass flow rate of working fluid (kg hr\(^{-1}\)) | 2500         |
| Temperature of working fluid at the inlet expander \( ^{\circ} \text{C} \) | 130           |
| Outlet pressure of expander (bar)    | 2             |
| Pressure losses during process (%)   | 0             |
| Heat losses during process (%)       | 0             |
| Isentropic efficiency of expander and pump (%) | 70          |

4. Results and discussion

4.1. Pyrolysis of Biomass

The yield of pyrolysis product (char, bio-oil, and syngas) are shown in Figure 3. At 300 \( ^{\circ} \text{C} \), the amount of char is about 28\%. This amount decreases with increasing temperature pyrolysis. This also happens to syngas. On the contrary, the production of syngas increases with increasing temperature. At higher temperatures, the water gas shift reaction started, carbon monoxide and hydrogen were created, and the amount of carbon began to decrease. This part significantly differs from the experimental one. Water was evaporated below 200 \( ^{\circ} \text{C} \) and collected after the cooler in a condensate container, so it could not react with carbon in the reactor at higher temperature.
Figure 3. Yield of pyrolysis product.

The gas composition of pyrolysis product shown in Figure 4. H$_2$ and CO mole fractions increase with increasing temperature, whereas CO$_2$, and CH$_4$ show the opposite trend. The concentrations of light hydrocarbons were in a range on 400-500 °C, after that, light hydrocarbons were decomposing, which resulted in increases of H$_2$ concentrations. On the other hand, a half of the volume of produced gas was created below 400 °C that means without H$_2$.

Figure 4. Mole fractions of H$_2$, CO, CO$_2$, CH$_4$ in the gas product as functions of pyrolysis temperature.

4.2. ORC Analysis

The ORC plant performance is estimated to improve with increase in working pressure of inlet expander as shown in Figure 5. The system generated 15.33 kW of net power at the 9 bar of inlet pressure of expander. By raising the inlet pressure of expander until it reaches 13 bar, the net power increased by 16%.
5. Conclusions
In this study, it has been analyzed an ORC integrated with pyrolysis biomass. 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, 628 EFB per hour can generate 17.78 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. In addition, increasing the working temperature of pyrolysis resulted in increased amount of gas produced. Contrary to bio-oil and charcoal.

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