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Exergy analysis of biomass organic Rankine cycle for power generation

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Abstract. The study examines proposed small biomass-fed Organic Rankine Cycle (ORC) power plant through exergy analysis. The system consists of combustion burner unit to utilize biomass as fuel, and organic Rankine cycle unit to produce power from the expander. The heat from combustion burner was transfered by thermal oil heater to evaporate ORC working fluid in the evaporator part. The effects of adding recuperator into exergy destruction were investigated. Furthermore, the results of the variations of system configurations with different operating parameters, such as the evaporating pressures, ambient temperatures, and expander pressures were analyzed. It was found that the largest exergy destruction occurs during processes are at combustion part, followed by evaporator, condenser, expander, and pump. The ORC system equipped with a recuperator unit exhibited good operational characteristics under wide range conditions compared to the one without recuperator.

1. Introduction

The energy crisis that has occurred in Indonesia over the years has hampered national development, upgrading and developing technology. The rapid growth of national population leads to increasing the national energy demand. It has been predicted that the global energy consumption is likely to grow faster than the population growth [1-3]. The fuel consumption was growing from 777.925 million barrels of oil equivalent (MBOE) in 2000 to 1040.677 MBOE in 2015. Around 74% of Indonesia's energy supplies come from non-renewable energy. The primary energy supply by source for 2015 is 364.62 MBOE from coal, 444.81 MBOE from crude oil and products, 279.63 from natural gas and product, 34.597 MBOE from hydro power, 16.34 MBOE from geothermal, 309.73 MBOE from biomass, and 19.11 MBOE from biofuel [4]. The power plant installed capacity in Indonesia during 2000 is 37,287.19 MW, and have increased to 55,531.20 MW in 2015, where the power plant production reaches 176,472 GWh in 2015 [4]. About 88% of Indonesia's population has access to electricity compared to less than 68% in 2010 [5]. The most of Indonesian power plants are using non-renewable sources fuel such as natural gas, fuel oil, coal and diesel to generate electricity. Therefore, an important priority is to increase the national power generation capacity to complete the electrification of the country and meet increasing electricity consumption.

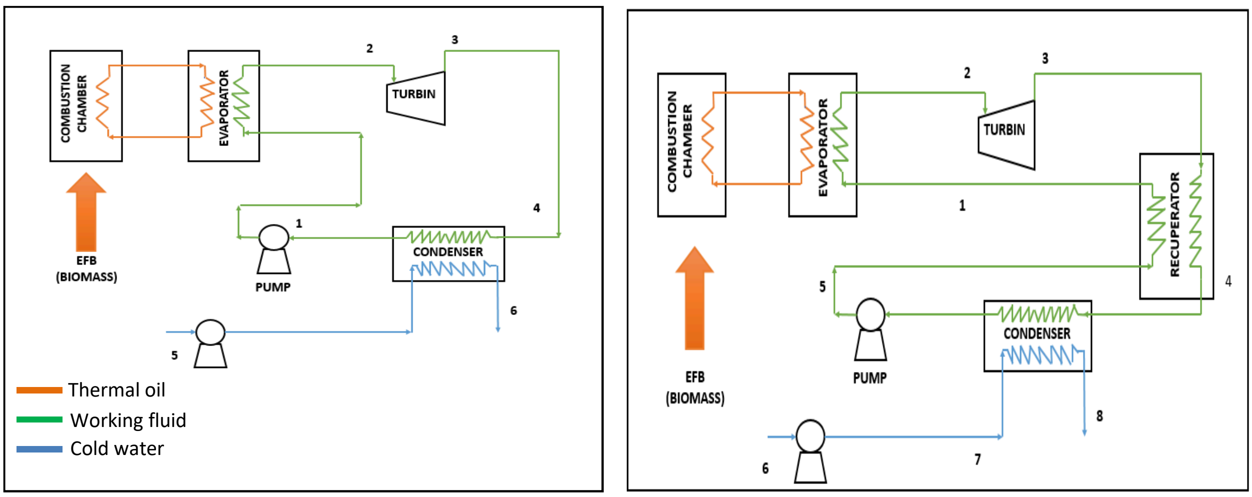
Due to the environmental issues from burning fossil fuels like greenhouse gas emission [6] and the fact that fossil fuel will be depleted one day, the dependency of Indonesian energy scenario to fossil fuels will have an adverse effect on the economy of Indonesia [7]. Therefore, action toward using renewable energy source should be put as the priority by the government.

Renewable energy sources in Indonesia, such as geothermal energy, solar energy, wind energy and biomass energy are the promising energy sources to replace fossil fuel energy. Indonesian's biomass energy policy basically follows government regulation No. 79/2014 on National Energy Policy. It set the targets for an optional energy mix in 2025, where renewables contribute at least around 23% of the total energy mix and should increase to at least 31% in 2050.

Referring to Indonesia condition as one of the biggest countries as palm biomass producer, research on utilizing of biomass energy to supply power generation is great significance. One of promising technology to extract biomass energy is by using biomass as fuel for organic Rankine cycle (ORC). The ORC uses an organic working fluid which is able to condense at a lower pressure and evaporate at a higher pressure. The working fluid as the organic substance can be better adapted than water for lower heat source temperatures. In the previous work (8,9), the biomass from empty fruit bunch (EFB) of palm oil has been used for ORC power plant to generate electricity. To study the quality of energy used during processes on the system to improve the performance of the ORC system is by using the exergy analysis method. Therefore, the objective of the present work is to perform exergy analysis on the design of ORC fueled by palm oil EFB. The configurations analyzed are similar to the proposed design in the preceding study [9].

2. Technology Description

Two ORC configurations were simulated in this analysis, (i) ORC without recuperator unit, and (2) ORC with recuperator unit, as shown in figure 1. The EFB of palm oil used as fuel in the thermal oil heater (TOH) combustion unit. The processes start from burning biomass fuel in TOH to generate heat which is then transferred to ORC working fluid by the thermal oil that goes in the evaporator section. The compressed ORC working fluid, R245fa, will evaporate in the evaporator prior entering to expander producing work by rotating shaft which then converted to electricity by a generator. A recuperator essentially increases the thermal efficiency thus a high-power output can be maintained for a decreased heat input to the ORC unit [8-10].



(a) (b)

Figure 1. Schematic diagram of the ORC system, (a) ORC without recuperator unit, (b) ORC with recuperator unit.

3. Methodology

3.1. Aspen Plus flowsheet
The Aspen Plus flowsheets of the ORC with biomass combustion system are depicted in figures 2-3. The systems are based on the following main assumptions: steady state operation, pressure drop neglected, working fluid is R-245fa, thermal oil is Syltherm XLT. More detailed about the configuration and firs law thermodynamic analysis can be found in the preceding study [8,9]. Here, in order to facilitate the exergy analysis, we display the schemes that have been used previously.

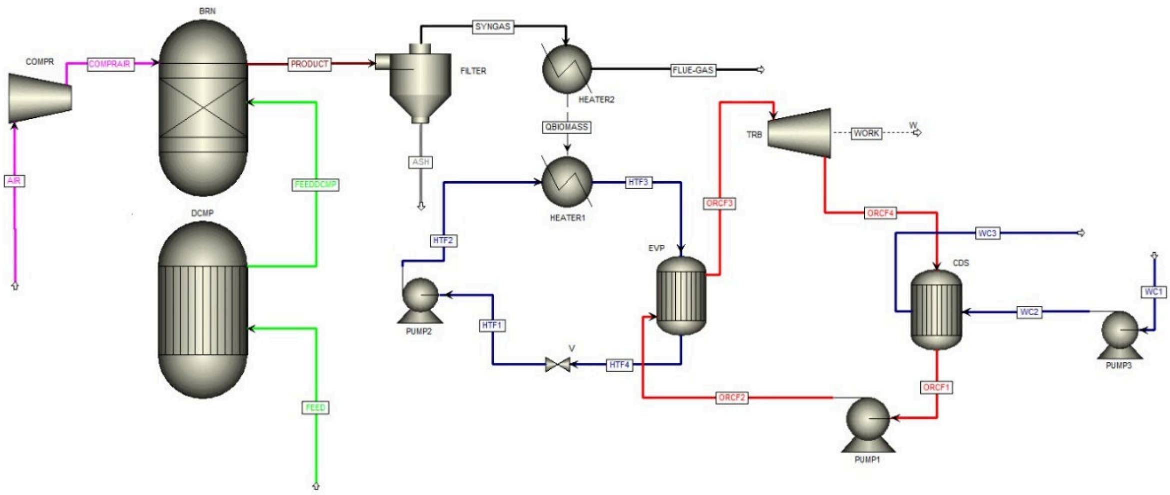


Figure 2. Aspen Plus simulation model for ORC plant without recuperator unit.

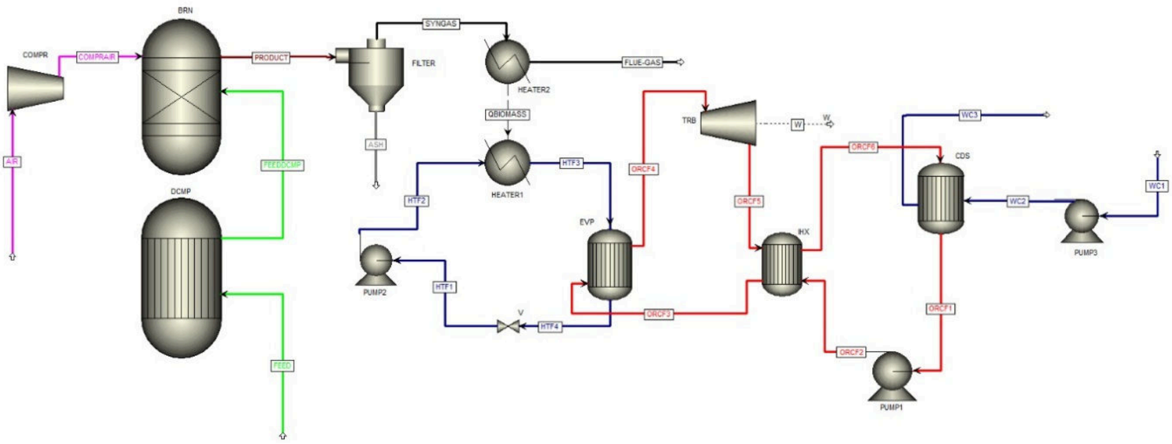


Figure 3. Aspen Plus simulation model for ORC plant with a regenerator unit.

3.2. System and Exergy Analysis
Exergy can exist in the forms of thermo-mechanical exergy and chemical exergy; there are also corresponding forms of exergy for kinetic, potential, and electrical energy. More details on exergy analysis method can be found in available references [11-14]. The exergy evaluation of the biomass fuel can be calculated by using the following [15]:

$$e = 1812.5 + 295.606C + 587.354H + 17.506O + 17.735N + 95.615S - 31.8A \quad (1)$$

Exergy destruction of each individual unit can be calculated by finding the difference between the exergy of input and output streams of this unit [12]. The total exergy destruction of the ORC system can be calculated as follow:

$$I_{total} = I_{pump} + I_{evaporatore} + I_{turbine} + I_{condenser} + I_{recuperator} + I_{combustion} \quad (2)$$

where I is the exergy destruction by each component. The main operational conditions for analysis are shown in table 1.

Table 1. Main operational conditions and assumptions for plant calculation.

EFB feed to boiler (kg hr^{-1})	100
Air feed to boiler (kg hr^{-1})	604
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 ORC working fluid at the inlet evaporator (°C)	70
Outlet pressure of expander (bar)	2
Pressure losses during process (bar)	0
Electric generator efficiency (%)	98.7
Dead state temperature (°C)	27-31

4. Results and discussion

The exergy destruction during processes on the ORC system without recuperator unit and system with recuperator unit are 176.311 kW and 156.51 kW, respectively. Figure 4-5 show the schematic diagram of both configurations with their temperature (°C), mass flow rate (kg/h), and exergy flow (kW). The exergy destruction on the combustion unit decreased due to reducing fuel consumption rate at the same system power output level by adding a recuperator unit. Combustion unit contributes to highest exergy destruction on the systems during processes. More results on effect of adding recuperator to fuel consumption rate can be found in the preceding study [9].

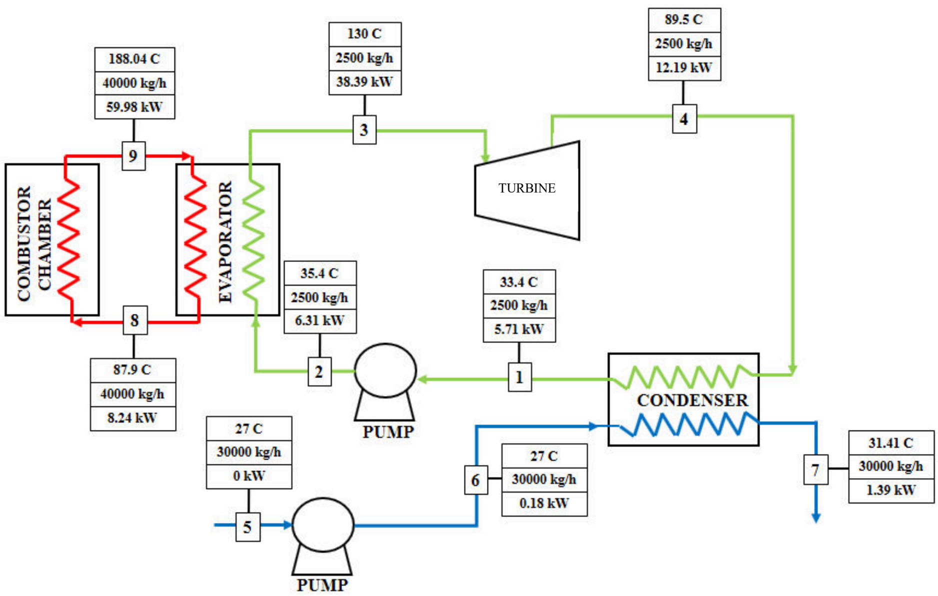


Figure 4. ORC system without recuperator with selective properties during processes whereas the expander inlet pressure of 13 bar.

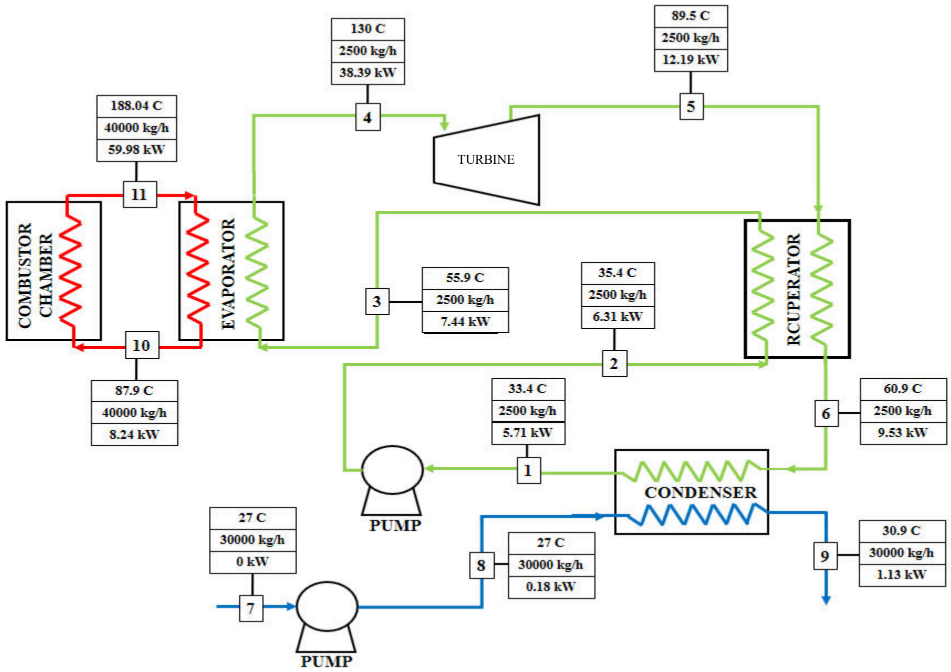


Figure 5. ORC system with recuperator with selective properties during processes whereas the expander inlet pressure of 13 bar.

4.1. Effect of various expander inlet pressure on the exergy destruction

The total exergy destruction on ORC system without recuperator unit decreased when increasing the expander inlet pressure, as shown in figure 6. Total exergy destruction decreased from 184.773 kW when expander inlet pressure at 9 bar to 176.311 if expander inlet pressure operated at 13 bar. Meanwhile, the total exergy destruction on ORC system with recuperator also decreased from 157.885 kW to 156.515 kW at the same conditions.

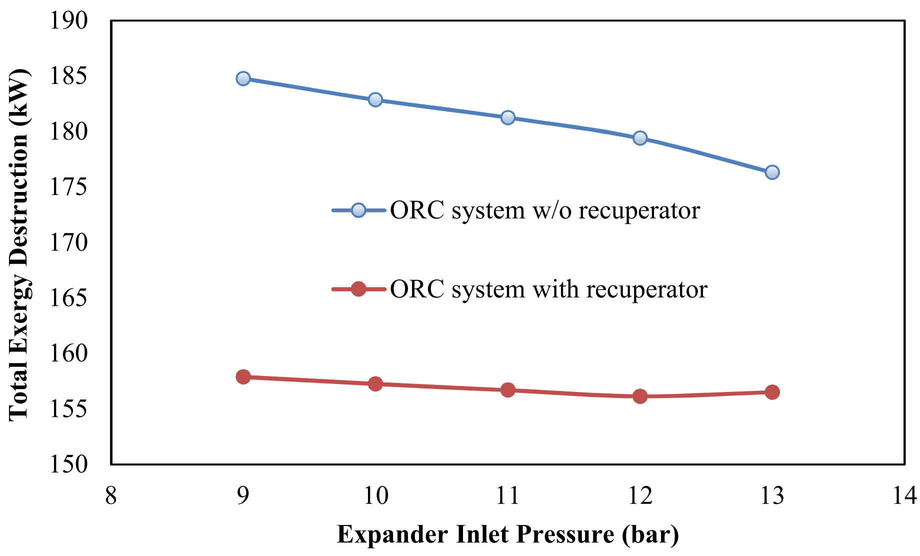


Figure 6. Effect of various expander inlet pressure on system total exergy destruction.

4.2. Effect of ambient temperature on exergy destruction

The effect of various ambient temperatures on the total system exergy destruction can be found in figure 7. It can be seen that when the ambient temperature increased, the total system exergy destruction for ORC system without recuperator decreased as from 176.311 kW at 27 °C to 171.499 kW with an ambient temperature of 31 °C. Meanwhile, for the ORC system with recuperator, the total system exergy destruction decreased from 156.515 kW to 152.833 kW at the same conditions.

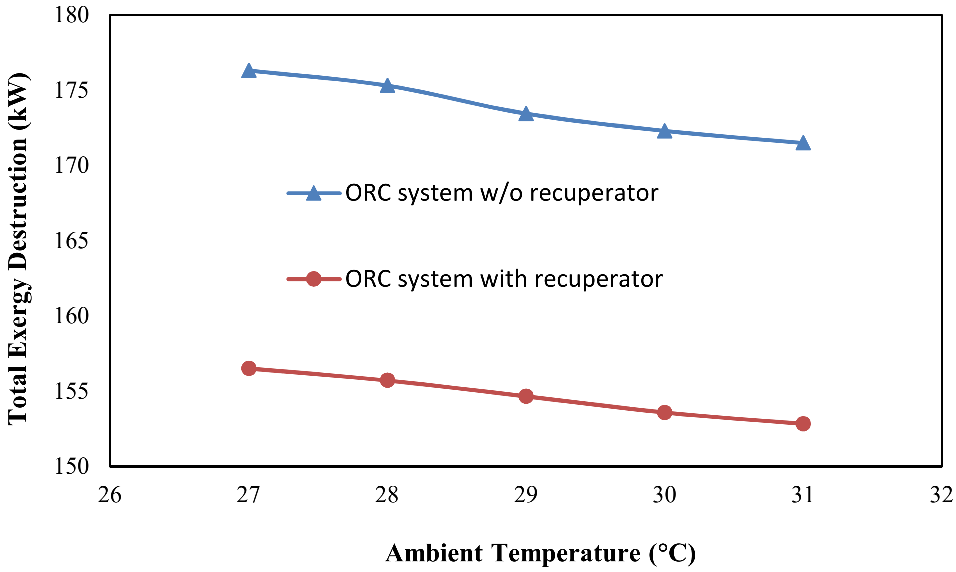


Figure 7. Total exergy destruction and environmental temperatur.

5. Conclusions

We performed exergy analyzed on the proposed ORC system fueled EFB. It was found that the highest losses by the destruction of exergy occurred in the combustion chamber unit, followed by the evaporator, condenser, expander, and pump. Adding a recuperator contributes to lower fuel consumption rate at the same level system power output hence decreasing exergy destruction on the combustion chamber. As the ambient temperature increased, the exergy destruction in the combustion chamber and condenser decreased, reducing the total exergy destruction of the system during the process. Although the exergy destruction in other units such as expander, pump, recuperator, and evaporator have increased, the total increase is lower than the rate of decrease of destruction exergy in the combustion chamber and condenser. A further analysis of the systems needs to be done, especially to see the effect of different working fluid to the system performance.

Acknowledgements

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