IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: S Ependi and T B Nur 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **309** 012055

IOP Conf. Series: Materials Science and Engineering **309** (2018) 012055 doi:10.1088/1757-899X/309/1/012055

Design and process integration of organic Rankine cycle utilizing biomass for power generation

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Abstract. Indonesia has high potential biomass energy sources from palm oil mill industry activities. The growing interest on Organic Rankine Cycle (ORC) application to produce electricity by utilizing biomass energy sources are increasingly due to its successfully used for generating electricity from rejected waste heat to the environment in industrial processes. In this study, the potential of the palm oil empty fruit bunch, and wood chip have been used as fuel for biomass to generate electricity based ORC with combustion processes. The heat from combustion burner was transfer by thermal oil heater to evaporate ORC working fluid in the evaporator unit. The Syltherm-XLT thermal oil was used as the heat carrier from combustion burner, while R245fa was used as the working fluid for ORC unit. Appropriate designs integration from biomass combustion unit to ORC unit have been analyzed and proposed to generate expander shaft-work. Moreover, the effect of recuperator on the total system efficiency has also been investigated. It was observed that the fuel consumption was increased when the ORC unit equipped recuperator operated until certain pressure and decreased when operated at high pressure.

1. Introduction

Renewable energy sources, such as geothermal energy, solar energy, wind energy and biomass energy are the promising energy sources to replace fossil fuel energy. The implementation of renewable energy will not only reduce the usage of fossil energy but also opportunities in reducing greenhouse gases (GHG) emissions. 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.

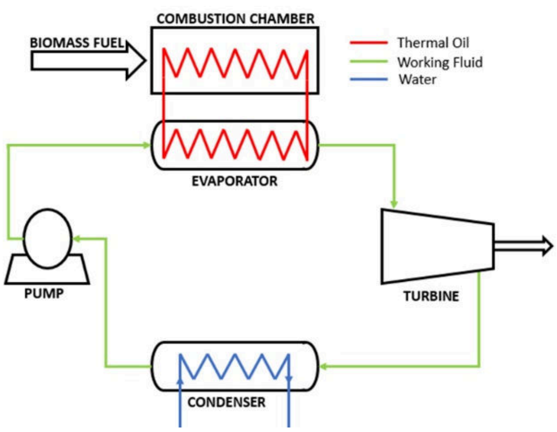
One of promising technology to extract biomass energy is by using biomass as fuel for organic Rankine cycle. The ORC uses an organic working fluid which is able to condense at a lower pressure and evaporate at a higher pressure. The working fluid as the organic substance can be better adapted than water for lower heat source temperatures. The heat releases during combustion process can be used to heat up system working fluid prior entering expander to produce electrical energy. Generally, the selection of working fluids to be used for ORC systems are based on their appropriate thermochemical properties, safety, cost, and environmental impact [1-4]. Numerous works in literature studied the performance evaluation of the ORC systems with different configurations. A review on the ORC architectures is given by Lecompte et al. [5].

Palm oil has been one of the success stories of the North Sumatera Province of Indonesian agricultural sector. The palm oil mills (POM) have depended on their own biomass, such as shells, fibers, empty fruit bunches (EFBs) as fuel to generate power. The power plant is usually located in the same area of POM itself. However, the EFBs have not been optimally used due to wet and bulky which are unfavorable during their handling in the power plant. However, the EFBs should be utilized effectively to overcome its disposal problem in the POM. A preliminary study to use the EFBs in the combustion processes have been analyzed [4]. In this study, we extend the analysis to more details integration processes of the ORC plant by utilizing EFBs and wood chip as biomass fuels.

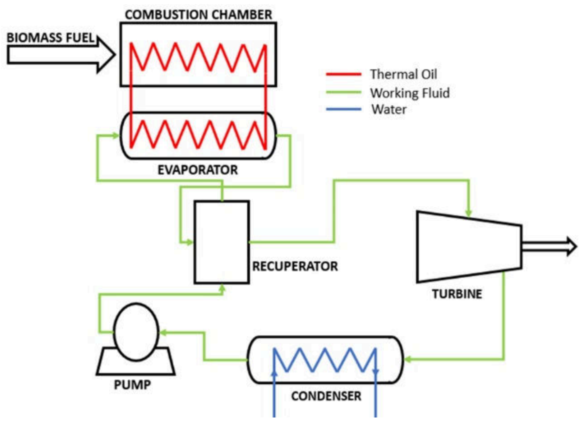
2. System Description

In this section, two different cycle architectures of ORC systems as shown in figure 1 are discussed bearing in mind the performance evaluation criteria. Each system consists of two unit: (i) thermal oil heater (TOH) unit, (ii) organic Rankine cycle (ORC) unit. The processes start from burning biomass fuel in TOH to generate heat which is then transferred to an ORC working fluid by the thermal oil that goes in the evaporator section. The compressed working fluid will evaporate in evaporator prior entering to expander producing work by rotating shaft which then converted to electricity by generator.

Several researchers [4,6-8] suggest a recuperator to reuse the heat after the expander to preheat the working fluid going to the evaporator by utilizing heat energy contained by the working fluid before entering the condenser. A recuperator essentially increases the thermal efficiency thus a high-power output can be maintained for a decreased heat input to the ORC unit [4,5].



(a)



(b)

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

3. Methodology

3.1. System Design, Integration, and Efficiency

The Aspen Plus flowsheets of the ORC configurations 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, and the biomass used is EFB and wood chip.

The biomass combustion will be simulated at near atmospheric condition. The Aspen Plus block units used to simulate combustion process are RYield, RGibbs, SSplit, Compr, Heater [4]. The

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biomass (FEED) was sent to RYield, labeled with DECOMPOSER, to predict the decomposition of the biomass into the reference components such as C, H_2, S, O_2, N_2, etc. DECOMPOSER is a dummy tool and not used in the actual condition. The RGibbs, labelled with COMBUSTOR, used to react biomass with the oxygen, by Gibbs free energy minimization and it does not require the stoichiometry reaction. The unit blocks of Pump, HeatX, Compr, and Valve were used to simulate and analyse the TOH and ORC units within the Aspen Plus. The oxygen was taken from the ambient air which supplied by a blower or compressor.

The biomass combustion produced heat that can be used to heat up the thermal oil (Syltherm XLT) until 188ºC. A high temperature thermal oil will enter the evaporator (EVP) and distribute the heat to R245fa rising its temperature and become a vapor. The low temperature thermal oil will be pumped to the burning heat source while the R245fa will enter and rotate the shaft on the expander. The rotation of this shaft will be converted to electrical energy by the generator. Low-pressure and temperature of R245fa will enter the condenser before being pumped back into the evaporator. To exploit the energy potential still contained in R245fa leaving the expander, a recuperator is installed. The use of a recuperator will increase the thermal efficiency of the system thus a high power output can be maintained for a decrease heat input to the system [4-6].

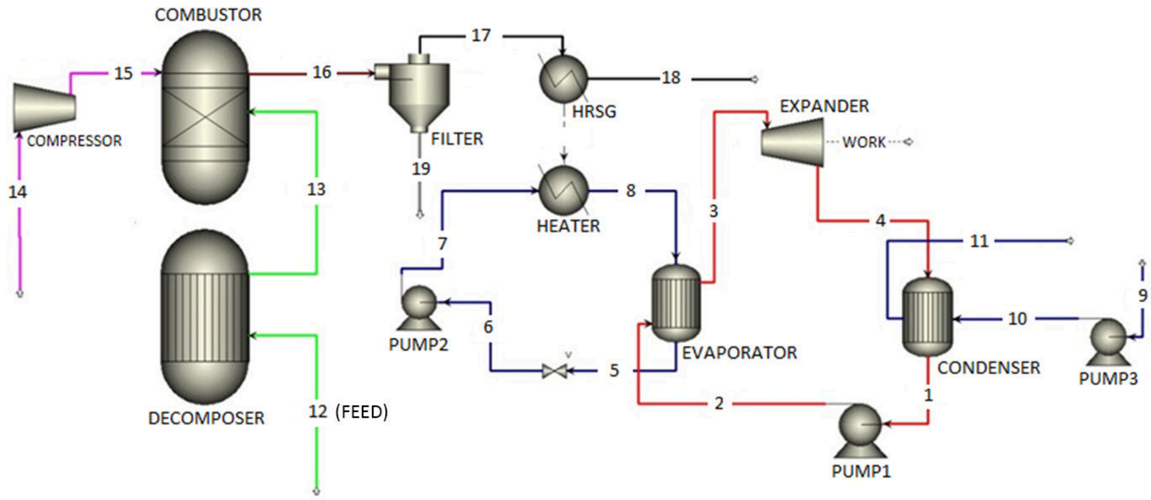


Figure 2. Aspen Plus simulation configuration for ORC plant without recuperator unit.

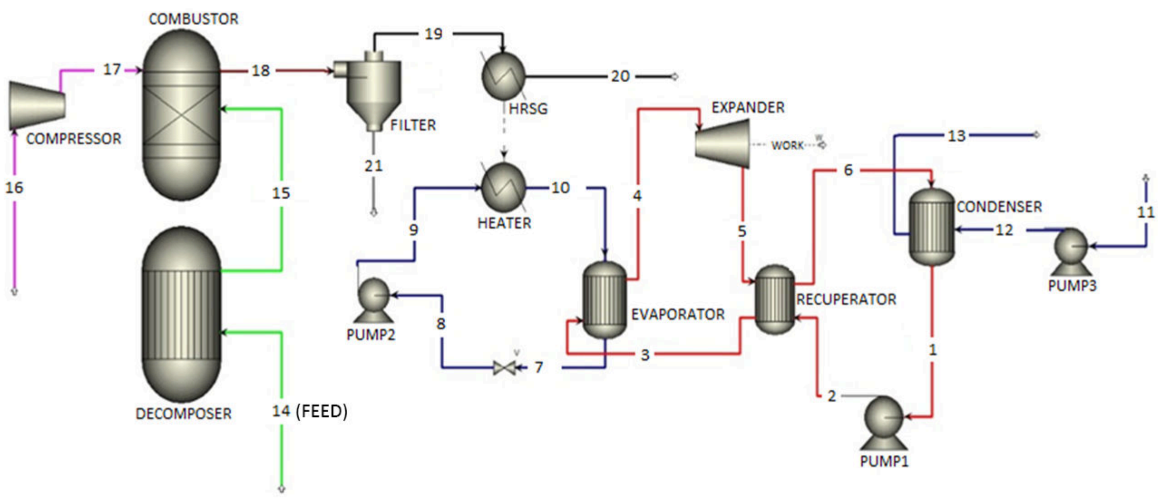


Figure 3. Aspen Plus simulation configuration for ORC plant with a regenerator unit.

The system efficiency will be analyzed based on results from Aspen Plus. The total efficiency of the system can be calculated by using:

$$\eta_{system} = (W_{expander} - E_{consumed})/Q_{in} \quad (1)$$

where $E_{consumed}$ is total energy consumed during the process.

3.2. Input data

EFB and wood chip were selected as the main fuel in this study because of its abundant availability in Indonesia, especially the province of North Sumatera. The feed composition of the EFB and wood chip are specified as described in table 1, while the main assumptions for analysis are shown in table 2.

Table 1. Composition of EFF and wood chip [10,11].

	EFB	Wood Chip
Proximate analysis (wt.%)		
Fixed carbon	18.84	17.94
Volatile matter	80	76.17
Moisture content	20	20
Ash content	5.89	1.16
Ultimate analysis (wt.%)		
Ash content	5.89	1.16
Carbon	48.63	51.19
Hydrogen	5.81	6.08
Sulphur	0.09	0.02
Nitrogen	0.63	0.2
Chlorine	0	0.05
Oxygen	38.95	41.3
Heating values (MJ/kg)		
Lower heating value (LHV)	18.5	19.09

The properties of Syltherm XLT as working fluid for TOH are given by Aspen Plus. Each biomass fuel will be burned with 20% excess air in a furnace operating at near ambient pressure.

Table 2. Main operational conditions and assumptions for plant calculation.

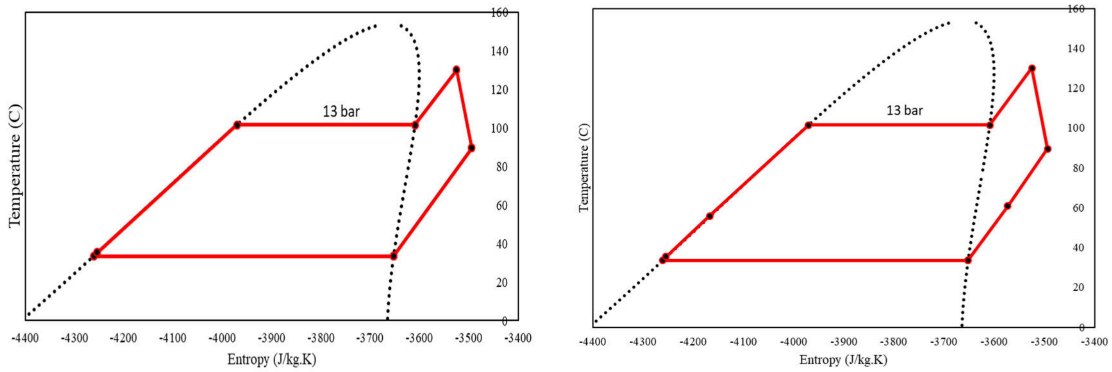
Flue gas temperature (°C)	60
Combustion temperature (°C)	400
Mass flow rate of thermal oil Syltherm XLT (kg/hr)	40.000
Outlet temperature of oil heater from evaporator (°C)	88
Mass flow rate of working fluid R-245fa (kg/hr)	2500
Outlet pressure of expander (bar)	2

4. Results and discussion

4.1. Design characteristic

Configuration 2, described in figure 2, was simulated with the inlet pressure of working fluid (R245fa) at the expander varied from 9 to 13 bar. According to the need of air required during combustion process, there are differences in air needs for each fuel. The above conditions are caused by differences in the composition of each fuel, especially carbon and hydrogen. The required air during combustion for EFB and wood chip are 7.28 kg air/kg of fuel and 7.54 kg air/kg of fuel, respectively. This indicates that the air supply in the use of fuel from wood chip leads to the use of more blower energy compared to the case of EFB as fuel.

In the case of EFB as fuel, results shown that 188.39 kW energy was used by the ORC system without recuperator configuration to reheat the working fluid up to 130°C at a pressure of 9 bar. Increasing the pressure of working fluid at the inlet of expander up to 13 bar, decreases the energy required to 184.02 kW. However, by introducing recuperator to the system (as shown in figure 3), the energy required can be reduced to 164.79 kW when operated at 9 bar and 164.77 kW when operated at 13 bar. It can be said that the recuperator provides an advantage in the integration of ORC system thus reducing energy losses during the process. In addition, the Temperature-Entropy diagram (T-S diagram) for both system configurations and selected properties for ORC system with recuperator are shown in figure 4 and table 3, respectively.



(a) ORC system without recuperation (b) ORC system with recuperation

Figure 4. Temperature-Entropy (T-S) Diagram for both system configurations.

Table 3. Selected properties of the ORC system with recuperator unit.

CODE	FLUID	T (^{O}C)	P (BAR)	ENTHALPY	QUALITY
1	R245fa	33.4	2	-8940.3	0
2	R245fa	35.4	13	-8937.5	0
3	R245fa	55.9	13	-8909.7	0
4	R245fa	130	13	-8672.5	1
5	R245fa	89.5	2	-8700.9	1
6	R245fa	60.9	2	-8728.6	1
10	Syltherm- XLT	188.04	1.5	-101.1	0
7	Syltherm- XLT	88	1.2	-115.9	0
12	Air	27	1.2	-15963	0
13	Air	30.9	1.2	-15945	0

4.2. System Efficiency

The total net power produced by ORC system without recuperator is 11.71 kW, and 12.25 kW for ORC system with recuperator in the case of EFB as fuel. The systems efficiency without recuperator and with recuperator are 6.84% and 7.91%, on the basis of LHV respectively. It can be seen that adding recuperator into system contribute to increasing system efficiency of 1.07 point. As shown in figure 5, it is also found that increasing the inlet expander pressure will increase the output power from the expander, the system efficiency, as well as decreasing fuel consumption rate during processes especially in the case of ORC system without recuperator unit. The recuperator plays an important role in lowering the fuel consumption of the system during the process by utilizing the latent heat of R245fa contained as it exits the expander before entering the condenser. The effects of adding recuperator unit to the system on reducing fuel consumption are shown in figure 6.

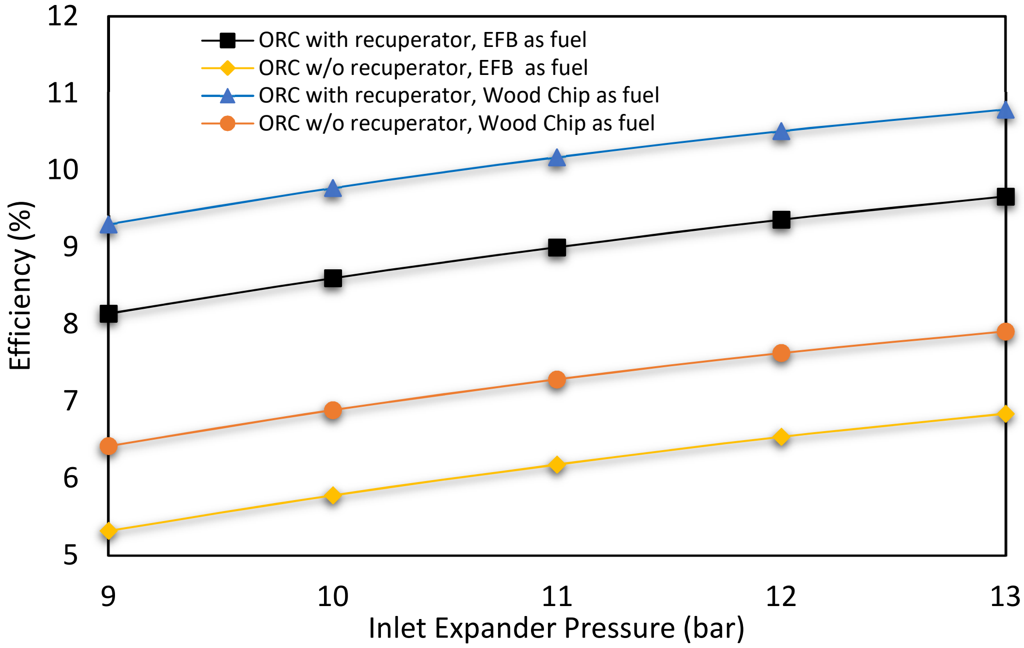


Figure 5. Effect of various inlet expander pressure on system efficiency.

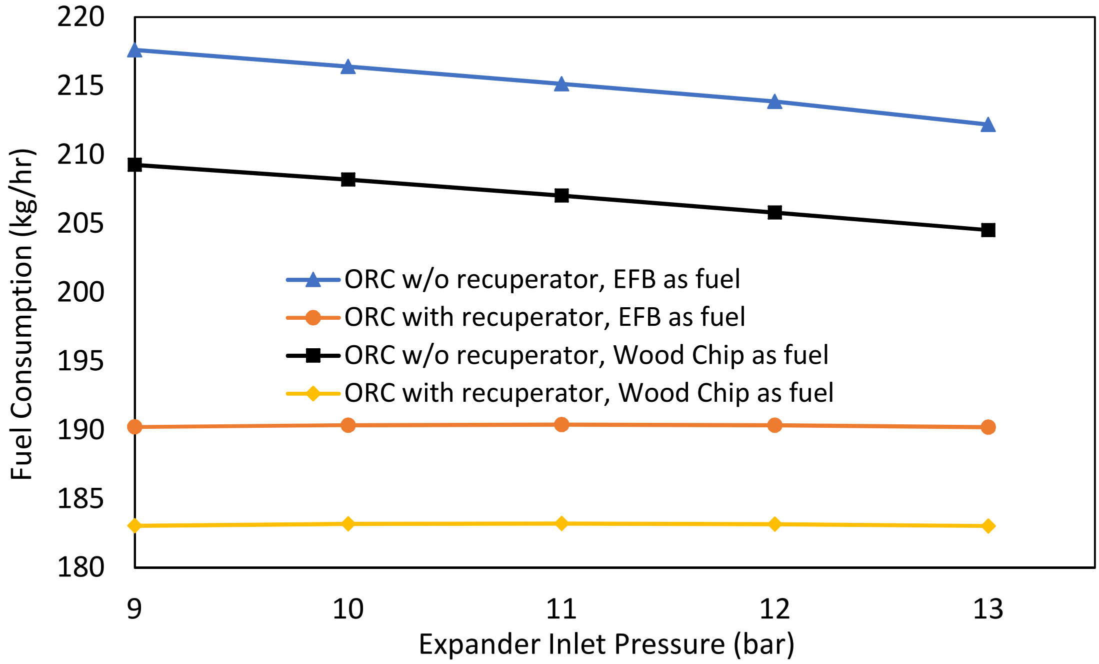


Figure 6. Effect of expander inlet pressure on fuel consumption.

5. Conclusions

The biomass combustion integrated to ORC to generated the electricity was analyzed in this study. Aspen plus was used to calculate the thermodynamic characteristics of the proposed design and integration models. It was found that the system efficiency will increase with increasing the expander inlet pressure. Adding a recuperator unit between expander and condenser will increase the system efficiency, and reducing fuel consumption during the process. However, the using of EFB as biomass fuel is good options, remembering this much available in Indonesia. Utilizing wood chip as biomass fuel for ORC system is better than biomass from EFB due to wood chip has highest LHV. However, due to the greater availability of EFB at the site, the use of biomass from EFB is more preferred.

Acknowledgements
This work has been fully supported by BP-PTN USU (Universitas Sumatera Utara), No: 6049/UN5.1.R/PPM/2016, July 19th, 2016.

References
[1] Li L, Ge Y T, Luo X, Tassou S A 2017 *App. Therm. Eng.* **115** pp 815-824
[2] Li G 2016 *Renew. Sust. Energ. Rev.* **53** pp 477-499
[3] Tanczuk M, Ulbrich R 2013 *Energy* **62** pp 132-141
[4] Nur T B, Pane Z, Amin M N 2017 *IOP Conf. Series: Materials Science and Engineering* **180** pp 1-7
[5] Lecompte S, Huisseune H, van den Broek M, Vanslambrouck B, Paepe M D 2015 *Renew. Sust. Energ. Rev.* **47** pp 448-461
[6] Saleh B, Koglbauer G, Wendland M, Fischer J 2007 *Energy* **32** pp 1210-1221
[7] Chen H, Goswami D Y, Stefanakos E K 2010 *Renew. Sust. Energ. Rev.* **14** pp 3059-3067
[8] Quoilin S, van den Broek M, Declay S, Dewallef P, Lemort V 2013 *Renew. Sust. Energ. Rev.* **22** pp 168-186
[9] Pezzuolo A, Benato A, Stoppato A, Mirandola A 2016 *Energy* **102** pp 605-620
[10] Wijono A 2014 *Simposium Nasional [National Symposium] RAPI XIII-2014 FT UMS ISSN* 1412-9612 pp 111-118
[11] Doherty W, Reynolds A, Kennedy D 2013 *Book Chapter:Material and Processes for Energy: communicating current research and technological development* ed A M Vilas (Formatex Research Centre) pp 212-220