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Design of an Electricity Generation Plant Utilizing Wasted Thermal Energy

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ABSTRACT

A combustion process, including the combustion of fossil and non-fossil-based fuels, will produce thermal energy. This energy can be converted into electrical energy utilizing a conventional Rankine cycle. However, there is still thermal energy left in the flue gas, characterized by a relatively high temperature of the flue gases. This energy is usually ignored and released into the atmosphere causing inefficient combustion. To increase combustion efficiency, the heat wasted from the flue gas cleaning unit can still be extracted using an adequate system. This article aims to obtain the best design of a system that utilized wasted heat to generate electricity using a thermodynamic system known as the organic Rankine cycle (ORC). Three working fluids of Hexane, R11, and R113 were used and simulated at the same operational conditions to get the optimum performance of the designed system. Performances were studied in terms of turbine output power and thermal efficiency. The results show that the Hexane working fluid produces higher turbine power compared to R11 and R113. Meanwhile, the temperatures and pressure do not greatly affect system efficiency, but the flow rate of the working fluid greatly affects the output power of the turbine. The simulation results show that the Hexane working fluid is the most suitable for use to recover the wasted heat of a combustion process included in the flue gases.

Keywords: *Combustion, Flue gases, Thermal energy, ORC System, Organic fluid.*

1. INTRODUCTION

Combustion is an activity that cannot be separated from human life on this earth. Combustion can be used to obtain thermal energy and to reduce and destroy materials that are no longer needed rather than becoming waste that negatively impacts the environment [1]. Generally, the problem caused by combustion is the increase in greenhouse gas emissions by CO_2 as a combustion product, but technology continues to develop to overcome this problem such as CO_2 capture technology [2][3][4]. In general, the main energy sources are fossil and non-fossil fuel based. In Indonesia, non-fossil fuels such as biomass and municipal solid waste have begun to be promoted due to the use of fossil fuels must be reduced because they are the largest contributor to greenhouse gas emissions [5]. Meanwhile, the government has declared zero emissions by 2060. Therefore, the government must immediately switch to non-fossil fuels because they are included in the zero-emission category. Efforts to utilize biomass and solid wastes as an energy source have already begun.

Combustion technology is superior because it can reduce solid waste by up to 90% and produce high thermal energy included in the exhaust gas. But in fact, the high temperature of combustion is very difficult to reach and it almost never happened. However, the temperature of the gas from biomass combustion can be increased by increasing the ability of the combustion reactor. The distribution of combustion air is the main key in the combustion process. Experimental results showed that the exhaust gas temperature of coconut shell biomass combustion can reach an average of 350 ºC [7]. High temperatures of flue gases indicate high thermal energy content which can be stored and used further [7].

It can also be utilized to generate small-scale power plants [8].

This article discusses how a small-scale power generation system is designed and analyzed to utilize thermal energy from solid waste combustion. The assumption is that the temperature of the flue gas from the combustor is constant in the range of 250 – 350 ºC. Thermodynamic models of the organic Rankine cycle is performed to predict the system performance.

2. SISTEM DESCRIPTION

Boilers are widely used in steam power generation systems using water as a working fluid, where a steam turbine is used to extract the thermal energy present in the water vapor into electric power through a generator. In Indonesia, steam power generation systems still rely on fossil fuels, generally coal. Along with the development of combustion technology, solid waste is also very potential to generate thermal energy in addition to reducing the volume of waste. Figure 1 shows a system that can utilize thermal energy from waste incineration. The main system is a power generation system using the conventional Rankine cycle and the 2nd system utilizes thermal energy that is still contained in the exhaust gas using the organic Rankine cycle (ORC). Combustion gases are important to clean before being released into the atmosphere. Generally, a cyclone is used to remove exhaust gases from particles that can float in the air [9]. However, the exhaust gas temperature is still very high after going through the cyclone. After going through a cyclone, the exhaust gas from burning coconut shell biomass can reach 380 ºC [10]. Such high temperatures are still very potential to generate small-scale electrical energy [11].

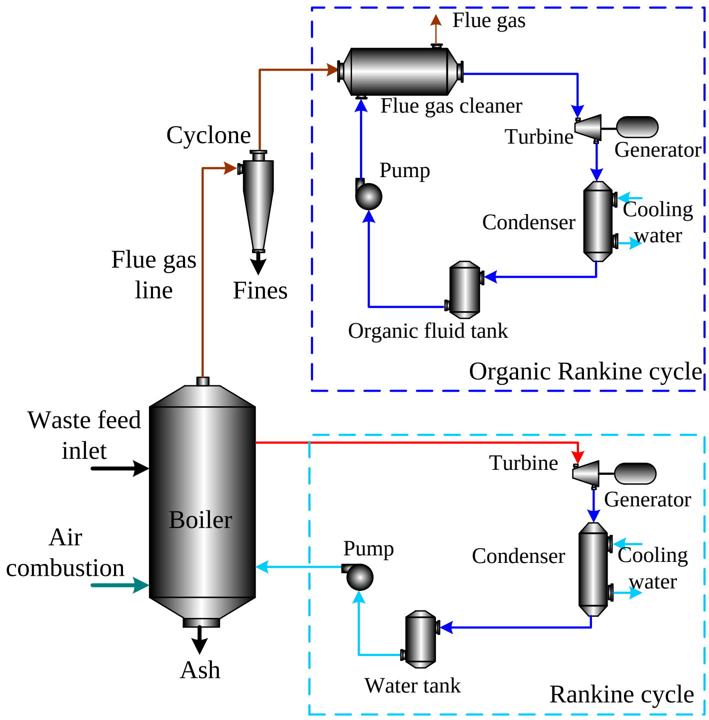

Figure 1. Diagram of power plant integrated with a waste incinerator.

ORC is a very precise system for extracting thermal energy from thermal energy sources at low temperatures [12]. The working fluid used is hydrocarbon-based which has a boiling temperature that is much smaller than water, so it does not require a large energy source to convert the working fluid into high-temperature and pressurized steam, just utilize thermal energy during the air cleaning process in the flue gas cleaner which becomes an evaporator in the ORC. The thermal energy in the refrigerant vapor is extracted using a turbine, then cooled back using a condenser. The working fluid that has returned to saturated fluid is accommodated in the collection tank and returned to the system using a pump. Thus, the system works to produce electrical energy through a generator.

3. MATERIALS AND METHOD

3.1. Materials

Three working fluids were tested in this study, namely Hexane, R11, and R113. These three working fluids are not too difficult to handle because they have a character like water. The three main properties of working fluids are shown in Table 1 below. Some of the advantages of ORC compared to water are safer and more environmentally friendly due to the organic working fluid used in ORC having a lower boiling point than water, reducing the risk of explosions and accidents due to high pressure. However, the disadvantages of ORC include the system's relatively high cost, lower efficiency compared to conventional water vapor Rankine cycles at high temperatures, and complexity in its design and operation

Table 1. Properties of working fluid used and its comparison with water

Working fluid	Molecular weight (kg/mol)	Boiling point (°C)	Critical pressure (bar)	Critical temperature (°C)
Water	0.018	99.97	220.64	373.95
Hexane	0.086	68.71	30.28	234.40
R11	0.137	23.67	43.94	198.02
R113	0.187	47.60	34.40	214.10

3.2. Diagram of simulation set-up

The simulation set-up diagram is shown in Figure 2. Working fluid at atmospheric conditions (1) is compressed using a pump until the working pressure increases at state (2). The working fluid is then fed into the heat exchanger to warm up the working fluid and increase its temperature at state (2a). The working fluid is then further heated in the evaporator by absorbing thermal energy from the flue gas into high-temperature and high-pressure saturated steam at state (3). The thermal energy in the working fluid is then extracted using a turbine. The working fluid exits the turbine at state (4) with saturated steam conditions and is put into the heat exchanger to warm the working fluid before entering the evaporator. The working fluid from the heat exchanger is then cooled using a condenser to convert it back into a liquid state (6).

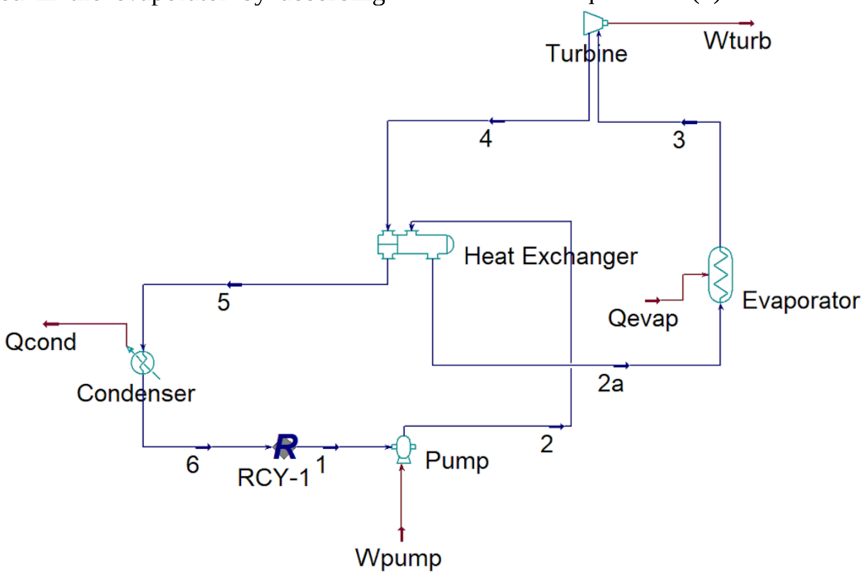

Figure 2. Diagram flow of the simulation set-up.

3.3. Method

The designed system was tested employing three different working fluids using operational parameters as shown in Table 2. Aspen Hysys V12.1 software is used as a simulator. Operating parameters such as evaporator temperature and pressure, as well as the working fluid flow rate, are customizable to study the characteristics of the ORC system. This is because the thermal energy of the working fluid on ORC increases with increasing temperature and pressure, and the working fluid flow rate is linear to the output power of the turbine.

Under predetermined conditions, the necessary data such as the temperature of the working fluid leaving the turbine (4) and heat exchanger (5), pumping power (W_{pump}) and turbine (W_{turb}), evaporator duty (Q_{evap}), and condenser duty (Q_{cond}) are recorded and analyzed to determine the performance of the system according to the working fluid used. All the required data are available in the workbook on Hysys. The results of the analysis of the three working fluids are displayed in this work and discussed comprehensively.

Table 2. Parameter used in the simulation

Parameter	Setup Value
Flue gas (ºC)	250-350
Refrigerant	Hexane, R11, and R113
Refrigerant mass flow rate (kg/h)	900, 1800, and 3600
Operating pressure (kPa)	300, 400, and 500
The temperature of the evaporator (ºC)	135, 160, and 185
Phase fraction at the pump outlet	0
Phase fraction at the turbine inlet	1
Outlet turbine pressure (kPa)	150
System pressure drop	0
Phase fraction at the turbine outlet	1
Phase fraction at the condenser outlet	0
Condenser outlet temperature (ºC)	20
Turbine efficiency (%)	75
Pump efficiency (%)	75

4. RESULTS AND DISCUSSION

Simulations have been carried out on each working fluid under the same operational conditions. The simulation results discussed refer to the data presented in the graph and are compared with the results of previous studies.

4.1. The effect of evaporator temperature on the turbine output power

The effect of evaporator temperature on turbine output power is shown in Figures 3, 4, and 5 for each three working fluids. Results show that Hexane generates greater turbine output power compared to R11 and R113. For the three working fluids, the increase in operating pressure (OP) greatly affects the performance of the turbine. The more the pressure rises, the turbine output power generated also increases. This is in accordance with the results of the research conducted by previous researchers using different working fluids [13][14]. However, it is different from the operational parameters of the evaporator temperature. The increase in evaporator temperature is followed by a slight increase in turbine power generated. This is because the temperature increase is not too high so the increase in turbine power is also not significant. These agree with the results of simulations study conducted by previous researchers [15]. So indeed, the most decisive factor in ORC is the working pressure of the system.

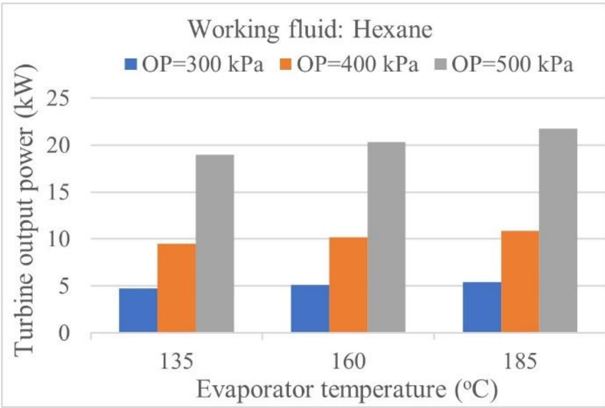

Figure 3. Evaporator temperature vs turbine output power on Hexane working fluid at different operating pressure and 900 kg/h of fluid flow rate.

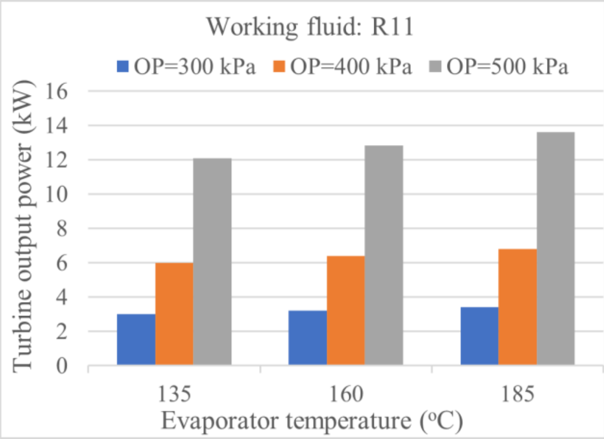

Figure 4. Evaporator temperature vs turbine output power on R11 working fluid at different operating pressure and 900 kg/h of fluid flow rate.

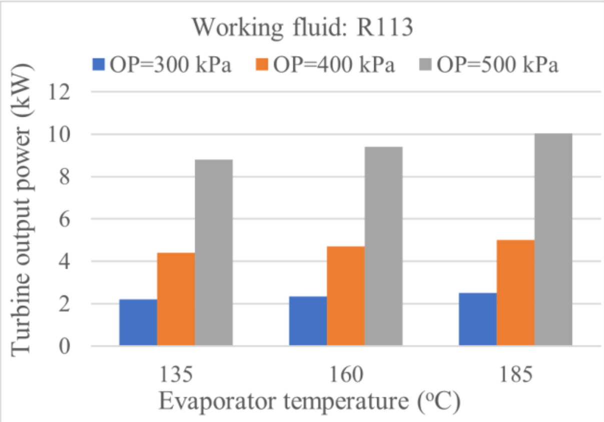

Figure 5. Evaporator temperature vs turbine output power on R113 working fluid at different operating pressure and 900 kg/h of fluid flow rate.

4.2. The effect of working fluid flow rate on the turbine power output and the thermal efficiency

The rate flow of the working fluid in the system greatly affects the turbine output power. From the graph in Figures 6 and 7, it can be seen that there is a very drastic increase in the turbine output power when the rate flow of the working fluid is increased as stated before in section 4.1. However, thermal efficiency is not affected by the rate flow of the working fluid. From the graph, it can be seen that there is no increase in efficiency when the flow rate of the working fluid is increased.

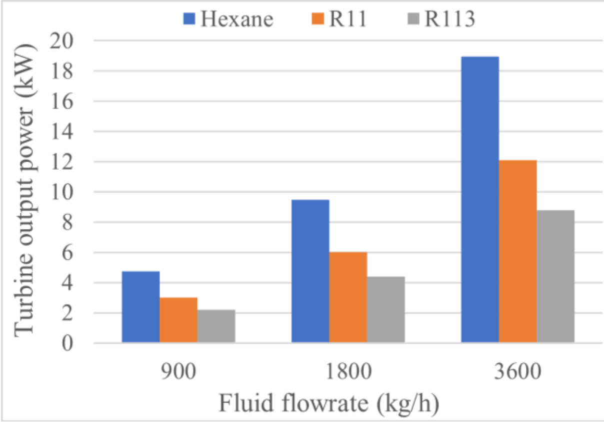

Figure 6. Fluid flow rate vs turbine output power at 300 kPa of operating pressure and 135 ºC of the evaporator temperature.

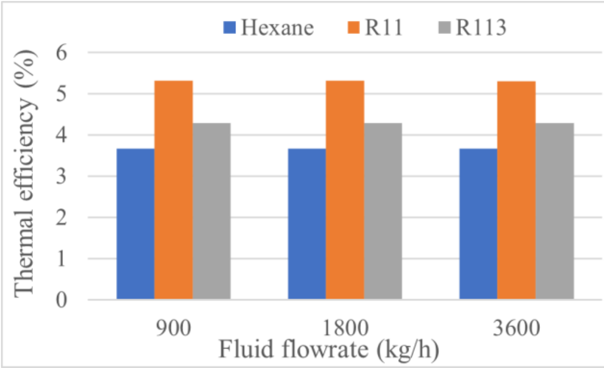

Figure 7. Fluid flow rate vs thermal efficiency at 300 kPa of operating pressure and 135 ºC of the evaporator temperature.

4.3. Comparison of turbine output power and efficiency in all three working fluids

The graph in Figure 8 shows a comparison of the performance of the three working fluids under the same operational conditions. The three working fluids show the same character where the increase in evaporator temperature is accompanied by an increase in turbine output power, but the increase is not too significant. This is once again because the temperature rise is not high (25 ºC), so the increase in output power is also slightly low. Hexane fluid shows the best performance among the three working fluids.

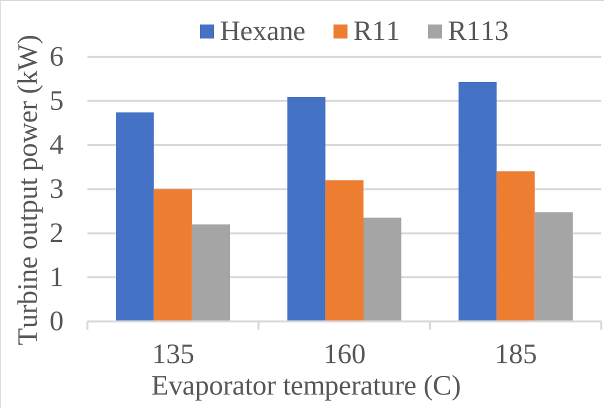

Figure 8. Evaporator temperature vs turbine output power at 300 kPa of operating pressure and 900 kg/h of working flow rate.

The graph in Figure 9 shows the tendency of thermal efficiency to the evaporator temperature. All three working fluids show the same trend that there is no increase in efficiency against the increase in evaporator temperature. This is because the higher the temperature of the evaporator, the cooling duty also increases. To overcome this case, additional units are used to reduce the duty of the condenser. Units that can be used for example as economizers.

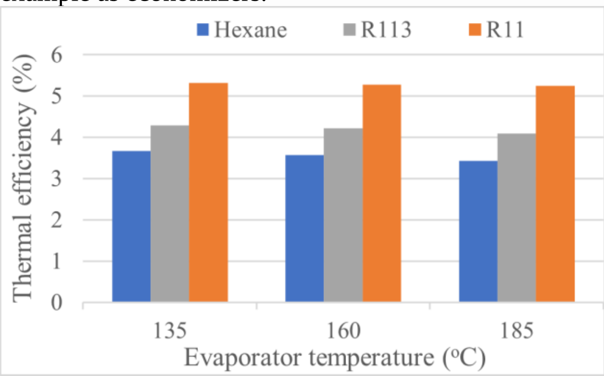

Figure 9. Evaporator temperature vs thermal efficiency at 300 kPa of operating pressure and 900 kg/h of working flow rate.

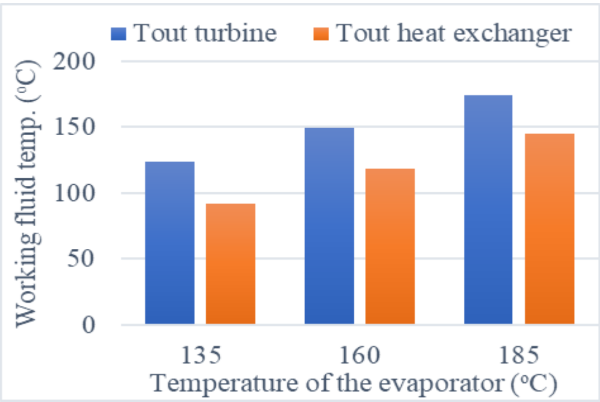

Figure 10. Working fluid temperature at the exit vs temperature of the evaporator at 300 kPa of operating pressure and 900 kg/h of working flow rate.

The graph in Figure 10 shows the temperature trend of the working fluid leaving the turbine and heat exchanger. It can be seen that the temperature of the working fluid leaving the heat exchanger is still relatively high. This is affected by the pressure of the working fluid leaving the turbine. In this study, the working fluid pressure in and out of the turbine was set at 300 kPa and 150 kPa respectively.

5. CONCLUSION

Simulations have been carried out on the design of small-scale power plant systems. The organic Rankine cycle is used as a thermodynamic model to predict the performance of power generation systems. Three organic working fluids are used to obtain better performance in the same operational work. The simulation results show that Hexane's working fluid is very suitable for small-scale power plants with energy sources from flue gases of solid waste combustion.

AUTHORS' CONTRIBUTIONS

J.P. Simanjuntak: Writing-Original Draft, Conceptualization, Investigation, Formal Analysis, Supervision. E. Daryanto, B.H. Tambunan, and Eswanto: Resources, Conceptualization, Investigation, Formal analysis. M. Ibrahim: Writing-Review & Editing, Resources, Visualization, Formal Analysis.

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