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Process design and simulation study of an electricity generation plant utilizing low-grade wasted thermal energy using aspen Hysys software

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ABSTRACT

An analysis of the operational parameters of a small-scale electrical generation facility that uses the thermal energy contained in the flue gases from rubbish waste incineration is the goal of this study. To assess this system, the organic Rankine cycle (ORC) thermodynamic system was used. Since the organic fluid has a lower boiling point than water and can be evaporated with less thermal energy, it was chosen as a heat transfer medium instead of water. Aspen Hysys was utilized as a simulation tool, while R11 was used as the working fluid. To maximize the amount of available electrical output power, the plant's operational temperature, working fluid flow rate, and pressure are all maximized. According to the simulation's findings, flue gas may generate electric power between the ranges of 3.12 – 29.71 kW at working pressures between 2.5 and 3.5 bar and working fluid flow rates between 3.600 and 7200 kg/h when the temperature is between 50 and 95 °C. The system reaches a thermal efficiency of about 8.30 at 350 kPa of working fluid pressure.

Keywords: Waste thermal; organic fluid; rankine cycle; aspen hysys; electric power

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1. INTRODUCTION

Along with the growth in the global population, there will be a corresponding rise in energy requirements and carbon emissions [1], [2]. The primary energy source in use today is still coal and fossil fuels, particularly liquid fuels. Extreme weather and climate change are, of course, the negative impacts of using fossil fuels. This is a result of the pollution and emissions emitted by these fuels [3]. Individual nations are required by the global agreement to cut their usage of fossil fuels; therefore, they must look into new energy options that emit little to no carbon dioxide. In Indonesia, the potential for using bioenergy to boost Indonesia's energy mix in 2050 is very promising [4].

The globe is currently grappling with detrimental effects brought on by an excess of garbage waste in addition to global warming. Leachate [5] and soil contamination from heavy metals [6] are the most detrimental effects, along with pollution from particulate matter, acidic gases, and dioxins. Even while correctly processed garbage waste can be a source of bioenergy [7] or an alternative liquid fuel source [8], the volume of garbage waste is continuously spiraling out of control.

The use of garbage waste as a source of thermal energy in boilers and the conversion of that thermal energy into electrical energy using turbines is one of the initiatives currently being developed. Two garbage waste power plants with a combined capacity of 46.2 million kWh were operating in 2006; however, due to low LHV, the garbage waste was blended with coal [9]. The use of garbage waste as a source of electrical energy is particularly effective in Indonesia. Two researchers were successful in simulating and forecasting the electrical power that can be gained from garbage incineration by taking garbage samples from landfills [10], [11].

Boilers as steam generators can be used to harness the thermal energy contained in combustion gases, but in order to keep the air clean, combustion gas cleaning devices are crucial [12]. However, the main weakness of the boiler as a steam generator that will be used to drive a steam turbine is that it must have a large capacity to be able to produce water vapor at high temperatures and pressures. This type of power plant is very prone to breakdowns and accidents. The solution needs to create a power generation system that works at low temperatures and pressures and produces low emissions. In addition, this kind of plant can be built on a small scale, even residential or industrial scale. This is what makes this kind of plant more important to develop compared to fossil fuel power plants.

The combustion chamber of a combustor must function better in order to lessen the pollution that results. The fundamental factor in achieving high combustion chamber temperatures is air distribution [13], [14]. In actuality, combustion emissions from incineration are still at a high level. The temperature of solid biomass waste combustion when it exits the chimney is still around 390 °C [15]. Before being inserted into the cleaning device or gas cleaning system (GCC) and released into the environment, this temperature needs to be lowered. For this reason, a heat exchanger, a device for reducing the temperature of combustion gas, is required. Working fluids like water and organic fluids, which can absorb heat energy and transmit it to thermal energy storage devices [16], where it can be used for other things like the creation of electrical energy [17], [18], can be used to lower the temperature of combustion gases.

Another method is to directly evaporate a working fluid in the evaporator by using hot combustion gases. The ability of the organic Rankine cycle to capture thermal energy even at low concentrations has long been understood. The working fluid employed most frequently has a low boiling point, frequently much lower than the boiling point of water. An organic Rankine cycle (ORC) [19] can use up to 31 different types of working fluids and a variety of thermal energy sources. There aren't many power-producing systems using ORC in the field right now. Testing is largely done through simulations, while research is still in the early stages.

Thermal energy is also obtained from a variety of sources, including hot gas produced by the burning of fuels other than solar and geothermal energy. The goal of this article is to describe how a small-scale power production system that uses the thermal energy from garbage waste combustion devices can be designed. Before being transferred to the gas cleaning unit, the hot combustion gas cooling unit obtains thermal energy that is appropriate for discharge into the atmosphere. Utilizing Aspen Hysys simulations, the performance of the organic Rankine cycle is evaluated as a thermodynamic system of a power plant depending on the properties of the working fluid.

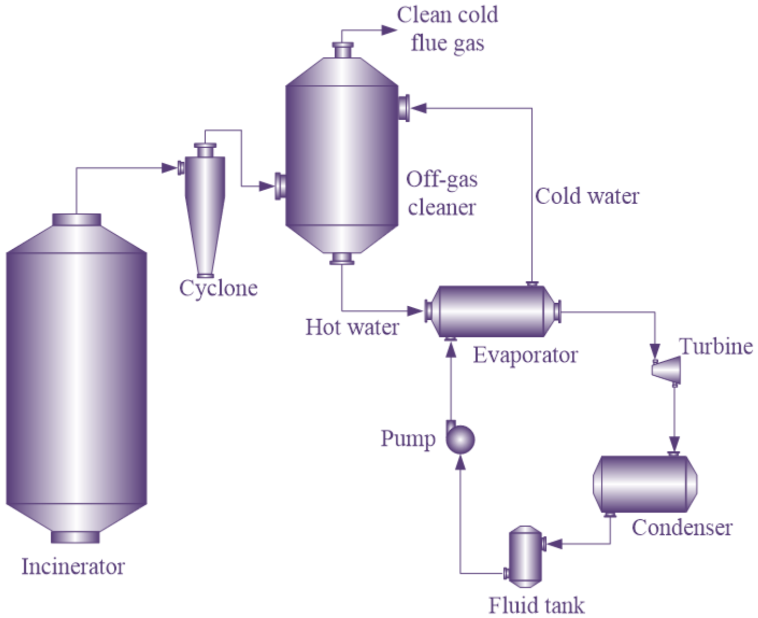

Figure 1: Power plan integrated with an incinerator

To achieve the best performance, numerous related operational factors are simulated for system optimization. The organic Rankine cycle, a thermodynamic cycle, is used in small power plants to use medium-to low-level thermal energy [20]. An integrated power plant comprising a boiler unit and a flue gas cleaning unit that uses thermal energy from garbage waste incineration is depicted in Figure 1. Additionally, it's not a good idea to release flue gas into the atmosphere when it's hot. As a result, it needs to be cooled first using a heat exchanger unit with high heat-capacity working fluids, like water and oil, or an organic fluid. The Rankine organic cycle is then used to extract the thermal energy from the working fluid, utilizing working fluids like hexane. At a temperature source between 150 and 350 °C, this working fluid is thought to be extremely acceptable.

2. MATERIAL AND METHODS

2.1 Material

The investigation's working fluid is R11, a hydrocarbon molecule with the molecular formula CC13F. This material has the following properties: 137.38 g/mol molecular weight; 23.71 °C boiling point; 197.96 °C critical temperature; and 44.07 bar critical pressure. This working fluid is already available in the Hysys fluid package. This substance is generally easy to handle and use because it is liquid, colorless, and has properties that are similar to those of water. It was found also that the payback period of ORC with R11 is a minimum (of 2.5 years) [21].

2.2 Method

This work is a simulation-type study that examines a design of a power generation system using Aspen Hysys V12.1 software with R11 as a working fluid. The main components of the system are assembled for real system installation as shown in Figure 2. Atmospheric condition R11 working fluid at state 3 is compressed using a pump until the working pressure rises at state 4. Working pressure according to this study can be adjusted using this pump. Following that, the working fluid is fed into the heat exchanger to raise the working fluid temperature at state 5. The temperature of the fluid is regulated using a heat source, namely hot water. The heat exchanger then uses the hot water energy to create high-temperature, high-pressure saturated working fluid steam to further warm the working fluid. The working fluid's thermal energy is subsequently extracted using a turbine. The working pressure out of the turbine can also be adjusted to determine its effect on turbine performance. After being cooled by a condenser to return to a liquid at state 2, the working fluid is then recycled into the system via a pump.

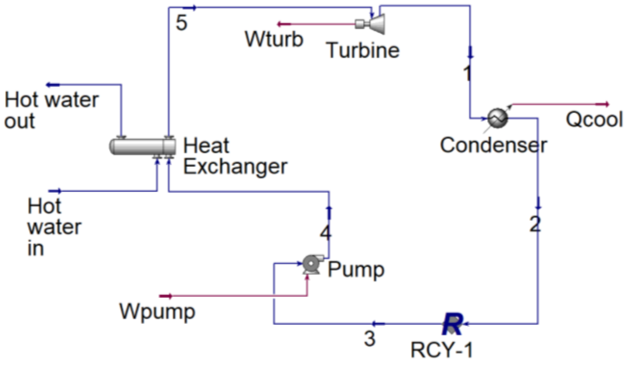

Figure 2: Aspen Hysys flow diagram of the simulation study

The diagram of the power plant system in Figure 2 was simulated by referring to the actual operational parameters of the real system, namely temperature, pressure, and working fluid flow rate. The operational parameters used are shown in Table 1.

Table 1: Parameter used on the simulation

Parameter	Set Value
Hot water temperature (°C)	65-95
Working fluid	R11
Working fluid mass flow rate (kg/h)	3600-10800
Outlet pump pressure (bar)	2.5-6.0
Phase fraction at the pump outlet	0
Phase fraction at the turbine inlet	1
Outlet turbine pressure (bar)	2.0
Cooling water mass flow rate (kg/h)	50000
Cooling water inlet temperature (°C)	27
Turbine efficiency (%)	75
Pump efficiency (%)	75

During the simulation process, necessary data such as turbine power output, pump work, and heating/cooling loads in response to operational parameter inputs are recorded and used to evaluate the performance of the system. All this data can be obtained in the data table that has been stored in Hysys during the simulation process. All data is presented in the form of graphs to facilitate the identification of system performance trends in response to operational parameters.

3. RESULTS AND DISCUSSION

By adjusting operational parameters for the working fluid flow rate, pressure, and temperature of the system, the investigation's simulation-based findings were attained and tabulated in Table 2. This table presents two main parameters that are very important in running the power generation system in this study. Working pressure and temperature are determinants in producing electric power because they are closely related to the characteristics of the working fluid R11. Under normal circumstances (standard air pressure), R11 will boil at a temperature of 23.71 ^{o}C. This means that by utilizing only low levels of thermal energy, at least with a temperature indicator of 55 ^{o}C this fluid will evaporate and can be used to drive steam turbines. Another important parameter is working pressure. The minimum usable working pressure is 250 kPa. Under these conditions, R11 will become vapor at a temperature of 55 ^{o}C. Below that temperature, R11 does not evaporate, so it cannot be put into the turbine. The results of the investigation showed that when raising the working pressure, the saturation temperature R11 will also increase.

Table 2: Condition of designed system performance parameters

Working Pressure Ranges (kPa)	Saturated Temp. Ranges (^{o}C)	Output Power Ranges (kW)
250 - 265	55 - 95	12.30 - 14.94
270 - 310	60 - 95	13.56 - 17.13
315 - 350	65 - 95	15.71 - 18.76
375 - 400	70 - 95	18.09 - 20.51
410 - 450	75 - 95	14.47 - 21.99
460 - 515	80 - 95	21.16 - 23.62
520 - 600	85 - 95	22.94 - 25.37

3.1. Working pressure's impact on electrical power output

A pump must be used to raise the working fluid pressure in order to get a high working fluid temperature. Pump pressure will also cause the working fluid's saturation temperature to rise, which will raise the enthalpy of the working fluid entering the turbine. As a result, the turbine's work output (W_{turb}) rises. It is clear from the graph in Figure 3 that the resultant turbine work tends to increase as turbine inlet pressure (P_{turb}) rises at a constant operating temperature. The outcomes of this simulation match those of an analysis that was done utilizing thermodynamic relationships [18]. Experimental research also showed the same trend when the evaporator pressure is increased, the turbine output power will also increase [22]. Although increasing the working pressure can improve the turbine's output power, this system cannot be pressed further. At a pressure of 325 kPa or above, the saturation temperature increased above 60 ^{o}C. If the working pressure is too high, it will be more difficult to operate this system. The working fluid must be evaporated with additional energy, which means amounts of hot water as an energy source is needed.

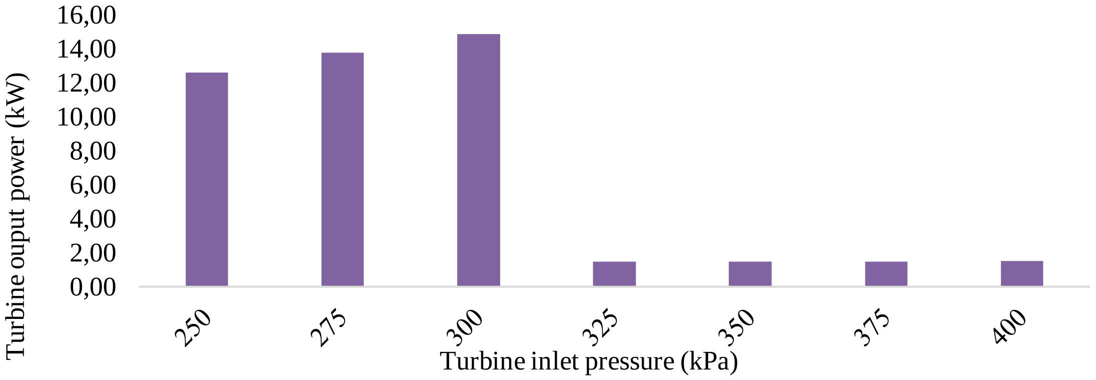

Figure 3: Output power as a function of turbine inlet pressure (P_{turb}) at a constant temperature of 60^{o} C

3.2. Working temperature's impact on turbine output power

As previously mentioned, increasing working pressure will raise the working fluid's saturation temperature. The saturation temperature will be attained for sufficient thermal energy sources, which will raise the working fluid's enthalpy and have an impact on boosting turbine power output, as illustrated in Figure 4. The outcome of this analysis utilizing thermodynamic connections is consistent with the outcome of the analysis [18]. The working fluid's flow rate and temperature can be increased to enhance the turbine's output power.

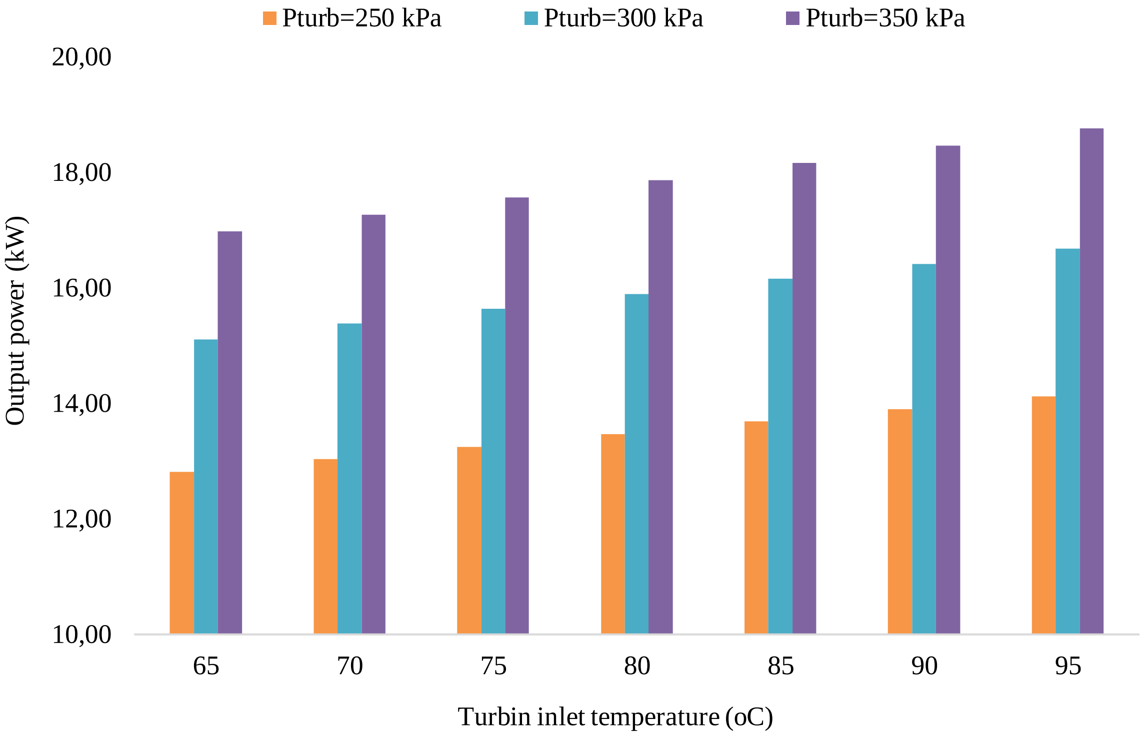

Figure 4: Output power as a function of inlet turbine temperature

3.3. Turbine inlet temperature's impact on thermal efficiency

Figure 5 shows the relation between temperature and thermal efficiency. From the graph, it can be seen that for every 50 kPa increase in working pressure, the thermal efficiency will also increase by an average of 13%. A parametric study proved that at working fluid pressures above 1000 kPa, an ORC produces an efficiency of 13.5% [23]. Referring to some experimental results, the thermal efficiency of ORC is still too low, regardless of the type of turbine used. Improving thermal efficiency is the main work of researchers, especially in the condenser section. By lowering the condenser temperature and increasing the cooling fluid flow rate, the thermal efficiency of an ORC can reach 3.04% [24].

From the graph, it is known that the thermal efficiency of the system is not influenced by the temperature of the working fluid. This is because high working fluid temperature entering the turbine will also be followed by a high load increase when cooling in the condenser resulting in relatively constant thermal efficiency. This finding is similar to the results of studies conducted by other researchers [22]. One thing that can be done to increase thermal efficiency is to use an economizer, where thermal energy that is still high when the working fluid leaves the turbine can still be used as a preheater of the working fluid before entering the evaporator so that the cooling load will decrease.

It can also be seen that thermal efficiency is strongly dominated by the operating pressure of the system. At an operational pressure of 350 kPa thermal efficiency can reach 8.30%. Operational pressure in an ORC system can affect thermal efficiency because pressure plays an important role in the process of changing the phase of the working fluid within the cycle. In the ORC cycle, the working fluid undergoes a phase change from liquid to vapor and back again to liquid. This phase change process occurs in condensers, evaporators, pumps, and turbines. Operational pressure affects phase change and heat transfer within each component of the cycle, and consequently, affects overall thermal efficiency.

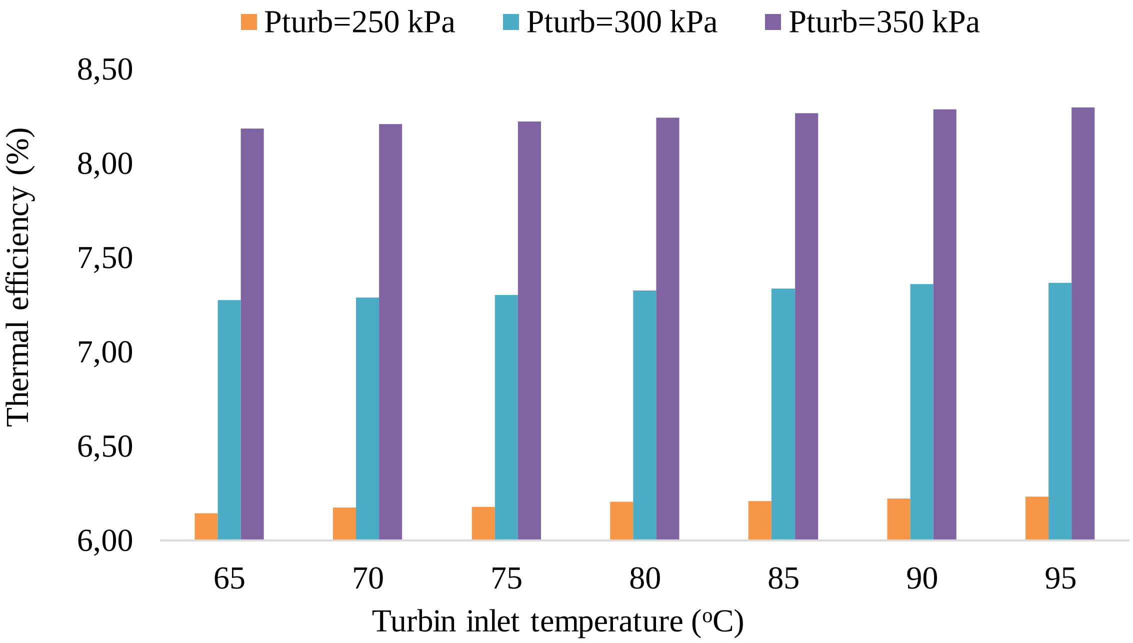

Figure 5: Thermal efficiency as a function of inlet turbine temperature

3.3. Working fluid flow rate impact on turbine output power

The graph in Figure 5 demonstrates how sensitive the turbine output is to the working fluid flow rate, with higher working fluid flow rates being accompanied by higher turbine output rates. These results show the same trend as the results of simulations conducted by previous researchers [25]. However, the flow rate is very limited due to the planned capacity of the turbine and the power required to raise its pressure through the pump. In addition, the saturation temperature of the working fluid will also increase when the working pressure is increased. From the graph, it can be seen that the turbine output power at a pressure of 350 kPa decreased drastically because the saturation temperature of the working fluid increased. At a temperature of 60 °C, the working fluid condition entering the turbine is wet and will reduce the enthalpy, which results in a decrease in turbine output power.

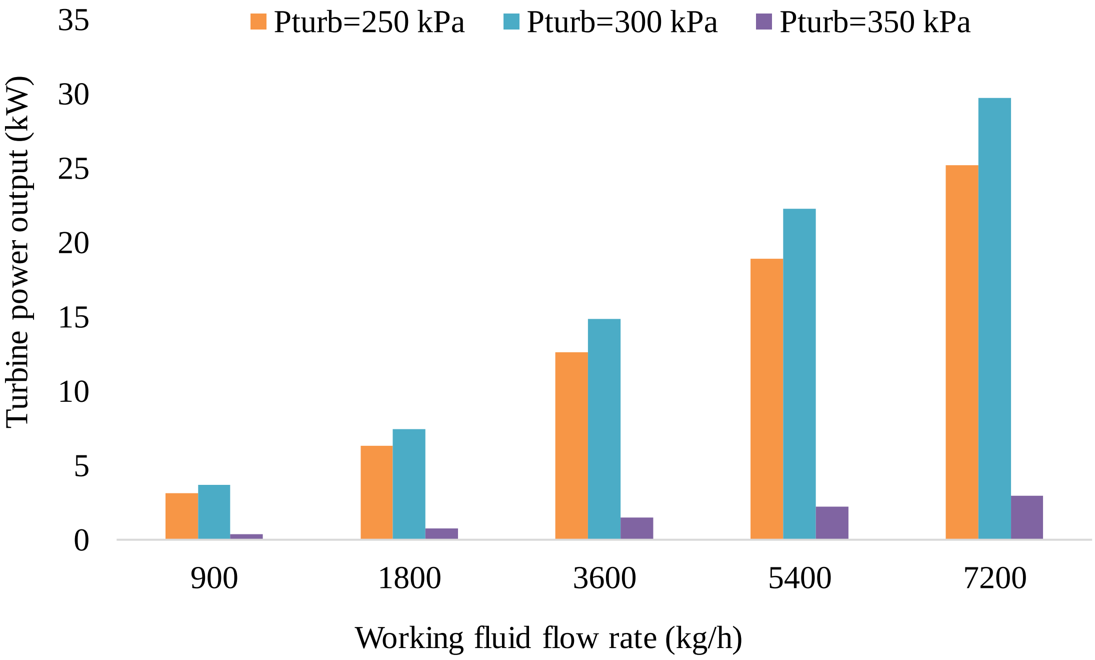

Figure 5: Turbin output power as a function of working fluid flow rate at temperature 60 °C

4. CONCLUSION

Incineration of solid fuels including garbage will produce hot smoke that still has value in terms of thermal energy. A simulation study has been conducted to determine the performance of a power generation system that utilizes hot smoke from burning waste as an energy source. Water is used as a thermal energy storage medium through a heat exchanger and then used as a working fluid heater in the same heat exchanger. The organic Rankine cycle was used as a thermodynamic model and Aspen Hysys V12.1 was used as the simulation tool. The simulation's findings demonstrate that it is still possible to produce small amounts of electrical energy on a small scale by using the thermal energy present in the waste combustion exhaust gas. The thermal energy potential in exhaust gases in a temperature range of 150–250 ^{o} C can be utilized to produce electrical power by using R11 as the working fluid. Low-temperature water 50 – 95 ^{o}C and low-pressure 250 – 350 kPa can produce electric power ranging from 3.12 kW to 29.71 kW.

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DECLARATIONS

Author contribution

J.P. Simanjuntak: Writing - Original Draft, Conceptualization, Investigation, Formal Analysis, Supervision. B.M.T. Pakpahan: Resources, Conceptualization, Investigation, Formal analysis. Purwantono: Writing - Review & Editing, Resources, Visualization, Formal Analysis. K. A. Al-attab: Writing - Review & Editing, Resources, Visualization, Formal Analysis

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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