Design of upi incinerator heat-electricity conversion system by applying classic rankine cycle

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Abstract. UPI has successfully developed a smokeless incinerator. Incinerator combustion occurs at high temperatures. High temperature is the potential energy that can be converted into electricity. The innovation space is still open here to increase the ability of the UPI incinerator to become part of a system that can generate electricity by utilizing the burning of waste that occurs in the incinerator. This conversion system uses the Rankine Cycle. The Rankine cycle utilizes water as its working fluid. This research is targeted to get the design of an incinerator heat energy conversion system into electricity by using classical basic Rankine cycle. The investigation will vary three different pumps to get the best performance. The performance parameter are the cycle thermal efficiency and net power produced by the cycle. The design process starts with the calculation of potential heat from waste combustion. The calculation uses the LHV value of municipal solid waste and the second heat source comes from reaction of LPG which consists of 48.5% propane, 48.5% butane and 3% pentane and air which consists of 79% Nitrogen and 21% Oxygen. The reaction is assumed perfect and Nitrogen is not reacted. Total heat is 581.4 kW which comes from 574 kW from LHV of municipal waste and 7.76 kW from the reaction of LPG and air. The heat transferred to work fluid comes from 50% LHV of municipal waste and 14% from the reaction of LPG and air. The cycle can produce 55.5 kW power and the efficiency is 13%. The cycle use 600W water pump with 8 liter/min debit. Debit is the important parameter to get better power output and efficiency from heat of incinerator waste combustion.

1. Introduction
UPI has made an incinerator for the Citarum Harum program based on news from Jabar Ekspres February 4th, 2019 edition. The article explains that the incinerator being developed was concerned to clean environment because the exhaust system used multilevel combustion and have post-processing combustion products.

The heat from this combustion has not been utilized. This heat must be used because it can be a source of energy. One solution is the Rankine cycle. The Rankine cycle describes how to use heat to convert it into work by evaporating water, and is currently known as the classic Rankine cycle (Moran et.al, 2014). This cycle can be used to take the heat generated by burning waste in the incinerator. In addition to the classic Rankine cycle using water as its working fluid, while the organic Rankine Cycle uses its working fluid as its working fluid (Lecompte et.al, 2015). Furthermore, Lecompte also revealed that in his review it was shown that the maximum temperature in the evaporator process is 350°C (Lecompte et.al, 2015). The temperature occurring in the UPI’s incinerator is more than 350°C. This
means that it needs to be considered in the design to include the Classic Rankine Cycle for converting device from heat to kinetic energy. Kinetic Energy will rotate generator for generating electricity.

This research aims to determine the theoretical amount of heat potential of the incinerator and whether the classical Rankine cycle is applied to exploit this heat, what is the output power and efficiency of this cycle.

2. Method

The Classic Rankine Cycle is used to accommodate the heat generated by municipal waste combustion. Here’s a diagram of the standard classic Rankine cycle and the names of the components.

![Figure 1: Basic schematic of the Rankine cycle to guess the power from combustion in incinerator](image)

The analysis starts with choosing three kinds of pump with different power input available pumps in market. Then, Thermodynamics analysis starts from pump as a system which water enter the pump in an environment condition (temperature 15°C and pressure 0.9 bar). Pump analysis is in a steady state, and there is only work from the pump given to the working fluid. Equation (1) is model describing pump control volume analysis.

\[
\dot{W}_p = \dot{m} (h_3 - h_4)
\]

where

\(\dot{W}_p\) : pump power (Watt)
\(\dot{m}\) : water massflow (kg/s)
\(h_3\) : water specific enthalpy when enter pump (kJ/kg)
\(h_4\) : water specific enthalpy when exit pump (kJ/kg)

Equation (1) cannot be applied directly to pump analysis because the main job of the pump is to increase the pressure. Therefore equation (1) can be changed to another form by assuming the working fluid is incompressible (specific volume (\(\nu\)) at condition 3 equals condition 4) and the internal energy in conditions (3) and (4) are the same so that equation (1) can be transformed into equation (2). Equation (2) allows us to find the value of the pressure after exiting the pump.
\[ \dot{W}_p = v_3 (p_3 - p_4) \]  \hspace{1cm} (2)

The variations of the pump input power used vary from 600, 640 and 1200 Watts. This power is different with the pump power \( W_p \) that delivered power to water as working fluid. The pump power increases the fluid pressure directly according to equation (2). The pump power can be calculated from the head and flow rate generated by the pump. The relationship between the pump power with head and flow rate is described in equation (3) (Munson et al., 2009).

\[ \dot{W}_p = \gamma (V/t) H \]  \hspace{1cm} (3)

\( \gamma \) : Specific Gravity (kg/m\(^2\).s\(^2\))

\( V/t \) : flow rate (m\(^3\)/s)

\( H \) : Head (m)

The incinerator as control volume is analyzed using equation (4). The input heat \( \dot{Q}_{in} \) comes from two sources, i.e. the calorific value of waste \( \dot{Q}_{LHV} \) and the enthalpy LPG-air reaction \( \Delta H_{LPG} \). The value of input heat \( \dot{Q}_{in} \) is described in equation (5).

\[ \dot{Q}_{in} = h_4 - h_1 \]  \hspace{1cm} (4)

\[ \dot{Q}_{in} = \dot{Q}_{LHV} + \Delta H_{LPG} \]  \hspace{1cm} (5)

The lower heating value of municipal solid waste \( LHV \) is 2049.11 kcal / kg (Novita, 2010). The mass of waste that can be accommodated by the UPI incinerator is 840 kg. The waste volume capacity of the UPI’s incinerator \( V_{inc} \) is 3.4 m\(^3\). The waste density \( \rho_{waste} \) is 246.9 kg/m\(^3\) (Widyawidura, 2016). The combustion time \( t \) was 3.5 hours, then the power generated from burning waste based on the lower heating value of municipal solid waste \( \dot{Q}_{LHV} \) is described in equation (6).

\[ \dot{Q}_{LHV} = \rho_{waste} \times V_{inc} \times LHV \times t \]  \hspace{1cm} (6)

The combustion of LPG gas is actually used to burn waste at the beginning, but this will also contribute to produce heat for the working fluid of the system. It is assumed that only 14% of the results of burning waste arrive at the working fluid. The LPG is modeled as a gas consisting of 97% of a mixture of propane and butane and the remaining 3% is pentane based on data from Pertamina with online news source tribunnews. LPG gas is reacted with air which assumes the composition of the air consists of 79% nitrogen gas (N\(_2\)) and 21% oxygen (O\(_2\)). Another assumption, the combustion reaction occurs perfectly which is described in the reaction below.

\[ A C_3H_8 + BC_4H_{10} + CC_5H_{12} + D(O_2 + 3.76N_2) \rightarrow EC O_2 + FH_2O + GN_2 \]

The coefficient A, B, C, D, E, F, and G are 16.17, 16.17, 1, 193.96, 118.19, 151.53, and 729.27 respectively. Then the reaction is evaluated by looking at the change in product enthalpy and reactant enthalpy to get the value of enthalpy LPG-air reaction \( \Delta H_{LPG} \).

After knowing how much potential heat or input heat to working fluid \( \dot{Q}_{in} \), the enthalpy of working fluid in state 1 \( h_1 \) can be known. The next thing is the power produced by the turbine, assuming the expansion process in the turbine occurs isentropically. This isentropic process occurs from the high pressure (exit incinerator) to low pressure (pressure when water enters the pump). Figure 2 shows the analysis process carried out and described in the T-s (temperature v entropy) diagram.
The value of the power generated from the turbine is found using equation (7) where $\dot{W}_t$ is the turbine power that occurs isentropically.

$$\frac{\dot{W}_t}{m} = h_1 - h_2$$  \hspace{1cm} (7)

Next analysis of the system component of the Rankine cycle is a condenser which functions to return the working fluid to its initial condition when it enters the pump. The heat dissipated in the condenser to restore the initial conditions $Q_{out}$ is determined by equation (8).

$$\frac{Q_{out}}{m} = h_2 - h_3$$  \hspace{1cm} (8)

The final step is to evaluate the thermal efficiency of the Rankine cycle that has been built, where the efficiency is defined by equation (9).

$$\eta_T = \frac{\dot{W}_T - \dot{W}_p}{Q_{in} - Q_{out}}$$  \hspace{1cm} (9)

Equations (1), (4), (7), (8) and (9) are equations taken from Moran (2014).

### 3. Result and discussion

The prediction of heat produced by combustion inside the UPI’s incinerator is 7,230 MJoule which took in 3.5 hours (duration based on experiment) so the power generated from incinerator waste burning reaches 574 kW. Then the assumption is that the heat can be transferred to the working fluid is 50% from the waste municipal combustion, so the value of $Q_{LHV}$ is 287 kW. In other hand, the result of combustion of LPG gas for the 3 tubes used is 7.76 kW and it is assumed that 14% of the heat from LPG-air reaction can transfer to working fluid. The conclusion from this part is that the heat from waste and LPG combustion to working fluid is 429.5 kW.

Figure 3 is illustration of the standard Classic Rankine cycle based on the equations for the pump input power of 600 W. The actual pump power that can be given to the working fluid is 55 Watt with a
flow rate 8 liters / minute. An overview of the Rankine cycle that occurs for the UPI incinerator can be seen in Figure 3 with the heat input generated by the incinerator.

Figure 3: Rankine Cycle T-s Diagram for Power Generation from UPI Incinerator

Figure 3 shows that the heat from the combustion in the UPI incinerator is able to change the water as working fluid from liquid to superheated. This is as expected because water in superheated phase has the small density allows the turbine not to break down quickly because the momentum load that will be small. Another thing from figure 3, the expansion in turbine is limited to environmental pressure at 0.9 bar. This can be seen in the cycle; the turbine expansion occurs in process 1-2’ which the phase of water in state 2’ is superheated vapor. The process 2’-2 is done by adding an expansion valve before entering the condenser. Then the condenser cooling consists two processes. First step process is cooling from the saturated vapor to saturated liquid and the second step is reducing temperature from a saturated liquid state to a room temperature which is ready to return to the pump.

Pump variations affect the amount of power generated by the turbine and cycle efficiency. Table 1 shows the variations in the pump input power to the resulting turbine power and the efficiency of cycle.

Table 1: Table 1 Turbine Power and Cycle Efficiency with various types of pumps

| Pump Input Power (Watt) | Delivered Power to Water ($W_p$) (Watt) | Flow Rate (liter/min) | Turbine Power (kWatt) | Cycle Thermal Efficiency $(\eta_T)$ |
|------------------------|----------------------------------------|----------------------|-----------------------|----------------------------------|
| 600                    | 55.5                                   | 8                    | 55.5                  | 13%                              |
| 640                    | 71.94                                  | 10                   | 26.2                  | 6%                               |
| 1200                   | 147.15                                 | 30                   | 21.9                  | 5%                               |

The numbers 600W, 640W and 1200W represent pump products on the market. The actual power that can be supplied to water is calculated based on head and flow rate data. What can be taken from table 1 is that the effect of the initial pressure exerted on the fluid is not just how much power is used but it is necessary to see the operational flow rate. Three pumps are different with different power and
flow rate but the same input heat, so the important thing is how to choose flow rate of working fluid. The more the flow rate, the greater heat to convert the water into the vapor phase to drive the turbine.

4. Conclusion
The standard classic Rankine cycle to utilize heat generated from combustion waste in the UPI incinerator is not entirely the same as the existing ideal cycle. This cycle needs an intermediary, namely in the expansion process it is not completely saturated steam but through the superheated phase first at atmospheric pressure then the pressure is lowered into a mixed phase so that the heat can be dissipated so that it becomes a water phase at environmental temperature and pressure. The result of building a Rankine cycle for an incinerator with a 600W pump produces a net power of 55.5 kWatt.

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