Thermo-environmental economic study on energy conversion system using thermoelectric generators (TEG SP1848) in cold storage condenser

by Risse Entikaria Rachmanita

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Thermo-environmental economic study on energy conversion system using thermoelectric generators (TEG SP1848) in cold storage condenser

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Abstract. Thermoelectric generator is an alternative energy that utilizes temperature differences into electrical energy. The use of a thermoelectric generator (TEG SP1848) by utilizing a heat source from the exhaust heat of a cold storage condenser requires thermodynamic, environmental thermal, and techno-economic analysis. The method used in this study is a qualitative approach with descriptive and evaluative methods. Thermodynamic analysis of the amount of heat wasted at each position of the engine pipe obtained T_1 pipe 38613.47 Watts, T_2 pipe 3960.35 Watts, and T_3 pipe 39651.80 Watts. The SP1848-based TEG energy conversion device absorbs 11.14 watts of heat energy placed in the T_3 pipe and has an efficiency of 0.23%. Analysis of the environmental conditions of the cold storage engine room based on the Predicted Mean Vote (PMV), Predicted Percentage Discomfort (PPD) and Temperature Humidity Index (THI) values shows that the engine room environment is not comfortable for human activities and can disrupt the balance of human metabolism. Techno-economic feasibility evaluation based on Net Present Value (NPV) and Payback Period (PBP) produces a negative value, while Benefit Cost Ratio (BCR) is 0.0012, indicating that the conversion tool is not feasible to run.

1. Introduction

The increasing demand for electrical energy has created a global problem, namely the depletion of potential reserves of fossil fuels. The price of crude oil fluctuates every second, causing instability in the world economy. These problems arouse many people to create and develop alternative energy sources. Indonesia has several sources of energy that can be used to generate electricity which are divided into two types. First, power plants with macro capacities that usually utilize water, steam, gas, and nuclear. Second, power plants with micro capacities, one of which is utilizing heat energy. The heat energy can come from sunlight and objects that release heat, such as home electronic equipment, motor vehicle exhaust and industrial kitchen combustion heat [1].

Thermoelectric generator is an alternative energy that utilizes the difference temperature into electrical energy and has a high economic value, as well as does not cause pollution so it is very environmentally friendly. A thermoelectric generator is a small plate-shaped device that operates as a heating engine by converting heat directly into electricity [2,3]. Thermoelectricity is influenced by three thermodynamic principles, Seebeck, Peltier and Thomson effects. Thermoelectric generator technology has been used by several researchers, in an effort to utilize waste heat energy from several heat sources in the surrounding environment converted into electrical energy [2]. Ryanuargo et al. (2013) have conducted research on centralized air conditioning systems (AC Central) in office buildings and shopping centers. Utilizing waste heat energy from the central AC condenser pipe which is designed to be winding and equipped with fins using the thermoelectric method [4]. Experiments on the condenser pipe have an average temperature of 34˚C which can produce a voltage of 3.14 Volts and a power of 0.16 Watts. Busthomy and Widyartono (2020) have investigated the use of a thermoelectric generator on the heat wasted from the combustion fire for charging mobile phone batteries, using 8 thermoelectric arranged in a mixture of series and parallel, producing a voltage of 4.2 Volts and a battery charging current of 0.34 Ampere with a difference flame temperature 48-50.1˚C [5]. The use of thermoelectric for charging batteries is also carried out by [6,7].The researcher used a thermoelectric TEG SP1848 and used a heat source from an exhaust heat of a cold storage condenser. The results of this study indicate that the 4 modules produce the highest output power of 2.07 Watts in a series circuit with an iron temperature of 110˚C and a resistance of 33 Ω. While the power of 0.144 Watts and efficiency of 0.24% is generated from the exhaust heat source of the condenser input pipe with a temperature difference of 24.17 K, using 5 modules connected in series.

Cold storage is a cooling machine that accommodates objects to undergo a cooling process. Cold storages are commonly used in everyday life to cool or preserve foods such as meat, vegetables and fruits as well as beverages [8]. Politeknik Negeri Jember has 5 cold storage units that operate for 24 hours, the cold storage is used to store fish and edamame. Utilization of alternative energy in waste heat energy from a hot object requires several aspects that need to be considered, such as aspects of the thermal and economic environment. The wasted heat certainly increases the temperature into the environment, with high ambient temperatures can interfere with thermal comfort for activities. According to [9], ideally aesthetic values are owned in a building, which provides a sense of security and provides thermal, visual and audio comfort.

Economic analysis is needed to compare the use of alternative energy technologies with existing conventional energy, as well as to determine the economic value invested in the development of thermoelectric technology. The Ministry of Energy and Mineral Resources and PLN 2020 determine the basic electricity tariff for the October-December 2020 period for the R-1/TR group with a power limit of 900 VA-RTM of IDR 1,352 per kWh and class I-4/TT with a power limit of 30,000 kVA and above of IDR 996.74 per kWh. Suryaningrat (2011) reveals that the principles of technical economics are used to analyze the uses of money, especially in relation to the physical assets and operations of an organization to help make decisions [10]. Based on the description of the background, this study aims to conduct an analysis in terms of thermodynamics, thermal environment, and economic aspects of the use of thermoelectric. This study is to create a comfortable working environment by developing thermoelectric technology that is economically efficient.

2. Methodology

The research method used is a qualitative approach with descriptive and evaluative methods. Heat transfer analysis data retrieval is carried out directly based on observations. The thermodynamic data retrieval on the cold storage condenser input pipe includes the size of the input pipe and the temperature of the condenser input pipe.Thermal comfort analysis data retrieval is carried out directly based on observations. Data retrieval of thermal comfort in the environment around the cold storage condenser includes space sketches, wind speed, air temperature, air humidity, clothing insulation and metabolic values based on activities carried out in that place. The techno-economic analysis data was collected based on the performance data of the thermoelectric energy conversion system. Data collection includes investment costs, replacement of thermoelectric components, depreciation, PBP (Payback Period), NPV (Net Present Value) and BCR (Benefit Cost Ratio).

This study uses several supporting tools including temperature data logger, anemometer, hygrometer, roll meter, timer, Global Positioning System (GPS), caliper, thermoelectric devices in the cold storage condenser input pipe and the environment around the cold storage condenser. Cold storage at Politeknik Negeri Jember has two operating machines and three inactive machines. The machine has a capacity of 40 tons with a room size of 3 × 14 × 4 meters and does not run for full 24 hours, but automatically turns on when the cold storage temperature is -19˚C and the machine turns off when the cold storage temperature is -27˚C. The operation of energy conversion system-based TEG SP1848 utilizes a heat source from the cold storage condenser input pipe. The condenser input pipe has several turns that start from the compressor then pass through the separator and end up entering the condenser. The condenser input pipe is made of copper and has two different diameter sizes, 28.60 mm (the pipe from the compressor output to before the condenser) and 34.9 mm (the condenser input and output pipe/pipe adjacent to the condenser). The size of pipe and position of sensor can be seen in Figure 1.

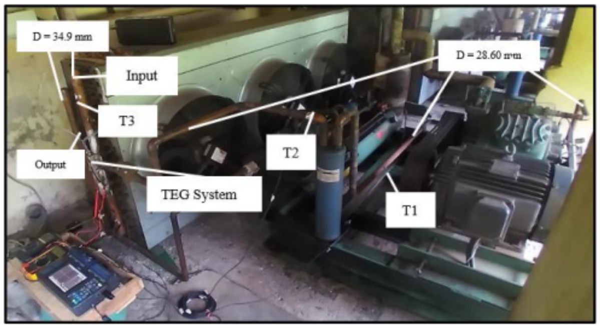

Figure 1. TEG system in cold storage condenser (sensor's position and pipe size)

2.1. Thermodynamic Analysis on Thermoelectric Generator System

Thermodynamic analysis includes [6]:

a. Heat transfer rate at the condenser input pipe

$$q = \frac{\Delta T}{R_{th}} = 2\pi k L \frac{T_i - T_o}{\ln\left(\frac{r_i}{r_o}\right)} \tag{1}$$

b. The amount of heat absorbed by the thermoelectric generator

$$Qh = N\,(\propto . T_h . I - 0{,}5 . I^2 . R + K . \Delta T) \tag{2}$$

2.2. Thermo Environmental Analysis

Thermo environmental analysis includes [11]:

a. Predicted Mean Vote (PMV) thermal comfort index

$$PMV = (0.303e^{-0.036}M + 0.028)((M - W) - H - E_c - C_{res} - E_{res}) \tag{3}$$

b. Predicted Percentage of Dissatisfied (PPD) Index

$$PD = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \tag{4}$$

c. Temperature Humidity Index (THI)

$$THI = 0.8T_a + \frac{(RH\,x\,T_a)}{500} \tag{5}$$

2.3. Techno-economic Analysis

Analysis of the feasibility of investing in energy conversion system includes [10]:

a. Depreciation

$$\text{Depreciation} = \frac{P - s}{n} \tag{6}$$

b. Net Present Value (NPV)

$$NPV = \sum_{t=0}^{n} \frac{(C)t}{(1+i)t} \sum_{t=0}^{n} \frac{(Co)t}{(1+i)^t} \tag{7}$$

c. Benefit Cost Ratio (BCR)

$$BCR = \frac{(PV)B}{(PV)C} \tag{8}$$

d. Payback Period (PBP)

$$PBP = \frac{C_r}{A} \tag{9}$$

Nomenclature:
q = Heat transfer rate (Watts)
k = Thermal conductivity (W/m°C)
T_i = Internal temperature (°C)
T_o = Outside temperature (°C)
L = Cylinder length (m)
Qh = Heat absorbed by TEG (Watts)
N = Number of thermoelectric thermocouples
α = Seebeck coefficient (Watt/ΔT)
Th = Thermoelectric hot side temperature (K)
K = Conductance of thermocouple (Watt/K)
M = Metabolic rate (W/m^2)
W = Effective mechanical power (W/m^2)
E_c = Evaporative heat exchange (W/m^2)
C_{res} = Respiratory convective heat exchange (W/m^2)
E_{res} = Respiratory evaporative heat exchange (W/m^2)
T_{sk} = Skin temperature (°C)
H = Heat loss through the skin (Joule)
Ta = Air temperature (°C)
RH = Humidity (%)

3. Results and Discussion

3.1. Thermodynamic Analysis on Thermoelectric Generator System

Thermodynamic analysis on the condenser input pipe was carried out at 08.00-16.00 West Indonesia Time for 7 days using a temperature data logger to record any temperature changes in the condenser input pipe every 1 minute. The data logger records the temperature of the condenser pipe at 3 points, the input pipe after the compressor (T1), the input pipe after the separator (T2), and the input pipe adjacent to the condenser (T3). The following data points for the temperature of the condenser pipe are presented in Figure 2.

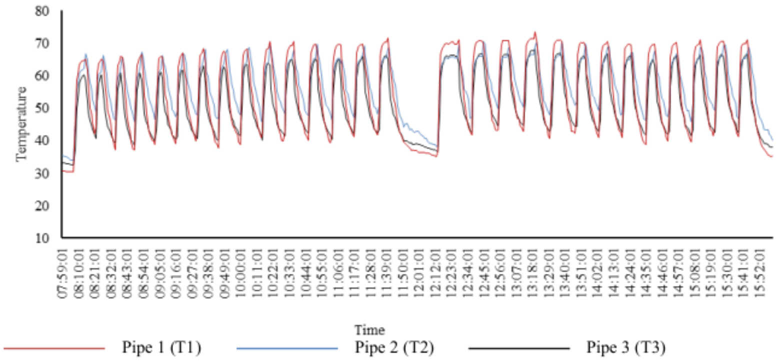

Figure 2. Temperature of condenser input pipe

The temperature of the condenser input pipe at the 3 observation points has different temperatures. The temperature of the input pipe after the compressor (T1) has an average temperature of 55.01˚C, with the highest temperature of 73.86˚C, and the lowest temperature of 29.25˚C. The temperature of the input pipe after the separator (T2) has an average temperature of 57.13˚C, with the highest temperature of 70.45˚C, and the lowest temperature of 31.62˚C. The temperature of the input pipe adjacent to the condenser (T3) has an average temperature of 54.39˚C, with the highest temperature of 71.78˚C, and the lowest temperature of 31.03˚C. The input pipe T1 has the highest temperature of 73.86˚C, when compared to the highest temperature of the T2 pipe of 70.45˚C and the highest temperature of the T3 pipe is 71.78˚C. The high temperature that occurs in the T1 pipe and T2 pipe is influenced by the wind of condenser fan when operating because the position of the two pipes is in front of the condenser fan, while the T3 pipe which is next to the condenser fan is not affected by the wind from the fan condenser. The position of the pipe that is affected by the condenser fan can result in a fairly rapid temperature drop in the T1 and T2 pipes, so that the two pipes cannot maintain the heat they receive.

The decrease temperature in pipe can be seen from the recorded data that has been observed for 7 days, when the three pipes reached their peak within ± 2 minutes, the temperature of T1 pipe decreased

±5˚C, the T2 pipe decreased ±6˚C, and the T3 pipe decreased ±4˚C. Observational data is used to calculate the amount of heat released from each pipe position. The heat released by pipes T1, T2 and T3 are 38613.47Watts, 3960.35Watts and 39651.80Watts. Pipes that have a high temperature, are stable and can maintain temperatures are one of the considerations for the placement and design of the energy conversion system-based TEG SP1848. The energy conversion system-based TEG SP1848 has been designed to utilize the heat wasted in the T3 pipe of 39651.80 Watts, which is one of the pipes that emits a large amount of waste heat because it is not affected by wind from the condenser fan.

The conductor in the energy conversion system is designed using aluminum material with a thermal conductivity of 202W/m˚C with a thickness of 1.8 cm. The conductor distributes heat to 5 thermoelectric of 55.71Watts. The exhaust heat produced by the T3 pipe is only 0.14% which can be absorbed by the thermoelectric to be used as electrical energy because the energy conversion system only utilizes a small part of the total length of the pipe. The operational results of the energy conversion system using 5 TEG SP1848 modules in series produce the highest power of 0.132 Watts, and have an efficiency of 0.23%. Utilization of exhaust heat in the cold storage condenser pipe optimally using TEG SP1848 can be reviewed based on the length of the condenser pipe that can be occupied by the energy conversion system based-TEG SP1848. The results of the identification of the measurement of the pipe length, the position of the pipe that can allow the energy conversion system to be occupied, namely the position of the T1 pipe and T3 pipe because the T1 pipe has a length of 105 cm and the length of the T3 pipe is 82 cm. TEG SP1848 module component has a size of 40 x 40 mm, so it can occupy as many as 26 modules on the T1 pipe and 20 modules on the T3 pipe. Optimizing the utilization of condenser exhaust heat by using the total length of the pipe can make it possible to reduce waste heat that is wasted in the environment and can generate considerable electrical energy. In the calculation of the heat that can be absorbed by 1 TEG SP1848 module is 11.14 Watts, then when using 26 modules can absorb heat of 289.64 Watts and 222.8 Watts when using 20 TEG SP1848 modules.

3.2. Thermo Environmental Analysis

a. Analysis of the relationship between PMV and PPD values

The results of measurement data, such as air temperature, relative humidity, air velocity, metabolism, and clothing resistance are used to calculate the PMV and PPD values. The CBE Thermal Comfort Tool For ASHRAE-55 program is a program that helps calculate PMV and PPD values. The results of the calculation show that the highest PMV value is 3.46 with the highest PPD 100% and the lowest PMV value 0.51 with the lowest PPD 10%. The average values of PMV and PPD are 2.37 and 83.96%, respectively. Figure 3 is a graph of the relationship between PMV and PPD.

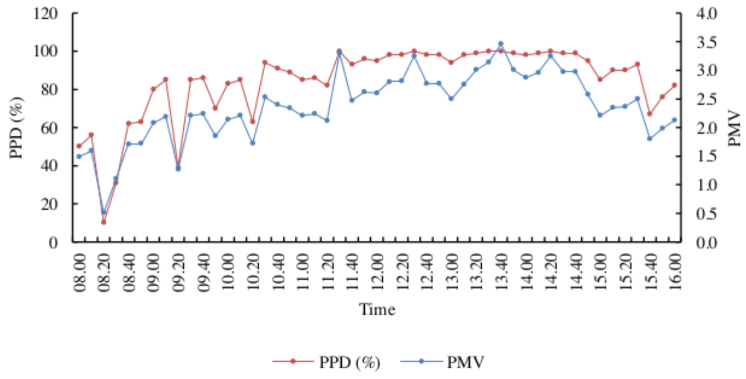

Figure 3. Relationship between PMV and PPD

The graph shows the PMV value from 0.51 to 3.46 while the PPD value is from 10% to 100%. This identifies that the thermal impression felt in the space is in the rather comfortable to hot category based on [12]. The room is dominated by the engine operating at the same time releasing exhaust heat to the environment, resulting in a fairly high indoor air temperature. The large number of ventilations and the high ceiling are not able to neutralize the room air temperature which is high enough so that it can immediately return to standard comfortable conditions, this is due to the small amount of natural air from the surrounding environment and the amount of heat that is wasted into the environment as a result of the reaction of the condenser engine.

These environmental conditions can greatly affect the balance of the human body's metabolism. The normal body temperature of a healthy human being mentioned by [13] is 37˚C. An increase in body temperature which is influenced by environmental temperature will result in a faster decrease in performance, besides that the content of lactic acid in the blood is also lower. As mentioned by [13] that during exercise at sub-maximal and maximal intensity, inhaled oxygen and pulse rate are at lower levels when exercising at ambient temperature is 22±1˚C from 10±1˚C and 35±1˚C. This statement means that at temperatures lower than 22^{o}C or higher, the oxygen uptake process is less than optimal, and the amount of lactic acid released due to metabolic processes is higher.

Someone who performs activities in the engine room will also experience an increase in dehydration, as a side effect of high air humidity from high environmental temperatures. This is an adjustment of body temperature to the environment, by enlarging the skin pores and also sweating more. It can be seen that high environmental temperature and humidity result in excessive sweat secretion, changes in body physiology also occur (changes in the metabolic/energy system), increased lactic acid in muscles, thereby accelerating fatigue in muscles and the body [14]. Incidences of heat exhaustion, stroke, asthenia and even heart attack may occur if a person is in the engine room long enough, without any additional body fluids.

b. Analysis of the relationship between PMV and THI values

The PMV and THI index parameters are two parameters that have the same function, namely to measure thermal comfort in a room or area. Despite having the same function, the two parameters have significant differences in measuring thermal comfort. The PMV index parameter was introduced by Fanger, 1982[11]. The PMV index uses 5 parameters, namely air temperature, relative humidity, wind speed, clothing insulation and value metabolism of an activity. The PMV index has a value limit that is from -3 to +3. While the THI index was developed by [12]. in 2003 which uses a combination method of temperature and humidity to determine the effect of hot conditions on human comfort, and has a value limit of 20-26. The results of the study of thermal comfort in the cold storage engine room, correlated the value of thermal comfort between the PMV and THI indexes. The graph of the relationship between PMV and THI is shown in Figure 4.

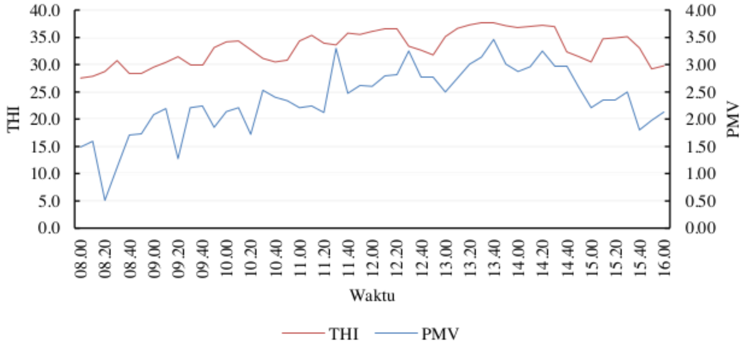

Figure 4. Relationship between PMV and THI

The PMV and THI index values presented in graphical form show that there is an opposite interaction, when the PMV value has decreased but the THI value has increased, the PMV value has increased but the THI value has decreased. Although the two thermal comfort indices have different value limits, there is still an interrelated relationship. The results of the PMV and THI index calculations also show the same category of environmental conditions, namely uncomfortable environmental conditions. The PMV index value in the cold storage engine room which is calculated at 0.51 – 3.46 indicates that the environment is in the rather comfortable to hot category. While the THI index value in the cold storage engine room which is calculated at 26.4 – 37.7 indicates that the environment exceeds the value limit for the comfortable condition category.

3.3. Techno-economic Analysis

The initial investment spent in the manufacture of energy conversion systems includes the purchase of TEG SP1848, water pumps, cooling radiators, adapters, radiator fans, power banks, cost of lathe, cost of cast aluminum, and other components. The total investment cost obtained is IDR 1,792,170.00. The investment costs incurred are calculated on the 0 year at the age of TEG SP1848.

The depreciation applied to energy conversion system is functional depreciation. Based on information on the electroniscomp.com, the TEG SP1848 has decreased function by 0.2% every year. The calculation of the cost of replacing components also needs to be taken into account because the age of the energy conversion system is based on the life time of the TEG SP1848 which is 200,000 hours or 23 years 1 month. There are 2 components that have a shorter life time than the TEG SP1818, including the water pump and radiator fan. The cost of replacing water pump components which is carried out every 3 years 5 months, and there are 6 replacements for 23 years. Meanwhile, the replacement of radiator fan components is carried out every 4 years 7 months, and there are 5 replacements for 23 years. The replacement cost of each of these components is included in the cost of expenditure or cash outflows at each of these times, the total replacement of components for 23 years is IDR 666,800.00.

NPV analysis was carried out after knowing the net cash flow from the energy conversion system-based TEG SP1848. Net cash flow is the difference between the cash inflows and cash flows out of the equipment over the life of the equipment. The cash inflow is an effort to save electricity from the amount of electrical power that can be produced by the TEG SP1848, while the cash outflow is the need for electrical power to operate the energy conversion tool, namely the use of a 12 W adapter to run the water pump and radiator fan. By using the standard reference of the PLN R-1/TR class TDL price with a power limit of 900 VA-RTM, which is IDR 1,352.00/kWh. Cash inflows and outflows are assumed to experience a price increase of 20% every 5 years because annually there is an increase in the value of inflation [15]. Cash inflow is an effort to save electrical energy from energy conversion electricity production by TEG SP1848 in 23 years amounting to 1,890 kWh with a cost that can be saved as much as IDR 2,809.34. The cash flow that comes out in year 0 is the investment cost used in the design of the energy conversion tool. The total cash outflow for 23 years is IDR 2,264,317,537.00. The NPV value that has been calculated from the energy conversion system using TEG SP1848 is the difference between cash inflows and cash outflows is IDR -2,261,508.2. The NPV value on the tool is negative, this indicates that the conversion tool is not feasible to be developed [15]. The NPV value is negative in the design of this system, because the cost of expenditure or cash outflow is greater than the cost of saving or cash inflow. The electrical power produced is very small so it is not optimal if it is used to save conventional electrical energy.

By using formula (8) and comparing the value of income with the value of costs to obtain the BCR value. According to [16], if the value of BCR>1 then the project deserves to be selected, but if the value of BCR<1 then the project is not feasible to be selected and run. The B/C value in the conversion system is 0.0012, so the energy conversion system is not feasible to run.

PBP analysis is obtained using the formula 3.7, then the PBP value from the energy conversion system using TEG SP1848 is -18.84 years or rounded up to -19 years. The negative sign in the payback period means that the investment in the energy conversion equipment has suffered a loss or cannot recover the investment cost.

4. Conclusion

The wasted heat from the 3 measured pipe positions including T1 pipe, T2 pipe, and T3 pipe is 38613.47Watts, 3960.35 Watts and 39651.80 Watts. The energy conversion system-based TEG SP1848 can absorb heat energy of 11.14 Watts which is placed in the T3 pipe and has an efficiency value of 0.23%. The environmental conditions of the cold storage engine room have a PMV value of 0.51-3.46, a PPD value of 10%-100% and a THI value of 26.4-37.7. These three parameter values indicate that the engine room environment is not comfortable for human activities, and can disrupt the balance of human metabolism which can cause heat exhaustion, stroke, asthenia and heart attack. The energy conversion system using TEG SP1848 which utilizes the cold storage condenser input pipe is declared unfeasible to run using the NPV, BCR and PBP methods.

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