A Study of Reducing Waste Heat Rejected By Condenser Using Thermoelectric Heat Pumps to Decrease Net Plant Heat Rate of Coal Fired Power Plant

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Abstract. Paiton 1-2 subcritical coal-fired power plant applied coal switching program in order to compete at Jawa-Bali electrical system. The calorific value of coal consumed is switched from 5200 kcal/kg to 4500 kcal/kg. As the result, it increases the net plant heat rate (NPHR) as well as the coal flow and produce more CO₂ emissions. Increasing final feed water temperature can reduce NPHR because less heat needed to produce steam. One of promising method to increase feed water temperature is reusing wasted energy being rejected to environment through condenser. There is opportunity to reuse this waste heat by use of thermoelectric heat pumps (THPs). THPs convert electrical energy into thermal energy using Peltier effect. It can capture the heat released by condensation process and reused for increasing the feed water temperature, which can increase the cycle efficiency. Furthermore, it will reduce coal flow, decrease NPHR and aid the reduction of CO₂ emissions. To maximize the energy recovery, a number of heat pumps can be used in series. This paper focused on finding the optimum number of heat pumps array. The expected feed water temperature rise gained from THPs arrangement is 19.81°C and potentially will contribute to 0.66% reduction on NPHR.

1. Introduction
Paiton 1-2 Coal-Fired Power Plant is a sub-critical thermal power plant constructed at 1993 and starts to produce electricity or commercial on date at 1994. It has designed to consume high coal quality rank (sub-bituminous A) with the calorific value is 6,000 kcal/kg and the thermal efficiency is about 37.84% [1] [2]. In the Jawa-Bali electrical system, Paiton 1-2 have to compete with other coal-fired power plant to get the maximum portion of load for supplying electricity to the grid. The distribution of load is arranged by dispatcher based on merit order. Merit order is the rank of coal-fired power plant depends on the production cost in Rp/kWh. The higher the rank in merit order, the higher the portion of load dispatched. Merit order is affected by some factors such as, net load, coal price, and coal calorific value.

The existence of the first Fast Track Program (FTP-1) coal-fired power plant and Independent Power Producer (IPP) with higher thermal efficiency and newer technology has been a trigger for Paiton 1-2 to continually improve and take some strategic decisions. One of them is applying coal switching program. The coal consumed in Paiton 1-2 switched from 5200 kcal/kg to 4500 kcal/kg. As
In the result, it automatically reduces the coal price so Paiton 1-2 could compete with others in merit order. In the other hand, coal switching program also increase the net plant heat rate (NPHR), coal flow and potentially produce more CO$_2$ emissions. Start from 2020, the competition will be harder for Paiton 1-2 because the government will build new coal-fired power plant with ultra-super critical boiler technology as the part of 35,000 MW program. This technology will produce higher thermal efficiency with the low coal quality rank as the fuel which more eco-friendly. This condition will challenge Paiton 1-2 to continually improve in order to can compete with others to get the maximum dispatched load.

NPHR is one of energy performance indicator of power plant which compare the energy input from fuel and the electric energy production. According to reference, increasing final feed water temperature can reduce NPHR because the less heat needed to produce steam [3]. It can lead to the reduction of coal consumption and CO$_2$ emissions. There are some ways to increase final feed water temperature which has been applied such as the use of high-pressure and low-pressure heater as regenerative cycle with the extraction steam from turbine as heating media. According to the research in energy assessment of coal-fired power plant [4], approximately 80% of wasted heat being rejected to environment through condenser. There is an opportunity to reduce this waste heat by use of thermoelectric heat pumps (THPs). THPs will capture the waste heat rejected by condenser and reused it to increase the feed water temperature.

To maximize the energy recovery, a number of heat pumps can be used in series, with the output of the preceding stage feeding the next stage [5]. However, the previous research did not mention about how much the number of heat pump that has to be used to maximize the heat absorbed. The THP’s data sheet gives the data comparation of increasing the temperature difference at hot dan cold side of THP to heat removed which is not linear. Based on that data, the optimal number of heat pump arrays can be predicted. This paper is aimed to find the total potential waste heat captured by thermoelectric devices which used to increase the feed water temperature and the optimum number of cascading stages of THPs which gives the maximum energy recovery. The calculation is based on a theoretical basis for the use of THPs in the condensation process of the Rankine cycle to increase cycle efficiency while maintain the minimum beneficial value of THPs coefficient of performance [4].

2. Material and method

2.1. Thermoelectric Heat Pump Theory

The principle of thermoelectricity was discovered in 1823 by Thomas Seebeck. He found that electric current continuously flow if close circuit of two dissimilar conductors formed and their joints kept at hot and cold junctions. The reverse phenomenon of Seebeck effect discovered later by Jean Charles Athanase Peltier. Peltier uses current as an interface among dissimilar conductor metals in circuit results, absorption of heat at one joint and release of heat at another joint [6]. The application of Seebeck effect and Peltier effect remained minimal until the development of semiconductor materials. With the advent of semiconductor materials came the capability for a wide variety of practical thermoelectric applications [7].

Thermoelectric modules consist of n- and p- type semiconductors usually arranged in square arrays that can be used in two different ways; heat pumping and power generating. In heat pumping mode, they utilize the flow of an electrical current through the module to produce a thermal gradient according to the Peltier effect and usually referred to as thermoelectric heat pumps (THPs). While in power generating mode, they generate an electrical current in an external circuit from an imposed temperature difference, exploiting Seebeck effect and referred to as thermoelectric generators (TEGs) [5].

Based on figure.1, as electrical power is applied to the n- and p- couples, it causes the movement of charge carriers, driving heat transfer through phonon transport. As the temperature difference across the device increases, the Seebeck effect has an increasingly significant role in producing an electromotive force that acts to counter the applied voltage, leading to reduce current flow. Due to the
electrical resistance of the semiconductor material, Joule heating is also present being proportional to the square of the current flowing in the device [5]. Joule heating is the process where the energy of an electric current is converted into heat as it flows through a resistance [8].

Figure 1. THP showing the applied power and direction of heat flow

2.2. Determine the Coefficient of Performance (COP) of Thermoelectric Heat Pump

The energy losses of Rankine cycle power plant are from energy rejected by condenser because of condensation process, electrical load which used for generate various pumps, compressors, fans, and flue gases (the combustion exhaust gas) which contain residual energy from combustion process [4]. Figure 2 shows the energy balance of Paiton coal-fired power plant. The net production of electricity is 395.5 MW (33.12%) and 704.46 MW energy rejected by condenser. Condenser has an amount of potential energy rejected that can be used to regenerative cycle. The proposed solution uses a heat pump to capture a portion of the enthalpy released in the isothermal conversion of the low-pressure steam to liquid after the last turbine stage in the power plant. By redirecting this energy back to the process, rather than rejecting it to the environment, the scavenged energy is used to raise the temperature of feed water returning to boiler, which can contribute to decrease coal consumption [9].

Figure 2. Energy balance of referred power plant

Coefficient of Performance (COP_H) is an indicator that used to determine the performance of heat pump. COP of a heat pump can be defined as a ratio of temperatures between the condensation process and the initial heat absorption process [10]. A fundamental requirement for economic use of heat pump at condenser is to ensure that the input power required for the pumping does not exceed the point at which use of the heat pumping system can reduce the overall cycle efficiency. Prior work [4] has determined theoretically that the break-even point above which the heat pump becomes beneficial is when the COP_H exceeds the reciprocal of the cycle efficiency.

\[
\text{COP}_H = \frac{1}{\eta_{\text{cycle eff}}} 
\]

(1)

where the cycle efficiency (\(\eta_{\text{process}}\)) may be expressed as:

\[
\eta_{\text{process}} = \frac{Q_e}{Q_{\text{in}}}
\]

(2)

where \(Q_e\) is the electrical output power and \(Q_{\text{in}}\) is the power input to the process.

2.3. Physical implementation

Conventional thermoelectric modules have various specifications for various applications. The dimensions vary from 3 mm\(^2\) by 4 mm thick to 60 mm\(^2\) by 5 mm thick with the maximum heat-pumping rate from 1 to 125 W. The maximum temperature difference between the hot and cold side
can reach 700°C. The pellets cross-sectional area and length have the impact on cooling performance of thermoelectric module. The module with cross-sectional area larger than 50 mm² or with long length usually suffer from thermally induced stresses at the electrical connection points inside the module and can cause a short because the cold side of the module contracts while the hot side expands [7]. For heat pumping, pellets with large cross-sectional area (>5 mm²) and short to medium length (<5 mm²) are preferred [11]. In this paper, the data of thermoelectric module comes from a selected commercially available THP; a European Thermodynamics Ltd. ET-127-20-15-RS with the dimensions 55 x 55 x 4.6 mm and 4 mm pellet length [12].

Design installation on condenser refer to figure 3. The thermoelectric modules have to install inside the condenser because it placed next to steam side of the condenser to ensure the maximum thermal conductivity. Refer to [10] modular design is suited for application in condenser. The modular design will reduce the effective thermal resistance from the hot side of a heat pump to the feedwater system. Numerous units of modular design connected in series to form a string of the desired length, and numerous strings may be connected in parallel to provide the total capacity.

The thermoelectric element within the heat pump is shown in figure 3 as “TEM”. The working fluid approaches the hot section of the heat pump and the flow is designed to be in the other of a pair of concentric pipes. A thermal gradient will therefore be established from the hot surface and extend some distance back towards the oncoming flow. After heating, the fluid will then be channeled away from the hot end in the inner of the concentric tubes. The walls of this inner tube also have a thermal conductance, and therefore energy will flow from the fluid being transported away from the heat exchanger to the fluid entering the heat exchanger. Each stage of thermoelectric module requires a separate electrical input power, and operates with a different ΔT and COP. As shown in figure 3, 4 and 5, the thermoelectric module for each stage installed inside condenser. The configuration is shown as being sandwiched between the heat sink and the external piping through which the condensate water passes.

**Figure 3.** Design installation of THP at condenser

**Figure 4.** Thermoelectric module

Thermoelectric heat pumps will be installed in five different ways; single, two, three, four and five-cascaded stage to aim the optimum number of THPs array. Referring to (1), the minimum beneficial
value of condenser COP_H is 3.02. The feed water will be raised from 40°C at outlet condenser to 59.81°C at feed water system with ΔT of 19.81°C. A sensible heat (Q_{retained} = 23.79 MW) will be required for feed water flow rate of 286.91 kg/s.

![THP installation inside condenser](image)

Figure 5. THP installation inside condenser

### 3. Analysis and result

Based on data reference from table 1, for the single cascade stage, water enter the THP’s first stage at the temperature of 40°C. To achieve the feed water exit temperature of 59.81°C, with using the measured thermal resistance of the heat exchanger is 0.070 C/W and flow rate of water (ṁ = 0.0013 kg/s) that could be absorbed for one module [5], so the temperature required on ‘heated’ side of the THP is 67.35°C. The temperature of cold side of THP is 39°C. Using data sheet of THP module and experimental data reference [5], for ΔT THP = 28.35°C the maximum COP_H is 2.1 at I = 3.81. Prior work has determined that the greatest COP_H available from the heat pump is in the region between 0.1 I/Imax – 0.3 I/Imax, where I/Imax is the normalized current ratio independent of the maximum heat pumping power achieved in testing [5].

| Cascade | Stage | T_{Win} (°C) | T_{Wout} (°C) | ΔT (°C) | T_{THP.hot} (°C) | T_{THP.cold} (°C) | ΔT_{THP} (°C) | COP | I (A) | V (V) | Q_H (W) |
|---------|-------|--------------|--------------|---------|-----------------|-----------------|--------------|-----|------|------|--------|
| 1       | 1     | 40           | 59.81        | 19.81   | 67.35           | 39              | 28.35        | 1.8 | 2.95 | 4.8  | 25.47  |
| 2       | 1     | 40           | 50           | 10      | 53.81           | 39              | 14.81        | 3.5 | 2.6  | 3.5  | 30.03  |
| 2       | 2     | 50           | 59.81        | 9.81    | 63.55           | 39              | 24.55        | 2.2 | 3.14 | 4.5  | 31.13  |
| 3       | 1     | 40           | 46.5         | 6.5     | 48.98           | 39              | 9.98         | 3.42 | 3    | 3.37 | 34.58  |
| 2       | 2     | 46.5         | 52           | 5.5     | 54.1            | 39              | 15.1         | 3.3  | 2.6  | 3.5  | 30.03  |
| 3       | 2     | 52           | 59.81        | 7.81    | 62.79           | 39              | 23.79        | 2.35 | 2.8  | 4.2  | 27.64  |
| 4       | 1     | 40           | 43           | 3       | 44.14           | 39              | 5.14         | 4.25 | 2.75 | 3    | 35.08  |
| 2       | 2     | 43           | 48           | 5       | 49.1            | 39              | 10.9         | 3.42 | 3    | 3.37 | 34.58  |
| 3       | 3     | 48           | 53           | 5       | 54.9            | 39              | 15.9         | 3.3  | 2.6  | 3.5  | 30.03  |
| 4       | 3     | 53           | 59.81        | 6.81    | 62.4            | 39              | 23.4         | 2.35 | 2.8  | 4.2  | 27.64  |
| 5       | 1     | 40           | 43           | 3       | 44.14           | 39              | 5.14         | 4.25 | 2.75 | 3    | 35.08  |
| 2       | 2     | 43           | 48           | 5       | 49.1            | 39              | 10.9         | 3.42 | 3    | 3.37 | 34.58  |
| 3       | 3     | 48           | 53           | 5       | 54.9            | 39              | 15.9         | 3.3  | 2.6  | 3.5  | 30.03  |
| 4       | 3     | 53           | 58           | 5       | 59.9            | 39              | 20.9         | 2.62 | 2.8  | 3.9  | 28.61  |
| 5       | 3     | 58           | 59.81        | 1.81    | 60.5            | 39              | 21.5         | 2.54 | 2.8  | 4    | 28.45  |
$I_{\text{max}}$ of THP module is 13.1 A, so the region between 1.31 A – 3.93 A is acceptable for this case. Using the modules characteristic and experimental data reference, this equates to supplying 14.14 $W_e$ (4.8 V at 2.95 A), and producing a resultant energy $Q_H = 25.47 W_{th}$. For the two, three, four and five cascaded stages, the result refer to table 1. Using these results, the potential for implement the heat pumping to a real system can be calculated. Refer to table 2 and figure 6, the single stage cascade needs 934,185 modules to produce $Q_{\text{retained}} = 23.79$ MW and total required power distributed to THP is 13.22 MW. In case of two, three, four and five cascade stage, the results refer to table 2.

Table 2. Total electrical power and module needed for THP cascaded stage configuration

| Cascade | Stage | Total Electrical Power ($W_e$) | Total Thermal Power ($W_{th}$) | Total Module |
|---------|-------|-------------------------------|-------------------------------|--------------|
| 1       | 1     | 13.22                         | 23.79                         | 934,185      |
| 2       | 1     | 3.64                          | 12.01                         | 399,882      |
|         | 2     | 5.36                          | 11.78                         | 378,526      |
| 3       | 1     | 2.28                          | 7.81                          | 225,778      |
|         | 2     | 2                             | 6.61                          | 219,964      |
|         | 3     | 3.99                          | 9.38                          | 339,407      |
| 4       | 1     | 0.85                          | 3.60                          | 102,722      |
|         | 2     | 1.76                          | 6.01                          | 173,675      |
|         | 3     | 1.82                          | 6.01                          | 199,968      |
|         | 4     | 3.48                          | 8.18                          | 295,949      |
| 5       | 1     | 0.85                          | 3.60                          | 102,722      |
|         | 2     | 1.76                          | 6.01                          | 173,675      |
|         | 3     | 1.82                          | 6.01                          | 199,968      |
|         | 4     | 2.29                          | 6.01                          | 209,890      |
|         | 5     | 0.86                          | 2.17                          | 76,414       |

Figure 6. Total required THP module for each cascade stage configuration

In consequence of the minimum COP$_H$ is 3.02 to be beneficial to this plant, As illustrated in figure 7, the COP$_H$ for single cascade stage is 1.8 so the new net electrical output becomes 382.28 $W_e$ (3.34% reduction of power required to supply the THPs) and a reduction in thermal energy rejected in the condenser is 14.8 $W_{th}$ (2.1% reduction). The total thermal energy which can be retained is 23.79
MW\textsubscript{th}. The new coal consumption rate is 98.01\%, therefore the new plant efficiency is 32.66 \%. For the two, three, four and five-cascaded stage configuration, the results refer to table 3 and figure 7-8.

**Table 3.** The power plant parameter after THP cascade stage configuration installed

| Cascade | New Net Electrical Output (MW\textsubscript{el}) | Thermal Energy Reduction Rejected (MW\textsubscript{th}) | New Fuel Consumption (%) | New Plant Eff (%) |
|---------|---------------------------------|---------------------------------|--------------------------|-------------------|
| 1       | 382.28                          | 10.57                           | 98.01                    | 32.66             |
| 2       | 386.51                          | 14.80                           | 98.01                    | 33.05             |
| 3       | 387.22                          | 15.52                           | 98.01                    | 33.12             |
| 4       | 387.60                          | 15.89                           | 98.01                    | 33.18             |
| 5       | 387.93                          | 16.22                           | 98.01                    | 33.16             |

**Figure 7.** COP\textsubscript{H} of THPs for each configuration

**Figure 8.** THP’s effect on plant efficiency
4. Discussion
The result of finding the optimum heat pump array described in figure 6, 7 and 8. For the single and two-cascaded stage configuration, the overall plant efficiency reduce 0.46% and 0.07% from 33.12% to 32.66 and 33.05%. It is because the value of $\text{COP}_{\text{H}}$ less than the minimum beneficial value of COP allowed. It explains the thermal energy retained by condenser to increase the temperature of feedwater is not profitable compared with the power used for THPs. For the three-cascaded stage configuration, the overall plant efficiency remain the same. The optimum heat pump array is four-cascaded stage configuration which can increase the overall efficiency by 0.06% from 33.12% to 33.18%. Theoretically, it becomes feasible to be applied. For five-cascaded stage configuration, the overall plant efficiency increases 0.04% from 33.12% to 33.16%. This result is lower than four-cascaded stage. The four-cascaded stage becomes the optimum number of THP series configuration because the combination of $\Delta T$ THPs in every stage give the maximum addition of $\text{COP}_{\text{H}}$ divided by number of stages. As described in [5], now in the market, the maximum $\text{COP}_{\text{H}}$ of THP module available in range of 4.5 to 5 and with the experiment data, it appears at $\Delta T$ THPs = 5°C. If the $\Delta T$ THPs more than 5°C, the result of $\text{COP}_{\text{H}}$ will decrease with nonlinear pattern. In the other hand, if the $\Delta T$ THPs less than 5°C, the $\text{COP}_{\text{H}}$ will not increase significantly. It can be concluded that the optimum number of heat pump array for being applied in Paiton 1-2 coal-fired power plant is four-stage cascaded configuration.

Based on the data from Operation and Efficiency Report: April 2019 [2], Paiton 1-2 coal-fired power plant consumes 235.225 ton/hour with 395.5 MW electricity produced. The decrease of 1.99% in coal consumption will automatically reduce coal flow from 235.225 ton/hour to 230.75 ton/hour in average. It potentially will save about 34321.9 ton of coal per year. The reduction of coal consumption aids the reduction of CO$_2$ released to atmosphere in the amount of 0.1034-ton CO$_2$-equivalent. It will also reduce the fly ashes and bottom ashes which are the part of the non-combustible residue of combustion in a coal-fired power plant.

The installation of THPs which needs the electrical power addition will potentially reduce the revenue of plant per year, but it will be covered by the addition of 23.79 MW of thermal energy to the plant as the result of THPs installation. Increasing the feedwater temperature will automatically reduce NPHR. Refer to operation manual book [3], the increase of 1.67°C temperature of feedwater will decrease NPHR -0.10%. Based on the data reference [13], THPs installation potentially will reduce NPHR until 0.66% or 18.08 kcal/kWh from 2739.3 kcal/kWh to 2721.22 kcal/kWh.

5. Conclusion
The THP’s modules technology theoretically is feasible to be applied in Paiton 1-2 coal-fired power plant with the optimum heat pump configuration is four-cascaded stage. The total energy retained from condenser is 23.79 MW. NPHR will reduce by 0.66% or 18.08 kcal/kWh from 2739.3 kcal/kWh to 2721.22 kcal/kWh in average. The plant efficiency will increase by 0.06% from 33.12% to 33.18%, the coal consumption will reduce by 1.99% from 235.225 ton/hour to 230.75 ton/hour, CO$_2$ released to atmosphere will be reduced about 0.1034 ton of CO$_2$-equivalent with respect to reduction in coal flow. Nowadays, thermoelctric module materials have maximum COP between 4.5 to 5. In order to gain megawatt heat transfer, it needs a lot of modules which increase the cost of investment. In the future, THPs will be a very profitable innovation because there is a great amount of heat rejected from condenser that potentially can be retained. In line with the development of THP modules, in the future, it will increase the COPH and automatically will decrease the total number of modules needed and increase the amount of heat rejected from condenser that can be retained.

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