Heat balance simulation for evaluating a 315 MW low rank coal-fired power plant performance

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Abstract. The domination of coal-fired power plant as power generation due to its feasibility to ensure a stable supply of electricity to customer. Unfortunately, the use of coal as power plant fuel faces an issue of air pollution. Some efforts have been proposed to make the operated coal-fired power plant meeting the environmental regulations. One of the most potential ways to solve the problem is by improving the coal-fired power plant efficiency and then equate to a greenhouse gas reduction. Thus, heat balance simulation of coal-fired power plant which operates in different conditions have to be studied in order to analyse the power plant performance. In this paper, the heat balance of a 315 MW low rank coal-fired power plant is simulated by Cycle-Tempo. The simulations are carried out for several different operation conditions of the power plant. The Heat Rate will increase of 3.66% when all HPH are on off-duty while it increases by 2.63% when all LPH are on off-duty. Furthermore, the increasing of Superheater temperature of 5 °C will decrease the Heat Rate of 0.59% and it will decrease of 0.39% when the temperature of Reheater increases of 5 °C.

Keywords: Coal-Fired Power Plant, Heat Balance, Heat Rate, Simulation.

1. Introduction

Power plant is important infrastructure in supporting the economic growth of developing country. The economic growing increases the electricity demand as the technology develops around the world. The developing country’s population has huge contribution on the electricity demand too. In general, the world energy demand will be increasing from 19,562 TWh in 2012 to 26,761 TWh in 2025 [1]. This increasing energy demand mainly occurs in developing countries such as Indonesia. Particulary in Indonesia, based on the assumption of population and economic growth, electricity demand is predicted to increase from 226 TWh in 2017 to 1,471 TWh in 2050 [2].

Among some typical power plants, coal-fired power plant is still dominated in supplying electricity to customers. The power plant is predicted to grow significantly within developing countries such as Indonesia [1]. Based on report by Indonesian Agency for the Assessment and Application of Technology [2], coal-fired power plant will dominate the electricity supply with a 52%
share, it will be about 55 GW. Moreover, the coal consumption as power plant fuel in Indonesia increases year by year. In 2017, the coal consumption was about 83 million tonnes (348 million SBM). This number shows the domination of coal as energy sources for power plant at about 65%. By the year of 2050, the share of coal as power plant fuel will be about 73% or around 556 million tonnes (2,308 million BOE). Figure 1 shows the share of power plant fuel demand [2].

![Figure 1. Sharing of power plant fuel demand [2]](image)

The domination of coal-fired power plant as power generation is caused by its feasibility to ensure a stable supply of electricity to customer [3, 4]. Unfortunately, the use of coal as power plant fuel faces an issue of air pollution. The international air-pollution standards and regulations demand a huge reducing on greenhouse gasses and air pollutants. Thus, all operated coal-fired power plants must consider it. Some efforts have been proposed to make the operated coal-fired power plant meeting the environmental regulations. Carbon dioxide capture and storage technology and an integrated coal-gasification combined cycle technology are among potential solutions for it. Unfortunately, the economic feasibility study showed that they are not ready to be implemented yet [5-7]. Currently, the most potential and feasible way to solve the problem is by improving the coal-fired power plant efficiency and then equate to a greenhouse gas reduction [8]. Thus, heat balance simulation of coal-fired power plant which operates in different conditions have to be studied in order to analyse the power plant performance.

2. The Efficiency and Heat Rate of Power Plant

A typical steam power plant (coal-fired power plant) is modelled as a thermodynamic cycle, showed by Figure 2. Based on a thermodynamic cycle, the steam power plant cycle is referred as the Rankine cycle. Basically, the Rankine cycle consist of four main components, they are a boiler, turbine, condenser, and pump. There are two parameters which generally measure the power plant performance, the Efficiency and the Heat Rate of power plant. The efficiency of power plant is defined as the electrical energy produced divided by the total energy released by the fuel consumed, while the Heat Rate (HR) of power plant is the amount of energy used by an electrical generator to generate one kilo watt hour (kWh) of electricity. Figure 3 shows a simple scheme of determining the power plant Efficiency and Heat Rate (HR) in which the input fuel represents the heat flow into the cycle through boiler (Q.in), the rejected heat indicates heat removal from condenser (Q.out), and power out stands for the net power generated by turbine (W.turbine - W.pump). The power plant Efficiency is calculated by Equation 1, while the power plant Heat Rate (HR) is determined by Equation 2.
The power plant efficiency could be increased by one of or combination of these schemes: reheating and regenerating [9]. The thermodynamic models of the reheating, regenerating, and a combined reheating-regenerating efficiency improvement are showed by Figure 4a, 4b, and 5, respectively. Comparing the thermodynamic model with the actual coal-fired power plant is obviously different due to the complexity of the actual coal-fired power plant. Thus, in order to analyse the Efficiency and Heat Rate of actual power plant the use of simulation tools is a must. Using a simulation tool of thermodynamic modelling, the performance of power plant operated at different conditions could be studied easily. In this paper, the heat balance of a 315 MW low rank coal-fired power plant is simulated by using a simulation tool of thermodynamic modelling, called Cycle-Tempo. The heat balance of the power plant is simulated at different operation conditions. Based on the simulation results, the performances of the power plant, namely Efficiency and Heat Rate, are analysed.

\[
\eta_{\text{cycle}} = \frac{P_{\text{net}}}{M_{\text{coal}} \times HHV}
\]

\[
HR_{\text{net}} = \frac{M_{\text{coal}} \times HHV}{P_{\text{net}}}
\]

3. Heat Balance Simulation
The heat balance of a 315 MW low rank coal-fired power plant is simulated by Cycle-Tempo. The simulations are performed for several different operation conditions of the power plant. Afterwards, the simulation results are analysed in order to study the power plant performance. The simulations start from the design condition of the power plant, as showed by Figure 6, and its results are compared to the empirical data from the power plant manufacturer. The comparisons lead to the
validation of the simulation set up on the simulation tool, Cycle-Tempo. Once the simulation results have a good agreement with the empirical data, the simulation set up for the design condition is utilised to simulate the actual condition of the power plant.

![Diagram](image1)

**Figure 4.** The thermodynamic models of the reheating (a) and regenerating (b) efficiency improvement [9]

![Diagram](image2)

**Figure 5.** The thermodynamic model of a combined reheating-regenerating efficiency improvement [9]

### 4. Simulation Parameters
Firstly the simulation carried out for the power plant design conditions, namely Valve Wide Open (VWO), Turbine Maximum Continuous Rate (TMCR), and 75% Load. Table 1 shows the operation parameter and the coal properties based on its Proximate and Ultimate Analysis for the power plant.
design condition. For the actual condition, the operation parameter and the Proximate and Ultimate Analysis is listed in Table 2. While Table 3 describes the simulation variation of the actual condition.

![Figure 6. The heat balance diagram of the power plant design condition](image)

### Table 1. The operation parameter and the coal properties for the power plant design condition

| Parameter                | Unit       | TMCR (Design) | Coal (Design)                           |
|--------------------------|------------|---------------|-----------------------------------------|
|                          |            |               | Total Moisture (as received basis)       |
|                          |            |               | 30.00 %                                 |
|                          |            |               | Ash Content (as received basis)         |
|                          |            |               | 5.00 %                                  |
| Load                     | MW         | 315.85        | Kcal/kWh                                |
| Total Moisture           | %          | 30.00         |                                        |
| Coal Mass Flow Rate      | Ton/jam    | 155.15        |                                        |
| Ash Content              | %          | 5.00          |                                        |
| Gross Plant heat rate    | kJ/kWh     | 8637.65       | Ultimate analysis (as received basis)   |
| Kcal/kWh                 |            | 2066.42       |                                        |
| Sulfur                   | %          | 0.23          |                                        |
| Gross Turbine heat rate  | kJ/kWh     | 7975.00       |                                        |
| Kcal/kWh                 |            | 1906.07       |                                        |
| Main steam Pressure      | MPa        | 17.42         |                                        |
| Main Steam Temperature   | Celsius    | 541.00        |                                        |
| Reheat steam Pressure    | MPa        | 3.47          |                                        |
| Main Steam Temperature   | Celsius    | 541.00        |                                        |
| Reheat steam Temperature | Celsius    | 541.00        |                                        |
| Main Steam flow          | t/h        | 971.10        | Lower Heating Value                     |
|                          | kg/s       | 269.75        | 17585 kJ/kg                             |
Table 2. The operation parameter and the coal properties for the power plant actual condition

| Parameter                  | Unit     | TMCR (Actual) | Coal (Actual) |
|----------------------------|----------|---------------|---------------|
| Load                       | MW       | 315.61        | Total Moisture (as received basis) 30.00 % |
| Coal Mass Flow Rate        | Ton/jam  | 155.16        | Ash Content (as received basis) 5.00 % |
| Gross Plant heat rate      | kJ/kWh   | 8517.7        | Ultimate analysis (as received basis) |
|                           | Kcal/kWh | 2037.73       | C 47.38 %     |
| Gross Turbine heat rate    | kJ/kWh   | 8544.52       | H 3.28 %      |
|                           | Kcal/kWh | 2042.19       | N 0.75 %      |
| Main steam pressure        | MPa      | 16.67         | O 13.36 %     |
| Reheat steam Pressure      | MPa      | 3.69          | Sulphur 0.23 %|
| Main steam Temperature     | Celsius  | 541.00        | Lower Heating Value 17238 kJ/kg |
| Reheat steam Temperature   | Celsius  | 541.00        |               |
| Main steam flow            | t/h      | 970.20        |               |
|                           | kg/s     | 269.50        |               |
| Reheat steam flow          | t/h      | 811.55        |               |
|                           | kg/s     | 225.43        |               |

Table 3. The simulation variation of the actual condition

| No. | Variation          | No. | Variation          |
|-----|--------------------|-----|--------------------|
| 1   | Design (Normal)    | 9   | LPH 6 off          |
| 2   | HPH1 off           | 10  | LPH 7 off          |
| 3   | HPH2 off           | 11  | LPH 8 off          |
| 4   | HPH 1&2 off        | 12  | All LPH off        |
| 5   | HPH 1&3 off        | 13  | HP turbine eff. ↑1% |
| 6   | HPH 2&3 off        | 14  | IP turbine eff. ↑1% |
| 7   | All HPH off        | 15  | LP turbine eff. ↑1% |
| 8   | LPH 5 off          | 16  | SH temperature ↑5°C |
|     |                    | 17  | Reheater temp. ↑5°C |

5. Simulation Results and Discussion
In order to validate the thermodynamic model of the power plant, the heat balance simulation of the power plant was carried out for three different conditions: VWO, TMCR, and 75% load. Table 4 shows the simulation results. Based on Table 4, it can been seen that there are a good agreement between
the design condition and the simulation results for all conditions. The deviations are at between 0% to 3%. These deviations are contributed by a slightly difference model between the design model and the actual one. In the design model the desuperheater spray does not exist, while in the actual model there is a desuperheater spray.

Table 4. The comparison of the design data and the simulations results

| Parameters       | Unit  | VWO        | TMCR       | 75%         |
|------------------|-------|------------|------------|-------------|
|                  |       | Design     | Cycle Tempo| % error     | Design      | Cycle Tempo| % error     |
| Load             | MW    | 330.12     | 330.09     | 0.01        | 315.85      | 315.88     | -0.01       | 236.89      | 236.52      | 0.16        |
| Turbin Heat Rate | kJ/kWh| 7969.00    | 8082.38    | -1.42       | 7975.00     | 8072.24    | -1.22       | 8136.00     | 8285.71     | -1.84       |
|                  | Kcal/kWh | 1904.64  | 1931.74    | -1.42       | 1906.07     | 1929.31    | -1.22       | 1944.55     | 1980.34     | -1.84       |
| Main Steam Flow  | t/h   | 1025.00    | 1027.75    | -0.27       | 971.06      | 971.00     | 0.01        | 706.80      | 709.14      | -0.33       |
|                  | kg/s  | 284.72     | 285.49     | -0.27       | 269.74      | 269.72     | 0.01        | 196.33      | 196.98      | -0.33       |
| Reheat Steam Flow| t/h   | 839.43     | 856.75     | -2.06       | 798.10      | 812.24     | -1.77       | 593.15      | 603.31      | -1.71       |
|                  | kg/s  | 233.18     | 237.99     | -2.06       | 221.70      | 225.62     | -1.77       | 164.76      | 167.59      | -1.71       |

Figure 7 shows the comparison of three different simulation conditions: design, commissioning, and actual. For Commissioning and Actual, either Gross Plant HR or Gross Turbine HR is higher than the design condition. The deviations may come from the different calorific value of the fired coal between the design coal and the actual coal. The actual coal has lower calorific value than the design one, thus the actual power plant demands more coal mass flow than the operation design. Demanding more coal mass flow will increase the utility power of pulverized unit. Based on Figure 7 it can be seen that the lifetime of the power plant will decrease the performance of the power plant. At the beginning (commissioning data test), the power plant efficiency was 36.94%, but after it has been operated for years, the power plant efficiency decrease to be 34.71%.
The simulation results for the different operation condition of the power plant are showed by Figure 8 and 9. The variation of the operation condition is listed by Table 3. Regarding Figure 8 and 9, in term of referring to the design condition, the change of the power plant Heat Rate can be summarised. Based on variations listed on Table 3, the HR increases when either High Pressure Heater (HPH) cut-off or Low Pressure Heater (LPH) cut-off occurs. While the increasing of turbine efficiency and the increasing of hot turbine temperature lead to decrease the HR, it means the power plant performance become better. These trend lines of the HR due to the change of power plant operation parameter have a good agreement with the trend lines changing as explained in Heat Rate Hand Book published by Southern Company, USA [10].

For the power plant operation related to High Pressure Heater (HPH) duty, while one of three HPH is on off-duty, the off-duty of HPH #3 has highest increasing on the HR of 2.14% and the HR will increase of 3.66% when all HPH are on off-duty. Moreover, the power plant operation related to Low Pressure Heater (LPH) duty, while one of three LPH is on off-duty, the off-duty of HPH #8 has an increasing on the HR of 0.48% and the HR will increase of 2.63% when all LPH are on off-duty. Comparing the off-duty of all HPH and the off-duty of all LPH, HPH has more significant in increasing the power plant HR. It may means HPH has more significant role in determining the power plant performance. Furthermore, the increasing of Superheater temperature of 5 oC will decrease the HR of 0.59%. This is also occurred when the temperature of Reheater increases of 5 oC, the HR decreases of 0.39%.

Based on Figure 8 and 9, the change of the output power due to the operation parameter with constant coal mass flow rate can be analysed. Referring to the variations listed on Table 3, the output power of the power plant increases as the increasing of the turbine efficiency and the hot turbine temperature. In contrast, the power output will decrease when either HPH or LPH is off-duty. The highest increase of 0.61% is achieved as the Superheater temperature increase by 5 oC. While the increase of the efficiency of the High Pressure Turbine and the Intermediate Pressure Turbine by 1% lead to upgrade the output power of 0.18%. Moreover, the most significant output power drop of 3.6% occurs when all HPH are on off-duty. Whilst if LPH #6 or #7 is on off-duty, the output power of the power plant will drop of 0.18%.

![Figure 8. The simulation results for different operation condition of the power plant (based on the variations listed on Table 3)](image_url)
6. Conclusion
The simulation results for the different operation condition of the power plant are analysed. The trend lines of the HR due to the change of power plant operation parameter have a good agreement with the trend lines changing as explained in Heat Rate Hand Book published by Southern Company, USA [10]. The Heat Rate will increase of 3.66% when all HPH are on off-duty while it increases by 2.63% when all LPH are on off-duty. Furthermore, the increasing of Superheater temperature of 5 oC will decrease the Heat Rate of 0.59% and it will decrease of 0.39% when the temperature of Reheater increases of 5 oC.

![Figure 9](image)

**Figure 9.** The simulation results for different operation condition of the power plant (based on the variations listed on Table 3)

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