The Effect of Decreasing Gas Turbine Flue Gas Temperature on The Performance of Muara Tawar Combined Cycle Power Plant

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Abstract. Muara Tawar combined cycle power plant consists of three gas turbines, three heat recovery steam generators and one steam turbine. An update of gas turbine blades in 2016 effected on decreasing gas turbine flue gas temperature by 8°C up to 20°C. This study aims to analyse the effect of decreasing gas turbine flue gas temperature on output power of steam turbine. The output power of steam turbines is simulated by using Cycle-Tempo software, based on combined cycle heat balance. Variations of decreasing gas turbine flue gas temperature are configured on three gas turbines, two gas turbines and one gas turbine. The result shows that every 2°C decrease in flue gas temperature of three gas turbines will decrease output power of steam turbines by 0.787%. Whereas if decrease in flue gas temperature of two gas turbines and one gas turbine will decrease output power of steam turbine by 0.532% and 0.267% respectively. Meanwhile, the simulation results show that the decrease in the output power of the steam turbine after update of the gas turbine blades, 72.8% is caused by a decrease in gas turbine flue gas temperature and 27.2% by other factors.

1. Introduction

Combined Cycle Power Plant is a combination of gas turbine power plant and steam turbine power plant. Combined cycle technology (CC) has been commonly used in fossil fuel power plants because it has lower emission levels than individual gas turbine (Brayton) cycles [1]. Typical heat rates of the Combined Cycle Power Plant are lower compared with steam turbines or a simple cycle gas turbine [2]. The process of heat exchange between two fluids that are at different temperatures and separated by a solid wall occurs in many engineering applications [3]. At combined Cycle Power Plant, the thermal energy of the Gas Turbine flue gas which is still as high as 500°C is used to produce water steam in heat recovery steam generator (HRSG) as the main driver of the Steam Turbine Power Plant, therefore a performance of the Combined Cycle Power Plant is more effectively.

Operating parameters such as ambient temperature, compression ratio, and turbine inlet temperature (TIT) are significantly effect on the overall performance of combined cycle power plant [4]. The Gas Turbine power output increases with the TIT’s increase, it is because it increases the work of the Gas Turbine relative to the air compressor of a Gas Turbine. The Steam Turbine power output also increases with the TIT’s increase, it is because the steam generated in HRSG increases. The increase in the boiling temperature in the heat recovery steam generator (HRSG) will result in...
greater heat exchange between the working fluid and the heat source [5]. High turbine inlet temperatures provide a challenging environment for turbine blades which are subject to a variety of damage mechanisms, including high temperature oxidation, creep, corrosion, and thermo-mechanical fatigue [6]. An increase in the turbine metal temperature, caused by increasing the engine firing temperature, and also increase centrifugal stress in the turbine blades will be reduces the life cycle of the turbine blades [7]. Therefore, the value of turbine inlet temperature will be affect to the lifetime of turbine blades. In the operation of power plants, it is necessary to find the optimal point between performance, operating costs and maintenance costs so that the profit obtained is optimal. High efficiency, low energy losses and long expected life are the important factors which make combine cycle power plants unique in compression with another type of plants [8].

Combined Cycle Power Plant of Muara Tawar block 1 has a total installed capacity of 660 MW consisting of 3 gas turbines, 3 HRSGs, and 1 steam turbine [9]. The power plant operates under the scheme of 3-3-1 (3 gas turbines, 3 HRSGs, and 1 steam turbine) in daily operations. In some lower loads, it may operate under the scheme of 2-2-1 or 1-1-1. The average electricity production per year is 4393 GWh which is supplied to the Java-Bali interconnection system. In mid-2016, gas turbine blades were upgraded to extend their lifetime by increasing cooling on the turbine blades and slightly reducing turbine inlet temperature. However, this upgrade has an impact on reducing the temperature of the flue gas of the gas turbine so that reduces the steam turbine output power.

This study aimed to investigate the effect of a decrease in the temperature of the flue gas of the gas turbines on the decrease in the steam turbine power. Thus, it can be known whether the reduction in the steam turbine power is only caused by a decrease in the temperature of the flue gas or other factors. This research was conducted using software Cycle-Tempo.

2. Methods

2.1. Modelling
In this study, the combined cycle power plant of Muara Tawar is modeled and simulated by using Cycle-Tempo software. The model is created according to heat balance as described in Figure 1. The software will provide symbols, requirements, and number of the apparatus, and will confirm the flow of the media: air, fuel, gas, water, and steam [10].
Once the modelling is complete, the next stage is to enter the data in the form of properties on all apparatus and medium. Each apparatus requires different data entry properties. The data entry apparatus is an important step in the simulation. The data obtained from the results of performance tests before the replacement of the turbine blades. If the input data and properties did not match and meet the matrices of mass and energy balance, then an error warning message will alarm and the simulation is not able to run. The simulation process is considered to be successful when there are no errors or warnings which indicate a violation of conditions and constraints. The model of CCPP with all properties corresponding to the heat balance can be seen in Figure 2.
2.2. Equation Heat Balance

The heat from the flue gas from the gas turbine should be sufficient to generate the steam and pressure in the waste heat recovery steam generator (HRSG).

2.2.1. The heat transferred from the flue gas.

\[ q_{ex} = m_g \cdot C_{pg} \cdot (T_4 - T_{stack}) \]  

where:
- \( m_g \): mass flow rate of flue gas (kg/s)
- \( C_{pg} \): the specific heat of flue gas (J/kg.K)
- \( T_4 \): the superheated temperature (K)
- \( T_{stack} \): flue gas temperature in stack (K)

2.2.2. The heat is absorbed or gained in the boiler.

\[ q_{ex} = m_s \cdot (h - h_w) \]  

where:
- \( m_s \): mass flow rate of steam (kg/s)
- \( h \): enthalpy of superheat steam (J/kg)
- \( h_w \): enthalpy of feed water (J/kg)

The superheat temperature is fixed by \( T_4 \) and the terminal temperature difference, and the enthalpy will depend on the pressure. The pinch point temperature \( T_p \) is fixed by pinch point difference and the saturation temperature of the steam. Therefore, heat balance between steam and flue gas is

\[ m_s \cdot (h - h_f) = m_g \cdot C_{pg} \cdot (T_4 - T_p) \]  

The stack temperature can be obtained from

\[ m_s \cdot (h_f - h_w) = m_g \cdot C_{pg} \cdot (T_4 - T_{stack}) \]
2.2.3. The gas turbine works.

\[ W_T = \dot{m}_a (h_{\text{in}GT} - h_{\text{out}GT}) \]  
(5)

Where:
- \( W_T \): the gas turbine work (kW)
- \( \dot{m}_a \): air flow rate inlet turbine (kg/s)
- \( h_{\text{in}GT} \): enthalpy of air inlet to turbine (kJ/kg)
- \( h_{\text{out}GT} \): enthalpy of air outlet from turbine (kJ/kg)

2.2.4. Total pumping work.

\[ W_P = \dot{m}_{fw} (h_{\text{out}P} - h_{\text{in}P}) \]  
(6)

Where:
- \( W_P \): the total pumping work (kW)
- \( \dot{m}_{fw} \): feed water mass flow rate inlet to pump (kg/s)
- \( h_{\text{in}P} \): enthalpy of feed water inlet to pump (kJ/kg)
- \( h_{\text{out}P} \): enthalpy of feed water outlet from pump (kJ/kg)

2.2.5. Total steam turbine work.

\[ W_{ST} = \dot{m}_{st} (h_{\text{out}ST} - h_{\text{in}ST}) \]  
(7)

Where:
- \( W_{ST} \): the total steam turbine work (kW)
- \( \dot{m}_{st} \): steam flow rate inlet to turbine (kg/s)
- \( h_{\text{in}ST} \): enthalpy of steam inlet to turbine (kJ/kg)
- \( h_{\text{out}ST} \): enthalpy of steam outlet from turbine (kJ/kg)

2.2.6. Heat rejected from condenser

\[ Q_{\text{out}} = \dot{m}_{mix} (h_{\text{in}C} - h_{\text{out}C}) \]  
(8)

Where:
- \( Q_{\text{out}} \): heat rejected to condenser (kW)
- \( \dot{m}_{mix} \): mixture mass flow rate inlet condenser (kg/s)
- \( h_{\text{in}C} \): enthalpy of mixture inlet to condenser (kJ/kg)
- \( h_{\text{out}C} \): enthalpy of mixture outlet from condenser (kJ/kg)

2.3. Validation

After properties data entry is complete and the software runs successfully, the next step is to validate operational parameters by comparing the modeling result with the existing data (performance test result), which is resumed in Table 1. The error in the validation process is acceptable if it is not more than 5%. The error value is calculated by:

\[ Error = \frac{(D_s - D_e)}{D_e} \times 100\% \]  
(9)

where:
- \( D_s \): simulation result
- \( D_e \): existing data

From resumed table 1 below, the most deviated value is low pressure steam flow 1.2 that is 3.146%. However the value is still below the acceptable error so the model is considered as a valid model.
2.4. Variation of flue gas temperature

Variations of flue gas temperature may be established just after successful validation. The variations are configured in several different schemes, namely a decrease in the flue gas temperature in three gas turbines, a decrease in the flue gas temperature in two gas turbines (with the flue gas temperature of one fixed gas turbine) and a decrease in the flue gas temperature in one gas turbine (with two flue gas temperatures fixed gas turbine). Each scheme is evaluated for its impact on the reduction in steam turbine power.

The next step is to evaluate the reduction in flue gas temperature after the turbine blades replacement by entering the flue gas temperature data from the performance test result after the turbine blades replacement into the model. The output power of the steam turbine from the simulation results are compared with the performance test results, to find out whether the current decrease in steam turbine power is only caused by a decrease in flue gas temperature or any other cause.

3. Result and discussion

Based on the model that has been validated above, then the input data is carried out to the model, the variation of the reduction in flue gas temperature from 0 °C up to 18 °C. It should be noted that the initial data of the flue gas temperature is based on existing data (performance test result). Tables 2, 3 and 4 show the results of modeling for the reduction of flue gas temperatures at three gas turbines, two gas turbines, and one gas turbine respectively.

A reduction in flue gas temperature of 2 °C in three gas turbines causes a decrease in steam turbine output power by 0.787% as shown in Table 2. Based on Table 3, a reduction in flue gas temperature of 2 °C in two gas turbines (while flue gas temperature of one gas turbine is constant) causes a decrease in steam turbine output power by 0.532%. Table 4 shows that each reduction in the temperature of 2 °C flue gas in only one gas turbine (while flue gas temperature of two other gas turbines is constant) causes the steam turbine output power to drop by 0.267%. Then Tables 2, 3 and 4 are plotted on a graph, as shown in Figure. 2.

Table 1. Comparison between modeling result and existing data.

| Parameter          | Unit  | Existing Data | Modeling Result | Deviation (%) |
|--------------------|-------|---------------|-----------------|---------------|
| GT 1.1 power output| kW    | 136090        | 136036          | -0.040        |
| GT 1.2 power output| kW    | 136653        | 136686          | 0.024         |
| GT 1.3 power output| kW    | 136133        | 136128          | -0.004        |
| ST power output    | kW    | 205470        | 205468          | -0.001        |
| HP steam flow 1.1  | kg/s  | 54.93         | 54.13           | -1.454        |
| HP steam flow 1.2  | kg/s  | 54.01         | 54.22           | 0.394         |
| HP steam flow 1.3  | kg/s  | 54.90         | 54.77           | -0.244        |
| LP steam flow 1.1  | kg/s  | 25.97         | 25.68           | -1.136        |
| LP steam flow 1.2  | kg/s  | 25.98         | 25.17           | -3.146        |
| LP steam flow 1.3  | kg/s  | 25.98         | 25.77           | -0.829        |
**Table 2.** Effect of decreasing flue gas temperature for three gas turbine units.

| No | Decreasing of flue gas temperature (°C) | Steam turbine power output (kW) | Deviation (%) |
|----|----------------------------------------|---------------------------------|--------------|
| 1  | 0                                      | 205468                          | 0            |
| 2  | 2                                      | 203851                          | -0.787       |
| 3  | 4                                      | 202234                          | -1.574       |
| 4  | 6                                      | 200618                          | -2.360       |
| 5  | 8                                      | 199002                          | -3.147       |
| 6  | 10                                     | 197387                          | -3.933       |
| 7  | 12                                     | 195774                          | -4.718       |
| 8  | 14                                     | 194160                          | -5.504       |
| 9  | 16                                     | 192548                          | -6.288       |
| 10 | 18                                     | 190936                          | -7.073       |

**Table 3.** Effect of decreasing flue gas temperature for two gas turbine units.

| No | Decreasing of flue gas temperature (°C) | Steam turbine power output (kW) | Deviation (%) |
|----|----------------------------------------|---------------------------------|--------------|
| 1  | 0                                      | 205468                          | 0            |
| 2  | 2                                      | 204375                          | -0.532       |
| 3  | 4                                      | 203282                          | -1.064       |
| 4  | 6                                      | 202190                          | -1.595       |
| 5  | 8                                      | 201098                          | -2.127       |
| 6  | 10                                     | 200006                          | -2.658       |
| 7  | 12                                     | 198915                          | -3.189       |
| 8  | 14                                     | 197825                          | -3.720       |
| 9  | 16                                     | 196735                          | -4.250       |
| 10 | 18                                     | 195646                          | -4.780       |

**Table 4.** Effect of decreasing flue gas temperature for one gas turbine unit.

| No | Decreasing of flue gas temperature (°C) | Steam turbine power output (kW) | Deviation (%) |
|----|----------------------------------------|---------------------------------|--------------|
| 1  | 0                                      | 205468                          | 0            |
| 2  | 2                                      | 204920                          | -0.267       |
| 3  | 4                                      | 204371                          | -0.534       |
| 4  | 6                                      | 203823                          | -0.801       |
| 5  | 8                                      | 203275                          | -1.067       |
| 6  | 10                                     | 202727                          | -1.334       |
| 7  | 12                                     | 202180                          | -1.600       |
| 8  | 14                                     | 201633                          | -1.866       |
| 9  | 16                                     | 201086                          | -2.133       |
Based on performance test data after the turbine blades replacement, it is known that the flue gas temperature drops to 519.32 °C, 524.88 °C and 524.28 °C in GT 1.1, GT 1.2 and GT 1.3 respectively. While the steam turbine power drops to 190720 kW. Then the flue gas temperature data is entered into the model, the steam turbine power obtained is 194731 kW as shown in table 5. Thus, the current decrease in the steam turbine power caused by a reduction in flue gas temperature of 72.8% or around 10739 kW. While the remaining 27.2% or 4011 kW are caused by other factors.

Table 5. Comparison between before and after replacement of turbine blades.

| Parameter               | Unit | Before replacement | After replacement |
|-------------------------|------|--------------------|-------------------|
| Flue gas temp. of GT    | °C   | 537.65             | 519.32            |
| 1.1                     |      |                    | 519.32            |
| Flue gas temp. of GT    | °C   | 533.98             | 524.88            |
| 1.2                     |      |                    | 524.88            |
| Flue gas temp. of GT    | °C   | 536.96             | 524.28            |
| 1.3                     |      |                    | 524.28            |
| ST power output         | kW   | 205470             | 190720            |
|                         |      |                    | 194731            |

4. Conclusion
A heat balance model is developed to determine the functional relationship between decreasing of flue gas temperature of gas turbine and steam turbine output power. The model is developed by using software Cycle-Tempo, based on heat balance data from the performance test result of the power plant.

It can be concluded that the output power of the steam turbine is estimated to decrease by about 0.787% every 2 °C decrease in flue gas temperature of three gas turbine units. Whereas if the reduction in flue gas temperature occurs on two and one gas turbine units, the output power of the steam turbine is estimated to decrease respectively around 0.532% and 0.267%. Based on the simulation results from the model, it was found that the reduction in steam turbine power caused by
the reduction in flue gas temperature after turbine blade replacement was 72.8% or around 10739 kW. Thus, there is an estimated 27.2% or 4011 kW decrease in the steam turbine power caused by others.

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