A study on the Performance and Reliability Effect of Low-Rank Coal to the Steam Power Plant

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Abstract. The main purpose of utilizing lignite coal in Indonesia is to decrease fuel costs in electricity and Greenhouse Gas emissions. Still, on the other hand, it will affect the reliability and plant performance. This paper attempts to evaluate 340 MW subcritical coal-fired power plant's performance and reliability by comparing the impact of coal utilization below boiler design toward the baseline and identifying the significant factors that lead to plant efficiency and reliability. Performance tests conducted using the standard procedures at four segments of load, i.e., 50%, 65%, 80%, and 95%, with two scenarios: (1) use 3500 kcal/kg of coal calorific value, and (2) use 4500 kcal/kg of coal as the baseline. There are no adjustments during the test and all measurements, including pressure, temperature, flow, bomb calorimeter, etc., already calibrated. The results show that during 3500 kcal/kWh, 100% of the load is unable to reach. Plant performance becomes higher up to 2930 kcal/kWh, boiler efficiency decrease to 80.4%, and fans current increase to maximum capacity. The study's conclusion suggests that the utilization of LRC must be considering the energy amount to the boiler.

1. Introduction

Energy plays an essential role in economic development, people's quality of life, and poverty alleviation. To meet energy needs, the Ministry of Energy and Mineral Resources Republic of Indonesia has decided to use lignite coal for power generation, synthetic oil and gas fuel production, and other purposes. This effort is part of the national energy policy to stimulate optimal coal utilization possibilities in conjunction with the blueprint of diversifying energy program.

The idea of using lignite coal is mostly due to the abundance of its reserve, still unutilized so far, having low mining strip ratio, good quality in terms of sulfur and ash content. All of those will generate the security of supply and low-cost energy source [1].

Lignite coal utilization for coal-fired power plants (CFPP) in Indonesia increased significantly, especially at the first fast track program (FTP 1) initiated in 2007. A CFPP, as a part of FTP 1, generates 350 MW of electricity by coal, auxiliary power consumption, and high-speed diesel (HSD) as energy for the combustion process. According to an energy review at the beginning of 2020, it shows the intensity and cost of energy consumption shown in Table 1.

According to Table 1, coal is the most considerable energy, which consumes 98% of total energy, auxiliary power 2.25%, and 0.47% for HSD. Consequently, the boiler is a Significant Energy Use
Since early 2020, Indonesian government-owned electrical power corporations in Indonesia have decided to optimize the coal by downgrading its quality 3500-4200 kcal/kg to reduce electricity generation costs, especially fuel components. This decision affected the operation and maintenance facilities because it has the following issue: a lower CV than the required design, high moisture content, low thermal efficiency, rich in oxygen, and an increased tendency to spontaneously combustion [2].

Several studies examined the properties and impact of lignite coal on the combustion process and cost production. Barbara reported that during the combustion process, the boiler's heat loss to evaporate the coal's moisture causes a massive increase in fuel consumption with increasing boiler load [3]. On the other hand, lignite coal has high reactivity, high volatile matter content, low content of pollution, forming impurities such as sulfur, nitrogen, heavy metals, and low mining cost, which significantly affecting coal prices [4].

Several researchers conducted experimental design and simulation during the last decade using a computerized fluid dynamic (CFD) [5]. The others use mathematical models using MATLAB to analyze power plant performance and optimize plant efficiency [6], coal switching [7], burner ignition, and slagging and fouling phenomena. Experimental designs represent coal combustion behavior and find out plant performance without any actual testing [8]. However, in other cases and purposes, it
needs to compare with substantial testing to find how much the real degradation of plant performance and obtain information on the actual response of auxiliary equipment regarding coal utilization.

This study evaluates the power plant performance impact from coal utilization below the boiler manufacture design at a particular load based on some of the actual tests. These actual tests investigate how much boiler efficiency, net plant heat rate, availability of load, equipment reliability such as pulverizer, induced draft fan (IDF), forced draft fan (FDF), etc. and also to analyze the environmental effect of combustion process [9].

2. Materials and Methods

2.1. Material and measurements

The CFPP consists of six types of Low-Rank Coal (LRC) and divided into two varieties: (1) sub-bituminous coal group C with 4600-5277 kcal/kg, and (2) lignite coal group A with 3500 - 4600 kcal/kg of high heating value (HHV) [4]. The classification of LRC through the suppliers is presented in Table 3.

Table 4. Classification of LRC and suppliers.

| Class        | Group       | Suppliers                        | HHV, kcal/kg |
|--------------|-------------|----------------------------------|--------------|
| Subbituminous| Subbituminous C | Bukit Assam, Co. Ltd.             | 4600-5200    |
|              |             | PLN BB, Co. Ltd.                 | 4700-5200    |
| Lignite      | Lignite A   | PLN BB, Co. Ltd.                 | 4100-4400    |
|              |             | KII, Co. Ltd.                    | 3500-4200    |
|              |             | Hanson Energy, Co. Ltd.          | 4200-4600    |

The coal selected for this study comes from KII, Co. Ltd. With 3543 kcal/kg, by characteristics are summarized in Table 5 KII's coal also was analyzed by the Thermo Gravimetric Analyzer [10] and CHN Analyzer [11] that already calibrated and certified by the Nasional Accreditation Committee of Indonesia (KAN).

Table 5. Composition of fired coal during a performance test

| No | Parameter       | Mass Fraction, % |
|----|----------------|------------------|
|    | Proximate Analysis |                  |
|    | Moisture    | 40.84            |
|    | Ash         | 5.77             |
|    | Volatile    | 29.89            |
|    | Fixed Carbon| 23.50            |
|    | Ultimate Analysis |              |
|    | C           | 36.06            |
|    | H           | 2.85             |
|    | O           | 13.71            |
|    | N           | 0.47             |
|    | S           | 0.29             |

There is no special treatment while utilizing this coal, like blending coal on coal to increase the combustion quality [12] or coal pre-drying to reduce the moisture content [13]. In other words, this test only utilizes pure coal from the supplier to identify plant ability.

2.2. Performance Test

The actual performance test for the CFPP unit 2 conducted refers to ASME PTC 46 – overall plant performance [14], and ASTM D197 – 19 standard test method for sampling and fineness test of pulverized coal [15]. Although the initial plan was to carry out the test up to a full load of 340 MW, the actual test was only executed in three loads, 215 MW, 265 MW, and 300 MW, due to design limitations.
The instruments are calibrated, and all parameters are kept as steady as practicable and maintained throughout the test. General test steps are: (1) Thermal system is isolated to meet the test requirements; (2) Load adjusted to meet the test requirements; (3) Operating condition adjusted to meet the test requirements; (4) Test instruments commissioned individually following the function check; (5) Operation of turbine unit and associated equipment are stabilized for about an hour; (6) Condensate water flow controlled manually to keep deaerator water level stable; (7) Test started with a data acquisition system that can record automatically.

During the test, the following conditions also met the requirement: (1) Two feedwater pumps operated normally; (2) Two condensate water pump operated normally; (3) One vacuum pumps operated normally; (4) All regenerative water heaters operated normally. The performance test is divided by two main systems: boiler and turbine, as shown as the heat balance system in Figure 1. Boiler performance was calculated refers to ASME PTC 4-1998, which defined as:

\[ EF_{HHV} = 100 - Q_pL + Q_pB \]  

where \( EF_{HHV} \) is the fuel efficiency based on HHV,\%; \( Q_pL \) is the losses calculated on a % input from fuel basis; \( Q_pB \) is the credits calculated on a % input from a fuel basis. To determine boiler performance with heat loss method in the stack also can be defined as:

\[ EF_{HHV} = 100 - L_1 - L_2 - L_3 - L_4 - L_5 - L_6 - L_7 - L_8 - L_9 - L_{10} \]  

where \( L_1 \) is heat loss due to dry gas,\%; \( L_2 \) is heat loss due to hydrogen in fuel,\%; \( L_3 \) is heat loss due to moisture in fuel,\%; \( L_4 \) is heat loss due to moisture in air,\%; \( L_5 \) is heat loss due to combustible in refuse,\%; \( L_6 \) is heat loss due to surface radiation,\%; \( L_7 \) is unaccounted loss,\%; \( L_8 \) is heat loss due to sensible heat in bottom ash,\%; \( L_9 \) is heat loss due to sensible heat in fly ash,\%; \( L_{10} \) is heat loss due to formation carbon monoxide,\%.

![Turbine system](image1)

![Boiler system](image2)

**Fig. 1.** Heat balance system of coal-fired power plant.

Coal sampling was collected at operating feeders with a 30minute interval during two hours period of the test. At the end of the test period, the sample mixed and processed. For the sample, all coal increment was emptied in the form of a cone on the clean area and quickly mixed. The bulk sample was reduced to laboratory requirements by coning and quartering means. At each stage in the subtraction process, half the bulk sample rejected until the quantity of coal remained is sufficient to fill the requisite number of airtight sample containers.
ASME PTC 6-2004 was used to calculate steam turbine performance, including turbine heat rate (THR). THR is defined as the total amount of energy input from steam required to produce one kilowatt-hour. It can also be defined as the ratio of boiler heat duty to turbine mechanical work. The following equation is used to determine THR [14].

\[
\text{THR} = \frac{G_{ms}H_{ms} - (G_{ms} - H_{ms})H_{fw} - G_{fw}H_{fw} + G_{rhe}H_{rhe} - G_{rhe}H_{rhe} - G_{fw}H_{fw}}{P_m}
\]

where \(G_{ms}, H_{ms}\) is the main steam flow rate, t/hr, and enthalpy, kJ/kg respectively, at the main steam valve inlet; \(G_{rhe}, H_{rhe}\) is hot reheat steam flow rate, t/hr, and enthalpy, kJ/kg, respectively; \(G_{fw}, H_{fw}\) is boiler feedwater flow rate, t/hr, and enthalpy, kJ/kg, respectively; \(G_{rhe}, H_{rhe}\) is cold reheat steam flow rate, t/hr, and enthalpy, kJ/kg, respectively; \(G_{fw}, H_{fw}\) is boiler superheater spray water flow rate, t/hr, and enthalpy, kJ/kg, respectively; \(P_m\) is gross power output measured at generator terminal, MW;

The net plant heat rate (NPHR), or at this paper, called heat rate, described the amount of heat input into a system divided by the amount of power generated by a system in kCal/kWh. Heat rate is calculated by two methods: the direct method and the heat loss method [16]. The direct method is used to determine plant performance by measured directly. The heat input to the furnace was obtained from fuel consumption rate measurements, and the coal CV taken from the laboratory. The electrical output of the unit was obtained from measurements of the gross load and station service. Thus,

\[
\text{NPHR (direct method)} = \frac{CF \times HHV}{P_{net}}
\]

where \(CF\) is coal flow consumption, t/h; \(HHV\) is High Heating Value, kcal/kg; \(P_{net}\) is gross power output minus auxiliary power, MW. To analyze improper operation parameter control such as main steam pressure, main steam temperature, etc., calculation of heat rate in heat loss method formulated as:

\[
\text{NPHR (heat loss method)} = \frac{\text{THR}}{P_{net} \times FFHV}
\]

The net thermal efficiency, \(\eta_{net}\) is defined as follows,

\[
\eta_{net} = \frac{860}{NPHR} \times 100
\]

All subsystems, including the condenser, feedwater heater, and air preheater, are calculated refers to ASME PTC 12.2, ASME PTC 12.1, and ASME PTC 4.3, respectively.

2.3. Heat Rate Gap Analysis

The heat rate gap analysis is presented in Figure 2. This analysis is used to understand and determine the unit performance by comparing the best achievable performance at commissioning and actual performance. This heat rate gap analysis not only to know the heat rate value but also to identify the losses as accounted-for losses. Calculation of heat rate loss determined from relevant variables significant to the performance like condenser backpressure, auxiliary power, coal moisture, etc. All variables will be converted into heat rate unit, kcal/kWh, to simplify the impact calculation of performance parameter deviation on heat rate.
Heat rate loss parameters are classified by six factors, i.e., operator controllable, unit controllable turbine components, cycle components, boiler components, and other factors that mean undefined losses at power generation system.

3. Results and discussion.

3.1. Electricity Production

There are no significant problems during data collection, and all loads are achieved except for the fourth load, 340 MW. However, that condition was forecasted before by statistical data. All significant variables related to the boiler ability, such as total air and coal flow, fans current, % damper position, and pressure header, were identified through unit loads at various coal CV. The data captured in a 4month by 15minute interval and only stable condition was used for analysis.

Figure 3 shows that the airflow and coal flow increase proportionally through a unit load. At full load, maximum coal flow when five mills are running reach up to 225 t/h, while total airflow 1000 t/h. There is no excess flow during operation. Therefore when coal flow or airflow reaches more than this condition, it wouldn't get the load target.

Figure 4 shows the fans current in various coal flows. The orange zone indicates current limitation and its rated current at each fan. When the current reaches the orange zone, the fan system is still adequate to operate, but it needs extra monitoring and not allowed if it exceeded the rated current. The highest fans current and % to rated current during maximum operation shows in Table 6.

| Equipment | Fans Current, Amper | Rated Current, % |
|-----------|---------------------|------------------|
| PAF       | 189.55              | 91.1%            |
| FDF       | 36.25               | 59.2%            |
| IDF       | 180.77              | 63.2%            |

Figure 5 is related to Figure 6 and shows the percentage (%) damper position of FDF and IDF still in normal condition and proportional to coal flow and load changes. While % damper position of PAF relatively high from the beginning, this phenomenon indicated from the pressure header, which is
relatively low, nevertheless it still able to supply the air to PAF as needed. Figure 7 shows the current mill pattern that indicates it still has more capacity if it operates in the low CV of coal.

**Fig. 3.** Characteristic of coal flow and airflow through unit load

**Fig. 4.** Characteristic of coal flow through fans current

**Fig. 5.** Characteristic of coal flow through % damper opening
Based on Figures 3 to 7, the plant system's leading cause cannot reach the load is the boiler main equipment's ability. If the coal with very low CV enters the boiler, the fan system, coal feeder, and mill will operate in excess capacity. At the same time, every piece of equipment has imitation according to design and operator experience.

3.2. Plant Performance

Figure 8. shows the results of the heat rate calculation indirect method when 215 MW, 265 MW, and 300 MW of baseload. According to the pattern, the actual heat rate during coal utilization 3500 kcal/kg higher than the baseline. During the 300 MW load, the actual heat rate value 2847 kcal/kg lower than the actual. The waterfall diagram in Figure 9 indicates losses during the performance test. This tool is used to analyze the gap with a significant variable that relevant to the heat rate. The red bar shows losses of heat rate, while the grey bar shows credit to heat rate. According to Figure 9, the most significant losses are condenser vacuum, mmHg, moisture in fuel, %, auxiliary power, %, and hydrogen in fuel, %, respectively.

The condenser's loss reaches 33.62 kcal/kWh and occurs because of some problems that do not correspond to coal utilization. Based on the significant variable in the condenser system such as outlet exhaust steam from the low-pressure turbine, the inlet-outlet temperature of circulating water, condenser pressure, etc. The deviations are produced by the condenser tube's fouling, which causes the condenser pressure to increase and increases the turbine heat rate.
Increasing in turbine heat rate was also caused by operating main steam pressure below the baseline during 300 MW. It was supposed to be operated in 16.4 Mpa, but only 13.5 Mpa for the test. The leading cause that makes the main steam pressure below the baseline is decreasing the boiler feed pump turbine (BFPT) performance. According to the heat rate factor, when the main steam pressure has a gap 0.07 Mpa to the baseline, it will result in a loss of 0.04% NPHR or 4.32 kcal/kWh loss during operation.

The second rank that causes an increase in heat rate is auxiliary power. This parameter also indicates the boiler's main equipment's reliability level, like the fan system and mill. Figure 10 shows that FDF current increases significantly more than 5 Amper on average during the coal optimization test, both A and B side. Likewise, with total mill current, at 300 MW loads, five mills are running with an average of 235 Amper. At the same time, the PAF A and B have no significant increase during the highest load, and the current of IDF A and B same as FDF that increases significantly through load change. This phenomenon occurs because the moisture, as the third level of heat rate losses, has a higher volume in coal, around 42.4% compared to the baseline that only 31.3%. When the coal has a high moisture content, the boiler system will need more energy to generate load and separate moisture from the coal during the combustion process. More energy same as more coal consumption, and it will increase in the motor of the mill, PAF, FDF, and IDF.
Other significant losses that cause an increase in heat rate is moisture from hydrogen burning in the fuel. Hydrogen will increase the heating value of coal [17], but at the same time, it also reduces boiler efficiency.

Figure 11. shows that both hydrogen and moisture are significant losses that were decreasing the boiler's performance from 85.3% (baseline) to 80.4%, and of course, will increase the heat rate. According to Heat Rate Hand Book, a 1% hydrogen increase against the baseline increases 2% of heat rate [18]. In another case, heat loss due to dry gas happens because of incorrect fuel to air ratio. Fans and mill system support the fuel to air ratio. Yet, during the performance test, fans and mill system operated at maximum capacity so that air-fuel to ratio cannot reach boiler combustion requirements.
3.3. Environmental Impact

Figure 12 shows the environmental impact during performance tests that start from 9 to 10 June 2020, from 8 p.m. to 6 a.m., where taken from Continuous Emission Monitoring System (CEMS) at stack.

![Environmental impact graph](image)

**Fig. 12. Environmental impact**

Due to the utilization of 3510 kcal/kg coal, which has low sulfur, and nitrogen, the greenhouse gas emissions (GHG) from the CFPP lower than the emission-quality standard established by the Ministry of Environment and Forestry of The Republic of Indonesia. The average result from NOx is 357 mg/Nm³ and SO₂ 441 mg/Nm³. According to the standard, for a power plant operated and built before 2019, the NOx and SO₂ emission must be under 550 mg/Nm³.

4. Conclusions

The actual performance test during utilization of 3510 kcal/kg coal was conducted refers to ASME PTC 46. However, the maximum load of 340 MW cannot reach due to plant capacity. The test shows that coal has higher moisture and hydrogen content and consumed a larger volume for the boiler combustion process. The net plant heat rate increased to 2847 kcal/kWh, and boiler efficiency was decreased by up to 80.3% through baseline, indicating that the CFPP decreased plant performance. At the operation side, increasing NPHR occurs by condenser vacuum and auxiliary power consumption. While the boiler decrease by moisture in fuel, dry gas, and moisture from the burning of hydrogen in the fuel. Auxiliary power consumption increase due to mill and fans system were operated at maximum capacity to force the combustion process. This phenomenon was also causing improper air to fuel ratio, which results in a dry gas loss. On the other side, utilization the coal was decreased GHG emissions like SO₂ and NOx under the emission-quality standard of Indonesia. Therefore utilization of coal below the baseline will make more disadvantages than benefits, and management has to consider how much minimum CV for power generating unit.

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