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Energy Audit Analysis of Coal Boiler by using Direct and Indirect Methods: Case Study of PT. Pupuk Kalimantan Timur, Indonesia

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ABSTRACT

World energy consumption is increasing proportional to the rapid advancement of technology. While efforts to supply the ever-growing energy demand were done continuously, increasing the supply for pre-existing industries is expensive and bound by various limitations. Therefore, there is a growing interest in energy efficiency with energy audit analysis plays an important role in discovering energy-saving opportunities. The most potential equipment for energy efficiency in agricultural industry are the boilers of fertilizer factories. PT. Pupuk Kalimantan Timur, Indonesia's largest urea and ammonia producer, uses Circulating Fluidized-Bed Boiler; a very promising subject of energy audit analysis in agriculture industry. Case study using direct and indirect methods was done in order to identify coal efficiency and excessive energy use. Data were collected from primary and secondary sources and analyzed through several stages. Result shows that using medium-rank coal yields higher boiler efficiency. Using direct method, medium-rank coal efficiency is found to be 91.84% and 93.09% compared to using low-rank coal, which is 89.70% and 91.84%. Meanwhile, calculation using indirect method found the efficiency using medium-rank coal is 95.03% and 95.35% compared to using low-rank coal, 93.39% and 93.81%, respectively. This efficiency difference is influenced by coal calorific value, fuel and steam rates, flue gas, fuel factor, specific heat, and air temperature with the correlation between one another described in this study.

1. INTRODUCTION

PT. Pupuk Kalimantan Timur is Indonesia's largest urea and ammonia producer with manufacturing capacity 3.43 and 2.765 million tons respectively. This quantity is not counting 350 thousand tons of NPK (nitrogen phosphorous potassium) and 45 thousand tons of organic fertilizer produced annually. The ammonia is sold in liquid form at temperature of -33°C with purity of 99.5%. Meanwhile, urea fertilizer with the chemical formula $CO(NH_2)_2$ is the main fertilizer containing the highest nitrogen content, 46.67% by weight, which comes from the reaction between carbon dioxide (CO_2) and ammonia (NH_3). Currently, the company operates eight factories; units 1, 1A, 2, 3, 4, 5, 6 are known as coal boilers and unit 7 is known as NPK fertilizer production plant.

High rate of population growth, accompanied by rapid industrialization, urbanization, and an extraordinary economy, led to an increase in the consumption of fossil fuels to meet energy demand [1]. Therefore, coal was selected as boiler fuel in accordance with the government's focus on reducing dependence on oil and gas fuels. Additionally, a coal boiler was constructed to reduce the need for natural gas as boiler fuel considering the price increase and limited energy efficiency [2]–[4].

A boiler is a supporting equipment that plays an important role in the fertilizer factory process to produce steam. In simple terms, it works by burning the fuel with the heat energy used to evaporate the feed water. The steam produced comes from the heat in the furnace with the help of combustion air. The raw material for the steam obtained comes from demineralized water fed from the demineralization unit [5], [6]. The utility of the steam obtained is the main driver of the company's plant operations because it acts as one of the reactants of the product used to run process equipment, drive the steam turbine generator, and as a heat exchanger. one of the important things to consider in a heat exchanger is heat transfer. Hence, using the principles of mass and heat transfer, the various processes in a device can be simulated [7]–[9].

Six coal boiler plant operations department uses a circulating fluidized-bed boiler with coal as low and medium rank fuel to increase the boiler's efficiency and decrease energy use. It also has a system of restoring unburned coal through a cyclone, which separates the output from the furnace based on the object's weight. The unburned coal goes to the bottom of the cyclone and is re-circulated back to the furnace, while the dust and a small amount of light coal flow into the back pass. This region is useful for increasing boiler efficiency by

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restoring the heat possessed by the cyclone output dust to the feed water as an economizer and a heater for the feed air. This boiler works at a temperature of 800°C – 900°C, hence the potential for slagging is very low, making the amount of NOx much lower than the other types.

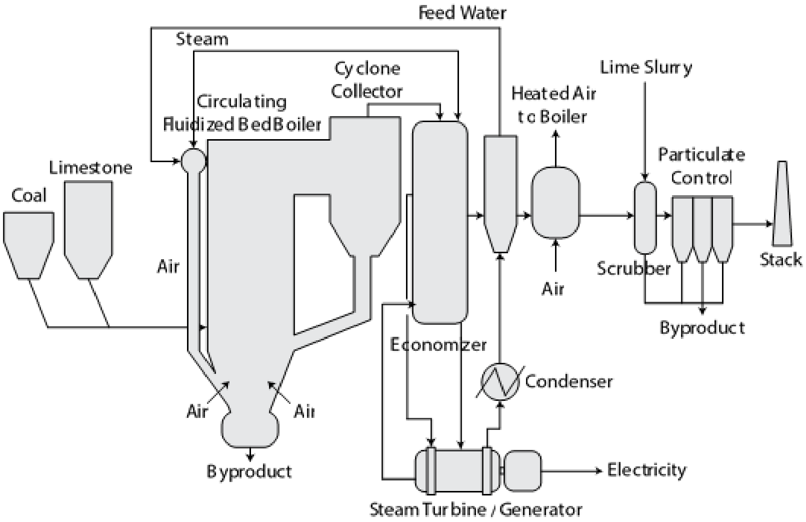

Fig. 1. Mechanism of CFB unit.

It is important to analyze the process to determine the characteristics of a system and the number of design variables needed to complete the flow of information [1], [7]. Determination of design variables is then necessary for analyzing the optimized variables. The distillation column depends on the operating pressure, number of columns, location of feed intake, reflux ratio, and product composition specifications as prominent variables in the column [1].

Over time, the performance of process equipment is likely to decline, as seen from the amount of steam produced with a rise in fuel demand. This also impacts the sustainability of the process assessed from cost, time, and product quality. Some important factors affecting boiler efficiency are dry gas, moisture, humidity, blow-down, unburnt carbon, and radiation losses. Economic calculations are very important in the industrial design of process tools [7].

On that account, several researches in the form of energy audit and efficiency studies have been conducted by various researchers in various applications. Farhan *et al.* investigated the effect of suction line on the evaporator performance with the using of R-134a [10]. It was found that major parameter at a concentric suction line is evaporator effectiveness, which offered the biggest enhancement of effectiveness by 15.45% compared to the reference capillary tube. Khaleel *et al.* tried to developed an analytical model to predict effectiveness based on the measured data available from a coal-fired thermal power plant via energy and exergy analysis [11]–[16]. This is similar to study conducted by Mohammed *et al.*, which involved the performance of energy and exergy analysis on a steam cycle power plant [17]. Other study by Zaidan *et al.* tried to enhance equipment performance by designing direct evaporative cooler and vapor compression cooling system [18].

However, the problem is that the studies approached to reduce energy costs by the integration of simple and complex processes for coal boilers, specifically circulating fluidized-bed boiler, are insufficient. Future work needs to focus on the simulation and optimization of energy costs [7]. This implies that it is necessary to evaluate the efficiency of this coal boiler performance as an aspect of maintenance and repair of process equipment [9], [19]–[23]. Thus, this study aims to evaluate coal boiler efficiency through a case study using direct and indirect methods in order to identify coal efficiency and excessive energy use.

2. METHOD

2.1 Data Collection

Primary and secondary data were used to carry out the boiler efficiency evaluation.

2.1.1 Primary Data

Primary data was obtained from observations and measurements of the operating size from field and the specifications of the tools used. It consists of the operation log sheet data when the boiler starts until it reaches a stream rate of 100%. It includes the following:

- Proximate analysis of coal, consisting of total moisture, ash, volatile matters, and fixed carbon based on supplier specifications.
- Coal ultimate analysis, consisting of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O) based on laboratory test data.
- Higher heating value (HHV) based on supplier specifications.
- Consumption of coal and water feed.
- Temperature and pressure of feed, recovered steam, and blow-down water.
- Amount and temperature of air fed.
- The humidity of the fed air.
- Amount of unburned coal based on lab test.

2.1.2 Secondary Data

Secondary data were obtained from the literature related to the evaluation of coal boilers. They consist of the following:

- The heat capacity of the flue gas and air.
- Enthalpy values of steam, feed, and blow-down water.
- Percentage of heat loss due to radiation based on surface and ambient temperature, as well as wind velocity and ABMA chart.

2.2 Data Processing

The steps taken to solve the problems are getting data from the field and through the literature to determine the efficiency of a coal boiler. This is followed by calculating the heat in and out of the system. Furthermore, direct and indirect calculation methods are used to assess the boiler's efficiency by comparing the energy contained in steam to coal and determining heat loss, respectively [24], [25]. The advantage is that each flow's complete material and energy can be determined, making it easier to identify alternatives to increase boiler efficiency based on heat loss information [24], [25].

Two analytical methods in calculating boiler efficiency to determine the factors that affect the value of boiler efficiency are the direct method and the indirect method. These methods are standardized methods in the Performance Test Code 4 (PTC 4) of The American Society of Mechanical Engineers (ASME) [26].

2.2.1 Direct Method

Direct method is a method of assessing boiler efficiency by directly comparing the energy contained in steam compared to the energy contained in coal [24].

In this efficiency study, LHV is used compared to HHV.

$$\text{Boiler efficiency } (\eta) = \frac{\text{Heat output}}{\text{Total heat output}} \text{x}100\% \tag{1}$$

$$\text{Boiler efficiency } (\eta) = \frac{Q_s \text{ x } (H_s - H_f)}{\text{q x LHV}} \text{x}100\% \tag{2}$$

where:
Qs : Amount of steam generated per hour (kg/hour)
Hs : Enthalpy of saturated steam (kcal/kg)
Hf : Enthalpy of feedwater (kcal/kg)
q : Amount of fuel used (kg/hour)
LHV: Low heat value of fuel (kcal/kg)

The advantages of using the direct method are as follows [24]:

- Boiler efficiency can be calculated quickly and accurately enough so that it can be evaluated immediately.
- Relatively few parameters are used to perform calculations.
- Without complicated evaluation instruments.

2.2.2 Indirect Method

The calculation of boiler efficiency can be accomplished by describing the lost energies from various factors. The indirect method in calculating boiler efficiency is done first to find the amount of heat loss that occurs in the boiler. The heat loss consists of dry gas loss, moisture loss, humidity loss, blowdown loss, unburn carbon loss and radiation loss. The lost energy then becomes a deduction from the maximum value of efficiency [24].

This is calculated by subtracting the heat loss-share from 100% as follows:

$$Boiler\ efficiency\ (\eta) = 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6) \tag{3}$$

where the variables L_1, L_2, L_3, L_4, L_5, and L_6 are heat losses with the following details:

L_1 : dry gas loss/dry flue gas
L_2 : moisture loss of water content in the fuel
L_3 : humidity loss of water content in the combustion air.
L_4 : blow-down loss/heat loss in the flow.
L_5 : unburn carbon loss/ in ash.
L_6 : radiation and convection loss by radiation and convection through the boiler surface.

3. RESULTS AND DISCUSSION

3.1 The Efficiency of Coal Boiler 1 and 2 with Direct and Indirect Methods of Low and Medium Rank Types

3.1.1 The efficiency of coal boiler 1 and 2 with direct method of low and medium rank types

Efficiency calculations of coal boilers 1 and 2 are using the direct method conducted from 14 to 28 February 2021, as shown in Table 1. Based on the calculation, it can be concluded that both coal boilers of medium rank have higher efficiency values of 91.84% and 93.09%, while the low-rank coals were 89.70% and 91.84%, respectively.

Table 1. Efficiency of coal boiler 1 and coal boiler 2 with direct method on low rank and medium rank.

Type	Boiler	Q (ton/jam)	Enthalpy (kcal/kg)		Coal consumption (kg/hour)	Boiler efficiency (%)
			Steam	Feed water		
Low Rank	1	208.79	800.68	149.02	39.92	89.70
	2	246.70	807.39	161.07	42.22	91.06
Medium Rank	1	210.71	810.31	149.02	28.10	91.84
	2	216.98	812.06	161.07	26.72	93.09

Boiler efficiency with the direct method is known as the input-output method because it only requires steam (output) and heat fuel (input). The amount of steam produced per hour is directly proportional to the efficiency of the resulting boiler. Coal boilers 1 and 2 are influenced by the amount of steam produced per hour, the enthalpy of saturated steam and feed water, as well as the amount of fuel used, and their net calorific value. Meanwhile, the low heat value of fuel (LHV) is influenced by the high heating value of hydrogen content and moisture. The combustion process will produce higher heat energy assuming the fuel used has a high HHV and vice versa [27], [28].

In conclusion, based on the direct method from the data above, the result of energy efficiency is influenced not only by the calorific value of coal but also by the fuel and steam rates in the boiler. This is due to the fact that the lower the fuel flow rate and the greater the steam rate in the boiler, the higher the efficiency value. The yield of medium-rank coal is higher because of its lower flow rate and increased calorific value above 4200 kcal/kg [19], [29].

3.1.2 The efficiency of coal boiler 1 and 2 with the indirect method of low and medium rank types

The efficiency calculation with the indirect method on coal boilers 1 and 2 is carried out using data from 14 to 28 February 2021, as shown in Table 2. Based on the efficiency calculations in Table 2, it can be concluded that the coal boilers of medium rank type have greater efficiency values of 95.03% and 95.35%, while the low-rank types are 93.39% and 93.81%.

Low and medium-rank coal types have values below 4200 kcal/kg and above 4200 kcal/kg., respectively [19], [29]. It releases difficulty to control the use of coal in the combustion process thereby leading to low quality in level one [30]. Calorific value is the main parameter and plays an important role in the combustion process in the boiler. The higher the calorific value of coal with fewer losses in the combustion process, the greater the efficiency of the boiler. When the coal is used with a fairly low calorific value, it consumes a tremendous amount. Therefore, the coal mixing process is carried out to be economically optimal [30].

The higher the calorific value of coal, the better the combustion process because it can produce a fairly good efficiency. Similar to previous study by Lidija *et al.*, some influences of coal quality to the boiler efficiency were studied [31]. This affects the economic value of the coal and optimizes the calorific value of both medium and low-rank coals, thereby reducing losses and obtaining optimal efficiency. Consequently, the efficiency value of medium-rank coal boilers is higher than the low rank [29], [32].

3.2 Coal Boiler Efficiency by Coal Type

3.2.1 The efficiency of coal boiler 1 with indirect method of low-rank type

Based on the calculations in Table 3, it can be concluded that the efficiency of a coal boiler is very good because limited heat is lost, with a 93.39% value for the low-rank type. The calculation using the indirect method obtains a 100% efficiency reduction with heat, dry gas, moisture, humidity, blow-down, unburnt carbon, and radiation losses. Based on the table above, the highest heat loss value is dry gas loss. Others are still very small hence boiler efficiency does not have much effect. The high value of the dry gas loss is because the greater the exhaust gas temperature, the higher the heat loss. This is due to the limitations of the economizer boiler in absorbing the heat generated from the combustion air. The ash deposit in the economizer area is the main factor that hinders heat transfer from flue gas to the economizer tube, thereby leading to a high value of the dry gas loss.

The efficiency difference between low-rank coal types is also influenced by dry flue gas to fuel mass, flue gas specific heat, flue gas, and air temperatures. This is similar to that previous study on flue gas which calculated heat transfer in the flue of the boiler [33] with its efficiency was tried to be enhanced in other studies [34]. This results in the amount of air supplied to the boiler hence the heat is reduced. The fuel factor expressed in terms of heat loss is in dry exhaust gases due to the formation of water from hydrogen content, fly, and unburned bottom ashes.

Table 2. Efficiency in coal boiler 1 and coal boiler 2 with the indirect method of low rank and medium rank types.

Type	Boiler	Coal consumption (kg/hour)	Dry gas loss (%)	Moisture loss (%)	Humidity loss (%)	Blowdown loss (%)	Unburn carbon loss (%)	Radiation loss (%)	Boiler efficiency (%)
Low Rank	1	39.92	4.57	0.55	1.24	0.002	0.0000186	0.3	93.39
	2	42.22	4.90	0.55	0.49	0.0019	0.0000185	0.3	93.81
Medium Rank	1	28.10	3.65	0.42	0.60	0.0022	0.0014	0.3	95.03
	2	26.72	3.76	0.42	0.17	0.0024	0.0014	0.3	95.35

Table 3. Efficiency in coal boiler 1 with low rank indirect method.

Type	Boiler	Coal consumption (kg/hour)	Dry gas loss (%)	Moisture loss (%)	Humidity loss (%)	Blowdown loss (%)	Unburn carbon loss (%)	Radiation loss (%)	Boiler efficiency (%)
Low Rank	1	39.92	4.57	0.55	1.24	0.002	0.0000186	0.3	93.39

3.2.2 The efficiency of coal boiler 1 with indirect method of medium rank type

Based on the calculations in Table 4, it can be concluded that the coal boiler efficiency value is very good at 95.03% with no much heat lost. Therefore, the highest heat loss effect is caused by the decrease in dry gas in medium-rank coal. This tends to occur due to the dry gas density and the high hydrogen contents of the coal. These losses are also influenced by the blending of each element of coal content in terms of oxygen, moisture, hydrogen, nitrogen, sulfur, and carbon, which are quite low [29].

Deposits on the water side of the tube wall can also reduce efficiency and damage the tube due to overheating [35]. These deposits are caused by high concentrations of suspended and dissolved solids. It also leads to the formation of the foam, causing carryover and heat dissipation, thereby resulting in a decrease in efficiency. Another contributing factor is the water content for hydrogen combustion in the fuel, which contains vapor that only mixes with the flue gases. It will absorb some of the heat generated by combustion in the boiler, reducing the heat used to evaporate the feed water. This is referred to as heat loss due to the combustion of air's water content, which decreases efficiency [36]–[38].

Table 4. Efficiency in coal boiler 1 with low rank indirect method.

Type	Boiler	Coal consumption (kg/hour)	Dry gas loss (%)	Moisture loss (%)	Humidity loss (%)	Blowdown loss (%)	Unburn carbon loss (%)	Radiation loss (%)	Boiler efficiency (%)
Medium Rank	1	28.10	3.65	0.42	0.6	0.0022	0.0014	0.3	95.03

4. CONCLUSION

In conclusion, based on calculations using the direct method, the efficiency values of coal boilers 1 and 2 using medium-rank coal are 91.84% and 93.09% compared to using low-rank coal, which is 89.70% and 91.84%. Meanwhile, with the indirect method, the efficiency values using medium rank greater efficiency values of 95.03% and 95.35% are obtained compared to using low-rank coal, which is 93.39% and 93.81%, respectively. This efficiency difference is influenced by coal calorific value, fuel and steam rates, flue gas, fuel factor, specific heat, and air temperature. The lower the fuel flow rate and the greater the steam rate in the boiler, the higher the efficiency value will be.

For future research and energy audit, general efficiency equation can be modified and other affecting factors can be written as mathematical variables. In this manner, the efficiency equation may better represent real process condition while can also be utilized in other companies, not limited to similar ones. This modified equation can then be used in energy audit simulations to further examine the boiler design and overall process system.

5. RESEARCH LIMITATIONS

Due to the nature of a case study research, this research heavily depends on the real time condition data collection site. In addition, in evaluating the efficiency of boilers within this study, a general energy efficiency equation is used. Nevertheless, primary data used in this study is obtained from real field observations and measurements. Therefore, results within this study are feasible to be used as references in determining production and maintenance schedule in PT. Pupuk Kalimantan Timur and other similar companies. While limited, companies which use coal boiler equipment may also refer to the analysis method used in this study with some adjustments according to respective field data. Therefore, we do also recommend to modify the general efficiency equation for future work and energy audit.

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