Energy Audit on Two 22-TPH Coal-fired Boilers of a Pineapple Processing Plant

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ABSTRACT

The price of coal used by a pineapple processing plant has increased from 3.90 Php/kg in 2018 to 8.60 Php/kg in 2022, thus increasing steam generation costs. This study conducted an energy audit on the two 22-TPH coal-fired boilers of the pineapple processing plant to determine boiler efficiency, quantify sources of heat loss, identify energy conservation measures, and calculate energy and coal savings. The coal-fired boilers investigated were fluidized bed combustion boilers with a reverse osmosis feedwater system. The boiler efficiency was calculated using an indirect method, considering energy losses from sensible heat in refuse and blowdown water. Of the three performance tests conducted, the average boiler efficiency is at 80.655%. The top five sources of heat loss were dry flue gas, hydrogen in coal, moisture in coal, surface radiation and convection, and boiler blowdown. These sources account for 18.322% of the energy input. The identified energy conservation measures include the installation of an automatic oxygen trim control, the installation of an economizer, the installation of a caustic injection system, and the insulation of uninsulated surfaces. These measures have a total potential energy savings of 52,494,974 MJ/yr and coal savings of 2,594,579 kg/yr. While a caustic injection system is not yet installed, setting blowdown TDS to 2,090 ppm can reduce energy consumption by 1,656,496 MJ/yr and coal consumption by 81,873 kg/yr. Using coal with lower hydrogen and moisture content can also reduce energy loss by 6,096,810 MJ/yr per 0.5% reduction in hydrogen content and 6,816,813 MJ/yr per 5% reduction in moisture content.

Keywords: Boiler performance test, energy audit, fluidized bed coal-fired boiler, indirect method efficiency, reverse osmosis

INTRODUCTION

Steam is primarily used in the canning operations of a pineapple processing plant for the thermal processing of its products. Two 22-TPH coal-fired boilers generate steam, with two oil-fired boilers as backup. But the price of coal has been increasing for the past few years. For the coal used by the pineapple processing plant, the price has increased from Php 3.90 per kg last January 2018 to Php 8.60 per kg in January 2022. Its increase in coal prices results in higher operating costs. In this study, an energy audit was conducted on the coal-fired boilers of the pineapple processing plant to determine energy conservation measures. The boilers audited in this study were fluidized bed combustion boilers. Due to process constraints, the steam system involved in this study does not have a condensate recovery system. Less than a year before the study was conducted, reverse osmosis equipment was installed in series with the existing water softeners to reduce boiler blowdown loss.

Several industries conducted energy audits to increase the operating efficiency of steam systems. These energy audits are conducted to identify energy conservation measures that could reduce the energy input or increase the energy output of a steam system. Varying methodologies are used in conducting energy audits. According to Kumar et al. (2018), an energy audit can range from a simple walk-through audit to a more detailed, comprehensive one. In addition to varying methodologies, energy audits can be applied to varying system types. For steam-generating unit audits, applications can be performed on varying boiler types.

Dalgleish and Grobler (2008) conducted a five-day walk-through audit to identify energy conservation opportunities for a pineapple processing facility. Conducting a walk-through energy audit is relatively simple. However, since it only relies on available data during the walk-through, it cannot accurately quantify the different sources of energy loss in the system. A more detailed comprehensive audit for coal-fired boilers was performed by Joshi et al. (2021), Sahai and Kumar (2017), Bora and Nakkeeran (2014), Kumar et al. (2018), Namdev et al. (2016), Gupta et al. (2011). In their studies, the sources of energy losses were quantified, and the indirect method boiler efficiency was determined. In calculating the indirect method boiler efficiency, the sources of energy loss considered by Joshi et al. (2021), Sahai and Kumar (2017), Bora and Nakkeeran (2014), and Kumar et al. (2018) were loss due to dry flue gas, loss due to evaporation of water formed from hydrogen in fuel, loss due to evaporation of moisture in fuel, loss due to moisture present in air, loss due to partial conversion of carbon to CO, loss due to radiation losses, and loss due to unburnt carbon. In addition to these seven sources of energy loss, Namdev et al. (2016) considered the loss from the sensible heat in fly and bottom ash, while Gupta et al. (2011) also considered both losses from the sensible heat in fly and bottom ash and loss due to boiler blowdown.

In addition to the varying methodologies used in energy audits, energy audits were also conducted in varying boiler types. Joshi et al. (2021) performed an energy audit on two 18

TPH traveling grate boilers and one 12 TPH fluidized bed combustion boiler. Sahai and Kumar (2017) determined the efficiency of a 100 TPH fluidized bed combustion boiler. Bora and Nakkeeran (2014) conducted a performance test on a coal-fired stoker boiler, while Kumar et al. (2018) conducted an energy audit on the pulverized coal boiler of a thermal power plant in India. Namdev et al. (2016) also conducted an energy audit on a pulverized coal boiler. Gupta et al. (2011) conducted an efficiency test for a coal-fired stoker boiler of a pulp and paper mill.

Previously conducted detailed energy audits on coal-fired boilers were able to determine the top contributors to the energy loss. Energy conservation measures were determined to increase boiler efficiency based on this information and the operating parameters recorded. In the study of Joshi et al. (2021), the oxygen level in the flue gas of the 12 TPH boiler and Thermax 18 TPH boiler could still be reduced to optimal values. In addition, the discharge flue gas temperature of the Thermax 18 TPH boiler was relatively high. The thermography survey also indicated regions with damaged or absent insulation. With these, the recommendations of Joshi et al. (2021) included reducing the excess air supplied, installing a secondary economizer, and repairing damaged insulation. In the study of Sahai and Kumar (2017), the three sources with the highest heat loss were consistently dry flue gas, hydrogen in fuel, and moisture in fuel. Recommendations from the study included controlling the excess air, preheating the combustion air, and proper fuel selection. According to Bora and Nakkeeran (2014), the source of energy loss with the highest contribution is heat in dry flue gas at 11.36%. With this, boiler efficiency improvements include recovering heat from the exhaust gases and improving the burner controls that manage the fuel-to-air ratio. In the energy audit conducted by Namdev et al. (2016), energy conservation measures identified include maintaining coal particle size within 70 to 74 microns to reduce the 6.1442% unburned carbon loss, continuous monitoring of excess air to reduce the 4.5993% dry flue gas loss, using of primary air from pre-heater to reduce the 1.7918% loss due to moisture of coal, and replacing old insulation to reduce the 1.0014% radiation losses. In the study of Gupta et al. (2011), the highest source of heat loss was combustibles in refuse, which resulted in a percentage loss of 6.03%. One of the recommendations to reduce heat loss from this source was to conduct a sieve analysis of coal once every shift to correct oversized coal fed to the boiler. Regular sampling of the ash for unburnt carbon analysis was also recommended. The second highest source of heat loss was dry flue gas, which resulted in a 5.93% percentage loss. Excess air was at 75%, which could be lowered to 40%–50%. Installation of an oxygen trim control was recommended. Without the oxygen trim control, flue gas analysis was recommended to be conducted every 2 hours to correct the excess air based on the reading. Other energy conservation measures identified were the repair of soot blowers, installation of automatic blowdown control, and proper insulation of boiler surfaces and fittings.

From the above studies, an energy audit determining the indirect method boiler efficiency could effectively identify major contributors to boiler energy loss. Energy conservation measures can be identified from the quantified losses, and energy savings from these measures can then be quantified. Looking at the methodology used by previous studies, only the study of Namdev et al. (2016) and Gupta et al. (2011) considered loss due to sensible heat in the refuse. In addition, only the study of Gupta et al. (2011) considered loss due to blowdown water. Bora and Nakkeeran (2014) indicate that most standards used in calculating boiler efficiency, including IS8753, ASME PTC 4.1, and BS845, do not include loss due to blowdown water in the efficiency calculations. However, for applications with zero to low condensate recovery percentage, like the steam system involved in this study, loss due to blowdown significantly affects the boiler efficiency. In this study, an energy audit that determines the indirect method of boiler efficiency was conducted. In determining the indirect method boiler efficiency, both the losses due to sensible heat in the refuse and due to blowdown water were considered. These losses were accounted for in the study of Gupta et al. (2011). However, in that study, the boiler investigated was stoker-fired. In this study, the boiler that will be investigated is a fluidized bed combustion boiler. Thus, this study's novelty is considering loss due to sensible heat in refuse and loss due to blowdown water in determining the indirect method efficiency of fluidized bed combustion boilers.

This study aims to conduct an energy audit on the two 22-TPH fluidized bed combustion coal-fired boilers of a pineapple processing plant to quantify the sources of energy loss and determine the indirect method boiler efficiency. Energy conservation measures were identified from the quantified sources of energy loss, and the potential energy and coal savings from the identified energy conservation measures were calculated in MJ/year and kg/year, respectively. According to Peña (2011), fluidized bed technology has higher combustion efficiency compared to grate boilers. It asserts the significance of conducting a study that performs a detailed energy audit on fluidized bed boilers. Specifically, the fluidized bed boilers investigated have a reverse osmosis feedwater system. From the study of Kocabas and Savas (2021), installing a reverse osmosis system for the boiler feedwater was one of the improvement suggestions to reduce blowdown loss. It asserts the significance of investigating the efficiency of a steam-generating unit that uses reverse osmosis equipment in its feedwater system. Aside from being used to improve the efficiency of the fluidized bed boilers investigated, the results of this study can also be used as a reference in conducting a detailed energy audit for other fluidized bed boilers. The energy conservation measures identified can be applied to fluidized bed boilers with similar operating conditions, especially those used in industrial steam systems with zero to low condensate recovery due to process constraints. In addition, the results of this study could be used as a reference on the degree of heat loss due to blowdown water on steam-generating units with zero to low condensate recovery if a reverse osmosis feedwater system is used.

MATERIALS AND METHODS

Performance Test

Performance tests were conducted to determine the boiler efficiency and quantify the sources of energy loss. The sources of energy loss considered in this study are unburned carbon in refuse, heat in the dry flue gas, moisture in coal, moisture from burning of hydrogen in coal, moisture from air supplied, formation of carbon monoxide, sensible heat in refuse, surface radiation and convection, and boiler blowdown. Since the operating parameters of the two 22-TPH coal-fired boilers are the same, the performance tests were only conducted on one boiler—for this study, coal-fired boiler 2. The results of the performance tests and the identified energy conservation measures, including the quantified energy conserved per year for each measure, were treated as applicable to coal-fired boilers 1 and 2. The performance tests were performed at three trials, each for 4 hours. Table 1 presents the data collected for each performance test, the frequency of data collection and the instrument or method used to collect the data. The ultimate analysis of the coal used was conducted by a testing laboratory based on ASTM D4239-18e1 (Method A), ASTM D5373-16, and ASTM D3176-15 (by difference). In determining the heat loss due to surface radiation and convection, the steam generating system was divided into sections and measurement points for each section were pre-determined. The uninsulated surfaces of the steam generating system were also determined prior to the performance test and were considered separate sections from the insulated portions. The equipment manual and as-built drawings determined data on surface areas and fan efficiencies needed to complete the calculations.

Table 1

Performance test data collection plan

Data	Frequency	Instrument / Method
Feedwater temperature	Every 15 minutes	Nutech Engineers RTD
Total dissolved solids (TDS)	Every 15 minutes	Myron L Company DS meter
Total feedwater supplied	Every Hour	Rosemount flow transmitter integrated with FactoryTalk View Site Edition Version 10
Steam pressure	Every 15 minutes	Baumer pressure gauge
Total coal input	Every Hour	Rotary feeder integrated with FactoryTalk View Site Edition Version 10
Heating value of coal	Start, Middle, End	CAL3K-A oxygen bomb calorimeter
The total mass of refuse	Every Hour	Adam CPWplus-150 weighing scale
Temperature of refuse	Every Hour	FLUKE TiS60+ thermal imager
Proximate analysis	Start, Middle, End	Navas Instruments TGA-2000A
Flue gas temperature	Every 15 minutes	Nutech Engineers RTD
Flue gas analysis	Every 15 minutes	ecom J2KN pro portable emission analyzer
Air supply DBT and RH	Every 15 minutes	Extech Instruments EN300 environmental meter
Power consumption of fans	Every Hour	FLUKE-435-II three-phase power quality analyzer

The performance tests were conducted during the operation of the pineapple processing plant. Thus, the steam load of the boiler during the tests depended on the facility's operation. The tests were conducted after the meal break of the canning operations to minimize load fluctuation during the test period.

Calculation of Heat Losses and Boiler Efficiency

The calculation procedures in the Steam Generating Units Power Test Codes of The American Society of Mechanical Engineers (1965) were used to determine the heat loss due to unburned carbon in refuse, heat in the dry flue gas, moisture in coal, moisture from burning of hydrogen in coal, moisture from air supplied, formation of carbon monoxide, and sensible heat in refuse. The Fired Steam Generators Performance Test Codes of The American Society of Mechanical Engineers (2009) calculation procedures were used to determine the heat loss due to surface radiation and convection. The heat loss due to unburned carbon in the refuse per kg of coal burned L_1 was obtained using Equation 1 from the kg of carbon in the refuse per kg of coal burned C_{refuse}.

$$L_1 = C_{refuse} \times 33,820 \tag{1}$$

The heat loss due to heat in the dry flue gas per kg of coal burned L_2 was obtained using Equation 2 from the mass of dry flue gas per kg of coal m_{dry}, mean specific heat of the dry flue gas $c_{p(dry)}$, and the difference between the discharge flue gas temperature T_f and air supply dry bulb temperature T_a.

$$L_2 = m_{dry} \times c_{p(dry)} \times (T_f - T_a) \tag{2}$$

The heat loss due to moisture in coal per kg of coal burned L_3 was calculated through Equation 3 using the percent moisture in coal $m_{w(coal)}$ from the coal proximate analysis, enthalpy of the water vapor in flue gas $h_{w(flue)}$, and enthalpy of saturated liquid at ambient conditions $h_{amb(liq)}$.

$$L_3 = m_{w(coal)} \times (h_{w(flue)} - h_{amb(liq)}) \tag{3}$$

The heat loss due to moisture from burning of hydrogen in coal per kg of coal burned L_4 and the heat loss due to moisture from air supplied per kg of coal burned L_5 were calculated using the percent hydrogen in coal H, kg of moisture per kg of dry air supplied $m_{w(a)}$, and kg of dry air supplied per kg of coal m_a. Equations 4 and 5 are used to calculate L_4 and L_5, respectively. $h_{amb(vap)}$ is the enthalpy of saturated vapor in ambient conditions.

$$L_4 = 8.936 \times H \times (h_{w(flue)} - h_{amb(liq)}) \tag{4}$$

$$L_5 = m_{w(a)} \times m_a \times (h_{w(flue)} - h_{amb(vap)}) \tag{5}$$

The heat loss due to the formation of carbon monoxide per kg of coal burned L_6 was determined through Equation 6 using the percent carbon monoxide in the flue gas CO, percent carbon dioxide in the flue gas CO_2, and the kg carbon burned per kg of coal C_b.

$$L_6 = \frac{CO}{CO_2 + CO} \times 23{,}516 \times C_b \qquad [6]$$

The heat loss due to sensible heat in refuse per kg of coal burned L_7 was calculated through Equation 7 using the specific heat of refuse $c_{refuse(A)}$, kg of refuse collected per kg of coal burned Ref_A and the difference between the refuse temperature $T_{refuse(A)}$ and ambient temperature T_a.

$$L_7 = \sum_{\text{All Collection Points}} c_{refuse\,(A)} \times (T_{refuse\,(A)} - T_a) \times Ref_A \qquad [7]$$

The heat loss due to surface radiation and convection per kg of coal burned L_8 was obtained through Equation 9 using the total heat transfer rate from all surfaces $\dot{Q}_{surf}$ and the average coal firing rate $\dot{m}_{coal}$. $\dot{Q}_{surf}$ is the sum of all heat transfer rates from a surface $\dot{Q}_{surf\,(S)}$, calculated using Equation 8. $H_{c(S)}$ is the convection heat transfer coefficient, $H_{r(S)}$ is the radiation heat transfer coefficient, A_s is the surface area, T_s is the surface temperature, and $T_{s(a)}$ is the average ambient air temperature within 2ft-5ft from the surface.

$$\dot{Q}_{surf\,(S)} = \frac{0.293}{1000}(H_{c(S)} + H_{r(S)})A_S(T_S - T_{S(a)}) \qquad [8]$$

$$L_8 = \frac{\dot{Q}_{surf}}{\dot{m}_{coal}} \qquad [9]$$

The heat loss due to blowdown per kg of coal burned L_9 was calculated through Equation 10 using the total mass of blowdown discharged $m_{tot(BD)}$, total mass of coal supplied $m_{tot(coal)}$, and the difference between the blowdown enthalpy h_{BD} and feedwater enthalpy h_{FW}.

$$L_9 = \frac{m_{tot\,(BD)} \times (h_{BD} - h_{FW})}{m_{tot\,(coal\,)}} \qquad [10]$$

After obtaining L_1 to L_9, the percent heat loss $L_{1(\%)}$ to $L_{9(\%)}$, which quantifies the portion of the heat input lost due to the corresponding source of heat loss, was then obtained using Equation 11. HHV_{coal} is the higher heating value of the coal used, and B is the energy from heat credits per kg of coal burned.

$$L_{n(\%)} = \frac{L_n}{HHV_{coal} + B} \times 100\% \qquad [11]$$

The indirect method boiler efficiency η_{Boiler} was then calculated using Equation 12 from $L_{1(\%)}$ to $L_{9(\%)}$.

$$\eta_{Boiler} = 100\% - L_{1(\%)} - L_{2(\%)} - L_{3(\%)} - L_{4(\%)} - L_{5(\%)} - L_{6(\%)} - L_{7(\%)} - L_{8(\%)}$$

$$- L_{9(\%)} \tag{12}$$

The boiler efficiency, percent heat losses, and significant operating parameters were determined for each trial. The average boiler efficiency, average percent heat losses, and average operating parameters were then calculated. These average values were used to identify steam energy conservation measures and quantify the potential energy and coal savings from the identified measures. This study did not conduct further experiments to determine actual energy and coal savings from the identified conservation measures.

RESULTS AND DISCUSSION

Boiler Efficiency and Heat Losses

The average boiler efficiency obtained from the three performance tests was 80.655%. The total heat loss is at 19.345%. Figure 1 presents the percentage contribution of each source to the total heat loss. The % heat loss quantifies the portion of the total energy input lost due to the corresponding source. The % total loss quantifies the portion of the total heat loss due to the corresponding source.

The highest percentage loss is due to the heat in the dry flue gas. It consumes 10.266% of the energy input and 53.071% of the total heat loss. From Equation 2, this source of heat loss increases as the mass of dry flue gas per kg of coal and flue gas discharge temperature increase. Since the mass of dry flue gas per kg of coal increases as the amount of air supplied per kg of coal increases, an increase in the excess air supplied to the boilers increases the heat loss due to heat in the dry flue gas.

The heat loss due to moisture from burning hydrogen in coal is 3.337%, 17.25% of the total heat loss. The heat loss due to moisture in coal is at 3.126%, which is 16.161% of the total heat loss. From Equations 3 and 4, these heat losses are directly proportional to the percent hydrogen in coal and the percent moisture in coal.

The fourth major contributor to the reduction in the efficiency of the steam-generating unit is the heat loss from surface radiation and convection. This source reduces efficiency by 0.892%, 4.613% of the total heat loss. From Equation 8, the heat loss from this source is significantly increased by an increase in the surface temperature.

After the heat loss from surface radiation and convection, boiler blowdown water is the source with the next highest heat loss. The heat loss from this source accounts for 0.701% of the energy input, which is 3.624% of the total heat loss. From Equation 10, the heat loss due to the blowdown is dependent on the total mass of the blowdown discharged. According to Harrell (2004), the mass of the blowdown discharged is proportional to the ratio between the feedwater TDS and the blowdown water TDS.
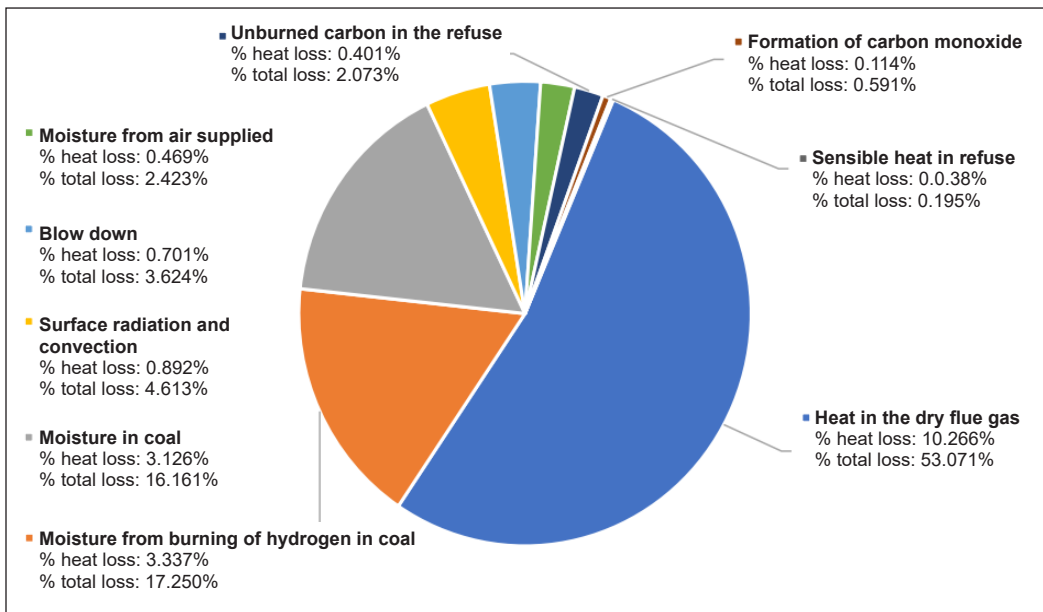
Figure 1. Percentage contribution of sources of heat loss

The heat loss due to moisture from the air supplied reduces the steam generating efficiency by 0.469%, which is 2.423% of the total heat loss. From Equation 5, the heat loss due to moisture from air supplied increases as the kg of moisture per kg of dry air supplied increases. The amount of moisture per kg of dry air supplied depends on the dry bulb temperature and relative humidity of the air supplied. In addition, heat loss due to moisture from the air supplied also increases as the air supplied per kg of coal increases. Thus, heat loss due to moisture increases as the excess air supplied to the boilers increases.

The heat loss due to unburned carbon in the refuse is 0.401%, 2.073% of the total heat loss. The heat loss due to the formation of carbon monoxide is 0.114%, which is 0.591% of the total heat loss. From equations 1 and 6, the heat loss due to these sources is calculated from the amount of carbon in the refuse per kg of coal burned and the percent carbon monoxide in the flue gas analysis. The source with the lowest heat loss is the sensible heat in refuse. The heat loss due to sensible heat in refuse is at 0.038%, which is 0.195% of the total heat loss.

Table 2 presents the identified operating parameters which significantly affect the sources of heat loss. Table 2 also gives the average values of these parameters during the three performance tests conducted.

Comparison of Results with Other Studies

Table 3 compares this study's results to previous studies using indirect method boiler efficiency. From the table, the source with the highest heat loss is heat in the dry flue

gas, except for the study of Namdev et al. (2016) and Gupta et al. (2011). UNIDO (2016) asserts that energy loss from dry flue gas almost always accounts for the highest energy loss in steam generation. Both in the study of Namdev et al. (2016) and Gupta et al. (2011), the factor identified that significantly affected the high loss due to unburned carbon is the size of the coal fed to the boiler. Table 3 also shows that the energy loss due to unburned carbon is less on fluidized bed boilers compared to the other types of boilers. Peña (2011) asserts that fluidized bed technology has higher combustion efficiency compared to grate boilers.

Comparing the results of this study with the fluidized bed boilers investigated by Joshi et al. (2021) and Sahai and Kumar (2017), for all three fluidized bed boilers, the three sources with the highest contribution

Table 2

Average values of significant operating parameters

Parameter	Unit	Average
Flue gas discharge temperature	°C	169.4313
Flue gas % oxygen	%	9.4908
Excess air percentage	%	89.915
Coal % hydrogen	%	2.8183
Coal % moisture	%	23.593
Average temperature of insulated surfaces	°F	118.72
The average temperature of uninsulated surfaces	°F	247.25
TDS of feedwater	ppm	81.2941
TDS of blowdown water	ppm	1610.784
Feedwater temperature	°C	94.09
Steam pressure	kg/cm²	10.7530
Ambient dry bulb temperature	°C	33.2049
Ambient relative humidity	%	76.1657
kg of carbon in the refuse per kg of coal burned	kg/kg	0.00241
Flue gas % carbon monoxide	%	0.0158

to the energy loss are the heat in the dry flue gas, moisture from burning hydrogen in coal, and moisture in coal. Looking at the heat loss due to the dry flue gas, the percent loss from this source obtained in this study was less than both boilers investigated by Joshi et al. (2021) and Sahai and Kumar (2017). The excess air of the boilers investigated in this study is significantly less at 89.92% compared to the excess air of the boiler investigated by Joshi et al. (2021) at 208.82%. For the boiler investigated by Sahai and Kumar (2017), the excess air was lower at an average of 41.48%, but the flue gas discharge temperature was higher at an average of 173.8°C. The higher heating value of the coal was significantly less at 13,464.11 kJ/kg versus the coal used in this study at 20,139.26 kJ/kg.

From Equation 11, the percent heat loss increases as the higher heating value decreases, resulting in a high percent heat loss due to heat in the dry flue gas in the study of Sahai and Kumar (2017). Looking at the heat loss due to moisture from burning hydrogen in coal, the percent loss from this source obtained in this study was also less than the boilers investigated by Joshi et al. (2021) and Sahai and Kumar (2017). It could be explained by the lower hydrogen content of the coal used in this study at 2.82%, compared to the hydrogen content of the coal used by Joshi et al. (2021) at 3.28% and Sahai and Kumar (2017) at 5.24%. Looking at the heat loss due to moisture in coal, the percent loss obtained

Table 3
Comparison with other studies which used indirect method boiler efficiency

|	Boiler Type	$L_{1(\%)}$	$L_{2(\%)}$	$L_{3(\%)}$	$L_{4(\%)}$	$L_{5(\%)}$	$L_{6(\%)}$	$L_{7(\%)}$	$L_{8(\%)}$	$L_{9(\%)}$	η_{Boiler}
This Study	Fluidized Bed	0.401	10.266	3.126	3.337	0.469	0.114	0.038	0.892	0.701	80.655
Joshi et al., 2021 (12 TPH Thermax)	Fluidized Bed	0.710	11.820	1.770	4.200	0.930	1.110	-	0.650	-	78.820
Sahai & Kumar, 2017	Fluidized Bed	1.848	12.932	2.000	9.424	0.637	0.293	-	0.321	-	72.456
Joshi et al., 2021 (18 TPH Thermax)	Traveling Grate	2.700	8.300	2.330	3.750	0.380	0.790	-	1.260	-	80.480
Joshi et al., 2021 (18 TPH ISGEC)	Traveling Grate	2.510	5.880	1.230	4.350	0.270	0.360	-	1.010	-	84.310
Bora & Nakkeeran, 2014	Stoker Fired	3.060	11.360	2.530	5.390	0.360	0.040	-	0.430	-	76.830
Gupta et al., 2011	Stoker Fired	6.030	5.930	1.140	3.770	0.255	0.079	0.410	0.700	0.700	80.980
Kumar et al., 2018	Pulverized Coal	3.610	6.873	3.410	5.250	0.280	1.420	-	0.397	-	77.720
Namdev et al., 2016	Pulverized Coal	6.144	4.599	1.792	2.875	0.116	0.271	0.469	1.001	-	82.730
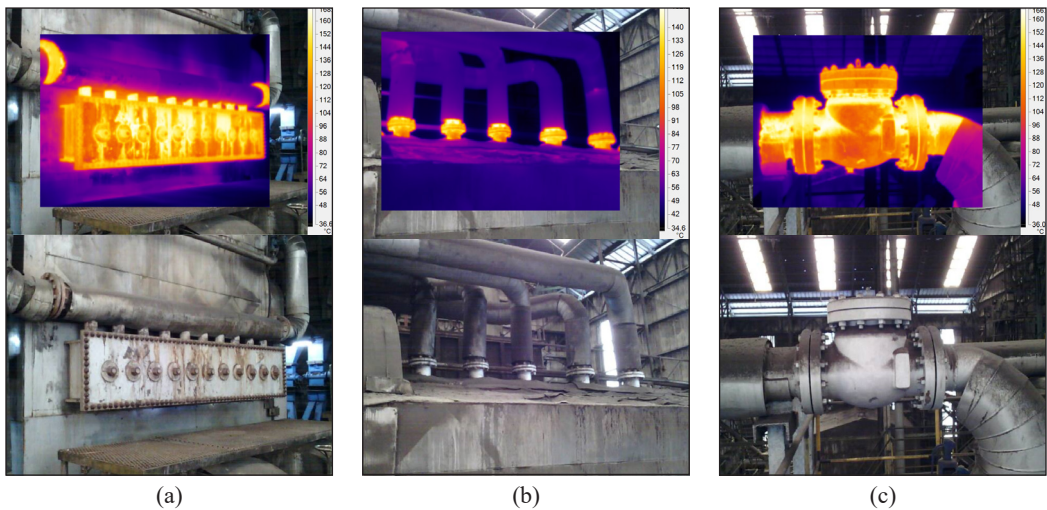
Figure 2. Thermal image of sample uninsulated surfaces: (a) Uninsulated inbed header at the riser side; (b) uninsulated row of flanges; and (c) uninsulated check valve

in this study was higher than both boilers investigated by Joshi et al. (2021) and Sahai and Kumar (2017). This source of heat loss is highly dependent on the moisture content of the coal. It is asserted by the significantly higher moisture content of the fuel used in this study at 23.593% compared to the moisture content of the coal used in the study by Sahai and Kumar (2017) at 9.88%. Comparing the efficiencies of the three fluidized bed boilers, the efficiency of the boiler audited in this study is higher than that of the other two. It could be explained by the significantly higher excess air in the study of Joshi et al. (2021) and the significantly lower heating value of the coal in the study of Sahai and Kumar (2017). The hydrogen content of the coal used in the studies of Joshi et al. (2021) and Sahai and Kumar (2017) was also higher than the coal used in the boiler investigated in this study.

Significant Operating Parameters

Heat in the dry flue gas was the source with the highest heat loss per kg of coal burned. The operating parameters obtained in the performance tests showed that the average excess air supplied to the boiler was 89.915%. It is significantly higher than the recommended excess air for fluidized bed boilers, according to Agrawal and Dubey (2016), which is 20%–25%. As a result, the oxygen percentage in the flue gas is also significantly high at an average value of 9.49% vs the standard value of 4%–4.5%. This deviation from the standard excess air and percent oxygen values was also observed by Joshi et al. (2021), Bora and Nakkeeran (2014), and Gupta et al. (2011) in the steam-generating units they investigated. In addition, the average temperature of the discharged flue gas was 169.43°C, which is higher than the ideal temperature of 148.89°C for coal-fired boilers, according to the Advanced Manufacturing Office (2012) of the U.S. Department of Energy. High flue

gas temperature was also recorded in the steam-generating units investigated by Joshi et al. (2021) and Bora and Nakkeeran (2014).

The second and third sources with the highest percent loss are the moisture from burning hydrogen in coal and the moisture in coal, respectively. From the performance test results, the average percent hydrogen of the coal supplied is 2.8183%, and the average percent moisture is 23.593%. Similar results were obtained in the fluidized bed boilers that Joshi et al. (2021) and Sahai and Kumar (2017) investigated. Following the heat loss due to heat in the dry flue gas, moisture from burning hydrogen in coal was the second highest source of heat loss. Moisture in coal, on the other hand, was the third-highest source of heat loss.

Heat loss from surface radiation and convection accounts for 4.613% of the total heat loss. From the conducted energy audit, 33.495m² of the steam generating unit's surface is uninsulated. From the performance tests, these uninsulated surfaces incur heat loss at an average rate of 32.64kW, contributing to 28.6% of the heat loss from surface radiation and convection. The surface temperature on these uninsulated surfaces reaches 140.78°C to 335.18°C. Figure 2 shows thermal images of sample uninsulated surfaces. Uninsulated boiler surfaces were also observed in the units that Joshi et al. (2021) and Gupta et al. (2011) investigated.

Heat loss from boiler blowdown water accounts for 3.624% of the total heat loss. Less than a year before the performance tests were conducted, a reverse osmosis system was installed in series with the existing water softeners to further treat the boiler feedwater. Before the reverse osmosis system was installed, the water softeners solely performed feedwater treatment, and the TDS output of these softeners was 280 ppm. The boiler water TDS was maintained at 2,500 ppm to prevent rapid scale build-up. Since the reverse osmosis system can reduce the feedwater TDS to 30 ppm, the supplier recommended setting the boiler water TDS so that a maximum of 50 cycles of concentration (COC) is used. It ensures that the maximum silica concentration is not exceeded in the boiler. It explains the low TDS of the blowdown during the performance tests at an average of 1,610.784 ppm. However, during the reverse osmosis system's operation, the feedwater's pH decreased to 5, versus the minimum pH requirement of 8.5. With this, reverse osmosis water was mixed with soft water not treated by the reverse osmosis system to satisfy the minimum pH requirement, resulting in the increase of the feedwater TDS from the system capacity of 30 ppm to an average of 81.2941 ppm in the performance tests. With the parameters obtained, the actual cycle of concentration is only at 19.81 COC. At this cycle of concentration, both the boiler silica and TDS are below the maximum concentration, indicating excessive boiler blowdown. Excessive blowdown was also highlighted in the study of Gupta et al. (2011).

The heat loss due to moisture from the air supply accounts for 2.423% of the total heat loss. The same with the heat loss due to heat in the dry flue gas, the heat loss due to moisture from the air supplied increases as the excess air supplied to the steam generating

unit increases. From the results of Joshi et al. (2021), heat loss due to moisture from the air supplied was 0.27% for the boiler with the lowest excess air percentage and 0.93% for the boiler with the highest excess air percentage.

The heat loss due to unburned carbon in the refuse and the formation of carbon monoxide is related to the steam-generating unit's combustion efficiency. The heat loss due to unburned carbon in the refuse and the heat loss due to the formation of carbon monoxide accounts for 2.073% and 0.591% of the total heat loss, respectively. The significantly low heat loss from these sources asserts Peña (2011) and Agrawal and Dubey (2016) that fluidized bed boilers have high combustion efficiency.

Energy Conservation Measures

An automatic oxygen trim control can be installed to control the excess air supplied and reduce the heat loss from heat in the dry flue gas. Joshi et al. (2021) and Gupta et al. (2011) also recommended this in their studies. An oxygen sensor installed at the flue gas duct will control the opening of the forced draft fan dampers to ensure that excess air supplied to the boiler is within 20%–25%. Reducing the excess air from the current average of 89.915% to an average of 22.5% reduces heat loss due to heat in the dry flue gas from 2,075.848 kJ/kg to 1,356.586 kJ/kg. In addition, it reduces heat loss due to moisture from air supplied from 94.8 kJ/kg to 61.326 kJ/kg. These reductions in heat loss per kg of coal translate to a 3.72% increase in boiler efficiency. With an average annual coal consumption of 41,360,043.33 kg, the oxygen trim control has a potential energy savings of 36,895,557.88 MJ/year, translating to a potential reduction in coal consumption of 1,823,573.56 kg/year.

The other factor contributing to the high heat loss due to heat in the dry flue gas is the high temperature of the discharged flue gas. An economizer can be installed after the dust collector, using excess heat to preheat the feedwater. Joshi et al. (2021) and Bora and Nakkeeran (2014) also identified this heat recovery system in their studies. Reducing the flue gas temperature from the current average of 169.43°C to 148.89°C reduces the heat loss from the current 2,075.85 kJ/kg to 1,763.083 kJ/kg. It translates to a 1.55% increase in boiler efficiency. It has a potential energy savings of 15,735,698.41 MJ/year, translating to a potential reduction in coal consumption of 777,741.42 kg/year.

Suppose both the automatic oxygen trim control and economizer are installed. In that case, the excess air will be reduced to an average of 22.5%, and the flue gas discharge temperature will be reduced to 148.89°C. These can potentially reduce boiler heat loss by 966.655 kJ/kg, translating to a 4.78% increase in boiler efficiency. These installations have a potential energy savings of 46,794,288.01 MJ/year, which translates to a potential reduction in coal consumption of 2,312,821.15 kg/year.

Heat loss is due to moisture from burning hydrogen in coal, and moisture in coal is dependent on the properties of the coal supplied. Thus, the heat loss from these sources can

only be reduced by changing the coal supply. For every 0.5% reduction in the hydrogen content of the coal supply, heat loss is reduced by 119.775 kJ/kg. It translates to a potential energy savings of 6,096,809.76MJ/year and a potential reduction in coal consumption of 301,336.58 kg/year. For every 5% reduction in the moisture content of the coal supply, heat loss is reduced by 134.036 kJ/kg. This potential is 6,816,812.51MJ/year in energy savings and 336,922.92 kg/year in coal consumption. The importance of the properties of the coal supplied to the boilers was asserted by the comparison of the results of this study with the results of Joshi et al. (2021) and Sahai and Kumar (2017). Percent loss due to hydrogen in coal in this study was lesser since the hydrogen content of the coal used was also lesser, and the percent heat loss due to moisture in coal in this study was higher compared to that of Sahai and Kumar (2017) since the moisture content of the coal used was also significantly higher.

The fourth source with the highest heat loss is surface radiation and convection. If uninsulated surfaces were insulated, the surface temperature would be reduced. This reduction in surface temperature reduces the heat loss due to the uninsulated surfaces from 32.64 kW to 7.257 kW. It will reduce the heat loss due to surface radiation and convection by 40.138 kJ/kg, translating to a 0.20% increase in boiler efficiency. This potential is 2,053,057.45 MJ/year in energy savings and 101,472.96 kg/year in coal consumption. Joshi et al. (2021) and Gupta et al. (2011) identified the same findings and recommendations in their studies.

To decrease the heat loss due to blowdown, the blowdown water TDS can be increased to 2,090 ppm. This TDS setting ensures the boiler does not exceed the maximum silica concentration. Setting the blowdown water TDS to 2,090 ppm increases the cycles of concentration to 25.71 COC, which would then reduce the total blowdown discharged by 22.85%. Heat loss due to blowdown will reduce from 141.745 kJ/kg to 109.376 kJ/kg, translating to a 0.16% increase in boiler efficiency. It has a potential energy savings of 1,656,496.30 MJ/year, which translates to a potential reduction in coal consumption of 81,872.81 kg/year. This energy conservation measure does not require investment since only the setting of the blowdown water TDS will be adjusted.

To fully utilize the capacity of the reverse osmosis system to reduce feedwater TDS to 30 ppm, a caustic injection system can be installed to increase the feedwater pH from 5 to 8.5 minimum requirement. To ensure that the boiler's maximum silica concentration is not exceeded, the blowdown water TDS will then be set to 1,500 ppm. It increases the cycles of concentration to 50 COC, which would reduce the total blowdown discharged by 60.33%. Heat loss due to blowdown will reduce from 141.745 kJ/kg to 56.239 kJ/kg, translating to a 0.42% increase in boiler efficiency. It has a potential energy savings of 4,361,534.33 MJ/year, which translates to a potential reduction in coal consumption of 215,570.09kg/year. The blowdown water TDS should be set to 1,500 ppm in this identified

energy conservation measure. It means that the previous energy conservation measure of setting the blowdown water TDS to 2,090 ppm can be implemented while a caustic injection system has not yet been installed.

Figures 3 and 4 summarize the identified energy conservation measures, the heat loss reduction from these conservation measures, and the corresponding energy and coal savings. Installing an automatic oxygen trim control, economizer, caustic injection system,
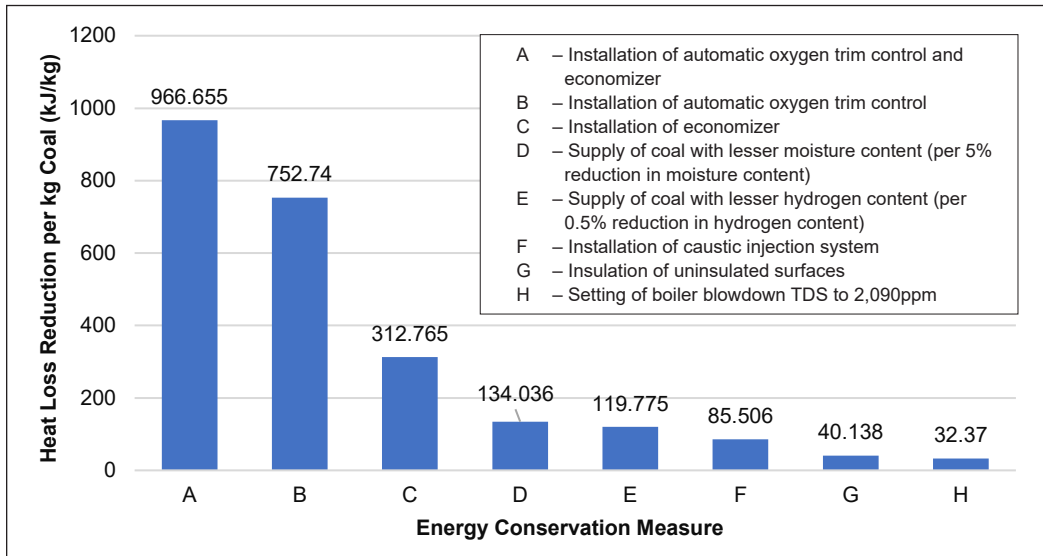

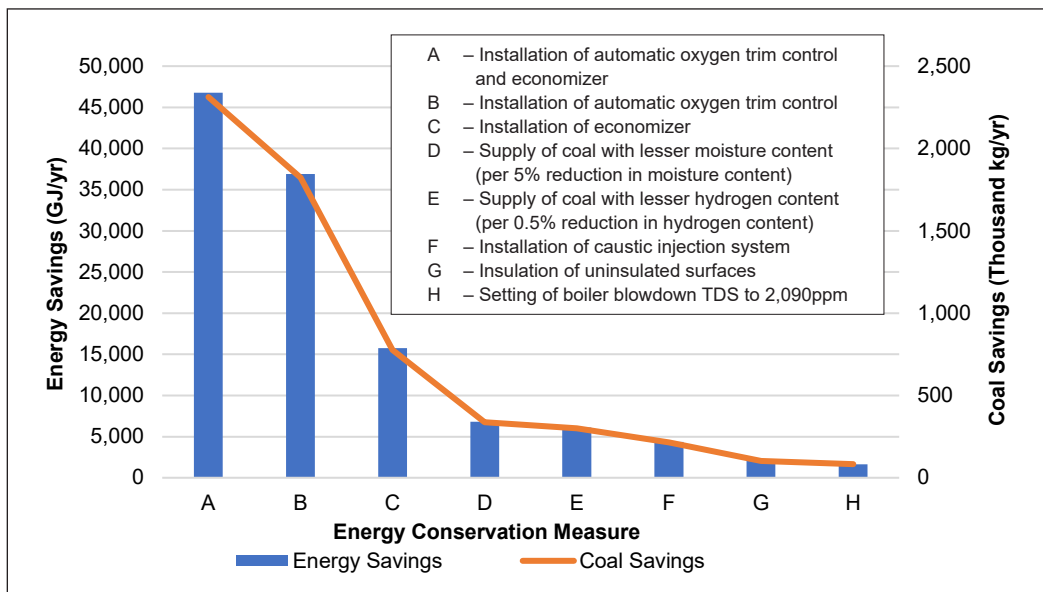*Figure 3*. Heat loss reduction of identified energy conservation measures

Figure 4. Energy and coal savings of identified energy conservation measures

and insulating uninsulated surfaces can reduce heat loss by 1,092.299 kJ/kg and increase boiler efficiency by 5.4%. It equals a total potential energy savings of 52,494,973.74 MJ/yr and coal savings of 2,594,579.18 kg/yr. Using coal supply with lesser hydrogen content results in a reduction in heat loss by 119.775 kJ/kg per 0.5% reduction in hydrogen content, while using coal supply with lesser moisture content results in a reduction in heat loss by 134.036 kJ/kg per 5% reduction in moisture content.

CONCLUSION AND RECOMMENDATIONS

From the performance tests, the average efficiency of the 22-TPH coal-fired boilers is 80.655%. The top five sources of heat loss are heat in the dry flue gas, moisture from burning hydrogen in coal, moisture in coal, surface radiation and convection, and boiler blowdown. These sources account for 18.322% of the energy input to the boilers.

The identified energy conservation measures include the installation of an automatic oxygen trim control, the installation of an economizer, the installation of a caustic injection system, and the insulation of uninsulated surfaces. These measures have a total potential energy savings of 52,494,974 MJ/yr and coal savings of 2,594,579 kg/yr. While a caustic injection system is not yet installed, setting blowdown TDS to 2,090ppm can reduce energy consumption by 1,656,496 MJ/yr and coal consumption by 81,873 kg/yr. Using coal with lower hydrogen and moisture content can also reduce energy loss. For each 0.5% reduction in hydrogen content, heat loss and coal consumption are reduced by 6,096,810 MJ/year and 301,337 kg/year, respectively. For each 5% reduction in moisture content, heat loss and coal consumption are reduced by 6,816,813 MJ/year and 336,923 kg/year, respectively.

Further study on the effect of decreasing the excess air on combustion efficiency can be conducted, and factors affecting the combustion efficiency can be further analyzed. With these, the ideal setting of the boiler operating parameters can then be determined to optimize combustion efficiency at the ideal excess air supply. In addition, fuel switching can also be investigated to consider alternate fuels. Energy analysis can then be conducted to determine efficiency and emission performance using identified alternate fuels (Arromdee & Kuprianov, 2021; Campli et al., 2021; Channapattana et al., 2023; Shi et al., 2020; Srinidhi et al., 2019).

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