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EFFECT OF COMBUSTIBLE CONTENT IN COAL ASH REFUSE ON THE EFFICIENCY OF THERMAL OIL HEATER SYSTEM

PENGARUH KANDUNGAN MAMPU BAKAR DALAM BUANGAN ABU TERHADAP EFISIENSI SISTEM PEMINDAH PANAS OLI

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ABSTRACT

This paper provides an analysis on the effect of combustible content in coal ash refuse the efficiency towards combustion and heat thermal oil heater system in a coal furnace that had been studied. The study investigated the discrepancy of the actual performance of the heater compared to that as stated in the design specification. The study assumed that coal type and operational problem were the cause of deviation. Both affect combustion efficiency and the amount of reactive materials within coal ash refuse. Combustible content within the coal ash refuse was the used as the source data. Using indirect method, the amount of losses can be determined from the amount of combustibles in the coal ash refuse. The work involved measuring the temperature of oil and flue gas, analyzing the ash content and calculating the losses based on two sets of operational data. System efficiency and heat exchanger rating were calculated by reducing the amount of total losses from the full design capacity. If the reactive composition within the coal ash in combustible content, the amount of coal consumption is higher in order to attain the heat desired capacity for heating. Such a contition is caused by decreasing the energy capacity and reducing the furnace effectiveness.

Keywords: coal characteristics, combustibles in ash, combustion efficiency, indirect method

SARI

*Makalah ini berisi analisis tentang pengaruh kandungan zat mampu bakar dalam abu batubara terhadap efektivitas sistem pemanas minyak bakar (*thermal oil heater*) yang menggunakan tungku batubara. Tujuan studi adalah mencari penyebab dari perbedaan unjuk kerja sistem pemanas saat dioperasikan dengan unjuk kerja yang dinyatakan dalam dokumen spesifikasi alat. Diasumsikan bahwa jenis batubara yang digunakan dan masalah operasional menjadi penyebab adanya deviasi tersebut. Jenis batubara yang digunakan dan operasional sistem dapat mempengaruhi efisiensi pembakaran batubara dan jumlah zat aktif yang terbawa buangan abu. Untuk itu, kandungan mampu bakar di dalam buangan abu digunakan sebagai sumber data untuk kegiatan analisis. Dengan metode tidak langsung, dapat ditentukan jumlah kehilangan zat mampu bakar dalam abu tersebut. Kajian meliputi pengukuran suhu minyak bakar dan gas buang, analisis abu serta perhitungan kehilangan dari dua set hasil analisis abu. Efisiensi serta peringkat sistem pemanas dihitung dengan mengurangi jumlah kehilangan yang tercantum dalam kapasitas disain. Hasil studi menunjukkan perbedaan persentase kandungan bahan reaktif dalam abu dapat menyebabkan perbedaan dalam jumlah pemakaian batubara. Jika kandungan reaktif dalam abu batubara tinggi maka konsumsi batubara yang akan diperlukan juga lebih tinggi untuk menghasilkan jumlah panas yang diperlukan untuk pemanasan oli. Hal ini disebabkan berkurangnya ketersediaan energi atau turunnya efektifitas tungku.*

Kata kunci: karakter batubara, kandungan mampu bakar abu, efektifitas pembakaran, metode tidak langsung

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INTRODUCTION

In thermal systems using coal fuel, the actual performance of a built system may not be in accordance to the design specification. Deviation in performace can occur which creates dissatisfaction to the operators. By ruling out design flaw, the discrepancy in the performance is normally caused by the type of coal used and operational problems. The quality of coal could differ from time to time and it is possible that the coal used is not suitable for the system. Operational problems such as irregularity in the air flow could affect combustion efficiency. The effect of these two factors can be determined by computational analysis using the content of disposed ash. This work is aimed to evaluate the actual performance of a thermal oil system compared to the design specification by calculating the amount of losses from the amount of combustibles carried over in the refuse.

Ash, produced from coal combustion contains unburned carbon as a result of coal property, furnace type, combustion residence time and operating conditions. Operating conditions include the burners adjustment, amount of excess air, and mixing method. The amount of unburned hydrocarbon, mainly char, can vary from 5 to 30 %. This variation will affect the combustion efficiency and the amount of heat generated in the furnace. The interaction between furnace design and coal properties and the amount of carbon loss was studied in 1940 by Hottel and Stewert (Sathyanathan, 2011). In a pulverized coal furnace, 80 % of ash goes to in fly ash, while 20 % is collected in bottom ash.

Effect of coal quality on boiler or heater performance has been studied over the years since the use of lower grade coal than that of the recommended design will cause problems. The coal quality is determined mainly by carbon and ash content, while the design of coal furnace depends on the type of coal to be used. Lower quality of coal is usually indicated by lower calorific value. Therefore, if a combustor uses a lower grade coal then the amount of heat transferred to the furnace will be reduced and thus decreasing the power generation capability. Furthermore, if the ash content is high, then it is more likely to be deposited in furnaces and boilers during combustion and disrupt the running of the boiler or heater by creating flame instability.

The effects of coal quality on the performance of utility furnace was studied by Smith et al. (1988) which relates coal quality to thermal performance of coalfired power-generating boilers. The relation was developed into a single-zone model using mass and energy balance. The ash deposit parameters comprised thermal conductivity, emittance and thickness. The effect on the furnace performance was determined by sensitivity analysis and by experiments and found to be critical to furnace performance. Their work also showed the thickness of the ash deposits varied from 1 - 20 mm with the reduction of thermal conductivity by 0.17 to 27.7 W/m.K. The experiment was carried out with coal having ash content varied from 8.78 - 19.1 % weight. With the increasing of combustion temperature, the ash changed its form from ash layer to fused and glassy layer. The melting ash was always a problem in a coal-fired power generation system if carried over into the flue gas stream.

Temperature and heat flux profiles in relation to coal high ash content was also studied by Kouprianov (2001) in a 500 MW boiler. The predicted temperature profile was compared with boiler load and the minimum load was examined according to the ash content. The calculation method employed energy balance over the furnace taking into account the radiant heat transfer. The ash content of the coal was in the range of 42 - 51 % weight. The study found that the minimum boiler load for such high ash content was 65 %, because the operating temperature will decrease down to 1485°C with the decrease of the boiler load. Whilst the maximum operating temperature with 100 % load was 1550°C. The increase in the ash content would decrease the volatile matter which in turn caused disturbances during combustion and invoked flame instability. In this study, the upper limit for the combustion temperature was 1615°C to avoid the formation of NOx.

In measuring the system efficiency of solid fuel burning heating system, flue loss method has long been used. Jaasma et al. (1991) presented their sensitivity study of the use of flue loss method for determining the efficiencies of solid fuel heaters. The composition of CO_2, CO, and O_2 gases in the flue gas stream as well as the temperature were measured for several types of woods. An energy balance was carried out according to the fuel composition, combustion chemistry, combustion efficiency and heat transfer efficiency. Fuel to air ratio was varied from 0 to 400 %, combustion efficiency was assumed to range from 65 to 100 %. The results showed that the percentage of CO loss was in conjunction with the combustion efficiency and thus the system efficiency. The sensitivity of the flue loss method for several sets of data was accurate. The method also indicated that fuel calorific value, fuel composition and air to fuel ratio played a siginificant role in determi-ning system efficiency. However, ash content variation was not sensitive for the case being studied. Prediction on combustion efficiency in a fluidized bed combustor based on the amount of losses also conducted by Pis et al. (1991). A study on the combustion mechanisms of bituminous coal was conducted by Walsh et al. (1988) in order to reduce the amount of losses through char entrainment. The study focused on the coal porosity that initiated fragmentation which would generate burned char and fines in an atmospheric fluidized bed combustor. The fragmentation was influenced by the amount of excess air and its superficial velocity. The study showed that the amount of burned carbon could be increased by reducing the amount of fines. The combustion efficiency was also affected by the length of resident time.

In the development of predictive tools for energy savings in a gas fired heater system, Bahadori et al. (2010) used the combination of combustion efficiency, excess air and flue gas temperature as parameters. A mathematical correlation was generated to define the combustion efficiency, excess air and the flue gas temperature. The results showed that the combustion efficency was in good match with the amount of excess air and flue gas temperature. If the excess air was increased, the stack temperature will decrease and hence the combustion efficiency. The tool was used in the operations of a gas-fired heater to enable the finding of optimum operating condition for maximum efficiency.

In a study on the influence of coal type conducted by Huang et al. (2000), several types of coal were used to calculate the effect on the plant performance. Beside calorific value and carbon content, it was found that ash content in coal was the most significant factor in determining plant performance. The higher the ash content in coal, the lower the plant efficiency would be. The study was conducted in a pressurized fluidized bed combustor. Ash management also played a major role in determining the efficiency of a circulation fluidized bed as shown in a paper by Redemann et al. (2008). By keeping the size of the ash within certain range, they could reduce the amount of combustible carried over in the ash disposal.

Another factor that degrades plant efficiency is unsteady combustion that usually occurs in grate coal boilers. The effect was studied by Ji et al. (2008) using experimental set up and simulation. Natural gas was used to simulate volatile matter in coal. They found out that the release mechanisms of volatile matter in coal during combustion caused the unsteady combustion. This phenomena is common when using raw low grade coal. Suyadal (2006) studied the bed-to-gas heat transfer coefficient of different kind of fuel to determine thermal inefficiency of a fluidized bed combustor. It was found that variations in the heat transfer coefficient resulted in a variation of heat rate. The aim of this study was to design a more efficient FBC reactor for certain type of fuel.

The methods used to analyze the performance of boiler system discussed above are based on mass and energy balance formulated into mathematical models. The models were developed to generate the relationship between coal quality and operating temperature. In this present work, mass and energy balance was used to analyze the performance of a solid fuel heater taking into account the effect of different ash composition in the refuse. Data were taken from a heater system using Therminol-66 fluid running on coal. Beside proximate and ultimate analysis of coal, measurement was taken at the flue gas temperature outlet and ash riddlings composition.

METHODOLOGY

This work used indirect method to assess the thermal performance of a coal-fired oil heater as described in British Standard BS 845-1:1987. Indirect method consisted of measurements of the flue gas temperature, flue gas composition, ash composition and fuel composition. Fuel characteristics were taken from coal sample ultimate and proximate analysis. Sample of bottom ash or refuse was analyzed as a basis for calculating the combustible losses in the riddlings. Two sets of operational data taken from actual measurement were used to calculate the system efficiency and performance. In this assessment, the system efficiency was obtained by calculating the amount of gross (gr) losses caused by heat carried in the flue gas stream, bottom ash and riddlings as well as heat loss due to radiation, convection and conduction factors of the furnace. The total heat flux in the carrier fluid was calculated using the temperature difference of the fluid, specific heat capacity, fluid density and volumetric flow of the fluid. Thermodynamic data of the fluid (therminol-66) was available for interpolation using polynomial equation approach.

The formula used to calculate losses comprises loss to sensible heat in dry flue gas, enthalpy of water in flue gas, unburned gases in flue gas, loss to combustible matter in ash, riddlings, grits and dust, and loss to radiation, convection and conduction. The loss due to sensible heat in dry flue gases (L_1) is given in the following equation (British Standard BS 845-1:1987).

$$L_{1gr} = \frac{k_{gr}(t_3 - t_a)[1 - 0.01(L_{4gr} + L_{5gr})]}{V_{CO2}}$$

while

$$k_{gr} = \frac{255C}{Q_{gr}}$$

t_3 is temperature of gases leaving the heater in °C, t_a equals temperature of air entering the combustion system in °C, C is carbon content in coal in %wt, Qgr is gross calorific value of coal in kJ/kg, and VCO_2 is % volume of CO_2 in gases leaving the furnace.

Loss due to enthalpy in the water vapor in the flue gases (L_2):

$$L_{2gr} = \frac{(m_{H2O} + 9H)(2488 - 4.2t_a + 2.1t_3)}{Q_{gr}}$$

In tropical areas, the humidity factor X_{gr} is added and thus increases the losses due to water vapor as stated in equation:

$$X_{gr} = \frac{1.88w\overline{W}\left(1 + \frac{a_3}{100}\right)(t_3 - t_a)}{Q_{gr}}$$

$$a_3 = \frac{9.5V_{O2}}{21 - V_{O2}}$$

Hence, the equation of losses through the water vapour becomes:

$$L_{2gr} = (1 + X_{gr}) * \frac{(m_{H2O} + 9H)(2488 - 4.2t_a + 2.1t_3)}{Q_{gr}}$$

m_{H2O} is the amount of moisture in coal, H is the amount of hydrogen in coal in %wt. Xgr is the gross humidity factor, w = 0.6 and $\overline{W}$ = 1.54. VO_2 is % volume of O_2 in gases leaving the furnace, and a_3 is humidity factor.

Loss due to unburned gases in the flue gases (L_3):

$$L_{3gr} = \frac{K_1 V_{CO}[l - 0.01(L_{4gr} + L_{5gr})]}{V_{CO} + V_{CO2}}$$

VCO is % volume of CO in gases leaving the furnace, K_1 is a constant that is equal to 63.

The calculation of loss due to combustible matter in ash and riddlings, L_4, requires the collection of ash produced and coal utilized in a certain period of time. The loss is counted based on the carbon content of the ash compared to the amount of coal used, which are expressed in the following equation.

$$L_{4gr} = \frac{33820 M_1 a_1}{M_f Q_{gr}}$$

For this work, however, the amount of ash produced and coal utilized was not available. Therefore the amount of loss in the riddlings was calculated by comparing the losses due to combustible in refuse ($1-a_{ref-gr}$) to the calorific value of fuel. The basis of the calculation was the amount of ash in the fuel. Hence the loss in riddlings is presented in the equation below:

$$L_{4gr} = \frac{\left(\frac{(a_{ash})}{1 - a_{ref-gr}}\right) Q_{ref-gr}}{Q_{gr}}$$

a_{ash} is the percentage of ash in coal in % wt, a_{ref-gr} is the combustible in refuse in gross percentage, Q_{ref-gr} is the gross calorific value of refuse in kJ/kg.

Loss due to combustible matter in grit and dust (L_5) is stated in:

$$L_{5gr} = \frac{33820 * M_2 * a_2}{M_f Q_{gr}}$$

In this case, M_2 = 0, therefore losses in grit and dust L_{5gr} = 0. All losses from combustibles in ash is accounted in L_{4gr}.

Radiation, convection and conduction losses, (L_6). Typical value for furnace with boiler and water wall : L_6 = 2%

Hence, the total losses or L_{tgr} becomes

$$L_{tgr} = \sum_{i=1}^{i=6} L_{igr}$$

Calculation of the gross thermal efficiency (E_{gr}):

$$E_{gr} = 100 - L_{tgr}$$

The heat flux in the heat carrier, Q_c is determined using the following equation:

$$Q_c = F_1 c(t_4 - t_5)$$

where F_1 is the thermal oil flowrate and c is the oil heat capacity. t_4 is the oil inlet temperature and t_5 is the oil outlet temperature both in °C.

The heat input into the furnace (Q_{in}) is obtained by dividing the heat flux and the thermal efficiency:

$$Q_{in-gr} = \frac{Q_c}{E_{gr}}$$

Hence, coal consumption (M_f) can be calculated using heat input and heat utilization:

$$M_f = \frac{Q_{in-gr}}{Q_{gr}}$$

Pump characteristics are required to determine power consumption, pumping efficiency and volumetric flowrate of fluid. Pump head (H) is given by the following equation.

$$H = \frac{(P_i - P_o)101325}{g * \rho}$$

where P_i is the pump inlet pressure in N/m^2, P_o is the pump outlet pressure, g is gravity in m/s and ρ is the oil density in kg/m^3.

RESULTS AND DISCUSSIONS

The setting point for the thermal oil heat exchanger was as follows:

- Maximum rated output	6,000,000 kcal/hr (25,000 MJ/hr);
- Final oil temperature (°C)	300;
- Feed oil temperature (°C)	260;
- Fuel type	Coal, CV = 5740 kcal/kg as received;
- Fuel consumption rating	1430 kg/hr.

Flue gas content was measured and the results were given as follows:

- Volume of CO_2 in gases leaving boiler (average), VCO_2	10.1 %;
- Volume of CO in gases leaving boiler (average), VCO	0.0496 %;
- Volume of O_2 in gases leaving boiler (average), VO_2	9.5 %;
- Insulation thickness, I_1	100.00 mm.

As for coal, the proximate and ultimate composition was given in Table 1 and 2.

The ash analysis for two different operational data was given in Table 3. The analysis was done based on the ash analysis, that is Sample 1 for Case 1 and Sample 2 for Case 2. Sample 1 was considered more efficient since the amount of combustible in the refuse was lower than that of Sample 2.

Data taken from field measurements show the relation of flue gas temperature and the amount of combustibles in the refuse. Table 4 and Table

Table 1. Coal proximate analysis

Analysis Parameter	Unit	As received
Total moisture	% wt	21.35
Ash	% wt	4.45
Volatile matter	% wt	32.19
Fixed carbon	% wt	42.01
Total sulfur	% wt	0.53
Gross calorific value	kcal/kg	5740
Net calorific value	kcal/kg	5426

Table 2. Coal ultimate analysis

Analysis Parameter	Unit	As received
Carbon	% wt	60.16
Hydrogen	% wt	3.69
Oxygen	% wt	8.47
Nitrogen	% wt	1.371
Sulfur	% wt	0.53
Mineral matter	% wt	4.45

fluctuated in similar manner in both cases. Figure 1 showed that the difference in temperature inlet and outlet was relatively the same at each measurement. This suggested that the amount of heat produced during combustion was almost constant. The situation could be proven by the constant profile in efficiency and heater rating, that is about 73 % for case 1 and 71 % for case 2, as depicted in Figure 3.

Table 3. Combustible content in two different data sets

Parameter	Unit	Sample 1 for Case I	Sample 2 for Case 2
Combustible in refuse - gross	%	18.61	39.0
GCV refuse - gross	Kcal/kg	1,219	2,897

5 below showed raw data as a result of field measurement. The amount of losses for each calculation was given in Table 6 and 7.

The thermal oil temperature profile diagram (Figure 1) showed how it fluctuated during the measurement conducted in an hourly basis. The inlet temperature profile was similar to that of the outlet; if the inlet temperature was higher, then the outlet temperature was also high. The diagram shows that it was possible for the temperature to reach the set point. The profile was similar to the coal consumption as shown in Figure 2 where it

The analysis of the thermal oil heater suggested that heating capacity of the system was limited to about 75 % of the rating capacity. The actual capacity of the heater depended on the amount of coal flowrate which cannot be maintained at a constant rate. For Case 1, the actual coal flow ranged from 983 to 1388 kg/hr, while the amount of coal consumption became 1415 to 1430 kg/hr when run in full capacity, which was within the set point (1430 kg/hr) of the heater system. For Case 2, the amount of actual coal consumption was higher than that of Case 1 since the losses was also higher, that was in the range of 1011

Table 4. Measurement data set for Case 1

Measurement data set	Combustible in fly ash (%)	Combustible in total refuse, %	GCV in refuse (kcal/kg)	Flue gas temperature (^oC)	Excess air (%)
1	-	18.61	1,219	302.5	9.5
2	-	18.61	1,219	313.6	9.6
3	-	18.61	1,219	315.3	9.5
4	-	18.61	1,219	310.2	9.6
5	-	18.61	1,219	302.1	10.1
6	-	18.61	1,219	309.7	9.7
8	-	18.61	1,219	313.0	9.8
9	-	18.61	1,219	314.4	9.5
10	-	18.61	1,219	312.6	9.7
11	-	18.61	1,219	313.3	9.8
12	-	18.61	1,219	310.2	9.5

Table 5. Measurement data set for Case 2

Measurement data set	Combustible in fly ash (%)	Combustible in total refuse, %	GCV in refuse (kcal/kg)	Flue gas temperature (^oC)	Excess air (%)
1	-	39.0	2,897	260	10.5
2	-	39.0	2,897	271	13.3
3	-	39.0	2,897	271	12.0
4	-	39.0	2,897	268	13.1
5	-	39.0	2,897	271	9.5
6	-	39.0	2,897	275	9.6
8	-	39.0	2,897	279	13.8
9	-	39.0	2,897	280	11.6
10	-	39.0	2,897	276	10.7
11	-	39.0	2,897	279	10.1
12	-	39.0	2,897	267	9.6

Table 6. Intermediate results for Case 1

Measurement	L1 gr	L2 gr	L3 gr	L4 gr	L5 gr	L6 gr	Lt gr	Egr
1	16,71	5,44	0,31	1,16	0,00	2,00	25,62	74,38
2	17,40	5,45	0,31	1,16	0,00	2,00	26,32	73,68
3	17,51	5,45	0,31	1,16	0,00	2,00	26,43	73,57
4	17,19	5,45	0,31	1,16	0,00	2,00	26,11	73,89
5	16,69	5,44	0,31	1,16	0,00	2,00	25,60	74,40
6	17,16	5,45	0,31	1,16	0,00	2,00	26,08	73,92
7	17,37	5,45	0,31	1,16	0,00	2,00	26,29	73,71
8	17,45	5,45	0,31	1,16	0,00	2,00	26,37	73,63
9	17,34	5,45	0,31	1,16	0,00	2,00	26,26	73,74
10	17,42	5,45	0,31	1,16	0,00	2,00	26,34	73,66
11	17,37	5,45	0,31	1,16	0,00	2,00	26,29	73,71
12	17,20	5,45	0,31	1,16	0,00	2,00	26,12	73,88

Table 7. Intermediate results for Case 2

Measurement	L1 gr	L2 gr	L3 gr	L4 gr	L5 gr	L6 gr	Lt gr	Egr
1	16,28	5,44	0,30	3,68	0,00	2,00	27,71	72,29
2	16,96	5,45	0,30	3,68	0,00	2,00	28,39	71,61
3	17,06	5,45	0,30	3,68	0,00	2,00	28,50	71,50
4	16,75	5,45	0,30	3,68	0,00	2,00	28,18	71,82
5	16,26	5,44	0,30	3,68	0,00	2,00	27,69	72,31
6	16,72	5,45	0,30	3,68	0,00	2,00	28,15	71,85
7	16,92	5,45	0,30	3,68	0,00	2,00	28,36	71,64
8	17,01	5,45	0,30	3,68	0,00	2,00	28,44	71,56
9	16,90	5,45	0,30	3,68	0,00	2,00	28,33	71,67
10	16,98	5,45	0,30	3,68	0,00	2,00	28,41	71,59
11	16,93	5,45	0,30	3,68	0,00	2,00	28,36	71,64
12	16,76	5,45	0,30	3,68	0,00	2,00	28,19	71,81

to 1428 kg/hr, while it became 1445 to 1461 kg/hr in full capacity. These cases showed how the operation of a coal fired thermal heater affected the amount of losses and the amount of coal used. The losses could be reduced by using more accurate control as to allow only a very small off set in the temperature set point. It is also important to follow the amount of combustion air entering the system. The high percentage of combustible in refuse means that an incomplete combustion occurs in the furnace. As for coal quality, it could be quite difficult to maintain the constant calorific value at all times since there are always differences in the quality of the coal supply.

CONCLUSIONS AND RECOMMENDATIONS

Combustible analysis in coal ash refuse can be used as indicator of inefficient performance in a coal fired thermal oil heater system. If the percentage of combustible in the refuse is high then the amount of coal fuel required is also high to compensate for the losses. If the amount of combustibles in refuse is low, then the amount of coal consumption is also low that is below the set point. Based on the above analysis, it is found that design operating condition can be achieved within this low limit. Since the system ratings is constant throughout the measurement during data

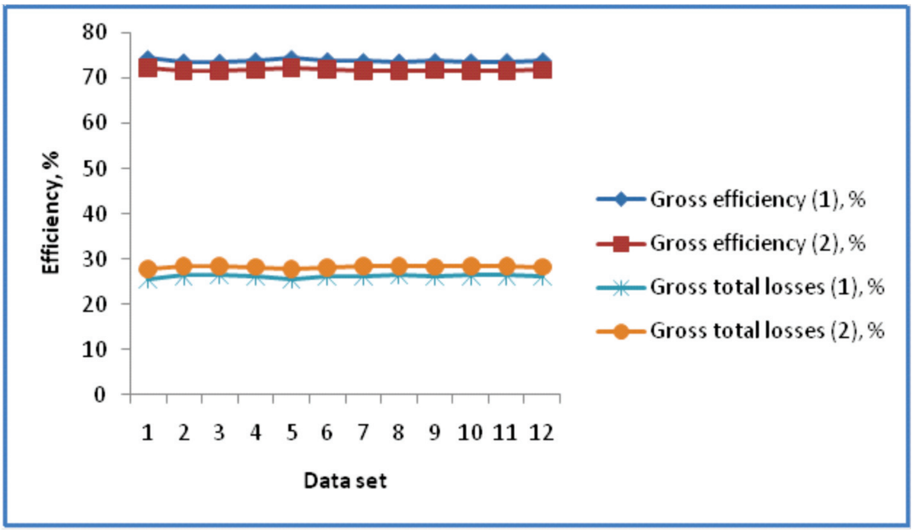

Figure 1. Thermal oil temperature inlet and outlet profile compared to the temperature set point

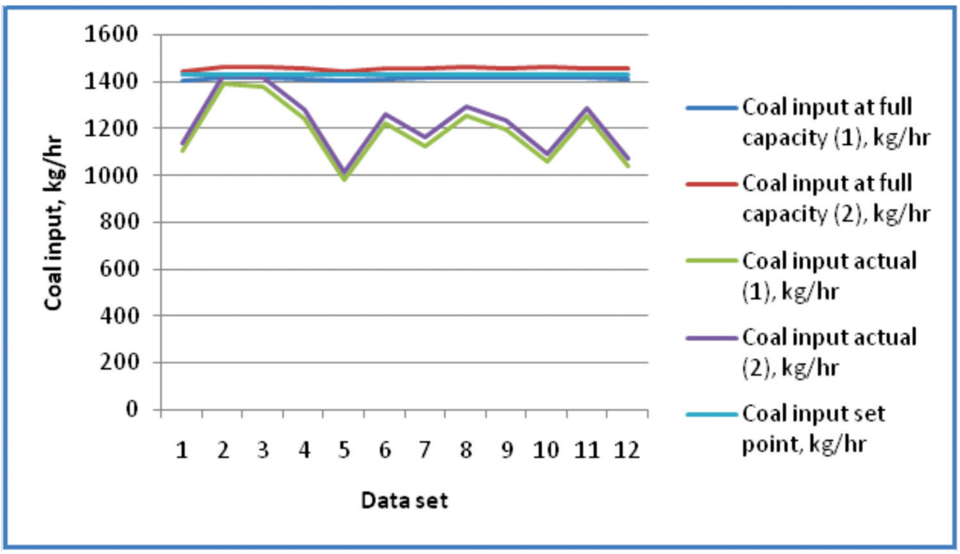

Figure 2. Coal input flowrate in correlation with the ash analysis for two cases

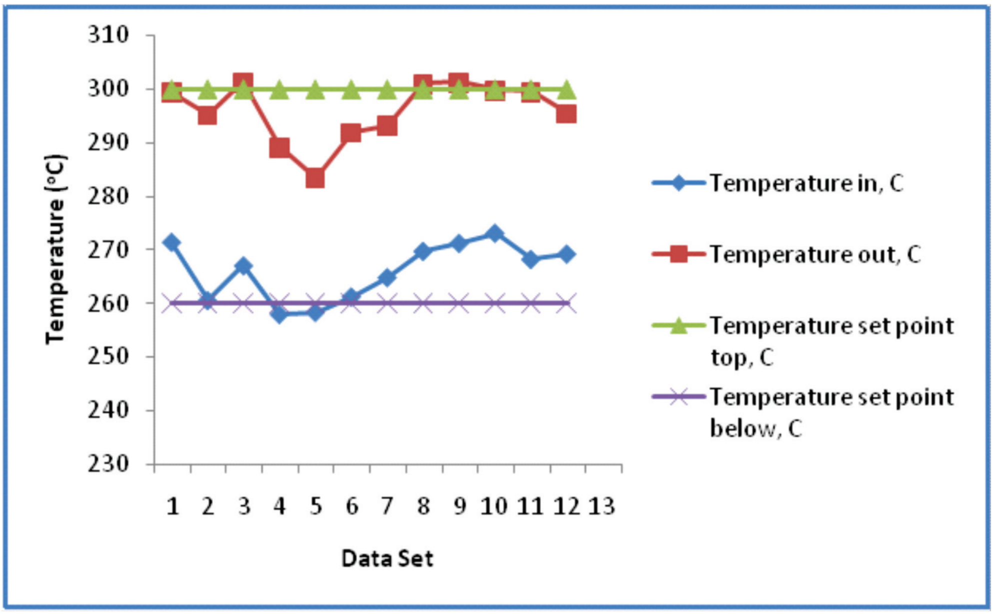

Figure 3. The difference of thermal oil heater efficiency in correlation with the ash analysis for two cases

collection, the high percentage of losses is due to defaults in the operations of the system, which cause higher coal consumption. For example, excess air is not kept to minimum, or the heater is operated under partial load. From this analysis it can be concluded that system operations play an important role in the successful running of an efficient system. Whenever possible it is also important to maintain the coal quality at all times according to the specification.

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