



Case Report

Efficiency of a Coal Fired Boiler in a Typical Thermal Power Plant

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Abstract: This paper presents briefly on the boiler efficiency evaluation procedures by direct and indirect methods useful in thermal power plants. In the direct method consideration is given to the amount of heat utilized while evaluating the efficiency of the boiler, whereas, indirect method accounts for various heat losses. The boiler efficiency evaluated by direct method is found to be lower than that evaluated by indirect method as per the ASME PTC-4.1 standards. However, the direct method helps the plant personnel to evaluate quickly the boiler efficiency with few parameters and less instrumentation.

Keywords: Coal Fired Boiler, Direct Method, Efficiency, Indirect Method

1. Introduction

Energy is the basic need and backbone of human activities in industry, agriculture, transportation, etc. It is one of the major inputs for economic development of a country. The whole world is in the grip of energy crisis and the increased pollution associated with energy use. A power plant is assembly of systems or subsystems to generate and deliver mechanical or electrical energy. The primary units of a coal-fired thermal power plant (Figure-1) are fuel handling system, boiler, turbine and generator and cooling system. The fuel can be in a solid or liquid or gaseous form. Abundantly available coal in India is being used as a solid type of fuel. The pulverized coal in fuel handling system transports to a closed container (boiler), which operates under high pressure and converts chemical energy of the fuel to thermal energy [1-3].

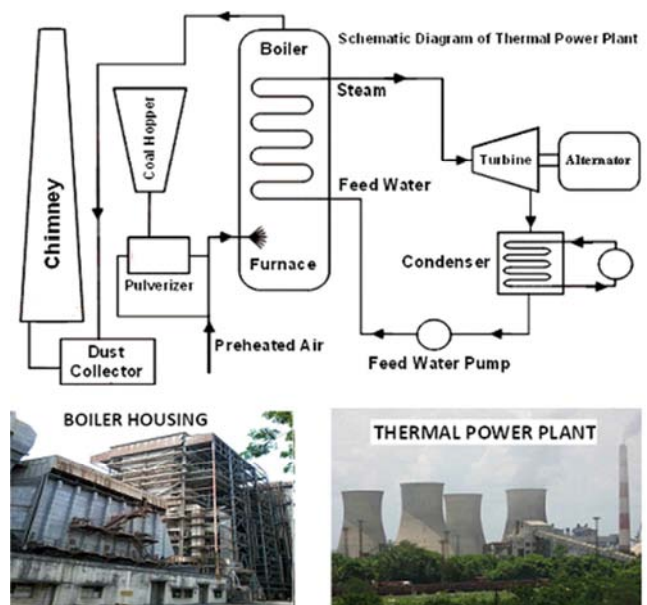


Figure 1. A coal-fired thermal power plant.

The combustion air will be supplied to the burners by the forced-draft fan, and pre-heated the air to dry the pulverized coal. Mixture of the fuel and air will be burned in the furnace. From combustion, the heat recovered by the boiler generates steam at the specified pressure and temperature. The flue gas passes through the boiler, economizer, air pre-heater, environmental control equipment, electrostatic precipitator (to extract fly ash), and flows to the stack through an induced-draft fan. The generated steam in the boiler under pressure flows through a super-heater and rises its temperature above water boiling point. The dry super-heated steam enters the turbine to drive the generator for producing electricity, and flows to the condenser for further use as boiler feed-water. This process completes its cycles from water to steam and then back to water.

Thermal efficiency reflects on the boiler operation & maintenance. Reduction in the boiler efficiency and evaporation ratio with respect to time is reported due to heat transfer fouling, poor combustion, operation & maintenance [4, 5]. Deterioration in the quality of fuel and water may also lead to poor boiler efficiency. Peter et al. [6] have estimated the mass rate of generation considering fuel flow to the boiler, fuel ash content and estimated combustion efficiency. Song and Kusiak [7] have applied a data-mining approach to optimize the boiler efficiency. The boiler efficiency loss at exit is due to rise in flue gas temperature, which is controlled by the absorption of heat in the primary and secondary air pre-heaters [8, 9]. Kaya and Eyidogan [10] have studied the energy efficiency for a natural gas fuelled boiler. Adhikary et al. [11] have adopted a semi-parametric reliability model in the failure analysis of the boiler.

Efficiency is one of the performance parameters useful for proper maintenance of a boiler due to its continuous variation of working parameters. Direct and indirect methods can be utilized for evaluating the efficiency of the boiler. This paper deals with the evaluation of boiler efficiency by direct method as well as indirect method and presenting their limitations.

2. Boiler Testing Standards

The boiler efficiency under steady loading conditions will be examined by operating for one hour. It is quoted by the British Standards (BS845-1987) as the percentage of available heat on the basis of its gross calorific value (). The German DIN 1942 standard recommends lower calorific value whereas the ASME PTC-4.1 standard demands higher calorific value. Direct and indirect methods can be employed for boiler efficiency evaluation. In direct method, the efficiency is evaluated by dividing the heat output with the fuel power (input) of the boiler, whereas indirect method considers the ratio of sum of major losses to the fuel power input of the boiler, which will be finally subtracted from unity [5].

3. Calorific Value of Fuels

The amount of heat (kJ) evolved by the complete

combustion of 1 kg of fuel is known as the calorific value of a fuel (kJ/kg) [12]. When the products of combustion are cooled down to the surrounding air temperature, the quantity of heat obtained by the complete combustion of 1 kg of a fuel is referred as the gross or higher calorific value (GCV_f). When the products of combustion are not sufficiently cooled down to condense the steam formed during combustion, the quantity of heat obtained by the combustion of 1 kg of a fuel is termed as the net or lower calorific value (LCV_f). From the chemical analysis of a fuel, the gross or higher calorific value can be obtained from the Dulong's formula [13]:

$$GCV_f = 33800C + 144000 \left(H_2 - \frac{O_2}{8} \right) + 9270S, \text{ kJ/kg} \quad (1)$$

Here C , H_2 , O_2 and S represent the mass of carbon, hydrogen, oxygen and sulphur in 1 kg of fuel. The numerical values in equation (1) represent their respective calorific values. The amount of heat per kg of steam (i.e., the latent heat of vaporization of water corresponding to a standard temperature of 15°C) is 2466 kJ/kg. The mass of steam formed in kg per kg of fuel is $9H_2$. The net or lower calorific value (LCV_f) can be obtained by reducing GCV_f with the amount of heat carried away by products of combustion [13]:

$$LCV_f = GCV_f - 9H_2 \times 2466 \text{ kJ/kg} \quad (2)$$

It should be noted that equations (1) and (2) yield only approximate values of GCV_f and LCV_f , whereas experiments provide the actual calorific value of the fuel. The bomb calorimeter is used for evaluating the calorific value of solid and liquid fuels, whereas Boy's gas calorimeter is used for gaseous fuel [12].

4. Boiler Efficiency by Direct Method

Direct method (also known as input-output method) compares the energy gain of the working fluid (water and steam) to the energy content of the fuel, which requires only the heat output (steam) and heat input (i.e. fuel) to evaluate the efficiency [14, 15]. This efficiency is defined as the ratio of heat output to the heat input. It is also defined as the ratio of heat addition to steam to the gross heat in fuel [5]. The heat input measurement for coal fuel requires the calorific value of the fuel and its flow rate in terms of mass. There is a need for setting up of bulky apparatus on the boiler-house floor. During the test, samples kept in sealed bags are sent to a laboratory for analysis and calorific value evaluation. This problem can be simplified by mounting the hoppers over the boilers on calibrated load cells. There are several methods for measuring heat output. The heat output measurement requires the flow meters to record the steam generation rate. The boiler efficiency (η_d) is defined as [5]

$$\eta_d = \frac{\text{Steam flow rate} \times (\text{steam enthalpy} - \text{feed water enthalpy})}{\text{Fuel firing rate} \times \text{Gross calorific value}} \times 100$$

$$= \frac{w_s \times [(h_2 - h_1) + (h_4 - h_3)]}{w_f \times GCV_f} \times 100 \quad (3)$$

Here GCV_f is the gross calorific value of the coal (kJ/kg), whose measurement is based on mass of coal for which hoppers are mounted over the boilers on calibrated load cells [15]. w_f is the fuel burning rate (kg/hr) taken from the load cell. w_s is the steam generation rate (kg/hr) obtained from the flow meter. For the specified temperature and pressure, h_1 , h_2 , h_3 , and h_4 are the enthalpies at super heater inlet, super heater outlet, re-heater inlet and re-heater outlet respectively. These enthalpies can be evaluated utilizing the steam tables with proper interpolation or using the online software package [16].

The temperature and pressure of the sub-saturated water at the super heater inlet measured are 285°C and 126.31 bar respectively for which the enthalpy, $h_1 = 1258.92$ kJ/kg. In the same way, enthalpies h_2 , h_3 and h_4 are obtained for the specified temperature and pressure in Table-1 as 3426.98, 3107.39 and 3522.07 kJ/kg. The boiler efficiency is worked out from equation (5) as 83.94%. From the chemical analysis of a fuel, the gross or higher calorific value (GCV_f) estimated from the Dulong's formula (1) using the input parameters in Table-2 is 15506 kJ/kg. However, the measured GCV_f of 15180.22 kJ/kg is considered in the present analysis. The steam generation rate, $w_s = 370000$ kg/hr and the fuel burning rate, $w_f = 75000$ kg/hr.

Table 1. Properties of steam at Super heater (SH) and Re heater (RH).

Enthalpy	Temperature (°C)	Pressure (bar)	Enthalpy (kJ/kg)
Sub-saturated water at SH inlet (h_1)	285	126.31	1258.92
Super heated steam at SH outlet (h_2)	540	145.14	3426.98
Super heated steam at RH inlet (h_3)	348	30.61	3107.39
Super heated steam at RH outlet (h_4)	528	27.6	3522.07

Table 2. Input parameters to account various heat losses in a coal fired boiler.

Gross calorific value of coal (GCV_f)	15180.22 kJ/kg
Gross calorific value of fly ash (GCV_{fy})	811.07 kJ/kg
Gross calorific value of bottom ash (GCV_{bottom})	598.03 kJ/kg
Specific heat of flue gas (C_{pf})	0.9627 kJ/kg°C
Specific heat of super heated steam (C_{ps})	1.8836 kJ/kg°C
Flue gas temperature (T_f)	147.24°C
Ambient temperature (T_a)	34.50°C
Mass of dry flue gas (m)	6.541 Kg/kg of fuel
Moisture present in the fuel (M)	0.1062 Kg/kg of fuel
Mass of total ash generated (m_a)	0.004614 Kg/kg of fuel
Actual air supplied (AAS)	7.9050 Kg/kg of fuel
Humidity factor (HF)	0.0163 Kg/kg of dry air
Hydrogen in fuel (H_2)	2.46 %
Oxygen (O_2)	8.47 %
Nitrogen	0.84 %
Sulphur (S)	0.41 %
Carbon monoxide in the flue gas (CO)	0.009 %
Carbon content in the fuel (C)	39.79 %
Carbon dioxide content in the flue gas (CO_2)	15.39 %

The direct method helps the plant engineers to quickly evaluate the boiler efficiency. It requires few parameters for evaluation and less instrumentation for monitoring. However, it is unable to hint the plant operators why the efficiency of the system is lower. It should be noted that heat losses are not taken into account while evaluating the efficiency (η_d) by the direct method. Hence, it is not possible to find various losses responsible for various efficiency levels. The steam is highly wet due to water carryover, which may mislead the evaporation rate and efficiency [5].

5. Boiler Efficiency by Indirect (or Heat Loss) Method

The boiler efficiency in the heat loss method (or indirect method) is evaluated by considering the sum of percentages of various heat losses and subtracting from 100 [15, 17]. For evaluation of boiler efficiency, the input parameters required are: Gross calorific value of coal (GCV_f), Gross calorific value of fly ash (GCV_{fy}), Gross calorific value of bottom ash (GCV_{bottom}), Specific heat of flue gas (C_{pf}), Specific heat of super heated steam (C_{ps}), Flue gas temperature (T_f), Ambient temperature (T_a), Mass of dry flue gas (m), Moisture present in the fuel (M), Mass of total ash generated (m_a), Actual air supplied (AAS), Humidity factor (HF), Hydrogen in fuel (H_2), Carbon monoxide in the flue gas (CO), Carbon content in the fuel (C), and Carbon dioxide content in the flue gas (CO_2). Theoretical (Stoichiometric) air fuel ratio (AFR) and excess air (EA) supplied are to be found prior to the boiler losses estimation.

Adequate supply of oxygen is essential for complete combustion of a fuel. For C kg of carbon, H_2 kg of hydrogen, O_2 kg of oxygen and S kg of sulphur in 1 kg of fuel, the total oxygen required for complete combustion of 1 kg of fuel from chemical equations is: $\left(\frac{8}{3}C + 8H_2 - O_2 + S\right)$ kg. Since air contains 23% of oxygen and the remaining 77% of nitrogen on the basis of mass, 1 kg of oxygen is contained in $\frac{100}{23}$ kg of air.

Hence, minimum air required for complete combustion of 1 kg of fuel (i.e., air fuel ratio, AFR in kg/kg of fuel):

$$AFR = \frac{100}{23} \left\{ \frac{8}{3}C + 8H_2 - O_2 + S \right\} \quad (4)$$

$$= 11.6C + 34.783 \left(H_2 - \frac{O_2}{8} \right) + 4.348S$$

As in Ref. [13], V is considered as the volume of the flue gas produced in m^3/m^3 of fuel gas (when minimum quantity of air is supplied) for complete combustion. V_l is assumed as the amount of air supplied in m^3/m^3 of gas in excess of that required for complete combustion. Air contains 21% of oxygen and 79% of nitrogen on the basis of volume. If O_2 be the quantity of oxygen in m^3/m^3 of exhaust gas, then the excess quantity of air which will contain this volume of oxygen will

be $\frac{O_2}{21}$. Therefore, $\frac{O_2\%}{21} = \frac{V_1}{V+V_1}$, which implies that $\frac{V_1}{V} = \frac{O_2\%}{21-O_2\%}$. From flue gas analysis, % Excess Air Supplied, $EA = \frac{O_2\%}{21-O_2\%} \times 100$. Actual mass of air supplied/kg of fuel, $AAS = \left(1 + \frac{EA}{100}\right) \times AFR$.

Boiler extracts such as flue gases and ash content are the major contribution to the loss of heat energy. To perform coal analysis, flue gas analysis and ash analysis [18] samples are

taken to laboratory. The heat utilized in producing steam is found to be less when compared to the heat liberated in the furnace. Their difference will provide the heat lost in the boiler. The Bureau of Energy Efficiency [5] described various heat losses in a boiler due to: Dry flue gas (L_1); Evaporation of water formed due to H_2 in fuel (L_2); moisture in fuel (L_3) and in air (L_4); Incomplete combustion (L_5); Radiation and convection (L_6); Un-burnt carbon in fly-ash (L_7) and in bottom-ash (L_8).

ASME PTC-4.1 standard suggests the boiler efficiency of boiler (η_i) by indirect method as the difference of the energy input and the sum of the heat losses:

$$\text{Boiler Efficiency, } \eta_i = 100 - \text{Total Heat loss (\%)} = 100 - \sum_{i=1}^8 L_i \quad (5)$$

Table 3. Various heat losses in a boiler.

Heat loss due to (Bureau of Energy Efficiency [5])	(%)
Dry flue gas, $L_1 = m \frac{C_{pf}(T_f - T_a)}{GCV_f} \times 100$ (m is the mass of dry flue gas in kg/kg obtained from ultimate analysis of coal; C_{pf} is the specific heat of flue gas in kJ/kg°C; T_f is the temperature of flue gas in °C; and T_a is the ambient temperature in °C)	4.6768
Evaporation of H_2O formed due to H_2 in fuel, $L_2 = \frac{9H_2\{584 + C_{ps}(T_f - T_a)\}}{GCV_f} \times 100$ (H_2 is kg of hydrogen present in fuel on 1 kg basis; C_{ps} is the specific heat of super heated steam in kJ/kg°C; and the numeric value 584 is the latent heat corresponding to partial pressure of water vapour)	1.1615
Moisture present in fuel, $L_3 = \frac{M\{584 + C_{ps}(T_f - T_a)\}}{GCV_f} \times 100$ (M is the moisture in kg per kg of fuel obtained from ultimate analysis of coal)	0.5571
Moisture present in air, $L_4 = AAS \times HF \times \frac{C_{ps}(T_f - T_a)}{GCV_f} \times 100$ (HF is the humidity factor (i.e., the kg of water per kg of dry air) and AAS is the actual air supplied per kg of fuel)	0.1803
Incomplete combustion, $L_5 = \left(\frac{\%CO \times C}{\%CO + \%CO_2} \right) \left(\frac{5744}{GCV_f} \right) \times 100$ (The numerical value 5744 is the heat loss due to partial combustion of carbon)	0.8800
For large capacity boilers, the heat loss due to radiation and convection, L_6	0.2000
Un-burnt carbon in fly ash, $L_7 = m_a \left(\frac{GCV_{fly}}{GCV_f} \right) \times 100$ (m_a is the mass (kg) of the total ash generated per kg of fuel. GCV_{fly} is the gross calorific value of fly ash in kJ/kg).	0.2170
Un-burnt carbon in bottom ash, $L_8 = m_a \left(\frac{GCV_{bottom}}{GCV_f} \right) \times 100$ (GCV_{bottom} is the gross calorific value of bottom ash in kJ/kg)	0.1600

Table-2 presents the input for the evaluation of heat losses in the boiler, whereas Table-3 gives the evaluated heat losses. The efficiency of boiler by indirect method is evaluated from equation (5) as 91.97%. The efficiency of the coal fired boiler calculated by the indirect method is found to be higher than that computed by the direct method. It should be noted that the direct method considers the heat energy utilized per unit of eat supplied, whereas the indirect method considers various heat losses. Measurement errors make insignificant change in efficiency by indirect method. For 90% boiler efficiency, 5%

measurement errors in direct method will make the change in efficiency from 85.5 to 94.5%, whereas in indirect method, the change is from 89.5 to 90.5%.

The boiler efficiency test is to be carried out under steady load operation. The combustion efficiency test does not account for the energy usage by burners, fans and pumps, and does not reveal standby losses in firing intervals. The efficiency test does not account for blow down losses and soot blower steam. It is necessary to have periodical cleaning, draft control and excess air control to achieve better performance.

In addition, periodical checks on percentage loading of boiler, boiler insulation and the quality of fuel. The overall efficiency of the plant, $\eta_{overall} = \eta_{boiler} \times \eta_{cycle} \times \eta_{turbine} \times \eta_{generator}$. For a typical thermal power plant [19, 20], the efficiency values are: $\eta_{boiler} = 0.92$, (whereas it is 0.9196 in the present study), $\eta_{cycle} = 0.44$, $\eta_{turbine} = 0.95$ and $\eta_{generator} = 0.93$. The overall efficiency of the power plant estimated is 0.36.

6. Conclusion

The efficiency evaluation procedures useful for coal-fired boilers in thermal power plants by direct and indirect methods from the Bureau of Energy Efficiency [5] are briefly described in this article. While evaluating the boiler efficiency, consideration is given to the amount of heat utilized in the direct method and various heat losses in the indirect method. The boiler efficiency by direct method is obtained as 83.94% whereas it is 91.96% by indirect method as per the ASME PTC-4.1 Standards. However, the direct method helps the plant personnel to evaluate quickly the boilers efficiency with few parameters and less instrumentation.

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