Abstract

This paper addresses the energetic and exergetic efficiencies and losses in different components and the overall system of a 250 MW coal based thermal power plant. The plant is operated under Bangladesh Power Development Board (BPDB), which is located at Barapukuria, Bangladesh and consists of 2 units (2 x 125 MW). The analyses have been carried out by considering design data for different designed and loading conditions of the plant. The overall energy efficiencies of the plant are 35.48%, 56.77%, 70.96% and 75.67% and the overall exergy efficiencies were 44.25%, 33.31%, 30.78% and 30.21% for 50%, 80%, 100% and 106% loading conditions respectively for the design data. However, the overall energy and exergy efficiencies of the power plant during operation are 39.2%, 46.6% and 27.9%, 27.2% for 57% and 67% loading conditions respectively, which are lower than the design value. The distribution of the exergy losses in power plant components has been assessed to locate the process irreversibility. The comparison between the energy losses and the exergy losses of the individual components of the plant shows that the maximum energy losses (~49.92%) occur in the condenser, whereas the maximum exergy losses (~68.27%) occur in the boiler. Exergy analysis can be particularly effective in identifying ways to optimize the performance of existing operations and designing the plant while energy balance gives heat transfer between the system and its surrounding.

Keywords: Energy efficiency; exergy destruction; coal base power plant; thermal power plant.

1. Introduction

Energy consumption is one of the most important indicators showing the development stages of countries and living standards of communities. Population increment, urbanization, industrializing and technological development result directly in increasing energy consumption. To achieve the maximum utilization of energy resources and reliability of the plant, researchers have the great interest on energy and exergy analysis of the power plant. In generally, the performance of thermal power plants is evaluated through energetic performance criteria based on the first law of thermodynamics, including electrical power and thermal efficiency [1]. In recent decades, the exergetic performance based on the second law of thermodynamics has found as useful method in the design, evaluation, optimization and improvement of thermal power plants. The majority of the causes of thermodynamic imperfection of thermal processes are not accounted for by energy (or the first law of thermodynamics), whilst the exergy (or second law of thermodynamic analysis) accounts the irreversibilities like heat transfer through a finite temperature difference, chemical reactions, friction, mixing, and unrestrained expansion. Practical devices involving energy conversion and transfer always observe energy conservation law, but the quality of energy degrades. Degradation of energy is equivalent to the irretrievable loss of exergy due to all real processes being irreversible. The loss of exergy or irreversibility provides a quantitative measure of process inefficiency [2].
The exergy consumption during a process is proportional to entropy creation, which accounts for inefficiencies due to irreversibilities. Therefore, exergy analysis is as important as energy analysis for design, operation and maintenance of different equipment and systems of a power plant. An exergy analysis can identify locations of energy degradation and rank them in terms of their significance. This knowledge is useful in directing the attention of process design, researchers, and practicing engineers to those components of the system being analyzed that offers the greatest opportunities for improvement [3].

At present 1880 GW of total electricity (5940 GW) is generated from coal (Source: IEA, June 2014) which is the 31.64% of total generation. As per statistics June 2014 of BPDB, the electricity production by coal is about 2.40% of total electricity generation of country [4]. Bangladesh has up to 2.7 billion short tons of high-quality coal reserves [5] and thus coal-based thermal power plants can play an important role for Bangladesh. Extensive research have been carried out concerning energetic and exergetic performances of coal-fired thermal power plants. Datta et al. [6] presented work on exergy analysis of a coal-based thermal power plant using the design data from a 210 MW thermal power plant. The exergy efficiency is calculated using the operating data from the plant at different conditions, viz. at different loads, different condenser pressures, with and without regenerative heaters. Rosen [7] presented energy and exergy-based comparison of coal-fired and nuclear steam power plants. The results show overall energy and exergy efficiencies are 37% and 36% respectively for the coal-fired and nuclear process. Ganapathy et al. [8] determined the energy losses and the exergy losses of the individual components of the lignite fired thermal power plant. The results represent the maximum energy losses of 39% occur in the condenser, whereas the maximum exergy losses of 42.73% occur in the combustor. Suresh et al. [9] provides insight to find out efficiency improvement in various components of a power generating system. The performance of the plant was estimated by a component-wise modeling followed by computer program, “Cycle-Tempo” was used for the study. The maximum exergy loss was found to be in steam generation unit followed by turbine. The off-design simulation resulted in an overall energy efficiency of 28.5% at 40% load factor compared to 31.5% at design rating. Rudra et al. [10] examined to increase coal-fired steam power plant efficiency by advance steam parameters. Although a considerable amount of research have been carried out, but more effective research is essential to investigate results on coal based thermal power plant using sub-critical, supercritical and ultra-supercritical steam conditions. This study represents the results considering both the energetic and exergetic performance criteria, efficient and effective usage of fuel resources by taking into account the quality and quantity of the energy used in the generation of electric power in coal based thermal power plants, which is operating on sub-critical steam conditions.

2. Process Description

Coal fired thermal power plant generally operates on Rankine cycle [11]. The schematic arrangement of equipments of this power plant is shown in Fig. 1. The major components of the plant are high, intermediate and differential low pressure turbines (HPT, IPT and DFLP), boiler (B), pumps (P), deaerator (D), generator (G), condenser (C), low and high pressure feed water heaters etc. The thermodynamic models of this power plant are based on fundamental mass, energy and exergy balances.
The plant consists of three turbines, namely high, intermediate and low pressure (HP, IP and LP) which are connected to the generator. Steam flows to HP turbine (point 1) with high energy and high exergy, after producing work on expansion in HP turbine, cold reheat steam (point 12) with low energy and exergy flows back to boiler for reheating, hot reheat steam (point 3). Wet steam (vapour fraction = 0.92) is exhausted from LP turbine to condenser at a very low pressure (86 kPa). Circulating water flows to the condenser (point 13) almost at ambient temperature takes away heat of condensation and flows back to the river (point 14). The condensate exits the condenser (point 15) with low energy and is pumped by the condensate extraction pump (CEP) to the deaerator through LP heaters (HTR1 to HTR4). Deaerator feeds (point 17) to BFP, which raise the pressure of feed water flow (point 18) to high value to flow through high pressure heaters (HTR6 and HTR7) and back to the boiler (point 11) for generation of steam and the cycle continues. Final feed water (point 11) temperature rises across feed heaters by transferring heat from turbine extraction steam and facilitates high temperature heat addition in boiler.

Table 1. Some baseline data of the Barapukuria 250 MW coal based power plant (Source: BPDB)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal flow</td>
<td>55 t/h</td>
</tr>
<tr>
<td>Ash production</td>
<td>6.6 t/h</td>
</tr>
<tr>
<td>Flue gas flow</td>
<td>700,000 Nm³/h</td>
</tr>
<tr>
<td>Flue gas temperature</td>
<td>150 °C</td>
</tr>
<tr>
<td>Emission SO₂ on average</td>
<td>0.600 t/h</td>
</tr>
<tr>
<td>Emission SO₂ max</td>
<td>0.735 t/h</td>
</tr>
<tr>
<td>Emission NOₓ max</td>
<td>500 mg/Nm³</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>50 mg/Nm³</td>
</tr>
<tr>
<td>Stack height</td>
<td>95m</td>
</tr>
<tr>
<td>Circulating cooling water</td>
<td>14,000 m³/h</td>
</tr>
</tbody>
</table>

Following additional considerations are made for calculation of the energy and exergy of the different components:
- Total auxiliary power consumption in the plant is considered in a consolidated manner as a percentage of the generated power.
- Atmospheric pressure and temperature are 25°C temperature and 1 atmospheric pressure.
- The relative humidity of the ambient air is assumed to be 80%.
- Incoming fuel temperature is 25°C.
3. Results and discussion

The design and operating data of Barapukuria 2 x 125 MW coal based thermal power plant have been used for the energy and exergy analysis at different state points. The total cycle of the power plant consists of six closed feed water heaters and one open feed water heater (deaerator). The T-s diagram is shown in Fig. 2. For this cycle, the working fluid passes isentropically through the turbine stages and pumps. The T-S diagram shows the principal states of the cycle. The steam (temp. 515 °C, 14.00 Mpa) enters the HP turbine at state 1 and expands to state 2, where a fraction of the total flow is extracted, or bled, into two closed feed water heater HTR6 and HTR7 (state 7 and state 31). Then the steam is reheated (temp. 510 °C, 1.078 Mpa) and enters the IP turbine at state 3 and expands to state 5. A fraction of the total flow is extracted, or bled, into one open feed water heater HTR5 (deaerator, state 30) and two closed feed water heater HTR3 and HTR4 (state 8B and state 8A). The rest of the steam expands through the LP turbine to state 6. Finally, after increasing the temperature by the feed water heater and increasing the pressure by the boiler feed pump to the steam generator pressure and enters the steam generator at state 27. The cycle is completed as the working fluid is heated in the steam generator at constant pressure from state 27 to 1.

![Fig. 2. T-s diagram of total power cycle.](image)

Energy and exergy efficiencies of the overall power plant are shown in Fig. 3(a) as function of 100%, 80% and 50% loading condition for the design data condition. The decrease in exergy efficiency is attributed to the loss of exergy in the steam generation unit (boiler) and turbine. Energy and exergy efficiencies of the overall power plant are shown in Fig. 3(b) as function of 57% and 67% loading condition for the operation condition. From the comparison of design and operating data of the overall power plant, it is found that the efficiency of the operating condition is low than the design condition.

![Fig. 3. Energy and exergy efficiencies of the overall power plant for (a) design data (b) operating data.](image)
The comparison of energy efficiency and exergy efficiency between different components of the power plant is specified in Fig. 4(a) - 4(c) for different loading conditions.

The comparisons of energy and exergy losses between the different subsystems of the plant are shown in Fig 5. It is noted that the maximum exergy loss occurs in the boiler subsystem (68.27% at 100% load). This might be due to the irreversibility of the combustion process in the combustor. The exergy destruction of the condenser is only 0.21%. The real loss is primarily back in the boiler where entropy was produced. Contrary to the first law analysis, this demonstrates that significant improvements exist in the boiler system rather than in the condenser. The calculated exergy efficiency of the cycle is 30.78% at 100% load. This indicates that remarkable opportunities are available for improvement. Energy efficiency of the turbine cycle is low (47.25% at 100% load) due to a large quantity of energy rejection in the condenser. But the derived exergy efficiency of the turbine is high (83.14 % at 100% load), this is due to the reason that a little exergy associated with turbine exhaust steam enters condenser, part of which is rejected to CW and partly consumed due to irreversibility.

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**Fig. 4.** Comparison of efficiency in the plant and components at (a) 50%; (b) 80%; (c) 100% load.

**Fig. 5.** (a) Energy (b) Exergy loss of different components of the plant at 100% loading condition.
Exergy analysis can also be effectively used to take important decisions pertaining to operation and maintenance. Any operation decisions based on the energy analysis will be incorrect for the overall plant performance. This corroborates to the overall plant performance degradation. First law analysis alone also often does not reflect properly the performance deterioration level of a single component. Exergy analysis can benefit by pinpointing the sources of irreversibility in different components of a power cycle.

4. Conclusions

Energy and exergy analyses are presented in this study to understand the performance of coal fired thermal power plants and identify design possible efficiency improvements. From the data presented and the subsequent analysis, following conclusions can be drawn:

- Exergy efficiency is lower than energy efficiency of the plant. Boiler is the main part that contributed to lower the exergy efficiency.
- It has been observed that 68.27% exergy loss occur in combustor (boiler) which represents combustor is not fully adiabatic and combustion might be incomplete. The large exergy loss is mainly due to the combustion reaction and to the large temperature difference during heat transfer between the combustion gas and steam. Other factors that might contribute to the high amount of exergy loss are tubes fouling, defective burners, fuel quality, inefficient soot blowers, valves steam traps and air heaters fouling.
- The major energy destruction occurs in the condenser which leads to inefficient heat transfer between hot stream (flue gas) and cold stream (water and air).
- Thus, energy analysis results lead to erroneous conclusion that major loss is associated with the heat rejection at the condenser, while exergy analysis quantitatively demonstrates that only a very small amount of work potential is lost in the condenser. Operation and maintenance decisions based on exergy analysis of the power plants proved more effective. Power station equipment involves high density of exergy transfer and therefore, it is important that exergy destruction is minimized in such devices. Exergy-based approach of performance monitoring in operating power plants helps in better management of energy resources and environment.

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References