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Exergy analysis of a thermal power plant with measured boiler and turbine losses

P. Regulagadda, I. Dincer, G.F. Naterer *

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, Canada L1H 74K

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ABSTRACT

In this paper, a thermodynamic analysis of a subcritical boiler–turbine generator is performed for a 32 MW coal-fired power plant. Both energy and exergy formulations are developed for the system. A parametric study is conducted for the plant under various operating conditions, including different operating pressures, temperatures and flow rates, in order to determine the parameters that maximize plant performance. The exergy loss distribution indicates that boiler and turbine irreversibilities yield the highest exergy losses in the power plant. In addition, an environmental impact and sustainability analysis are performed and presented, with respect to exergy losses within the system.

1. Introduction

The world energy needs rely heavily on fossil fuels for electricity generation. The majority of the world's power generation is met by fossil fuels, particularly coal and natural gas. Despite the growth of renewable energy installations like wind and solar power, the heavy dependence on fossil fuels is expected to continue for decades. Despite the depletion of fossil fuel reserves and environmental concerns such as climate change, the growth in oil demand is expected to be 47.5% between 2003 and 2030, 91.6% for natural gas and 94.7% for coal [1]. Even though cleaner renewable sources of energy are being rapidly developed, their relative cost and current state of technology have not advanced to a stage where they can significantly reduce our dependence on fossil fuels. Therefore, given the continued reliance on fossil fuels for some time, it is important that fossil fuel plants reduce their environmental impact by operating more efficiently.

As energy analysis is based on the first law of thermodynamics, it has some inherent limitations like not accounting for properties of the system environment, or degradation of the energy quality through dissipative processes. An energy analysis does not characterize the irreversibility of processes within the system. In contrast, exergy analysis will characterize the work potential of a system. Exergy is the maximum work that can be obtained from the system, when its state is brought to the reference or "dead state" (standard atmospheric conditions). Exergy analysis is based on the second law of thermodynamics. This paper will examine a detailed exergy analysis of a thermal power plant, in order to assess the distribution of irreversibilities and losses, which contribute to loss of efficiency in system performance.

Past exergy studies have evaluated the performance of power plants, as a means to optimize the performance and turbine power output. Rosen [2] evaluated the performance of coal-fired and nuclear power plants via exergy analyses. Habib and Zubair [3] conducted a second law analysis of regenerative Rankine power plants with reheating. Dincer and Muslim [4] performed a thermodynamic analysis of reheat cycle power plants. Sengupta et al. [5] conducted an exergy analysis of a 210 MW thermal power plant. Rosen and Dincer [6] performed an exergoeconomic analysis of power plants that operate on various fuels. They investigated the relationship between capital costs and thermodynamic losses. Kwak et al. [7] presented an exergetic and thermo-economic analysis of power plants.

Unlike these past studies, this current paper presents an exergy analysis of a uniquely configured Rankine cycle operating in subcritical conditions. The generator power output is 32 MW. The boiler is a circulating fluidized bed combustion boiler with a capacity of 140 TPH of steam at 100% BMCR at the rated steam parameters. The power plant is designed to utilize an air cooled condenser to condense the exhaust steam.

The main objective of this paper is to perform a thermodynamic exergy analysis, using design data of an actual power plant under construction in India. It will compare the results of the analysis to demonstrate how exergy analysis can be valuable for improving the system performance. This paper will identify major sources of losses and exergy destruction in the power plant. It will provide ways and means to improve the system performance and reduce environment impact. Finally, it will perform a parametric study to determine how the system performance varies with different operating parameters.

* Corresponding author.
E-mail addresses: prashant.regulagadda@uoit.ca (P. Regulagadda), Ibrahim.Dincer@uoit.ca (I. Dincer), Greg.Naterer@uoit.ca (G.F. Naterer).

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Nomenclature

BMCR	boiler maximum continuous rating
e_x	specific exergy (kJ/kg)
$\dot{E}x$	exergy rate (kW)
$\dot{E}x_d$	exergy destruction rate (irreversibility) (kW)
GCV	gross calorific value
h	specific enthalpy (kJ/kg)
h_{fo}	specific enthalpy of formation (kJ/kmole)
$\dot{m}$	mass flow rate (kg/s)
n	number of moles
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K or kJ/kmole K)
$\dot{S}_{gen}$	entropy generation (kJ/s K)
T	temperature (°C or K)
TMCR	turbine maximum continuos rating
$\dot{W}$	work rate (kW)
Greek	
η	efficiency
Chemical symbols	
C	carbon
CO_2	carbon dioxide
H_2	hydrogen
H_2O	water vapor
N_2	nitrogen
O_2	oxygen
Superscripts	
ch	chemical
tm	thermo-mechanical
Subscripts	
0	reference property
c	carbon
Comb	combustion
f	fuel
p	products
r	reactants

2. Exergy formulation of power plant

The process flow diagram for the power plant is shown in Fig. 1. The process parameters for the power plant are shown in Table 1. The following thermodynamic analysis of the power plant will consider the balances of mass, energy, entropy and exergy. Unless otherwise specified, the changes in kinetic and potential energies will be neglected and steady state flow will be assumed. The process parameters and data are based on actual plant design data for a 32 MW power plant being installed by Tecpro Power Systems Ltd., Chennai, India.

For a steady state process, the mass balance for a control volume system in Fig. 1 can be written as

$$\sum_i \dot{m}_i = \sum_o \dot{m}_o \tag{1}$$

The energy balance for a control volume system is written as

$$\sum_i \dot{E}_i + \dot{Q} = \sum_o \dot{E}_o + \dot{W} \tag{2}$$

The entropy balance for a control volume system is

$$\sum_i \dot{S} + \sum_i \frac{\dot{Q}}{T} + \dot{S}_{gen} = \sum_o \dot{S} + \sum_o \frac{\dot{Q}}{T} \tag{3}$$

The exergy balance for a control volume system is written as

$$\sum_i \dot{E}x_i + \sum_k \left(1 - \frac{T}{T_k}\right)\dot{Q}_k = \sum_o \dot{E}x_o + \dot{W} + \dot{E}x_d \tag{4}$$

where the exergy rate of a stream is

$$\dot{E}_x = \dot{m}(e_x) \tag{5}$$

$$\dot{m}(e_x) = \dot{m}(e_x^{tm} + e_x^{ch}) \tag{6}$$

The above exergy balance is written in a general form. For the combustion process, the heat input will be included when calculating the chemical exergy of coal. The heat exergy term in Eq. (4) will be used to calculate the exergy loss associated with heat loss to the surroundings. The specific exergy is given by

$$e_x^{tm} = (h - h_o) - T_o(s - s_o) \tag{7}$$

When combustion occurs in the boiler, coal is burned to form carbon dioxide, water vapor and other products of combustion. Since the chemical composition of coal changes, in addition to the thermodynamic state, the chemical component of exergy must also be considered. The combustion reaction that describes combustion of coal with the theoretical air component is

$$\begin{aligned}&5.08C + 2H_2 + 6.08(O_2 + 3.76N_2)\\&\quad = 5.08CO_2 + 2H_2O + 22.86N_2\end{aligned} \tag{8}$$

Assuming that the boiler operates with 20% excess air, the combustion reaction becomes

$$6.29C + 2H_2 + 7.29(O_2 + 3.76N_2) = 6.29CO_2 + 2H_2O + 27.41N_2 \tag{9}$$

On a "per mole" basis of carbon, it is written as

$$C + 0.32H_2 + 1.16(O_2 + 3.76N_2) = CO_2 + 0.32H_2O + 4.36N_2 \tag{10}$$

The exergy balance equation for the reaction is [10]

$$\sum N_p(\bar{h}_{f0} - \bar{h} - \bar{h}_0 - T_0\dot{s})_p = \sum N_r(\bar{h}_{f0} - \bar{h} - \bar{h}_0 - T_0\dot{s})_r \tag{11}$$

The exergy content of coal for the mass of carbon in coal is written as

$$E_{x,\text{coal}} = (E_{x,\text{reaction}} \times n_c \times m_f)/M_c \tag{12}$$

Then, the energy and exergy efficiencies of the power plant are written as

$$\eta_{\text{energy}} = \frac{w_{\text{output}}}{m_f \times cv} \tag{13}$$

$$\eta_{\text{exergy}} = \frac{w_{\text{output}}}{E_{x,\text{coal}}} \tag{14}$$

In the next section, the predicted results and sensitivity studies based on this exergy formulation will be presented (see Table 2).

3. Results and discussion

Coal is the supply fuel of the power plant, with the following components: moisture = 25%, ash = 0.88%, hydrogen = 4.06%, nitrogen = 1.1%, sulphur = 0.075%, oxygen = 7.935%, carbon = 60.95%, GCV = 21,981.75 kJ/kg. Fig 2 shows that the reference temperature does not have an effect on the energy efficiency, but it affects the exergy efficiency. The performance of the system depends on the