Thermoeconomic optimization of a boiler used in coal fired thermal power plants based on feed water temperature

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Abstract

The purpose of this study is to analyze the effect of feed water temperature on thermoeconomic performance of a boiler used in a coal fired thermal power plant. Thermoeconomic model of the boiler is developed based on second law of thermodynamics. Performance analyses based on exergetic and exergoeconomic criteria are done for the boiler used in a 55 MW power plant. The methodology is explained in detail with the help of an example in order to make comprehensive evaluations. Effect of feed water temperature on the exergetic efficiency of the boiler system, unit product cost of the boiler and unit product cost of feed water heaters has been shown in detail. Optimization has been done for the boiler system as a tradeoff between the unit product cost of feed water from the feed water heaters and unit product cost of the boiler system. The outcomes of this study provide a basis useful for boiler performance analysis and improvement.

Keywords: Thermoeconomic Performance; Feed water heaters; Boiler System; Exergetic Efficiency.

1. Introduction

Water supplied to the boiler which is converted into steam is called feed water. The two sources of feed water are: (i) Condensate or condensed steam returned from the processes and (ii) Makeup water (treated raw water) which must come from outside the boiler room and plant processes. For higher boiler efficiencies, the feed water is preheated by economizer, using the waste heat in the flue gas. The combination of exergetic and economic analysis called exergoeconomic analysis has become a powerful tool for assessing the performance of energy conservation systems.

Several thermodynamic relations have been developed to illustrate the relationship between the energy and exergy losses and capital cost for thermal systems in a modern coal fired electrical generation station [1, 2, 3, 4, 5]. The strategy for optimizing the thermal system using the exergetic cost theory and symbolic exergoeconomics has been explained in detail [6, 7]. The benefits of exergoeconomic analysis and optimization using the exergy- related variables that can be used to minimize the cost of a thermal system have been explained in detail [8]. Thermoeconomic technique has been used to optimize a single and double effect vapor absorption refrigeration system [9, 10, 11]. Exergoeconomic analysis of a co-generation system and optimization of cycle has been done for the cogeneration system [12].

2. Methodology

2.1. Boiler system

The boiler system provides does the job of conversion of water into steam which is used as a working fluid in the coal fired thermal power plant. It comprises of three systems:. (i)The feed water system provides water to the boiler and regulates it depending upon the steam demand. (ii)The steam system collects and controls the steam produced in the boiler. (iii)The fuel system includes all equipment used to provide fuel to generate the necessary heat.

The major streams entering and leaving the boiler have been shown in Fig. 1.

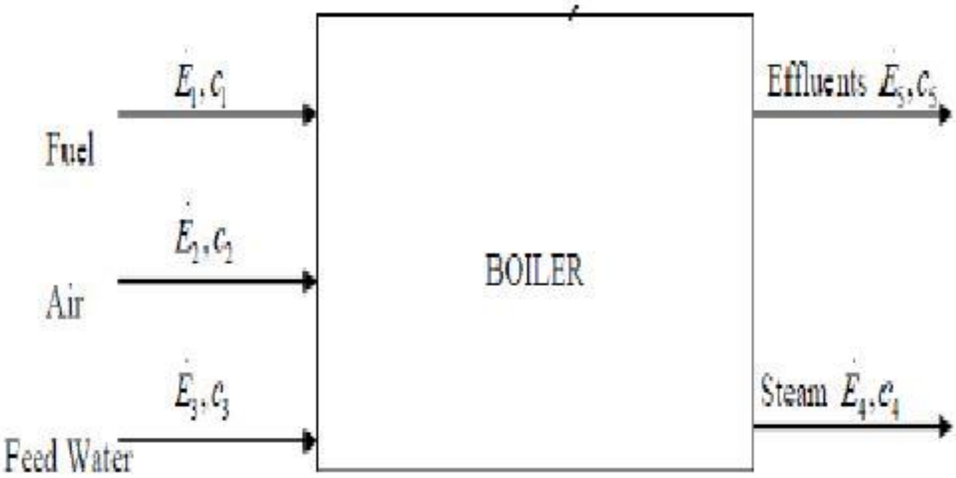

Fig. 1. Inlet and outlet Streams for a boiler system

2.2. Exergy analysis

It has been illustrated by many researchers over the years that for economic optimization of thermal systems it is much better to use the second law approach as it is easier to assign monetary values to exergy as compared to energy which forms the basis for the first law approach. The second law approach makes use of the following equations to analyze a thermal system.

The specific thermo- mechanical exergy (neglecting kinetic and potential exergy) is evaluated from the following equation [5]:

$$e_j = (h_j - h_0) - T_0 (s_j - s_0) \quad (1)$$

The total rate of exergy with any stream is calculated as

$$\dot{E}_j = \dot{m}_j e_j \quad (2)$$

The exergy balance equation for boiler is given as

$$\sum_e \dot{E}_{e,B} + \dot{W}_B = \dot{E}_{q,B} + \sum_i \dot{E}_{i,B} \quad (3)$$

The exergetic efficiency of the boiler system is given as

$$\varepsilon_B = \frac{\dot{E}_{P,B}}{\dot{E}_{F,B}} \quad (4)$$

2.3. Thermoeconomic analysis

As it is easier to assign monetary values to exergy hence, in this study, monetary costs have been assigned to specific exergy values of the fuel (coal) and the product (steam) for the boiler system.

Average costs per exergy unit of fuel and product for the boiler system are given as

$$c_{F,B} = \frac{\dot{C}_{F,B}}{\dot{E}_{F,B}} \quad (5)$$

$$c_{P,B} = \frac{\dot{C}_{P,B}}{\dot{E}_{P,B}} \quad (6)$$

The exergy costing equation for the boiler is established as per Fig. 1 and is given as

$$c_1 \dot{E}_1 + c_2 \dot{E}_2 + c_3 \dot{E}_3 = c_4 \dot{E}_4 + c_5 \dot{E}_5 \quad (7)$$

From the above equation, unit cost of product for the boiler is calculated as:

$$c_4 = [c_1 \dot{E}_1 + c_2 \dot{E}_2 + c_3 \dot{E}_3 - c_5 \dot{E}_5] / \dot{E}_4 \quad (8)$$

2.4. Optimization Process

During the thermoeconomic optimization for the boiler system the following assumptions are made:

(i) The exergy flow rate from the boiler is constant.
(ii) The unit cost rate for fuel is taken as constant.

In the exergoeconomic analysis and optimization process all the variables are taken as constant and the effect of feed water temperature coming from the feed water heaters on the unit product cost of boiler and exergetic efficiency of the boiler are studied and analyzed.

3. Case Study

For illustrating the methodology, a boiler used in an55 MW coal fired thermal power plant is considered. For the boiler system under consideration, the values for various unit exergy costs are calculated as per Fig. 1 and are given in Table 1.

Table 1. Values of unit costs for different streams for a boiler

S. NO.	STREAM NO.	Unit exergy cost (c) (Rs/ kJ)
1	1	0.0950
2	2	0.2241
3	3	0.3362
4	5	0.0950*

In the calculations, for the stream exiting to atmosphere, the unit exergetic cost is taken to be same as the input cost of fuel.

The range of temperature for the feed water is taken from 455 K to 471K.

Coal used in the plant is lignite with calorific value of 25427kJ/kg.

4. Results and discussion

The first step in the thermoeconomic process is to study and analyze the effect of feed water temperature on the exergetic efficiency of the boiler. Results of this variation are shown in Fig. 2. Exergetic efficiency is seen to increase with an increase in the feed water temperature as less exergy is required from the fuel to provide the same heating effect with an increase in the feed water temperature.

The second step is to study and analyze the variation of unit product cost of feed water heaters with changes in the feed water temperature. Results of this variation are given in Fig. 3. The unit product cost of feed water heater is found to increase with the increase in the feed water temperature as more money has to be spent to provide feed water at higher temperatures.

The final step in the thermoeconomic process is to study and analyze the variation of unit product cost of boiler with feed water temperature. The results are shown in Fig. 4. It is seen that with an increase in the feed water temperature, the unit product cost of boiler reduces, as less fuel is required to produce the same heating effect resulting in lesser fuel costs. This brings the reduction in the overall unit product cost of the boiler.

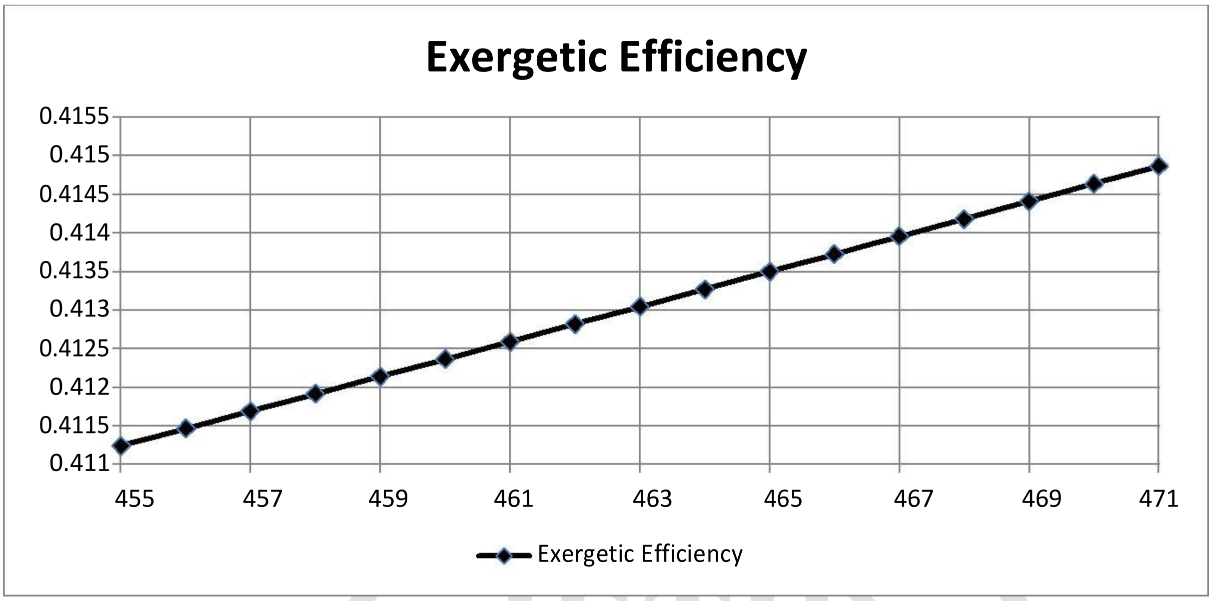

Fig. 2 Effect of feed water temperature on exergetic efficiency of the boiler system

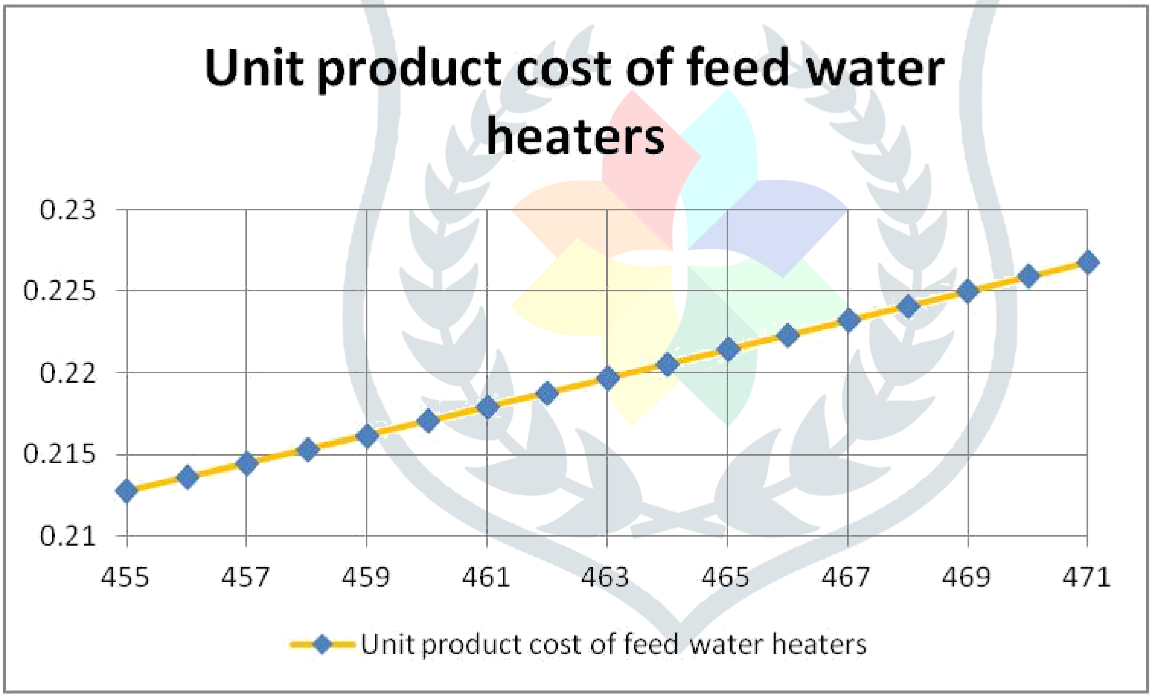

Fig. 3 Effect of feed water temperature on the unit product cost of the feed water heaters

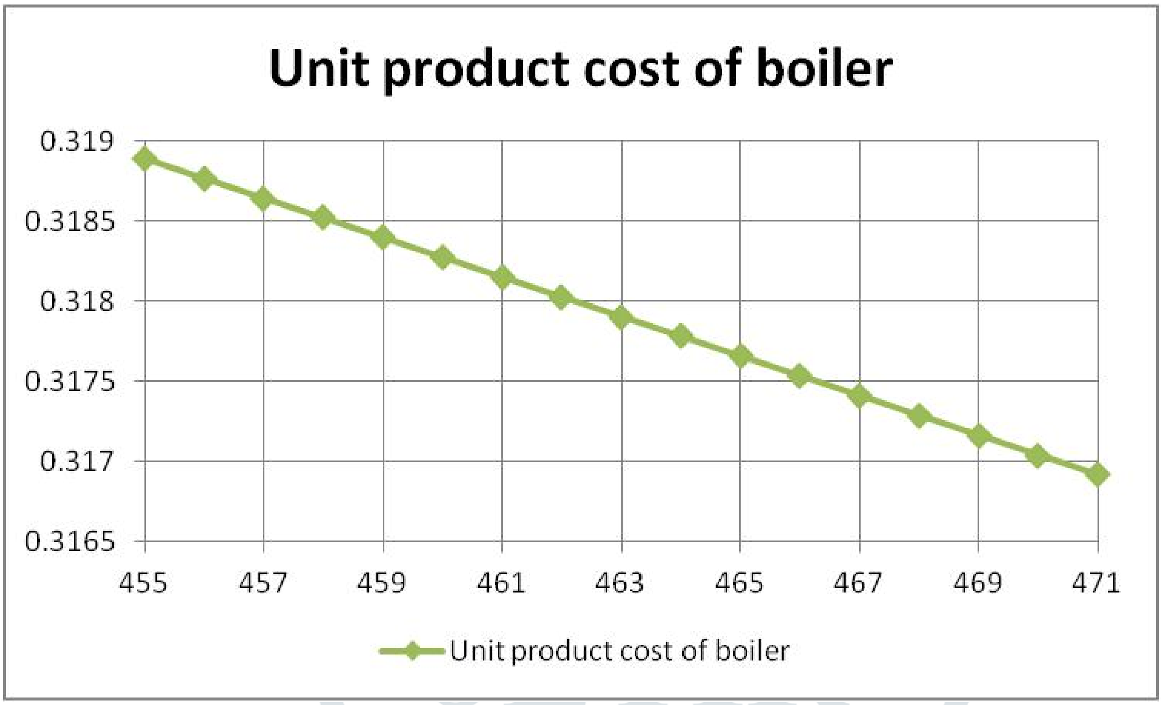

Fig. 4 Effect of feed water temperature on the unit product cost of the boiler system

For finding out the optimum value of the feed water temperature, results from Fig. 3 and 4 are combined. This combined analysis of the previous two steps given in Fig. 5 shows that, whereas unit product cost of feed water heaters increases with an increase in the feed water temperature, the unit product cost of boiler decreases. Hence a tradeoff has to be made to achieve the optimal state. This optimal state appears where the two curves are intersecting. At this point the feed water temperature is found to be 464 K and the unit product costs for the boiler and the air pre- heater are found to be 0.3177 Rs/MJ and 0.2205 Rs/ MJ. If further reduction in unit product cost of the boiler has to be achieved more money would have to be spent on providing air at higher temperatures resulting in an increase in the overall unit product cost of the boiler system.

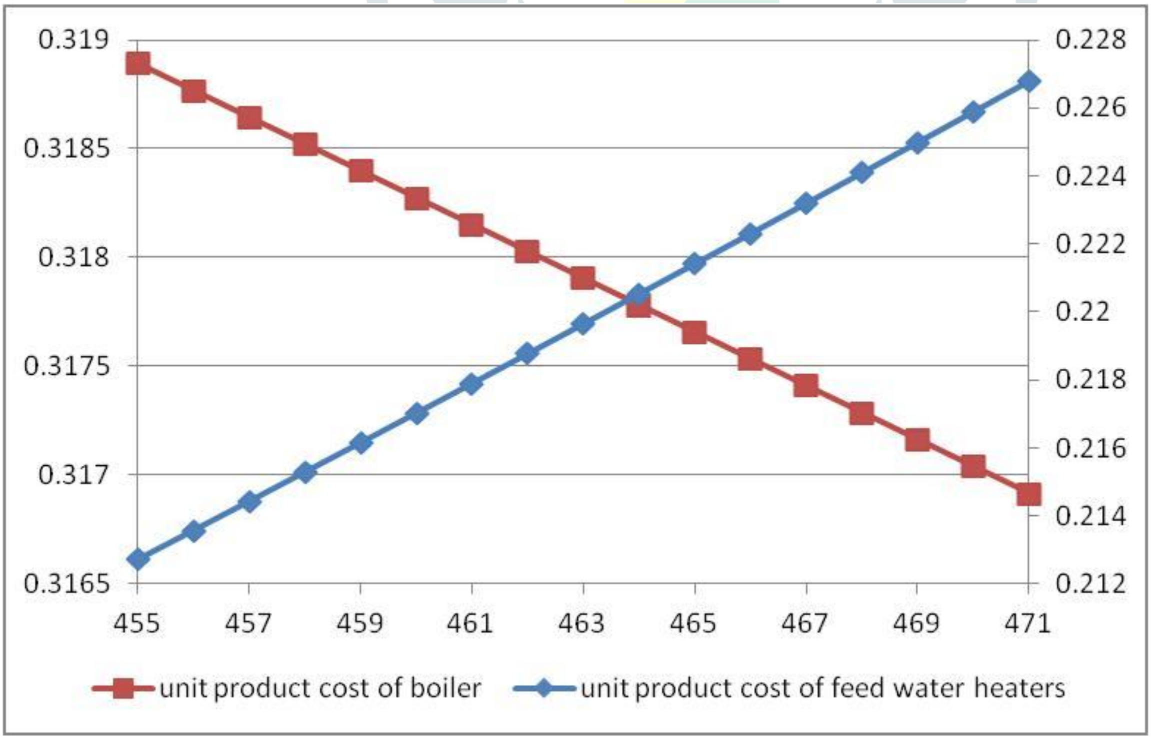

Fig. 5 Combined effect of feed water temperature on unit product cost of boiler and feed water heaters

Based on the results of the study logarithmic relations have been developed for exergetic efficiency of the boiler system, unit product cost of feed water heaters and unit product cost of the boiler system as functions of feed water temperature. Eqns. (9), (10) and (11) illustrate these relationships.

$$\varepsilon_b = -0.2309 + 0.1049\ln(T_{fw}) \quad (9)$$

$$c_{fw} = -2.281 + 0.4074\ln(T_{fw}) \quad (10)$$

$$c_b = 0.6687 + -0.0572\ln(T_{fw}) \quad (11)$$

The above relations have been tested for different temperature ranges of hot air and the results obtained from them have been satisfactory with small variations as the process variables change. These relations reduce the calculation time and have been found to be very useful in quick thermoeconomic analysis of boiler performance.

5. Conclusions

The concept of exergy provides a much better technique to analyze the thermal systems as compared to the conventional first law based approach as it is easy to assign monetary values to exergy. In a thermal power plant boiler is the component where maximum exergy destruction takes place which is key to improving the efficiency of the plant. The current study makes use of this concept to analyze the boiler system used in a coal fired thermal power plant and shows in detail the effect of hot air temperature on the performance of the boiler system. This study brings forth the key component affecting the performance of the boiler system which is the feed water temperature as it has significant bearing on the efficiency of the system.

Effect of feed water temperature on exergetic efficiency of the boiler, unit product cost of air pre- heater and unit product cost of the boiler have been carefully studied and analyzed. Optimization of the boiler system has been achieved on the basis of the fact that unit product cost of feed water heaters increase with increase in the feed water temperature and the unit product cost of boiler system decrease with the same. An optimal state has been achieved which provides the optimal value of the feed water temperature at which the feed water should be delivered to the boiler system.

Finally, a series of logarithmic relations have been established which correlate the feed water temperature to the exergetic efficiency, unit product cost of the feed water heaters and the unit product cost of the boiler. The validity of these correlations has been checked for different temperature range and it has been found that these relations provide a robust correlation model to analyze the boiler system with minor variations as a result of the process variables.

Overall this study provides a robust model and excellent means to analyze the thermoeconomic performance of the boiler system with respect to the hot air temperature.

References

[1] Rosen M. (2001) Editorial-Exergy in industry: Accepted or not? Exergy, An International Journal, 2, 67.

[2] Rosen M. (2001) Energy and Exergy based comparison of coal fired and nuclear steam power plants, Exergy International Journal, 180-192.

[3] Rosen M. (2002) Energy crisis or exergy crisis? Exergy, An In-ternational Journal, 125-127.

[4] Rosen M. and Dincer I. (2003) Thermoeconomic, Analysis of power plants: an application to a coal fired electrical generating station, Energy Conversion and Management, , 2743-2761.

[5] Bejan A., Tsatsaronis G. and Moran M. (1996) Thermal Design and Optimization, New York: Wiley.

[6] Valero A. and Torres C. (2002) On causality in organized energy systems: II. Symbolic exergoeconomics, University of Zaragoza, Spain.

[7] Valero A., Lerch F., Serra L. and Royo J. (2002) Structural theo-ry and thermoeconomic diagnosis: Part II, Application to actual power plant, Energy Conversion and Management, 1519-1535.

[8] Moran M.J. and Sciubba E. (1994) Exergy analysis: Principles and practice, Journal of Engineering for Gas Turbines and Power, 285-290.

[9] Mishra R.D., Sahoo P.K. and Gupta A. (2002) Application of exergetic cost theory to LiBr/H2O vapour absorption system, Energy, 1009-1025.

[10] Mishra R.D., Sahoo P.K. and Gupta A. (2003) Thermoeconomic optimization of single effect water/ LiBr vapour absorption refrigeration system, International Journal of Refrigeration, 158-169.

[11] Mishra R.D., Sahoo P.K. and Gupta A. (2005) Thermoeconomic optimization of double effect water/ LiBr vapour absorption refrigeration system, International Journal of Refrigeration, 331-343.

[12] Sahoo P.K. (2008) Exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming, Applied Thermal Engineering, 1580- 1588.