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OPTIMIZATION OF A STEAM BOILER USING BY LINEAR PROGRAMMING METHOD

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Abstract. *As energy and equipment costs increase, an efficient steam system becomes more important in the overall economics of processing plant. A linear programming model for the optimization of a steam boiler is presented in this paper. We have developed a mathematical model for analyzing the performance of total cost of a steam boiler. The optimal solution in the model is the size of heat exchangers of a steam boiler which is characterized by the lowest total costs, which consist of investment cost and cost of coal for ten years. Investigations show that total costs might maximally save up to 30%.*

Key words: *Steam Boiler, Optimization, Linear Programming*

1. INTRODUCTION

Technology processes in industry need heat. Heat is needed for space heating and different technological processes. When a steam boiler produces heat there is a need for its optimization. In this paper, a linear programming (LP) model is developed for that purpose.

There are many methods for the optimization of energy system performance. LP is one of several mathematical techniques that attempt to solve problems by minimizing or maximizing a function of several independent variables. This method is widely used and is among the best ones for analyzing complex systems. Typical application of linear programming is for the optimization of heat and mass exchanger networks [1], industrial building [2], energy systems [3,4,5,6] , large electric utility [7], etc.

We have studied a steam boiler which converts the feed water to superheated steam at pressure 36bar and temperature 450^{o}C. A steam boiler, shown in Fig. 1, comprises the following major elements: furnace (F), first (FSH) and second (SSH) super heater, convective surface (CS), drum (D), economizer (ECO) and air heater (AH). Water enters at ECO where it is heated at temperatures below the boiling point for about 30^{o}C. Heated

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water is sent to F and CS where water turns into steam. The steam water mixture rises into a steam boiler drum where water separates from steam and generation of dry saturated steam at 39bar is ensured. Super heater is made up of two parts. In FSH saturated steam is superheated at 400°C. Then steam flows through cooler (C) where it mixes with feed water which reduces its temperature to 360°C. That steam is sent to SSH and from that point superheated steam at 36bar and 450°C leaves the steam boiler.

For a particular heat exchanger we assumed that the product of its heating size and coefficient of thermal transmittance *Z=FU* is a constant and characteristic value of this heat exchanger. Depending on the type and cost of fuel, mass flow rate at a steam boiler exit and costs we obtained characteristic values for minimum total cost of a steam boiler. In our case total costs consist of investment costs of heat exchanger and costs of fuel for ten years.

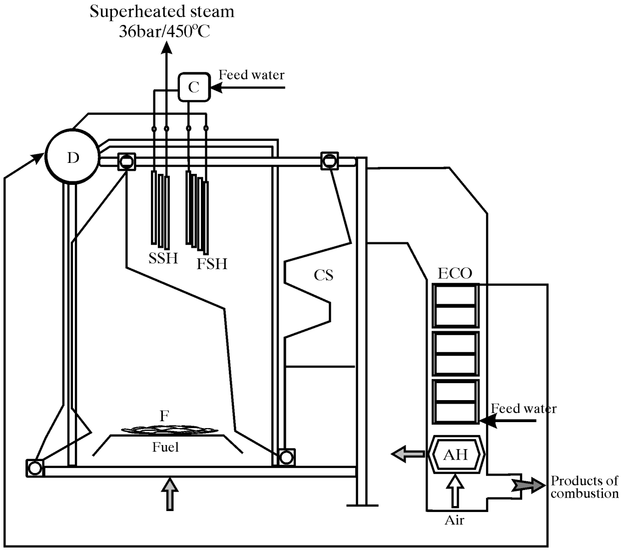


Fig. 1. Schematic diagram of a steam boiler

2. MATHEMATICAL MODEL

Figure 2 shows the heat exchanger network used to model the energy system of the steam boiler of Fig. 1. The mathematical representation of the mass and energy flow consists of a set of linear and nonlinear equations. The linear equations of mathematical model of the system are:

$$m_w = m_{w1} + m_{w2} \tag{1}$$

$$m_A = L \cdot B \tag{2}$$

$$m_{cp} = V \cdot B \tag{3}$$

$$m_{out} = m_w + m_1 \tag{4}$$

$$m_w \cdot h_4 + m_1 \cdot h_1 = m_{out} \cdot h_5 \tag{5}$$

where m_w [kg/s] is the mass flow of water or steam, m_{w1} [kg/s] is the mass flow of water through F, m_{w2} [kg/s] is the mass flow of water through CS, m_A [kg/s] is the mass flow of air, L [kg/kg] is the mass of air required for combustion, B [kg/s] is the consumption of fuel, m_{cp} [kg/s] is the mass flow of combustion products, V [kg/kg] is the mass of combustion products for 1 kg of fuel, $m_{out} = (6\div10)$ [kg/s] is the mass flow of steam at a steam boiler exit, m_1 [kg/s] is the mass flow of feed water, $h_4 = 3211$[kg/s] is the specific enthalpy of steam from FSH, h_1=591,9[kJ/kg] is the specific enthalpy of feed water and h_5=3113[kg/s] is the specific enthalpy of steam at exit of C.

Here, Eq. (1) presents the mass balance for node A; Eq. (2) presents the mass balance of air for combustion; Eq. (3) presents mass balance of product of combustion; Eq. (4) and (5) present mass and energy balances of C.

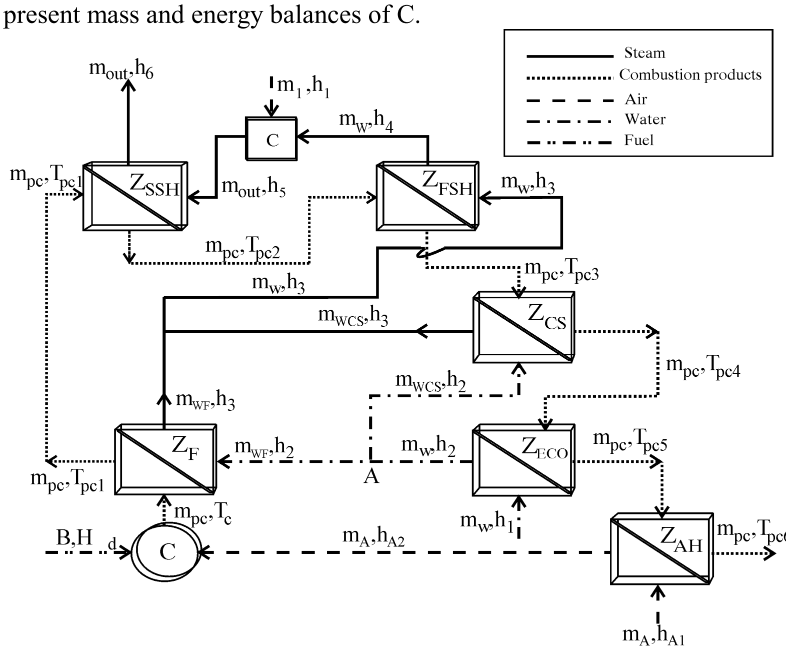


Fig. 2. Schematic diagram of heat exchanger network of the steam boiler

Nonlinear equations of mathematical model of the system are the following energy balances at:

- Furnace F:

$$m_{cp} \cdot c_{pcp} \cdot (T_c - T_{cp1}) = m_{w1} \cdot (h_3 - h_2) \tag{6}$$

$$\frac{Z_F}{2} \cdot (T_c + T_{cp1} - T_2 - T_3) = m_{w1} \cdot (h_3 - h_2) \tag{7}$$

- the Second super heater SSH:

$$m_{cp} \cdot c_{pcp} \cdot (T_{cp1} - T_{cp2}) = m_{out} \cdot (h_6 - h_5) \tag{8}$$

$$\frac{Z_{SSH}}{2} \cdot (T_{cp1} + T_{cp2} - T_5 - T_6) = m_{out} \cdot (h_6 - h_5) \tag{9}$$

- the First super heater FSH:

$$m_{cp} \cdot c_{pcp} \cdot (T_{cp2} - T_{cp3}) = m_w \cdot (h_4 - h_3) \tag{10}$$

$$\frac{Z_{FSH}}{2} \cdot (T_{cp2} + T_{cp3} - T_3 - T_4) = m_w \cdot (h_4 - h_3) \tag{11}$$

- Convective surface CS:

$$m_{cp} \cdot c_{pcp} \cdot (T_{cp3} - T_{cp4}) = m_{w2} \cdot (h_3 - h_2) \tag{12}$$

$$\frac{Z_{CS}}{2} \cdot (T_{cp3} + T_{cp4} - T_2 - T_3) = m_{w2} \cdot (h_3 - h_2) \tag{13}$$

- Economizer ECO:

$$m_{cp} \cdot c_{pcp} \cdot (T_{cp4} - T_{cp5}) = m_w \cdot (h_2 - h_1) \tag{14}$$

$$\frac{Z_{ECO}}{2} \cdot (T_{cp4} + T_{cp5} - T_2 - T_3) = m_w \cdot (h_2 - h_1) \tag{15}$$

- Air heater AH:

$$m_{cp} \cdot c_{pcp} \cdot (T_{cp5} - T_{cp6}) = m_A \cdot (h_{A2} - h_{A1}) \tag{16}$$

$$\frac{Z_{AH}}{2} \cdot (T_{cp5} + T_{cp6} - T_{A1} - T_{A2}) = m_A \cdot (h_{A2} - h_{A1}) \tag{17}$$

where c_{pcp} [J/kgK] is the specific heat of combustion products, T_c [K] is the temperature of combustion, T_{pci} [K] is the temperature of combustion products, Z_i [kW/K] is the characteristic value of heat exchanger of the steam boiler, $T_{A1} = 333$ [K] is the temperature of cold air, $T_{A2} = 373$ [K] is the temperature of heated air, $h_2 = 994$ [kJ/kg] is the specific enthalpy of heated water, $h_3 = 2801$ [kJ/kg] is the specific enthalpy of saturated steam, $h_6 = 3324$ [kJ/kg] is the specific enthalpy of superheated steam at exit of the steam boiler and temperatures of water and steam at actual place of the steam boiler: $T_1 = 413$ [K], $T_2 = 492$ [K], $T_3 = 523$[K], $T_4 = 673$[K] $T_5 = 633$[K] and $T_6 = 723$ [K].

Considering these mass and energy balances we assumed the following: the heat exchangers of the steam boiler are counter-flow type; the coefficient of thermal transmittance is constant throughout the exchanger; instead of mean logarithmic temperature difference we used the mean arithmetic temperature difference; the excess air coefficient is constant value of $\lambda = 1{,}2$; and there are no heat losses through connecting piping and passages.

The constraints of the mathematical model are given by using the following inequalities:

$$T_c > T_{cp1} \tag{18}$$

$$T_{cp1} > T_{cp2} \tag{19}$$

$$T_{cp2} > T_{cp3} \tag{20}$$

$$T_{cp4} > T_{cp5} \tag{21}$$

$$T_{cp5} > T_{cp6} \tag{22}$$

$$T_{cp6} > 130 \tag{23}$$

$$m_{w1} > 0{,}8 \cdot m_w \tag{24}$$

$$m_F > 0{,}5 \cdot m_{out} \tag{25}$$

Objective function, which is to be minimized, is the total costs of the steam boiler (investment cost of piping, valves and accessories are not analyzed):

$$F = IN + G = C_F \cdot Z_F + C_{SSH} \cdot Z_{SSH} + C_{FSH} \cdot Z_{FSH} + C_{CS} \cdot Z_{CS} + C_{ECO} \cdot Z_{ECO} + C_{AH} \cdot Z_{AH} + C_F \cdot B \cdot \tau \tag{26}$$

where $IN = \sum_{i=1}^{6} C_i \cdot Z_i$ [€] is the investment costs of heat exchangers, G [€] is the fuel cost, period of time τ =10 years.

Nonlinear terms in energy balances are mass flow m_{cp} times temperature of combustion T_{cpi} and the characteristic value of heat exchanger Z_i times T_{cpi}. Nonlinear terms were linearized by using Taylor series expansions.

Firstly, the initial values are assumed for the 13 linearized variables: $(T_{cp1})_c$, $(T_{cp2})_c$, $(T_{cp3})_c$, $(T_{cp4})_c$, $(T_{cp5})_c$, $(T_{cp6})_c$, $(Z_F)_c$, $(Z_{SSH})_c$, $(Z_{FSH})_c$, $(Z_{CS})_c$, $(Z_{ECO})_c$, $(Z_{AH})_c$ and $(m_{cp})_c$. Then we calculated T_{cp1}, T_{cp2}, T_{cp3}, T_{cp4}, T_{cp5}, T_{cp6}, Z_F, Z_{SSH}, Z_{FSH}, Z_{CS}, Z_{ECO}, Z_{AH}, B, m_w, m_{wF}, m_{wCS}, m_{pc}, m_A and m_1. from the previous equations (1-17). The values for the linearized variables are compared to their assumed values. If there is a difference then the calculated values are taken as the initial values for the new iteration. This procedure is repeated until all the calculated values are almost equal to the input values. To solve this problem we have used software "SYSTEM".

3. RESULTS OF OPTIMIZATION

The linear programming model ran for two scenarios: A and B.

The first scenario A was carried out for three types of coal (lignite, dark coal and stone coal), coal cost C_f = 0,06 [€/kg] and investment costs in [€K/kW]: C_L = 27500, C_{SPP} = 22500, C_{PPP} = 20000, C_{KP} = 21000, C_{EKO} = 15000 and C_{ZW} = 12500. Fig. 3. shows the optimal total characteristic value of the steam boiler for different mass flow rate at the steam boiler exit and different type of coal. A greater mass flow at the steam boiler exit causes a higher total characteristic value of the steam boiler $Z_{tot} = \sum_{i=1}^{6} Z_i$, which means a greater heating size of the steam boiler. The highest value Z_{tot} exists when the steam boiler's fuel is lignite, and the lowest value exists when the fuel is stone coal. Reductions of total heating size of the steam boiler, in relation to the case when coal is lignite, are up to 18% for dark coal and 23% for stone coal. Total costs are reduced up to 25% for dark coal and 30% for stone coal.

The second scenario B was carried out when m_{out} = 8 [kg/s] and fuel is dark coal. The first set is the same as in the previous scenario A. In the second and third set investment costs are higher per 50% while the cost of coal is reduced per 20% in relation to the previous scenario.

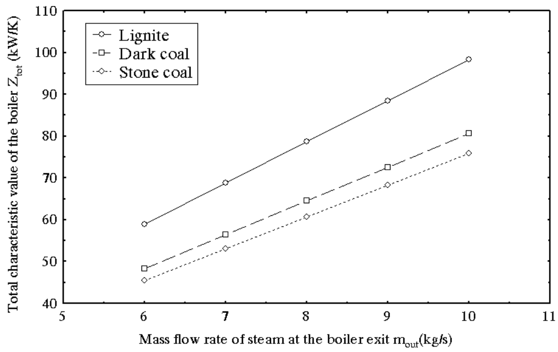
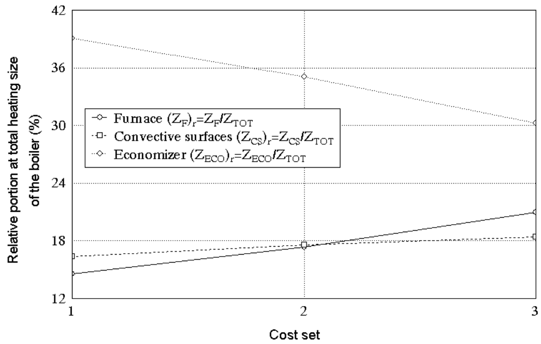
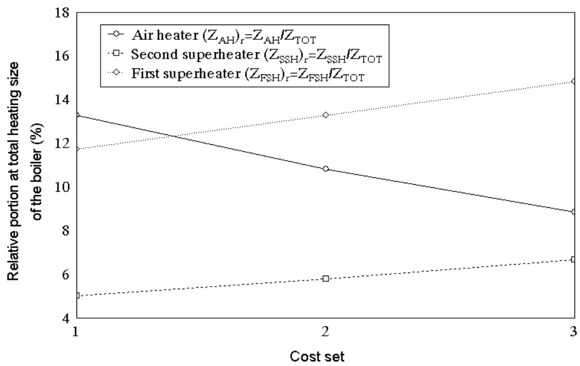


Fig. 3. Optimal total characteristic value of the steam boiler vs. mass flow rate at the boiler exit for different coals

Figure 4 shows the change of the relative portion of heating sizes at total heating size of the steam boiler. Total heating size of the steam boiler decreases with the increase in its investment costs. The changes of costs set from 2 to 3 cause the following reductions: furnace 2%, convective surface 15%, the first super heater 9%, the second super heater 6%, economizer 32%, and air heater 35%. For this case reduction of the total heating size of the steam boiler is 18%.



a)



b)

Fig. 4. Relative portion of heat exchanger size at total heating size of the steam boiler for three different sets of costs

The reduction of total heating size of the steam boiler is greater than the reduction of heating size of furnace, convective surface, and the first and second super heater for the change of cost sets 1 to 3. These cause the growth of their relative portion at total heating size of the steam boiler. However, the reduction of total heating size of the steam boiler is lower than the reduction of heating size of economizer and air heater because their relative portion decreases. The changes of cost set from 1 to 3 cause the decrease of the total cost of the steam boiler. In relation to the first set the total cost at the second set is lower for 13% and at the third set for 22%.

4. Conclusion

The paper shows that it is possible to use linear programming model to find optimal heating size and consumption of coal for the minimal total cost of the steam boiler. Depending on the mass flow rate of steam at the steam boiler exit we get optimal results for different types of coal. Also, the paper presents the change of relative portion of major heating sizes at total heating size of the steam boiler for three cost sets. These results can be used for optimization of the steam boiler in order to avoid losses of energy and money.

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OPTIMIZACIJA PARNOG KOTLA PRIMENOM LINEARNOG PROGRAMIRANJA

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U uslovima rasta cena energije i opreme energetskih sistema optimalan rad sistema postaje veoma bitan. U radu je prikazana optimizacija parnog kotla primenom metode linearnog programiranja. Realizovan je matematički model i analizirani su ukupni troškovi korišćenja parnog kotla. Rezultati optimizacije parnog kotla su veličine njegovih grejnih površina za koje su ukupni troškovi, koji se sastoje od investicionih troškova i troškova korišćenja goriva za period od 10 godina, minimalni. Isptivanja su pokazala da se ukupni troškovi mogu smanjiti do 30%.