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Exergy Efficiency of Bulgarian Lignite fired Steam Boiler P-62 at various Load and Fuel Quality

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Abstract

The article is presented a study of exergy and energy efficiency of steam boiler Ep 670/140 also referred as P-62 that burns low-quality Bulgarian lignite. Both efficiencies were determined in design modes of the boiler: on two loads - 70 % and 100 % and using on each load three different qualities of fuel in terms of its lower heating value - deteriorated 5525 kJ/kg (1320 kcal/kg), guaranteed 5945 kJ/kg (1420 kcal/kg) and improved 6700 kJ/kg (1600 kcal/kg). Due to the specific design features of the boiler - "T" shape design and numerous heat transfer surfaces the "fuel-product efficiency" method for calculation is used. The obtained results show that exergy efficiency in whole range of load and lignite quality change is low - between 31 and 34 %. This require detailed exergy analysis of the boiler to determine its internal exergy losses and improve exergy efficiency.

Keywords: exergy analysis; energy and exergy efficiency; steam boiler; low rank lignite.

1. Introduction

Bulgaria has large deposits of lignite in the Maritsa-East basin. Eight 220 MW power units in two TPP are equipped with boilers P-62. The steam boiler P-62 is designed to use local lignite with very low quality - its lower heating value (LHV) is between 5525 kJ/kg (1320 kcal/kg) and 6700 kJ/kg (1600 kcal/kg).

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A specific feature of Bulgarian lignite is that they have a higher content of sulfur, ash and moisture. Burning these coals has a negative impact on the environment.

Therefore the boilers that burn such coal should have high efficiency. During designing of P-62 steam boiler besides high reliability is sought high energy efficiency, but not defined boiler exergy efficiency.

It is known that the biggest exergy losses and destruction are in the boiler, so it is important to determine boiler exergy efficiency.

2. Short description of the boiler and fuel base

2.1. Boiler P-62

The P-62 steam boiler is produced in Russia by JSC Machine Building Factory of Podolsk.

It has "T-shape" design - one combustion chamber and two gas streams respectively two drums and two main water-steam lines, including reheating [10].

The main operational parameters of the boiler (on 100 % load) are:

- capacity (main steam production) - 186.11 kg/s (670 t/h);
- main steam pressure - 12.75 MPa (130 kgf/cm^2);
- main steam temperature - 545 °C;
- reheat steam flow - 161.11 kg/s (580 t/h);
- reheat steam pressure - 2,55 MPa (26 kgf/cm^2);
- reheat steam temperature - 545 °C;
- feed water temperature - 242 °C;
- flue gas temperature - 158÷160.5 °C (depends coal quality);
- range of load change - 70÷100 %.

All P-62 boilers burn local lignite coal from Maritsa East basin.

2.2. Fuel base of boiler P-62

The lignite coals from Maritsa East basin have very bad and changed quality.

For that reason the boiler is designed to use coal with middle quality called guaranteed coal, and furthermore coal with worse quality called deteriorated coal also coal with better quality called improved.

The composition of these three in terms of quality coals by ultimate analysis and their lower heating value (LHV) are presented in table 1.

Table 1: Lignite coal composition and LHV (ultimate analysis)

Coal quality	Composition, w. %							LHV, kJ/kg (kcal/kg)
	C	S	H	O	N	W	A	
Deteriorated	17.56	1.74	1.61	6.49	0.31	56.5	15.79	5525 (1320)
Guaranteed	18.54	1.74	1.68	6.75	0.33	56.0	14.96	5945 (1420)
Improved	20.66	1.67	1.69	7.52	0.23	56.0	12.23	6700 (1600)

As can be seen from table 1 the used lignite coal have some not good characteristics - high content of moisture and ash, resp. not large LHV.

3. Methodology for exergy efficiency evaluation

The exergy efficiency of a boiler can be obtained in two ways. In the first way the boiler is considered as a system divided on some subsystems - combustor and heat exchangers and for every subsystem exergy analysis is done [1, 6, 7]. This method is suitable for gas (fire) tube boilers and water tube boilers with small number of heat exchangers. In the second way the boiler is considered as one system with inputs and outputs representing inlet and outlet mass and energy flows. This way is used in the present study because of "T" shape design of the boiler. Presenting of the boiler as a system with inputs and outputs is shown in figure 1. In addition to the usual inputs and outputs of a steam boiler with steam reheating on water-steam side is shown an input "sprays". This is done because the water sprays for main superheated steam temperature control have different pressure and temperature from feed water pressure and temperature.

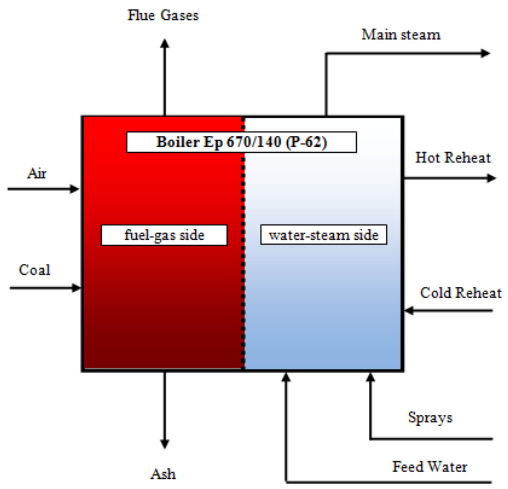

Figure 1: Boiler inlet and outlet mass flows

There are many formulation of exergy efficiency proposed in the literature. They can divided in two groups [2]:

- input-output efficiency;
- produced-consumed efficiency.

In case that can be defined product derived from fuel burning is suitable to use the formulation from the second group "fuel-product efficiency" [5]. According this formulation the exergy efficiency is:

$$\eta_{ex} = \frac{product\ exergy}{fuel\ exergy} = \frac{Ex_p}{Ex_f} \tag{1}$$

3.1. Calculation formulas for product exergy

The products of steam boiler are main (primary) superheated and reheat (secondary) steam. Then product exergy is sum of main (MS) and reheat (RS) steam exergy:

$$Ex_p = Ex_{MS} + Ex_{RS} \tag{2}$$

Exergy of main steam is:

$$Ex_{MS} = \dot{m}_{MS}e_{MS} - \dot{m}_{FW}e_{FW} - \dot{m}_{spr}e_{spr} \tag{3}$$

where

$\dot{m}_{MS},\ \dot{m}_{FW},\ \dot{m}_{spr}$ – mass flow rate of main steam, feed water and sprays in kg/s;

$e_{MS},\ e_{FW},\ e_{spr}$ – specific exergy of main steam, feed water and spray flows in kJ/kg.

Exergy of reheated steam is:

$$Ex_{RS} = \dot{m}_{RS}(e_{HR} - e_{CR}) \tag{4}$$

where

$\dot{m}_{RS}$ *is* mass flow rate of reheated steam in kg/s;

$e_{HR},\ e_{CR}$ – specific exergy of hot and cold reheat steam in kJ/kg.

The specific thermo-mechanical exergy (neglecting kinetic and potential) is calculated by known expression:

$$e = (h - h_0) - T_0(s - s_0) \tag{5}$$

where

h, h_0 - specific enthalpy of steam/water at operational and reference conditions in kJ/kg;

s, s_0 - specific entropy of steam/water at operational and reference conditions in kJ/(kg.K);

T_0 - reference (environment) temperature in K.

3.2. Calculation of fuel exergy

The design of the boiler is done for environmental conditions - temperature T_0=298 K and pressure P_0=101325 Pa.

These values are assumed as reference environment (dead state). The coal enters to the boiler (to its coal preparation systems) with the same temperature and pressure.

In this case the fuel exergy is its chemical exergy only. Likewise the combustion air enters to the boiler (to its air pre-heater) with dead state temperature and pressure, therefore air exergy is zero.

Many correlations have been proposed to estimate the specific chemical exergy of different types of fuels including coals [3, 8, 9].

Every correlation has certain limitation concerning coal composition. For lignite composition (Table 1) is applicable Kotas correlation related to solid fuels with a mass ratio of oxygen to carbon (O/C) less than 0.667 [4]. Bulgarian lignite from table 1 have ratio O/C between 0.36 and 0.37.

The expression for specific chemical exergy of solid industrial fossil fuels is:

$$e_f = \left(LHV + W.h_{fg}\right)\varphi_{dry} + 9417.S \qquad (6)$$

where

W is mass fraction of moisture in the fuel;

h_{fg} =2442 kJ/kg is the enthalpy of evaporation of water at temperature 25 °C ;

S is mass fraction of sulphur in the fuel.

$$\varphi_{dry} = 1.0437 + 0.1882\frac{H}{C} + 0.0610\frac{O}{C} + 0.0404\frac{N}{C} \qquad (7)$$

4. Input design data for product exergy calculation

The needed input data to calculate exergy of the fife input/output streams connected with boiler water-steam side are presented in table 2.

Table 2: Design data of boiler water-steam side

fuel	stream	70 % load mass flow kg/s	70 % load pressure bar	70 % load temperature °C	100 % load mass flow kg/s	100 % load pressure bar	100 % load temperature °C
1320 kcal/kg	main steam	133.33	132.39	545	186.11	137.29	545
	feed water	118.92	142.59	225	167	155.93	242
	sprays	14.42	161.81	154	19.11	175.54	163
	hot reheat steam	116.67	18.63	545	161.11	25.5	545
	cold reheat steam	116.67	20	313	161.11	27.46	337
1420 kcal/kg	main steam	133.33	132.39	545	186.11	137.29	545
	feed water	119.64	142.59	225	168.25	155.93	242
	sprays	13.69	161.81	154	17.86	175.54	163
	hot reheat steam	116.67	18.63	545	161.11	25.5	545
	cold reheat steam	116.67	20	313	161.11	27.46	337
1600 kcal/kg	main steam	133.33	132.39	545	186.11	137.29	545
	feed water	120.19	142.59	225	167.97	155.93	242
	sprays	13.14	161.81	154	18.14	175.54	163
	hot reheat steam	116.67	18.63	545	161.11	25.5	545
	cold reheat steam	116.67	20	313	161.11	27.46	337

5. Results

The specific chemical exergy of used lignite coal, calculated by expressions (6) and (7), is presented in table 3.

Table 3: Specific chemical exergy of lignite coal

Coal quality	LHV, kJ/kg (kcal/kg)	φ_{dry}	e_f kJ/kg	e_f/LHV
Deteriorated	5525 (1320)	1.0842	7568	1.39
Guaranteed	5945 (1420)	1.0836	7999	1.36
Improved	6700 (1600)	1.0817	8782	1.33

Figure2 and Figure 3 show exergy of input fuel flow and exergy of products - main steam and reheat steam, calculated using expressions (3), (4) and (5).

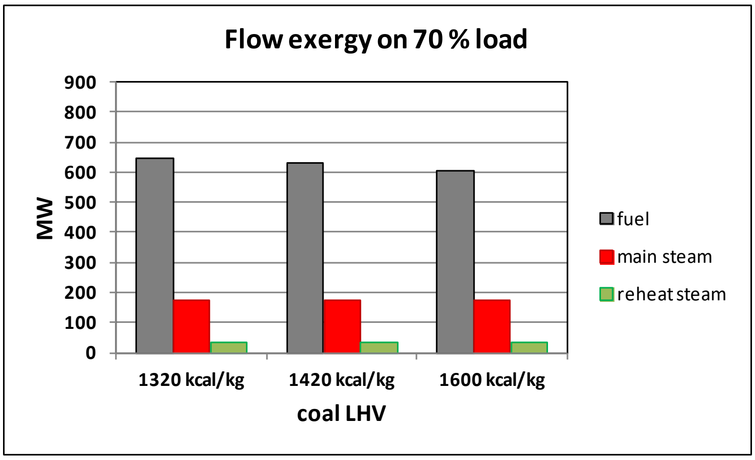

Figure 2: Input and output exergy on 70 % boiler load

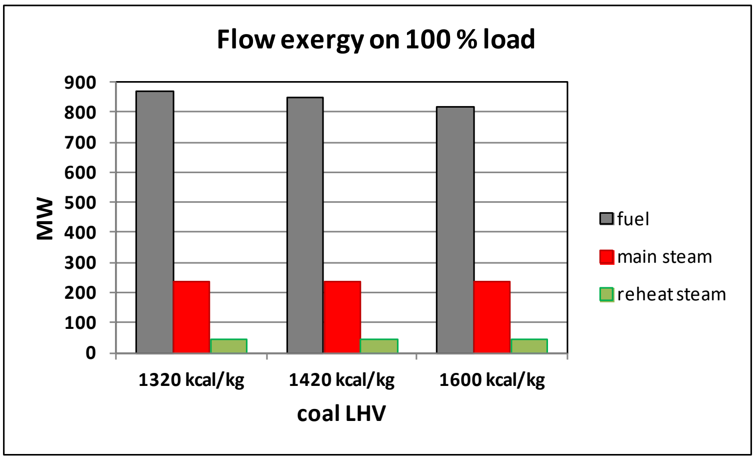

Figure 3: Input and output exergy on 100 % boiler load

The results for exergy efficiency of P-62 boiler using the three types of fuel in terms of its quality and works on two loads - 70 % and 100 % are presented in figure 4. The results for energy efficiency under the same design conditions are presented in figure 5.

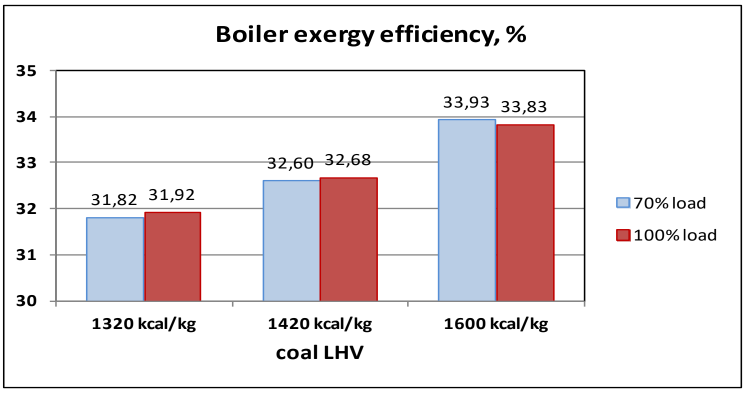

Figure 4: Exergy (second law) efficiency of P-62 boiler

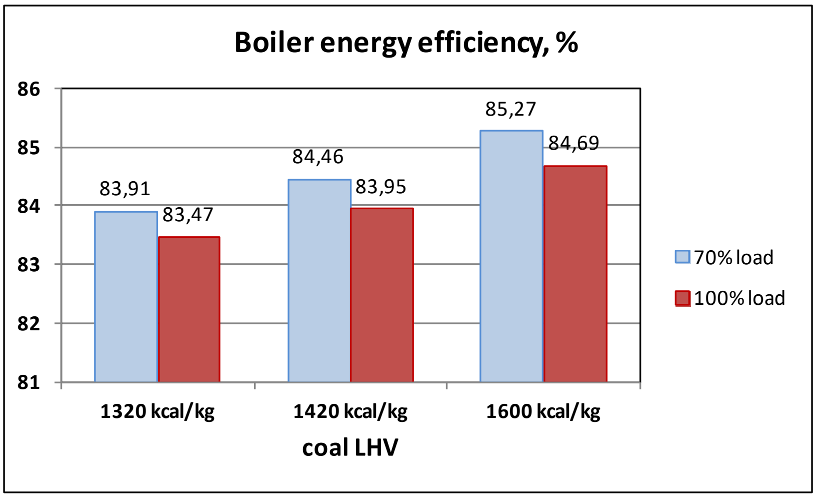

Figure 5: Energy (first law) efficiency of P-62 boiler

6. Conclusion

In the study was performed calculation of exergy efficiency of steam boiler Ep 670/140 (P-62) burns Bulgarian lignite. For higher accuracy of the results, the boiler is regarded as an object with input/output substance flows. The calculations are done using efficiency formulation "fuel-product efficiency".

The values obtained for specific chemical exergy of fuel are much bigger on their lower heating value - the ratio specific chemical exergy to lower heating value is 1.33÷1.39. The reason for this is high content of moisture in the Bulgarian lignite - about 56 %.

Exergy efficiency is obtained for two various loads - 70 % and 100 % and on every one with three different in term of fuel composition and its lower heating value. The calculated exergy efficiency varies between 31 % and 34 %, while the energy efficiency varies between 83 % and 86 %. With an increase of fuel LHV increasing exergy and energy efficiencies. The lower value of exergy efficiency at 100% of that at 70% load and 1600 kcal/kg is due to the increased spray flow rate in this case.

The obtained exergy efficiency by the procedure "fuel-product efficiency" does not reveal where and how much are the exergy losses and destruction. So as further work is necessary to make a detailed exergy analysis of P-62 boiler to reveal the larger exergy losses and possibly to improve its exergy efficiency.

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