Efficiency assesment of a lignite-fired steam generator

Dosa, Ion and Marica, Laura

University of Petrosani, University of Petrosani

January 2017

EFFICIENCY ASSESSMENT OF A LIGNITE-FIRED STEAM GENERATOR

***Dosa Ion*[1], *Marica Laura*[2]**
Associate professor PhD[1], Assistant Professor PhD[2]
University of Petrosani

Abstract: Research on lignite-fired power plants highlighted that the efficiency of lignite-fired is 88.9% for PC (pulverized coal) and USC PC (ultra-supercritical pulverized coal) units while for CFBC (circulating fluidized bed combustion) is 87.0%. The efficiency assessment carried out for the boiler presented in this paper revealed that the highest efficiency achieved in actual operating conditions is 83% while the rated efficiency is 85%. Retrofitting old boilers to reach the efficiency of modern ones, around 95% is not an option since they will not comply with environmental standards.

1. INTRODUCTION

The primary method of producing steam for power generation is by using combustion boilers. The need to increase energy efficiency in the EU is underlined in the Directive 2012/27/EU on energy efficiency. The goal is to achieve 20% savings on the Union's primary energy consumption by 2020 compared to projections [1]. One way to achieve this goal is by increasing efficiency of electrical power production, and as a result less fuel is required to generate each kWh.

Efficiency of retrofitted steam generators represents an important part of papers published on boiler efficiency, but just as much papers were analyzing the efficiency of modern ones, built using state of the art technologies.

An extensive research on lignite-fired power plants was carried out by Qian Zhu [2], highlighting that the efficiency of lignite-fired is 88.9% for PC (pulverized coal) and USC PC (ultra-supercritical pulverized coal) units while for CFBC (circulating fluidized bed combustion) is 87.0%.

2. PROBLEM PRESENTATION

According to NPC [3] report 76% of steam generators produced 30 years ago, are still in USA, as a result of the long life-cycle and expensiveness. The same situation can be found in the rest of the world too. New generation of steam generators are developed with higher efficiency and low-emissions to meet these requirements. As new units became operational, the average efficiency of power plants will improve, rather than by retrofitting older ones, but this is a process which can take a long time.

The right time for steam generator replacement can be estimated by assessment of energy performance of boilers, which requires heat balance calculations.

Energy auditing in Romania is regulated by the state and supervised by the regulatory authority ANRE. Calculations must be carried out according to the published guide [4], based on algorithms and equations for heat balance calculations of various installations and equipment found in relevant literature [5][6].

2.1. A brief presentation of steam generator

CRG-1666 is a water tube steam generator (Fig. 1) with natural circulation, two Π shaped flue gas paths, a steam drum and 420 $t \cdot h^{-1}$ steam output at 137 bar pressure and 540 °C temperature. The rated efficiency is 85%. The rated feed water temperature is 230 °C at 158 bar pressure.

The steam drum is a horizontal cylinder holding a large volume of water, placed on the upper part of the steam generator, from which the down comers are supplied with water. In the steam drum the liquid phase is separated from the steam.

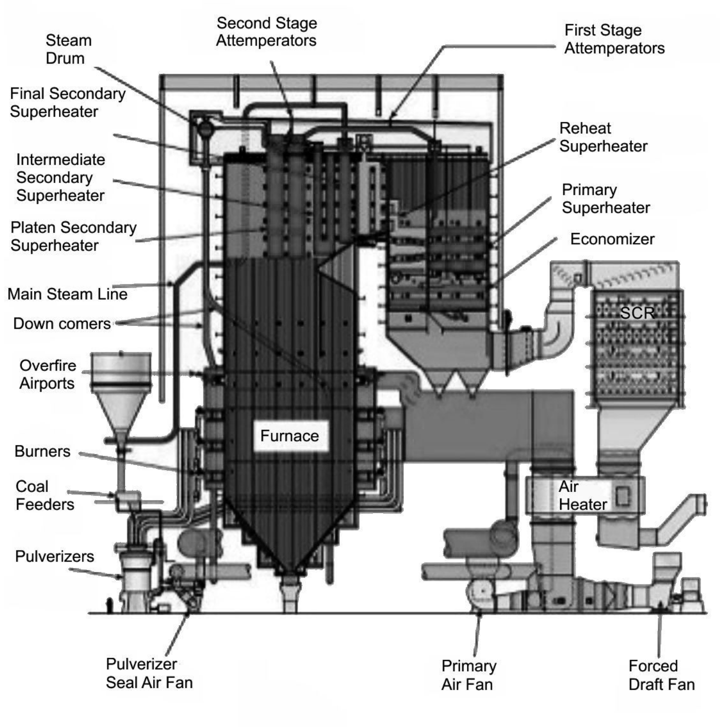

Fig. 1
Schematic of water tube boiler [7] (steam generator)

The water drum is fed with water using feedwater pumps through the economizer where the water is preheated at 230 ºC. In the economizer, the water is heated using flue gases from the second flue gas path. As a result, the temperature of water is near the vapor temperature. In the vapor circuit: steam drum – water wall – drum a natural circulation occurs. The water reaches vapor temperature (approximately 345 ºC) and the liquid phase is separated in the steam drum. The vapours are superheated in the platen and the rear superheater of the second flue gas path, side walls of second flue gas path, I, II, III and IV superheater. These heat exchange surfaces are connected one after another on the steam side. Finally steam temperature reaches 540 ºC.

Between I and II superheater and II and III+IV superheater attemperators are placed, injecting feed water in order to regulate steam temperature.

The steam generator is equipped with a data acquisition system in order to track boiler operating parameters, also, indicator panels are located in the control room of the unit.

2.2. Balance outline and measured data

Balance outline corresponds with the physical contour of the CRG-1666 steam generator.

Inputs: the mixture of lignite-heavy fuel oil, air needed for combustion, boiler feed water. Outputs: flue gas, the produced superheated steam, blowdown, discharged ash (fly and bottom), heat lost through the walls of the steam generator.

As stated by regulations, in order to perform a proper heat balance analysis at least three different loads must be taken into account. The loads for performance tests were fixed to 295 $t \cdot h^{-1}$ – 70.24%, 360 $t \cdot h^{-1}$ – 85.71% and 400 $t \cdot h^{-1}$ – 95.24%.

Most data on steam generator operation were obtained from the data acquisition system and in addition to that, measurements were carried out in order to obtain more accurate data on combustion. Data on flue gas composition, flue gas temperature T_{ga} and coefficient of excess air λ is obtained (Table 1), using a TESTO 350 portable emission and combustion analyzer. During measurements coal samples were taken in order to obtain data on composition and lower heating value of used lignite (Table 2).

Table 1.
Flue gas composition

Nom.	**U.M.**	**CRG-1666 load**		
		70.24%	**85.71%**	**95.24%**
O_2	%	7.6	7.2	8.1
CO	%	0.038	0.03	0.177
CO_2	%	12.8	13.2	12.3
SO_2	%	0.021	0.022	0.0006
NO	%	0.02	0.009	0.009
T_{ga}	°C	151.3	156.7	152.9
λ		1.56	1.51	1.61

Table 2.
Lower heating value of lignite and heavy fuel oil

Load [%]	**Lignite**	**Heavy fuel oil**
	Lower heating value $kJ \cdot kg^{-1}$	
70.24	6,597.8	40,668.0
85.71	6,632.6	40,668.0
95.24	6,592.5	40,668.0

Also, samples taken from bottom and fly ash during operation were analyzed. Results on the average unburnt coal in bottom ash were: 2.47%, 2.65% and 2.69% while for fly ash were: 4.5%, 4.2% and 4.7%. During testing, different flow rates of heavy fuel oil (1,380, 1,495 and 1,587 kg·h-1) were mixed with pulverized lignite in order to sustain the flame.

Table 3.
Elemental analysis of heavy fuel oil and lignite

Nom.	**Symbol**	**Heavy fuel oil composition, r%**	**Lignite composition, r%**
Carbon	C	87.73	25.60
Sulphur	S	0.37	0.56
Hydrogen	H_2	10.65	1.08
Oxygen	O_2	0.70	6.85
Nitrogen	N	-	1.01
Nitrogen (gas)	N_2	0.15	-
Humidity	W	0.20	-
Humidity overall	W_t	-	41.00
Ash	A	0.20	23.90
Total, %		100.00	100.00

3. RESULTS OBTAINED

Results of calculations are presented in Table 4. In the columns item values for 70.24% load, 85.71% load and in the last column 94.24% load can be found.

Table 4.
Actual hourly heat balance

Nom.	**70.24% load**		**85.71% load**		**95.24% load**	
	GJ	**%**	**GJ**	**%**	**GJ**	**%**
INPUT						
Chemical heat of fuel Q_{cBi}	881.59	72.80	1062.64	72.21	1208.72	72.16
Physical heat of fuel Q_B	25.85	2.13	31.14	2.12	35.78	2.14
Physical heat of feed and injection water Q_a	284.57	23.50	356.36	24.22	404.98	24.17
Physical heat of air Q_L	19.03	1.57	21.39	1.45	25.62	1.53
TOTAL INPUT (Q_i)	**1211.04**	**100.00**	**1471.53**	**100.00**	**1675.10**	**100.00**
USEFUL HEAT OUTPUT						
Heat of produced steam Q_D	997.91	82.40	1224.85	83.24	1372.15	81.91
Total useful heat output Q_u	**997.91**	**82.40**	**1224.85**	**83.24**	**1372.15**	**81.91**
HEAT LOSS						
Mechanical incomplete combustion Q_{cmec}	5.54	0.46	7.20	0.49	8.42	0.50
Chemical incomplete combustion Q_{cga}	2.30	0.19	2.12	0.14	15.06	0.90
Heat loss through flue gas Q_{gacos}	137.56	11.36	162.56	11.05	189.88	11.34

Heat loss by bottom ash Q_{sg}	21.91	1.81	26.92	1.83	31.04	1.85
Heat loss by blowdown Q_{pj}	14.08	0.56	14.88	1.01	15.60	0.93
Wall loss Q_{per}	6.81	1.16	7.02	0.48	7.11	0.43
Unaccounted losses ΔQ	24.93	2.06	25.98	1.76	35.84	2.14
Total heat loss Q_p	**213.13**	**17.60**	**246.68**	**16.76**	**302.96**	**18.09**
TOTAL OUTPUT (Q_e)	**1211.04**	**100.00**	**1471.53**	**100.00**	**1675.10**	**100.00**

The net energy efficiency η_n, gross energy efficiency η_{tb} and specific fuel consumption *c* for different loads are presented in Table 5.

Table 5.
Efficiency parameters

Nomenclature	Load	Values
Net energy efficiency η_n [%]	**70.24%**	82.40
	85.71%	83.24
	95.24%	81.91
Gross thermal efficiency η_{tb} [%]	**70.24%**	80.91
	85.71%	81.73
	95.24%	80.02
Specific fuel consumption c [g e.f.· (kg steam)$^{-1}$]	**70.24%**	102.02
	85.71%	100.85
	95.24%	102.50

In order to compare actual parameters with optimal data values, an optimal heat balance was also calculated. Calculation were performed at rated parameters of steam generator: steam flow rate 420 t·h^{-1} output at 137 bar pressure and 540 °C temperature. Coefficient of excess air was considered 1.25 which is the rated value for this type of steam generator fired with lignite. The values of unburnt coal in bottom ash was considered 2.87% while for fly ash 1.27% (according to literature [5][6]). Flow rate of heavy fuel oil taken into account was 1,000 kg·h^{-1}. Results are presented in Table 6. No losses due to chemical incomplete combustion or blowdown were taken into account.

Table 6.
Optimal hourly heat balance

HEAT INPUT			**HEAT OUTPUT**		
Nomenclature	GJ	%	Nomenclature	GJ	%
HEAT INPUT			***USEFUL HEAT OUTPUT***		
Chemical heat of fuel Q_{cBi}	1,153.79	71.17	Heat of produced steam Q_D	1,443.28	89,02
	34.60	2.13			

Physical heat of fuel Q_B			***Total useful heat Q_u***	**1,443.28**	**89.02**
			HEAT LOSS		
Physical heat of feed and injection water Q_a	415.54	25.63	Mechanical incomplete combustion Q_{cmec}	7.14	0.44
			Heat loss through flue gas Q_{gacos}	132.26	8.15
Physical heat of air Q_L	17.41	1.07	Heat loss by bottom ash Q_{sg}	30.94	1.91
			Wall loss Q_{per}	7.71	0.48
			Unaccounted losses ΔQ	0	0
			Total loss Q_p	**178.05**	**10.98**
TOTAL INPUT (Q_i)	**1,621.33**	**100.00**	**TOTAL OUTPUT (Q_e)**	**1,621.33**	**100.00**

Table 7.
Optimal efficiency parameters

Nomenclature	Values
Net energy efficiency η_n	89.02%
Gross thermal efficiency η_{tb}	89.07%
Specific fuel consumption c [g e.f.· (kg steam)$^{-1}$]	93.73

4 CONCLUSIONS

Data records in Table 4 and 5 were compared with data in Table 6 and 7:

1. Values for chemical heat of fuel Q_{cBi}, were found within 72.16 to 72.8%, compared to 71.17% for optimal heat balance, indicating higher fuel consumption, between 100.85 to 102.5 g e.f.· (kg steam)$^{-1}$compared to the optimal 93.73 g e.f.· (kg steam)$^{-1}$;
2. Values of feed water contribution in total input heat were lower, between 23.5 to 24.2% compared to 25.63% for optimal heat balance, as feed water temperature was lower than the expected 230 ºC.
3. Contribution in heat input of the physical heat of air was between 1.45 to 1.57% compared with 1.07%, as ambient temperatures at the time of measurements were between 27.6 and 28.9 °C, and for optimal heat balance 25 ºC was considered.
4. Losses through mechanical incomplete combustion Q_{cmec}, heat of bottom ash Q_{sg}, wall loss Q_{per} were within normal ranges, consistent with values found in various sources [8][9][10].
5. Flue gas loss was the major source of loss, with values within 11.05 to 11.36% compared with 8.15% for optimal heat balance.
6. Net energy efficiency values computed for the considered loads were found within 81.91 to 83.24%, lower values than rated 85% and much lower than the 89.02% value resultant from optimal heat balance. Variation of energy efficiency and specific fuel consumption as function of steam generator load is presented in Fig. 2.

7. Unaccounted losses were between 1.77 to 2.14%, compared to ±2.5% admitted [4].

Variation of efficiency reaches maximum at a load of approximately 85% as expected. Corroborated with that, minimum fuel consumption was 100.9 g e.f. · (kg steam)$^{-1}$ at maximum efficiency.

Improving energy efficiency of steam generator operating under the circumstances analyzed in present paper consists mainly in reducing values of flue gas loss, while reducing blowdown can bring another 1%.

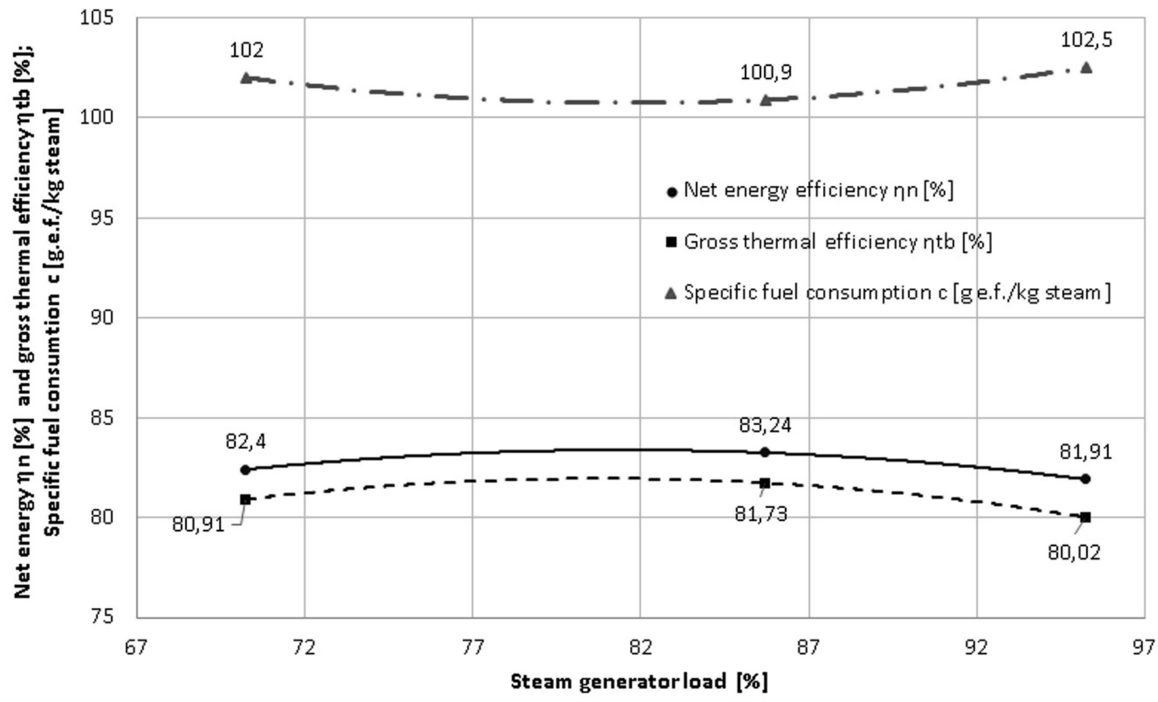

Fig. 2.
Efficiency and fuel consumption

The higher values found for flue gas loss are generated by values of excess air were between 1.51 and 1.61 (Table 1), much higher than 1.25, the optimal value considered. In same Table, flue gas temperature values are listed between 151.3 to 156.7 values in the recommended range for lignite.

Conclusively, an average growth of 3.1% of net energy efficiency could be achieved, if excess air coefficient is kept around 1.25 and flue gas temperature around 150 ºC.

Even after its long-term operation, energy efficiency of analyzed steam generator is decent, compared to values in literature [2].

For steam generators operating for a long time environmental aspects must be taken into account. Retrofitting boilers to meet environmental standards can affect efficiency [9][11][12]. As highlighted in literature, scrubbers can reduce efficiency by 1%, SCR (selective catalytic reduction) by 2% and carbon capture by 5-10% [12].

A better alternative could be replacing the steam generators with new ones, built to meet environmental standards at high efficiency. In case of studied steam generator, a proper replacement can be the lignite-fueled E-420-13,8-560BJ steam generator with the following characteristics: 420 $t \cdot h^{-1}$ steam output at 138 bar pressure and 560 °C temperature. The rated efficiency is 92.1% while NO_x emissions are 700 $mg \cdot m^{-3}_N$.

References:

[1] http://ec.europa.eu/energy/efficiency/eed/eed_en.htm.

[2] Zhu, Q., **Update on lignite firing**, CCC/201, ISBN 978-92-9029-521-1, Publisher IEA Clean Coal Center, June 2012, p.64. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.697.960&rep=rep1&type=pdf

[3] http://www.npc.org/study_topic_papers/4-dtg-electricefficiency.pdf

[4] National Energy Regulatory Authority**, Guide to development and analysis of energy balance**. Approved by decision nr. 2123/23.09.2014.

[5] Carabogdan, I. Gh., et al., **Energy Balances - problems and applications.** Tehnica Publishing House, Bucharest, (1986) pp.121-140.

[6] Berinde, T., et al., **Elaboration and analysis of energy balance in the industry**. Tehnica Publishing House, Bucharest, (1976), vol. I, pp.50-95.

[7] http://www.slideshare.net/MohammadShoebSiddiqu/steam-generator-part-2

[8] http://www.aceee.org/files/proceedings/2009/data/papers/6_92.pdf

[9] Zhang, D., Xu, M. and Li, A. (2012), *Techno-economic analysis of a 300 MWe coal-fired power plant retrofitted with post-combustion CO_2 capture.* Asia-Pacific Jrnl of Chem. Eng, 7: S201–S208. doi: 10.1002/apj.614.

[10] Petrilean, D.C., **Elaborating and Analysing the Real Balance of Heat for the Steam Generator RGL 10/DD 2008**, Annals of the University of Petroşani, Mechanical Engineering, vol.10 (2008), ISSN:1454-9166, pp. 155-160.

[11] http://www.aceee.org/files/proceedings/2009/data/papers/6_92.pdf.

[12] http://www.npc.org/study_topic_papers/4-dtg-electricefficiency.pdf