Energy Performance of Steam Generator after Its Long-Term Operation

DOSA ION
Department of Mechanical Engineering,
Industrial Engineering and Transportation
University of Petrosani
Address Str. Universitatii nr. 20, 332006, Petrosani, jud. Hunedoara
ROMANIA
i_dosa@hotmail.com   http://www.upet.ro

Abstract: The paper presents energetic characteristics of Pp-330/140-P55 steam generator after its long-term operation, at different loads. Energy efficiency is an important aspect of modern economy. The importance of energy efficiency is emphasized by regulations as Directive 2012/27/EU on energy efficiency, which is mandatory in all EU countries. The steam generator's rated efficiency is 90.07%, but it is operational since 1968 so a drop in his efficiency is expected.

Key-Words: Steam generator, energy performance, long-term operation, heat balance

1 Introduction

Combustion boilers are widely used to generate steam for power generation. Since energy efficiency is an important aspect of modern economy, high efficiency power generation has an important impact on the whole economy.

Directive 2012/27/EU on energy efficiency emphasized the need to increase energy efficiency in the Union to achieve the objective of saving 20 % of the Union's primary energy consumption by 2020 compared to projections [1].

By increasing efficiency, less fuel is required to generate each kWh. In consequence, more fuel supply will be available than would be otherwise. Increasing efficiency of power plants means decreasing heat rate, and the National Petroleum Council (NPC) report [3], estimates for coal technology a range from 8,138 - 9,785 $kJ\cdot kWh^{-1}$ (44% - 37% efficient HHV).

A significant part of papers published on boiler efficiency were analyzing efficiency of retrofitted steam generators or the efficiency of modern ones, built using state of the art technologies.

In paper [4] Vagner analyzes the BKZ-210-140F boiler of the West-Siberian Cogeneration Plant. In order to raise the efficiency of operation and lower emissions the boiler was reconstructed. As a consequence high stability of ignition of pulverized coal was ensured, lowered the optimum excess air factor at the outlet from the superheater to 1.2 – 1.25, and increased the gross efficiency of the boiler to 91.5 – 91.7%.

In paper [5], Yue et al., carried out a heat balance analysis on Baima's 300MWe CFB boiler. Calculations were made by the use of DL/T964-2005 standard in China, and the efficiency of this boiler under the Ml load was 91.9089%.

Paper [6] (Bhatt and Jothibasu) presents the results of study in 22 coal fired thermal power stations of capacities 30–500 MW. Solutions are suggested to improve the boiler efficiency from 71–86% to 86–87% immediately and 89–90% on a 5–10 yr basis.

Effect of post-combustion capture process combined with a typical Chinese coal-fired power plant and the economic performance were analyzed in paper [7]. The results indicated that the net power outputs of the retrofitted power plant dropped from 302.62 to 249.45 MWe for lignite, 254.97 MWe for bituminous coal and 249.90 MWe for anthracite, respectively. For three cases, the net efficiencies decreased about 7%.

No other data on Pp-330/140-P55 type boiler was found except paper published earlier by the author [8].

2 Problem Presentation

Industrial steam generators are complex and expensive equipment, with a long life-cycle. As a result, a great majority of steam generators produced 30 years ago are still in use, as report of NPC [3] shows, about 76% in USA. The situation is the same in the other parts of the world, too. Technology improvements driven by need of higher efficiency and low-emissions led to a new generation of steam generators, meeting these requirements. The average efficiency of power plants will improve as new units come online, rather than by retrofitting older ones, and this will be a process which can take a long period of time, depending on the number of units due to replace.

Assessment of energy performance of boilers can help in determining the moment when replacement of steam generators must be considered.

Assessment of energy performance requires heat balance calculations.

Energy auditing in Romania is regulated by the state and supervised by the regulatory authority ANRE, and must be carried out according to the published guide [9].

Algorithms and equations for heat balance calculations of various installations and equipments can be found in literature [10][11][12].

2.1 A brief presentation of steam generator

Pp-330/140-P55 [13] steam generator is a once-through coal-fired boiler, built in 1968 in the former USSR.

Construction of the steam generator is carried out in two distinct bodies, symmetrical with the axis of the group, operating in parallel to the K-210-130-1 steam turbine. The steam output of generator (one body) is 330 $t \cdot h^{-1}$, at a pressure of 140 bar and 550 °C for live steam and 24.4 bar at 550 ºC temperature for reheat steam. Each of the two bodies can work independently with the turbine as they are equipped with adequate valves to be isolated.

Each steam generator body Fig. 1 is designed with two flue gas paths - in the shape of Π - one ascending and one descending, tied together with a reverse room. Abbreviations in Fig. 1: SCAA - steam-steam heat exchanger, ZSR II - upper radiation section ZMR – median radiation section, ZIR – lower radiation section, SCP - primary convection superheater, SCI - intermediate convection superheater, ZT – transition section, ECO – economizer, PA – regenerative air heater (SCAA and SCI are part of the reheater circuit).

Fuels used in furnace chamber can be solid (pulverized coal), liquid (heavy fuel oil) or gaseous (natural gas).

The ascending path is the furnace chamber area, where the radiation heat exchangers are located and the descending path consists in the convection heat exchange surfaces.

Combustion air and the air used for the transport of pulverized coal are blown by a centrifugal air fan.

The basic fuel is crushed coal, obtained in hammer mills (4 mills for each body of the steam generator). To start and support the flame, auxiliary fuel is used (natural gas or heavy fuel oil).

Heavy fuel oil injector, gas burner and the pulverized coal burner have a unitary construction.

The burners are located on the sidewalls of the furnace in two floors with 4 burners on a floor. Each burner can be powered with gas or heavy fuel oil alone.

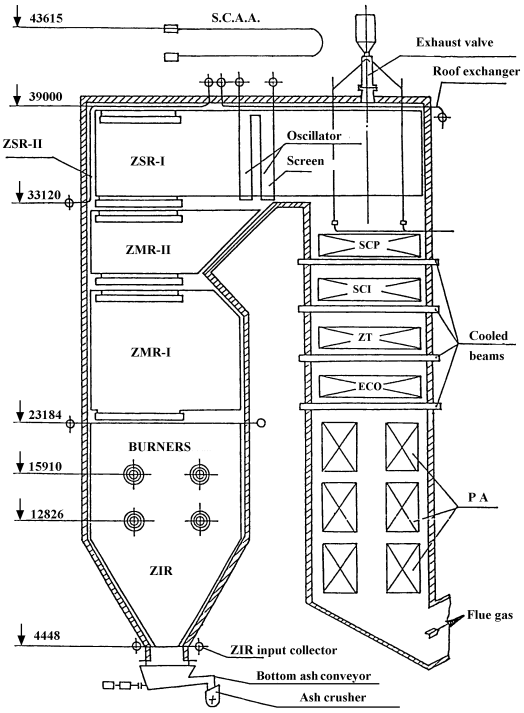

Fig. 1. Pp-330/140-P55 steam boiler [3]

One mill, delivers crushed coal for two burners placed in cross on each side of the furnace chamber.

Flow of coal in grinding mill is provided by the raw coal feeder (with scraper band) whose speed can be adjusted remotely by the voltage applied to the DC drive motor.

Large share of radiation heat exchange surfaces ensures that the project parameters are delivered even down to 70% of rated load.

Boiler efficiency at rated load reaches 90,07% (by project) especially by placing particular areas of regenerative convection heat exchangers (economizer and air preheater), leading to lower flue gas temperature to a value of 151 °C, when operating exclusively on pulverized coal.

Supply water parameters at steam generator rated load are: pressure 188 bar, temperature 242 °C.

Discharge of bottom ash is dry and the discharge of fly ash captured in the electric filters is done hydraulically.

The unit is equipped with a data acquisition and process control system in order to track boiler operating parameters.

Also indicator panels are located in the control room of the unit.

2.2 Balance outline

Balance outline corresponds with the physical contour of the Pp-330/140-P55 type steam generator.

Inputs: the mixture of coal-natural gas, air needed for combustion, boiler feed water and cold steam from HP turbine stage. Outputs: flue gas, the produced superheated and reheated steam, discharged ash (fly and bottom), heat lost through the walls of the steam generator.

2.3 Measured data

In order to perform a proper heat balance analysis at least 3 different load must be taken into account.

As the steam generator has two distinct bodies, and a perfect balance between the loads it is practically impossible, for each load, two sets of measurements are performed. The two bodies will be denoted with the unit number, which in this case is 5, followed by A or B.

The loads for performance tests were fixed to 230 $t \cdot h^{-1}$ - 70%, 280 $t \cdot h^{-1}$ – 85% and 310 $t \cdot h^{-1}$ – 94%.

Most data on steam generator operation at different loads are obtained from the data acquisition and process control system. In addition to that, measurements are carried out in order to obtain more accurate data on combustion. Using a TESTO 350 portable emission and combustion analyzer, data on flue gas composition, flue gas temperature T_{ga} and coefficient of excess air λ is obtained, Table 1.

During measurements coal samples were taken in order to obtain data on composition and lower heating value of the used coal.

Samples are taken from bottom and fly ash during operation, and analysis were carried out. Results on the average unburnt coal are presented in Table 2. Temperature of bottom ash was also measured during operation.

During testing different flow rates of natural gas (1,762.46 to 4,958.05 $m^3_N \cdot h^{-1}$) was mixed with pulverized coal in order to sustain the flame.

Table 1. Flue gas measurements

Nomenclature	U.M.	70% load		85 % load
		Boiler 5A	Boiler 5B	Boiler 5A
O_2	%	10,69	9,54	8,46
CO	%	$4 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
CO_2	%	8,45	8,99	11,11
SO_2	%	0,1	0,1	0,2
T_{ga}	°C	174,5	176,1	183,2
λ		2,01	1,79	1,66
Nomenclature	U.M.	85 % load	94% load	
		Boiler 5B	Boiler 5A	Boiler 5B
O_2	%	8,01	8,16	8,47
CO	%	$5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$5 \cdot 10^{-4}$
CO_2	%	11,01	10,77	10,4
SO_2	%	0,2	0,1	0,1
T_{ga}	°C	181	175	172,1
λ		1,6	1,61	1,65

Table 2. Unburnt coal in bottom and fly ash

Unburnt coal	70% load		85 % and 94% load	
	Boiler 5A	Boiler 5B	Boiler 5A	Boiler 5B
Bottom ash	2,87	2,40	2,97	2,65
Fly ash	1,27	1,47	1,70	1,53

Table 3. Lower heating value of coal

Load [%]	5A body	5B body
	Lower heating value $kJ \cdot kg^{-1}$	
70	15,746.75	14,959.49
85	14,355.70	14,556.09
94	14,252.93	13,896.65

3 Results obtained

Results of calculations are presented in Table 4. In the first row of every nomenclature item values for 70% load, in the second row for 85% load and in the last row for 94% load can be found.

Table 4. Actual hourly heat balance

	5A body		**5B body**	
Nom.	**GJ**	**%**	**GJ**	**%**
INPUT				
Chemical heat of fuel Q_{cBi}	775.612	77.51	801.50	77.58
	950.53	76.21	938.34	76.03
	1,006.82	76.19	1,055.93	76.30
Physical heat of fuel Q_B	5.96	0.60	6.87	0.66
	8.86	0.71	8.16	0.66
	9.45	0.72	10.21	0.74
Physical heat of feed and injection	202.12	20.20	208.93	20.22
	267.98	21.49	267.32	21.66
	289.63	21.92	301.72	21.80

water Q_a				
Physical heat of air Q_L	17.00	1.70	15.83	1.53
	19.87	1.59	20.38	1.65
	15.54	1.18	16.05	1.16
TOTAL INPUT (Q_i)	**1,000.70**	**100**	**1,033.12**	**100**
	1,247.23	**100**	**1,234.20**	**100**
	1,321.44	**100**	**1,383.91**	**100**
USEFUL HEAT OUTPUT				
Heat of produced steam Q_D	779.07	77.85	804.27	77.85
	993.44	79.65	984,16	79.74
	1,050.81	79.52	1,092.90	78.97
Heat recovery by reheating	98.07	9.80	98.97	9.58
	119.05	9.54	116.41	9.43
	125.26	9.48	125.86	9.09
Total useful heat output Q_u	**877.15**	**87.65**	**903.24**	**87.43**
	1,112.48	**89.20**	**1,100.56**	**89.17**
	1,176.07	**89.00**	**1,218.76**	**88.07**
HEAT LOSS				
Mechanical incomplete combustion Q_{cmec}	4.68	0.47	4.66	0.45
	5.16	0.41	5.07	0.41
	5.49	0.42	6.16	0.45
Chemical incomplete combustion Q_{cga}	0.018	0.002	0.017	0.002
	0.014	0.001	0.023	0.002
	0.010	0.001	0.026	0.002
Heat loss through flue gas Q_{gacos}	103.69	10.36	98.13	9.50
	106.80	8.56	107.47	8.71
	121.95	9.23	124.62	9.01
Heat loss by bottom ash Q_{sg}	6.58	0.66	7.62	0.74
	10.00	0.80	9.00	0.73
	12.09	0.91	12.93	0.93
Wall loss Q_{per}	5.18	0.52	5.18	0.50
	4.22	0.34	4.22	0.34
	6.26	0.47	6.26	0.45
Unaccounted losses ΔQ	3.40	0.34	14.27	1.38
	8.55	0.69	7.85	0.64
	-0.42	-0.03	15.15	1.09
Total heat loss Q_p	**123.55**	**12.35**	**129.88**	**12.57**
	134.75	**10.80**	**133.64**	**10.83**
	145.38	**11.00**	**165.15**	**11.93**
TOTAL OUTPUT (Q_e)	**1,000.70**	**100**	**1,033.12**	**100**
	1,247.23	**100**	**1,234.20**	**100**
	1,321.44	**100**	**1,383.91**	**100**

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	5A body	5B body
Net energy efficiency η_n [%]	70%	87.65	87.43
	85%	89.20	89.17
	94%	89.00	88.06
Gross thermal efficiency η_{tb} [%]	70%	87.03	86.63
	85%	88.85	88.80
	94%	88.04	86.85
Specific fuel consumption c [kg e.f./kg steam]	70%	0.1167	0.1168
	85%	0.1128	0.1118
	94%	0.1130	0.1139

An optimal heat balance was also calculated in order to compare actual parameters with optimal values. To show influence of natural gas used for flame support on energy performance of steam generator, optimal heat balance was calculated in both cases, with and without flame support.

Calculation were performed at rated parameters of steam generator, for only one body, considering excess air value 1.2, and natural gas flow ratio of 2,000 $m^3_N \cdot h^{-1}$.

Results are presented in Table 6.

Table 6. Actual hourly heat balance

	With flame support		**Without flame support**	
Nom.	**GJ**	**%**	**GJ**	**%**
HEAT INPUT				
Chemical heat of fuel Q_{cBi}	972.43	73.47	971.64	73.44
Physical heat of fuel Q_B	8.34	0.63	8.72	0.66
Physical heat of feed and injection water Q_a	332.57	25.13	332.57	25.14
Physical heat of air Q_L	10.26	0.78	10.03	0.76
TOTAL INPUT (Q_i)	**1,323.6**	**100**	**1,323.0**	**100**
USEFUL HEAT OUTPUT				
Heat of produced steam Q_D	1,096.8	82.86	1,096.8	82.90
Heat recovery by reheating	130.08	9.83	130.08	9.83
Total useful output Q_u	**1,226.9**	**92.69**	**1,226.9**	**92.74**
HEAT LOSS				
Mechanical incomplete combustion Q_{cmec}	8.29	0.63	8.73	0.66
Heat loss through flue gas Q_{gacos}	69.91	5.28	67.99	5.14

Heat loss by bottom ash Q_{sg}	15.94	1.20	16.79	1.27
Wall loss Q_{per}	4.32	0.33	4.32	0.33
Unaccounted losses ΔQ	***-1.73***	***-0.13***	***-1.73***	***-0.13***
Total heat loss Q_p	**96.73**	**7.31**	**96.73**	**7.31**
OUTPUT (Q_e)	**1,323.6**	**100**	**1,323.0**	**100**

Table 7. Optimal efficiency parameters

Nomenclature	With flame support	Without flame support
Net energy efficiency η_n	92.69%	92.74%
Gross thermal efficiency η_{tb}	91.97%	92.04%
Specific fuel consumption c [kg e.f./kg steam]	0.1047	0.1046

4 Conclusions

Notes on data in Table 4 and 5 compared with data in Table 6 and 7:

1. Values for chemical heat of fuel Q_{cBi}, are found within 76.03 to 77.58%, compared to 73.44% for optimal heat balance, indicating higher fuel consumption as can be seen in Table 4 and 6 too;
2. Values of feed water contribution in total input heat are lower, between 20.20 to 21.92% compared to 25.14% for optimal heat balance, as feed water temperature is lower than expected 242 ºC.
3. Contribution in heat input of the physical heat of air is between 1.16 to 1.70% compared with 0.76%, as ambient temperatures at the time of measurements were between 26.06 and 36.63 °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} are within normal ranges, consistent with values found in various sources [11][12][14][16]. Unaccounted losses are between -0.03 to 1.38%, compared to ±2.5% admitted [9].
5. Flue gas loss is the major source of loss, as values are within 8.56 to 10.36% compared with 5.14% for optimal heat balance.
6. Net energy efficiency values computed for the considered loads are found within 87.43 to 89.20%, lower values than rated 91.12% (90.07% gross thermal efficiency computed for coefficient of excess air 1.42) lower than the 92.74% value for calculated optimal heat balance. Variation of energy efficiency and specific fuel consumption as function of steam generator load is presented in Fig. 3 for 5A body and in Fig. 4 for 5B body of steam generator.

As expected, energy efficiency variation is limited 1.98% for net energy efficiency, as certified by the manufacturer that the project parameters are delivered even down to 70% of rated load.

And again, the variation of efficiency reaches maximum at a load of approximately 85%, a normal value. Corroborated with that, the minimum of fuel consumption is at maximum efficiency.

Conclusively, to ensure high efficiency values and low specific fuel consumption, the steam generator must be operated around 85% of rated load.

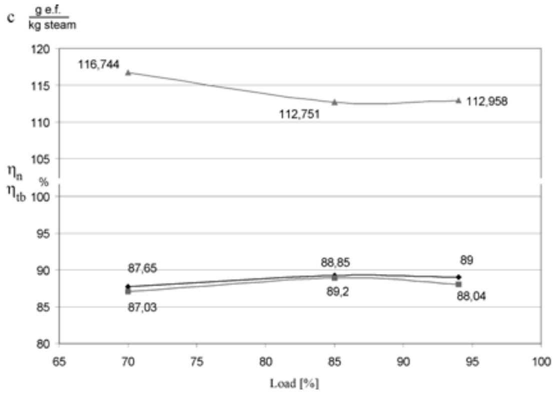

Fig. 3. Efficiency and consumption for 5A body

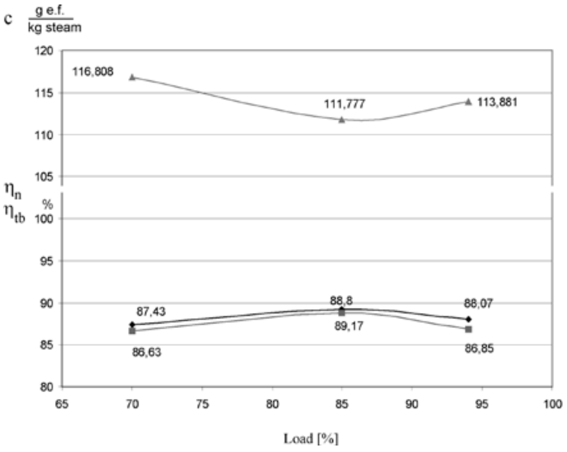

Fig. 4. Efficiency and consumption for 5B body

Another interesting result is highlighted in Table 6 and 7, where lower net energy efficiency (0.05%) is obtained when operating steam generator with flame support. The gross thermal efficiency is also lower with 0.7% in case of operating with flame support, dropping from 92.04% without flame support to 91.97% with flame support, while heat loss through flue gas Q_{gacos}, increases with 0.14% from 5.14% to 5.28%.

This effect is produced by the air needed for combustion which is 4.12 (m^3_N air)·(kg coal)$^{-1}$ for hard coal, compared to 9.4 (m^3_N air)· (m^3_N gas)$^{-1}$ for natural gas (theoretical). Elementary analysis carried out on given coal and methane gas, revealed that the theoretical air needed for combustion is 4.132 (m^3_N air)·(kg coal)$^{-1}$ for coal, and 9.487 (m^3_N air)· (m^3_N gas)$^{-1}$ for natural gas. Use of flame support must be limited as a greater quantity of combustion air is needed, and subsequently a greater quantity of flue gas is produced, increasing flue gas loss.

Improving energy efficiency of steam generator operating under the circumstances analyzed in present paper consists mainly in reducing values of flue gas loss.

First step is finding source of loss. As Table 1 shows, values of excess air are between 1.6 and 2.01 much higher than the optimal value considered 1.2 an even higher than 1.35, the value given by the equipment manufacturer [13] as standard. In same Table, flue gas temperature values are listed between 172.1 to 183.2 values exceeding the recommended 151 °C [13].

Conclusively, a growth between 3.54% and 5.31% of net energy efficiency could be achieved, if excess air coefficient is maintained around a value of 1.2 and flue gas temperature around 151 ºC. This can be achieved by the means of process control systems, and by the use of quality coal (increased lower heat value).

Even after its long-term operation, as proper maintenance was carried out, energy efficiency of analyzed steam generator is good, compared to values in literature 90.3% [2].

Environmental aspects of steam generators must be taken into account when considering replacement. Retrofitting boilers to meet environmental standards can affect efficiency [15] [7], e.g. scrubbers can reduce efficiency by 1%, SRC by 2% and carbon capture by 5-10% [3].

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