Energy Balance of a Coal-Fired Power Plant in Condensing Operation

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Abstract: Paper analyzes energetic characteristics of a coal power plant 210 MW unit. Different operating loads are considered. Following assessment of energy characteristics possible ways of improving energy efficiency are analyzed.

Key-Words: Coal fired power plant, energy performance, efficiency, heat balance

1 Introduction

As needs for electricity is growing rapidly in many countries, it is expected that the increase of electricity by 2030 is doubled [1], given that power generation by coal is 40% in the world. Therefore coal consumption will increase and it is estimated the increase of 50%.

Another forecast [2] of US Energy Information Administration reveals that electricity generating capacity produced in combined cycle power plants will increase with a growth rate of 1.4%.

Fossil fuels, renewables, nuclear energy will play their parts, but fossil power generation will continue to play a major role in the future. Coal will be used continuously due to its stable supply and lower price.

Directive 2012/27/EU on energy efficiency emphasizes the need to increase energy efficiency in order to achieve the objective of saving 20 % of the Union's primary energy consumption by 2020 [3]. This can be achieved by means of high efficiency power generation.

Paper [4] suggests that fossil fuel-fired thermal power plants representing 66% of all electricity production of Russia in 2000 will retain their importance. Their contribution to electricity production in 2030 is expected to be 64 to 68%. The share of condensing plants, about 42% at the beginning of 2000, is expected to slightly increase to 46% by 2030.

Coal consumption by electric power plants will almost double, or even increase threefold by 2030, depending on considered scenario [4].

Meanwhile, the production cost of coal can be expected to rise slowly until 2030, although coal will remain the cheapest in-place fuel.

As Russia will remain the European Union's main partner in energy trade, energy efficient power generation may have a major impact on EU economy.

Spliethoff shows in paper [5] that energy efficiency of a condensation power plant is 39%.

In another study, according to Hans-Dieter Schilling (Energie-Fakten), the average efficiency of all coal power stations in the world currently stand at around 31% [6].

In paper [7] Bezdek and Wendling shows that average operating efficiency of U.S. coal plants is about 31.8 %, and the costs and implications of increasing this average level of efficiency to 36.8 % were assessed.

2 Problem Presentation

Building a power plant is a major decision with long term impact on economy and environment, due to its complexity and high development and maintenance costs.

Power plant life-cycle spans over many decades and many of them are still in use after more than 40 yr of service.

As presented in paper [8] average thermal efficiency of steam power generation was around 43% in 1970s

As new technologies were developed countries are upgrading constantly their coal power plant fleet [8] [9].

The efficiency of a new power plant is largely a function of economic choice, given that technology is well understood. In order to produce a highly efficient plant, higher pressure and temperatures are required involving use of special alloy materials which increases the cost of the plant.

Therefore a decision must be taken in repowering or rebuilding power plants as happened in the former East Germany in 1990s.

First step in decision making is assessment of energy performance of steam power plant, which requires heat balance calculations.

In Romania, the regulatory authority ANRE, published a guide for energy auditing. Heat balance calculations must be carried out according to the published guide [10].

Heat balance calculations examples for various installations and equipments can be found in literature [11][12].

2.1 A brief presentation of power plant unit

The 210 MW power plant unit schematic diagrams is presented in Fig. 1. The unit consists of a steam turbine with reheating, steam generator, regenerative feed water heaters, condenser, feed water, condensate and drain pumps and other necessary related equipment.

K 200-130-1 steam turbine is a condensing type turbine and was designed to operate at 3,000 rpm, 13 MPa, and 545 °C with one steam reheat to a temperature of 545 °C at a pressure of 2.44 MPa. The exhaust pressure is 0.0034 MPa. The turbine has seven bleeder connections for regenerative feed water heating to a maximum of 242 ºC. From the High Pressure Turbine (HPT) steam is directed to reheater at a pressure of 2.89 MPa and a temperature of 350 ºC from which is returned to the Reheat Turbine (RT). The Low Pressure Turbine (LPT) is of a double-flow design.

Steam for turbine is provided by Pp-330/140-P55 type steam generator, a once-through coal-fired boiler.

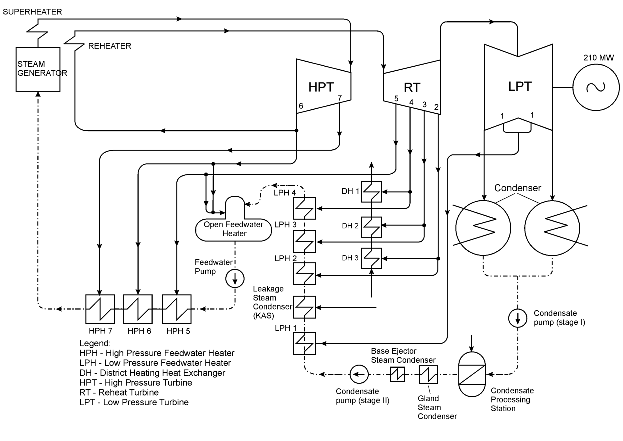

Fig. 1. Schematic diagram of 200 MW unit

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-200-130-1 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.

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

At the time of construction the steam turbine was used only for electricity production. Later, as nearby city grew bigger, 3 heat exchangers where added in order to provide district heating. The steam required for water heating is drawn from bleeder 4, 3 and 2. Steam required by de-aerator (open feed water heater) was drawn off from bleeder no. 5.

2.2 Balance outline

Balance outline consist in: the generator terminals for electricity output; main flow control valve of turbine and ramification of parallel pipeline which draws steam from turbine for technological purpose to the de-aerator pressure reduction and cooling station abbreviated SRRD, on steam side; inlet of demineralized makeup water and inlet sections of cooling water used in condenser, electrical generator and turbine lubricating oil system, on water side; inlet of combustion air fan and outlet of flue gas; inlet section of burners and slag tap.

Balance outline contains the steam generator, the steam turbine, the condenser, the regenerative cycle, the regenerative feed water heaters; feed water and condensate pumps.

In the defined balance outline some energy and mass flows corresponding to different subsystems became internal flows. As a result, some of them cannot be highlighted otherwise than splitting the power plant in subsystems, computing energy balances for them and gathering data in the final balance sheet.

2.3 Measured data

As regulations require, for heat balance calculations measurements must be carried out for least 3 different loads. The loads for performance tests were fixed to 460 $t \cdot h^{-1}$ - 70%, 560 $t \cdot h^{-1}$ – 85% and 620 $t \cdot h^{-1}$ - 94%. Rate of steam flow to the turbine D_0 is 660 $t \cdot h^{-1}$, at rated load.

Distributed Control System (DCS) of unit provided most of data. In addition, measuring equipment was placed in different locations. Also data from indicator panels located in the control room of the unit can be obtained.

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After analyzing data available from DCS and measuring equipment in place, points for measuring additional data were chosen. As an adequate amount of data was available from DCS regarding temperature pressure and rate flow of feed water through HPH 5, 6 and 7, condensate at outlet of LPH 4, measuring additional data in order to calculate the steam flow rate of bleeders from their heat balance has been decided.

3 Results obtained

As energy balance for the steam generator and steam turbine were elaborated and presented in earlier papers. Data required for the energy balance of steam power plant are gathered in the tables below, along with losses calculated according to the actual balance outline.

The names of input output and loss categories are kept alike the names in energy balance of steam generator and steam turbine in order to visualize where they came from.

Table 1. Actual hourly energy balance 70% load

INPUT		
Nom.	**MW**	**%**
Chemical heat of fuel Q_{cBi}	438.09	97.16
Physical heat of fuel Q_B	3.56	0.79
Physical heat of air Q_L	9.12	2.02
Physical heat of makeup water P_{aad}	0.153	0.03
TOTAL INPUT	**450.92**	**100.0**
OUTPUT		
USEFUL OUTPUT		
Output power P_g	144.84	32.12
Energy of steam extracted for technological use P_{SRRD}	4.43	0.98
TOTAL USEFUL	**149.27**	**33.10**
LOSSES		
Mechanical incomplete combustion Q_{cmec}	2.59	0.58
Chemical incomplete combustion Q_{cga}	0.01	0.002
Heat loss through flue gas Q_{gacos}	56.06	12.43
Heat loss by bottom ash Q_{sg}	3.95	0.87
Wall loss Q_{per}	2.88	0.64
Mechanical loss ΔP_m	2.04	0.45
Generator loss ΔP_g	1.84	0.41
Heat rejected by condenser P_{cd}	210.1	46.59
Loss in piping between steam generator and turbine P_{cdab}	2.45	0.54
Loss in piping between HPH 7 and steam generator economizer P_{cdpc}	9.14	2.03
Loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}	4.062	0.90
Unaccounted losses ΔP_{bil}	6.55	1.45
TOTAL ENERGY LOSS	**301.65**	**66.90**
TOTAL OUTPUT	**450.92**	**100.0**

Table 2. Actual hourly energy balance 85% load

INPUT		
Nom.	**MW**	**%**
Chemical heat of fuel Q_{cBi}	524.69	96.92
Physical heat of fuel Q_B	4.73	0.87
Physical heat of air Q_L	11.81	2.07
Physical heat of makeup water P_{aad}	0.78	0.14
TOTAL INPUT	**541.37**	**100.0**
OUTPUT		
USEFUL OUTPUT		
Output power P_g	175.17	32.36
Energy of steam extracted for technological use P_{SRRD}	4.96	0.92
TOTAL USEFUL	**180.13**	**33.28**
LOSSES		
Mechanical incomplete combustion Q_{cmec}	2.84	0.53
Chemical incomplete combustion Q_{cga}	0.01	0.002
Heat loss through flue gas Q_{gacos}	59.52	10.99
Heat loss by bottom ash Q_{sg}	5.28	0.98
Wall loss Q_{per}	2.35	0.43
Mechanical loss ΔP_m	2.11	0.39
Generator loss ΔP_g	2.29	0.42
Heat rejected by condenser P_{cd}	259.99	48.02
Loss in piping between steam generator and turbine P_{cdab}	1.29	0.24
Loss in piping between HPH 7 and steam generator P_{cdpc}	12.64	2.33
Loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}	4.52	0.84
Unaccounted losses ΔP_{bil}	8.43	1.56
TOTAL ENERGY LOSS	**361.24**	**66.73**
TOTAL OUTPUT	**541.369**	**100.0**

Table 3. Actual hourly energy balance 94% load

INPUT		
Nom.	**MW**	**%**
Chemical heat of fuel Q_{cBi}	572.99	97.49
Physical heat of fuel Q_B	5.46	0.93
Physical heat of air Q_L	8.78	1.49
Physical heat of makeup water P_{aad}	0.55	0.09
TOTAL INPUT	**587.77**	**100.0**
OUTPUT		
USEFUL OUTPUT		
Output power P_g	193.60	32.94
Energy of steam extracted for	5.41	0.92

technological use P_{SRRD}		
TOTAL USEFUL	**199.01**	**33.86**
LOSSES		
Mechanical incomplete combustion Q_{cmec}	3.24	0.55
Chemical incomplete combustion Q_{cga}	0.01	0.002
Heat loss through flue gas Q_{gacos}	68.49	11.65
Heat loss by bottom ash Q_{sg}	6.95	1.18
Wall loss Q_{per}	3.48	0.59
Mechanical loss ΔP_m	1.86	0.32
Generator loss ΔP_g	2.45	0.42
Heat rejected by condenser P_{cd}	274.1	46.63
Loss in piping between steam generator and turbine P_{cdab}	1.16	0.20
Loss in piping between HPH 7 and steam generator economizer P_{cdpc}	13.22	2.25
Loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}	4.82	0.82
Unaccounted losses ΔP_{bil}	9.025	1.54
TOTAL ENERGY LOSS	**388.76**	**66.14**
TOTAL OUTPUT	**587.77**	**100.0**

Optimal energy balance was computed for the optimal steam flow rate of 634 $t \cdot h^{-1}$, value provided by the manufacturer of the turbine. Therefore, some results obtained for 94% load representing 620 $t \cdot h^{-1}$, are expected to be close to the optimal values. Other values used in calculus are those provided by the manufacturer as rated values.

Table 4. Optimal hourly energy balance

INPUT		
Nom.	**MW**	**%**
Chemical heat of fuel Q_{cBi}	539.8	98.11
Physical heat of fuel Q_B	4.85	0.88
Physical heat of air Q_L	5.57	1.01
Physical heat of makeup water P_{aad}	0.0	0.0
TOTAL INPUT	**550.2**	**100.0**
OUTPUT		
USEFUL OUTPUT		
Output power P_g	210.0	38.17
Energy of steam extracted for technological use P_{SRRD}	6.41	1.16
TOTAL USEFUL	**216.4**	**39.33**
LOSSES		
Mechanical incomplete combustion Q_{cmec}	4.85	0.88
Chemical incomplete combustion Q_{cga}	0.0	0.0
Heat loss through flue gas Q_{gacos}	37.77	6.86
Heat loss by bottom ash Q_{sg}	9.33	1.70
Wall loss Q_{per}	2.40	0.44
Mechanical loss ΔP_m	10.47	1.90
Generator loss ΔP_m	3.11	0.57
Heat rejected by condenser P_{cd}	261.7	47.56
Loss in piping ΔP_{cdt}	5.84	1.06
Loss through pressure drop for piping and valves, wall loss and leakage loss P_{div}	4.99	0.91
Unaccounted losses ΔP_{bil}	-6.62	-1.20
TOTAL ENERGY LOSS	**333.8**	**60.67**
TOTAL OUTPUT	**550.2**	**100.0**

As parasitic load (PL) value for the power plant can have values between 8 and 10%, performance characteristics summarized in Table 5 where determined accordingly.

Table 5. Performance characteristics

Nom.	Load		
	70%	85%	94%
Gross thermal efficiency %	33.10	33.27	33.86
Net energetic efficiency (8 % PL) %	29.84	30.04	30.58
Net energetic efficiency (10 % PL) %	29.20	29.39	29.92
Gross heat rate $kJ \cdot kWh^{-1}$	10,875	10,820	10,632
Net heat rate (8% PL) $kJ \cdot kWh^{-1}$	12,063	11,983	11,771
Net heat rate (10% PL) $kJ \cdot kWh^{-1}$	12,331	12,249	12,032
Specific fuel intake (g e.f.) $\cdot kWh^{-1}$	396.05	397.59	387.48

Table 6. Optimal performance characteristics

Nom.	Optimal
Gross thermal efficiency %	39.33
Net energetic efficiency (8 % PL) %	35.53
Net energetic efficiency (10 % PL) %	34.74
Gross heat rate $kJ \cdot kWh^{-1}$	9,153
Net heat rate (8% PL) $kJ \cdot kWh^{-1}$	10,133
Net heat rate (10% PL) $kJ \cdot kWh^{-1}$	10,358
Specific fuel intake (g e.f.) $\cdot kWh^{-1}$	344.6

4 Conclusions

Notes on comparison data in Table 1 to 6 can be summarized as follows:

1. Input represented by chemical heat of fuel Q_{cBi} ranges from 96.92 to 97.49% compared to 98.11 for optimum as a result of high environmental temperatures at the time of measurements (from

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26.06 to 36.63 °C, and for optimal heat balance 25 ºC was considered).

2. Physical heat of fuel ranges from 0.79 to 0.93% compared to 0.88% optimal.

3. Physical heat of combustion air ranges from 1.49 to 2.07% compared to 1.01% optimal due to high environmental temperatures.

It's important to notice that for optimum balance no makeup water was considered but in actual operating conditions makeup water was 3.73%, 5.74% and 1.41% of feed water flow rate. Shri V.K. Anand in paper [13], points that value between 0 to 3% are normally acceptable for a cycle make up to offset cycle water losses which may be on account of various retrievable leakages, boiler blow down, soot blowing and passing of valves and leakages.

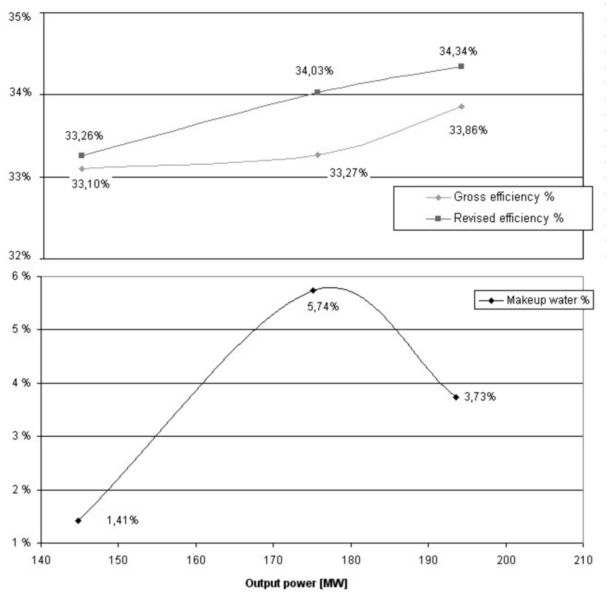

Fig. 2. Influence of cycle water loss

Influence of cycle water losses are evaluated to approx 0.4% increase in heat rate and reduction of 0.2% on output [15] for every 1% lost.

Influence of makeup water on power plant efficiency is presented in Fig. 2 along with the revised efficiency.

As majority of losses are in normal range, losses through heat ejected by condenser, flue gas and piping are going to be analyzed as follows:.

a. The amount of heat rejected by condenser represents the greatest loss (as expected), having values of 210.076 MW (46.59%), 259.989 MWh (48.02 %) and 274.059 MWh (46.63%), for loads of 70%, 85% and 94%, compared to optimal 261.675 MWh (39.11%).

Different papers provide different values for usual amount of heat rejected by condenser. Paper [14] points to 39%, while in paper [15] 52.5% are found, and further in paper [5] 44% is given.

Conclusively values obtained are higher than optimal, but are in the range of values given in literature.

A major problem is condenser pressure, which is too high, reducing power output with 5% for 70% load 5.9% for 85% load and 5.5% for 94% load.

The influence of condenser pressure on efficiency and the revised efficiency is presented in Fig. 3.

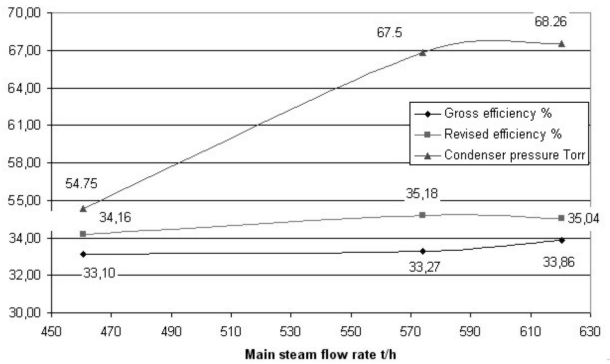

Fig. 3. Influence of condenser pressure

Enhancing efficiency of turbine can be achieved by means of restoring optimal pressure in condenser improving its heat transfer capability by maintaining heat exchange surfaces clean. At the same time actions must be considered in order to improve the sealing of condenser to prevent air infiltration, and a proper maintenance of ejectors to guarantee the vacuum.

b. Flue gas loss is another major source of loss, as values are within 10.99 to 12.43% compared with 6.86% for optimal heat balance.

Reducing values of flue gas loss will boost efficiency but first step is finding source of loss.

Analyzing data, values of excess air are found in range of 1.6 to 2.01 much higher than the optimal value considered 1.2 an even higher than 1.35, the value given by the equipment manufacturer as standard. Associated with excess air, flue gas temperature values are listed between 172.1 to 183.2 values exceeding the recommended 151 °C.

Conclusively, reducing values above can lead to an average growth of 5% of energy efficiency. This can be achieved by the means of process control systems, and by the use of quality coal (increased lower heat value).

c. Piping loss values between steam generator and turbine are relatively small, in range from 0.20% to 0.54%. This is not true for losses between outlet of HPH 7 and steam condenser. This category of loss is high, as the optimal value for piping losses (between steam generator and turbine plus HPH 7 and steam generator) is 1.06%. Values are found to be in range of 2.03 to 2.33%.

Analyzing feed water path from outlet of HPH 7 to steam generator, a main feed controller valve of boiler (RPA) and a differential pressure controller (RDP) valve designed to take over the load of main feed controller of boiler (RPA) at low loads and provide a differential pressure on the boiler injections can be found. In standard operating mode, these valves are wide open, and loss should be much smaller. Data measured suggests that valves are not wide open, and as a result piping losses are higher. Using the valves as designed in standard operation mode should solve the problem.

Gross efficiency is 33.10%, 33.27% and 33.86%, for loads of 70%, 85% and 94%, compared to optimal 39.33 %.

Heat rate values are 10,874.98 $kJ \cdot kWh^{-1}$, 10,819.57 $kJ \cdot kWh^{-1}$ and 10,632.35 $kJ \cdot kWh^{-1}$ for loads of 70%, 85% and 94%, compared to optimal 10,133.09 $kJ \cdot kWh^{-1}$.

Comparing values with data in literature conclusion is that values are better than average [5][6][7][16], but far worse than state of the art power plants [8][9].

Therefore considering actual efficiency and operating parameters compared to values for modern power plant, retrofitting existing power plant units must be considered

This could be a good alternative since similar units have been already retrofitted with good results, as presented in paper [17].

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