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ANALYSIS OF REHEATER SIZE IMPACT ON POWER PLANT PERFORMANCE

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ABSTRACT

In order to be able to analyze performance of the coal fired thermal power plant, a detailed mathematical model of thermo-hydraulical processes in the steam generator, steam turbine and feedwater line has been developed. Attention has been focused on the influence of the reheater package size on the thermal efficiency of the plant. History of the plant shows that the reheater size had been decreased due to problems with coal ash slugging, what eventually resulted in lower power output and thermal efficiency decrease. Simulation results showed that change of utilised coal for the type with improved slugging characteristics would not achieve design temperatures unless the reheater size would be restored. In this case the plant thermal efficiency would be increased for 0.4-0.7 % resulting in some 140000 euro/a operational cost savings.

INTRODUCTION

The pulverized coal-fired Power Plant Plomin 1 (Croatia) experienced a lot of problems burning domestic bituminous coal (from the mine Rasa) with a high content of sulfur (8-12 %) and unfavorable ash characteristics.

Due to intense ash slugging and other problems that appeared when burning Rasa coal, dimension of the second (end) reheater had been reduced very soon after entering the plant operation. Namely, due to formation of ash deposits, heat flow rate in the furnace was less than designed and the temperature of flue gases in the reheater region was higher than design value. This had led to lower steam production and to higher temperature of reheated steam, above the design value of 540 °C, even with the maximum cooling water injection flow on the 2nd injector (used for temperature control). Therefore, it had been decided to reduce the dimension of the reheater from initial 1138 m^2 to 935 m^2 by the subsequent reconstruction.

Later on, when the coal reserves in the Rasa mine were depleted, the idea of using imported coal, which would not provoke intense slugging and would have a slightly higher heating value than the Rasa coal, has been grown. But, it was suspected that it would be difficult to achieve design values of the reheated steam temperature (540 °C) due to smaller size of the reheater. Therefore, it was necessary to carry out the analysis of reheater size effect on the reheated steam temperature and consequently to the plant efficiency.

For this purposes, a detailed mathematical model of the Thermal Power Plant Plomin 1 has been developed that would allow simulation and assessment of the behavior of the plant in different operational situations. The mathematical model was tested and then adjusted according to available measured data mainly extracted from operational records.

The mathematical model was translated into Visual Basic programming language in the MS Excel environment. The software package is rather user friendly with interface shown in Figure 1. It represents the basic input-output file, which allows almost complete communication of the user with the program.

NOMENCLATURE

B	[kg/s]	*Fuel mass flow rate*
ΔB	[t/a]	Annual fuel savings
c	[%]	Coal carbon content
Cc	[W/K^4m^2]	Black body radiation coefficient
Cs	[-]	Coefficient accounting for tube layout
Cz	[-]	Coefficient accounting for less tube rows than 10
dv	[m]	Outer tube diameter
Hd	[MJ/kg]	Lower heat value
k	[W/m^2K]	Total heat transfer coefficient
M_{CO2}	[t/a]	Annual CO_2 emissions
ΔM_{CO2}	[t/a]	Annual reduction in CO_2 emissions
pc	[euro/t]	Coal price
Pe	[MW]	Plant electric output
Pr	[-]	Prandtl number
p_{CO2}	[euro/t]	Price of CO_2 emission
s	[m]	Tube wall thickness
Sc	[euro/a]	Annual savings due to fuel coal reduction
S_{CO2}	[euro/a]	Annual savings on CO_2 emissions
T	[K]	Temperature

u_g	[m/s]	Flue gas velocity

Special characters

α_g	[W/m^{2}K]	Heat transfer coefficient on gas side
α_k	[W/m^{2}K]	Heat transfer coefficient of convection
α_w	[W/m^{2}K]	Heat transfer coefficient on water side
α_{zr}	[W/m^{2}K]	Heat transfer coefficient of radiation
ε	[-]	Emissivity
ξ	[-]	Coefficient of surface contamination
λ	[W/mK]	Heat conductivity
ν	[m^2/s]	Kinetic viscosity
η	[%]	Plant electrical efficiency
τ	[h/a]	Annual number of operational hours

MATHEMATICAL MODEL

The mathematical model has been developed and used in order to simulate steady-state behavior of the power plant. It consists of the thermal and hydraulic models of the steam generator water-vapor tract, the thermal and aerodynamic models of flue gas-air tract, a model of the condensing turbine and a feed-water line with regenerative feed-water preheaters.

Boundary conditions for calculation are:

- electrical power on the electro-generator,
- pressure and temperature of superheated steam,
- air inlet temperature and excess air ratio,
- cooling water inlet temperature in the condenser.

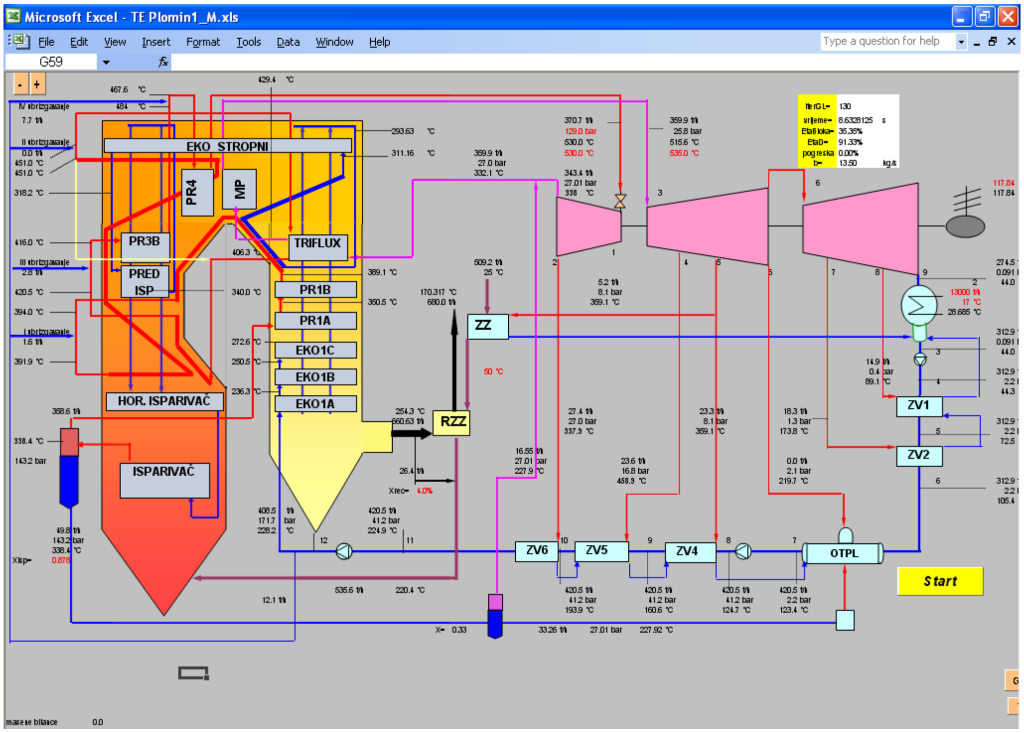
Other input data required for simulation:

- heating value and chemical composition of coal,
- geometry, characteristics and layout of tubes within the steam generator packages,
- geometry and data for air heaters,
- pressure and steam flow profiles through the turbine for a known operational regime,
- geometry and other characteristics of the feedwater preheaters.

Thermodynamic calculation of the steam generator has been based on the "normative" method [3]. For this purposes, flue gas tract has been divided into 12 control volumes, while the water and steam tract has been divided into 36 control volumes. The difference in number of control volumes comes from the fact that some of the water-steam heat transfer packages, extend over several flue gas control volumes, so that their number is three time larger than number of flue gas volumes.

Since this paper is focused on the reheater performance, only basic formula for heat transfer calculation in reheater package will be depicted. The coefficient of heat transfer in the transverse flow of flue gas through the reheater with parallel tube layout, is calculated by the following formula:

$$\alpha_k = 0.2 \cdot C_Z \cdot C_S \cdot \frac{\lambda}{d_v} \cdot \left(\frac{u_g \cdot d_v}{\nu}\right)^{0.65} \cdot Pr^{0.33}.$$



IterGL= 130
vrijeme= 8.6328125 s
EtaBloka= 35.35%
EtaD= 91.33%
pogreska 0.00%
b= 13.50 kg/s

Figure 1 Program interface: plant layout

Due to high temperature of flue gas in the reheater region, radiation has to be taken into account, either:

$$\alpha_{zr} = C_c \cdot \frac{\varepsilon_s + 1}{2} \cdot \varepsilon \cdot T_g^3 \cdot \frac{1 - \left(\frac{T_s}{T_g}\right)^4}{1 - \left(\frac{T_s}{T_g}\right)}$$

The heat transfer coefficient on the flue gas side is

$$\alpha_g = \alpha_k + \alpha_{zr} \,.$$

The coefficient of heat transfer on inner side of reheater tube is calculated by Dittus-Bölter correlation:

$$\alpha_w = 0.023 \cdot \frac{\lambda_p}{d_{ekv}} \cdot \left(\frac{u_p \cdot d_{ekv}}{\nu_p}\right)^{0.8} \cdot Pr_p^{0.4} \,.$$

The total coefficient of heat transfer is then

$$k = \frac{\xi}{\frac{1}{\alpha_g} + \frac{s}{\lambda} + \frac{1}{\alpha_w}}$$

NUMERICAL MODEL VALIDATION

Testing of the mathematical model was carried out according to the available operating data from November 2005. The data were available for the load of 117.84 MW (approximately 94% load). The comparison was carried out on the much more comprehensive data set, but for the sake of this presentation we will focus only on the reheater relevant data: temperature, pressure and flow profiles along the steam generator as well as the plant and the steam generator efficiency.

Table 1 Plant conditions

Steam temperature	530	°C
Steam pressure	136.2	bar
Reheated steam temperature	530	°C
Ambient temperature	25	°C
Flue gas recirculation	11	%
Condenser cooling water flow	13000	t/h
Condenser water inlet temperature	18.9	°C

A comparison of Table 1 with design data may reveal a difference: end temperature of fresh and reheated steam is lowered from 540 °C to 530 °C due to attempt to prolong operational life of the superheater and reheater.

Figures 2-4. show that the mathematical model is well tuned to the operational data and that accurately simulate the thermal and hydraulic processes in the thermal power plant Plomin 1.

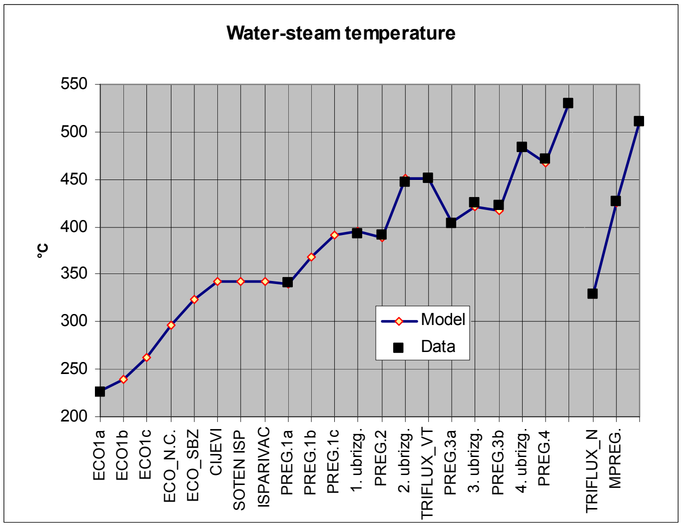


Figure 2 Water-steam temperature profiles comparison along steam generator

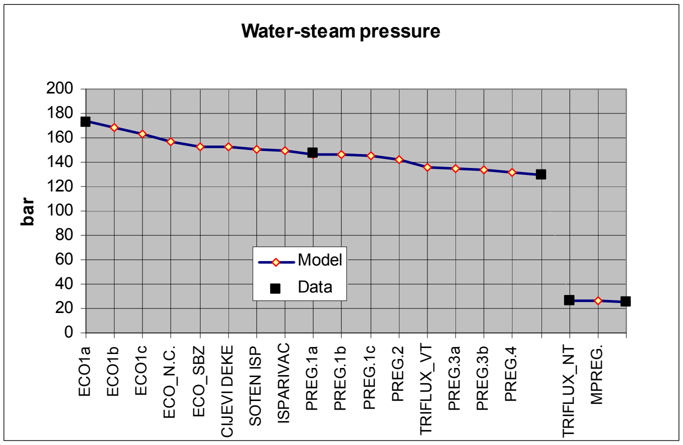


Figure 3 Water-steam pressure profiles comparison along steam generator

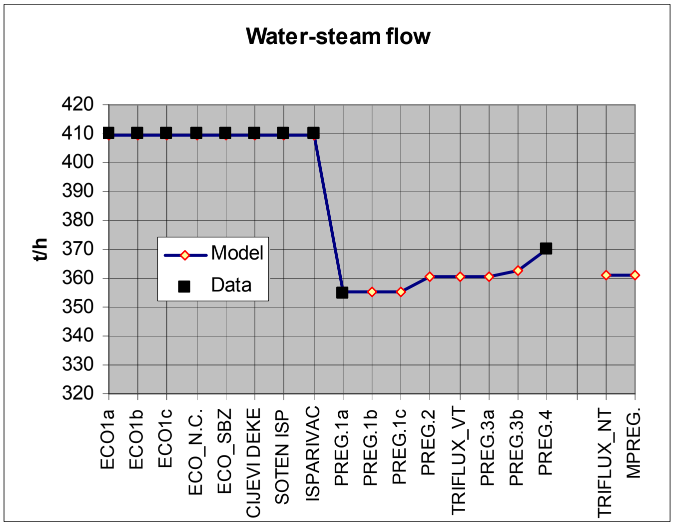


Figure 4 Water-steam mass flow profiles along steam generator

RESULTS

Calculation of the impact of the reaheater dimension on the plant performance was conducted by varying reheater heat transfer area in three steps, from 935 m^2 (actual area), and 1138 m^2 (design area) to 1238 m^2 (to see the impact of a larger area for 100 m^2), with otherwise identical boundary conditions. It should be noted that the surface area of 1238 m^2 was introduced here only as a hypothetical value and not a real possibility, since there is no room for placing a larger reheater than designed (without much larger and more expensive reconstruction, what is not justified due to age of the plant). The analysis was made for loads of 65-95-125 MW. We calculated the influence of reheater dimension on:

1. fresh steam flow,
2. steam generator efficiency,
3. plant efficiency,
4. reheat steam temperature.

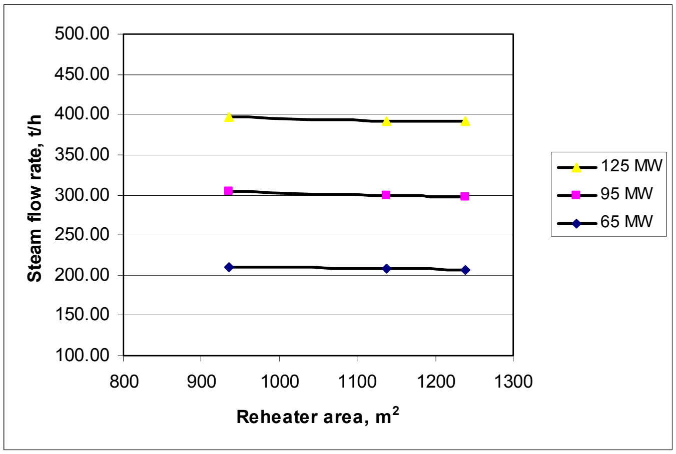


Figure 5 Steam flow vs. reheater dimension

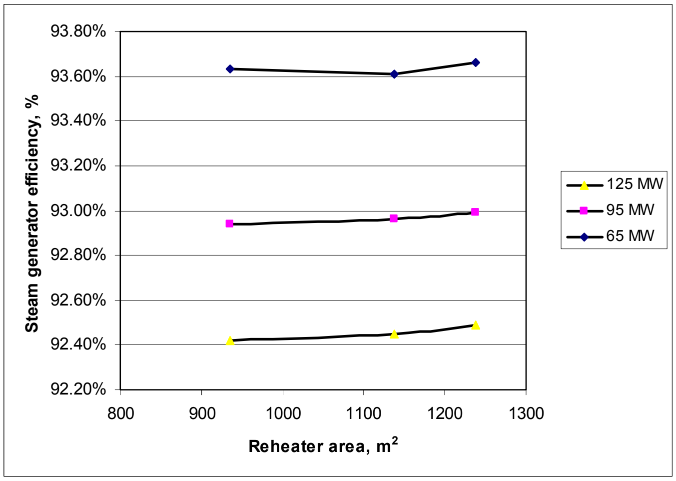


Figure 6 Steam generator efficiency vs. reheater dimension

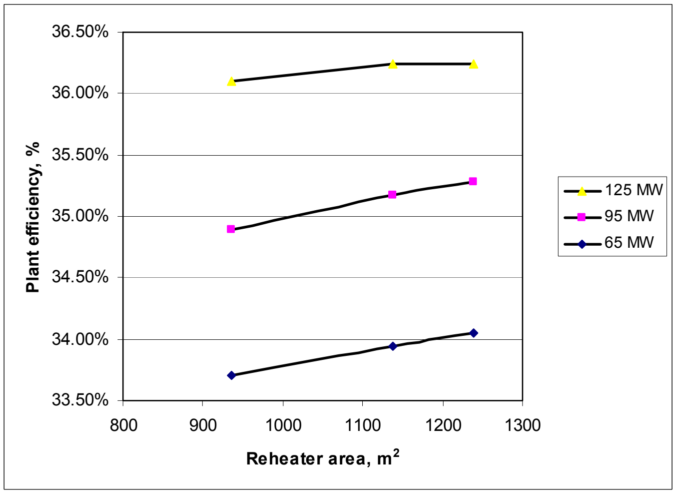


Figure 7 Plant efficiency vs. reheater dimension

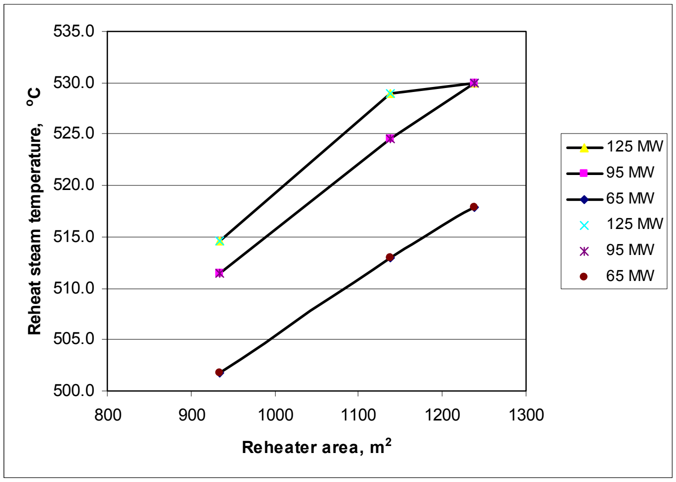


Figure 8 Reheat steam temperature vs. reheater dimension

From Figure 7, showing plant efficiency, it is evident that efficiency is increased as reheater area grows. This is primarily due to the rise of reheated steam end temperature (see Figure 8). After the upper temperature limit is reached (in this case 530 °C), there is no further efficiency enhancement. Namely, to control the temperature limit, cooling water is injected what is thermodynamically unfavorable process that reduces efficiency. Efficiency improvement with increase of surface area, due to temperature increase, is ranging from 0.4 % at full load up to more than 0.7 % at partial load of 50 %.

Figure 5 shows the reduction in the required flow rate of fresh steam with increase of reheater area, which is the logical consequence of the fresh steam enthalpy increase. Namely, equal turbine power can be obtained with less steam flow when enthalpy difference is increased.

Figure 8 shows the superheated steam temperature as a function of the reheater area increase. It is rather obvious that the reheater area even larger than the design value would fail to ensure reheated steam temperature of 530 °C, for loads less than 95 MW (76 %).

SAVINGS

Reconstruction of the reheater in order to return the design dimension would lead to improving the plant efficiency. Increased efficiency would ensure savings from two origins. The first part would steam from the decrease of the coal consumption and the second part from reduction in CO_2 emissions.

1. Savings due to reduced coal consumption

The average electrical power output Pe and operational hours τ

$Pe = 100$ MW average annual electrical power,
$\tau = 6000$ h/a,
$Hd = 25$ kJ/kg,
$\eta = 35.2$ %,

would increase the plant thermal efficiency for
$\Delta\eta = 0.4$ %.

It would result in fuel savings ΔB

$$B = \frac{Pe}{\eta \cdot Hd} = 11.364 \quad \text{kg/s},$$

$B = 245462$ t/a,

$\Delta B = 981.8$ t/a.

If the coal price is assumed
$p_C = 80$ euro/t,
the savings on fuel is
$S_C = 78548$ euro/a.

2. Savings due to reduction in CO_2 emissions

Average carbon content in coal

$c = 56.5$ %,

give the total CO_2 annual emission of
$M_{CO_2} = 508562$ t/a.
Fuel savings result in the reduction of CO_2 emissions of
$\Delta M_{CO_2} = 2034$ t/a.
With the price of CO_2 emissions of
$p_{CO_2} = 30$ euro/t_{CO2},
the CO_2 emission savings are
$S_{CO_2} = 61020$ euro/a.

Total savings expressed in terms of money is about 140000 euro/a.

CONCLUSION

Replacing of the domestic coal fuel with imported bituminous coal in the Thermal Power Plant Plomin1 was feared, would not lead to sufficient thermal efficiency and power increase. Due to operational difficulties when firing domestic coal with unfavorable ash slugging characteristics the size of the second reheater had been decreased from the original design value, as well as the plant power output (from 125 MW to 100 MW). A new coal could recover design characteristics when size of the second reheater would be returned to the design value.

In order to carry out the analysis of the reheater size effect on the reheated steam end temperature a detailed mathematical model of the Thermal Power Plant Plomin 1 has been developed that allowed simulation and assessment of the behavior of the plant in different operational situations.

The mathematical model was tested and then adjusted according to available measured data mainly extracted from operational records.

The results show that the most effective measure for increasing temperature and thermal efficiency is an increase from the current second reheater area of 935 m^2 to design value of 1138 m^2. Even a slightly increased area for 100 m^2 above the design value would be welcome, if it were structurally feasible. Recovery of the second reheater area to the design value, would achieve increase of plant efficiency of 0.4 % at full load up to more than 0.7 % at 50 % load.

The current reheater area would not achieve reheater temperature of 530 °C neither on the full nor on partial load. The increase of reheater area to the design value would hardly ensure rehaeat temperature of 530 °C, only for the full load.

The increase of thermal efficiency would achieve substantional savings of some 140000 euro/a on fuel savings and CO_2 emission costs.

REFERENCES

[1] Lu, S., Dynamic modelling and simulation of power plants systems, *Proceedings of the Institute of Mechanical Engineers, Part A: Journal of power and energy*, vol. 213, No. 1, Sage Publications, 1999, pp. 7-22

[2] Freire, R.G., Lemos, J.M. and Soares, A.O., J.D., Modelling the air/flue gas circuit of a thermoelectric power plant unit, http://www.apca.pt/~apca_docs/CONTROLO2004/controlo2004/papers/pdf0048.pdf

[3] Bogdan, Z. and Kopjar, D., Improvement of the cogeneration plant economy by using heat accumulator, *Energy,* Vol. 31, No. 33, 2006, pp. 1949-1956

[4] Schneider, D. R. and Bogdan, Z., Effect of heavy fuel oil/natural gas co-combustion on pollutant generation in retrofitted power plant., *Applied Thermal Engineering*, vol. 27, No. 11-12, 2007, pp. 1944-1950