TECHNICAL AND ECONOMICAL ASPECTS OF THE OPTIMISATION OF THE STEAM BOILER

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Abstract
Steam boiler belongs to the principal energy sources. Its objective is the production of steam for the energy purposes. Because of gradual improvements its optimisation potential was almost exhausted. Steadily increasing environmental requirements and high production costs require compensation of their technical and operational parameters. More important contributions can be achieved by knowledge based optimisation, which would enable to operate the boiler at its technical and economical limitations. Presented paper is oriented on the boiler economical analysis. Performed analysis is based on operational data and on simulations executed on the mathematical model, specially generated for these purposes. Analysed were possibilities of the technical and operational optimisation. Possibilities of the individual alternatives were evaluated from the viewpoint of their impact on the production economy. From the achieved results follow important possibilities to increase the boiler economical effects while maintaining the environmental requirements.

Keywords: boiler, thermodynamics, boiler modelling, energy analysis, technical optimization, operational optimization

1 Introduction

Coal fired power plants provide stabile source of energy and are still worldwide a major energy source [1]. Objective of the steam boiler is to operate the power plant with maximum achievable profit (maximum efficiency) under the constraints imposed by technology (life-time, energy requirements, asset health) and environmental impacts (CO, NO_X emissions) [2,3,4]. Performance improvement of the boiler can be achieved by boiler retrofits for emissions reduction and by operational improvement. Critical features for efficient boiler operation is fast responsiveness to varying economic conditions, real-time optimisation and operator decision support (off-line) [5,6,7].

Optimization of the steam boiler provides a low-cost, high-return alternative to boiler retrofits for emissions reduction and operational profit improvement. Performance measurements show that overall efficiency can be improved by 2 to 3% [8]. Economical optimisation is in dual relation to the technical optimisation. The duality principle enables to solve problems of the boiler economic efficiency on the technical level. The principal boiler process is the combustion.

It directly influence heat, NO_X and CO generation, heat transfer and heat accumulation [9]. New advancements in combustion technologies, such as flue gas recirculation (FGR) and low NO_X burners (LNB), have made it possible to achieve ultra low NO_X levels without using expensive post-combustion flue gas clean-up technology. Any increase in combustion air temperature results in increasing the adiabatic flame temperature, which in turn increases NO_X formation [10].

Air preheaters recover energy from the hot exhaust gases and transfer it to the incoming combustion air. The most cost-effective approach for reducing NO_X from air-preheated systems is by flue gas recirculation (FGR). In the FGR NO_X control process a portion of the exhaust flue gas is recycled back into the combustion air stream. Recycling the flue gas helps in reducing NO_X emissions by up to 90%, depending on the recirculation rate. Unlike other combustion control system improves fuel and air mixing inadequacies and in certain cases improves the energy efficiency [11,12].

Purpose of the research in this field was to reveal the global characteristics of the boiler and to determine combustion methods for lowering NO_X and CO emissions and high efficiency of heat generation. Developed NO_X reduction concept is based on assurance of adequate condition for low NO_X generation and elimination [13,14,15].

Contemporary approaches, oriented on the boiler efficiency increasing, reside on the staged combustion. This approach can be realized inside or outside of the burner. Its objective is to promote constitution of chemical and physical conditions for optimal combustion, including minimal fuel air ratio and minimal NO_X generation. Combustion improvement inside the burner is based on internal recirculation. Improvement of external combustion and heat transfer can be influenced by external recirculation and coflow. Proposed solutions are still in the development stage. Further development is mainly influenced by contradictory requirements of individual methods. Research purpose was to identify the global characteristics of the boiler and to determine combustion methods for lowering NO_X and CO emissions and to achieve high efficiency of the heat generation. Developed NO_X reduction concept is based on assurance of adequate condition for low NO_X generation and its elimination [16,17].

2 Experimental materials and methods

At the current operation of the boiler desired operating parameters are frequently achieved with increased operation costs. Increasing of the boiler economic efficiency is focused on the decreasing of NO_X, decreasing of the combustion residues and on increasing of slag proportion on the cost of the ash decreasing. Contemporary solutions are based on selection from existing alternatives. All actual alternatives should be included into the decision process. However, conceptually more convenient alternatives are frequently not taken into account. Because direct comparison of chosen alternatives on the plant scale is not possible, mathematical and physical modelling was used. [3,10,11,12]

2.1 Characteristics of the boiler

Analysed boiler (**Fig. 1**) is a melted slag steam boiler with maximal capacity of 215 t/h of the superheated steam with 9 bar pressure and temperature 520°C. Boiler is a part of the energy plant consisting of group of boilers. The boiler is categorized as big pollution source. Its principal fuel is energy coal. As subsidiary fuel is the blast furnace gas. As stabilizing fuel coke oven gas is used. Boiler has two principal production modes which are presented in **Table 1**. Boiler input and output data are presented in **Table 2**. Boiler economy can be mainly influenced by combustion efficiency and environmental impacts. [18] [19]

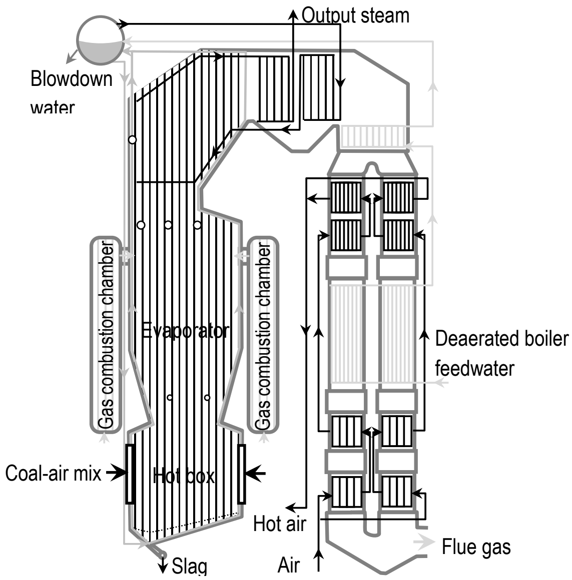

Fig. 1 Scheme of the boiler

Table 1 Boiler production mode

Type	Production mode
Mode I	Energy coal combustion with reburning fuel. Mode without gas combustion outside reburning (20% boiler capacity). Boiler production is limited with minimal throughput 204 t/h at feed water temperature 195 °C, respectively, 194 t/h at feed water temperature 160°C. Mode I present pulverized coal heating without stabilization fuel with slag melting.
Mode II	Coal co-firing with gas fuel (BFG, COG and NG). This mode is not limited by the minimal boiler capacity as long as other boiler parameters are maintained.

Table 2 Parameters of the boiler

Performance parameter	Value
Nominal thermal capacity	159,7 MWt
Coal – thermal capacity	179,4 MWt
Thermal capacity – coal co-firing	183,6 MWt
Superheated steam quantity	215 $t.h^{-1}$
Temperature of superheated steam	540 ºC
Superheated steam overpressure	9,41 MPa
Capacity level at stabilised working conditions for steam output	70 – 215 Mp($t.h^{-1}$)

2.2 Physical model of the boiler

Physical modelling was realized on the isothermic hydraulic boiler model. As modelling substance the water was used. Parameters of the input substances for boiler reference state (Mode I.) are presented in **Table 2**. From the view point of the hydrodynamic process similarity the automodelling principles was used. Input media quantities were selected from the view point of the effective visualization. The physical model represents furnace part of boiler in the scale ratio 1:20. Shape and dimensions of the physical model are presented on **Fig. 2**.

For convection and mixing visualisation in the boiler marking media and modification of water level was used. As marking medium was used paints (**Fig. 3**), seeds (**Fig. 4**) and indicator Ph. As paints painter's colours were used colours represented individual or medium. As seeds were used grass-seeds, mustard and sugar beet seeds. As Ph indicator phenolphthalein was applied.

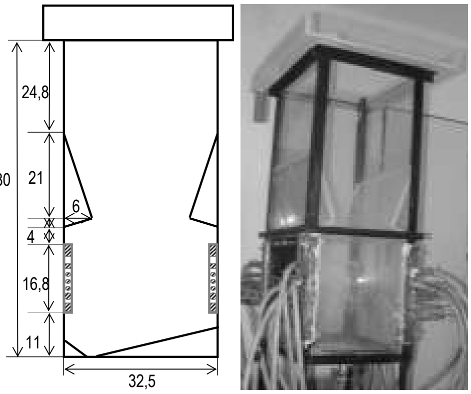

Fig. 2 Physical model of the boiler

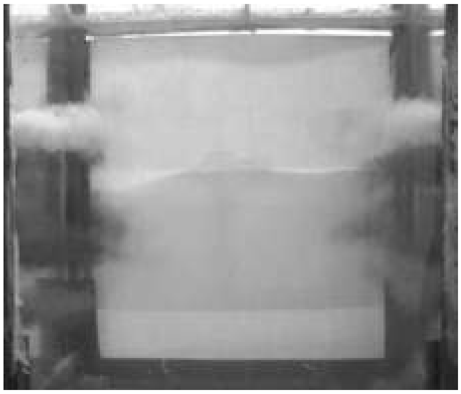

Fig. 3 Flow visualization with paints

Flow is possible to visualize by decreasing the water level to position of outflow opening. The water level was on top position of the burner chambers. This allowed to visualize the flow without markers (**Fig. 5**). [20] [21]

Fig. 4 Physical modelling – flow visualisation by seeds

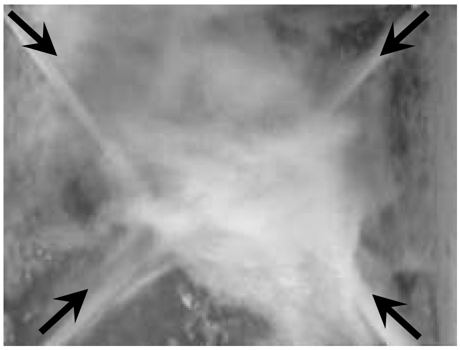

Fig. 5 Visualization by water level adjustment

2.3 Mathematical model of the boiler

Purpose of the mathematical model of the boiler (**Fig. 6**) was digital simulation developed for the purpose of obtaining information about the processes taking place in the boiler, as well as for determining principal boiler activity indicators such as NO_X, combustion residue and slag quantities. [9]

Model development was based on the elementary balance method. Processes on-going in the element are running in mutual interaction of the coal and gaseous media at the case of coal burning or interaction between gaseous media in case of gas burning. Model of the element includes processes of combustion, heating and cooling, drying, pyrolysis, gasification and NO_X

formation. Model of NO_X generation and extinction includes fuel and thermic NO_X. In the model of the element mass and heat balance is preserved. Basic reactions in the element are:

- pyrolyses

$C + 2 H_2 \rightarrow CH_4$ (1.)

$2 C + 2 H_2 \rightarrow C_2H_4$ (2.)

- gasification

$C + CO_2 \rightarrow 2 CO$ (3.)

- water gas generation

$H_2O + C \rightarrow CO + H_2$ (4.)

- carbon combustion

$C + O_2 \rightarrow CO_2$ (5.)

Mathematical model was developed in the open-source programming languages FreePascal with graphical environment Lazarus. Model was calibrated to the real plant based on operational measurement. Reference state was adjusted on standard operation. [22] [23]

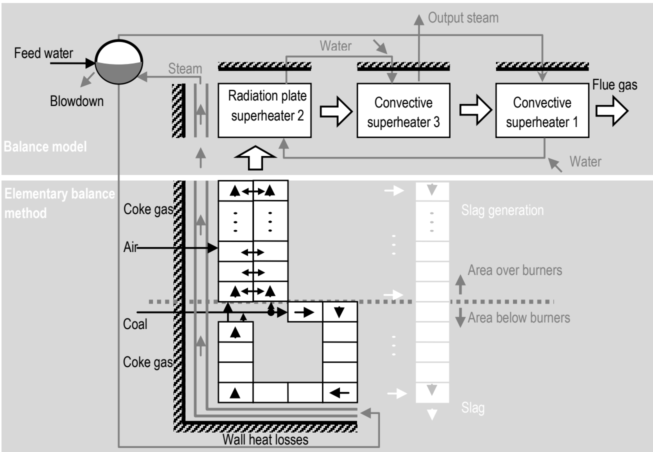

Fig. 6 Structure of the boiler mathematical model

3 Results

3.1 Analysis of the boiler activity

Objects of the boiler analysis were boiler operation and processes in the boiler. Operational analysis was based on the operational data, and on the boiler simulation. Process time behaviour at the reference state I. is presented on **Fig. 7**. The process has an oscillating character with a relatively stable mean value. In comparison with steady state mode oscillatory boiler operation is not desirable and production rate and other boiler parameters are reduced.

For the mode I and mode II reference conditions are presented **Table 1** and **Table 2**. [24]

3.2 Operational optimization

The objective of the operational optimization is to secure the boiler operation optimally. Identification of optimal indexes was realized on mathematical model (**Fig. 8**). In the framework of operational optimization the following factors were analysed:

- air surplus (**Fig. 10**),
- air redistribution (**Fig. 11**),
- primary air proportion,
- pulverized coal granulometry (**Fig. 12**).

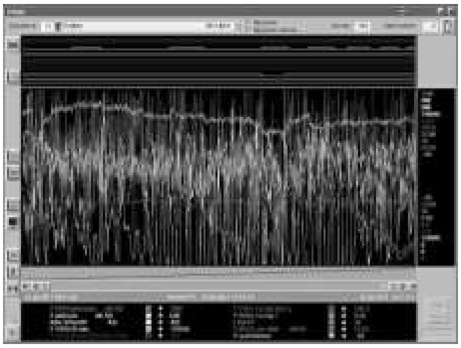

Fig. 7 Boiler quantities behaviour

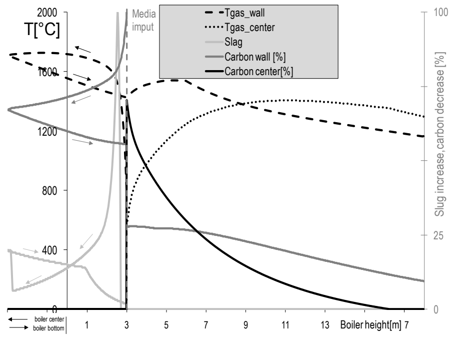

Fig. 8 Mathematical simulation – process parameters behaviour

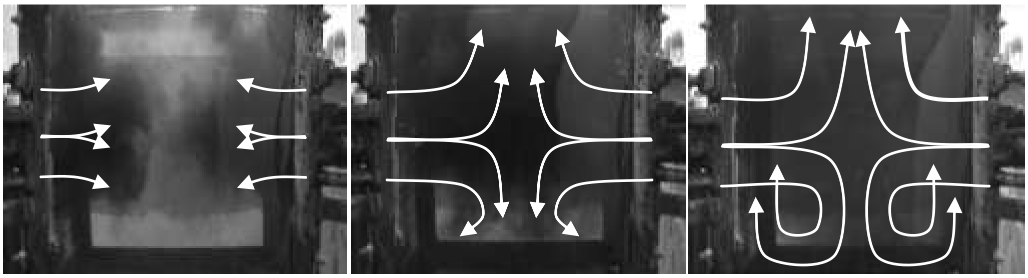

Fig. 9 Flow scheme at the boiler burner part (Reference state I.)

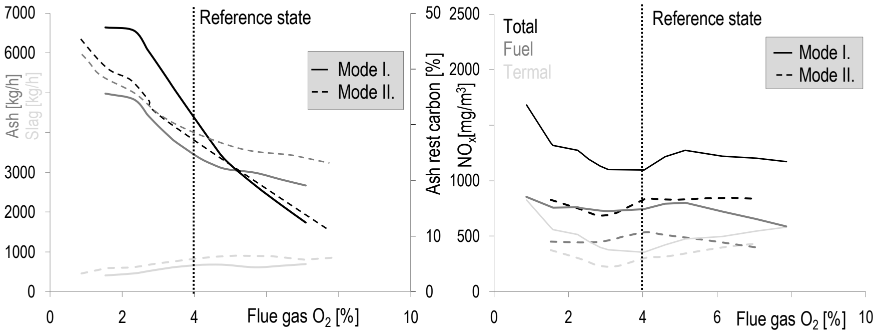

Fig. 10 Influence of O_2 in the flue gas on ash, slag, residue and NO_X (RS I, RS II)

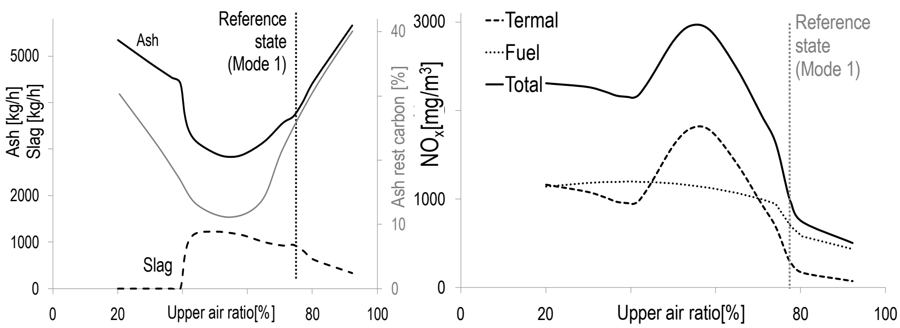

Fig. 11 Impact of air distribution on ash, slag, residue and NO_X (RS I)

Air excess causes increase of NO_X due to increase of the maximum boiler temperature in the burner and decrease of the content of unburned coal. Total NO_X content and unburned coal is lower and the quantity of the ash and slag is higher. Because of that further simulations of the operational measures were made for the worse case (Mode I). From the given behaviours it follows that boiler operational positions are in the optimal boiler operation area. That means that current technical possibilities to improve boiler performance are practically exhausted. Small improvements by realizing the process in the optimum vicinity can be achieved. [24] [25]

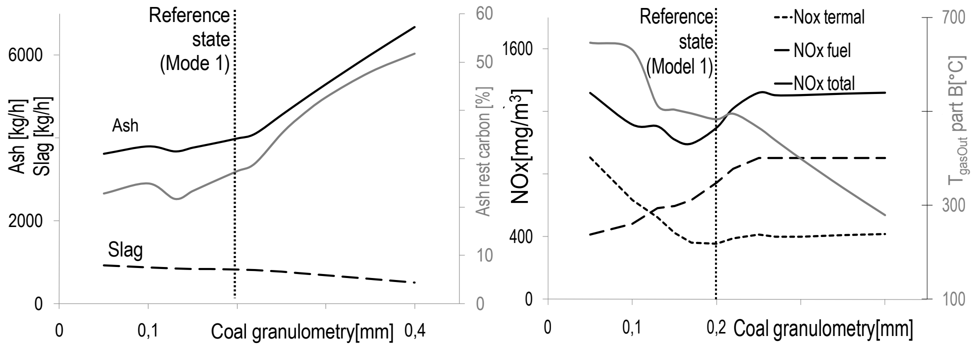

Fig. 12 Effect of pulverized coal grain size on ash, slag, residue and NO_X (RS I)

3.3 Boiler technical optimization

Through technical optimization the boundary possibilities are moved which can improve technical and economic parameters of the boiler. The measures of the technical optimization are oriented on the improvement of flow inside the boiler, air fuel mixing and combustion. The compared alternatives are in **Table 3, Fig. 13** and **Fig. 14**.

Table 3 The influence of the technical measures on the boiler operation parameters

Alt.	NO_X therm. [%]	NO_X fuel [%]	NO_X total [%]	Residual C [%]	Slag [%]	Notes
1	100	100	100	4	100	Reference state - mode I. (RS I)
2	100	100	100	4	100	Reference state – mode II. (RS II)
3	409	160	240	1	92	RS I + burner with combustion air
4	370	157	226	0	90	RS I + burner with combustion air, decrease of fuel input
5	280	138	190	4	84	RS II + burner with combustion air
6	118	36	62	4	70	RS I + low emissivity burner
7	109	38	61	3	89	RS I + low emissivity burner, decrease of fuel input
8	83	34	52	5	78	RS II + low emissivity burner
9	80	36	51	3	120	RS I + coflow (PT I)
10	34	32	33	4	120	RS II + coflow (PTD II)

In the framework of analysed alternatives the selected indexes do not overlap at one point but are partially contradictory. A suitable solution should contribute to the simultaneous improvement of all three parameters. From the point of view of NO_X generation, a high impact on its generation has combustion of pyrolysis gas. In the current conditions pyrolysis gas generation is slow and the gas is combusted with high primary air surplus. These conditions are convenient for NO_X generation [14]. Its decrease can be achieved by gas fuel input into the pulverized coal burners and its combustion. In this way temperature and pyrolysis process rapidly increase and oxygen content decreases. Combustion of pyrolysis gas occurs at high temperature and low oxygen content which causes a substantial decrease of fuel NO_X.

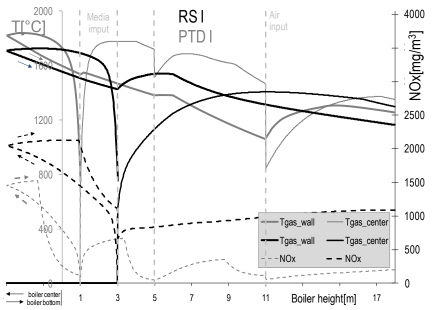

Fig. 13 NO_X and flue gas temperature behaviour at RS II and PT II

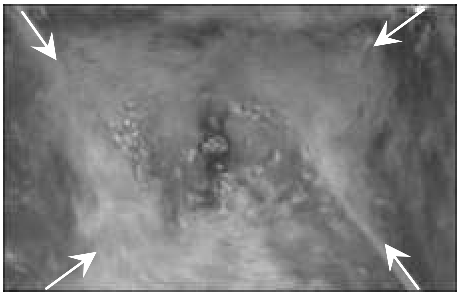

Fig. 14 Physical modelling without marker (tangential flow, burners deflection 22,5°)

In the next step coal combustion is realized. It is required that combustion process in the first stage should be realized in oxidizing atmosphere and in the second stage in the reduction region. It is important that in the reduction region the NO_X content is maximally decreased. Subsequently follows the process of thermic NO_X generation, which depends on air surplus and mainly on the temperature. Effective combustion in this region is characterized by multistage combustion at which we can create conditions for elimination of NO_X. [9] [26]

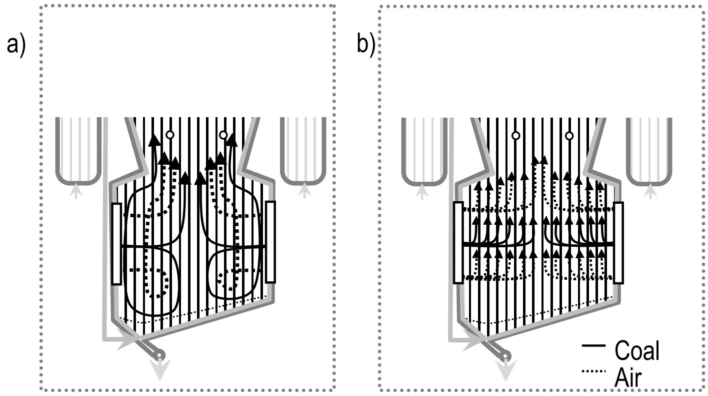

Fig. 15 A simplified flow diagram of the boiler a) the reference state b) conceptual design with co-flow

4 Discussion

Combustion residue is mainly influenced by the intensity and time of coal combustion. It is required to realize the process as quickly as possible. For its realization quick fuel mixing with air and long residential time is required. For slag generation the temperature and the quantity of combusted coal in boiler smelting zone is determining. To this requirement corresponds co-flow arrangement with reburning. In **Fig. 15** is shown the co-flow with coal combustion and its comparison with reference solution.

5 Conclusion

Performed simulations of the influence of operational and technical measures on the steam boiler improvement allowed to specify ways to increase its technical and economic efficiency. From the analysis of the boiler it follows that the operational state of the boiler is in the vicinity of its optimum. Present feedback control system generates high fluctuations of the boiler. For their elimination the most convenient is predictive control system, which is reducing the number of interventions.

By operational optimization cannot by fulfill the principal requirement, which is decreasing of the NO_X content to less than 200 mg/m^3. As best alternative from the technical measures, most convenient is the co-flow arrangement by which the following results were achieved: 35% NO_X decreasing, 80% fuel residue decreasing and 80% of slag decreasing. Economic contribution from this technical solution is very promising.

References

[1] B. Miller: *Clean Coal Engineering Technology*. 1st ed., Butterworth Heinemann, Burlington, 2010

[2] F. M. Steingress: *High Pressure Boilers*. 4th ed., Am. Technical Pub., Orland Park, 2009

[3] R. D. Wilson: *Boiler Operator's Workbook*. 4th ed., Am. Technical Pub., Orland Park, 2008

[4] N. Spitz, R. Saveliev, E. Korytni, M. Perelman, E. Bar-ziv: *Prediction of Performance and Pollutant Emission from Pulverized Coal Utility Boilers*. 1st ed., Nova Science Publishers, Hauppauge, 2009

[5] D. A. Saez, A. Cipriano, A. W. Ordys: *Optimisation of Industrial Processes at Supervisory Level: Application to Control of Thermal Power Plants*. 1st ed., Springer, London, 2001

[6] S. Rebennack, P. M. Pardalos, M. V. F. Pereira, N. A. Iliadis: *Handbook of Power Systems* I, 1st ed., Springer, London, 2010

[7] H. Taplin: *Boiler Plant and Distribution System Optimization Manual*. 2nd ed., Prentice Hall, Upper Saddle River, 1997

[8] J. Buchetti: *Engine Tests and Boiler Efficiencies*. 1st ed., Cornell University, Ithaca, 2009

[9] D. Foerter, W. Jozewicz: *Cost of selective catalytic reduction (SCR) application for NOx control on coal-fired boilers*. 1st ed., Books LLC, Memphis-Tennessee, 2011

[10] G. Domazetis, P. Barilla, B. D. James: Fuel Processing Technology, Vol. 91, 2010, No. 3, p. 255-265

[11] S.Y. Ahn et al.: Applied Thermal Engineering, Vol. 31, 2011, Vol. 6-7, p. 1163-1171

[12] J. Andries, J.G.M. Becht: Energy Conversion and Management, Vol. 37, 1996, Vol. 6-8, p. 855-860

[13] Ch. E. Baukal: *Industrial Burners Handbook (Industrial Combustion)*. 1st ed., CRC Press, Boca Raton, 2003

[14] K. McCarthy, S. Laux, J. Grusha: *Improved Low NOx Firing Systems for Pulverized Coal Combustion*. In: 24th International Technical Conference on Coal Utilization & Fuel Systems - Clearwater, Florida, 1999, p. 1-11

[15] B. Čech, R. Malý: All for Power, 2009, *Optimalizace primárních a sekundárních metod snižování emisí NOx pro dosažení limitu 200 mg/m^3*, [13.2.2012], http://www.allforpower.cz/UserFiles/files/2009/malycech.pdf

[16] G. Richards et al.: *Development of an Enhanced Combustion Low NOx Pulverized Coal Burner*. In: 31st International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, Vol. 31, 2006

[17] K. Ochi, K. Kiyama, H. Yoshizako, H. Okazaki, M. Taniguchi: Hitachi Review, Vol. 58, 2009, No. 5, p. 187-193
[18] M. Sidorová, G. Wittenberger: Acta Montanistica Slovaca, Vol. 11, 2006, No.1, p. 162-165
[19] J. Krajňák, M. Urbanský, P. Gurský, T. Brestović: Transactions of the Universities of Košice, 2011, No. 2, p. 49-56
[20] D. Malindžák, J. Spišák: Uhlí-Rudy-Geologický průzkum, Vol. 4, 1997, No. 5, p. 162-165 (in Czech)
[21] J. Spišák, D. Malindžák: Acta Montanistica Slovaca, Vol. 1, 1996, No. 4, p. 329-336 (in Slovak)
[22] J. Mikula et al.: Acta Metallurgica Slovaca, Vol. 15, 2009, No. 1, p. 197-204
[23] Zs. Vaszi, A. Varga: Acta Metallurgica Slovaca, Vol. 15, 2009, No. 1, p. 352-358
[24] F. Michalíková, V. Jacko, M. Sisol, I. Kozáková: Acta Metallurgica Slovaca, Vol. 10, 2005, No. 1, p. 49-55 (in Slovak)
[25] R. V. Filkoski, I. J. Petrovski, P. Karas: Thermal Science, Vol. 10, 2006, No. 3, p. 161- 179
[26] A. Olijár, M. Zelko, D. Dorčák, J. Lišuch, I. Koštial: Waste Forum, 2010, No. 4, p. 283-289 (in Slovak)

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