SELECTION OF SUSTAINABLE TECHNOLOGIES FOR COMBUSTION OF BOSNIAN COALS

by

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This paper deals with optimization of coal combustion conditions to support selection a sustainable combustion technology and an optimal furnace and boiler design. A methodology for optimization of coal combustion conditions is proposed and demonstrated on the example of Bosnian coals. The properties of Bosnian coals vary widely from one coal basin to the next, even between coal mines within the same basin. Very high percentage of ash (particularly in Bosnian brown coal) makes clear certain differences between Bosnian coal types and other world coal types, providing a strong argument for investigating specific problems related to the combustion of Bosnian coals, as well as ways to improve their combustion behaviour.

In this work, options of the referent energy system (boiler) with different process temperatures, corresponding to the different combustion technologies; pulverised fuel combustion (slag tap or dry bottom furnace) and fluidized bed combustion, are under consideration for the coals tested. Sustainability assessment, based on calculation economic and environment indicators, in combination with common low cost planning method, is used for the optimization. The total costs in the lifetime are presented by General index of total costs, calculated on the base of agglomeration of basic economic indicators and the economic indicators derived from environmental indicators. So, proposed methodology is based on identification of those combustion technologies and combustion conditions for coals tested for which the total costs in lifetime of the system under consideration are lowest, provided that all environmental issues of the energy system is fulfilled during the lifetime. Inputs for calculation of the sustainability indicators are provided by the measurements on an experimental furnace with possibility of infinite variation of process temperature, supported by good praxis from the power plants which use the fuels tested and by thermal calculations of the different options (different temperature in the boiler furnace) of the referent energy system.

Key words: *sustainability, combustion, coal, indicator, slagging, emission*

Introduction

Due to increase of the world energy consumption and rising problem of global warming and climate change, the attention is focused on sustainability of energy power systems.

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Thus, sustainability assessment is recommended to be performed and offered to decision makers when new application in coal-based energy system is under consideration. Under such an assessment, the system is considered from economical, environmental, technological, social, political, ethical and some other aspects [1]. The aim of that procedure is providing an environmental friendly, economically feasible and socially just coal-based system.

Proper furnace and boiler design is key issue in modern coal-based energy generation. As far as pulverised fuel (PF) boiler is concerned, three key factors: coal, furnace design, and furnace operation, can cause operational problems. The traditional slagging and fouling indices like the base-acid ratio, the silica ratio, the slagging factors, *etc*., do not take the latter two factors into account. Thus, their use in such a traditional way is not reliable for furnace and boiler design [2, 3]. Therefore, coal behavior predictors, here called slagging/fouling indicators, which take into account temperature conditions of combustion as well, must be developed to support furnace and boiler design. Parameters important for emissions of CO_2, SO_2, NO_x, and trace elements must be accepted as well, to consider environmental indicators during furnace and boiler design, [3].

In this paper, the attention is focused on development of the methodology allowing optimization of temperature conditions of combustion of the tested fuel, from the aspect of sustainability of the energy system which uses the tested fuel, in this case Bosnian coal.

Methodology of optimization model

Principally, the methodology proposed in this work is based on identification of those combustion technology and combustion conditions for the given coal for which the total costs in lifetime of the referent energy system under consideration are lowest, provided that all environmental issues, like emission limit values, are fulfilled during the lifetime of the energy system. The total costs in the lifetime are presented here by General index of total costs (G).

Definition of sustainability indicators

In the paper, economic and environmental criteria are proposed to optimize combustion conditions, under which several sustainability indicators (SI), which are influenced the most on the overall costs, are defined and used in the analysis. The most important SI defined here are Indicator of investments, Indicator of O&M costs, and Indicator of fuel consumption as economic indicators, and Indicator of SO_2, Indicator of NO_x,and Indicator of CO_2 as environmental indicators, fig. 1. Social indicators, like Indicator of new jobs and Indicator of working hours, as well as some economic indicators of fixed costs, like Indicator of salaries of employees and Indicator of environmental fee, are considered to be constant for all options under consideration and will not be particularly considered within this analysis. All SI used in this work, with explanation of the meaning, are listed in nomenclature.

Formation of General index of total costs

The chart flow in fig. 1 shows procedure for formation of General index of total costs [4]. It can be noticed that the environmental indicators are transited into derived economic indicators, by calculation the investments needed for reducing emissions below emission limit values. Then, there are jointed to basic economic indicators to form aggregated economic indica-

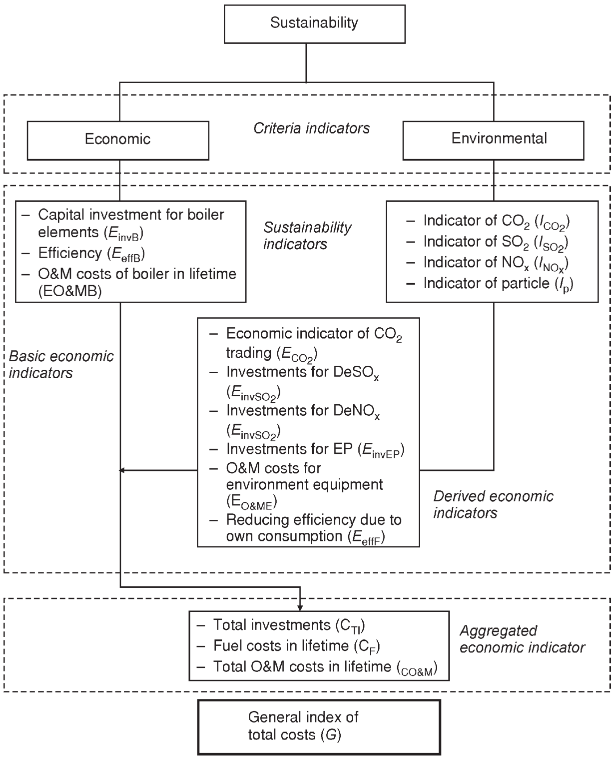

Figure 1. Flow chart of generation of General index of the costs [4]

tors. So, all options of combustion technology or temperature conditions under consideration are evaluated as function of costs consisted of aggregated economic indicator as follows:
- total investment costs for the energy system (C_{TI}),
- costs of the fuel used in the energy system during lifetime (C_F), and
- O&M costs for the energy system during lifetime ($C_{O\&M}$).

Mathematical interpretation of the formation of General index of total costs is given as

$$G_j = \sum_{i=1}^{T} (C_{TI\,j,t} + C_{F\,t,t} + C_{O\&M\,t,t}) \tag{1}$$

where G_j is function of costs for given option *j, t* – the time in years (1, 2, …, *T*), and *T* – the lifetime in years.

As motioned above, aggregated indicators from eq. (1) are agglomerated from the costs related to the selected combustion system (*basic economic indicators*) and from additional costs needed for fulfilling environmental issue in the lifetime (*derived economic indicators*). Different temperature conditions corresponding to the different combustion techniques – PF combustion with slag tap, PF combustion with dry slag, and fluidized bed combustion – are under consideration for the coals tested. After calculation of sustainability indicators, and their transition into costs, a common low cost planning (LCP) method is used for optimization of the options under consideration. Within LCP method, economic indicators are aggregated first into total costs, and then, the optimization is performed according to the following term:

$$\text{Minimum } G_j \tag{2}$$

For all options of temperature conditions under consideration, General index of total costs is generated according to eq. (1) and then compared and ranked according to eq. (2).

Inputs for the sustainability indicators

The key point of the proposed method is measuring the indicators, *i. e.* providing reliable inputs for calculation of the indicators [1, 4]. This point is prerequisite to get reliable results of the optimization process. Inputs for calculation of the indicators in this work are provided by the measurements on an experimental furnace, specially designed for performing the tests at variable and at-will-adjustable combustion temperature. Also, experience and measurements from existing power plants which use the fuels tested and thermal calculation of the energy system (boiler) under consideration are also used to support calculation of the indicators.

Measurements on the experimental furnace

Experimental furnace design. For purpose of the research, a special lab-scale furnace *electrically heated entrained PF flow reactor* is designed at Mechanical Engineering Faculty of Sarajevo University and used for the experiments [3-5]. In essence, the experimental reactor comprises a 3 m length alumina-silicate ceramic tube, with a diameter of 230/200 mm, where combustion takes place, surrounded by SiC stick-type electric heaters and three-layer insulation, fig. 2.

The temperature of the reaction zone is controlled by a programmable logic controller (PLC) with thyristor units for each of the heating zones, allowing the process temperature to be varied at will across the range from ambient to 1560 °C. The maximum power of the electrical heaters used to maintain temperature in the reaction tube is 70 kW, while nominal or thermal power of the reactor is 20 kW. Pulverized fuel is introduced into the reactor by means of a volumetric feeder, mounted above the reactor. The feeder is equipped with a speed controller, allowing mass flow in the range of 0.25-5 kg/h. Samples of ash deposit are taken out from the reactor for analysis by means of water-cooled lance probe, which can be moved along the reaction tube axis and set at the desired position, fig. 2. High temperature resistance ceramic probes are attached to the lance by a special support, so that there is negligible cooling of the ceramic probes. Thus, regarding the deposition process on the ceramic probes, the resulting situation in the reactor is comparable to the

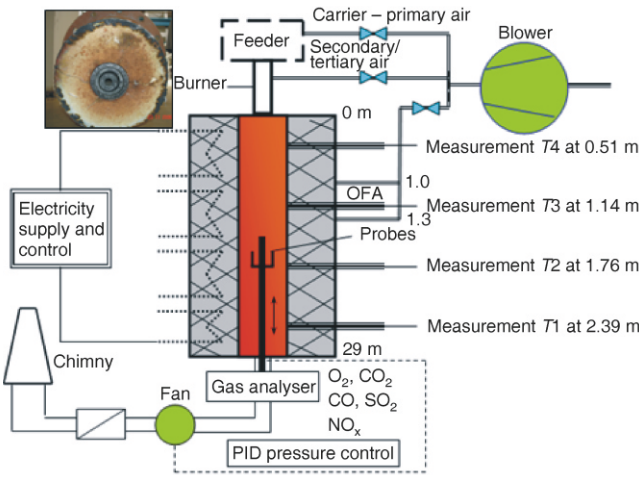

Figure 2. Scheme of the experimental furnace

formation of secondary deposit layer in a real boiler situation [3]. The burn-out time and the residence time of particles in the reaction tube were estimated and compared during design. The unburnt rate, which was measured at the point of ash deposit sampling (results reported in [5]), confirmed proper design of the reactor.

Air for combustion, coming from the air blower, is divided into carrier air (primary air), secondary air, tertiary air, and over fire air (OFA) line. The first three air portions are introduced into the reactor over the swirl burner settled on the top of the reactor, so the air-fuel particle mixture flows downward, fig. 2.

Fuel test matrix. Within the research, 7 types of Bosnian coals have undergone the tests on the experimental furnace. Lignite Dubrave (D) from Tuzla coal basin was tested alone, and also it is mixed with lignite Sikulje (80:20 wt.%) to form blend L, and with lignite Sikulje and brown coal Banovici to form blend LB (L:B = 75:25 wt.%). Those coals are regularly being used in coal-based power plant Tuzla TPP (1 unit of 110 MW, 2 units of 200 MW, 1 unit of 215 MW). Brown coal Kakanj from Middle Bosnia coal basin was tested alone, and also with the coals Breza, Zenica, Bila, and lignite Gracanica to form blend M1 (with 61 wt.% of Kakanj brown coal) and blend M1A (with 73 wt.% of Kakanj brown coal). Those coals are being used in coal-based power plant Kakanj TPP (2 units of 110 MW and 1 unit of 230 MW). Finally, lignite Gracanica, from coal basin Bugojno, was tested alone.

Table 1. Ultimate and proximate analyses of the coals tested

	D	K	G	L	LB	M1	M1A
Proximate analysis [%], as-received							
Moisture	30.4	11.30	38.11	34.22	35.34	12.99	12.46
Ash	30.3	41.43	15.37	23.62	20.55	35.30	36.75
Volatiles	25.3	25.88	29.13	24.32	25.46	28.74	28.13
Fixed C	14.0	21.39	14.15	17.42	19.32	22.97	22.66
Combustible	39.3	47.28	46.52	42.16	44.78	51.72	50.80
Ultimate analysis [%], as-received							
Carbon	27.0	35.11	38.21	29.58	31.84	38.65	37.89
Hydrogen	2.3	2.78	2.55	2.49	2.55	2.86	2.85
Sulfur	0.77	2.28	2.56	0.73	0.94	2.51	2.45
utoNitrogen	0.46	0.96	0.59	0.48	0.60	0.98	0.98
Oxygen	9.3	7.03	3.80	9.29	8.60	7.81	7,66
Heating value [kJkg^{-1}], as-received							
Gross	13490	13490	11095	10889	11603	14753	14497
Net	12657	12657	9764	8588	10265	13864	13622

In tab. 1, ultimate and proximate analyses for the coals tested are given. It can be noticed that brown coal Kakanj has a high percentage of ash of 41.43 wt.%, while lignite Dubrave also has untypically high percentage of ash for lignite of 30.3 wt.%. From the other side, lignite Gracanica has a very high percentage of sulphur (2.56 wt.%), but also a high percentage of volatiles (29.13 wt.%).

In tab. 2, ash chemical composition as well as ash fusion test (AFT) for the coals tested are given. It can be noticed that lignite from Tuzla basin (D and L) have high percentage of SiO_2 and Al_2O_3, while lignite from Bugojno basin (G) has low percentage of SiO_2 and very high percentage of CaO, which reduced the melting temperatures of the ash of this coal. Considering brown coals from Middle Bosnia basin (K, M1, and M1A), it can be noticed that increase of percentage of Kakanj coal in the blend increases percentage of SiO_2 in the ash and consequently the molten temperatures of the coal rose up.

Table 2. Ash chemical composition and AFT of the coals tested

	D	K	G	L	LB	M1	M1A
Ash chemical composition, [%]							
SiO_2	50.30	43.23	9.92	49.88	46.79	38.70	39.96
Al_2O_3	24.02	19.13	6.74	24.16	25.38	17.19	17.71
Fe_2O_3	10.50	10.40	9.58	10.42	10.21	10.03	10.11
CaO	4.36	12.60	35.20	4.41	6.35	16.77	15.62
MgO	3.22	2.97	6.80	3.18	2.83	4.40	4.05
K_2O	1.68	1.13	1.84	1.61	1.40	1.18	1.16
Na_2O	0.13	0.66	0.65	0.13	0.24	0.66	0.66
TiO_2	0.90	0.71	1.23	0.83	0.78	0.72	0.71
SO_3	3.97	5.36	28.14	4.38	5.14	7.58	6.96
Ash fusion test – AFT, [°C]							
Sintering	1085	1247	1020	1088	1057	1220	1225
Softening	1157	1273	1120	1158	1101	1262	1262
Hemisphere	1260	1289	1220	1258	1201	1280	1279
Molten	1342	1306	1280	1328	1277	1292	1293

Test procedure and conditions. In each test run, fuel was pre-dried at approximately $w = 0\%$ and then supplied into the feeder tank. Fuel thermal load was kept at approximately 5 kW_t in all runs. Process temperature varied from 880 °C to 1550 °C and excess air ration from 0.92 to 1.4.

Depending on the fuel and excess air used, the total airflow rate was between 4.29 m_n^3/h and 6.60 m_n^3/h. The primary (carrier) air flow rate was set at 1.50 m_n^3/h for all runs, with the rest of the air divided into secondary and tertiary portions, at a ratio of 2.6:1. During the tests, ceramic probes were set 2 m from the top of the burner (see fig. 2). After 90 minutes of ash collecting, the ceramic probes with ash deposits are carefully removed for analysis.

NO, NO_2, SO_2, and CO emissions were measured in ppm by a TESTO 350 instrument with an integrated TESTO 339 dry unit, and emissions were then converted at [mg/m_n^3, dry, 6% O_2]. Measurements were repeated several times during each test to eliminate the influence of accidental phenomena. Measurement error was estimated at 18 ppm (2.8%) for the NO emissions and at 59 ppm (2.6%) for the SO_2 emissions. Gas temperature was measured at the point in the partially insulated outlet tube where the gas sample was taken for emission measurement. Depending on the test run, gas temperature was between 50 °C and 140 °C. The processes in the flue gas line were frozen; there was no post combustion from the reactor to the TESTO instrument [3, 6].

Applicability and reliability of the tests results. It should be noted that, as a result of combustion, the temperature of the gases in the flame region (the coal particle temperature) and in post-combustion zone could be higher than the reactor wall, with potential implications for the ash transformation and deposition processes.

As regards the run time of 90 minutes, it should be stressed that it was the initial stage of slagging that was being examined during these tests.

As regards the type of testing procedure used, it should be noted that such tests using test furnaces are not yet considered standard testing procedure, although many laboratories worldwide do use them, including TU Clausthal [7-10], IVD Stuttgart [11], and the University of Newcastle [2]. This type of testing procedure is accompanied by standard ancillary techniques for sample preparation, see *e. g.* [9], or standard chemical techniques that provide useful information, *e. g.* AFT or oxide determination. These chemical techniques are, however, imperfect slagging or fouling predictors, and testing by experimental facility is advisable, as it provides a more reliable evaluation of the slagging/fouling propensity of the given fuels, see [2].

Finally, with regard to the deposition evaluation methodology used, it is important to note that the reliability of results, *i. e.* of the evaluation of the temperature limits for the specific deposition zones, strongly depends on the number of measurement points [3]. The mentioned facts should be taken into account in considering the results presented here.

Results of the tests. The tests on the reactor have been performed at different temperatures – from 860 °C to 1550 °C (corresponding to the different combustion technologies), varying excess air ratio from 0.92 to 1.4 to optimize emission figures for the coals tested.

Slagging and fouling indicators are based on 6-criteria evaluation of ash deposits formed into the reactor, described in detail in [12]. Basically, shape, state, and structure of the ash deposit sample are determined on the base of visual observation (photographically) and optical observation by a microscope. Rate of adhesion and cohesion of the ash deposit are determined by physical acting to the ash sample [12, 9]. Finally, deposition rate is defined as a mass of the deposit collected at the probe, divided by the deposition area, as a function of time [7, 8, 12].

After analyses within above mentioned single criteria, those single evaluations are aggregated into final evaluation on propensity to the slagging/fouling for the given coal and process conditions [6]. The final evaluation on slagging/fouling propensity is expressed linguistically by the following terms:

– low slagging/fouling,
– moderate slagging/fouling,
– strong slagging/fouling, and
– very strong slagging/fouling.

The procedure of aggregation of single criteria evaluations into final evaluation is given in tab. 3.

Table 3. Principle of aggregation of single criteria evaluations into final evaluation of propensity to slagging/fouling

Final evaluation	LOW	MODERATE	STRONG	VERY STRONG
Zone	A	B	C	C
Prevailing gradation	i	ii	iii	iv, v
Criteria 1 Shape	Pyramid (i) Cone (ii)	Cone (ii) Truncated cone (iii)	Truncated cone (iii) Flat (iv)	Flat (iv)
Criteria 2 Melting state	Dry (i)	Start of melting (ii)	Melted (iii)	Molten (iv)
Criteria 3 Structure	Powder (i)	Particles (ii)	Particles (ii) Fibres (iii)	–
Criteria 4 Adhesion	Low (i)	Moderate (ii)	Moderate (ii) Strong (iii)	Very strong (iv)
Criteria 5 Cohesion	Low (i)	Moderate (ii)	Moderate (ii) Strong (iii)	Very strong (iv)
Criteria 6 Deposition intensity	Low (i)	Moderate (ii)	Moderate (ii) High (iii)	High (iii) Very high (iv)

Principally, in aggregation process, weighting factors given to the single criteria may be different, provided that their sum always must be equal to 1. In this work, equal weighting factors are given to all single criteria to aggregate final evaluation.

In tab. 4, evaluation of slagging and fouling behaviors found by the tests is given for the coals tested.

For the further analysis, the test points, reflecting above-mentioned final evaluations on propensity to slagging/fouling, are plotted against the appropriate coal indices onto graphic diagrams, fig. 3. On the base of such a diagram, limit values for certain slagging/fouling indicators may be set as function of combustion temperature. This presents an improvement of the use of traditional slagging/fouling indices, which use so far was based on the chemical ash composition only, see [9, 10]. By this methodology, beside ash chemical compozition, combustion temperature is taken into account as well, making the analysis of slagging/fouling propensity more reliable [6].

Table 4. Final evaluation of slagging and fouling propensity at different temperature conditions of combustion process for the coals tested

ºC	D	K	G	L	LB	M1	M1A
880	–	–	Low	Low	–	–	–
960	Low	–	Moderate	Low	Moderate	–	Moderate
1050	–	–	Moderate	Low	–	–	–
1140	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Strong
1250	Moderate	Moderate	Strong	Strong	Moderate	Strong	Strong
1400	Strong	Strong			Very strong	Very strong	Strong
1550	–	Very strong			–	Very strong	–

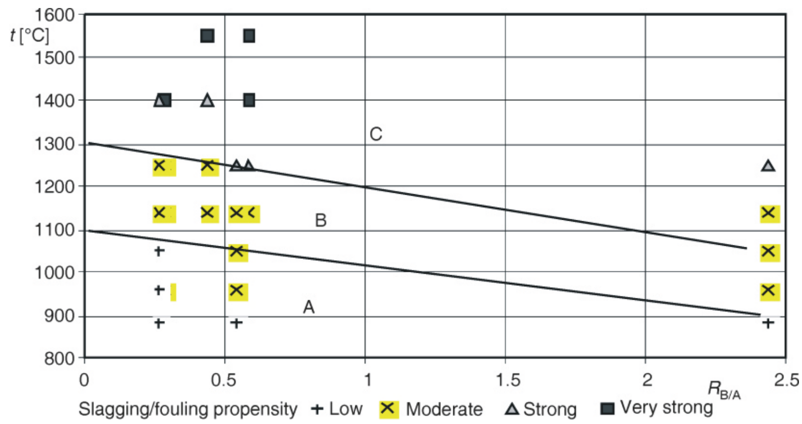

Figure 3. Slagging/fouling behavior of the Bosnian coal tested as funcion of combustion temperature [9]
A: low slagging/fouling zone, B: moderate slagging/fouling zone, C: strong slaging/fouling zone

NO_x and SO_2 emission indicators are formed on the base of measurements of the emissions at different temperatures, air distribution and excess air ratios [3-5]. Emissions are measured in ppm, and then converted into mg/m^3_n at 6% O_2 dry. In fig. 4, emission of NO_x as function of process temperature for the coals tested is shown (Indicator of NO_x emission), while fig. 5 shows emissions of SO_2 as function of process temperature (Indicator of SO_2 emission).

Presented results of emissions (emissions indicators), are used as input data for calculation of derived economic indicators.

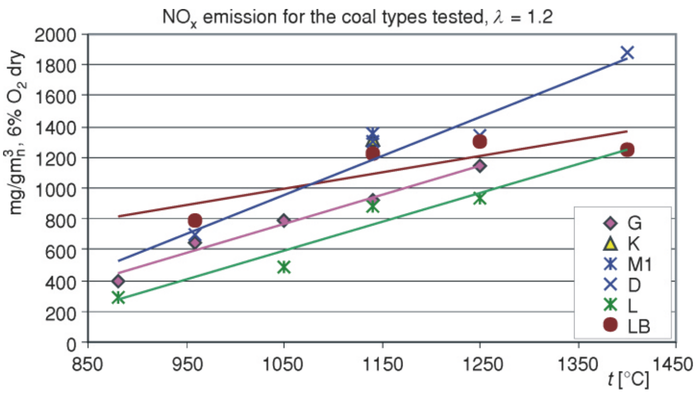

Figure 4. Emissions of NO_x as function of process temperature for the coals tested

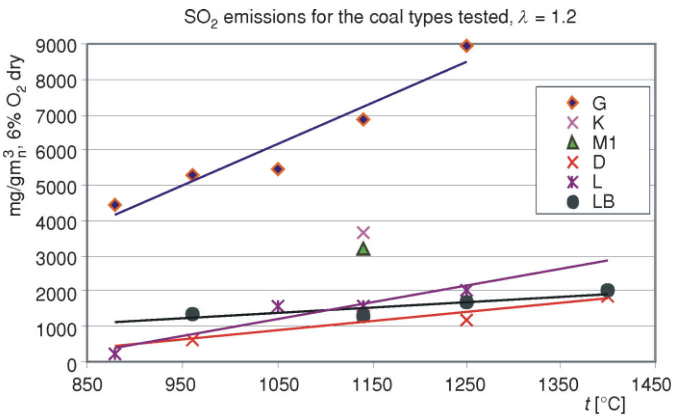

Figure 5. Emissions of SO_2 as function of process temperature for the coals tested

Good praxis from existing power plants

As supplement to the experimental results described, good praxis from two Bosnian power plants – Tuzla TPP and Kakanj TPP – where the coals tested are being burnt into regular operation, is used in the analysis. Thus, lignite Dubrave (D) and lignite blends of Dubrave and Sikulje (L and LB) are used in Tuzla TPP boilers with dry bottom furnace at temperature of 1150 °C to 1250 ºC. Brown coals tested are burnt into Kakanj TPP boilers with slag tap furnace at temperature of 1450-1550 ºC. Experience on ash deposit formation under actual combustion conditions in those boilers, as well as measurements of emissions from the power plants, are used in the analysis within this research, to support measurement results from the experimental reactor and calculation the indicators.

Thermal calculation of the energy system

Thermal calculation of the energy system (boiler) is used to provide inputs for calculation of Indicator of investment – related to boiler heating surfaces and Indicator of efficiency as well. Gurvich's model of the adiabatic temperature in the furnace [4], is used in thermal calculation of boiler in this work. Heating surfaces were calculated for the different combustion temperatures corresponding to the different options under consideration, which is one of the most important inputs for calculation of Indicator *Capital investment for boiler elements* (E_{invB}).

Boiler efficiency used in the boiler thermal calculation is estimated on the base of furnace efficiency (η_F) which mostly depends on *factor related to fouling of heating surfaces* (ξ) [4]. In the work, factor ξ is rated on the base of final evaluation on slagging and fouling propensity given in tab. 4.

Calculation of the indicators and the general index

After measurements and determination environmental indicators of CO_2, NO_x, SO_2, and particles for the coals tested, derived economic indicators are calculated, *i. e*. the costs for all major equipment for reducing emissions, *e. g*. $DeSO_x$ plant, $DeNO_x$ plant, electrostatic precipitator (EP), *etc*. For instance, different temperature conditions or combustion technology under consideration require consequently different percentage of SO_2 removal needed for the fuel, effecting the value of Economic indicator of SO_2 (E_{invSO_2}), tab. 5.

Table 5. SO_2 emissions, $DeSO_x$ percentage, and assumed SO_2 economic indicator for Gracanica lignite

	880 ºC	960 ºC	1050 ºC	1140 ºC	1250 ºC
SO_2 [mgm_n^{-3}] 6% O_2 dry	4430	5323	5873	7106	8962
$DeSO_x$ [%]	91	92.5	93.2	94.4	95.6
SO_2 [mgm_n^{-3}] after $DeSO_x$	<400	<400	<400	<400	<400
€ per MW	110000	125000	132000	144000	156000

Concerning basic economic indicators, the most interesting indicators are Capital investments for boiler elements (E_{invB}) and Indicator of efficiency (E_{effB}). First one mostly depends on combustion system selected and on heating surface of the furnace. Assuming that for all options under consideration low NO_x burners and over fire air system for NO_x reduction are applied, the area of the heating surface of the furnace is key element influencing to the value of E_{invB}. It is known that for same thermal input larger furnace reduces temperature in the furnace. So, if designed temperature of combustion is decreased, capital investments for boiler elements become higher. From the other side, Indicator of efficiency is important for calculation of fuel consumption in lifetime, and it is rated on the base of slagging and fouling behaviors of the fuel at given ambient conditions of combustion, assuming that all other parameters effecting the boiler efficiency are same for all options under consideration.

After calculation of all indicators and General index, common LCP method is used for final optimization. Typical cost curve with varying combustion temperature values, as shown in fig. 6, is obtained by the method. This final part of the methodology presents a new approach to the economical optimization, that can be used in various technical brunches today [13]. Taking into account environmental issue by various environmental indicators described in this work, that an approach could give a good effectiveness in boiler and furnace design to optimize ambient conditions of combustion process of the fuel.

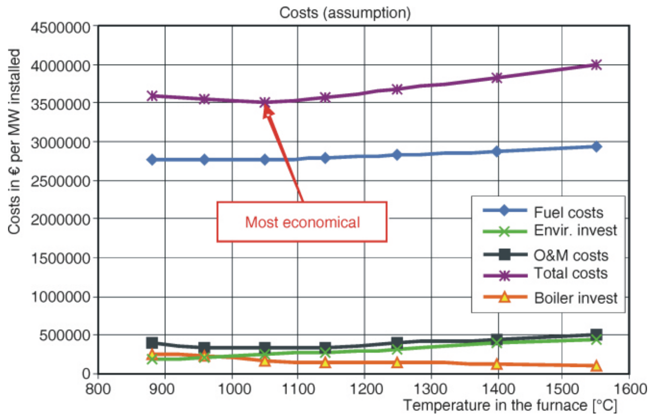

Figure 6. Typical cost curve, assumed for a 230 MW unit, fuel M1, *T* = 20 years, (c_{fuel} = 2.2 €/GJ)

Conclusions

Proper boiler design is crucial issue for providing sustainable coal-based power plant in the lifetime. Coal combustion behaviour indicators that take into account temperature conditions of combustion must be developed to support furnace and boiler design. Furthermore, parameters important for emissions of CO_2, SO_2, NO_x, and trace elements must be accepted as well, to consider environmental indicators during furnace and boiler design. The methodology proposed in this work is based on identification of that combustion technology and ambient conditions for given fuel for which the total costs in lifetime of the system under consideration are lowest, provided that all environmental issue of the energy system is fulfilled during the lifetime. Economic and environmental criteria are proposed to optimize ambient conditions of PF combustion, under which several sustainability indicators (SI) are defined. After derivation of aggregated economic indicators, a common method low cost planning (LCP) is used for optimization of the options under consideration.

The key point of the procedure is providing reliable inputs for calculation of the indicators. For that purpose, an experimental furnace is designed and used in this research to provide data related to different ambient conditions of the PF combustion, supported by results from the power plants where the tested coal types are used in regular operation. Additionally, in order to provide inputs for calculation of the economic indicators, boiler thermal calculation is used in the analysis.

The methodology demonstrated in the work took a real example of the energy system using a blend of Bosnian brown coals. Using the methodology, optimal temperature conditions of combustion of the coal tested can be appointed between options under consideration, provided that all environmental issue of the energy system is fulfilled during the lifetime.

Nomenclature

C_F – costs of the fuel used in the energy system during lifetime
C_F – indicator of fuel costs in lifetime, [€ per MW]
$C_{O\&M}$ – O&M costs for the energy system during lifetime
C_{TI} – total investment costs for the energy system
c_{fuel} – fuel price per heat unit, [€ per GJ]
E_{CO_2} – economic indicator of reducing emission of CO_2, [€ per tCO_2]
E_{effB} – indicator of boiler efficiency
E_{effE} – indicator of own consumption
E_{invB} – economic indicator of investments for boiler equipment, [€ per MW]
E_{InvEP} – economic indicator of reducing emission of particles, [€ per MW]
E_{InvNO_x} – economic indicator of reducing emission of NO_x, [€ per MW]
E_{InvSO_2} – economic indicator of reducing emission of SO_2, [€ per MW]
$E_{O\&MB}$ – economic indicator of O&M costs for the energy system during lifetime, [€ per MW]

$E_{O\&ME}$ – economic indicator of O&M costs of flue gas cleaning facilities/plants, [€ per MW]
G – General index of total costs
I_{CO_2} – environmental indicator of CO_2, [$kgMWh^{-1}$]
I_{NO_x} – environmental indicator of NO_x, [mgm_n^3]
I_p – environmental indicator of particles, [mgm_n^3]
I_{SO_2} – environmental indicator of SO_2, [mgm_n^3]
t – temperature, [°C]
T – lifetime, [year]
T_1 – temperature in heating zone 1, [°C]
T_2 – temperature in heating zone 2, [°C]
T_3 – temperature in heating zone 3, [°C]
T_4 – temperature in heating zone 4, [°C]

Greek letters

η_F – furnace efficiency
λ – excess air, [$kgkg^{-1}$]
ξ – factor related to fouling of heating surfaces

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