LAB-SCALE INVESTIGATION OF MIDDLE-BOSNIA COALS TO ACHIEVE HIGH-EFFICIENT AND CLEAN COMBUSTION TECHNOLOGY

by

Izet SMAJEVIC [a,b], Nihad HODZIC [b], and Anes KAZAGIC [a*],

[a] EP Electric Utility of B&H, Sarajevo, Bosnia and Herzegovina
[b] Faculty of Mechanical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina

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This paper describes full lab-scale investigation of Middle-Bosnia coals launched to support selection an appropriate combustion technology and to support optimization of the boiler design. Tested mix of Middle-Bosnia brown coals is projected coal for new co-generation power plant Kakanj Unit 8 (300-450 MW_e), EP B&H electricity utility. The basic coal blend consisting of the coals Kakanj:Breza:Zenica at approximate mass ratio of 70:20:10 is low grade brown coal with very high percentage of ash – over 40%. Testing that coal in circulated fluidized bed combustion technique, performed at Ruhr-University Bohum and Doosan Lentjes GmbH, has shown its inconveniency for fluidized bed combustion technology, primarily due to the agglomeration problems. Tests of these coals in PFC (pulverized fuel combustion) technology have been performed in referent laboratory at Faculty of Mechanical Engineering of Sarajevo University, on a lab-scale PFC furnace, to provide reliable data for further analysis. The PFC tests results are fitted well with previously obtained results of the burning similar Bosnian coal blends in the PFC dry bottom furnace technique. Combination of the coals shares, the process temperature and the air combustion distribution for the lowest NO_x and SO_2 emissions was found in this work, provided that combustion efficiency and CO emissions are within very strict criteria, considering specific settlement of lab-scale furnace. Sustainability assessment based on calculation economic and environmental indicators, in combination with Low Cost Planning method, is used for optimization the power plant design. The results of the full lab-scale investigation will help in selection optimal Boiler design, to achieve sustainable energy system with high-efficient and clean combustion technology applied for given coals.

Key words: *coal, combustion, emissions, power plant, boiler, furnace, ash, slagging, sustainability*

Introduction

The energy challenge is one of the greatest tests faced by World today, due to rising problem of global warming and climate change. A long-term commitment to the decarburization path, with a target for the EU and other industrialized countries of 80 to 95% cuts in greenhouse gas emissions by 2050, related to 1990 levels, has been given, [1]. Energy efficiency is the central objective of EU energy strategy – it is a key factor in achieving long-term energy and climate goals. Relating to power industry, energy efficiency should become an essential criterion for the authorization of generation capacities, [2]. For an energy policy, the

*Corresponding author; e-mail: a.kazagic@elektroprivreda.ba

attention is focused on security of supply, competitiveness and sustainability, [1, 2]. Thus, a sustainability assessment is recommended to be performed and offered to decision makers when a new application in energy power system is under consideration. Under such an assessment, the energy system is considered from economical, environmental, technological, social, political, ethical and some other aspects. The aim of that procedure is providing an environmental friendly, economically feasible and socially just energy system, [3]. According to Energy Roadmap 2050, coal in the EU adds to a diversified energy portfolio and contributes to security of supply. With the development of carbon capture and sequestration and other emerging clean technologies, coal could continue to play an important role in a sustainable and secure supply in the future, [1].

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, [4, 5]. Therefore, coal behavior predictors, here called slagging/fouling indicators, which along with coal and ash characteristics take also into account the process temperature, must be developed to support furnace and boiler design, [5]. Parameters important for emissions of SO_2, NO_x, particle matters and trace elements must be accepted as well, to consider environmental indicators during furnace and boiler design, [6].

In this paper, the attention is focused on further development and demonstration of the methodology, proposed in work [6], which enable optimization of the process conditions for given fuel, including combustion temperature, from the aspect of sustainability of the energy system. The methodology is based on the lab-scale testing the fuel to acquire the data necessary for further calculations and analysis of coal-based energy system, to achieve a high-efficient and cleaner combustion technology for the given fuel. The procedure is demonstrated in this work on an example of Middle-Bosnia coals projected for the planned coal-based power plant Kakanj unit 8, EP B&H Power utility, Bosnia and Herzegovina (B&H). Within the work, for the first time the circulated fluidized bed combustion (CFBC) tests were launched to investigate possibilities to apply that technique to a high-ash Bosnian brown coal. Along with that, series of pulverized fuel combustion (PFC) tests of the Middle-Bosnia coals, including but not limited to the same blends, have been performed to acquire the data necessary for the further sustainably analysis to be applied in this work.

System under consideration

The coal reserves and characteristics

The modest territory of B&H is endowed with both lignite and brown coal reserves. Current estimates posit exploitable coal reserves of approximately 3.8 billion tones – 40% being brown coal and 60% lignite. Geological coal reserves are estimated at 8.5 billion tonnes. Taking into account estimated future consumption rates, these coal reserves are expected to last some 150-200 years.

The Bosnian coal types, lignite and brown coal, are generally low ranking, exhibiting a strong tendency to slagging and fouling, high sulphur content and low net calorific value [5]. The quality of Bosnian lignite and brown coal varies widely from one coal basin to the next and even between coalmines within the same basin. The calorific value of Bosnian coal is between 7 and 21 MJ/kg. The very high percentage of ash (particularly in Bosnian brown coal) makes clear certain differences between Bosnian coal types with other world coal types, providing a strong argument for investigating the specific problems related to the combustion of Bosnian coals, as well as ways to improve their combustion behavior. Co-firing with wooden biomass is one of the combustion technologies that might be used in existing and new power plants, [5-7].

Basic characteristics of new coal-based power plant Kakanj unit 8

Thermal power plant (TPP) Kakanj is one of the power stations within JP Elektroprivreda B&H d.d.-Sarajevo (EPB&H), the largest public power utility in Bosnia and Herzegovina. Construction and operation a new coal-based power plant Kakanj Unit 8 is planned (commissioning of the power unit is scheduled for 2020), to replace existing power units in that power station, further improve energy efficiency and continue to provide security of energy (power and heat) supply, respecting social aspect of the local community and provided that all environmental requirements are fulfilled in the power unit lifetime. The Kakanj TPP Unit 8 will use indigenous low-rank brown coals, from local coalmines Kakanj (app. 70%), Breza (app. 20%), and Zenica (app. 10%). Secondary fuel is biomass, used in co-firing regimes at minimum 7%w in the fuel blend, investigated for the used coals and woody biomass in the research reported in [5, 7, 8]. The installed power of the Unit 8 depends on the technology to be used, available space in the power station area, as well as financial situation in EPB&H in the next period. Two basic variants are under consideration; 300 MW and 450 MW of electrical power installed. For the further analysis within the work, the option of 450 MW of electrical power installed will be considered only, as a more realistic option at this time-point of view. Regarding boiler (steam) technology to be applied, two options are under consideration for a new TPP Kakanj Unit 8; Boiler with subcritical steam parameters, and Benson-type boiler with supercritical steam parameters. For the purpose of a cost analysis in this work, high-efficient option of Benson-type boiler with supercritical steam parameters will be a basis.

Methodology

Optimization model

Subject of the design optimization within this work is related to selection an optimal combustion technique and selection respecting combustion conditions (optimization process temperature for the given coal), as a function of the energy system sustainability in the lifetime rated by defined criteria. Specific optimization procedure related to selection a sustainable combustion technology as well as an optimal furnace and boiler design is applied in this work, based on coal combustion lab-scale and full-scale investigations. The methodology is proposed and described in details in [6], and in this work is being demonstrated on the example of the brown coals of Middle-Bosnia projected for new TPP Kakanj Unit 8. Regarding the combustion technique, at the first moment three kind of the techniques have been considered; first was PFC with slag tap furnace, designed for the existing TPP Kakanj Units 5, 6, and 7 because of a high ash content in the coal – over 40%, second was PFC with dry bottom furnace and third is CFBC. Due to the certain lacks of the first technique (PFC with slag tap furnace) that had been observed during a long-term operation in Kakanj power station, reflected in a very high temperature in the furnace (1,450-1,550 °C) required for a melting the ash and a continuous slag flow, and which had being resulted in higher maintenance costs and higher emission of SO_2 and NO_x, that technique was excluded from further analysis at the very beginning stage of the assessment process. For two remaining techniques, PFC and CFBC, lab-scale investigations have been performed at referent research institutions – at Faculty of Mechanical Engineering of University in Sarajevo (MEFUS), and at Ruhr-University Bohum in co-operation with Doosan Lentjes GmbH, respectively, to provide reliable data for the further analysis.

Sustainability assessment based on calculation economic and environmental indicators, in combination with low cost planning (LCP), method, is used for optimization power plant design, [6]. The methodology is based on identification of those combustion technologies and combustion conditions for coals tested for which the total costs in lifetime of the power plant under consideration are lowest, provided that all environmental issues of the power plant, particularly related to emission limit values, is fulfilled during the lifetime. At this, emission limit values and net efficiency of the power plant, considering also the thermal power installed, are based on the requirements according to industrial emission directive (IED).

Definition of sustainability indicators

In the paper, economic and environmental criteria are proposed to optimize combustion conditions, under which several sustainability indicators (SI), effecting 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, 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 explanations of the meaning are given in fig. 1.

Formation of General index of total costs

The chart flow in fig. 1 shows procedure of formation General index of total costs, [6]. It can be noted that the environmental indicators are transformed into *derived* economic indicators, by calculation the investments needed for reducing emissions below *emission limit values*. Then, they are being jointed to *basic* economic indicators to form *aggregated* economic indicators. 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 ($C_{\mathrm{O\&M}}$).

Mathematical interpretation of the formation of General index of total costs is given by eq. (1):

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

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

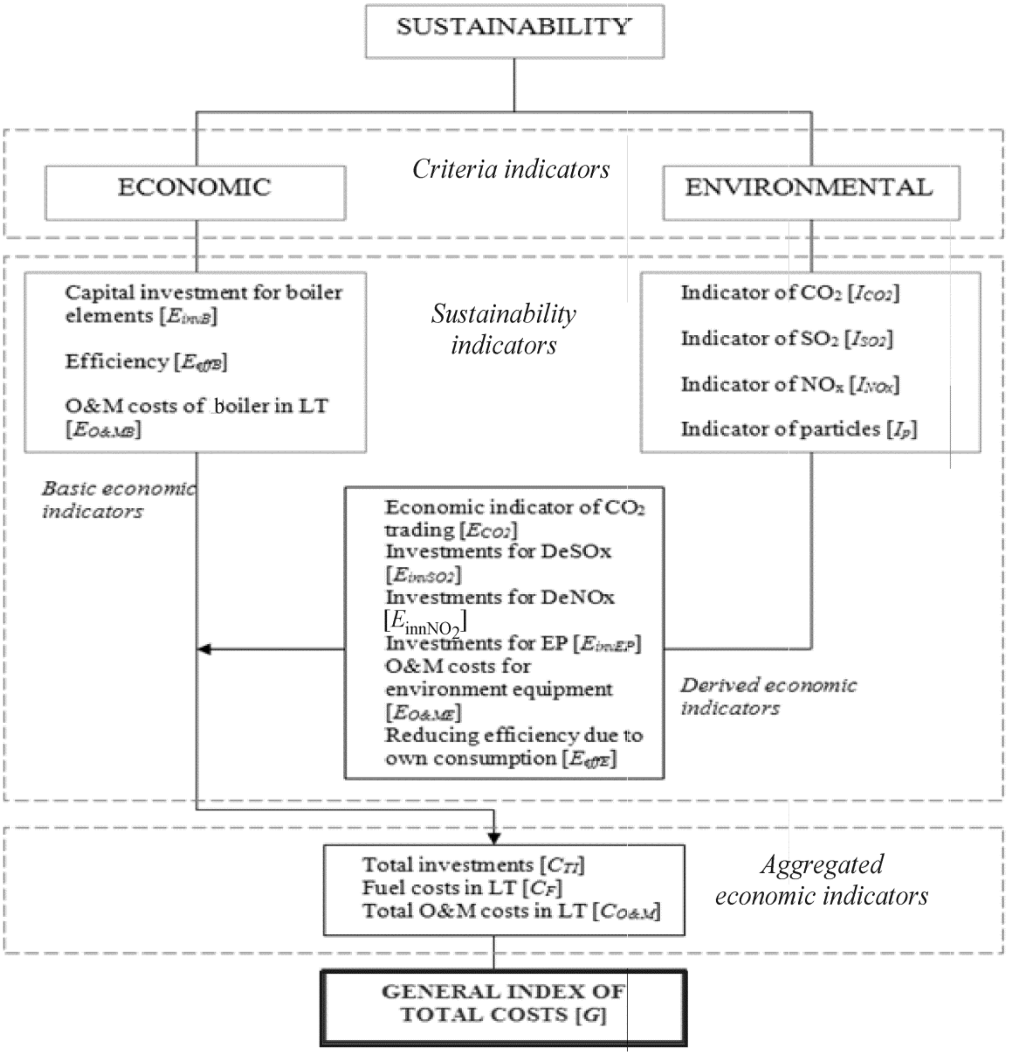

Figure 1. Flow chart of generation of General index of the costs, [6]

Different temperature conditions corresponding to the combustion techniques under consideration – PFC and CFBC – are evaluated for the coals tested. After calculation of sustainability indicators, and their transition into costs, a common 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 by the following term:

$$MinG_j \tag{2}$$

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, [3, 6]. 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 experimental furnaces within the lab-scale investigations on FBC and CFBC. Also, experience and measurements from the existing power plants which use the fuels tested, as well as the thermal calculation of the energy system (boiler) under consideration, are also used to support calculation of the indicators.

Lab-Scale tests

Fuel tested

Blends of brown coals from Kakanj coal-mine, Breza coal-mine and Zenica coal-mine, at basic mass ratio K-B-Z = 70-20-10, were tested for PFC and CFBC to investigate if those techniques are appropriate for the given coals and to define optimal process conditions and parameters for combustion as function of the process efficiency and emissions of NO_x, SO_2, CO, and particle matter.

The coals and their blends tested are low-grade coal types characterized by very high percentage of ash (39-49%), resulting in a low heating value (12.5-13.5 MJ/kg), then by high content of sulfur (2.25-2.75%) and an inconvenient ash composition, see fig. 2, which makes those coals to be with high propensity to the slagging and fouling, [8]. Ash fusion test, according to DIN 51730, shows pretty low melting temperatures varying in the range of 1,200-1,220 °C for the temperature of softening (spherical), 1,245-1,265 °C for the temperature of hemisphere and 1,265-1,290 °C for the flow temperature, whereat higher values from the ranges corresponding to the higher content of coal Kakanj in the blend. Detailed coal characteristics are given in [8].

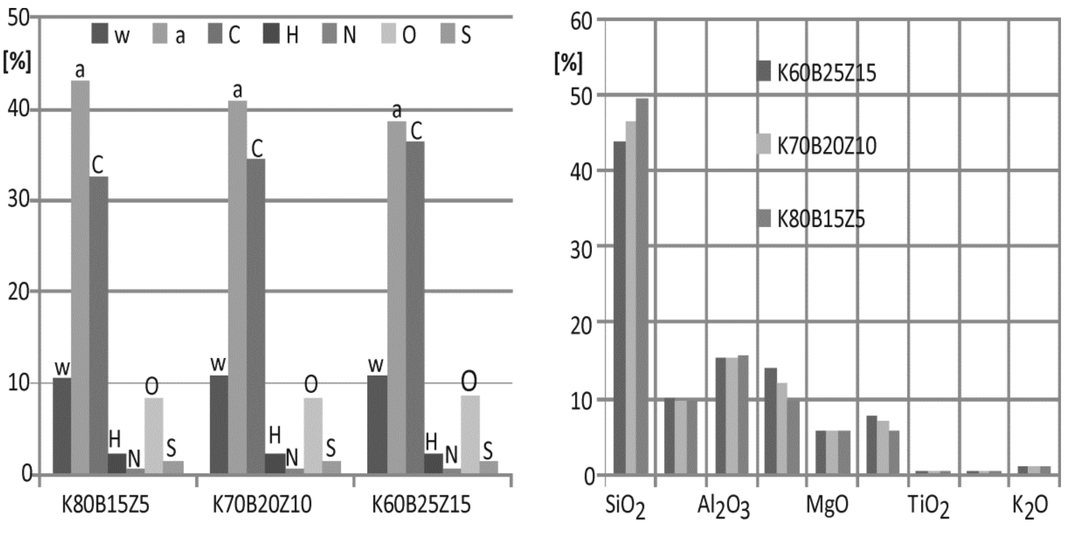

Figure 2. Characteristics of three tested coal blends: ultimate analysis (left) and ash chemical composition (right)
w – water, a – ash, C – carbon, H – hydrogen, N – nitrogen, O – oxigen, S – sulphur **[8]**

Pulverized fuel combustion tests

For purpose of the PFC research, a lab-scale furnace *electrically heated entrained PF flow reactor,* designed at MEFUS, was used for the experiments. 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, surounded by SiC stick-type electric heaters and three-layer in insulation, fig. 8. 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 1,560 °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 control ler, 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. 3.

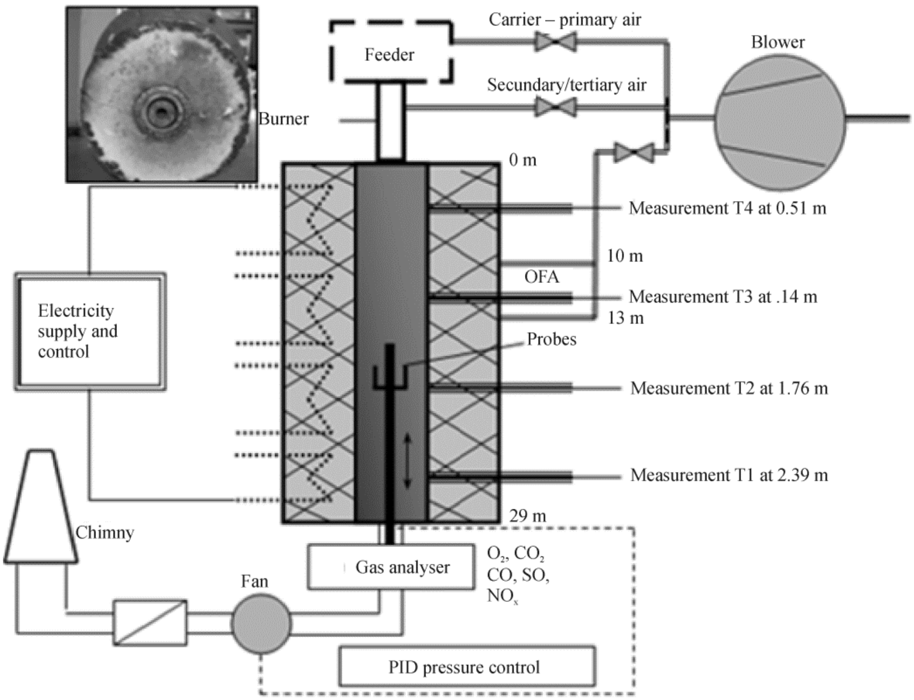

Figure 3. Scheme of the experimental PFC furnace at MEFUS, [5-7]

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. 3. For high process efficiency, the temperature range 1,150-1,350 °C for PFC is recommended for the coals tested. Investigation of slagging/fouling potential of the coal blend K70B20Z10 with a Base/Acid ration (RB/A) of 0.5

has shown a moderate propensity to the slagging/fouling for the temperature range 950-1,250 °C. If temperature has exceeded 1,250 °C, strong slagging took place with a tendency to a very strong slagging for temperature 1,350 ºC and above. These findings are in line with earlier FBC tests of Bosnian coals reported in [6] and it can be noted that the slagging behaviors observed are quite well fitted to the earlier obtained slagging diagram for Bosnian coals reported in [6], see fig. 4. The similar procedure for research into coal ash-related problems was used in the works reported in [4, 9, 10].

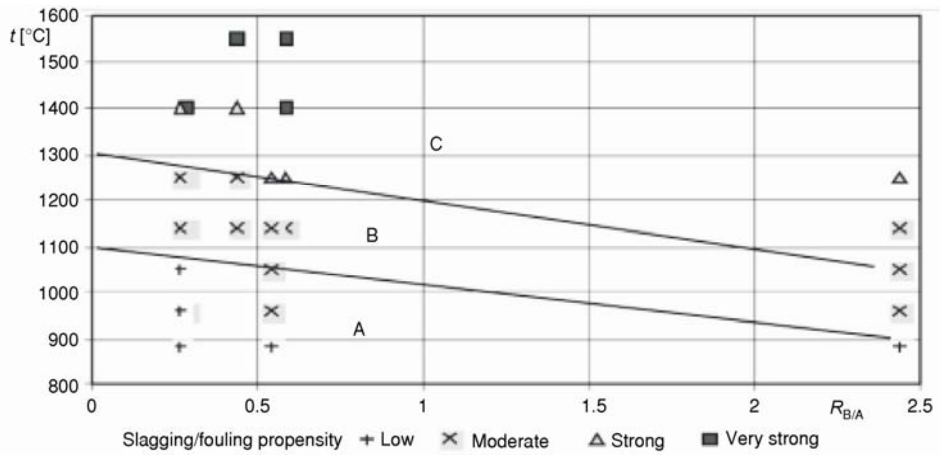

Figure 4. Slagging/fouling propensity of Bosnian coals tested in PFC technology, [6]

Highest sulfur capture rate of 74% was found for the test combination K-100, at 950 °C, λ_1/λ = 0.95/1.15. Results of the emissions from the PFC tests for referent coal blend K70Z20B10 are given in tab. 1, [8].

Table 1. Summary of the average flue gas concentrations at 6 vol.-% oxygen, PFC tests, [8]

Test	Air staging, air supply	Temperature [°C]	SO_2 [mg/m$_n^3$]	NO_x [mg/m$_n^3$]	CO [mg/m$_n^3$]
#1	Yes, 0.95/1.15	950	2329	502	339
#2	No, 1.15/1.15	950	2588	615	232
#3	No, 1.20/1.20	950	2503	622	163
#4	Yes, 0.95/1.15	1150	2897	555	297
#5	No, 1.15/1.15	1150	2793	622	223
#6	No, 1.20/1.20	1150	3213	735	230
#7	Yes, 0.95/1.15	1250	3331	697	238
#8	No, 1.15/1.15	1250	3588	792	227
#9	No, 1.20/1.20	1250	3532	850	160
#10	Yes, 0.95/1.15	1350	3643	710	71
#11	No, 1.15/1.15	1350	3979	837	56
#12	No, 1.20/1.20	1350	4063	921	13

It can be noted that air staging, as well as reduction in combustion temperature, reduces NO_x emissions. The results are in line with those reported in [11, 12].

Circulated fluidized bed combustion tests

Circulated fluidized bed combustion tests have been performed on a 100 kW_t CFBC lab-scale furnace at Rurh-University Bohum. The objective of the CFB combustion tests was the operation of the CFB test rig at constant conditions in order to determine the amount of limestone required to meet the limit of sulphur dioxide emissions and the necessity of air staging to keep the NO_x emissions limit, similarlly to the approach applied to FBC testing some other WB coals reported in [13-15].

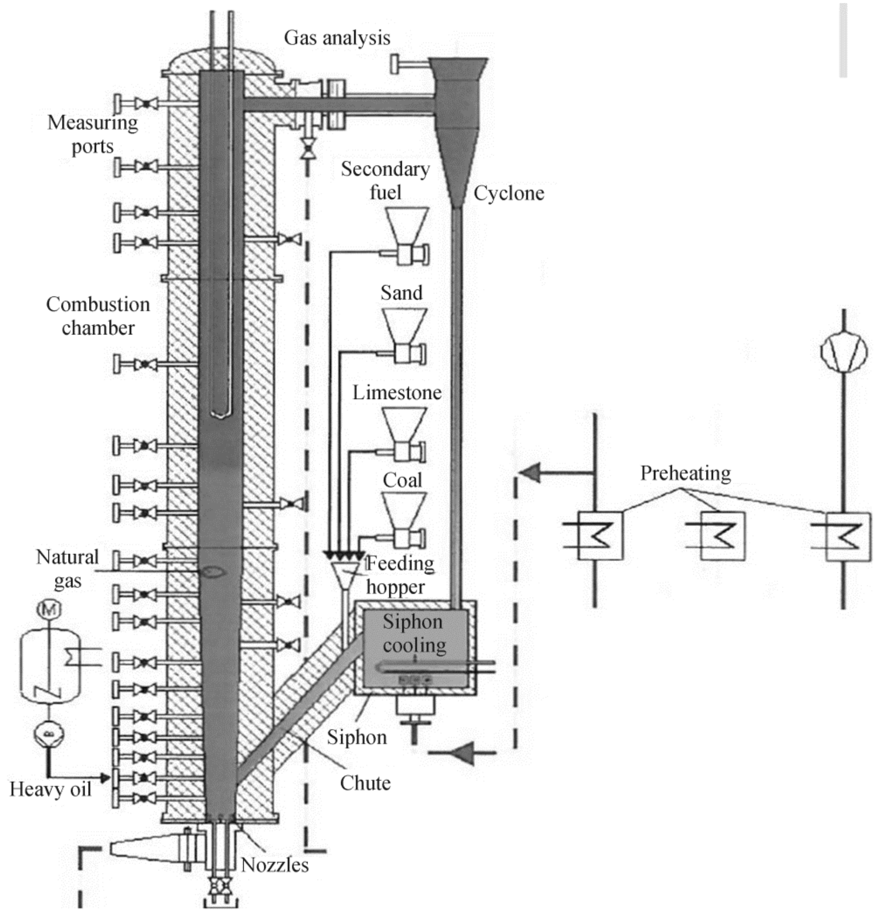

Figure 5. Scheme of the experimental CFBC test rig at Rurh-University Bochum [16]

Central part of CFBC test rig is a combustion chamber of 6 m length and of 200-300 mm inner diameter, fig. 5, [16]. The particle size distribution of the tested K70B20Z10 coal blend as well as the particle size distributions of limestone and quartz sand (used as bed material) are decided based on experience with low grade coals and in consolation with Doosan Lentjes GmbH, [13]. Overview of the experimental conditions for the tested K70B20Z10 coal blend is given in tab. 2.

Table 2. Overview of the CFBC experimental conditions

Test	$T_{av.}$ [°C]	Air ratio overall	Air staging	Limestone addition	Flue gas recirculation
#1	830	1.15-1.20	–	–	+
#2			+	–	+
#3			+	+	+
#4	870		–	–	+
#5			+	–	+
#6			+	+	+

All tests (#1 to #6) could be realized at stable combustion conditions. Flue gas and ash samples were taken for all combustion test settings. Test #1 shows basic emissions at an average combustion chamber temperature of 830 °C. Adjusting air staging reduces the NO_x emission under the emission limit of 200 mg/m^3 at 6 vol.% oxygen (test #2). While limestone was added (test #3) the emission of NO_x was increased over the emission limit. Similar corelation between the limestone adding and NO_x emissions was reported by Leckner in [17]. The SO_2 emission could not decreased under the emission limit of 200 mg/m^3 at 6 vol.% oxygen. For an average combustion chamber temperature of 870 °C the flue gas emissions were sample during test #4. Again the NO_x emission could be reduced under the emission limit by adjusting air staged combustion conditions (test #5). The SO_2 emissions were reduced to approx. 591 mg/m_n^3 at 6 vol.% oxygen. Therefore, the emission limit of 200 mg/m^3 at 6 vol.% oxygen could also not be reached at an average combustion chamber temperature of 870 ºC. The summary of the average emission values is presented in tab. 3.

Table 3. Summary of the average flue gas concentrations at 6 vol.% oxygen, CFBC tests

Test	Average temperature [°C]	SO_2 [mgm_n^{-3}]	NO_x [mgm_n^{-3}]	CO [mgm_n^{-3}]	N_2O [mgm_n^{-3}]
#1	835	4,139	310	562	170
#2	831	3,844	185	463	126
#3	819	1,146	215	353	147
#4	872	4,375	219	750	109
#5	882	5,774	194	383	80
#6	848	591	235	309	114

At an average combustion chamber temperature of 830 °C, adjusting air staging reduces the NO_x emission under the emission limit of 200 mg/m^{3}at 6 vol.% oxygen (test #2). While lime stone was added (test #3) the emission of NO_x was increased over the emission limit. The SO_2 emission could not decreased under the emission limit of 200 mg/m_n^3 at 6 vol.% oxygen. For an average combustion chamber temperature of 870 °C, the NO_x emission could be reduced under the emission limit only by adjusting air staged combustion conditions (test #5). The SO_2 emissions were reduced to approx. 591 mg/m^3 at 6 vol.% oxygen with an addition of limestone (test #6). Therefore, the emission limit of 200 mg/m^3 at 6 vol.% oxygen could also not be reached at an average combustion chamber temperature of 870 °C, [13]. Regarding evaluation of suitability CFBC technology to the coal blend tested from the aspect of slagging/fouling and an appropriate efficiency of the combustion process, the main problems designated by the combustion tests are the low melting temperature of the ash, the tendency towards the creation of ash agglomeration and coating of particles in combination with low fuel reactivity. Problem with ash agglomeration and melting at such low temperatures of 800 °C, the case also reported and discussed in [14, 18], can still cause significant disruption to fluidization within the combustion chamber to such an extent as to prevent circulation through the primary circuit (burner, cyclone, fluidized siphon). Because of this phenomenon, working with CFBC power plant for this coal blend cannot be recommended, [13]. Other results of the tests such as low sulfur capture rate can have a crucial impact on the cost of investment and economic operation of the entire power plant. For example, a high ratio of Ca/S which is needed to meet the SO_2 emission limits are directly related to the size of limestone silos, delivery systems, ash handling plant system and the overall efficiency of the power plant. For the reasons mentioned above, CFBC technology is excluded from further analysis for selection combustion technology of TPP Kakanj unit 8.

Calculations the indicators and general index

After determination the environmental indicators for the coals tested, the derived economic indicators were calculated, *i. e.* the costs for major equipment for reducing the emissions. Thus, different combustion technology and temperature conditions require different rate of SO_2 removal needed for the given fuel, effecting the value of Economic indicator of SO_2 ($E_{\mathrm{invSO_2}}$), tab. 4.

Table 4. SO_2 emissions, desulphurization rate and assumed SO_2, economic indicator for tested K70B20Z10 coal blend

Technique	**PFC**			
Temperature options	950 °C	1,150 °C	1,250 °C	1,350 °C
SO_2 [mgm_n^{-3}] 6% O_2 dry	2,588	3,213	3,588	4,063
$DeSO_x$ [%]	93	94	95	96
SO_2 [mgm_n^{-3}] after $DeSO_x$	≤ 200	≤ 200	≤ 200	≤ 200
EUR/MW	110,000	120,000	130,000	140,000

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 OFA 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 combustion conditions, assuming that all other parameters effecting the boiler efficiency are same for all options under consideration. Another key issue influencing significantly to the total costs, is CO_2 cost. It has been calculated for the considered PFC temperature level options assuming CO_2 price projections in EU for the period 2020-2045, [2, 19].

After calculation of all indicators and General Index, common LCP method was used for final optimization. Typical cost curve with varying combustion temperature for PFC is obtained by the method applied, as shown in fig. 6. As can be seen, a PFC boiler and furnace design with combustion temperature of 1,230 °C is economical for the given coal.

This final part of the methodology presents a new approach to the economical optimization, that can be used in various technical brunches today, [6]. Taking into account also environmental issue considered by various environmental indicators described in this work, such an approach could give a good effectiveness in boiler and furnace design to optimize process conditions and parameters of combustion for the given coal.

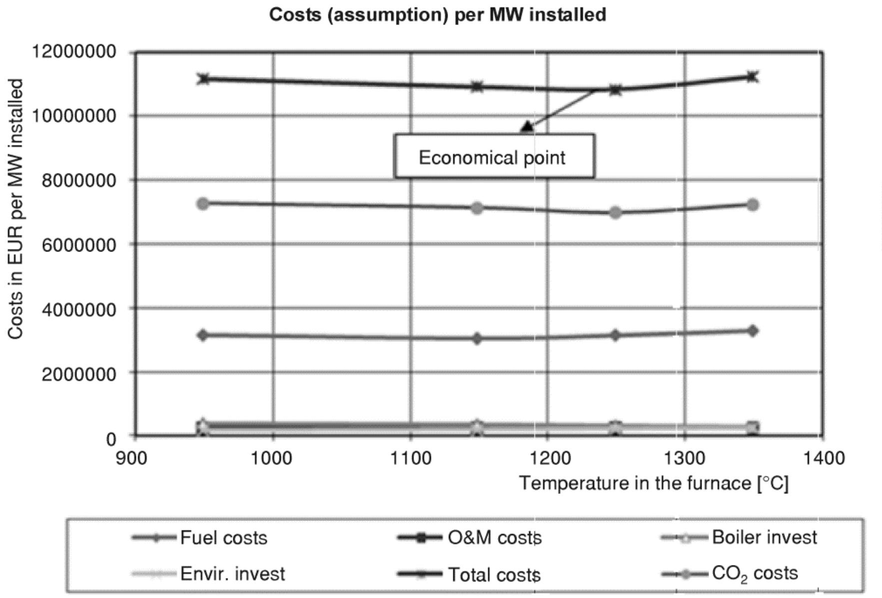

Figure 6. Typical cost curve, assumed for a 450 MW HP/LP FGHR SC power unit, fuel K:B:Z = 70:20:10, *T* = 25 years, cfuel = 2.4 EUR/GJ

Conclusions

Lab-scale tests of pulverised fuel combustion and circulated fluidised bed combustion have been performed for Middle-Bosnia coals to provide reliable data for selection. Tests results and further sustainability analysis give an advantage to the option of the power plant design based on PFC technology, including measures for NO_x reduction, installation of appropriate dust filter and flue gas desulphurization (FGD), against an option of power plant based on CFBC technology for the given coal which also require FGD installation following results of lab-scale CFBC tests. Regarding PFC technology, test combination K70-B20-Z10 at 950 °C and λ_I/λ = 0.95/1.15 provides lowest emissions, resulting in NO_x emissions of 502 mg/m_n^3 at 6% O_2 dry and SO_2 emissions of 2,329 mg/m_n^3 at 6% O_2 dry. For highest combustion efficiency, temperature range from 1,150 till 1,350 °C is recommended. From the aspect of deposits form and structure, as well as melting and sticky characteristics of the ash depozits, it was shown for all coal blends tested that process temperature does not have to exceed 1250 °C. Taking into account fuel costs, O&M costs, boiler and flue gas clenining equipment investments, as well as projected CO_2 costs in the lifetime of 25 years, a PFC boiler and furnace design with a combustion temperature at 1,230 °C is economical for the projected blend of Midle-Bosnia coals.

Nomenclature

C_F – indicator of fuel costs in lifetime, [€ per MW]
$C_{O\&M}$ – O&M costs for the energy system during lifetime, [€ per MW]
c_{fuel} – fuel price per heat unit, [€ per GJ]
C_{TI} – total investment costs for the energy system, [€ per MW]
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_{InvNOx} – 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, [€ per MW]
I_{CO_2} – environmental indicator of CO_2, [$kgMWh^{-1}$]
I_{NOx} – environmental indicator of NO_x, [mgm_n^{-3}]
I_p – environmental indicator of particles, [mgm_n^{-3}]
I_{SO2} – environmental indicator of SO_2, [mgm_n^{-3}]
T – lifetime (LT), [year]
t – temperature, [°C]

Greek symbols

λ – excess air, [$kgkg^{-1}$]
λ_1 – excess air in the first combustion stage, [$kgkg^{-1}$]

Acronyms

CFBC – circulated fluidised bed combustion
EP B&H – public electricity utility of Bosnia and Herzegovina (JP Elektroprivreda B&H)
LCP – low coast planning
MEFUS – Faculty of Mechanical Engineering of University in Sarajevo
OFA – over fire air
PF – pulverised fuel
PFC – pulverized fuel combustion
PLC – programmable logic controller
PM – particle matter
SI – sustainabilty indicator
TPP – thermal power plant
WB – western Balkans

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