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Analysis the Impact of Coal Mixing on Boiler Characteristics

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Abstract: Due of the depletion of the mines that were basis for the design and construction of the Thermal Power Plants in Macedonia, the necessary quantities of coal have to be supplied from other mines. The issue is further complicated by the fact that the current mines are providing coal with higher mineral matter content and lower calorific values towards the end of their operation, resulting in a lower quality compared to the originally intended specifications. Utilizing such coal in boilers has a number of disadvantages, such as lower efficiency, limited power, higher load on the fuel supply and preparation system, as well as slag and ash removal systems, an increased frequency of failures, and so on. To increase the quality of coal the existing one should be mixed with coal of a higher quality. This paper analyzes the selection of coal for blending, coal characteristics, and boiler operation with a few types of coal. Through analyzing calculation results, ash composition, and fusion temperatures, it is evident that the choice of coal for mixing should not solely focus on increasing calorific value but should consider a broader range of characteristics for a comprehensive analysis.

Keywords: Coal, Mixing, Boiler, Ash, Slagging

1. Introduction

Over the time, the best lignite was depleted from our coal mines. Now there currently exists only poor coal (low quality) available for exploitation in our mines. We have to keep using that coal because this type of energy is still required. Utilizing these coals requires overcoming the difficulties related to operating with variable and poor quality coal. For the seamless operation of thermal power plants (regarding fuel) it is essential to supply a sufficient amount of coal with the required quality. From the perspective of the mines, it makes sense to exploit the areas of the mine where the coal is lower quality because doing increases resource utilization, prolongs the mine's life time, etc.

However, from the perspective of the thermal power plant, the acceptance of low quality coal is always met with resentment because its combustion necessitates a higher fuel oil consumption to support the burning, lowers the thermal power plant's output, increases maintenance issues and costs, etc. Mixing coals of lower quality with coals of higher quality and homogenization are the methods to prevent the problems mentioned above and achieve satisfactory coal quality. Homogenization is a procedure for equalizing the quality of the coal delivered to the thermal power plant, refers to coal sourced from a single mine. The homogenization, it would be increased the amount of coal whose exploitation is justified, to reduce the costs of transport, the costs of burning coal, conveyance and ash deposition, as well as enhance environmental protection systems against contamination—particularly during combustion phases [1].

Combining lower quality coal with higher quality coal involves mixing coal from different mines to improve its overall quality. This process aims to increase the calorific value of coal, improve combustion, and reduce harmful elements such as sulfur and nitrogen for environmental benefits [1]. The paper discusses specific factors that should be taken into account when mixing coal which directly or indirectly affect the performance of the boiler. Furthermore, the calculation and analysis of efficiency for different types of coal used in the combustion process of the boiler model are given. Coal types A, B, and C belong to the same mine, while types D, E, and F are obtained by mixing coal from different mines. In the table 2 are presents the ultimate and proximate analyses of these coals.

Coal blending is a process that aims to produce a fuel with characteristics closely matched to the fuel designed in the boiler. This fuel allows the boiler and its auxiliary equipment, such as fuel supply systems, slag and ash removal systems, air supply systems, and gas removal systems, to achieve maximum efficiency.

2. Characteristics of coal that should be taken into account in coal mixing and that affect the combustion

Coal mixing should create a coal mixture that meets design coal characteristics such as heat value, moisture, ash content, coal grindability (HGI), etc. In addition, it should check the micro petrographic composition of coal, chemical analysis of ash, temperatures of deformation, softening, hemispherization and flow, discriminant indexes of ash, comprehensive index, etc. or in other words the affinity of coal for slagging.

The calorific value of coal is an important indicator in determining its quality. When coal has a lower-than-designed calorific value, it can result in unstable and incomplete combustion, which may turn off the flame within the furnace and make it difficult to achieve the required temperature. On the other hand, burning coal with a calorific value higher than designed can lead to overheating of heating surfaces, higher temperatures within the gas tract, and potential shutdown of the boiler for protection if temperature regulation along the water-steam tract is not possible. Such issues can significantly impact the normal operation of boilers.

Coal moisture is to some extent compatible with volatile matter. A small amount of moisture can have a positive impact on the overall combustion process. From a combustion kinetics perspective, moisture vapor at high temperatures has a catalytic effect on combustion, accelerating the burning of coal dust coke and enhancing flame emissions. Furthermore, during the breakdown of moisture vapor, hydrogen and hydroxide compounds are produced, which contribute to more efficient heat transfer within the flame.

However, too high a moisture content in coal can negatively affect the combustion process. When the moisture content is too high, the necessary heat for ignition substantially increases, leading to excessive heat consumption for evaporating excess water in the coal. Consequently, this reduces the temperature of hot gases which adversely impacts the ignition process.

Increased moisture content in the coal causes increased fuel consumption to achieve the required input heat in the furnace [2]. Especially mills' capacity is particularly sensitive to moisture in coal [3].

The ash content of coal does not produce heat during burning. Instead, energy is used to heat the ash. When there is more ash content in the coal, the amount of heat produced is reduced. In these conditions, the ignition process of coal is more difficult and may lead to a delay in ignition. The furnace temperature and the burning rate of the coal also drop, and the amount of combustible matters in the fly ash rises significantly.

As the ash content increases, the surrounding ash prevents the carbon particles from interacting with oxygen, resulting in incomplete combustion. As the ash concentration increases, so does the fly ash concentration, resulting in increased abrasion on the convection heating surfaces. Physical heat losses due to fly ash and slag also increase, resulting in decreased boiler efficiency [4].

Volatile matters have a significant impact on the combustion process. They are separated at low temperatures (150 to 180°C) in the brown coals [5]. During combustion, coke particles warm up quickly, allowing them to ignite and burn. The more volatile matters in the coal, the easier it is to ignite and the faster it burns. In other words, coal with a large amount of volatile matters ignites more quickly, but coal with a low percentage of volatile matters has a significantly higher ignition temperature, making it much more difficult to ignite. In this case, it will take longer to reach the ignition point, which reduces combustion stability. In addition, the center of combustion rises higher, reducing heat in the furnace while increasing heat absorbed by the convective heating surfaces. The temperature of the flue gas is then increased increasing the flue gas loss. Coal with a low volatile matters content should be finely milled.

When the coal particles are too large, they remain in the furnace for a very short time, so the coke does not have time to burn. In this case, the slag's carbon concentration rises, increasing heat loss due to the slag's physical heat. When the coal particles are too small, they pass easily through the furnace, do not make good contact with oxygen, and are carried out with flue gas, resulting in increased heat losses due to the fly ash. In order to prevent the above situations, the coal grinding fineness must be adjusted according to: coal quality and grindability, the flow of secondary air, the type of combustion in the furnace, etc. The grindability of coal is determined by the Hard Growth Index, HGI. The coal with a higher HGI, is easier to grind and vice versa. When grinding harder coal, mill capacity drops [6].

Coal affinity for slagging is an important factor to take into account while blending coals, because slagging affects combustion, heat transfer, boiler efficiency, etc. The coal ultimate analysis, ash concentration, ash melting temperature, and the mineral composition in the ash can all be used to evaluate the coal's tendency for slagging. By calculating the discriminant index [7], which includes the base-acid ratio, silicon ratio, silica-alumina ratio, iron-calcium ratio, and comprehensive index, the slagging characteristics of coals can be anticipated. The following expressions specify each relationship [8]:

Base-Acid ratio, $B/A = (Fe_2O_3+CaO+MgO+Na_2O+K_2O)/(SiO_2+Al_2O_3+TiO_2)$ (18)

Silicon ratio, $G=100\ SiO_2/(SiO_2+Fe_2O_3+CaO+MgO)$, (19)

Silica-Alumina ratio $= SiO_2/Al_2O_3$ (20)

Iron-Calcium ratio $= Fe_2O_3/CaO$ (21)

Comprehensive index, $R = 5{,}415-0{,}002ST+1{,}237B/A-0{,}019G+0{,}282SiO_2/Al_2O_3$ (22)

In the table 1 are shown the limits values of the discriminant indexes for slagging. The composition and properties of the minerals, determine the bituminous coal's and lignite's slagging characteristics [9]. For the same coal, results based on discriminant indexes may sometimes show results that are completely at disagreement with each other and have little precision. The slagging characteristics of coal can be precisely predicted by determining fusion temperatures [8].

Table 1. The limits values of discriminant indexes for slagging [9]

Index	Tendency of slagging		
	slight	medium	severity
B/A	<0,206	0,206-0,4	>0,4
G	>78,8	78,2-66,1	<0,66
SiO_2/Al_2O_3	<1,87	1,87-2,65	>2,65
Fe_2O_3/CaO	Out of 0,3-3	0,3-3	Near 1
R	<1,5	1,5-2,5	>2,5

In same literature [10], one can also find the parameter of AFT (Ash Fusion Temperature) next to the other relevant indicators for slagging. The ash fusion temperature serves as an indicator of ash agglomeration and deposition resulting from combustion, and it can be calculated using a specific formulation:

$$AFT = (4DT+HT) / 5 \quad (6)$$

where DT and HT are ash temperatures for deformation start and hemispheric temperature respectively. If the calculated AFT values fall within the range of 1052 to 1232 ^{o}C, that is indicator for high potential for slagging. Conversely, if the values are below 1052 ^{o}C, there is a high probability of significant slagging occurring [14,15].

3. Analysis and discussion of research results

The boiler type P65, which was designed for burning lignite coal in a flight, was the subject of the study. According to the literature, the boiler furnace is octagonal-shaped, and the fuel is fed by six fan mills [13]. The calculation for determining boiler efficiency, heat losses, required amount of fuel, etc. was performed in accordance with European Standard EN 12952, Part 15. Six types of coal were used, with characteristics given in Table 2.

Table 2. Coal specifications

Coal Specification	Unit	Coal					
		Type A	Type B	Type C	Type D	Type E	Type F
Water, W	[%]	39,12	37,8	37,2	42,61	44,56	42,99
Ash, A	[%]	32,70	34,28	32,99	23,47	21,61	28,03
Carbon, C	[%]	16,39	16,73	17,72	22,2	22,07	18,3
Hydrogen, H	[%]	1,47	1,57	1,67	2,02	1,95	1,71
Sulphur, S	[%]	0,84	0,67	0,9	1,09	0,72	1,04
Oxygen, O	[%]	9,19	8,7	9,65	8,71	9,03	7,8
Nitrogen, N	[%]	0.30	0,25	0,31	0,49	0,47	0,42
Law Heat Value, LHV	[KJ/kg]	5856	5534	6006	7465	7225	5974

Tables 3 and 4 show the fusion temperature and chemical analysis of the ash for the respective coals.

Table 3. Summary of the formatting rules

Ash from coal	Deformation Temperature (DT) [^{0}C]	Softening Temperature (ST) [^{0}C]	Hemisphere Temperature (HT) [^{0}C]	Flow Temperature (FT) [^{0}C]
Typ A	1246	1366	1379	1398
Typ B	1278	1368	1382	1394
Typ C	1370	1438	1458	1472
Typ D	900	995	1220	1270
Typ E	900	995	1230	1220
Typ F	890	985	1220	1355

Table 4. Ash analysis of the relevant types of coal

Ash from coal	SiO_2 [%]	Al_2O_3 [%]	TiO_2 [%]	Fe_2O_3 [%]	K_2O [%]	CaO [%]	MgO [%]	Na_2O [%]
Typ A	57,25	20,15	0,73	6,49	2,86	2,89	1,60	1,13
Typ B	55,52	20,88	0,83	5,99	2,78	2,90	1,77	1,48
Typ C	55,07	24,43	0,82	7,24	2,73	2,80	1,92	0,89
Typ D	50,51	24,09	0,82	7,61	1,30	6,26	3,54	0,10
Typ E	53,33	25,12	0,77	6,75	1,34	6,15	2,22	0,11
Typ F	52,93	30.49	0.8	6.37	1.61	3.55	2.31	0.11

A computer calculation was performed in order to compare the operation of the boiler with above mentioned types of coal (Fig. 1). The input data included ultimate and proximate coal analysis, design values for flow, pressure, and temperature of feed water, temperature of heating surfaces, etc. It is assumed that the boiler will operate with a maximum steam production of 700t/h with design parameters [13]. The calculation was made according to the European standard EN 12952, part 15, applying case 4, where the flow of slag and fly ash is determined from the ash balance and with the estimated degree of ash separation in the furnace [14].

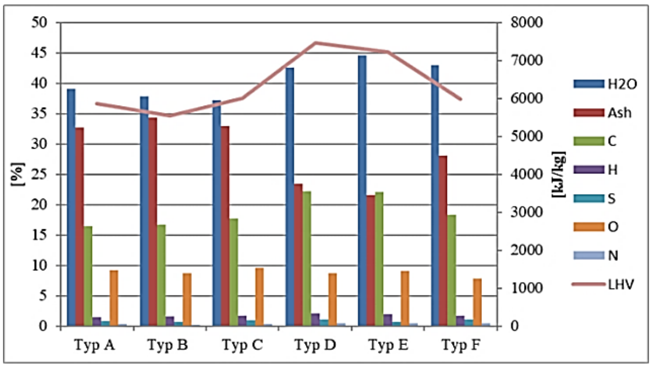


Figure 1. The coal's characteristics type A, B, C, D, E, F

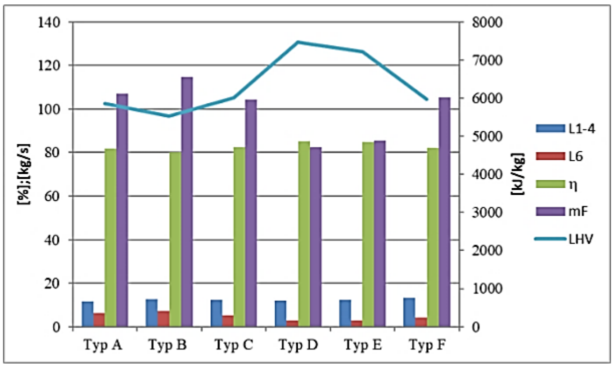


Figure 2. The calculation's results

It is evident from the characteristics of the analyzed types of coal (Fig. 1) that all types have a relatively high ash content (23,61 to 34,28%), which is higher than the fuel designed (max 20%), for the boiler taken as a model. This is certainly reflected in the boiler efficiency through increased losses (L6) due to the unburned in slag and ash (Fig.2). Naturally, a higher ash content is reflected in the coal's reduce calorific value. Due to the reduced calorific value of coal, more fuel is required, resulting in an increase in (mF) fuel consumption (Fig. 2). The amount of fuel needed to supply the boiler for its maximum capacity while burning coal types A, B, C, and F is 107 kg/s; 114,9 kg/s; 104,5 kg/s; 105,3 kg/s respectively and is greater than the mills' capacity (100 kg/s) [13] . This indicates that it is not possible boiler to operate with maximum capacity when burning coals of these types. Calculations show that types of coal D and E enable the boiler to operate at its maximum capacity with fuel consumption of 82,6 and 85,4 kg/s and efficiency at 85,1% and 84,8%, respectively. In the calculation is assumed that the sealing of the gas-air and coal tract, is within the range of acceptable values.

According to the chemical analysis of the ash (Fig. 3), the ash from coal types D and E contains more than twice of CaO as that of other types of coal. Also, types C, D, E, and F coal ash contain an Al_2O_3 more than 20% compared to types A and B.

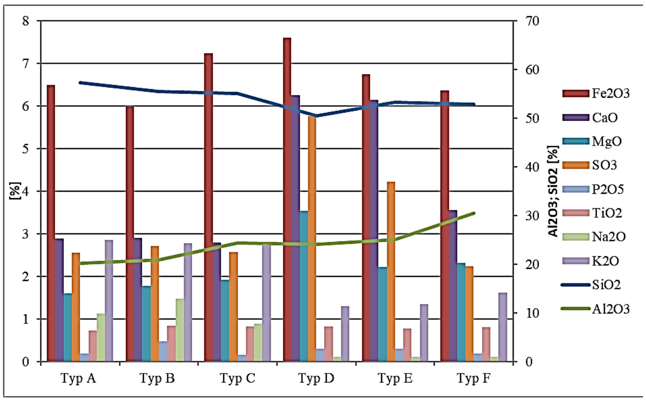


Figure 3. Chemical analysis of the ash of coal types A, B, C, D, E, and F

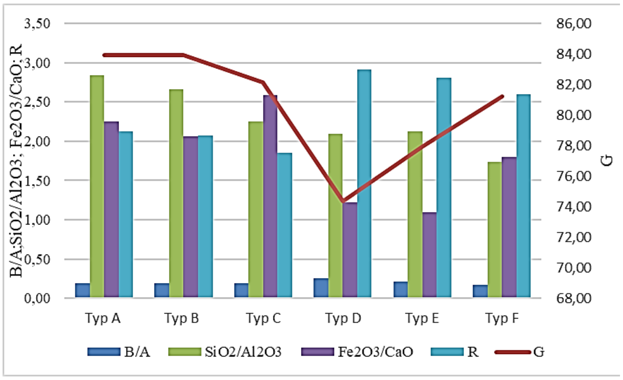
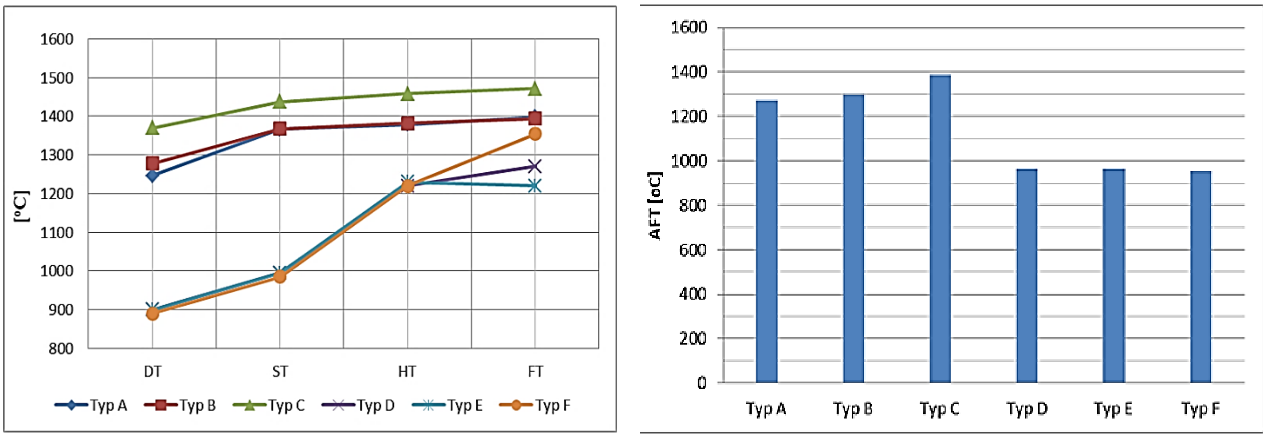


Figure 4. Discriminant indexes for slagging for coal types A,B,C,D, E, F

The discriminant indexes for slagging B/A, G, SiO_2/Al_2O_3, Fe_2O_3/CaO, and the comprehensive index R are calculated using these ash oxide values [8]. Figure 4 shows that the B/A, G, and SiO_2/Al_2O_3 index values for D and E-type coal ash are in the range corresponding to coals with medium tendency of slagging, while the Fe_2O_3/CaO index values and the total R index indicated coal with severity slagging tendency. For other types of coal A,B,C and F, only the Fe_2O_3/CaO index and the comprehensive index R show that have a medium tendency to slagging, while the other indexes show a slight tendency.

Analysis of the ash fusion temperatures is needed since, as I already indicated, the indexes sometimes give a different interpretation. The diagram (Fig. 5) shows typical ash temperatures for the considered coal types, including deformation temperature (DT), softening temperature (ST), hemispheric temperature (HT), and flow temperature (FT) and calculated AFT (Ash Fusion Temperature).



a) b)

Figure 5. Characteristic ash temperature (a) and calculated ash fusion temperature (AFT) for coal types (b)

The fusion temperatures of the ash from coal types D, E, and F overlap at several locations on the diagram (Fig. 5a), but they are lower than the corresponding temperatures for ash from coal types A, B, and C. The temperature for the beginning of deformation (DT) of ash in coal types D, E, and F is lower by more than 300ºC, while the hemisphere temperature (HT) is lover by less than 200ºC. Namely, coal types D and E have lower flow temperatures (1270 and 1220ºC), coal types A, B, and F have higher and with close values (1398, 1394, and 1355ºC respectively), and coal type C has the highest flow temperature 1472ºC. Based on the calculated values of ash fusion temperature (AFT) for various types of coal (as shown in Figure 5b), significant differences can be observed between coal types A, B, and C compared to coal types D, E, and F. Specifically, the AFT values for types A, B, and C are 1272°C, 1298.8°C, and 1387.6°C, respectively, while for types D, E, and F, they are 964°C, 966°C, and 956°C, respectively. Based on these values, it can be inferred that coal types A, B, and C exhibit moderate potential for slagging, whereas types D, E, and F demonstrate a serious propensity for slagging.

The consequences of poor coal selection are shown in fig.6. Due to the slagging, Unit 3 at the TPP Bitola was non-operational for over three months in 2023 year.

Figure 6. Slagging in the boiler furnace

4. Conclusions

Based on the calculations of the boiler with different types of coal it can be concluded that only with coal types D and E boiler may reach maximum production with design parameters and efficiency of 85,1% and 84,8% respectively. Additionally, other types of coal make it hard to attain maximum output since they require more fuel than the mills' capacity. On the other hand, considering the values of the discriminant indexes and the ash fusion temperatures, the operation of the boiler with coal types D and E can be troublesome. Namely, the values of the indexes B/A, G, and SiO_2/Al_2O_3 for ash from coal types D and E are in the range of coals with a medium slagging tendency, but the values of the index Fe_2O_3/CaO and the comprehensive index R indicate coal with a severity tendency of slagging.

Furthermore, the ash fusion temperatures of coal types D, E, and F are notably lower by approximately 200 to 300 °C compared to types A, B, and C, suggesting a probability of slagging during combustion of these coal types. This observation is supported by the calculated AFT values of 964°C, 966°C, and 956°C for types D, E, and F, respectively, placing them within the category of coals with a significant potential for slagging.

It can be summarize that when burning D and E types of coal due to their high calorific value, the boiler's maximum production would be achieved, but there would be a risk of the boiler furnace slagging due to the ash's slagging characteristics.

While selecting coal for mixing with existing coal, it is essential to consider not only the required calorific value, but also other coal and ash characteristics. Specifically, it is necessary to carry out the following tasks: analyzing the properties of the coal to be mixed, calculating the initial coal ratio for mixing, conducting test burns of the theoretically obtained optimal coal ratio, monitoring parameters during test combustion, collecting data beginning with the coal preparation system (grinding, humidity, air mixture temperature, etc.), temperature distribution to furnace heights, temperatures in recirculation ducts, temperatures of heat surfaces, temperature of the flue gas at the boiler's exit, amount of ash and slag and analysis, as well as data collecting and analysis. According to the results at the end have to prepare conclusion for coal selection, rate and methodology in order to achieve a homogeneous mix.

References

[1] D.Ignjatovic, D Knezevic, B.Kolonja, N.Lilic, R.Stankovic,: Management with coal quality, Belgrade 2007.
[2] R.R.Leonard: The role of coal characteristics in boiler operation, 27th Annual Steam Power Plant Operation Conference, University of Wisconsin, November 6-7, 1978.
[3] Lidija Joleska Bureska: Choice of coal for mixing with existing for improving the performance of energetic boilers, International Conference Power Plants 2023, November 8-10, 2023, Zlatibor.

[4] L.J.Bureska: Influence of the coal quality on the boiler efficiency and opportunity for improvement, GREDIT 2016,Skopje 31.03-01.04.2016,University Cyril and Methodius, Technical Campus.
[5] Petrovski J. Ilija: Steam boilers, 2004г.
[6] R.R.Leonard: The role of coal characteristics in boiler operation, 27th Annual Steam Power Plant Operation Conference, University of Wisconsin, November 6-7, 1978.
[7] B.T.Rhodes: An empirical study of the relation of chemical properties to ash fusion temperature. J. Eng. Power 97(3) (1975) 393-403.
[8] L.Guo, et al., Comparison of bituminous and lignite during combustion: Combustion performance, coking and slagging characteristics, Journal of the Energy Institute (2018).
[9] M.Grigore, R.Sakurov, D.French, et al., Mineral matter in coals and there reaction during coking . Int. J. Coal Geol.76(4)(2008) 301-308.
[10] Singer J.G., 1981. Combustion Fossil Power Systems, 3rd ed., Combustion Engineering,Windsor,USA. pp. 67-95.
[11] McLennan A.R., Bryant G.W., Stanmore B.R. and Wall T.F., 2000. Ash formation mechanisms during combustion in reducing conditions. Energy & Fuels 14(1), 150-159.
[12] Dunnu G., Maier, J., and Scheffknecht G., 2010. Ash fusibility and compositional data of solid recovered fuels. Fuel 89(7), 1534-1540
[13] S.Pecakov: Local instruction for exploitation steam boiler Pp-700-13,8-545 (P65)
[14] European Standard EN 12952-15:2003