

## Impact Of Burning Coal from Different Mines on Energetic Boilers Performance

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**ABSTRACT:** Over the time, the best coal from our mines that were basis for the design and construction of the Thermal Power Plants in Republic of Macedonia was depleted. Now there currently exists only poor coal, coal with higher mineral matter content and lower calorific values making it of inferior quality compared to the original design specifications. Utilizing such coal in boilers present several disadvantages, including reduced efficiency, limited power output, increased strain on fuel supply and preparation systems, as well as slag and ash removal systems, heightened risk of operational failures, and other related issues. To address these challenges and enhance the coal quality, a strategy involving blending the existing coal with higher-quality coal is proposed usually. This paper delves into the selection process for coal blending, coal characteristics, and the operational implications on boiler when using different coal types. Through a comprehensive analysis encompassing calculation results, ash composition, and fusion temperatures, it is evident that the selection of coal for blending should not solely focus on increasing calorific value but also consider a broader range of characteristics to ensure optimal performance and efficiency in boiler operation. The last section illustrates the consequences of choosing inappropriate types of coal for mixing.

**KEYWORDS:** coal, boiler, efficiency, slagging etc.

### I. INTRODUCTION

Over the time, the highest quality lignite has been depleted from our coal mines. Today, only poor coal (low quality) is available for extraction. Despite its lower quality, this coal must still be used, as it continues to play role in meeting current energy demands. However, utilizing such coal presents challenges due to its variability and poor combustion characteristics. To ensure the reliable operation of Thermal Power Plants (TPP), it is crucial to supply a sufficient volume of coal that meets specific quality requirements. From the mining perspective, extracting lower-quality coal

makes sense because it improves resource utilization, extends the operational life of the mine, and reduces unused reserves. In contrast, TPP are often reluctant to accept low quality coal. Its combustion typically requires increased use of fuel oil to sustain burning, reduces plant efficiency, and leads to more frequent maintenance and higher operational cost. One effective solution is to mix lower quality coal with higher –quality coal and apply homogenization techniques.

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, commonly referred to as coal blending, involves mixing coal from different mines to improve the overall coal quality. The primary objectives of this process are to increase the calorific value, enhance combustion efficiency, and reduce the concentration of harmful elements such as sulfur and nitrogen, thereby contributing to better environmental benefits [1]. Coal blending aims to produce a coal with properties closely aligned with the design specification. This alignment enables the boiler and its auxiliary systems such as the coal supply system, slag and ash removal system, air and gas system to operate at maximum efficiency. The paper examines key factors that must be considered during coal blending, as they directly or indirectly impact boiler performances. Namely factors are calculated for six coal types. Samples coal types 1 and 2 were derived from the same mine, whereas samples coal types 3 through 6 consist of blended coals obtained from multiple mines. Proximate and ultimate analyses of the coal samples are summarized in Table 2.

## II. COAL CHARACTERISTICS TO CONSIDER IN BLENDING AND THEIR IMPACT ON COMBUSTION

Coal blending should aim to produce a mixture that closely matches the design specifications for key coal properties such as calorific value, moisture content, ash content, and grindability (HGI). Additionally, detailed characterization should include micro-petrographic analysis, chemical composition of ash, ash fusion temperatures (initial deformation, softening, hemispherical and flow temperatures), discriminant indices of ash, comprehensive slagging indicators – all of which determine the coal's slagging propensity.

The calorific value is a critical parameter in assessing coal quality. If the coal has a lower-than-designed calorific value, it can lead to unstable and incomplete combustion. This may result in flameouts within the furnace and make it difficult in maintaining the target operating temperature. Conversely, coal with a calorific value higher than designed can cause overheating of heating surfaces, elevated flue gas temperatures, and potential shutdown of the boiler to prevent thermal damage, especially if temperature regulation along the water-steam circuit is inadequate. Such deviations can severely disrupt stable boiler operation.

Moisture in coal is, to some extent correlated with its volatile matter content. A moderate amount of moisture can positively influence the combustion process. From a combustion kinetics standpoint, moisture vapor at high temperatures exhibits a catalytic effect, promoting the combustion of coal char and enhancing flame emissions. Additionally, the thermal decomposition of water vapor can generate reactive species such as hydrogen and hydroxyl radicals, which contribute to improved heat transfer within the flame.

However, excessive moisture content can have detrimental effects on combustion. When coal contains high levels of moisture, the energy required for ignition increases significantly, as a substantial amount of heat must be consumed to evaporate the excess water. This leads to a reduction in flame temperature and a corresponding drop in the temperature of the flue gases, which impairs ignition stability and combustion efficiency. 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].

Ash in coal does not contribute to heat generation during combustion, instead, it absorbs thermal energy. As ash content increases, more heat is required to raise the temperature of inert ash particles, thereby reducing the net thermal output. This can hinder the ignition process, potentially causing delays in ignition and lowering furnace temperature and combustion rates. Consequently, the proportion of unburned carbon in fly ash may increase significantly. Higher ash content also creates a physical barrier around carbon particles, limiting their contact with oxygen and leading to incomplete combustion. Moreover, increased fly ash concentration, contributes to greater abrasion on the convection heating surfaces and particulate loading in the flue gas. These factors, increase physical heat losses due to fly ash and slag, and result in a noticeable decline in overall boiler efficiency [4].

Volatile matters have a significant influence on the coal combustion process. In brown coals, volatile components begin to evolve at relatively low temperatures (150 oC to 180oC) [5]. During combustion, coke particles rapidly heat up and ignite. Coals with a higher volatile matter content ignite more easily and burn more rapidly. In contrast, coals with low volatile content have significantly higher ignition temperatures, making ignition more difficult and time-consuming. This delay reduces combustion stability. Furthermore, when volatile content is low, the combustion zone shifts higher in the furnace. As a result, less heat is released in the low furnace region and more is absorbed by the convective heating surfaces. This leads to an increase in flue gas temperature and higher flue gas heat losses. To mitigate these effects, coals with low volatile content should be finely milled to improve ignition and combustion efficiency.

If coal particles are too large, their residence time in furnace is insufficient for complete combustion, resulting in unburned coke. This increases the carbon content in the slag and leads to elevated heat losses due to the physical heat retained in the slag. Conversely, excessively fine coal particles may pass through the combustion zone too quickly, limiting contact with oxygen and allowing unburned particles to be carried out with the flue gas. This contributes to increased heat losses via fly ash. To avoid these issues, coal fineness must be optimized based on the factors as coal quality and grindability, secondary air distribution, and the type of furnace combustion system.

Coal grindability is typically measured using the Hardgrove Grindability Index (HGI). Coals with a higher HGI are easier to grind, while those with a lower HGI are more resistant. When

grinding harder coal (lower HGI), mill throughput is reduced [2].

Coal's slagging tendency is a critical factor to consider during blending, as slagging directly impacts combustion performance, heat transfer efficiency, and overall boiler operation. The effect of coal blending on ash deposition, depending on the mineral matter in coal and the blending ratio, is diverse and unpredictable. Coal blending may mitigate ash deposition, but in some cases would also aggravate ash deposition due to the mineral interactions. Therefore, understanding the effect of coal blending on mineral transformation and ash deposition during combustion of low rank coal is essential to extend its utilization.

temperature, soot blowing patterns, and of particular concern the heat transfer surface temperature are also responsible for ash deposition [6]. Several parameters can be used to assess slagging potential, including the coal's ultimate analysis, ash content, ash fusion temperatures, and the mineralogical composition of the ash. A more comprehensive evaluation can be performed by calculating the slagging discriminant index [7], which incorporates multiple ratios such as the base-to-acid ratio, silicon ratio, silica-to-alumina ratio, iron-to-calcium ratio, and an overall comprehensive index. These indices provide predictive insight into the slagging behavior of different coal blends. The following expressions define each of these relationships [8]:

The operating conditions and boiler design including boiler load, air to fuel ratio, gas

- Base-Acid ratio,  $B/A = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2)$  (1)
- Silicon ratio,  $G = 100 SiO_2 / (SiO_2 + Fe_2O_3 + CaO + MgO)$ , (2)
- Silica-Alumina ratio  $= SiO_2 / Al_2O_3$  (3)
- Iron-Calcium ratio  $= Fe_2O_3 / CaO$  (4)
- Comprehensive index,  $R = 5,415 - 0,002ST + 1,237B/A - 0,019G + 0,282SiO_2 / Al_2O_3$  (5)

Table 1. The limits values of discriminant indices 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 <sub>2</sub> / Al <sub>2</sub> O <sub>3</sub>	<1,87	1,87-2,65	>2,65
Fe <sub>2</sub> O <sub>3</sub> /CaO	Out of 0,3-3	0,3-3	Near 1
R	<1,5	1,5-2,5	>2,5

Table 1 shows the limits values of the discriminant indices used to assess slagging tendency. The composition and properties of the minerals, determine the bituminous coal's and lignite's slagging characteristics [9]. However, for a given coal sample, the discriminant indices may sometimes yield conflicting or imprecise results. Therefore, a more reliable method for evaluating slagging characteristics involves measuring the ash fusion temperatures [8].

In some literature [10] the Ash Fusion Temperature (AFT) is also cited alongside other key indicators of slagging tendency. The AFT serves as a critical parameter for assessing the potential for ash agglomeration and deposition during combustion. It can be estimated using a specific empirical formulation:

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

where DT and HT represent the ash start deformation temperature and hemispherical

temperature respectively. If the calculated AFT values are within the range of 1052 to 1232 o C, this indicates a high slagging potential. Conversely, AFT values below 1052 o C, suggest a very high likelihood of severe slagging [11, 12].

### III. ANALYSIS AND DISCUSSION OF RESEARCH RESULTS

The subject of this study as the P65 boiler, designed for the combustion of lignite coal in a suspension firing flight. The boiler furnace is octagonal shaped, and fuel is supplied by six fan mills [13]. Calculations for determining boiler efficiency, heat losses, fuel requirements, and other parameters were performed in accordance with European Standard EN 12952, Part 15. Six types of coal were used in the analysis, with their characteristics listed in Table 2..

Table 2. Proximate and Ultimate Analysis of Coal Samples [14]

Coal Specification	Unit	Coal					
		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
Water, W	[%]	37,8	37,2	42,61	44,56	42,99	38,24
Ash, A	[%]	34,28	32,99	23,47	21,61	28,03	32,35
Carbon, C	[%]	16,73	17,72	22,2	22,07	18,3	14,78
Hydrogen, H	[%]	1,57	1,67	2,02	1,95	1,71	1,7
Sulphur, S	[%]	0,67	0,9	1,09	0,72	1,04	0,78
Oxygen, O	[%]	8,7	9,65	8,71	9,03	7,8	12,24
Nitrogen, N	[%]	0,25	0,31	0,49	0,47	0,42	0,41
Law Heat Value, LHV	[KJ/kg]	5534	6006	7465	7225	5974	5861

During coal combustion at high temperatures, the mineral matter in coal undergoes complex mineral transformations and interactions, leading to new mineral phases that differ from its original mode of occurrence. The behaviours of the mineral matter at high temperatures are directly responsible for ash deposition. Thus, understanding the mineral

transformations and interactions of the mineral matter subjecting to high temperature environment during combustion are essential for understanding ash deposition and deposit properties [15]. Tables 3 and 4 present the fusion temperatures and chemical composition of the ash for the respective coal types.

Table 3. Fusion Temperatures of Different Coal Types [14]

Ash from coal	Deformation Temperature (DT) [°C]	Softening Temperature (ST) [°C]	Hemisphere Temperature (HT) [°C]	Flow Temperature (FT) [°C]
Typ 1	1278	1368	1382	1394
Typ 2	1370	1438	1458	1472
Typ 3	900	995	1220	1270
Typ 4	900	995	1230	1220
Typ 5	890	985	1220	1355
Typ 6	1070	1180	1270	1300

Table 4. Chemical Composition of Ash from Different Coal Types [14]

Ash from coal	SiO <sub>2</sub> [%]	Al <sub>2</sub> O <sub>3</sub> [%]	TiO <sub>2</sub> [%]	Fe <sub>2</sub> O <sub>3</sub> [%]	K <sub>2</sub> O [%]	CaO [%]	MgO [%]	Na <sub>2</sub> O [%]
Typ 1	55,52	20,88	0,83	5,99	2,78	2,90	1,77	1,48
Typ 2	55,07	24,43	0,82	7,24	2,73	2,80	1,92	0,89
Typ 3	50,51	24,09	0,82	7,61	1,30	6,26	3,54	0,10
Typ 4	53,33	25,12	0,77	6,75	1,34	6,15	2,22	0,11
Typ 5	52,93	30,49	0,8	6,37	1,61	3,55	2,31	0,11
Typ 6	61,92	19,31	0,93	7,45	1,32	2,98	1,86	0,86

A computer calculation was performed to compare the operation of the boiler using the above mentioned types of coal (Fig. 1). The input data included ultimate and proximate coal analyses, design values for flow, pressure, and temperature of feed water, temperature of heating surfaces, and other relevant parameters. It is assumed that the boiler operates at a maximum steam production of

700t/h under the specific design parameters [13]. The calculation was conducted 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 (EN 12952-15:2003).

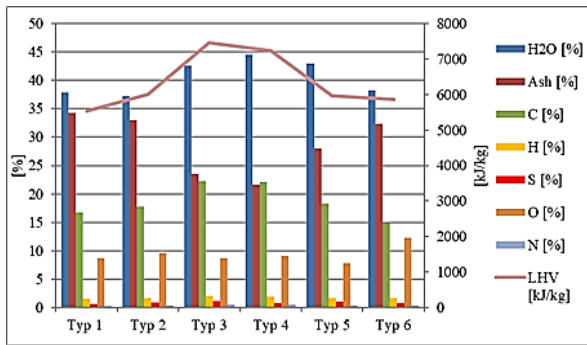


Fig. 1. Characteristics of Coal Types 1-6

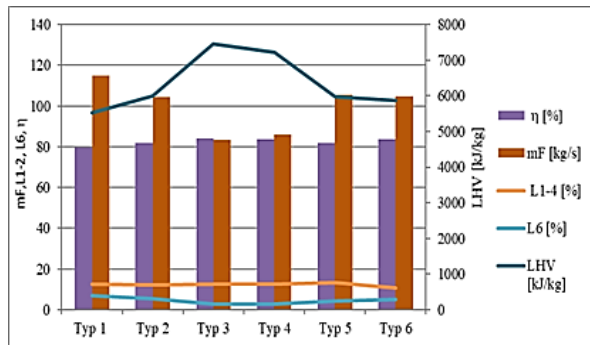


Fig. 2. Results of the Calculations

It is evident from the characteristics of the analysed coal types (Fig. 1) that all types have a relatively high ash content (23,61 to 34,28%), which exceeds the design limit of 20% for the boiler used as a model. This high ash content negatively affects boiler efficiency by increasing losses (L6) due to the unburned in slag and ash (Fig.2). Naturally, a higher ash content also leads to reduction in the coal's calorific value. As a result, more fuel is required to produce the same energy output, which increases fuel consumption (mF) (Fig. 2). The amount of fuel required to operate the boiler at maximum capacity

when burning coal types 1, 2, 5, and 6 is 114,9 kg/s; 104,5 kg/s; 105,3 kg/s; 104,9 kg/s respectively. These values exceed the mills' capacity of 100 kg/s [13], indicating that the boiler cannot operate at full capacity with these coal types. In contrast, calculations show that coal types 3 and 4 allow the boiler to operate at maximum capacity, with fuel consumption of 83 and 86 kg/s and efficiency of 84 % for both. The calculations assume that the sealing of the gas-air and coal systems is within acceptable limits.

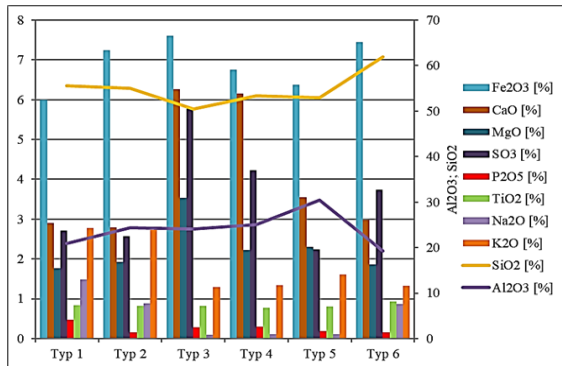


Fig. 3. Chemical Analysis of Ash from Coal Types 1-6

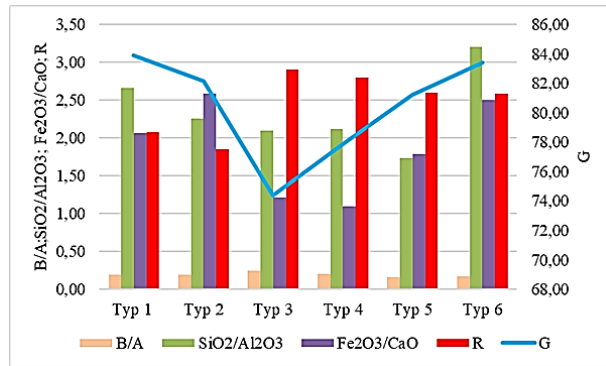


Fig. 4. Discriminant indices for slagging of Coal Types 1-6

According to the chemical analysis of the ash (Fig. 3), the ash from coal types 3 and 4 contains more than twice the amount of CaO compared to the other coal types. Additionally, the ash from coal types 2, 3, 4, and 5 contains more than 20% Al<sub>2</sub>O<sub>3</sub>, which is significantly higher than that in types 1 and 6.

The discriminant indices for slagging B/A, G, SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>/CaO, and the comprehensive index R are calculated based on chemical analysis of the ash [8]. Figure 4 shows that the B/A, G, and SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> index values for coal types 3 and 4 fall within the range corresponding to a medium slagging tendency, while coal type 6 according SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> index, is in the coal with severity tendency for slagging. The Fe<sub>2</sub>O<sub>3</sub>/CaO index

indicated a severe slagging tendency for coal types 3 and 4, and a medium slagging tendency for other coal types (1, 2, 5 and 6). Similarly, the comprehensive R index shows a severe slagging tendency for coal types 3, 4, 5 and 6, while for coal types 1 and 2, a medium slagging tendency.

An analysis of the ash fusion temperatures is necessary, as the indices may sometimes lead to differing interpretations, as previously mentioned. Figure 5 presents typical ash temperatures for the coal types under study, including deformation temperature (DT), softening temperature (ST), hemispheric temperature (HT), and flow temperature (FT) and calculated Ash Fusion Temperature (AFT).

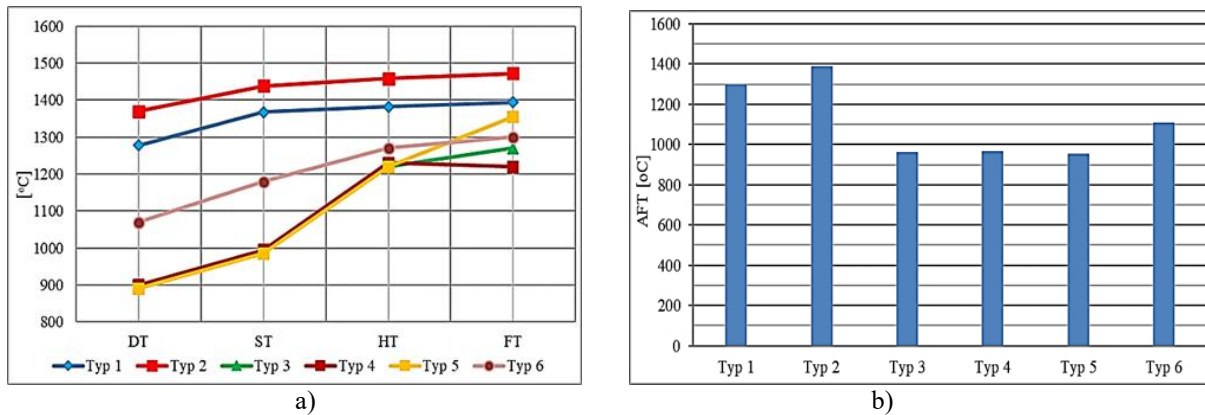


Fig. 5. Characteristic ash temperatures (a) and calculated ash fusion temperature (AFT) (b) for coal types 1-6.

The fusion temperatures of ash from coal types 3, 4, and 5 overlap at several points in the diagram (Fig. 5a), but they are lower than the corresponding temperatures for ash from coal types 1, 2, and 6. The deformation temperature (DT) of ash in coal types 3, 4, and 5 is more than 300°C lower, while the hemispherical temperature (HT) is lower by less than 200°C. Specifically, coal types 3 and 4 have lower flow temperatures (1270°C and 1220°C, respectively), while coal types 1, 2, 5 and 6 have higher flow temperatures (1394°C, 1472°C, 1350°C and 1300°C respectively). Notably, coal type 2 has the highest flow temperature at 1472°C. Based on the calculated ash fusion temperature (AFT) for the various coal types (as shown in Fig. 5b), significant differences are observed between

coal types 1 and 2 compared to coal types 3, 4, 5 and 6.

The AFT values for coal types 1 and 2 are 1299°C and 1388°C, respectively, while for types 3, 4, and 5, they are 964°C, 966°C, and 956°C, respectively. The AFT for coal type 6 is moderately higher, at 1110°C. Based on these values, it can be inferred that coal types 1 and 2 have moderate tendency for slagging, whereas types 3, 4 and 5 exhibit a strong slagging tendency. Coal type 6 also show a high potential for slagging, consistent with findings reported by [11, 12]. The consequences of poor coal selection are illustrated in Fig.6. Specifically, due to the slagging caused by improper coal selection, Unit 3 at TPP Bitola was non-operational for over three months in 2023 year.

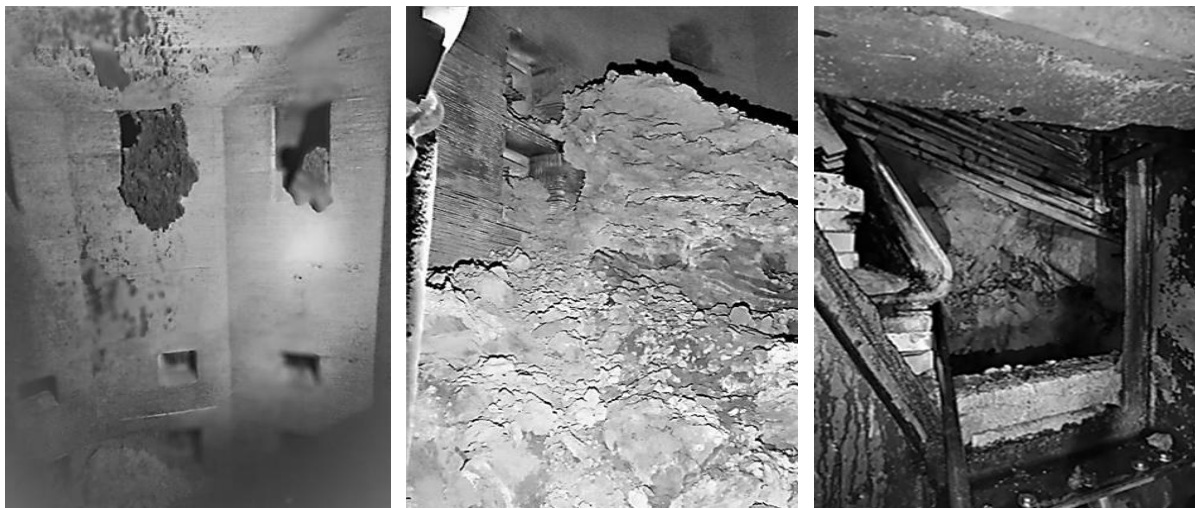


Fig. 6. Slagging in the boiler furnace [3]

#### IV. CONCLUSION

The analysis of boiler performance using various coal types indicates that only coal types 3 and 4 enable the unit to achieve maximum output

under design conditions with corresponding efficiencies of 84,1% and 83,9% respectively. In contrast, the remaining coal types require fuel quantities that exceed the capacity of the milling system, thereby preventing the boiler from reaching

its maximum production. Despite the favorable calorific properties of coal types 3 and 4, their ash characteristics present a significant risk of slagging. While the B/A, G and  $\text{SiO}_2/\text{Al}_2\text{O}_3$  indices classify the ash as having a medium slagging tendency, the  $\text{Fe}_2\text{O}_3/\text{CaO}$  ratio and the comprehensive slagging index (R) indicate a pronounced tendency toward slag formation. Additionally, the ash fusion temperature (AFT) of coal types 3,4, and 5 are significantly lower by approximately 300 to 400 °C compared to those of coal types 1 and 2. Specifically, the AFT values for coal types 3,4, and 5 are 964°C, 966°C, and 956°C, respectively, placing them within the category of coals with a high slagging potential. The coal type 6 exhibits a moderately high slagging tendency, with an AFT of 1110°C. These temperature characteristics future support the likelihood of slag formation during the combustion of coal types 3, 4, and 5.

In summary, although coal types 3 and 4 facilitates optimal boiler performance due to their high calorific values, they simultaneously introduce operational risks related to slag formation, primarily due to their ash chemistry and lower fusion temperatures. Consequently, when selecting coal for blending with existing ones, it is imperative to consider not only calorific value but also the physical and chemical properties of both the coal and its resulting ash. To ensure safe and efficient operation, the following methodology is recommended:

- Comprehensive characterization of the coal intended for blending;
- Determination of an initial theoretical blend ratio based on performance and slagging indices;
- Execution of controlled test combustions using the proposed blend;
- Systematic monitoring and analysis of key operational parameters including: Coal preparation system performance (e.g., grinding efficiency, moisture content, primary air temperature), Furnace temperature profile across various heights, Temperatures in recirculation ducts and heat surfaces, Flue gas temperature at the boiler outlet, quantity and qualitative assessment of ash and slag.

Based on the collected data, a final recommendation should be formulated concerning the suitability of the coal blend, optimal blending ratio, and necessary operational adjustments to maintain stable combustion and mitigate slagging risks. This approach will facilitate the development of a homogeneous and efficient fuel mix aligned with both performance and operational reliability requirements.

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