

## CRITERIA SELECTION FOR THE ASSESSMENT OF SERBIAN LIGNITES TENDENCY TO FORM DEPOSITS ON POWER BOILERS HEAT TRANSFER SURFACES

by

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*Based on investigations of ash deposit formation, semi-empirical indicators for slagging and fouling, based on ash chemical composition and its fusion temperature, have been determined. These criteria-indicators, in suggested limits, describe the coals on which they are based (North-American and British) well. However, the experience in the thermal power production sector of Serbia shows that their literal application to domestic coals does not produce satisfactory results. This contribution provides an analysis of applicability and the choice of criteria that are suitable for Serbian coals. The focus of the contribution is on coal slagging indicators, since slagging has much heavier consequences on heat transfer inside the steam boiler, and on boiler operation as a whole. The basis for the analysis of chosen criteria comprises of the results of investigations of four coal fields – Kostolac, Kolubara, Kosovo (Serbia), and Ugljevik (Bosnia and Herzegovina).*

Key words: lignite, ash, slagging

### Introduction

Lignite is dominant energy source in Serbia, which is characterized by high moisture and mineral matter content. As mineral matter plays an active role in processes taking part inside the furnace and in the convective sections of boiler, the unfavourable consequences of its presence in coal are evinced as deposition on boiler heat transfer surfaces. Studying of the deposit formation process is based on semi-empiric correlations – criteria based on ash chemical composition and its fusion temperature, which indicate the tendencies of deposit formation. These criteria are the simple and the most acceptable way to gain information about coal tendencies to form ash deposits on boiler heat transfer surfaces. The criteria defined in the literature [1-6] describe the coals on which they are based (North-American and British) and for the other type of coals, especially lignites, it is necessary to examine the possibility to use defined criteria and the suggested limits.

In this paper an attempt was made to perform a thorough analysis and to choose the deposit propensity criteria suitable for domestic lignites. This is very important for thermal power plants in Serbia, as the boiler facilities will be refurbished in next few years, based on the quality of the coal available in the future. The base for the criteria analysis consists of chemical compositions and ash fusion temperatures of domestic lignites, determined by verified institutions in Serbia (Faculty of Mechanical Engineering and Faculty of Mining and Geology in Belgrade; Mining In-

stitute in Zemun, and the Vinča Institute of Nuclear Sciences). Particularly it should be emphasized that the Laboratory for Thermal Engineering and the Vinča Institute as the biggest research organization in the field of thermal engineering and coal combustion in the country (as it also had been in the former Yugoslavia) and the considerable and comprehensive database of physical and chemical properties of coals, foremost of lignites, from the region of former Yugoslavia has been developed. Furthermore, throughout the years long-term investigations were carried out in the same Laboratory in order to decrease deposit formation on boilers heat transfer surfaces, and for this purpose suitable measurement methods for investigations, in real operating conditions in boilers and under laboratory conditions, were developed. This fact is verified by numerous papers that have served as a rich source of information for this article [7-21].

In this paper properties of coals that comprise the database used for criteria analyses are described and the summary of key empirical correlations for slagging and fouling is given. Based on the previous, the correlative analysis of chosen criteria is performed and the corresponding conclusions are drawn from these analyses and they could be used for determination of deposits formation during coal combustion.

## Fundamentals

### *Characteristics of lignites comprising the database for criteria analysis*

Out of total coal reserves on the territory of Serbia, without the provinces, lignites account for 89.37%, with 88.28% of total coal reserves being concentrated in Kolubara and Kostolac open pit mine. Due to high moisture and ash contents, and low heating value (approximately 7000 kJ/kg, as received), the usability of Serbian lignites is limited to power production [22]. These coals could be classified according the national standard SRPS B.H0.001 as lignites and brown coals and according to International Classification\* as the sub-bituminous coals and C-bituminous coals with high content of volatile, respectively.

For the analysis, coal samples from four different mines (Kostolac, Kolubara, and Kosovo in Serbia, and Ugljevik, Bosnia and Herzegovina) are selected. The total number of ash samples is 132 (Kostolac-30, Kolubara-68, Kosovo-12, and Ugljevik-22 samples). The summary of coal and ash characteristics is given in tab. 1 [21]. Considering ash fusion temperatures, it is very important to underline the inability to measure temperature values above 1400 °C in laboratory conditions precisely, which to an extent deteriorates the precision of its determination, as well as the value of average fluid temperature ( $T_3$ ) of the ash itself.

As it can be observed from tab. 1, there is a certain similarity in chemical compositions of the ashes of Kolubara and Kostolac coals. The predominant compounds of Kostolac coal ash are the oxides  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , but the increased  $\text{Fe}_2\text{O}_3$  content points to higher disposition of this lignite to slagging, when compared to Kolubara coals. The increased contents of CaO and  $\text{SO}_3$  makes Kostolac coal quite different from Kolubara coal, regarding the tendency to form solid, bound deposits. The alkali content of Kostolac coals is low. Ash fusion temperatures are lower than those of Kolubara coals.

The ash of Kolubara coals is characterized by high contents of acid-type oxides (silica and alumina oxides) and low contents of base-type oxides (CaO and MgO), and relatively high ash fusion temperatures. The alkali content is low, as well as contents of sulphur oxides.

\* Classification of coals by ASTM, 2000 Annual Book of ASTM Standards, section 5, volume 5.06

Table 1. Properties of lignites that form the database for criteria analysis

PROXIMATE ANALYSIS												
	Values											
	Minimum			Average			Maximum					
	Kostolac	Kolubara	Ugljevik	Kosovo	Kostolac	Kolubara	Ugljevik	Kosovo	Kostolac	Kolubara	Ugljevik	Kosovo
Ash [%, as received]	6.32	4.64	12.08	11.92	17.41	16.05	20.30	16.46	34.51	37.19	32.41	22.06
H [%, as received]	31.30	14.50	21.21	22.70	40.50	44.00	33.40	39.90	53.00	52.00	37.14	46.60
Volatile matter [% daf]	55.22	56.00	43.72	47.72	58.96	60.93	41.17	56.1	63.77	65.83	62.13	66.4
Net calorific value [kJkg <sup>-1</sup> daf]	23253	19029	18346	19030	25345	24468	24706	21100	27784	26864	27734	23887.66
CHEMICAL COMPOSITION OF LABORATORY ASH												
	Values											
	Minimum			Average			Maximum					
	Kostolac	Kolubara	Ugljevik	Kosovo	Kostolac	Kolubara	Ugljevik	Kosovo	Kostolac	Kolubara	Ugljevik	Kosovo
[%]	22.54	23.25	12.54	24.55	41.41	52.17	26.78	30.06	56.24	78.17	39.57	34.71
SiO <sub>2</sub>	11.94	9.17	1.66	3.28	19.78	22.31	12.98	6.74	26.05	31.77	20.34	9.50
Al <sub>2</sub> O <sub>3</sub>	4.84	1.87	2.68	4.82	10.43	6.35	13.97	7.21	31.24	18.74	21.67	9.08
Fe <sub>2</sub> O <sub>3</sub>	3.32	2.21	7.93	36.22	12.01	8.35	21.17	38.92	21.58	26.95	67.76	43.21
CaO	1.03	1.16	0.93	2.68	3.43	2.76	3.07	4.02	5.9	5.41	5.2	4.95
MgO	0.29	0.13	0.07	0.63	0.57	0.49	1.21	1.10	1.39	2.00	1.99	1.80
Na <sub>2</sub> O	0.45	0.06	0.16	0.20	1.01	1.00	1.32	0.43	2.89	2.62	1.94	0.52
TiO <sub>2</sub>	0.00	0.00	0.06	0.00	0.8	0.73	0.58	0.20	1.30	1.95	1.03	0.58
P <sub>2</sub> O <sub>5</sub>	0.00	0.00	0.02	0.00	0.16	0.12	0.19	0.26	0.59	0.87	0.63	2.07
SO <sub>3</sub>	2.76	0.98	9.65	7.34	10.3	5.69	18.74	11.17	20.15	21.98	26.77	15.84
Ash fusion temperatures [%]												
T <sub>1</sub>	1030	1040	1120	1120	1130	1187	1174	1161	1210	1435	1275	1200
T <sub>2</sub>	1110	1200	1165	1200	1249	1336	1231	1244	1395	1575	1400	1290
T <sub>3</sub>	1135	1235	1190	1205	1284	1357	1268	1262	1410	1590	1400	1310

The moisture and ash content of Kosovo coals are similar to those of other lignites. The ash of Kosovo coal samples is characterized by high CaO and SO<sub>3</sub> contents, which leads to conclusion that these coals have the propensity to form solid deposits on the heat transfer surfaces. The ash of this coal has the lowest mean ash fusion temperatures, due to its base character.

The ash of Ugljevik samples has high CaO, Fe<sub>2</sub>O<sub>3</sub>, and SO<sub>3</sub> contents and substantially low acid character. All this, as well as low fusion temperatures, classifies this coal as prone to slagging.

### *Summary of key empirical correlations for slagging and fouling*

A numerous of empirical correlations based on ash chemical composition and its fusion temperature are used to evaluate the behavior of mineral matter and their possible effects on deposition, both on the furnace walls and on convection tube banks. A summary of key empirical correlations for slagging and fouling is presented in tabs. 2 and 3.

Ash fusion temperature is considered as one of the most acceptable method for the assessment of coal ash tendency to slagging. In most countries, this method is standardized, as well as in our country (SRPS B.H8.325).

The interval between the initial deformation ( $T_1$ ) and fluid ( $T_3$ ) temperatures gives a good insight into the kind of deposits that can be expected on furnace surfaces. If the interval is small, a thin, liquid layer of slag will be created on the furnace walls, which is extremely difficult to control by sootblowing. With the growth of the interval, and thickness of deposits formed prior to the formation of liquid slag layer increases and bond between the tube and the deposits is weaker. This kind of deposits is easily removed by sootblowing.

The gas temperature at the entrance to the tube bundles banks section is designed to be lower than the temperature of deformation, in order to avoid fouling on heat transfer surfaces.

The criteria  $T_{250}$  represents the temperature at which slag viscosity is equal to 250 poise (25 Pa·s), and it can be determined experimentally, using a viscosimeter. To avoid the cost of the test and to save time, this temperature can be calculated from known composition of the ash sample by method of Watt and Fereday presented in tab.2

The temperature of critical viscosity ( $T_{CV}$ ) is the temperature at which the solid phase starts to crystallize from the melt. The most commonly used method for its determination is the method of Hoy, Roberts, and Wilkins, given in tab. 2. Since  $T_{CV}$  is determined with the inaccuracy of  $\pm 111$  °C and  $T_{250}$  with the inaccuracy of  $\pm 85$  °C [2], neither of these two temperatures can be used on ashes having the differences between  $T_{CV}$  and  $T_{250}$  lower than 190 °C. This is the case for 95% of all coals.

Gray & Moore [3] have established slagging index (FS), which is based on initial deformation and hemispherical temperatures obtained by the AFT test, with the limit values listed in tab. 2.

In order to determine the indicators for slagging/fouling characteristics of coal, the chemical analysis of ash according to the procedure prescribed by national standards is carried out. The national standard SRPS B.H8.312 has established a method for the determination of ash content in the solid fuel, while SRBS B.H8.359 provides methods for the chemical analyses of ash. According to the ASTM\* standard two different types of ash can be distinguished:

(1) bituminous ash type (ash with an acid reaction):  $(\text{CaO} + \text{MgO}) < \text{Fe}_2\text{O}_3$  or alternatively  $\text{SiO}_2 > (\text{Fe}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O})$ , and

\* American Society for Testing and Materials

**Table 2. Summary of key empirical correlations for slagging**

Indicators for slagging based on ash fusion temperature															
Indicator	Values/suggested limits														
<p><b>1. Ash fusion temperature</b> [°C] [1]  <math>T_1</math> – initial deformation temperature  <math>T_2</math> – hemispherical temperature  <math>T_3</math> – fluid temperature</p> <p>Application: all coals*</p>	<p><math>T_1</math> – used to select maximum furnace exit temperature  <math>T_3 - T_1 \downarrow</math> – thin fluid slag layer, extremely hard to remove by sootblowing  <math>T_3 - T_1</math> – increased deposit thickness, easy to remove by sootblowing</p> <table border="1"> <thead> <tr> <th><math>T_3</math> [°C]</th> <th>Slagging</th> </tr> </thead> <tbody> <tr> <td>1200</td> <td>High</td> </tr> <tr> <td>1200-1350</td> <td>Medium</td> </tr> <tr> <td>1350-1650</td> <td>Low</td> </tr> </tbody> </table>		$T_3$ [°C]	Slagging	1200	High	1200-1350	Medium	1350-1650	Low					
$T_3$ [°C]	Slagging														
1200	High														
1200-1350	Medium														
1350-1650	Low														
<p><b>2. Temperature at 250 poise – <math>T_{250}</math></b> [2]                      analytical determination:                      Normalize  <math>\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} = 100\%</math>  <math>M = 0.00835 \text{ SiO}_2 + 0.00601 \text{ Al}_2\text{O}_3 - 0.109</math>  <math>C = 0.0415 \text{ SiO}_2 + 0.0192 \text{ Al}_2\text{O}_3 + 0.0276 \text{ Fe}_2\text{O}_3 + 0.016 \text{ CaO} - 3.92</math>  <math>T_{250} = \sqrt{\frac{10^7 M}{\log_{250} C}} - 150</math> [ C]</p> <p>Application: all coals</p>	<table border="1"> <thead> <tr> <th rowspan="2"><math>T_{250}</math> [°C]</th> <th>Dry bottom furnaces</th> <th rowspan="2">Wet bottom furnaces</th> </tr> <tr> <th>slagging</th> </tr> </thead> <tbody> <tr> <td>&lt;1275</td> <td>Low</td> <td rowspan="4">1425</td> </tr> <tr> <td>1400-1150</td> <td>Medium</td> </tr> <tr> <td>1245-1120</td> <td>High</td> </tr> <tr> <td>&lt;1200</td> <td>Severe</td> </tr> </tbody> </table> <p>There is a considerable overlap between classes</p>	$T_{250}$ [°C]	Dry bottom furnaces	Wet bottom furnaces	slagging	<1275	Low	1425	1400-1150	Medium	1245-1120	High	<1200	Severe	
$T_{250}$ [°C]	Dry bottom furnaces		Wet bottom furnaces												
	slagging														
<1275	Low	1425													
1400-1150	Medium														
1245-1120	High														
<1200	Severe														
<p><b>3. Temperature of critical viscosity – <math>T_{CV}</math></b> [2]                      analytical determination:                      Normalize as 2  <math>T_{CV} = 2990 - 1470 \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3} - 360 \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}^2 - 14.7(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO}) + 0.15(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO})^2</math> [°C]</p> <p>Application: all coals</p>	<p>Temperature at which viscosity changes from Bingham Plastic to Newtonian                      If <math>T_{250} &lt; T_{CV}</math> <math>T_{250}</math> is meaningless</p>														
<p><b>4. Slagging index-<math>F_s</math></b> [3]                      analytical determination:  <math>F_s = \frac{4T_1 - T_2}{5}</math> [ C]</p> <p>Application: all coals</p>	<table border="1"> <thead> <tr> <th><math>F_s</math> [°C]</th> <th>Slagging</th> </tr> </thead> <tbody> <tr> <td>1232-1342</td> <td>Medium</td> </tr> <tr> <td>1052-1232</td> <td>High</td> </tr> <tr> <td>&lt;1052</td> <td>Severe</td> </tr> </tbody> </table>	$F_s$ [°C]	Slagging	1232-1342	Medium	1052-1232	High	<1052	Severe						
$F_s$ [°C]	Slagging														
1232-1342	Medium														
1052-1232	High														
<1052	Severe														

\* All coals regardless of bituminous or lignitic ash type *i. e.* all coal ranks  
 – increase; – decrease

‡ For the purpose of uniformity of assessing the coal tendency towards deposit formation, the following characterization was introduced:

- low – coals not prone to the formation of deposits,
- medium – coals showing no significant tendency towards deposit formation, but with occurrences of deposit formation
- high – coals with significant tendency towards deposit formation
- severe – coals that are highly problematic with regard to deposit formation

Table 2. (continuation)

Indicators for slagging based on ash composition			
	Bituminous Lignitic	Ash type	CaO + MgO < Fe <sub>2</sub> O <sub>3</sub> or SiO <sub>2</sub> > Fe <sub>2</sub> O <sub>3</sub> + CaO + Na <sub>2</sub> O CaO + MgO > Fe <sub>2</sub> O <sub>3</sub> or SiO <sub>2</sub> < Fe <sub>2</sub> O <sub>3</sub> + CaO + Na <sub>2</sub> O
Indicator	Values/suggested limits		
<b>5. Base-to-acid ratio – B/A</b> [2] analytical determination: $\frac{B}{A} = \frac{\text{Fe}_2\text{O}_3 \text{ CaO MgO Na}_2\text{O K}_2\text{O}}{\text{SiO}_2 \text{ Al}_2\text{O}_3 \text{ TiO}_2}$ <i>Application:</i> all coals	<i>B/A</i>		Furnace
	0.5		Dry
	0.27		Wet
	0.4-0.7		High slagging coal
<b>6. Silica-to-alumina ratio</b> – $\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$ [4]  <i>Application:</i> all coals	$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$		Slagging
	<0.31 or >3 0.31-3		Low High
If two coals have the same B/A index, the one with higher index has higher SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> slagging potential.			
<b>7. Iron oxide-to-calcium oxide ratio</b> – $\frac{\text{Fe}_2\text{O}_3}{\text{CaO}}$ [4] <i>Application:</i> all coals	Eutectics formed between 0.3 and 3 increase slagging		
<b>8. Dolomite percentage – DP</b> [4] analytical determination: $DP = \frac{\text{CaO MgO}}{\text{Fe}_2\text{O}_3 \text{ CaO MgO Na}_2\text{O K}_2\text{O}} \cdot 100\%$ <i>Application:</i> for coals with B > 40%	40% < DP < 98% ⇒ DP↓ slagging propensity of coal		
<b>9. Slagging factor – R<sub>s</sub></b> [2] analytical determination: $R_s = \frac{B}{A} S$ [%] on dry coal <i>Application:</i> coals with bituminous ash type	<i>R<sub>s</sub></i> [%]		Slagging
	<0.6		Low
	0.6-2		Medium
	2-2.6 >2.6		High Severe
<b>10. Fusibility index – I<sub>t</sub></b> [1] analytical determination: $I_t = \frac{\text{SiO}_2 \text{ Al}_2\text{O}_3}{\text{Fe}_2\text{O}_3 \text{ CaO MgO Na}_2\text{O K}_2\text{O}}$ <i>Application:</i> all coals	<i>I<sub>t</sub></i>		Slagging
	0.2-1.5		High
	1.5-2.5 >2.5		Medium Low
<b>11. Iron oxide in the ash – Fe<sub>2</sub>O<sub>3</sub> [%]</b> [3]  <i>Application:</i> for coal ashes that contain Na <sub>2</sub> O ≤ 2.5% or CaO ≤ 7.5%	Fe <sub>2</sub> O <sub>3</sub> [%]		Slagging
	3-8		Low
	8-15 15-23		Medium High
<b>12. Silica ratio – S<sub>o</sub></b> [3] analytical determination: [%] $S_o = \frac{\text{SiO}_2}{\text{SiO}_2 \text{ Fe}_2\text{O}_3 \text{ CaO MgO}} \cdot 100\%$ <i>Application:</i> for coal ashes that contain Na <sub>2</sub> O ≤ 2.5% or CaO ≤ 7.5%	<i>S<sub>o</sub></i> [%]		Slagging
	72-80		Low
	65-72		Medium
	50-65		High

(2) lignitic ash type (ash with an base reaction):  $(\text{CaO} + \text{MgO}) > \text{Fe}_2\text{O}_3$  or alternatively  $\text{SiO}_2 < (\text{Fe}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O})$ .

Eight major oxides in the ash without the sulfates, can be divided into “acid” in the pyrochemical sense ( $A = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2$ ) and the “base” ( $B = \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O}$ ). Acid oxides are responsible\* for high ash fusion temperature, while with the increase of base oxides this temperature is reduced. As most of the elements react with each other depending on their acid or base properties, B/A ratio expresses the potential of metallic compounds to combine into low melting salts during the combustion process, and therefore characterizes the melting and the viscosity properties of ash. Very high and very low values of B/A indicate minimal potential for the formation of compounds with low melting temperatures.

The  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio provides additional information regarding ash fusibility. Both  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are acid oxides with high fusion temperatures. However  $\text{SiO}_2$ , when compared to  $\text{Al}_2\text{O}_3$ , forms compounds (with base reaction ash components) that have lower fusion temperatures (silicates). Therefore, if two coals have the same B/A ratio, the one with higher  $\text{SiO}_2/\text{Al}_2\text{O}_3$  would have lower fusibility temperatures.

Iron oxide to calcium oxide ratio ( $\text{Fe}_2\text{O}_3/\text{CaO}$ ): out of all oxides with base reaction, iron and calcium oxides are the most important primarily because they form the majority of base compounds.

Dolomite percentage (DP) is used primarily for coal ashes with base-oxides content over 40% and it is in the range from 40 to 98%. For a given value of B, a higher DP means higher fusion temperatures and higher slag viscosities.

The slagging factor ( $R_s$ ) has been developed in order to establish a correlation between the ash content obtained by standard laboratory procedure, and the deposits formed on furnace walls and other surfaces exposed to flame radiation.

The criterion fusibility index  $I_t$  has been defined by Post and Teune [1], as the ratio of oxides with low and high ash fusibility temperatures.

Raask [3] has introduced the criterion iron oxide content in the coal ash  $\text{Fe}_2\text{O}_3$  [%] in order to simplify iron percentage (IP) criterion which is defined as:

$$IP = \frac{\text{Fe}_2\text{O}_3}{\text{Ekviv. Fe}_2\text{O}_3} 100\%$$

$$\text{Ekviv. Fe}_2\text{O}_3 = \text{Fe}_2\text{O}_3 + 1.11\text{FeO} + 1.43\text{Fe},$$

which are determined by chemical analysis of actual furnace slag.

According to Raask [3] silica ratio ( $S_o$ ) could be simplified by introducing the criterion  $SP: PC = \text{SiO}_2/(\text{SiO}_2 + \text{Ekviv. Fe}_2\text{O}_3 + \text{MgO} + \text{CaO})100$ , by replacing  $\text{ekviv. Fe}_2\text{O}_3$  with  $\text{Fe}_2\text{O}_3$  content in the ash obtained in laboratory conditions. He applied this new criterion to rank British coals respect to the slagging potential.

The alkali metals, sodium and potassium, have long been associated with the fouling tendencies of coal ash. Volatile forms of these elements evaporate in the furnace at combustion temperature and react with sulfur in the flue gas and other elements in the ash, form compounds that deposit on convection surfaces.

The total content of  $\text{Na}_2\text{O}$  in the laboratory ash as an indicator of harmful effect deposits in case that all sodium evaporates.

\* Acid oxides are more stable at high temperatures than base oxides, therefore we consider them as “responsible” for high melting temperatures

**Table 3. Summary of key empirical correlations for fouling**

Indicators for fouling			
Indicator	Values/suggested limits		
<b>1. Sodium content of coal ash – Na<sub>2</sub>O [%]</b> [2, 5]  Application: all coals	Na <sub>2</sub> O [%]		
	Bituminous coal ash	Lignitic coal ash	
	<2	<0.5	
	2-6	0.5-1	
	6-8	1-2.5	
	>8	>2.5	
<b>2. Total alkali content of coal ash – Na<sub>2</sub>O<sub>Σ</sub> [%]</b> [2, 5] analytical determination: Na <sub>2</sub> O <sub>Σ</sub> = (Na <sub>2</sub> O + 0.6589 K <sub>2</sub> O)% Application: all coals	Same as 1.		
<b>3. Total alkali content on coal – Na<sub>2</sub>O<sub>eq</sub> of coal</b> [2, 5] analytical determination: Na <sub>2</sub> O <sub>eq</sub> of coal = (Na <sub>2</sub> O + 0.6589 K <sub>2</sub> O) $\frac{\text{Ash}}{100}$ [%] Application: coals with bituminous type ash	Na <sub>2</sub> O <sub>eq</sub> of coal [%]	Fouling	
	<0.3	Low	
	0.3-0.45	Medium	
	0.45-0.6	High	
	>0.6	Severe	
<b>4. Fouling factor – R<sub>f</sub> (R<sub>f</sub>)</b> [2, 5] analytical determination: $R_f = \frac{B}{A} \text{Na}_2\text{O} [\%]$ in ash $R_f = \frac{B}{A} \text{Na}_2\text{O} [\%]$ water soluble/low temperature ash Application: R <sub>f</sub> – coals with bituminous type ash R <sub>f</sub> – coals with lignitic type ash	R <sub>f</sub>	R <sub>f</sub>	Fouling
	<0.2	<0.1	Low
	0.2-0.5	0.1-0.25	Medium
	0.5-1	0.25-0.7	High
	>1	>0.7	Severe
<b>5. Chlorine content of coal – Cl [%]</b> [2]  Application: all coals	Cl of coal [%]	Fouling	
	>0.2	Low	
	0.2-0.3	Medium	
	0.3-0.5	High	
	>0.5	Severe	

Total alkali content of coal ash: Influence of alkali metals (sodium and potassium) on the fusibility and deposition propensity increases in proportion to their contents in the ash.

The total alkali content on coal (Na<sub>2</sub>O<sub>eq</sub>) of coal is more meaningful than the previous indicator, since it takes into account the total quantity of alkali compounds entering the furnace per mass unit of fuel.

The fouling factors R<sub>f</sub> and R<sub>f</sub> are parameters empirically developed to correlate the chemical tests on small laboratory samples of fuel to the tendency of fuel ash to form alkali bonded deposits on convection surfaces, especially on superheaters and reheaters surfaces that are not exposed to radiant heat from the furnace.

The chlorine content (Cl) of coal has been used as an indication of easily volatilized sodium and potassium present in coal.



**Criteria analysis**

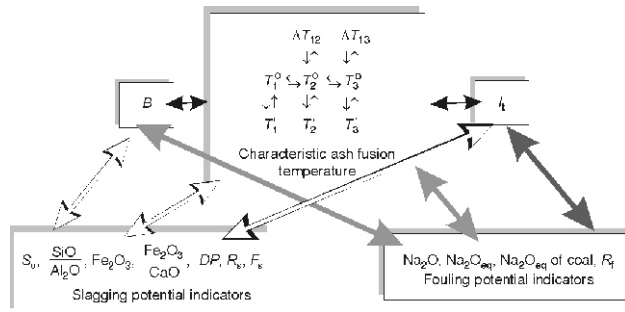
The foregoing criteria and the suggested limits (tabs. 2 and 3) are developed for North-American and British coals. The correlative analysis was performed for the investigated coals with the intention to define the possibility of utilization of foregoing criteria and with special attention to the limits of validity.

A correlative analysis has been performed with respect to the three most widely accepted criteria (fig. 1):

- the fusion temperature,
- the base number (*B*), and
- the fusibility index (*I<sub>f</sub>*)

The mutual dependence analysis were done and presented in tab. 4.

The shaded cells represent a lack of functional dependence between the corresponding criteria, or their insufficient sensitivity. For the criteria with established functional dependence (labeled with numbers in tab. 4) the detailed analysis is presented in following chapters.



**Figure 1. Scheme of correlative analysis**

**Table 4. Schematic review obtained from the mutual dependence analysis**

	<i>T<sub>2</sub></i>	<i>B</i>	<i>I<sub>f</sub></i>	<i>B/A</i>	<i>S<sub>0</sub></i>	SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> /CaO
<i>T</i>	3.1	3.3						
<i>B</i>	3.2		3.4	3.6	3.8		3.10	
<i>I<sub>f</sub></i>		3.5		3.7	3.9		3.11	
	<i>PD</i>	<i>R<sub>s</sub></i>	<i>F<sub>s</sub></i>	Na <sub>2</sub> O	Na <sub>2</sub> O <sub>eq</sub>	Na <sub>2</sub> O <sub>eq</sub> of coal	<i>R<sub>f</sub></i>	
<i>T</i>								
<i>B</i>	3.12	3.14						
<i>I<sub>f</sub></i>	3.13	3.15						

It is important to emphasize that the criteria “temperature at 250 poise” (*T<sub>250</sub>*) and “chlorine content of coal” (*Cl*) were not the subject of the analysis, for none of 132 coal samples which comprise the database for the analysis met the conditions of the *T<sub>250</sub>* criterion, and the chlorine content data were not available.

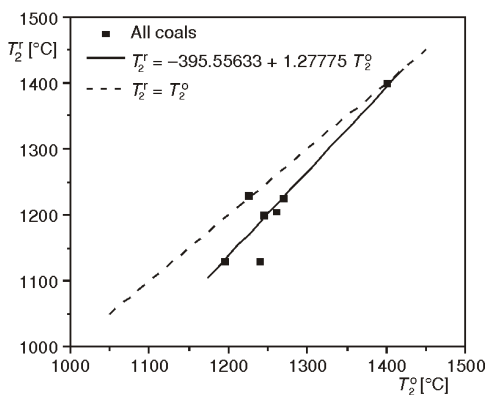
*Ash fusion temperatures analyses*

Although it is recommended for engineering calculations to use fusion temperatures determined in reducing atmosphere, the ash fusibility data for investigated coals mostly refer to oxidizing atmosphere. Out of 132 coal samples, only 7 had the values of temperatures deter-

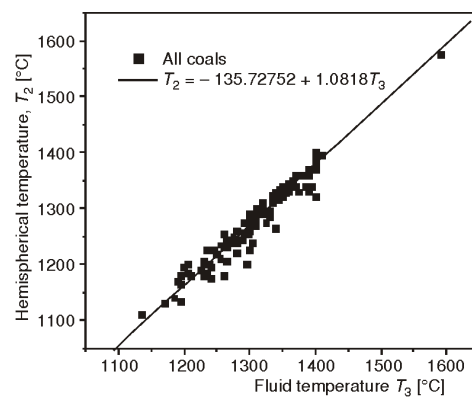
mined both in oxidizing and in reducing atmospheres. Notwithstanding this small number of samples, an effort has been made to establish the link between these temperatures (fig. 2).

The hemispherical temperature  $T_2$  has been chosen to represent ash fusion temperatures for the following reasons:

- the initial deformation temperature  $T_1$  is not sensitive enough to the aforementioned three criteria;
- the fluid temperature  $T_3$ , often used as representative in Serbian practice [8] dealing with slagging problems, has been determined less precisely, due to the inability to measure temperatures above 1400 °C.



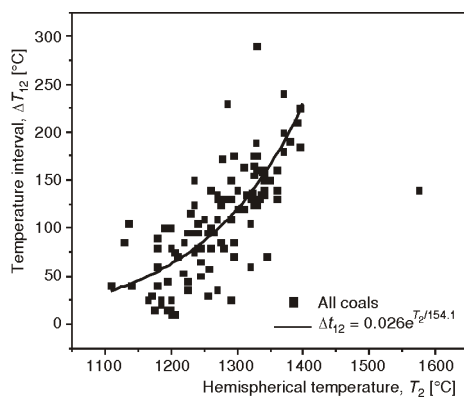
**Figure 2. Dependence between ash fusion temperatures determined in oxidizing and reducing atmospheres**



**Figure 3. Dependence between fluid and hemispherical temperatures**

The diagram in fig. 2, disregarding the small number of samples and the inability to measure temperatures above 1400 °C, is important, since it shows the tendency of temperatures determined in oxidizing and reducing conditions to equalize with their increase.

Additionally, the linear dependence between fluid –  $T_3$  and hemispherical –  $T_2$  temperatures is established (fig. 3) and the linear dependence is obtained:



**Figure 4. Dependence between hemispherical temperature and characteristic temperature interval**

$$T_2 = -135.7275 + 1.0818 T_3 \quad (1)$$

which confirms that adopting of hemispherical temperature as representative fusion temperature as representative fusion temperature was justified.

On fig. 4, an exponential dependence of the temperature interval  $\Delta T_{12} = T_2 - T_1$  and the hemispherical temperature –  $T_2$  is given. For this analysis the values of  $T_2$  equal to 1400 °C have not been taken into consideration. However, a significant dispersion of data around the dependence can be spotted and therefore this interval has not been used for any analyses further on.

*The dependence of the ash fusion temperature and the base number,  $T = f(B)$*

The correlation between ash fusion temperature and the base number of referred coals is shown on fig. 5. The characteristic shape of this correlation with minimum base number value 35-55% is noticeable. The dependence  $T_2 = f(B)$  could be presented with polynomial expression of the 6<sup>th</sup> order (fig. 5):

$$T_2 = 30041 - 235.38B + 13.262B^2 - 0.3985B^3 - 0.0066B^4 - 5.6716 \cdot 10^{-5}B^5 + 1.98913 \cdot 10^{-7}B^6 \quad (2)$$

Coal samples from mine Kosovo and Ugljevik, which are otherwise known to have a tendency to slagging, are positioned in the curve's minimum, while the Kostolac and Kolubara samples are mainly located on the rising part of the curve.

Although there is a distinct grouping of data points around the curve  $T = f(B)$ , there exists a significant dispersion of data. Nevertheless, based on this diagram the additional dependence has been determined.

*The dependence of the base number and the ash fusion temperature,  $B = f(T) = B_T$*

Based on the presented on fig. 5, the limits of the base number as a function of ash fusion temperature ( $B = f(T) = B_T$ ) are given in tab. 5.

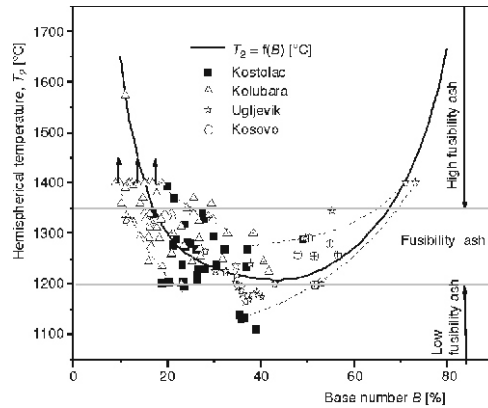
This analysis could be associate with the range limits of the ash fusion temperature criterion from the review of criteria (tab. 2) and the following conclusions could be made:

- Coals having the ash fusion temperature lower than 1200 °C can be classified as high-slagging coals, notwithstanding the base number; the majority of these coals has the base number in the range of 34 to 52%;
- Coals with ashes characterized by base number  $B < 17\%$  or  $B > 67\%$  can be referred to as coals not inclined to slagging, or as low-slagging coals;
- For  $B = 17-34\%$  and  $B = 52-67\%$ , coals are medium slagging.

*The dependence of the fusibility index and the base number,  $I_t = f(B)$*

The dependence  $I_t = f(B)$  is represented with an exponential curve (fig. 6):

$$I_t = 25.154e^{\frac{B}{4}} - 12.25e^{\frac{B}{16}} \quad (3)$$



**Figure 5. Ash fusion temperature as a function of base number**

**Table 5. Suggested limits of the base number as a function of ash fusion temperature**

$B_T$ [%]	Slagging
34-52	High
17-34 and 52-67	Medium
<17 and >67	Low

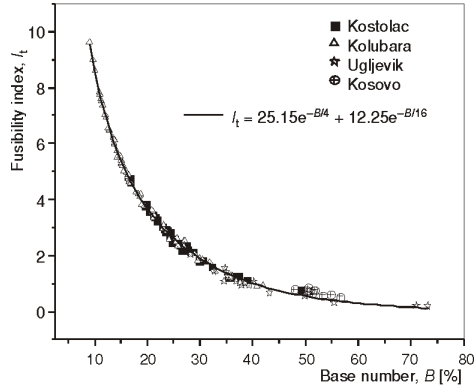


Figure 6. The dependence of the fusibility index and the base number,  $I_t = f(B)$

Table 6. Suggested limits of the base number as a function of the fusibility index

$B_{I_t}$ [%]	Slagging
34-67	High
26-34	Medium
<26	Low

Table 7. Suggested limits of the base number

$B$	Slagging
34-67	High
17-34	Medium
<17 and >67	Low

This regular grouping of points around the curve could be explained with the definition of the fusibility index:

$$I_t = \frac{\frac{\text{SiO}_2}{B} + \frac{\text{Al}_2\text{O}_3}{B}}{\frac{A}{B} + \frac{\text{TiO}_2}{B} + \frac{A}{B}} \quad (4)$$

since titanium-oxide content in ash is usually lower than 1%.

*The dependence of the base number and the fusibility index,  $B = f(I_t)$*

Based on the previously defined dependence (3) and the range limits of the fusibility index criterion from the review of criteria (tab. 2), recommended values for the base number as a function of the fusibility index ( $B = f(I_t) = B_{I_t}$ ) are obtained and presented in tab. 6.

The limits for  $B_{I_t}$  are such that (fig. 5):

- for  $B < 26\%$ , coals do not show a significant inclination towards slagging, but a vast number of samples can be classified as medium fusible ashes,
- for  $26\% < B < 34\%$ , almost all samples are in the range of medium fusible ashes and therefore there is an ideal match,
- for  $34\% < B < 67\%$ , there are not only high-slagging but also medium-slagging coals, and
- for  $B > 67\%$ , coals are not prone to slagging, which shows an ideal match with the range limits for the  $I_t$  criterion.

Base number values given in tabs. 5 and 6 have been determined using two commonly accepted criteria: ash fusion temperature (base number  $B_T$ ) and fusibility index (base number  $B_{I_t}$ ). By coupling these two criteria, in the way that low slagging region is more narrow to  $B < 17$  and  $B > 67$ , and high slagging region is widened to  $34 < B < 67$ , a more “strict” combined criterion  $B_c$  is obtained, which satisfies both ash fusion temperature and fusibility index criteria. The final range limits for the base number are given in tab. 7.

*Base to acid ratio dependence of the base number,  $B/A = f(B)$*

Often, instead of the base number, the ratio of base-to-acid oxides is used. On fig. 7, an exponential dependence  $B/A = f(B)$  is given:

$$\frac{B}{A} = 0.1137e^{\frac{B}{19.5}} \quad (5)$$

The dispersion of data from the curve  $B/A = f(B)$  is bigger if coal ash contains more sulphur oxides, which is the case with coals from Ugljevik and Kosovo mines.

*Base to acid ratio – fusibility index dependence,  $B/A = f(I_t)$*

The function  $B/A = f(I_t)$  is approximately equal to the reciprocal value of the fusibility index (fig. 8):

$$\frac{B}{A} = \frac{1}{0.08867 I_t} \quad (6)$$

*Silica ratio – base number dependence,  $S_o = f(B)$*

Silica ratio – base number dependence ( $S_o = f(B)$ ) is given on the total interval of base number values (fig. 9):

$$S_o = f(B) = 9.485 - 84e^{-\frac{B}{8}} + 148e^{-\frac{B}{27}} \quad (7)$$

and for  $B < 40\%$  the curve  $S_o = f(B)$  has a linear function:

$$S_o = 105.68762 - 1.63736B \quad (8)$$

The dissipation of the values for coal samples Ugljevik and Kosovo could be explained with high CaO content in ash.

*Silica ratio – fusibility index dependence,  $S_o = f(I_t)$*

As opposed to the previous diagram, where there are significant deviations for  $B > 40\%$ , the curve  $S_o = f(I_t)$  from the following diagram (fig. 10) describes this range quite well:

$$S_o = f(I_t) = 87.8 \frac{1081.1}{1 + e^{\frac{I_t - 5.59}{2.13}}} \quad (9)$$

Since the dependences  $S_o = f(B)$  and  $S_o = f(I_t)$  are distinctly shown on the total number of investigated samples (all 132 samples together), this criterion can be applied to all coals without restrictions.

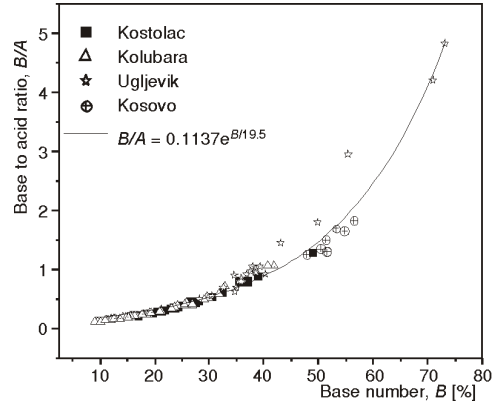


Figure 7. Base to acid ratio dependence of the base number,  $B/A = f(B)$

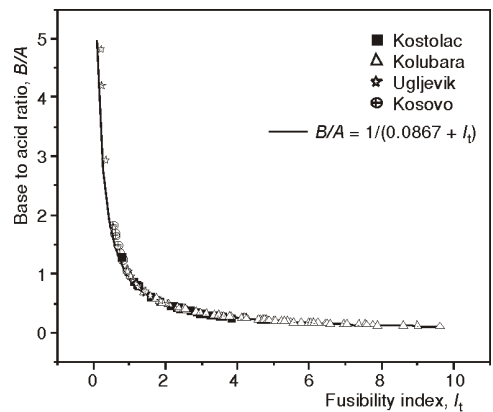


Figure 8. Base to acid ratio – fusibility index dependence,  $B/A = f(I_t)$

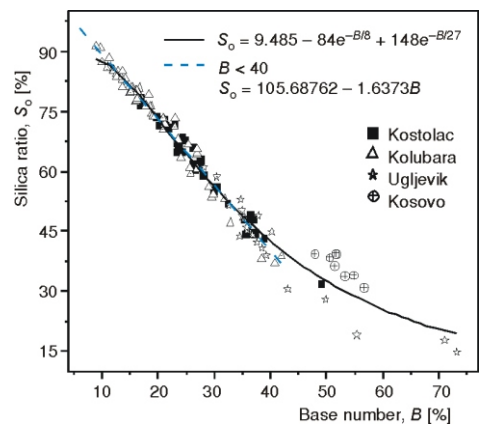


Figure 9. Silica ratio – base number dependence,  $S_o = f(B)$

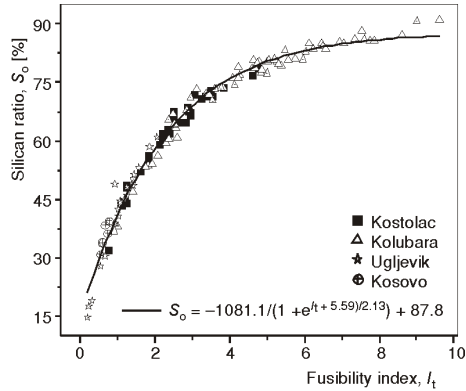


Figure 10. Silica ratio – fusibility index dependence,  $S_o = f(I_t)$

Table 8. Suggested limits of the fusibility index, the base to acid ratio and the silica ratio

$I_t$	$B/A$	$S_o$	Slagging
0.2-1.5	0.64-3.5	21-50	High
1.5-4.6	0.24-0.64	50-78	Medium
>4.6 and <0.2	<0.24 and >3.5	<21 and >78	Low

Based on obtained critical base number values and on clearly shown functional dependences of  $B$ ,  $I_t$ , and  $S_o$ , given in relations (3), (5), and (7), corrected critical values for the mentioned criteria have been obtained (tab. 8).

#### Iron oxide of ash – base number dependence, $Fe_2O_3 = f(B)$

The database for the next diagram (fig. 11) consists of coals with ashes having calcium and sodium oxides contents ( $CaO$  and  $Na_2O$ ) lower than 7.5% and 2.5% in the ash, respectively.

Using the suggested limits from the review of criteria, the coals having  $Fe_2O_3$  content in the range between 3 and 8% can be principally classified as low slagging coals. The coals that meet this condition have base numbers lower than 19% ( $B < 19\%$ ).

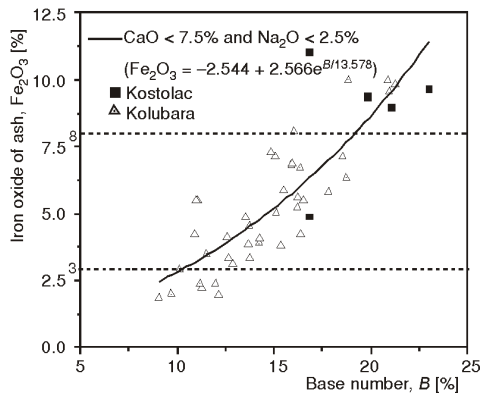


Figure 11. Iron oxide of ash – base number dependence,  $Fe_2O_3 = f(B)$

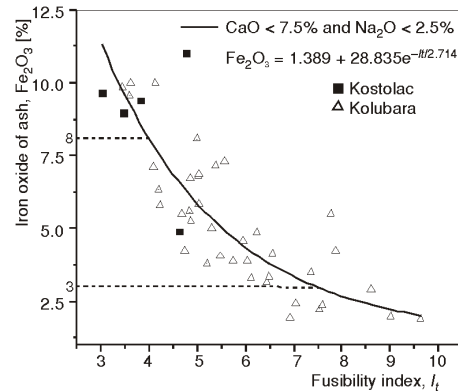


Figure 12. Iron oxide of ash – fusibility index dependence,  $Fe_2O_3 = f(I_t)$

#### Iron oxide of ash – fusibility index dependence, $Fe_2O_3 = f(I_t)$

The database for the diagram (fig. 12) is the same as for the previous diagram.

Same as in the previous diagram, the coals having  $Fe_2O_3$  content in the range between 3 and 8% can be principally classified as low slagging coals. The coals that meet this condition have fusibility index between 4 and 8 ( $4 < I_t < 8$ ).

*Dolomite percentage – base number dependence,  $DP = f(B)$*

The criterion dolomite percentage ( $DP$ ) is applied in the range  $40 < DP < 98\%$  and for  $B > 40\%$ , which is confirmed by the diagram (fig. 13).

Since coals with  $40 < B < 67$  are already classified as high slagging coals, the dependence  $DP = f(B)$  shows that coals with higher  $DP$  have a higher base number, and according to the diagram  $T = f(B)$  (fig. 5) also have a higher ash fusion temperature, and therefore have a lower propensity for slagging. This means that this criterion can be used for comparison of heavy slagging coals.

*Dolomite percentage – fusibility index dependence,  $DP = f(I_t)$*

From the diagram in fig. 14, it can be definitely concluded that coals with  $DP > 95\%$ , *i. e.*  $I_t < 0.2\%$ , are not prone to slagging.

*Slagging factor – base number dependence,  $R_s = f(B)$*

The database for figs. 15 and 16 is made of coals with bituminous type ashes, which account for only 12% of the total sample. Since the range for the criteria “base number” and “fusibility index” have been determined from the complete database, the limits of this criterion remain within the original recommendations (tab. 2).

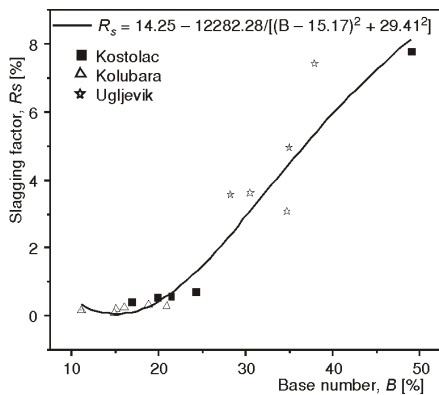


Figure 15. Slagging factor – base number dependence,  $R_s = f(B)$

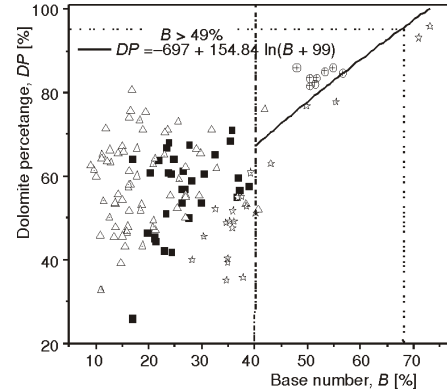


Figure 13. Dolomite percentage – base number dependence,  $DP = f(B)$

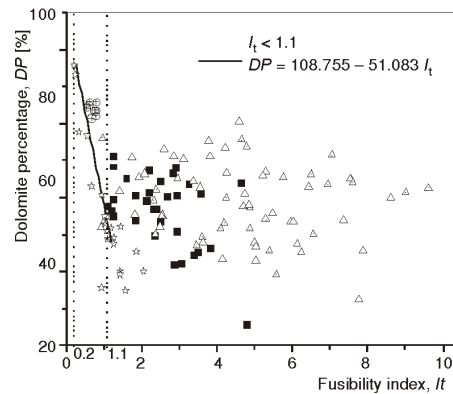


Figure 14. Dolomite percentage – fusibility index dependence,  $DP = f(I_t)$

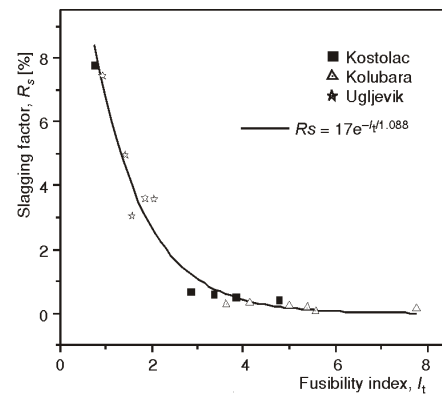


Figure 16. Slagging factor – fusibility index dependence,  $R_s = f(I_t)$

### Slagging factor – fusibility index dependence, $R_s = f(I_f)$

Dependence  $R_s = f(I_f)$  given on fig. 16, as previously noted, is formed on a small number of samples, and it should be taken with caution.

### Concluding remarks

The occurrence of deposits is possible, in principle, on all boiler heat transfer surfaces, but their building-up inside boiler furnaces (slagging) has the most serious consequences to its normal operation. These deposits are more difficult to remove, and even thin deposit layers of few millimeters cause a notable decrease of the heat absorbed by the furnace screens, since fused deposits have heat conductivities similar to good insulation materials. The combustion products temperatures along the boiler are hence increased, and so is the emission of pollutants into the atmosphere. The metal of convective heat transfer surfaces is superheated, which shortens their lifetime. Cleaning of the deposits which have caused a critical downfall of the heat absorbed in the furnace can very often be done only manually, during stoppages, which has a negative influence on the availability, *i. e.* economical operation of the facility.

The formation of deposits is inevitable, since any economically justified process for mineral matter removal from the coal prior to combustion in the boiler does not exist. Therefore deposit formation can only be alleviated and put under control by adequate designing of the boiler and its regimes of operation, respecting, among other parameters, the propensity of coals to form deposits.

Based on the results of correlative analyses of investigated lignites, it has been determined that a distinct functional dependence exists between the criteria  $B$ ,  $B/A$ ,  $I_t$  and  $S_o$  (relations (3), (5-9)). The limits for the application of these criteria are in accordance, and therefore any of these four criteria can be used for the assessment of the slagging tendency of investigated lignites.

Coals with ashes characterized by  $\text{CaO} < 7.5\%$  and  $\text{Na}_2\text{O} < 2.5\%$ , and at the same time  $3 < \text{Fe}_2\text{O}_3 < 8\%$ , are not prone to slagging.

The criterion  $DP$  (dolomite percentage) is applied only for  $B > 40\%$ , and is used for comparison of heavy slagging coals, in the way that coals with higher  $DP$  are less inclined to slagging.

The slagging factor  $R_s$  is valid only for coals with bituminous type ash and should be used in “original” limits.

All analyses carried out with reference to the characteristic ash fusion temperature or characteristic temperature intervals show a large dispersion of results around the determined functional dependences.

The criteria for the assessment of fouling potential do not show any dependence or sensitivity enough to the criteria “base number”, “fusibility index” and “ash fusion temperature”, which could have been expected, since these three criteria refer to coal slagging potential. As an appropriate criterion for the assessment of coal fouling potential, the criterion “total alkali content in the ash” should be taken, because it takes into account the influence of  $\text{K}_2\text{O}$  (potassium oxide) on the fouling process.

The application of these criteria enables coals to be classified as light, medium and heavy slagging/fouling. In this way, information can be obtained, which can be useful both to experts at power plants in operational conditions, and to designers, during boiler design or reconstruction.

Based on the 132 samples from 4 coal open pit mines, it can be concluded that:



lignitic-type-ash coals account for 88% of the database, Kolubara coals, although with chemical composition varying in a very wide range, are not prone to heavy slagging, Kostolac coals can be high slagging, although the majority of these are medium slagging, coals from Ugljevik and Kosovo fields are basically prone to slagging, and examined coals, due to low Na<sub>2</sub>O content, are not in general prone to fouling of boiler heat transfer surfaces.

These conclusions are consistent with the conclusions from the domestic literature [7-11].

The fact whether a coal is going to form slag or foul the convective sections depends not only on the chemical composition of its ash and on the ash fusion temperature, but also on the combustion conditions, that is thermal and flow conditions in the boiler. However, if data are not available, and if measurements on the boiler itself can't be done, which is the case with new fields (coal mines) and during boiler design, the utilization of the adopted criteria still represents the most acceptable method for getting an information about the propensity of the coal ash to form deposits on heat transfer surfaces.

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