QUALITATIVE ANALYSIS OF COAL COMBUSTED IN BOILERS OF THE THERMAL POWER PLANTS IN BOSNIA AND HERZEGOVINA

by

Slavko N. DJURIĆ [a*], ***Petko Č. STANOJEVIĆ*** [b], ***Dragan B. DJURANOVIĆ*** [b], ***Saša D. BRANKOV*** [a], **and *Srdjan M. MILAŠINOVIĆ*** [c]

[a]Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia
[b]Faculty of Transport and Technical Sciences, University of East Sarajevo, Doboj, Bosnia and Herzegovina,
[c]High Business Technical School, Doboj, Bosnia and Herzegovina

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In this paper we have looked into the qualitative analysis of coals in Bosnia and Herzegovina. The analysis includes the following characteristics: moisture, ash, combustible matter and lower heating value. From the statistic parameters we have determined: absolute range, arithmetic mean, standard deviation and variations coefficient. It has been shown that the coal characteristics have normal distribution. The analysis show that there are considerable deviations of ash characteristics: moisture (36.23%), ash (34.21%), combustible matter (16.15%), and lower heating value (25.16%) from the mean value which is shown by the variations coefficient. Large oscilations of mass portions: W, A, V^g, and H_d around the mean value can adversely influence the function of a boiler plant and an electric filter plant in thermal power plants in Bosnia and Herzegovina in which the mentioned types of coal burn. Large ash oscilations (34.21%) around the mean value point out to the inability of application of dry procedures of desulphurisation of smoke gasses due to the additional quantity of ash. It has been shown that the characteristics of Bosnian types of coal do not deviate a lot from the characteristics of coal in the surrounding countries (coals of Serbia and Montenegro). The results can be used in analysis of coal combustion in thermal power plants, optimisation of electrical-filtre, reduction of SO_2 in smoke gas, and other practical problems.

Key words: *coal, thermal power plant, qualitative analysis*

Introduction

Installed power in the four thermal power plants in Bosnia and Herzegovina (B&H) for the production of electricity is 1957 MW with the production of about 8300 GWh or 60.6% of total produced electricity (tab. 1). From tab. 1 can be seen that the blocks installed in (B&H) have been used mainly between 25 and 30 years, some over 40 years. In normal circumstances, for these blocks, a question of replacement can be raised. The basic criteria for such decision, apart from the price of capital, are the prognosis of market situation of electricity (placement and price), prognosis of production expenses (energetic efficiency of a plant and the price of fuel), as

* Corresponding author; e-mail: djuricns@uns.ac.rs

well as meeting the conditions of the minimal effect of the plant to the environment [1, 2]. Industrial testings of electric filter plants in the observed thermal power plants show large emissions of sulphur oxides and emission of ash into the atmosphere [3].

Table 1. Basic data on thermal power plants in B&H [3, 4]

Thermal power plants	Operating from	Type of coal*	Installed power, [MW]	Available power, [MW]
Tuzla	1964	LM	779	671
Kakanj	1956	M	578	486
Gacko	1983	L	300	265
Ugljevik	1985	M	300	268
Total			1957	1690

* M – brown coal, L – lignite, LM – lignite and brown coal

Coals that combust in the boiler plants of thermal power plants in B&H are bad quality (large quantity of sulphur, moisture, and ash) (fig. 1 and tab. 2).

Figure 1. Map of mines and thermal power plants in B&H

In the revitalisation process, thermal powerplants in B&H will have to adjust to the new quality of coals which is in reality very often a mixture (homogenisation) of coals [5, 6]. In that aspect the aim of this article is the qualitative analysis of coals combusted in boilers of thermal power plants in B&H. Analysis should determine the quality of used coals and the possibility of application of obtained results in practice (coal homogenisation, electric filter optimisation, reduction of SO_2 in smoke gasses, designing devices for desulphurisation of smoke gasses (FGD), *etc.*). In the qualitative analysis of coals in B&H, the following characteristics are included: moisture, ash, combustible matter, and lower heating value.

Table 2. Characteristics of Bosnian coals [4, 7, 8]

Characteristics of coal	Kreka	Uglje-vik	Gacko	Stanari	Zenica	Banovići	Breza	Kakanj	Mostar
	Proximate analysis [wt.%]								
Moisture, W	35.00	32.20	41.14	50.00	25.30	35.50	20.00	15.10	21.93
Ash, A	16.48	9.21	11.76	9.80	18.18	20.98	14.72	26.25	19.11
Total sulphur, S_u	0.44	5.28	1.02	0.15	3.36	0.91	2.67	1.75	4.40
Coke, K	39.85	37.69	30.63	25.50	44.48	43.07	48.00	-	46.33
Fixed carbon, C_{fix}	21.37	28.48	18.87	15.63	26.30	22.09	33.28	-	27.22
Volatile, $V_{vol.}$	25.12	30.11	27.07	24.50	30.22	21.43	32.00	29.90	31.74
Combustible, V^g	48.52	58.59	45.94	40.20	56.22	43.52	65.28	58.65	58.96
Upper heat value of coal, H_g, [kJkg^{-1}]	13506	17364	11078	10874	16262	13007	19562	19578	16208
Low heat value of coal, H_d, [kJkg^{-1}]	12060	15709	9491	9100	14943	11575	18266	18469	15343
	Ultimate analysis [wt.%]								
Carbon, C	31.37	39.32	27.96	26.00	39.29	31.70	47.30	43.60	39.89
Hydrogen, H	2.54	3.78	2.48	2.33	3.05	2.42	3.54	4.30	3.20
Combustible sulphur, S_{com}	0.17	3.46	0.37	0.07	2.41	0.50	2.07	-	-
Nitrogen + oxygen, N+O	12.08	12.03	15.23	11.81	11.77	8.90	12.37	9.00	12.67

Qualitative rating of coal characteristics in B&H

Of the statistic parameters we have determined [9-11]:

(1) absolute range $R = \max. X_i - \min. X_i, (i = 1, 2, 3, ..., n)$ (1)

(2) arithmetic mean $$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, \quad \text{or} \quad \overline{X} = \frac{1}{n}\sum_{i=1}^{n} f_i X_i \tag{2}$$

(3) standard deviation $$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2}, \quad \text{or} \quad S = \sqrt[n]{\frac{1}{n-1}\sum_{i=1}^{n} f_i (X_i^* - \overline{X})^2} \tag{3}$$

(4) variation coefficient $$C_V = \frac{S}{\overline{X}}100 \tag{4}$$

where n is the number of elements of sample characteristics, X_i – the value of considered coal characteristics, and X_i^* – the mean interval of coal characteristics.

Pearson's χ^2 criterium will check whether the coal samples are in concordance with the assumption that a random variable (coal characteristics) X has the function of distribution $F(x)$ (normal distribution), or the deviations are large so the assumption has to be discarded. When determining the value of Pearson's χ^2 criterium, the following is used:

$$k = 1 + 3.3\log n \tag{5}$$

$$i = \frac{R}{k} \tag{6}$$

$$u_i = \frac{X_i - \overline{X}}{S} \tag{7}$$

$$\Phi(u_i) = \frac{1}{\sqrt{2\pi}} \int_0^{u_i} e^{-t^2/2} dt \tag{8}$$

$$p_i = P(X_{i-1} < X < X_i) = \Phi(u_i) - \Phi(u_{i-1}) \tag{9}$$

where k is the number of intervals, i – the size of an interval, p_i – the probability that the random variable $X \in N(\mu, \sigma)$ takes the value in the interval $[X_{i-1}, X_i]$, P – the probability, μ – the mean value of statistic population, σ – the standard deviation of statistic population, u_i – the replacement (alternation) of variables, and $\Phi(u_i)$ – the Laplas function.

Testing of the mean values of coal characteristics has been carried out by using Student's t test at the level of significance (risk) $\alpha = 0.05$ and the following expressions have been used:

$$l = n - 1 \tag{10}$$

$$\left[\overline{X} - \frac{t_{n-1,\alpha}}{\sqrt{n-1}} S; \quad \overline{X} + \frac{t_{n-1,\alpha}}{\sqrt{n-1}} S \right] \tag{11}$$

where l is the number of degrees of freedom, $t_{n-1,\alpha}$ – the variable which is determined from the table for Student's distribution at the selected level of significance (trust) α, and for the degree of freedom $l = n - 1$.

By using numerical values of coal characteristics from tab. 2 and the expressions from (1) to (4) the calculation of some parameters for coal characteristic „moisture" is:

$$R = \max.X - \min.X = 50.00 - 15.10 = 34.90\%$$

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i = \frac{35.00 + 32.20 + \ldots + 15.10 + 21.93}{9} = 30.69\%$$

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2} = \sqrt{\frac{(X_1 - \overline{X})^2 + (X_2 - \overline{X})^2 + \ldots + (X_9 - \overline{X})^2}{9-1}} =$$

$$= \sqrt{\frac{(35.00 - 30.69)^2 + (32.20 - 30.69)^2 + \ldots + (15.10 - 30.69)^2 + (21.93 - 30.69)^2}{8}} = 11.12$$

$$C_V = \frac{S}{\overline{X}} 100 = 36.23\%$$

In tab. 3 the statistical results of calculation for the coals of B&H are shown.

Variations coefficient (C_v) points out to deviations of the observed coal characteristics from the mean value. The largest deviation from the mean value refers to the coal characteristic moisture (W) and it is 36.23 % and ash (A) of 34.21%. This points out to larger oscillations of mass contents of ash and moisture in coals of B&H which can adversely influence the function of a boiler plant and an electric filter plant in thermal power plant objects such as power plants.

Table 3. Qualitative characteristics of Bosnian coals

Coal characteristics	Statistic parameters			
	R	$\overline{X}$	S	C_V [%]
W, [%]	34.90	30.69	11.12	36.23
A, [%]	17.04	16.28	5.57	34.21
V^g, [%]	25.08	52.88	8.54	16.15
H_d, [kJkg^{-1}]	9369.00	13884	3493.72	25.16

According to expressions (5) to (11) for the feature (characteristic) of coal „moisture“ the calculation of certain parameters is:

$$k = 1 + 3.3 \log n = 1 + 3.3 \log 9 = 4.15 \approx 4$$

$$i = \frac{R}{k} = \frac{34.90}{4} = 8.73$$

The lowest value of standardised variable $u_i = (X_i - \overline{X})/S = (15.10 - 30.69)/11.12 = -1.40$ has been replaced with $-\infty$, and the largest value of standardised variable $u_i = (X_i - \overline{X})/S = (50.00 - 30.69)/11.12 = 1.74$ with $+\infty$ since the random variable $X \in N(\mu, \sigma)$ has been defined in the interval $(-\infty, +\infty)$. All the calculations have been arranged and shown in tab. 4.

Table 4. Result of calculations for the feature (characteristic) of coal „moisture“

Intervals $[X_{i-1}, X_i]$, [%]	Centre of interval x_i^*, [%]	Frequencies f_i	$X_i^* - \overline{X}$, [%]	Normed intervals $[u_i, u_{i-1})$	$p_i = \Phi(u_i) - \Phi(u_{i-1})$	np_i	$(f_i - np_i)^2$	$\frac{(f_i - np_i)^2}{np_i}$
[15.10;23.83]	19.465	3	–11.225	(–∞;–0.62)	0.2676	2.4084	0.3500	0.1453
[23.83;32.56]	28.195	2	–2.495	[–0.62;0.17	0.2999	2.6991	0.4887	0.1811
[32.56;41.29]	36.925	3	6.235	[0.17;0.95	0.2614	2.3526	0.4191	0.1781
[41.29;50.02	45.655	1	14.965	[0.95;+∞]	0.1711	1.5399	0.2915	0.1893
Total Σ	–	9	–	–	1.0000	9	–	$\chi^2_{sr} = 0.6938$

The result we got is $\chi^2_{sr} = 0.6938$. From the tables for the level of significance $\alpha = 0.05$ and number of degrees of freedom $r = k - r - 1 = 4 - 2 - 1 = 1$ ($r = 2$, number of unknown parameters μ and σ), the critical value $\chi^2_{kr} = \chi^2_{0.05;1} = 3.84$ can be found. Since $\chi^2_{sr} < \chi^2_{kr}$ the assumption on normal distribution of coal characteristic „moisture" can be adopted. In a similar way it can be shown that other coal characteristics (A, V^g, H_d) are liable to normal distribution law. Now, we are going to determine the interval within which the real value of coal characteristic „wetness" with the probability of 95% moves.

For the number of degrees of freedom $l = n - 1$ and the level of significance $\alpha = 0.05$ and from the Sudent's table of distribution it can be seen that $t_{n-1;\alpha} = t_{8;0.05} = 2.31$ *i. e.* according to the expression (11):

$$30.69 - \frac{2.31}{\sqrt{8}}11.12 < \mu < 30.69 + \frac{2.31}{\sqrt{8}}11.12$$

or

$$21.61\% < \mu < 39.77\%$$

For other coal characteristics (A, V^g, H_d) the intervals of reliability are shown in tab. 5. If the mean values of coal characteristics belong to the calculated intervals (tab. 5) then, possible differences $|\bar{X} - \mu|$ can be assigned accidental, otherwise they are significant.

Table 5. Calculation results of determining intervals of reliability for coal characteristics

Coal characteristics	$\bar{X}$	S	$t_{n-1;\alpha}$	$\bar{X} - \frac{t_{n-1;\alpha}}{\sqrt{n-1}}S$	$\bar{X} + \frac{t_{n-1;\alpha}}{\sqrt{n-1}}S$	$\bar{X} - \frac{t_{n-1;\alpha}}{\sqrt{n-1}}S < \mu < \bar{X} + \frac{t_{n-1;\alpha}}{\sqrt{n-1}}S$
W, [%]	30.69	11.12	2.31	21.61	39.77	$21.61 < W < 39.77$
A, [%]	16.28	5.57	2.31	11.73	20.83	$11.73 < A < 20.83$
V^g, [%]	52.88	8.54	2.31	45.91	59.85	$45.91 < V^g < 59.85$
H_d, [kJkg^{-1}]	13884.00	3493.72	2.31	11030.65	16737.35	$11030.65 < H_d <$ < 16737.35

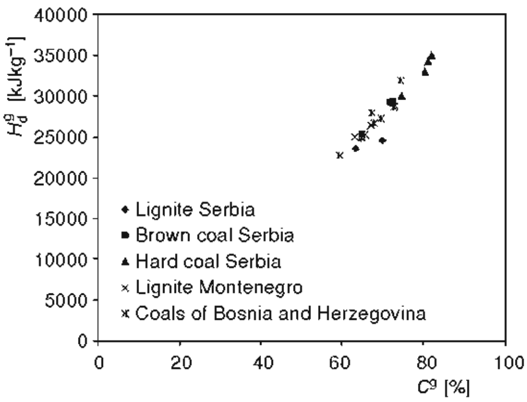

Figure 2. Dependence of upper heating value of coal and carbon reduced to combustible mass

For the purpose of comparing coal characteristics of Bosnian coals to the surrounding coals (Serbia and Montenegro [7, 12]) on fig. 2 to 5 we have shown the dependence of lower heating value of coal, carbon, volatile components and fixed carbon reduced to combustible mass (basis without moisture and ash). It can be seen that coal characteristics in B&H do not deviate a lot from coal characteristics used in furnaces of boiler plants in Serbia and Montenegro, hence, the results can be applied not only on thermal power plants in B&H, but also on the thermal power plants in the surrounding area (Serbia and Montenegro).

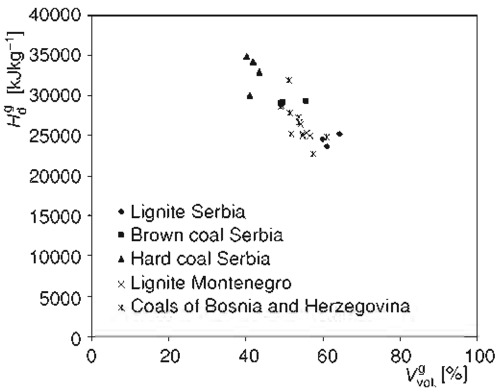

Figure 3. Dependence of upper heating value of coal and volatile components reduced to combustible mass

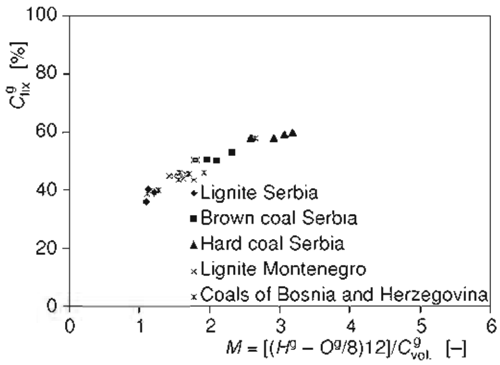

Figure 4. Dependence of fixed carbon and coefficient *M* reduced to combustible mass

Conclusions

By qualitative analysis of characteristics of Bosnian coals it has been shown that it is possible to accept the assumption that the considered coal characteristics (W, A, V^g, H_d) have normal distribution. If the mean values of coal characteristics belong to the calculated intervals (tab. 5) then, possible differences $|\overline{X} - \mu|$ can be assumed to be accidental, otherwise they are significant. The analysis shows that there are significant deviations of considered characteristics: moisture 36.23%, ash 34.21%, combustible matter 16.15%, and lower heating value 25.16% from mean values, which is shown by the variations coefficient C_v (tab. 3). Large oscilations of mass parts of considered coal characteristics around the mean value can adversely influence the function of a boiler plant and an electric filter plant in thermal power plants in B&H. This also points out to inability of application of dry procedures of FGD due to the additional quantity of ash. Unsteadiness of coals quality used in thermal power plants in B-H indicates the need of equalization (homogenisation) of coals quality. Using a blended (homogenised) coal would cause a wide range of positive effects like: increasing a heating value, lowering a moisture, and ash in coal which results in better combusting and more stability in thermal power plant production. This is in concordance with the result of measuring and testing electric filter plants in thermal power plants in B&H and the need for reconstruction of existing and building new thermal blocks for coal.

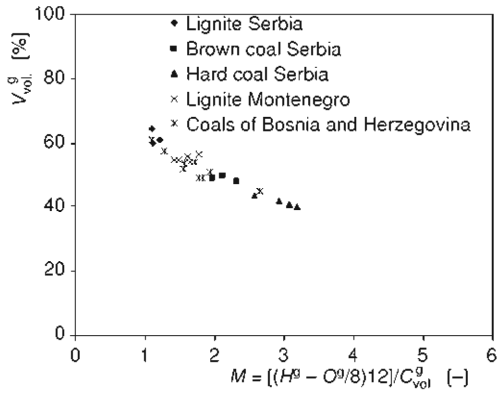

Figure 5. Dependence of volatile components and coefficient *M* reduced to combustible mass

As B&H coal characteristics do not deviate a lot from other coals in the surrounding countries (coals of Serbia and Montenegro) (fig. 2-5), the results can be applied to thermal power plants in Serbia and Montenegro in which lignite burns. This conclusion is in concordance with the testing results and practical measuring.

Nomenclature

A – ash mass content in coal, [%]
C – carbon mass content in coal, [%]
C_{fix} – mass content of fixed carbon in coal, [%]
C_v – variation coefficient, [%]
f_i – frequency, [–]
H – mass portion of hydrogen in coal, [%]
H_d – lower heating value of coal, [kJkg^{-1}]
H_g – upper heating value of coal, [kJkg^{-1}]
i – interval size, [–]
k – number of intervals, [–]
l – number of degrees of freedom, [–]
N – mass portion of nitrogen in coal, [%]
n – number of elements in a sample, [–]
O – mass portion of oxygen in coal, [%]
p_i – probability for random variable to take value within interval (X_{i-1}, X_i), [–]
R – absolute range, [%]
S – standard deviation, [%]
S_u – mass partion of sulphure in coal, [%]
$t_{n-1;\alpha}$ – variable determined from the table for Student's distribution at the selected level of significance (trust) α and the degree of freedom $l = n - 1$
u_i – replacement (alternation) of variables
V^g – combustible matter, [%]
$V_{vol.}$ – mass portion of volatile components in coal, [%]
$\bar{X}$ – arithmetic mean, [%]
X_i – values of considered (features) characteristics of coal, [%]
X_i^* – centres of intervals of coal characteristics, [%]

Greek symbol

$\Phi(u_i)$ – Laplas function, [–]

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