A STUDY ON THE GRINDABILITY OF SERBIAN COALS

by

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Original scientific paper
UDC: 662.933.1
DOI: 10.2298/TSCI1101267R

Thermal power plants in the Republic of Serbia are making considerable efforts and even more considerable investments, not only to maintain electricity production at maximum design levels, but even to additionally increase the power output of existing generating units. Capacities of mills used in pulverized coal preparation are identified as one of the main constraints to achieving maximum mill plant capacity, while coal grindability is seen as one of the factors that directly affect capacities of the coal mills utilized in thermal power plants. The paper presents results of experimental investigation conducted for the purpose of determining Hardgrove grindability index of coal. The investigation was conducted in accordance with ISO 5074 and included analysis of approximately 70 coal samples taken from the open pit mine of Kolubara coal basin. Research results obtained indicate that coal rich in mineral matter and thus, of lower heating value is characterized by higher grindability index. Therefore, analyses presented in the paper suggest that characteristics of solid fuels analyzed in the research investigation conducted are such that the use coals less rich in mineral matter i. e. coals characterized by lower grindability index will cause coal mills to operate at reduced capacity. This fact should be taken into account when considering a potential for electricity production increase.

Key words: *Hardgrove grindability index, mill, coal, mineral matter*

Introduction

Coal is dominant energy source in Serbia, as it is used in power plants for electricity generation. Two open pit mines (Kolubara and Kosovo) with total year production of 35 Mt per year are used for 65% of total electricity production. The energy strategies carried out in last few years emphasized the importance of Serbian lignites utilization in power plants in future. As these lignites are characterized with huge variations in chemical and physical properties, the numerous investigations of coal characteristics and theirs impact on combustion process have been made with the intention to improve energy efficiency in thermal power plants as they are old more than forty years and the important environmental projects (deSO_x and deNO_x) are in the beginning stages (designing and erection).

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The grindability is considered an important coal parameter, particularly useful in the design and operation of coal grinding *i. e*. mill plants. The coal milling facilities utilized in thermal power plants represent a typical example of such plants. Mills installed and operated in thermal power plants in Serbia are fan-type mills, used for grinding of low rank coals (lignite). The coal is ground in terms of achieving a predefined particle size distribution, in order to prepare pulverized fuel to be combusted in the furnaces of the thermal power plant boilers. The operation and capacity of the mills depend on several factors, as specified in expression (1):

$$B_{\max} = k_1 k_2 \frac{n_1^2 D_1^3 b(0.0034 \cdot HGI^{1.25} + 0.61)}{1000\left(\dfrac{R_{5000}}{20}\right)^m \left(\ln\dfrac{100}{R_{90}}\right)^{0.5}} k_3 k_4 \tag{1}$$

According to the expression (1), one of the characteristics that directly affect mill capacity is the grindability of coal. The process of coal pulverization is followed with significant energy consumption [1]. In the same time, the grindability has the important influence on coal burn-out during the combustion process and as consequence has the impact on energy efficiency of the whole plant. Additionally, several investigations have shown the influence between the optimization NO_x emission and the content of unburnt carbon in fly ash [2]. The grindability is determined experimentally, in accordance with standard procedures. It is most commonly expressed in terms of the Hardgrove grindability index (HGI) determined by Hardgrove method designed for high rank coals. In recent years, the possibilities of Hardgorve method utilization for prediction of low rank coal grindability have been the subject of special interest.

Literature review reveals that effects of different factors on coal grindability have been extensively analysed. Most commonly, the analyses were conducted by subjecting the experimentally determined values of the HGI to regression analysis, whereby the HGI was analysed as a function of moisture, ash, volatile matter and fixed carbon content [3-7]. However, there are also other approaches used in the analysis of coal grindability. For example, some researchers analyse coal the HGI as a function of the petrological composition of coal [8, 9] and define certain regression correlations which enable coal grinding behaviour to be predicted.

The investigated coal is very heterogeneous. The petrographic composition of the coal Kolubara is characterized with dominant huminit content, very low clay content, and the carbonate presence is sporadic. The maceral composition is characterized with dominant content of textinite and xylite and practically similar content of atrinite, ulminite, densinite, and gelinite [10].

Anyhow, it is quite clear that coal HGI, as well as experimental procedure used and sample preparation technique applied in determining the index, affects a large number of coal characteristics. For the said reason, in order to be able to compare values of the HGI determined by Hardgrove method for different coals and coal excavation localities, a series of other parameters need to be taken into account, such as proximate and ultimate coal analyses, petrological composition of coal, moisture content, sample condition, *etc*. On the other hand, the coal HGI represents a factor of extreme importance for proper operation of coal mills installed in thermal power plants and hence must be known. In that respect, the main goal of the research conducted was to examine grindability of low rank coals (lignite) combusted in largest thermal power plants in Serbia.

Experimental investigation

The experimental investigation was conducted using the standard Hardgrove apparatus manufactured by EKO-LAB, type 02H/04. The device operation principle is based on the use of a ball mill, equipped with eight 25.4 mm diameter steel balls (fig. 1). Experimental procedure for determining the HGI was determined in accordance with ISO 5074 *i. e*. equivalent national standard SRPS ISO 5074. The method was based on the treatment of pre-prepared coal samples, having particle sizes ranging from 0.6 mm to 1.18 mm. Experiments were performed in the laboratory device under control conditions. The HGI was determined by sieving a 50 g coal sample through a 0.075 mm sieve and subsequently utilizing the equation HGI = 13 + 6.93(50 – m_1), where m_1 is a mass (in gramms) of coal sample residue remaining on the screen of 0.075 mm sieve.

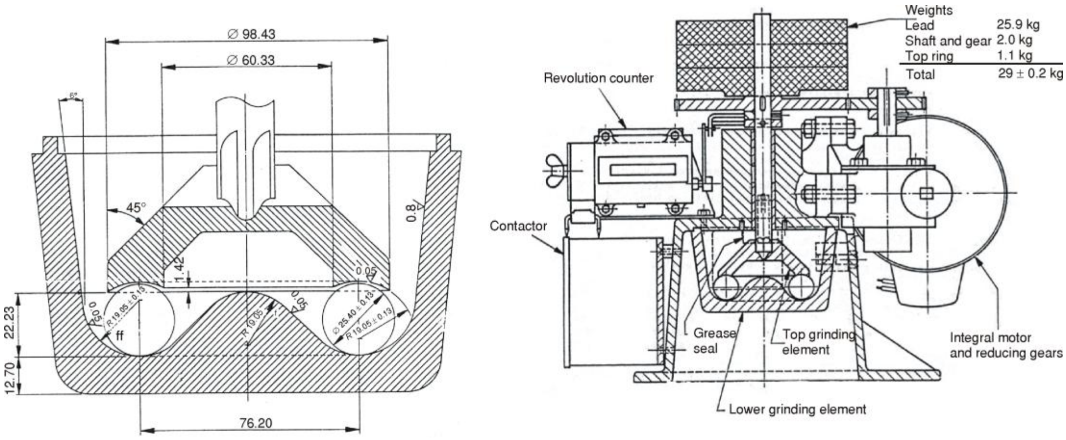

Figure 1. Hardgrove grindability index estimation apparatus

The experiments were performed on 70 coal samples for which respective values of the HGI were determined. Prior to the experiments, all coal samples were dried in ambient air until reaching the equilibrium moisture content. Depending on the meteorological conditions and the condition of initial sample, drying lasted from two to three weeks. Table 1 presents data on representative coal samples.

The samples used in the investigation conducted were split into three groups. The first group, marked A1-A22, included samples of coal combusted in the unit B1 of Thermal Power Plant "Nikola Tesla B" (TENT B), taken directly from the boiler coal feeding line. The second group, marked B1-B19, included samples taken from the coal yards of TENT A and TENT B. The second-group samples were characterized by significantly higher moisture content when compared to the samples of the first group. Finally, the third group of samples, marked C1-C4, included the pieces of dry riddle coal sold under a commercial name *Dried Kolubara*. The third-group of samples were characterized by considerably higher particle sizes compared to the coal samples in the other two groups. For that reason, prior to being grinded in the laboratory mills, the third-group coal samples were crushed in a crusher. All samples were of the same origin *i. e*. the coal excavated from the open pits of „Kolubara" coal mine.

Table 1 shows data on the analysed coal samples, including the values of the HGI obtained.

Table 1. Data on the analysed coal samples

Sample ID	Moisture content in the raw sample, [wt%]	Equilibrium moisture content (testing sample) [wt%]	Ash content [wt%]		Higher heating value [kJkg^{-1}]		HGI
			Dry basis	Testing sample	Dry basis	Testing sample	
A1	50.02	8.33	32.71	29.99	16176	14829	44.2
A2	49.81	8.28	35.39	32.46	16892	15493	44.0
A3	48.17	9.11	37.28	33.88	14447	13131	40.7
A4	49.39	9.28	32.42	29.41	16756	15201	37.9
A5	47.91	8.40	37.03	33.92	15487	14186	40.9
A6	44.46	7.72	46.18	42.61	12117	11182	56.9
A7	56.53	8.75	36.46	33.27	15422	14073	44.9
A8	48.99	8.85	32.74	29.84	15722	14331	40.3
A9	47.41	8.93	38.47	35.03	14292	13016	46.3
A10	47.21	9.16	31.81	28.90	16126	14649	38.7
A11	47.68	9.05	29.76	27.07	17739	16134	42.9
A12	47.43	9.61	30.09	27.20	16285	14720	39.6
A13	49.00	12.54	35.10	30.70	16767	14664	40.9
A14	49.50	11.60	32.28	28.54	17552	15516	37.5
A15	52.60	13.31	21.94	19.02	20323	17618	30.7
A16	52.10	14.90	20.46	17.41	20756	17663	30.7
A17	49.80	11.08	34.26	30.46	17122	15225	40.8
A18	49.70	10.95	32.21	28.68	17421	15513	46.8
A19	50.30	13.56	28.57	24.70	18306	15824	38.1
A20	49.10	9.92	35.95	32.38	16189	14583	41.0
A21	50.60	10.30	31.58	28.33	18142	16273	43.7
A22	51.60	8.60	28.10	25.68	19050	17412	42.8
B1	40.46	7.79	39.28	36.22	16036	14787	45.5
B2	73.14	7.73	32.02	29.54	16783	15486	40.9
B3	90.05	7.78	32.26	29.75	17588	16220	41.8
B4	75.54	6.58	39.90	37.27	15290	14284	48.2
B5	88.21	7.42	34.94	32.35	16819	15571	42.0
B6	78.85	7.62	32.91	30.40	17158	15851	42.0
B7	84.27	8.32	32.36	29.67	16624	15241	41.4
B8	78.64	8.69	31.32	28.60	16854	15389	39.8
B9	92.21	8.34	27.73	25.42	18164	16649	37.1
B10	82.03	8.04	29.72	27.33	18047	16596	39.2
B11	72.69	7.74	28.01	25.84	17733	16360	38.2
B12	81.94	8.04	36.05	33.15	15941	14659	40.1
B13	74.74	8.02	33.17	30.51	16552	15225	39.1
B14	70.20	8.36	32.32	29.62	17211	15772	44.2
B15	75.71	7.19	30.92	28.70	17538	16277	39.7
B16	75.26	7.34	32.86	30.45	17021	15772	41.0
B17	69.79	7.60	35.39	32.70	18570	17159	39.3
B18	57.79	7.84	26.87	24.76	18301	16866	40.4
B19	70.41	7.66	38.53	35.58	16421	15163	38.9
C1	30.99	8.57	15.11	13.82	23986	21930	40.3
C2	39.85	8.08	18.65	17.14	22141	20352	41.7
C3	27.20	9.40	15.41	13.96	23893	21647	40.5
C4	23.38	9.99	13.93	12.54	23510	21161	40.3

Analysis of experimental results obtained

In order to present the findings of the HGI investigation more clearly, the results obtained are graphically presented in figs. 2 and 3.

The results obtained clearly indicate that based on the HGI values determined, coal samples from the A and B sample groups may be considered similar. This conclusion is quite expected having in mind that samples of both groups represented samples of rough Kolubara lignite and that respective coal HGI values were not determined for wet coal samples but for the samples that were dried until reaching the equilibrium moisture content. In the investigation conducted, effect of moisture on the coal HGI was not analysed.

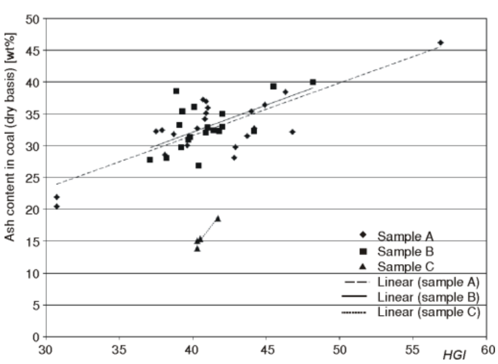

Figure 2. Experimentally determined correlation between HGI and the content of mineral matter in the fuel

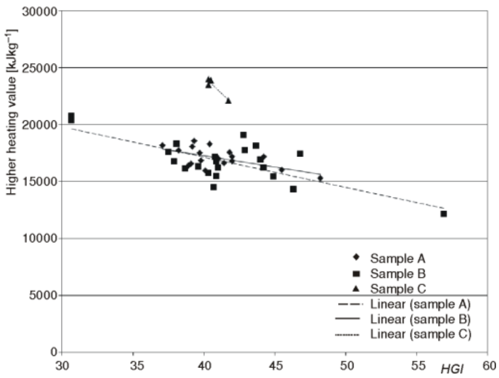

Figure 3. Experimentally determined correlation between HGI and heating value of the fuel

The group C samples were the samples of the so called *Dried Kolubara* dry coal which had been subjected to certain technological processes in order to improve the coal quality. Such treatment enabled a portion of mineral matter in the coal to be eliminated, thus increasing its heating value when compared to the heating value of rough coal delivered and combusted in Serbian thermal power plants. The HGI values determined for the group C samples exhibit different trends when compared to the trends observed for the samples of the group A and B.

The coal under a commercial name *Dried Kolubara* is not used for combustion in thermal power plant boilers. Because considered thermal power plants use closed system of preparation of pulverized, this coal can not be used for the analysis of mill characteristics.

Experiments performed with the samples of Kolubara coal have indicated that respective values of HGI varied from 30.7-56.9. Coal samples were taken in the period from May 2009 to June 2010. Due to such long sampling period the samples taken were considered representative of the current coal quality excavated at Kolubara coal mine. Although the indicated range may be considered quite wide, clearly the HGI values determined for majority of the samples varied over a much more narrow range *i. e.* 37.1-48.2, which is considered typical. The effect of coal HGI on mill operation may be observed from the related change in maximum milling capacity of the fan mill B_{max}. This change is calculated from eq. (1) presented earlier, using the HGI values obtained in the experimental investigation conducted and for all other mill operation parameters unchanged:

$$\frac{B_{\max,1}}{B_{\max,2}} = \frac{0.0034 \cdot HGI_1^{1.25} + 0.61}{0.0034 \cdot HGI_2^{1.25} + 0.61} = \frac{0.0034 \cdot 48.2^{1.25} + 0.61}{0.0034 \cdot 37.1^{1.25} + 0.61} = 1.131 \quad (2)$$

The result obtained indicates that variation of HGI in the range of 37.1-48.2 may cause an increase in the mill capacity of even up to 13.1%. Such change in the capacity of mill plant is considered quite significant. However, since this increase is achieved for the coal of higher HGI and therefore of higher content of mineral matter and lower heating value, it is clear that such increase shall not necessarily cause a proportional (in the same percentage) increase in the electricity production of associated thermal power plant. It should be mentioned that HGI of design coal used for construction of TENT B (the guaranteed quality of the coal) was 56, which is quite high considering the current coal excavation at Kolubara coal mine. Using eq. (2), for tested coal samples, ratio of maximum capacities of coal pulverizer, for the coal samples with HGI range of 37.1-48.2 and guaranteed quality of coal with HGI of 56, can be calculated. This ratio is in the range of 0.815-0.921. This means, that capacity of coal pulverizer, due to lower HGI of currently used lignite coal of Kolubara basin, is reduced for 7.9-18.5%. This data represent very important performance indicatior of the pulverizer.

Results obtained clearly show that the content of mineral matter in the samples significantly affects coal grindability. Coal rich in mineral matters is characterized by lower heating value as well as higher HGI. There are a large number of expressions found in the literature that describe correlations between coal HGI and other coal characteristics. Some of the expressions are presented in tab. 2.

Table 2. Expressions for calculating HGI of certain types of coals, as specified in the literature

Type of coal	Expression*	Correlation coefficient, R	Literature source
Indian coals	*HGI* = 93.25 + W(0.256 + 0.196W) + 3A(1.097 – 0.009A) – – 3VM(1.165 – 0.029VM) – 5FC(1.103 – 0.0166FC)	–	[3]
Turkish coals	*HGI* = 2.532 + 0.487Q + 1.165NM	0.96	[4]
Chinese coals	*HGI* = 95.11266 – 1.869W – 0.9145VM + 0.46A	0.66	[5]
Chinese coals	*HGI* = –167.5 – 10.1W + 4.933A + 2.17VM + 2.55FC + + 1.99W^2– 0.0356A^2 – 0.015VM^2 – 0.0038FC^2	0.76	[5]

* Mass contents: W – moisture, A – mineral matter, VM – volatile matter, FC – fixed carbon, Q – quartz, NM – water and acid-soluble mineral matters

Based on the data shown in tab. 2, it can be concluded that higher content of mineral matter in the coal is linked to higher value of HGI. However, results of investigation presented in [8] indicate that the said is not always the case, *i. e.* that for some types of coal higher content of mineral matter may be associated with lower HGI.

As indicated in tab. 1 and fig. 2, higher content of mineral matter in the analysed samples of Kolubara coal is associated with higher HGI. The statistical analysis of the results obtained yields the following expression illustrating the correlation mentioned:

$$HGI = 1.2160A + 1.5395 \tag{3}$$

whereby the correlation coefficient of experimentally obtained data with the presented linear function equals R = 0.82, which is generally considered acceptable. The eq. (3) shows a correlation between the HGI and the content of mineral matter in coal, but only for the coal excavated from Kolubara mine. The correlation cannot be used to predict the HGI of different coals since it does not take into account effects of other coal parameters (primarily the content of moisture, fixed carbon and volatile matter) which were not considered. The equation primarily qualitatively describes a trend towards higher HGI values associated with higher content of mineral matters in the coal, as observed in the investigation conducted.

Results of grindability investigation carried out on the samples of *Dried Kolubara* coal (samples C1-C4, tab. 1) indicate that pre-treatment of rough coal, which primarily include partial separation of mineral matter, drying, and production of riddle coal, increases the coal heating value, also affecting the coal grindability. Values of HGI obtained for C1-C4 samples were in the expected range, *i. e.* of 40-42. However, the stated values of HGI were recorded for coal samples characterized by quite lower content of mineral matter. For that reason it is concluded that organic part of *Dried Kolubara* coal has significantly better grinding properties then the associated rough Kolubara coal. Such result was also expected having in mind that the treatment of rough coal causes a portion of ligneous matter, known as very difficult or impossible to grind, to be removed from the lignite analysed. However, the trend towards higher HGI values associated with higher content of mineral matters in the *Dried Kolubara* coal is still present.

Conclusions

Based on experimental investigation of HGI of coal, conducted on the large number of samples taken from Kolubara coal mine, the following is concluded:

- The HGI values determined for the analysed samples vary over a relatively wide range (37.1-48.2); the said fact may significantly affect capacities of the mills operating in Serbian thermal power plants firing the coal examined; future design of mill plants should take into account the fact that the obtained values are quite lower than the initially guaranteed values (existing thermal power plants were designed and constructed for the guaranteed coal HGI of 56).
- The experiments have undoubtedly confirmed that higher content of mineral matter in the coal results in higher HGI as well as lower heating value of the fuel; this observation is in accordance with the literature date on the grindability of low rank coals.
- The treatment of rough coal, carried out for the purpose of improving the coal quality, significantly affects, among other things, coal grindability; this was confirmed by experimental results obtained for the samples of *Dried Kolubara* coal for which the equivalent HGI values have been recorded for much lower content of mineral matter in the coal examined; the said observation indicates that better grindability of organic (combustible) matter in the coal is achieved.

Nomenclature

B_{max} – maximum milling capacity of fan mill, [kgs^{-1}]

b – width of impact plate, [m]

D_1 – outer diameter of the mill impact volute, – [m]
HGI – Hardgrove grindability index, [–]
k_1 – milling process coefficient (depends on the type, composition, and structure of coal, content of mineral matter and other factors; it equals k_1 = 4.5-5.5), [–]
k_2 – impact body wear (usually taken to be k_2 = 0.8-0.9), [–]
k_3 – coefficient indicative of coal wetness which depends on the inlet fuel moisture content and the content of *hygroscopic* moisture, [–]
k_4 – coefficient indicative of pulverized coal wetness, which depends on the moisture content of the fuel entering and leaving the mill, [–]
m – exponent defining the type of coal (0.06 for brown coal, 0.114 for lignite), [–]
n_1 – impact body speed *i. e*. number of revolutions per second, [s^{-1}]
R_{5000} – 5000 μm sieve residue of coal entering the mill, [%]
R_{90} – 90 μm sieve residue of pulverized coal leaving the mill, [%]

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Paper submitted: February 14, 2011
Paper revised: March 4, 2011
Paper accepted: March 20, 2011