Study of Selected Parameters of Coal Burned in a Combined Heat and Power Plant

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ABSTRACT
The paper discusses the use of fossil fuels and the process of their extraction in Poland. Hard coal used on a daily basis in one of the Polish combined heat and power plants was described, followed by monthly measurements of coal parameters. Daily and total analyzes of the obtained measurement results of hard coal were carried out in accordance with the applicable standards. The differences in the values of coal from the same source but imported at different time intervals are shown, which result from the weather conditions and the method of hard coal storage. Negative correlations occurred between ash content and calorific value, heat of combustion and volatile matter, as detailed in the work conclusions.

Keywords: coal, heat and power plant, energy, combined heat and power

INTRODUCTION
Fossil fuels are most commonly used in combined heat and power plants [1]. These are energy resources that classify their origin to organic [2]. The main fossil fuels include, first of all, hard coal, lignite, crude oil, natural gas and peat [3]. Although there is more and more talk about switching from fossil fuels to ecological fuels, most combined heat and power (CHP) plants in Poland still use coal, however, thanks to modernized systems and installations, it is possible to reduce coal combustion or modernization CHP plants over switch to biofuels or create biomass-fired power units [4]. There are solutions on the market that use biomass from e.g. sunflower [5]. One of the most popular is the willowleaf sunflower [6]. Some plants also use biogas [7]. It is worth adding that for several years Poland has been reducing the amount of coal burned in accordance with the regulations of the European Union. In previous years, over 3 million tons less hard coal was burned as in 2016–2018. Coal is influenced by many factors which then influence the combustion process [8].

Currently, about 20 hard coal mines are operating in Poland. Most of them are located in the vicinity of Upper Silesia [9, 10]. Hard coal from different mines will differ in their parameters [11]. However, hard coal itself is divided into several types [12]. The most important types of hard coal include: steam coal, gas-steam coal, gas-coking coal, gas coal, ortho-coking coal, meta-coking coal, lean coal, anthracite coal, anthracite and meta-anthracite. In domestic stoves, flame, gas-coke and lean coal are most often used. However, the first two have a high volatile content [13]. Anthracite has the lowest volatile content. Detailed types of coal and its use are presented in Table 1.

When it comes to coal consumption over the last two decades, it can be noticed that, according to the data of the Central Statistical Office, the consumption of hard coal in relation to 2005 increased in Mazowieckie (by 27.1%), Opolskie (by 15.0%) and Świętokrzyskie (by 24.1%); in the others there was a decrease [15]. Figure 1 shows the amount of coal used by voivodships in Poland.

Compared to Europe in recent years, it can be seen that Poland is at the top when it comes to...
Table 1. Type of coal [14]

| Type of coal       | Content volatile parts V% | Short characteristic                                      | The use of coal                                                                 |
|--------------------|---------------------------|-----------------------------------------------------------|--------------------------------------------------------------------------------|
| Steam coal         | over 28                   | High volatile matter content, none or poor sintering ability, long, strongly glowing flame | Power generation, for all types of furnaces.                                   |
| Gas-steam coal     | over 28                   | High volatile matter content, medium sintering ability     | Power generation, for all types of furnaces.                                   |
| Gas coal           | over 28                   | High gas and tar efficiency, significant sinterability      | Power generation, grate and pulverized fuel furnaces, industrial boilers, gas plants and blends for the production of coke in coking plants. |
| Gas-cooking coal   | over 28                   | High gas and tar yield, good sinterability, medium pressure depressurization | For the production of coke in coking plants, gas plants and gas-cooking plants. |
| Ortho-cooking coal | from 20 to 31             | Typical coking coal, medium volatile matter content good sinterability, high pressure depressurization | Production of coke in coking plants.                                           |
| Meta-cooking coal  | from 14 to 28             | Good sinterability, high pressure depressurization          | Production of coke in coking plants.                                           |
| Semi-cooking coal  | from 14 to 28             | Low volatile matter content, poor sinterability, medium pressure depressurization | For blends for the production of coke in coking plants; may also be utilized for power generation in specially constructed furnaces and for production of smokeless fuel. |
| Lean coal          | from 14 to 28             | Low volatile matter content, none or poor sinterability, short flame | For blends for the production of coke in coking plants; may also be utilized for power generation in specially constructed furnaces and for production of smokeless fuel. |
| Anthracite coal    | from 10 to 14             | Low volatile matter content, none sintering ability         | For blends for the production of coke in coking plants; may also be utilized for power generation in specially constructed furnaces and for production of smokeless fuel. |
| Anthracite         | from 3 to 10              | Very little part content volatile, no sintering ability     | Power generation in specially constructed furnaces and for the production of carbon electrodes. |
| Meta-anthracite    | to 3                      | Very little part content volatile, no sintering ability     | Power generation in specially constructed furnaces and for the production of carbon electrodes. |

Fig. 1. Consumption of hard coal in 2019 in Poland [15]

hard coal mining [16]. Heat and power plants try to use various coal mixtures to obtain the best energy effects, but also to minimize the emission of elements to the atmosphere by selecting the most advantageous coal [17, 18]. In order to check the monthly parameters of coal, the results were collected from one CHP plant in Poland, which uses hard coal for energy production [19, 20]. The
collected data included such parameters of coal as: moisture, ash content, sulfur content, heat of combustion, calorific value, and volatile parts [21]. The individual parameters were made more precise in order to obtain as many results as possible, which may prove the remaining components of carbon factors [22, 23]. The aim of this study is to present daily changes in hard coal parameters. With the help of the performed tests, it is possible to observe the influence of environmental factors on the quality of hard coal burning.

MATERIAL AND METHODS

Gas coal samples were taken in an OR-type steam boiler. The OR boiler is a steam boiler used in a combined heat and power plant. It is the main boiler cooperating with EKM (steam) and WP (water-dust) boilers. The OR boiler in the CHP plant in question is the OR50-N model. His basic technical data include rated steam capacity (50 t/h), minimum steam capacity ≥ 30.0 t/h, steam pressure at the outlet 67 bar, steam temperature at the outlet 490.0 ± 5 °C, steam temperature for min. steam capacity 420.0 °C and feed water temperature 105.0 °C. The tested hard coal is used in a combined heat and power plant, which in 2019 produced 101,477 MWh/year of electricity and heat production was 1,668,312 GJ/year. In the analyzed samples collected in one of the Polish heat and power plants, a variety of parameters can be noticed. It should be added that samples were taken every day at similar times of the day. In the parameters related to moisture, the transient moisture content Wtrans, analytical moisture Wana, total moisture Wt and moisture content in air-dry coal Wad called hygroscopic moisture were checked. The weighting method was used to determine the coefficients, and the unit is expressed as a percentage. The moisture content was tested using the PN-80/G-04511 standard. The considered gas coal in its working condition had a calorific value of 21,755 kJ/kg. In the tested samples, the content of analytical ash Aana and ash in the working fuel Atrans was also checked. The ash content was tested according to the PN-G-04560: 1998 standard. The study was also performed using the weight method using the percentage unit. The total analytical sulfur content Sana and the sulfur content in the working fuel Strans were also examined. The high-temperature combustion method with IR detection was used to perform the measurement [24, 25]. In the analyzed hard coal, the sulfur content was tested in accordance with the PN-G-04584: 2001 standard. In the obtained tests performed using the calorimetric method from the calculations, the analytical calorific value Qana and the calorific value in the working fuel Qtrans were obtained. [26, 27]. The heat of combustion was tested according to PN-81/G-04513. The last parameter tested was volatile matter. As with the previous parameters, the analytical value Vana and the value in an ashless Vad sample were tested here. The measurement was made by the weight method and the results are expressed as a percentage unit. Measurements were made in accordance with the PN-G-04516: 1998 standard.

RESULTS

The results were collected from the 26 days of the reporting period, the last two days are included in other the reporting period, therefore only 26 days of the month were selected. The results of moisture content from 26 days are presented in Table 2. The table shows the measurements made in the winter. The samples were taken from the OR 50-N boiler.

It can be noticed that the highest transient moisture occurred on the fourth measurement day, and on the ninth and tenth day, transient moisture was the lowest. The result could be due to the same weather conditions outside where the coal is stored. The distribution of all moisture is shown in the diagram in Figure 2. The results of ash content are shown in Figure 3.

The collected data of sulfur content in coal samples are presented in Table 3. The results are shown in percentage units. The ash content shows a downward trend until the 16th day. This may be due to a change in the furnace settings and the weather conditions.

The samples tested in the middle of the month contained the most sulfur. This could be caused by a change of coal that was stored with the remaining coal in the combined heat and power plant. That is, the stored coal often consists of several deliveries from the same source, however, the parameters of the coal may change when it is extracted from different areas of the extraction site. With the increase in the total sulfur content, the value of the tested sulfur in the working fuel also increases. As for the heat of combustion Qana, it was observed that the tested coal shows values
### Table 2. Moisture content in the tested coal

| Day | W<sup>ex</sup> | W<sup>a</sup> | W<sup>b</sup> | W<sup>h</sup> |
|-----|---------------|---------------|---------------|------------|
| 1   | 6.6           | 2.1           | 2.4           | 8.8        |
| 2   | 7.3           | 2.4           | 2.5           | 9.6        |
| 3   | 8.2           | 2             | 2.2           | 10.2       |
| 4   | 8.4           | 2.2           | 2.1           | 10.3       |
| 5   | 7.3           | 2.1           | 2.1           | 9.2        |
| 6   | 7.8           | 2.3           | 2.7           | 10.3       |
| 7   | 6.8           | 2.2           | 2.9           | 9.5        |
| 8   | 7.5           | 2.5           | 3             | 10.3       |
| 9   | 6             | 2.2           | 2.2           | 8.1        |
| 10  | 6             | 2.2           | 2.2           | 8.1        |
| 11  | 7.2           | 2.8           | 2.4           | 9.4        |
| 12  | 7.6           | 2.3           | 2.3           | 9.7        |
| 13  | 7.9           | 1.9           | 2             | 9.7        |
| 14  | 7.9           | 2.1           | 2.1           | 9.8        |
| 15  | 8             | 1.7           | 1.8           | 9.7        |
| 16  | 8.2           | 2.2           | 2.3           | 10.3       |
| 17  | 7.8           | 2             | 2.2           | 9.8        |
| 18  | 8.3           | 1.9           | 2             | 10.1       |
| 19  | 8.3           | 1.8           | 1.8           | 10         |
| 20  | 7.1           | 2.2           | 2.2           | 9.1        |
| 21  | 7.8           | 1.6           | 1.8           | 9.5        |
| 22  | 8             | 1.8           | 1.8           | 9.7        |
| 23  | 7.6           | 2.2           | 2.4           | 9.8        |
| 24  | 8.2           | 2.3           | 2.4           | 10.4       |
| 25  | 8.1           | 2.1           | 2.1           | 10         |
| 26  | 8.1           | 2.2           | 2.2           | 10.1       |

### Table 3. Results of sulfur content

| Day | S<sub>1</sub><sup>ex</sup> | S<sub>1</sub><sup>a</sup> |
|-----|--------------------------|------------------------|
| 1   | 0.63                     | 0.59                   |
| 2   | 0.61                     | 0.56                   |
| 3   | 0.59                     | 0.54                   |
| 4   | 0.64                     | 0.59                   |
| 5   | 0.62                     | 0.57                   |
| 6   | 0.61                     | 0.56                   |
| 7   | 0.56                     | 0.52                   |
| 8   | 0.58                     | 0.53                   |
| 9   | 0.58                     | 0.55                   |
| 10  | 0.58                     | 0.55                   |
| 11  | 0.6                      | 0.56                   |
| 12  | 0.61                     | 0.56                   |
| 13  | 0.6                      | 0.55                   |
| 14  | 0.68                     | 0.63                   |
| 15  | 0.7                      | 0.64                   |
| 16  | 0.66                     | 0.61                   |
| 17  | 0.65                     | 0.6                    |
| 18  | 0.65                     | 0.6                    |
| 19  | 0.64                     | 0.59                   |
| 20  | 0.6                      | 0.56                   |
| 21  | 0.63                     | 0.58                   |
| 22  | 0.59                     | 0.54                   |
| 23  | 0.63                     | 0.58                   |
| 24  | 0.66                     | 0.61                   |
| 25  | 0.65                     | 0.6                    |
| 26  | 0.65                     | 0.6                    |

**Fig. 2. Distribution of all moisture**
above 25,000 J/g. The maximum obtained measurement was 26,423 J/g. Figure 5 shows the results obtained from the measurement of the heat of combustion.

Similar values were found when measuring the calorific value. The measured thermal effect is related to the weight of the sample. The measurement method consists in the complete and complete combustion of the fuel sample with oxygen atmosphere at a specific pressure in the calorimetric bomb and measuring the gain water temperature in the calorimetric vessel and determining corrections for additional effects thermal [28, 29]. The ARX (AutoRegressive with eXogenous input) [30] model fit (Fig. 6) and the transfer function model (Fig. 7) were used to illustrate the data distribution. The signal of the ARX model was generated from two calorific values as shown in Figure 5. The ARX model is a discrete input-output model for stochastic processes. You can see the consequence between the measurements and the correctness of the measurement taken, which is also within the tolerance of the measurements.

A certain dependence regarding the volatile parts in the ashless sample was noticed. Where there was a high level of total sulfur, there was also a high level of volatile matter. The highest volatile matter content was read on the eleventh day. The amount of volatile matter in the analytical sample was 31.14% on that day. Figure 8 shows the dependencies between the volatile matter content and the total sulfur content.
In order to illustrate the dependencies, the correlations between the parameters of coal were investigated with the use of the R program tools. The R language is widely used among and data miners for developing statistical software [31]. The R program is developed by R Core Team. The results are shown in Figure 9. The presented correlations show how the parameters of coal change with respect to each other. All parameters were tested in accordance with the standards.
CONCLUSIONS

The same measurement results were observed on days 17 and 18. This could be due to the same coal charge to be burned. When analyzing the parameters of coal, it was noticed that the parameters concerning the ash content and the volatile matter content are negatively correlated with the calorific value. The same applies to the correlation between the ash content and the heat of combustion. This correlation is also negative. There was a significant positive correlation between the calorific value and volatiles. Positive correlation occurs between the transient moisture content and the total moisture content, and that the moisture in the analytical sample correlates with the moisture content in air-dry carbon. This means that as the first factor increases, so does the second. A positive correlation, but lower than in other cases, also occurs between the total sulfur content in the analytical sample and the tested sulfur in the working fuel, as well as between the sulfur content and the transient moisture content. Positive correlations also occurred between the heat of combustion and the calorific values. Negative correlations occurred between the ash content and the calorific value, combustion heat and volatile parts. In the presented article, the intended goal was achieved.

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