

Introduction

The demand for hard and brown coal as fuel is large in Poland, especially during winter, both for individual as well as industrial customers. The winning – raw coal constitutes a commercial grade only in a limited amount. Due to this, depending on the requirements of the recipient, physiochemical properties of coals are shaped in the beneficiation plant based on their petrographic and chemical composition as well as on the type of mineral substance occurring in them. On the other hand, environmental protection requirements determine that coals used as fuel have high calorific value and low content of elements responsible for air pollution. The process of coal classification and enrichment is aimed at recovering coal grain from raw coal and at achieving physiochemical properties in products required by the recipient, e.g. lowering the content of: ash, sulphur and nitrogen, as well as increasing the content of the coal and hydrogen elements, thus increasing the combustion heat values which guarantee preserving the emission limit. In the processes of crushing, classifying and enriching hard coals, grains undergo numerous collisions, which results in their spontaneous grinding. Creating an additional number of fine coal fractions below 1 mm is not favourable and leads to burdening water-sludge circulations [2,3,4]. Briquettes or pellets created on the basis of hard or brown coal may fulfil the requirements for eco fuel with lowered emission of nitrogen oxides, sulphur, ashes, organic pollution to the atmosphere and cancerous substances. Low emission indicators may be obtained through a suitable selection of coal types, catalysts and binder. Besides, coals changed structurally as a result of mechanical processing have different porosity and strength [1] depending on the recipient's requirements.

Preparation a feed of tested coals for pressure agglomeration and their elementary analysis

For the purpose of pressure agglomeration, two kinds of hard power coal were used, type 31 (fine coals) from KWK "Janina" and KWK "Wieczorek", as well as brown coal from KWB Bełchatów, "Szczerców" panel. A grain size analysis was performed of feeds – raw coals for tests. The flow-offs of specific grain classes were calculated and size analysis curves were charted for the tested coals. The results were presented in Figure 1. Small coal fractions below 2 mm occur up to 25.5% in raw coal for coal from KWK "Janina", up to 22.1% in the coal from KWK "Wieczorek" and up to 58% in brown coal from KWB "Bełchatów", "Szczerców" panel.

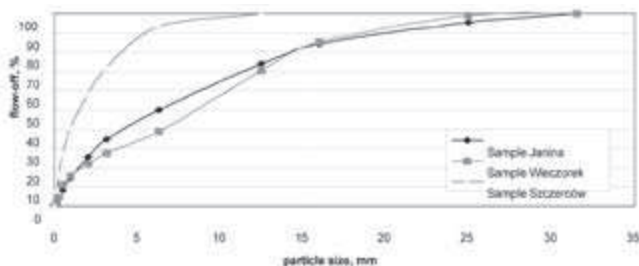


Fig. 1. Size analysis for initial coals [5]

In order not to increase the ratio of fine classes, the class below 2 mm was sifted from the feed. The class above 2 mm was intended for grinding. Before grinding, a grain size analysis was performed. The flow-offs of specific grain classes were calculated and their size analysis curves were charted. The results were presented in Figure 2.

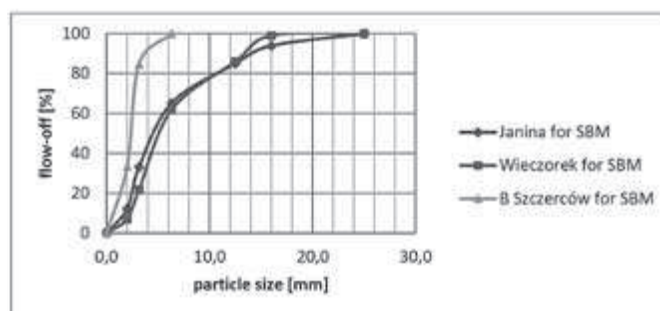


Fig. 2. Size analysis of coals before impact crusher SBM

The process of grinding the class above 2 mm was carried out in a rotor impact crusher by SBM Mineral Processing from Austria. In this type of crusher, a material is obtained with a generally even particle size distribution, in narrow size grades. The products obtained after crushing were subjected to grain size analysis and its results were presented in Figure 3. Then, feeds below were separated into narrow size grades and subjected to elementary analysis. It proved interesting to test the impact of the manner of obtaining a grade below 2 mm on mechanical and energy properties of the obtained pellets.

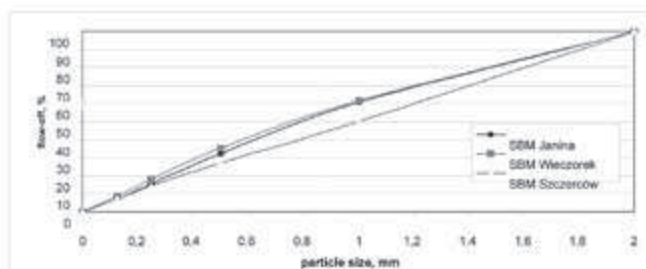


Fig. 3. Size analysis of coals after impact crusher SBM [5]

Results of elementary analysis were presented in Table 1 [5].

An elementary analysis of power coals showed that coals type 31 from KWK "Janina" and "Wieczorek", in natural feed as well as in the product after crushing in an impact crusher (SBM), in the grade from 0 to 0.125 mm have the largest ash content with a low grade flow-off, high sulphur content and low nitrogen content, low carbonification and low hydrogen content, which in consequence is reflected in low combustion heat. In the case of brown coal from the Bełchatów coal bed, "Szczerców" panel, the distribution of ash and elementary components is relatively even and the product's combustion heat with particle size distribution 0-2 mm equals approx. 16,800 kJ/kg and is approx. 1,400 kJ/kg higher than before crushing [5].

Table I

Results of coal elementary analysis

| Carbon | Size grades [mm] | Flow-off g [%] | Ash A ^a [%] | Sulphur S ₂ ^b [%] | Nitrogen N ^c [%] | Carbon C ₂ ^d [%] | Hydrogen H ^e [%] | Combustion heat Q _p ^f kJ/kg |
|-------------------------------------|------------------|----------------|------------------------|---|-----------------------------|--|-----------------------------|---|
| KWK "Janina" after sifting | (0-0.125) | 7.75 | 41.98 | 1.97 | 0.60 | 36.50 | 2.62 | 14493 |
| | (0.125-0.5) | 23.82 | 22.25 | 1.49 | 0.83 | 51.10 | 3.49 | 20339 |
| | (0.5-2) | 68.43 | 11.46 | 1.24 | 0.94 | 59.60 | 3.97 | 23352 |
| | (0-2) | 100.00 | 16.95 | 1.38 | 0.90 | 55.60 | 3.73 | 22172 |
| KWK "Janina" after SBM | (0-0.125) | 7.01 | 19.64 | 2.71 | 0.82 | 51.80 | 3.34 | 20609 |
| | (0.125-0.5) | 25.31 | 10.72 | 1.80 | 0.94 | 58.90 | 3.92 | 23736 |
| | (0.5-2) | 67.68 | 11.57 | 1.35 | 0.97 | 59.80 | 4.06 | 24019 |
| | (0-2) | 100.00 | 11.75 | 1.63 | 0.93 | 58.80 | 3.88 | 23680 |
| KWK "Wieczorek" after sifting | (0-0.125) | 8.92 | 23.75 | 0.63 | 1.14 | 60.40 | 3.81 | 23655 |
| | (0.125-0.5) | 41.42 | 34.39 | 0.61 | 1.10 | 52.50 | 3.53 | 20602 |
| | (0.5-2) | 49.16 | 18.02 | 0.62 | 1.37 | 65.00 | 4.33 | 26282 |
| | (0-2) | 100.00 | 24.08 | 0.66 | 1.40 | 63.00 | 4.04 | 25138 |
| KWK "Wieczorek" after SBM | (0-0.125) | 8.93 | 15.63 | 0.60 | 1.27 | 68.80 | 4.07 | 26840 |
| | (0.125-0.5) | 26.36 | 8.90 | 0.50 | 1.46 | 75.90 | 4.86 | 30075 |
| | (0.5-2) | 64.71 | 10.38 | 0.48 | 1.44 | 74.60 | 4.86 | 29790 |
| | (0-2) | 100.00 | 11.47 | 0.51 | 1.36 | 72.00 | 4.72 | 29285 |
| KWB "Szczerców" panel after sifting | (0-0.125) | 14.24 | 16.52 | 0.73 | 0.60 | 40.40 | 3.28 | 15634 |
| | (0.125-0.5) | 32.43 | 21.51 | 0.80 | 0.57 | 40.90 | 3.48 | 15749 |
| | (0.5-2) | 53.33 | 21.38 | 0.78 | 0.53 | 39.40 | 3.33 | 15118 |
| | (0-2) | 100.00 | 20.74 | 0.75 | 0.54 | 39.60 | 3.25 | 15413 |
| KWB "Szczerców" panel after SBM | (0-0.125) | 6.91 | 20.25 | 0.84 | 0.65 | 43.70 | 3.15 | 16649 |
| | (0.125-0.5) | 20.27 | 20.43 | 0.78 | 0.56 | 41.70 | 3.48 | 15984 |
| | (0.5-2) | 72.82 | 19.04 | 0.80 | 0.54 | 42.20 | 3.38 | 16220 |
| | (0-2) | 100.00 | 20.23 | 0.80 | 0.57 | 42.50 | 3.50 | 16817 |

Moreover, tests were carried out of the phase composition of hard coal samples from KWK "Janina" and KWK "Wieczorek" as well as brown coal samples from the Bełchatów coal bed, using an X-ray method. A Philips X-ray diffractometer with an XI Pert system was used for the tests. The tests showed the occurrence of pure coal in all samples. Coal from KWK "Wieczorek" has a crystalline structure. Apart from coal, its composition includes also SiO₂. Coal samples from KWK "Janina" contain coal in crystalline form, SiO₂ and kaolinite Al₂Si₂O₅(OH)₄. Brown coal from the Bełchatów coal bed was characterized by an amorphous structure.

Initial granulation test in a closed die

Before granulation attempts of coal samples prepared as in the previous chapter on a granulator with a flat die, initial tests of their granulation were performed in a closed die. The purpose of these tests was to determine densification and proper working characteristics. The shifting of the stamp was registered with a precision of up to 0.01 mm. The stamp's pressure was measured with a 2% precision, a pressure of 5 N/mm² and 0.2% in the upper measurement scope. The measurement of the stamp's pressure and the height of the compacted sample allows for drawing up a densification characteristics in the system: normal pressure [N/cm²]- mass volume [cm³/g], and normal pressure [N/cm²]-density [g/cm³]. After performing a densification characteristics, a function is established which describes the relation

between the agglomerate's mass volume and the normal pressure necessary for evoking its change. The carried out tests indicated that the exponential function in the form as in equation (1) very well describes the dependence of normal pressure on the inverse density of the agglomerate obtained under its effect.

$$\sigma_n = ae^{bv} \tag{1}$$

where:

a, b – coefficients determined using regression equations

v – mass volume

Unit work [J/g] was calculated as an integral set from equation (2).

$$A = \int_{v_p}^{v_k} \sigma_n d(v) + C \tag{2}$$

Where: v_p – initial mass volume; v_k – final mass volume; C – integration constant. The value of the integration constant was calculated from initial conditions assuming that at the moment of starting the granulation process the value of initial work is equal to zero. For such formulated assumption, constant C was calculated from equation (3)

$$C = \frac{a}{b} e^{b v_p} \tag{3}$$

Figures 4 ÷ 6 present densification characteristics of tested coals in the system pressed density – required normal pressure. The symbols used in the figures denote: Lgc – denotes an addition of binder in the form of sodium lignosulphate; SBM – denotes that the sample was precrushed in a crusher.

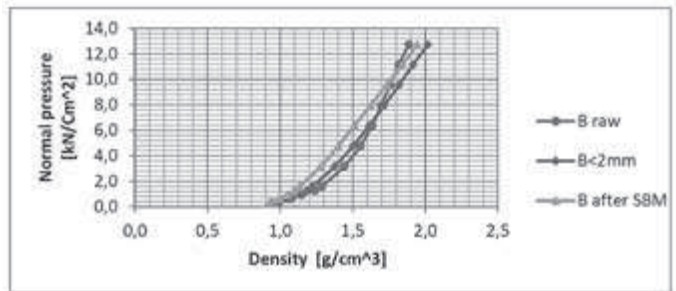


Fig.4. Agglomeration characteristics of brown coal – "Szczerców" Field

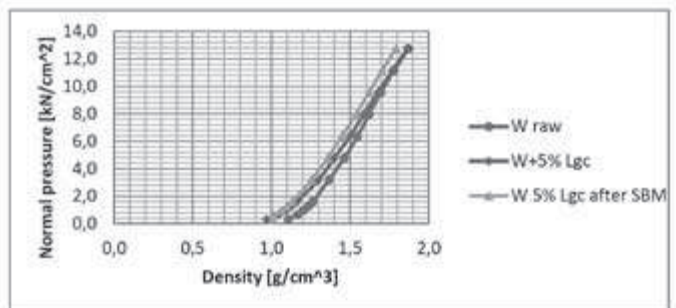


Fig.5. Agglomeration characteristics of hard coal "Wieczorek"

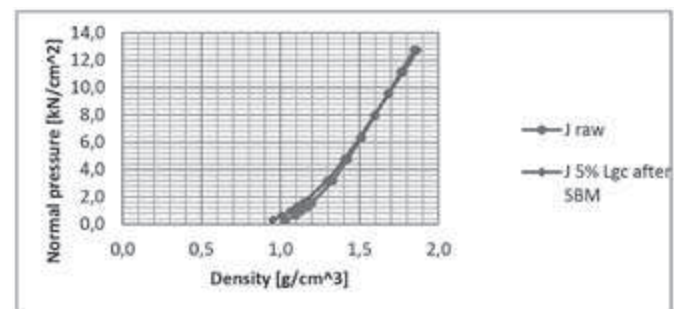


Fig.6. Agglomeration characteristics of hard coal "Janina"

Figures 7÷9 present the dependence of required normal pressure in the function of volume mass. These dependencies were used to determine the coefficients of equation (1) and to calculate proper work necessary for obtaining the required density of the agglomerate in accordance with equation (2).

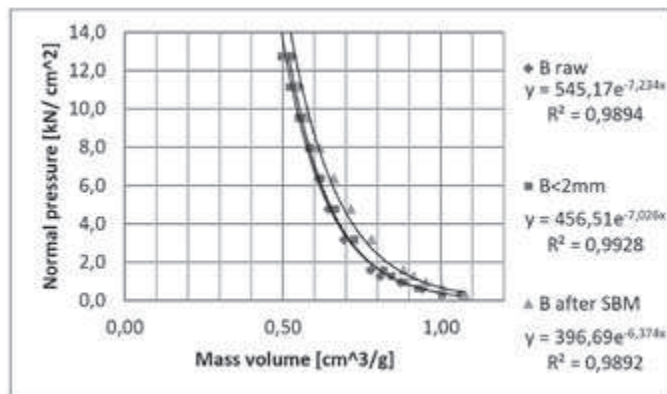


Fig. 7. Characteristics of normal pressure end mass volume of brown coal – "Szczerców" Field

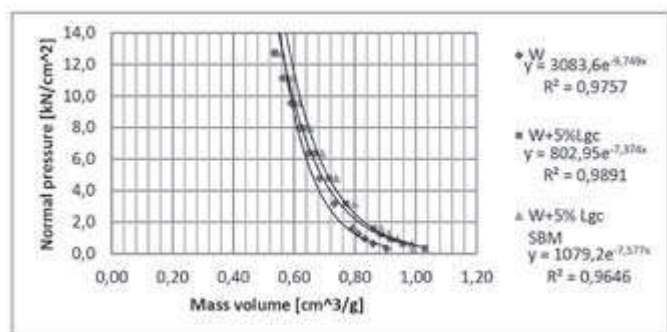


Fig. 8. Characteristics of normal pressure end mass volume of hard coal "Wieczorek"

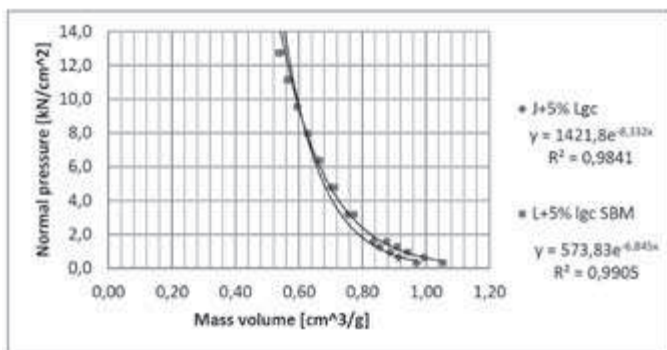


Fig. 9. Characteristics of normal pressure end mass volume of hard coal "Janina"

Using equations provided in Figures 7÷9 and dependencies (2) and (3), unit work values were calculated for the tested coals. The calculated unit work pertains only to the work necessary for obtaining a specific agglomerate density. It does not include the work necessary for overcoming the resistance of mass flow through the openings in the pelletizer die nor the work of friction in them and on the surfaces of dies and rolls. Results of these calculations are presented in Figure 10.

An analysis of the demand for specific work necessary for obtaining the required density for tested coals shows that samples after crushing require more unit work than raw coal samples.

Attempts of coal pressure agglomeration on a granulation with flat die

Attempts of coal agglomerations were carried out on a laboratory pelletizer with a flat die, which is presented in Figure 11.

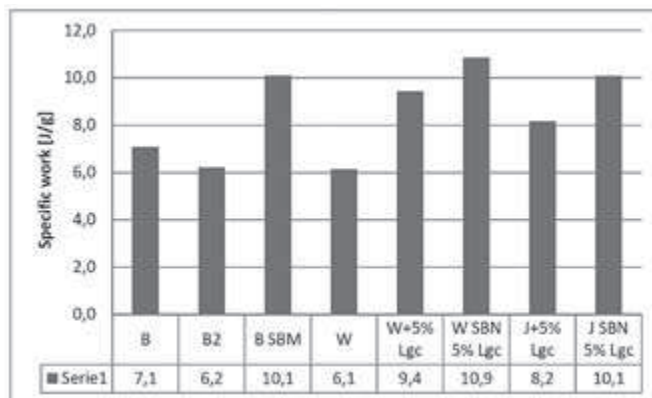


Fig. 10. Specific work of coals agglomeration

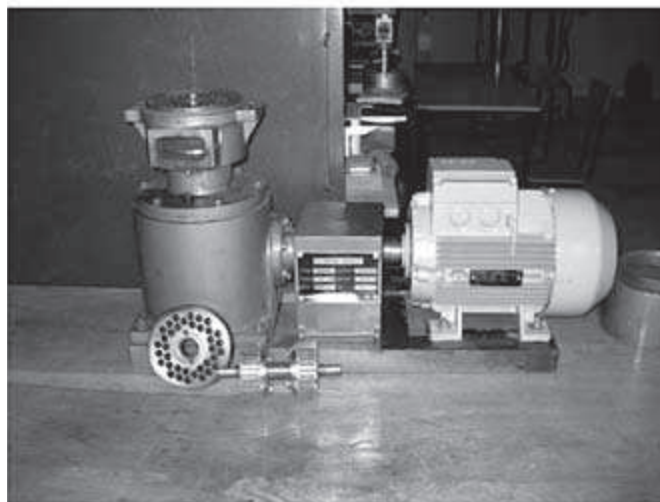


Fig. 11. Laboratory pelletizer with flat die

The pelletizer is fitted with a die with a diameter of 120 mm and thickness of 25 mm. The die has 36 cylindrical openings with an 8 mm diameter. In the upper part of the opening there are 2.5 mm deep conical undercuts with a 60° angle. The granulator is fitted with two pressure rolls with a diameter of 60 mm and width of 40 mm. On the roll's surface there are 30 incisions which are parallel to the rolls' axis. Incisions are made in the form of grooves with a width of 3 mm and depth of 3 mm. The rotary speed of the die is 300 rev/min. The granulator is driven by a 2.2 kW three-phase motor. The distance of rolls from the die was set at $h=0.1$ mm. Before the trials, the die and rolls were heated to a temperature of approximately 70°C using a mixture of bran-water-oil-corundum powder. The resulting pellets were obtained in a test of single passage of the raw material through die openings.

Brown coal samples were prepared the following way: water was added to fine coal so that its mass ratio equalled 18%. Then, the elements were mixed for 10 minutes in a roll mixer. Such prepared mixture was placed in an airtight container for 12 hours in order to achieve full homogeneity. Then the mixture was directed onto the pelletizer. In the case of hard coals, the preparation process occurred in the following way: 5% of binder, i.e. sodium lignosulphate (Lgc) in the form of a powder was added to the dry coal feed. Then the components were mixed in an airtight container. After mixing the components, the mass was moistened to a humidity of 10% of the mass ratio and then mixed again. Such prepared hard coal mixtures were directed onto the pelletizer. Pellets obtained during agglomeration were seasoned for 24 hours in air with a temperature of 24°C. After this time, their resistance to pressure was determined. For these tests, 8 pellet pieces from each batch with a mass of 0.7 to 1.2 grams were selected. Their mass was determined with a precision of up to

0.001 g. Each sample was subjected to a destructive force applied perpendicularly to the direction of the normal pressure in the process of their creation. Tests were performed on a Zwick 1120 testing machine. The destructive force was measured with a precision of up to 1 N. Mass resistance was determined as the relation of destructive force to the mass of the sample subjected to tests. Test results were presented in Figures 12÷ 14.

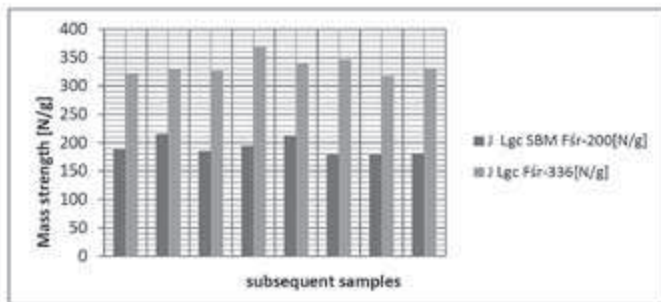


Fig.12. Compressive strength of 8 mm pellets – hard coal "Janina"

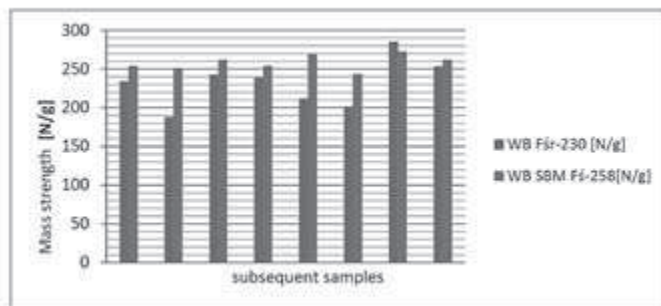


Fig.13. Compressive strength of 8 mm pellets – brown coal – "Szczerców" Field

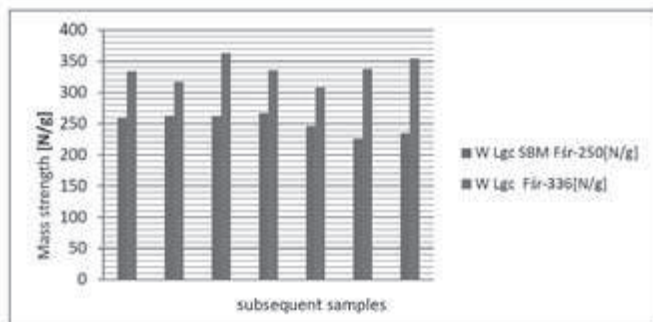


Fig.14. Compressive strength of 8 mm pellets – hard coal "Wieczorek"

Tests of resistance to pressure showed that the average resistance of a pellet from raw brown coal equals 230 N/g, while after SBM it is a bit higher and equals 258 N/g. Resistance to pressure of pellets from hard coals with a 5% addition of sodium lignosulphate as the binder is higher in the case of raw coals and equals on average 336 N/g for "Janina" and "Wieczorek" coals. After their crushing in an SBM it equals 200 N/g for the "Janina" coal and 250 N/g for the "Wieczorek" coal.

Conclusion

The results of elementary analysis, specific work and pellet resistance jointly lead to the following conclusions:

In the case of fine hard coal fractions before their granulation the 0-0.125 mm grade must be separated, which will cause a decrease of ash content, a decrease of sulphur content and an increase of combustion heat in the case of raw coals as well as coals after crushing.

Hard coals subjected to crushing require larger amount of specific work in the process of pressure agglomeration, while the pellets obtained from them show smaller mass resistance.

With regard to brown coal, sifting the 0-0.125 mm grade and crushing does not cause significant changes of combustion heat nor ash content. Their crushing causes an increase of the densification specific work and practically does not impact their mass resistance.

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Literature

1. Skoczylas N.: „Wybrane właściwości mechaniczne i gazowe brykietów węglowych”, *Przegląd Górniczy*, 2009, 7-8, 91-95
2. Dubiński J., Pyka I., Wierzchowski K.: „Stan aktualny i niektóre aspekty poprawy jakości węgla użytkowanego w energetyce zawodowej” *Przegląd Górniczy* 2011, 7-8, 46-52;
3. Błaszczczyński S., Szpyrka J.: „Weryfikacja przemysłowa wzbogacania drobnouziarnionych węgla metodą wibrofluidalną”, *Przegląd Górniczy* 2011, 7-8 59-64
4. Osoba M.: „Technologie wzbogacania grawitacyjnego węgla kamiennych w Polsce”, *Przegląd Górniczy* 2011, 7-8, 53-58
5. Temat Badawczy nr 2.1.2: pt. „Badania wzbogacania węgla na drodze przeróbki mechanicznej” 2011r. AGH – projekt NCBR pt. "Zaawansowane technologie pozyskiwania energii" Opracowanie niepublikowane nr 23.23.100.8498/R34.

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