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Optimisation of coal beneficiation in a jig in changing hydrodynamic conditions of its operation

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Abstract
The paper presents the analysis of hard coal beneficiation in a jig with regard to the optimal useful fraction recovery in concentrate and non-useful fraction in tailings. The process was evaluated based on the industrial sampling of a jig for coal fines and granulometric and densimetric analyses of collected product samples under laboratory conditions. In separated size-density fractions of partition products, yields of products were calculated, and their ash contents were determined. The beneficiation curves were plotted on the basis of the results of granulometric, densimetric and chemical analyses of obtained size-density fractions, the balance of partition products and appropriate calculations. This made it possible to evaluate the process to optimise the device's operation to obtain higher recovery with the possibly highest concentrate quality.
In the paper, the hard coal beneficiation results were evaluated with regard to the optimal organic fraction recovery in concentrate and mineral components in tailings with respect to the process control. The obtained characteristics of beneficiation were analysed to select the optimal technological coefficients for optimisation of the device's operation on the basis of the Fuerstenau curve, Halbich curve and selectivity curve.
Multi-criteria elaboration of research material, on the basis of the qualitative approach of selectivity and Fuerstenau curves, indicated differentiation during the beneficiation of fine and coarse particles from the range of granulation being directed to the jigging process. This is a commonly known fact, but it is not necessarily used in industrial practice.

Keywords
coal fines, jig, beneficiation selectivity, partition efficiency.

Introduction

The mineral raw materials beneficiation is a process necessary to obtain a product with the appropriate quality parameters (for example, useful component content or pollution level) and various characteristics, including strength parameters, required by the customer. Providing the appropriate product parameters, apart from satisfying the customers' expectations, also significantly affects the natural environment and can substantially contribute to the minimisation of negative effects, for example, in the case of coal combustion in the household or industrial installations which are not equipped with appropriate devices for exhaust cleaning. The key process of obtaining the appropriate product quality is the beneficiation process, during which the raw material is partitioned into streams containing various component levels. Depending on the requirements concerning the final product quality as well the efficiency of useful component recovery, beneficiation processes may be very complex. Many methods combined in an appropriate technological scheme are used during these processes to achieve the production capacity. The complex and complicated technological schemes cause an increase in the producers' operational costs and unfortunately lead to an increase in the raw material's price. In the case of coal, this leads to searching for alternative energy sources or purchasing cheaper coal with low-quality parameters that are not adequate for the installation in which combustion occurs. The alternative for complicated and complex technological schemes may be raising the efficiency of operations applied in the current technological systems of mineral processing plants. Such action is also justified by producers' aspirations to achieve the better efficiency of applied technologies. The improvement in technological processes requires a good knowledge of factors and parameters affecting their course. This is a significant element enabling the appropriate control of the technological process and its optimisation. Apart from the knowledge of the mutual relations between material and process parameters, it is also necessary to know the functional relations between them and the product quality. Currently, the correctly applied beneficiation processes allow achieving the appropriate product quality at relatively low operational costs. An example of material beneficiation with low operational costs is the partition process in a jig, during which the difference in settling velocities of particles of various densities is used.

Because of the big differentiation in amounts of impurities in exploited seams of individual deposits, it is necessary to first remove non-useful components by means of methods and processes of mineral processing, as far as possible and efficient, before operations leading to the production of energy from hard coal. Needs in this regard and the analysis of the effects were the topic of papers by numerous authors such as (Blaschke, 2008; Brożek and Surowiak, 2005; Heyduk and Pielot, 2014; Gawlik and Mokrzycki, 2017; Pielot, 2017; Kumar and Venugopal, 2020). The qualitative parameters of produced assortments depend on the adequacy of these devices' operation, which can be measured mainly by ash content, sulphur content, calorific value, etc. On the other hand, various factors related to constructive movement (technological) parameters or feed properties affect the jigging effects. It is crucial to monitor and adjust these parameter values to control process quality correctly. This can be done in accordance with various rules, depending on the processed material, liberation (Surowiak, 2013), type of device and most importantly, the assumed goal. In the literature, many approaches to this problem were made, such as radiometric density measurements (Cierpisz and Joostberens, 2015; Cierpisz and Joostberens 2016; Cierpisz 2017) and modelling done in accordance to it (Cierpisz et al., 2016), a numerical study of the multiphase flow (Dong et al., 2010), investigation of jig frequency influencing on the process quality (Ferreira et al., 2012), classical statistical modelling of the process effects (Tripathy et al., 2016), application of neural networks to simulate the process (Panda et al., 2012), 3D response surface methodology applications (Kumar and Venugopal, 2020), CFD simulation (Xia et al., 2007). Furthermore, the dry jigging applications to coal processing (Gouri et al., 2011; Sampaio et al., 2008; Yang et al., 2013), altair jig applications (Mohanty et al., 2002), Kelsey jig analysis (Richards et al., 2004), fluid motion modelling (Mishra and Adhikari, 1999), the influence of the shape of material (Phengsaart et al., 2018) were also discussed in the aspect of achieving possibly best results of the processing. The general trends in coal beneficiation, including jigging, are discussed, among others in (Venkoba et al., 2017; Gagarin et al., 2008; Mukherjee et al., 2005, Paul and Bhattacharya, 2018).

The pulsation cycle is among hydrodynamic parameters like, for example, hutch water which highly affect partition effects (Lyman, 1992; Wills and Napier-Munn, 2006). The pulsating water movement should be selected in such a manner so as to ensure that particles settle when water moves downwards. The pulsation cycle can be symmetrical or asymmetrical. In the first case, the time of raising and lowering water with mineral particles is the same; in the latter one - these times are different. The shape of water pulsation characteristics strongly affects the partition process course through the appropriate selection of amount and time of delivered air and the frequency of pulsations (Osoba, 2014).

When water with material moves downwards, a negative phenomenon, which absorbs lighter particles inside heavier ones, occurs. This negatively affects the partition efficiency. In order to reduce this phenomenon, hutch water is delivered to the jig. Its purpose is to increase water movement in the upward direction in the working part and lower the settling velocity of the water. Hutch water flows from the jig together with the beneficiated material. The amount of hutch water significantly affects the degree of material loosening. A too small amount will cause the material not to be sufficiently loosened, and the partition process will be inefficient. There is also a relation between the jig efficiency and partition accuracy. The higher the efficiency is, the lower the partition accuracy is because the time spent by the material in the jig bed is shorter. Therefore, the dissipation of particles to neighbouring products increases (Blaschke, 2008).

In the paper, the effect of variable feed properties (granulation) and hydrodynamic conditions of the jig operation on technological coefficient values for narrow particle fractions of coal subjected to partition was analysed in terms of the provided hutch water. The analysis allowed determining the effect of the amount of the provided hutch water on the jig operation. The water was added in order to adjust the device's operation parameters to ensure the appropriate efficiency of the beneficiation process of the feed with given beneficiation characteristics. The Fuerstenau, Halbich curves and coefficients and a selectivity curve were implemented as a tool to evaluate beneficiation. This kind of analysis is commonly used as a tool to evaluate the efficiency of the beneficiation process course and for the purposes of its optimisation or improvement of technological coefficients, especially for processing ores. In the case of coal, the application of Henry's beneficiation curves or Mayer's mean value curves is more common as well using Tromp curves to evaluate the efficiency of separation. These were also used to evaluate the results of this jig work presented in the paper (Surowiak, 2018). The application of a Fuerstenau curve, and particularly a selectivity curve proposed by the Authors in the papers (Drzymała and Ahmed, 2005; Drzymała, 2006; Drzymała, 2007; Duchnowska and Drzymała, 2011; Foszcz et al., 2015; Foszcz et al., 2018; Surowiak et al., 2019) for this purpose is some new approach to evaluate the coal partition process.

The applied research methods and methods of evaluation of hard coal ability to beneficiation described in this paper are commonly known and being applied. The research problem is very important because the level of coal cleaning from gangue and sulfur significantly influences coal combustion processes, especially on the value of emitted pollution and, in this way, on human life quality. In this context, the investigations presented in the paper beneficially register into very important problems of hard coal cleaning as the main fuel for energy production sector (quality of combusted coal is extremely significant because of the fact that process of transformation of many countries for which main energy carrier is coal will be time-consuming. That is why it is so important to limit energy during the period of transferring into other energy sources). The novelty of the paper is based on the fact that for this purpose, Fuerstenau curves were applied, which are rarely used for hard coal beneficiation. Furthermore, the selectivity of beneficiation was determined by means of factors calculated on the basis of these curves. The application of Fuerstenau curves to evaluate the efficiency of hard coals beneficiation processes, including coal fines, allows to look wider and in different ways on both production effects of high quality concentrates for the energy sector and the efficiency of hard coal beneficiation processes in general. The conduction of the analysis of jigging process course in the aspect of changeable hydrodynamic conditions of its work and determination of optimal recoveries of flammable parts in concentrate as well ash in tailings, in the aspect of considering clean technologies of hard coal applications, may occur to be a valuable direction of analyses. The evaluation of beneficiation processes by means of this method was elaborated primarily by Prof. Douglas Fuerstenau exactly for coal beneficiation processes. However, in world literature, it exists mainly as the method of evaluating the beneficiation of metal ores. The choice of the factor for multi-variant evaluation of beneficiation effects on the basis of the Fuerstenau method is a beneficial direction in searching for optimal conditions of coal fines beneficiation.

Materials and Methods

The industrial experiment consisted of sampling a jig in which coal fines are beneficiated was conducted. The experiment was to determine the possibilities of improving technological coefficients: the combustible matter recovery and combustible matter content in beneficiation products – concentrate and middlings. In order to determine characteristics of the coal fines beneficiation depending on the amount of the additional water, the so-called hutch water, the representative samples of products were collected from a three-product jig at one of the coal processing plants. The device operation efficiency was maintained at the constant level and equal to 300 Mg/h, while hutch water in the amount of 35, 50 and 70 m^3/h was the variable parameter. Each collected partition product was subjected to the densimetric analysis in zinc chloride solutions, which allowed to obtain the following density fractions -1.3; 1.3-1.4; 1.4-1.5; 1.5-1.6; 1.6-1.7; 1.7-1.8; 1.8-2.0 and +2.0 Mg/m^3. Next, each densimetric fraction was screened on an appropriate set of sieves 2.0; 3.15; 5.0; 6.3; 8.0; 10.0; 12.5; 16.0 and 20.0 mm which allowed to obtain narrow size-density fractions. For each such fraction, chemical analyses of ash content were performed. Ash content in industrial conditions during sampling for each experiment was on the level of 40-47% in the feed.

Figure 1 presents the balanced ash content in individual particle size fractions for individual experiments.

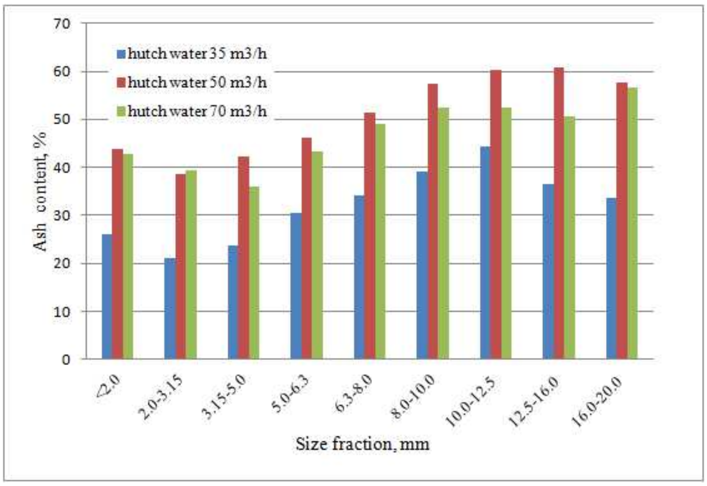


Fig. 1. Ash content in individual particle size fractions

The analysis of ash content for individual particle size fractions indicates that increased ash content in coal fines occurs in coarser particle size fractions above 8 mm, which results from a higher susceptibility to comminution of coal than of gangue particles and its accumulation in finer fractions.

Particle size distribution of the beneficiated feed is the important factor affecting the efficiency of the jig operation. Figure 2 shows percentage shares of individual particle size fractions in feeds for which beneficiation characteristics were evaluated.

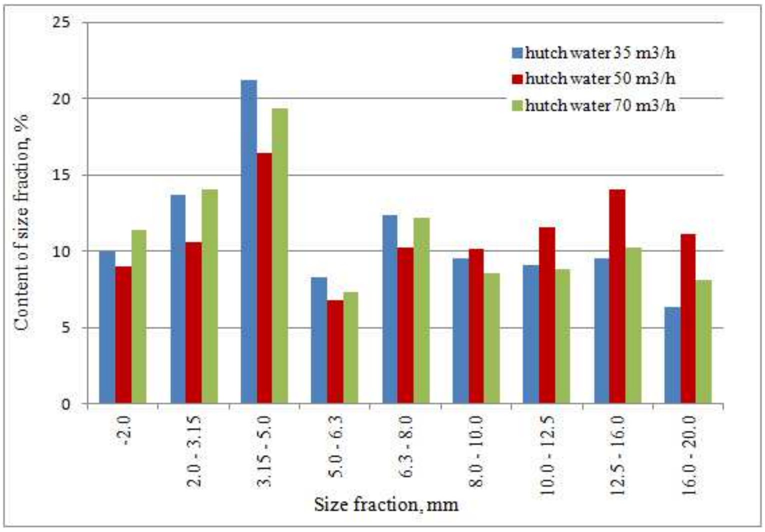


Fig. 2. Particle size fractions content in investigated coal fines for individual experiments

While analysing the variability of granulation for particle size fractions in individual experiments, a high increase in particle size fractions above 8.0 mm is found in experiments with hutch water in the amount of 50 m^3/h and significantly finest granulations for beneficiated raw coal during experiments with water in the amount of 35 m^3/h. It explains the change in ash content in the investigated raw coal for individual experiments, which is in accordance with the given relation resulting from coal susceptibility to comminution and its accumulation in finer particle fractions. The methodology for evaluating hard coal beneficiation results in terms of the optimal organic fraction recovery in concentrate and mineral components in tailings on the basis of Fuerstenau, Halbich and selectivity curves and the analysis of obtained beneficiation characteristics in order to select the optimal technological coefficient values for the purposes of the device operation optimisation was presented in the paper (Surowiak et al., 2019; Surowiak, 2019). Therefore, this paper presents beneficiation characteristics for the feed and selected particle size fraction from one experiment. The identical calculations were done for all feeds and particle fractions in order to obtain selectivity coefficients. The upgrading selectivity index for the feed and size classes was calculated according to the formula (Foszcz et al., 2015):

$$\boldsymbol{S = \frac{\alpha-\vartheta}{\beta-\vartheta}\frac{\beta}{\alpha}\cdot 100 + \left(100 - \frac{\alpha-\vartheta}{\beta-\vartheta}\cdot 100\right)\frac{100-\vartheta}{100-\alpha} - 100} \qquad (1)$$

where: α, ϑ, β – denotes ash content according to feed, concentrate and tailings.

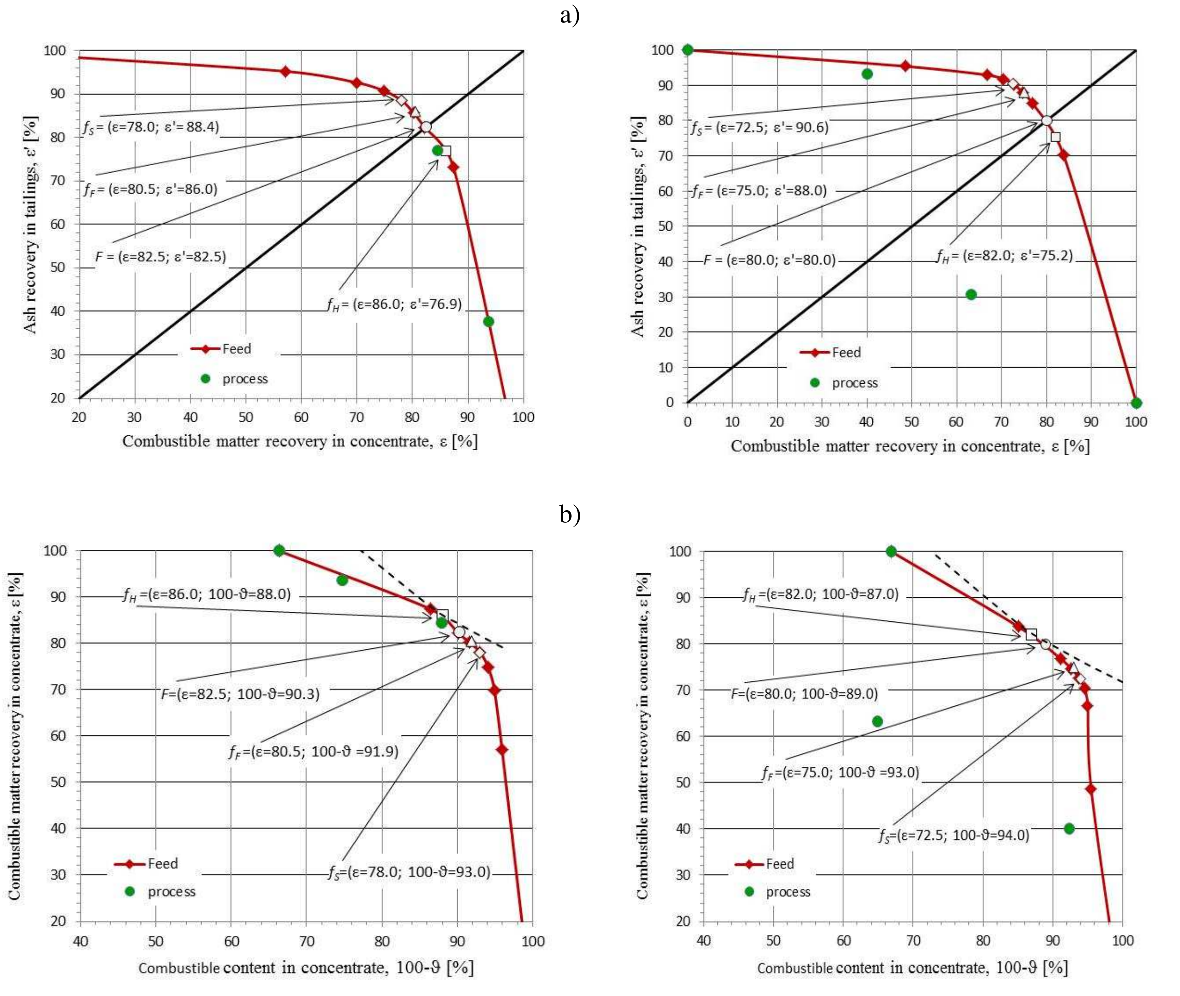
The selectivity index value is calculated as the sum of the balance of the useful component in the concentrate and the remaining components in the waste. The selectivity index S has a clear optimal point because the dependence of this index, for example, in the system $S = f(\beta)$, is parabolic.

Results and discussion

The obtained results allowed calculating coordinates and plotting Fuerstenau and Halbich curves, of which the indicators were determined f_F and f_H (Surowiak et al., 2019). In this work, for the evaluation of the upgrading results, upgrading selectivity curves were drawn, to which the upgrading indexes f_F and f_H were added to show the technological optimum determined based on various tools - descriptive curves. The selectivity upgrading curve presents the sum of recoveries of useful components in concentrate and remaining components in tailings in the component content in concentrate for the obtained narrow particle size fractions of the feed. It allowed determining realisable values of beneficiation technological coefficient values, such as the combustible matter recovery in concentrate and their content in concentrate. The certain characteristics presented in this paper allowed indicating the described points in which the technological optimum is realised with various criteria. The purpose of the presented considerations and conducted calculations was to determine optimal points on beneficiation curves enabling more precise determination of potential possibilities of the raw material with regard to obtaining certain values of technological coefficients of the partition process course. Consequently, this allows controlling the process in order to optimise its results. The calculations were performed for individual particle size fractions of the feed and for the fractions in total, that is, the feed subjected to beneficiation in a jig, which allowed to analyse the process efficiency in the function of the processed material granulation. Figure 3 shows an example of the characteristics with marked optimal points for particle fraction 16.0-20.00 mm and the feed for the experiment in which the amount of hutch water was equal to 35 m^3/h. The curves presented in Figure 3 show the values of coefficients obtained during beneficiation in a jig under industrial conditions.

Fraction 16.0-20.0 mm

Feed



c)

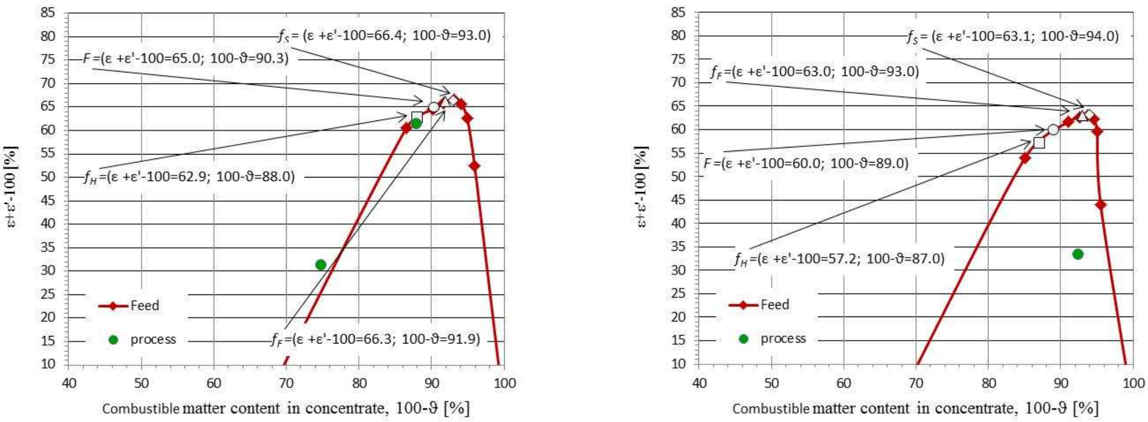


Fig. 3. Beneficiation characteristics for the feed and selected particle fraction, hutch water in the amount of 35 m^3/h; a) Fuerstenau curves, b) Halbich curves, c) upgrading selectivity curves

Figure 4 shows a change in the value of selectivity coefficient f_S for individual particle size fractions and the feed for performed experiments.

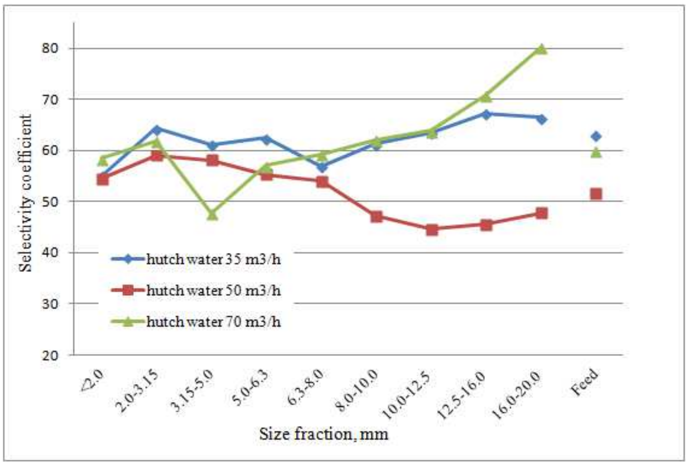


Fig. 4. A change in the value of coefficient f_S for individual particle fractions and the feed

This coefficient is a measure of the potential of individual particle size fractions with regard to gravity beneficiation and can be useful to evaluate the process course under industrial conditions. Figure 5 shows a change in the value of the obtained coefficient under industrial conditions for individual fractions and the feed.

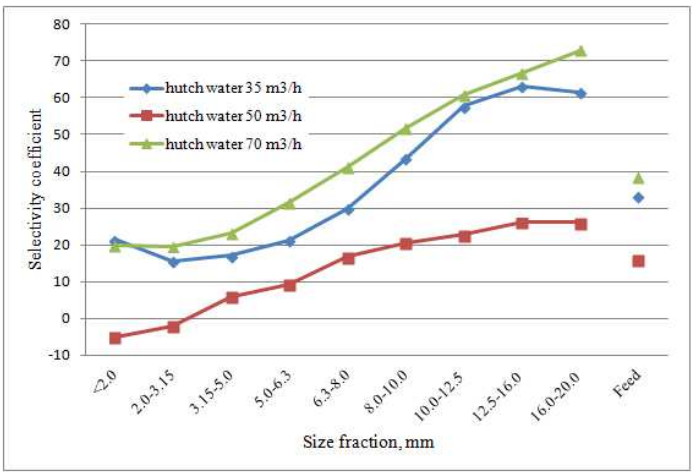


Fig. 5. A change in the value of coefficient f_S obtained under industrial conditions for individual particle size fractions and the feed

In order to determine the level of achievement for the selectivity coefficient value determined on the basis of the densimetric analysis of individual particle size fractions, the ratio of the coefficient value obtained under industrial conditions to a certain value of this coefficient from the beneficiation characteristics constituting its optimal beneficiation value was calculated – Figure 6.

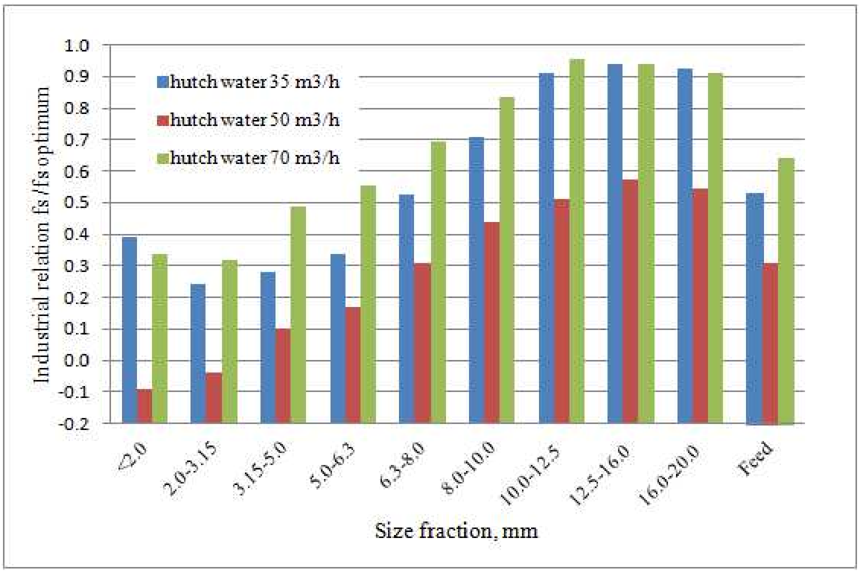


Fig. 6. The level of achievement for the optimal value of coefficient f_s for particle size fractions and the feed

Based on the calculated level of achievement for the optimal value of beneficiation coefficient in individual particle size fractions, it is possible to conclude that size fractions above 8.0 mm are optimal for beneficiation in a jig. The level of achievement for the optimal value for these fractions is higher than 0.7 (for fractions 10.0-12.5 mm; 12.5-16.0 mm; 16.0-20.0, this level is above 0.9).

The analysis of the beneficiation efficiency for variable parameters of the jig operation with regard to the added amount of hutch water indicates that a higher amount of water (70 m^3/h) improves the efficiency of beneficiation in a jig. It especially concerns the fine particle fractions for which a higher value of the level of achievement for the optimal selectivity coefficient was obtained.

The negative value occurs from the fact that in the enriched product – concentrate and middlings – the value of ash content was higher than in the case of tailings. This causes that the values of the useful component recovery and the related values of the recovery of the remaining components in tailings are not natural.

The final product quality is a significant parameter determining recovery. Figure 7 presents differences in obtained values of the combustible matter content in concentrate for certain optimal values and the obtained combustible matter content in concentrate from a jig.

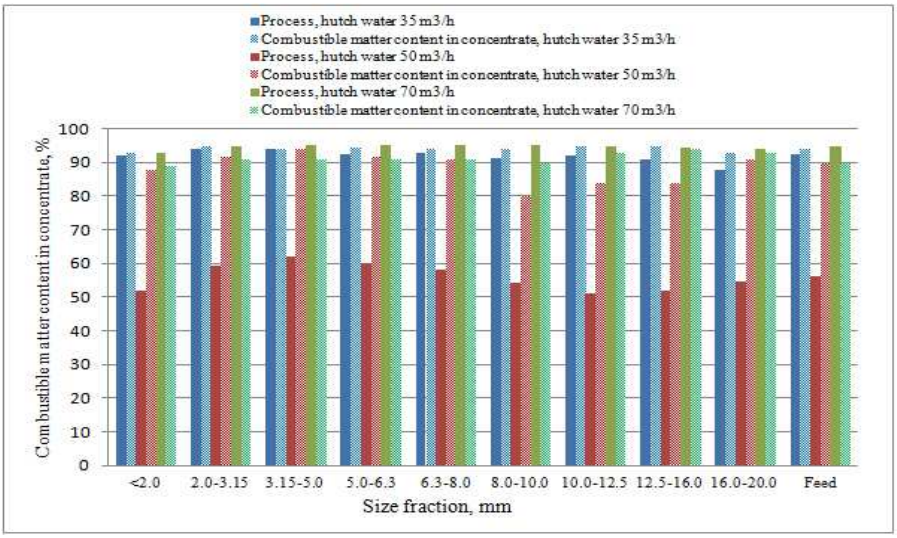


Fig. 7. Values of the combustible matter content in concentrate determined on the basis of the selectivity coefficient and obtained under industrial conditions

The analysis of obtained values of the concentrate quality measured by the combustible matter content in this product for industrial results indicates that in the case of hutch water in the amount of 70 m^3/h, the optimal value was exceeded for the majority of analysed particle size fractions. This contributed to obtaining a lower level of achievement for the optimal value of the selectivity coefficient due to the lower combustible matter recovery in concentrate. In the case of hutch water in the amount of 35 m^3/h, the obtained industrial value of the concentrate quality is lower than the one achievable on the basis of the selectivity coefficient.

In the case of hutch water in the amount of 50 m^3/h, the industrial values are much lower than the values determined on the basis of the potential of raw coal particle size fractions for gravity beneficiation. Causes of such a situation can be searched in the change in the particle size distribution of the feed subjected to beneficiation and in the increased ash content in the feed.

Considering the environmental aspect of atmospheric emission of substances produced during coal combustion, energy production from coal should cause the necessity to pay careful attention to the quality of coal for combustion processes. The important elements related to the process of coal beneficiation include the necessity to optimise the combustible matter recovery due to the energy spent on extraction and beneficiation processes as well as environmental effects of storage or economic use of tailings from coal processing. The presented analysis of partition effects concerning the optimal possibilities of the combustible matter recovery in concentrate and non-useful components in tailings is one of the key aspects in controlling the process and selecting jig operation conditions in order to produce coal fines concentrates for the energy sector. The approach to the analysis of jig operation effects presented here indicates the possibility to expand the range of tools to evaluate the jig operation in which mainly coal fines are beneficiated for the energy sector. The presented analyses demonstrated that, on the basis of the knowledge of the particle size distribution of the feed directed to a jig, the amount of hutch water should be accordingly controlled in order to optimise the production of hard coal fines concentrates for the production of energy from coal with regard to the concentrate quality and level of the gangue matter recovery.

In the literature, one can notice the increasingly widely used Halbich and Fuerstenau upgrading curves or selectivity curves to assess the enrichment indexes of various types of raw materials (Drzymała et al., 2010; Foszcz et al., 2015). Oney (Oney et al., 2020) was proven that upgrading curves are applicable in concentrate technologies. Comparison of upgrading curves proved that the Knelson concentrator is quite efficient in cleaning fine coals, and it allowed the evaluation of which parameters would occur with certain expectations. Fuerstenau enrichment curves were also used to evaluate the effects of graphite flotation (Oney et al., 2019). Sahbaz (2013) applied Halbich curves to determine the flotation effects of lignite. Therefore, it can be concluded that the described methodology can be useful for predicting different materials' future industrial separation results and process optimisation.

Conclusions

The presented evaluation method of the jig operation allowed determining the most beneficial values of technological coefficients of the partition process course. These values enable controlling the process in order to optimise the obtained results for the industrial beneficiation of raw material. The conducted densimetric analysis in particle size fractions for the partition process products in a three-product jig allowed finding the conditions for achieving the high efficiency of industrial beneficiation in a jig in terms of granulation directed to the jig with the given hydrodynamic characteristics.

Certain optimal values occurring from the analysis of characteristics of ability to beneficiation were compared with achieved values in industrial conditions. Such an approach allowed evaluating the efficiency of the jigging process dependably on particle size distribution. High values of the factor of achieving a certain optimal level were registered for coarser particle size fractions, which confirms that coarser particle size fractions, like 10.0-20.0 mm, can be beneficiated more efficiently. For fractions below 10.0 mm, the beneficiation efficiency measured by the recovery of combustible matter in concentrate and the content of combustible matter in concentrate is lower. The obtained relations of achieving optimal values in the context of the amount of hutch water show that this parameter is more important in finer particle size fractions. To adjust separation parameters, the amount of hutch water should be increased. It causes an appropriate loosener of pulsating bed and allows fine particles to be transferred to appropriate products.

The conducted research and analysis of results allowed to verify the suitability of the proposed methods for evaluation of the efficiency of the beneficiation process course in a jig in the context of beneficiation characteristics of narrow size fractions of the feed directed to the process. The obtained results allowed to establish recommendations for coefficients affecting the obtained results of the partition process and possibilities to control it in order to optimise the concentrate recovery and quality.

The obtained results of the jig operation evaluation indicate that a higher amount of added hutch water allows achieving higher efficiency of the partition process, especially for fine particle size fractions directed to a jig. The appropriate control of the process, particularly the concentrate quality, is crucial to achieving optimal values concerning useful component recovery.

The evaluation of the results of hard coal beneficiation because of the optimal recovery of organic phase in concentrate and mineral components in tailings was done in the aspect of process monitoring. The analysis of obtained characteristics of ability to beneficiation was done in purpose of selecting optimal technological factors for the needs of optimisation of device work – in this range, the particle size distribution of the feed was verified in the context of adjustment of variable, which is the amount of hutch water influencing on particles motion on jig bed. It determines the appropriate loosener of pulsating layers of various densities. Such an approach allowed evaluating the influence of changes of added hutch water on separation efficiency in recovery of useful component and amount of combustible matter in concentrate by changeable granulation what allowed to provide guidelines in this range for the needs of conducting the process in industrial conditions.

The certain characteristics presented in this paper allowed selecting the described points in which various criteria realise the technological optimum. The purpose of presented considerations and conducted calculations was to establish optimal points on beneficiation curves allowing more precise determination of potential possibilities of the raw material in the range of obtaining certain values of technological factors of separation process course and, in consequence, monitoring of the process in the purpose of its results optimisation.

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