Utilization of the secondary hard coal preparation in clean coal technologies

J Pielot
Silesian University of Technology, Faculty of Mining and Geology, 2 Akademicka Street, 44-100 Gliwice, Poland
E-mail: Joachim.Pielot@polsl.pl

Abstract. Hard coal remains a valuable power raw material, especially in aspect of clean technology application. The first stage of these technologies is to prepare coal concentrate of low ash content. The paper illustrates the quantitative growth of production value of good quality concentrate by means of concentrate re-preparation using two jig system. Jigs separation curves present the shape that diverge from perfect curve; this fact causes that incorrect grains appear during gravity separation process. Secondary preparation in jigs improves the shape of resultant separation curves. Due to this fact, in two jig system, at the same demanded ash content of final concentrate it is possible to gain the significantly greater production value than in case of single jig – especially in case of small demanded ash content. Increase of production value is especially meaningful in case of hard-dressed coal. If there are more jigs in preparation plant, thus the purposeful operation is to use them properly by means of economically profitable secondary preparation utilization. During secondary preparation it is possible to gain concentrate of lower ash content than in case of a single jig.

1. Hard coal as a source of energy
The world coal resources are quite significant; one forecasts that they will be sufficient for 130 and even more than 200 years [1, p.16, 2, p.9]. The resources are located relatively uniformly, transport of coal is not burdensome, and prices are competitive in relation to other energy sources.

Forecasts say that in 2030, more than 70% of electric energy shall be produced from hard coal using clean coal technology [1, pp.15-16]. This fact shall provide undisturbed availability and accessibility of energy. In 2030, hard coal should provide the needs of about 45% of world energy demand. In developed countries (OECD), increase of coal consumption by 27 percent is forecasted during the period under consideration, in developing countries (Non-OECD), increase by more than 100% as well as decrease of consumption by 12% in Europe; however despite acute restrictions of carbon dioxide emission new coal power plants are constructed or existing ones are modernized [3, pp.504-506].

Generating the electrical energy during coal combustion in traditional power plants is connected with issue of high carbon dioxide emission. Clean coal technologies are implemented, due to which coal combustion is less burdensome for natural environment [3, p.498].

The sore issue is the power safety problem. Power sources that provide this safety are different in various countries, depending on type and condition of resources of primary energy sources as well as nature of power industry. Thus, a lot of states base their power safety on hard coal. The power safety in Poland should also depend on hard coal and brown coal as well, because about 95% electric energy is generated in coal power stations [1, p.18]. However, lack of fuel-power balance is a large difficulty to plan the production [4, p.26].
One may sum up this subsection with a statement that coal is far-reaching (perspective) fuel to produce the electric energy, despite – obviously essential – searching and development of alternative sources of energy [3, p.512].

2. Hard coal preparation perspectives
Hard coal is a fossil fuel that appear in the world in the largest quantity. Being the carrier of energy, it is characterized first of all by grain composition as well as by calorific value. Under raw state, it is a mixture of coal grains (organic substance), concrecences of coal with stone, or other contaminating minerals and water. Parameters of these grains – geometrical dimensions, mass density, calorific value, ash contents, sulphur, moisture – are very diversified. Contaminations of crude coal consist of various mineral substances. The mutual proportions of components of raw coal subject to continuous, temporary changes, and petrographic composition also changes within long period of time. Raw coal is subjected to preparation processes that improve and stabilise the quality of trade products, depending on domestic and foreign customers' requirements. Domestic customers of hard coal are: professional power industry, industry and individual customers.

Coal preparation in preparation plants may be executed using various methods and due to several reasons, because preparation depends on technological properties of raw coal (preparation ability), applied preparation operations in technological system, in which separation is executed, as well as intensity of preparation dependent on trade products parameters required by contracts. The configuration of technological system frequently results from current while projecting the technical-technological level as well as lack of new investments. In specified technological system the preparation processes are, as a rule, precisely determined ones.

Obtaining the required quantitative-qualitative parameters of trade products is possible by means of changes of demanded separation parameters values of preparation operations. The technological system of coal preparation is – from the point of view of control theory – the extreme object, that is illustrated by numerous examples, contained, for instance in papers [5, 6, 7, 8]. Possibility of getting various production values of demanded quality results directly from the nature (type) of the controlled plant – especially – getting the maximum value of production is possible and economically advisable. The questions of production value maximization as well as various aspects of optimization both single preparation operations and the whole technological system of coal preparation plant are presented in numerous publications¹. Three kinds of preparation products most frequently constitute the result of coal preparation processes: the concentrate (or concentrates), intermediate product and wastes. The quantitative and qualitative parameters of preparation products depend on mining-geological conditions of deposit that influence the technological proprieties of raw coal, as well as on intensity and accuracy of preparation; thus on technique level and technology in preparation plant. Also needs of coal customers, determined by trade contracts, force the suitable quality².

Both the preparation scope, and the technical level of preparation plants equipment depend on type of coal – the higher coal type, the wider range of coal preparation (as a rule) and more modern machines; this, in turn, allows getting concentrates of quality that approximate the potentially possible one, resulting from preparation ability.

In numerous studies [19, 20, 21, 22] the preparation methods and technological configurations of coal preparation plants in Poland have been characterized. At present, preparation the coking coal and sometimes the power coal is accomplished within the full range of grains dimension. One foresees full preparation the power coal in all plants in the future³. Due to these reasons, one stipulates for necessity

¹ There can be enlisted several exemplary publications [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].
² It is obvious that quality parameters in concentrate are mutually dependent; thus it is not possible to gain arbitrary values of all quality parameters that create the price (in case of power coal – calorific value, ash content and sulphur). Only one quality parameter value may be selected, the remaining are resultant ones. However, we may obtain the values of three quality parameters that are included in some, interdependent, intervals of values.
³ It is forecasted that power coal shall be dressed within the full range of graining up to 2000 [22, p.255]; this shall allow to improve its quality. In West-European countries, there is demand for power coal of good quality of ash content below 12–14%, whereas
to develop and to improve existing methods of coal preparation, in order to obtain better separation accuracy. More than once a barrier to introduce new technologies (e.g. heavy liquid cyclones) could be the usual lack of place or financial problems. Though a part of plants represent the world level [1, p.14], nevertheless one may generally affirm that the stage of utilization of productive abilities within the range of coal preparation is unsatisfactory.

Because burning the coal unfavourably influences the natural environment, in countries of the highest technological level the technologies of the pure coal are applied at present that reduce the negative burning effect. Under domestic conditions they are applied in limited stage and implemented with large delay, because they require to construct modern power stations$^4$.

The power, economy and ecological efficiency of coal burning processes is nowadays being increased using the methods of coal quality improvement, modern technologies of burning and application of devices reducing the emission [24, p.3]. This three-stage operation complex – before, during and after burning – constitutes the technologies of clean coal (Clean Coal Technologies – CCT), and, more practically saying, technologies of clean burning the fossil fuels [25, p.15, 26].

During the first stage of creating the clean coal the conventional methods of preparation in gravitational separators and in flotation process are utilized, due to which waste rock grains and interlayer grains of large ash content are removed from raw coal. Configuration of technological system of preparation plant depends on preparation ability of coal. Cleaning the coal consists in total removal of stone as well as removal of maximum quantity of pyrite grains. Preparation is very intense, the coal is crushed (selectively) to release small pyrite and waste rock grains, and then coal is dressed using flotation, selective flocculation, agglomeration and other methods.

Coal preparation is, at the same time, the most economically effective method to decrease dusts emission, sulphur dioxide and quantity of wastes. As a result of larger calorific value of dressed coal, necessary quantity of coal decreases and therefore costs of coal transportation and coal tailing transportation shall also decrease [24, p.11].

During the second stage emphasis is put on improvement the energy conversion efficiency while burning the coal. During the third stage, combustion gases are cleaned by means of high effective dust cleaners that eliminate almost entirely an emission of dusts as well as desulphurization is made, significantly reducing sulphur oxides and nitrogen oxides emission [24, p.11].

Conventional coal preparation is applied basically in Polish plants, however additional preparation of more clean coal is not used. A part of power dusts is not still dressed that leads for skipping the process of selective crushing.

The question of future role of coal is a subject of many studies [1, 20, 27, 28, 29]. Authors from Agencja Rynku Energii SA [Agency for Energy Market SA] forecast some drop of coal consumption [2, p.16], however coal remains the perspective source of energy [29]. Unfortunately, many preparation plants are undercapitalized ones, some coal mines are closed as well as coal balance resources have been reduced drastically. This leads to obvious conclusion that raw coal mined should be economically and effectively utilized as much as possible. The growing demand for energy shall force an intense raw coal preparation and various methods of coal preparation may be used here. National foresight indicates development of coal preparation as well as the full automation of preparation processes [19, 21]. The various methods of preparation efficiency improvement should have the right of existence, including multiple preparation in groups of separators with recirculation or without recirculation of intermediate product [30]. Numerous multi-variant analyses of preparation processes in such layouts were conducted. Multiple preparation enrolls into current postulated improvement of preparation methods [19, 21] as

$^4$ Average coal burning efficiency in world power plants is higher than 30%; in case of most modern burning technologies the efficiency is by 10% better. However in future one forecasts the increase of coal burning efficiency up to over 50% [1, p.16].
well as constitutes the trial to answer the widespread opinions that preparation plants have in practice already small possibilities of development [31, p.2].

It has been proven so far [7, 8, 18, 30, 32, 33, 34], that while using gravitational separators groups layout the essential growth of concentrate production value was obtained as compared with single separator; this growth appears during concentrates production of good qualitative parameters. The present report that relates to secondary preparation issue in concentrate jigs, is the modest illustration of improvement possibilities of coal quality during the first stage of clean coal technology.

3. Profitability assessment of secondary coal preparation in group of two jigs

If the separation process of raw coal stream in gravitational separator would run perfectly, then all grains of density smaller than separation density would enter the concentrate, and all grains of larger density would constitute wastes. In the case of perfect separators the separator curve has discrete character. Separation numbers for concentrate \( f(\delta) \) assume only three values, depending on density of elementary fractions of feed \( \delta \) in relation to separation density \( \delta_{50} \):

\[
\begin{align*}
  f(\delta) &= 1 & \text{for } \delta < \delta_{50} \\
  f(\delta) &= 0.5 & \text{for } \delta = \delta_{50} \\
  f(\delta) &= 0 & \text{for } \delta > \delta_{50}
\end{align*}
\]

(1)

Preparation processes cannot be perfect by their nature; that is why real separation curves have the shape worse than the perfect curve and in the case of a coal concentrate they are continuous monotonically diminishing curves. Due to the non-perfect course of preparation processes incorrect grains appear in preparation products. They are waste fractions grains of density larger than separation density, that enter into concentrate and constitute its contamination as well as grains of coal of density smaller than separation density, that enter into wastes and that constitute coal losses in wastes. Figure 1 presents separation curves of jig that relate to various grain classes of feed. Curve designated with number 1 relates to the smallest grains, i.e. below 0.12 mm, the curve designated with number 7 relates to the largest grains above 7.6 mm.

![Figure 1. Generalized partition curves of a two-product jig.](image-url)
3.1. Technological systems under consideration

Figure 2 presents preparation systems considered in Section 3.

Figure 2.Coal preparation system layouts: a) with one jig (1 jig). b) with two jigs with concentrate re-preparation (2 jigs).

Layout with one jig (figure 2.a) is the reference layout. Figure 2.b presents layout of two jigs with concentrate re-preparation (2 jigs). This is the secondary preparation layout but without crushing intermediate products. The layouts of secondary preparation with recirculation and without recirculation of products are well-known in theory and mineral raw materials preparation technique [10, 18, 35], however in case of gravitational coal preparation are used seldom. In the monograph [30] it was pointed out that the usage of second jig, both in layout 2 jig as well as in an layout with temporary product recirculation, improves the shape of supplementary separation curves of two jig layout treated as one two-product separator (separation curves assume the shape closer to a perfect curve). The shape improvement of equivalent separation curves in layouts of two jigs reduces the coefficient of preparation inaccuracy $E_p$. Due to this fact, in order to obtain the suitable concentrate quality defined by the ash content, the larger separation densities in both jigs should be demanded than in reference layout with one jig 1 jig, this gives in result a larger output of final concentrate and larger value of production.

The raw, hard-washable coal was assumed for an analysis presented below. While preparation such a coal, quantity of incorrect grains is a large one and in this case usage of jig layout is purposeful in which the effect of shape improvement of equivalent separation curve proceeds. Table 1 presents density and quality profile features of raw coal within the scope of grain classes 8-20 mm.

Table 1. Density and quality characteristics of raw coal feed.

| Fraction density (g/cm$^3$) | Fraction output (%) | Ash content (%) | Total sulphur content (%) | Calorific value (kJ/kg) |
|-----------------------------|---------------------|----------------|--------------------------|------------------------|
| < 1.30                      | 12.15               | 4.67           | 0.84                     | 30 680                 |
| 1.30 – 1.35                 | 17.96               | 7.40           | 0.86                     | 29 630                 |
| 1.35 – 1.40                 | 10.95               | 10.99          | 0.97                     | 27 300                 |
| 1.40 – 1.50                 | 8.47                | 17.92          | 1.10                     | 25 750                 |
| 1.50 – 1.60                 | 7.43                | 26.61          | 1.24                     | 22 550                 |
| 1.60 – 1.70                 | 7.02                | 35.81          | 1.25                     | 19 160                 |
| 1.70 – 1.80                 | 3.95                | 43.81          | 1.13                     | 16 220                 |
| 1.80 – 1.90                 | 4.04                | 51.03          | 1.12                     | 13 560                 |
| 1.90 – 2.00                 | 2.57                | 57.08          | 1.39                     | 11 330                 |
| > 2.00                      | 25.45               | 75.84          | 2.75                     | 4 420                  |
| Sum                         | 100.00              | 33.67          | 1.46                     | 19 960                 |

While preparation the coal of such grain dimensions, the jig model is reduced to one separation curve designed in figure 1 with number 7, at which separation accuracy in jig is the best one (the separation
curve has the shape most approximate to a perfect one. While preparation smaller grains, the increase of production value in two jig layouts is even larger, because separation curves of every jig have worse shape and renewed preparation results in more essential improvement of shape of equivalent curves.

3.2. The increase of production value at secondary coal preparation

Production value $PV_C$ of concentrate in layouts illustrated in figure 2 is understood as a product of concentrate weight $M_C$ and its unit price $UP_C$, determined according to 4th version of market formula of 2002 [36]. These magnitudes depend on separation density $\delta$ in a one jig or in multiple jigs. At next ash contents ($i$) in the concentrate the production value equals:

$$PV_{C_{1i}}(\delta_{jig}) = M_{C_{1i}}(\delta_{jig}) \cdot UP_{C_{1i}}(\delta_{jig})$$  \hspace{1cm} (2a)$$

$$PV_{C_{2i}}(\delta_{jig1}, \delta_{jig2}) = M_{C_{2i}}(\delta_{jig1}, \delta_{jig2}) \cdot UP_{C_{2i}}(\delta_{jig1}, \delta_{jig2})$$  \hspace{1cm} (2b)$$

Functions (2a) as well as (2b) are maximized using an equality limitation that constitutes the demanded ash content in concentrate. The simulation patterns of preparation operation as well as production maximization algorithm of demanded quality were described in works [6, 30].

The relative maximum production value of demanded quality is shown in figure 3 [32]. Every point on these graphs was obtained each time at optimum separation density. In the 2 jig layout the optimum separation densities in both jigs are the same [30]. Maximum production value in layout with single jig, obtained at optimum ash content 19.2% was assumed as reference level (100%). The optimum ash content in the concentrate depends mainly on raw coal preparation ability characteristics as well as on price structure in market formula [30, p.246]. However, such ash content in concentrate is too high for clean coal technologies. It is also obvious that concentrate production of smaller ash content yields smaller output. Due to this reason, production value of better quality is always smaller than at optimum ash content 19.2%. Value of production in layouts with two jigs may be however significantly larger than in case of single jig at the same ash content in final concentrate; this results from better accuracy of preparation in the 2 jigs layout (figure 2.b). The better quality of produced concentrate the relative value of production is larger in layout 2 jigs as compared with the layout 1 jig. It also results from figure 3 that obtainment of concentrate of lower ash content is possible in two jig layout than in case of single jig.

The production value increase $\Delta PV_C$ in the layout 2 jigs (figure 2.b) including a second jig, in relation to production value in the layout 1 jig (figure 2.a), at next ash contents ($i$) in the concentrate equals:

$$\Delta PV_{C_{2i}} = \left[ M_{C_{2i}}(\delta_{jig1}, \delta_{jig2}) - M_{CKi}(\delta_{jig}) \right] \cdot UP_{C_{2i}} = \Delta M_{Ki} \cdot UP_{C_{2i}}$$  \hspace{1cm} (3)$$

The largest production value increase appears at the smallest ash contents in intermediate and final concentrates. Together with increase of demanded ash content in final concentrate – production value increase diminishes significantly.
3.3. The increase of operation costs
Resolving the issue, whether in appropriate short time is it possible to compensate for investment costs of purchase and installation of an additional jig is the important question. It is worth to mention that the said jig could be a machine of smaller efficiency, because smaller quantity of material for preparation is fed to it (F2 on figure 2.b).

The investment and repair costs bill used here has been presented in the study more in detail [37]. In order to determine the increase of operation costs in the technological system with 2 jigs. that results from installation of an additional jig, the constant unit cost of preparation in the jig $UC_{jig}$ was assumed. covering the operation materials costs, operation maintenance, repairs as well as personal costs. The increase of productions operation costs $\Delta C$ in the layout with 2 jigs is then the product of those unit costs and weight of feed $M_{F2}$ to the second jig

$$\Delta C_i = M_{F2i} \cdot UC_{jig}$$  

(4)

Operation costs in the layout 2 jigs increase together with quantity of dressed coal in the second jig, that constitutes the intermediate concentrate from the first jig. While output increase of this intermediate concentrate, ash content both in intermediate concentrate and in final concentrate increase. This results from increasing and the same separation density values in both jigs, as it was mentioned already above. Thus operation costs in the layout 2 jigs increase together with increase of ash content in the final concentrate.

3.4. Profit of preparation plant resulting from installation of second jig
The difference between production value increase and operation costs increase constitute the profit of plant that results from installing the additional jig:

$$P_i = \Delta PV_i - \Delta C_i = \Delta M_{Ci} \cdot UP_{ki} - \Delta C_i$$  

(5)
Figure 4 presents increase of production value, the increase of operation costs and profit of preparation plant in layout 2 jigs (in relation to these values in the layout 1 jig). This profit results only from installation of second jig. The concentrate production of content slightly above 10% is the point of reference. Thus the costs increasing together with ash content in the concentrate compensate with diminishing increase of production value and the profit of preparation plant has zero value. In such a case, installation of second jig does not provide any advantage. As can be seen from figure 4, the profit of plant occurs at the small ash content in the final concentrate, i.e. when its quality is good. In the face of the postulated improvement of dressed coal quality, within the programme of clean coals production technology [30], installing an additional jig is remunerative at small ash content in final concentrate.

![Figure 4: Increases in maximum production value, operation costs, and profit in 2 jig layout at different demanded values of ash contents in concentrate.](image)

4. Conclusions
The very important question is obtaining the maximum production value from raw coal at execution of the various trade contracts. Looking for new methods to increase production value is a significant issue. The paper presents economic analyses for coal preparation in two jigs with secondary preparation the intermediate concentrate.

Real jig separation curves present the shape that diverge from perfect curve; this fact causes that incorrect grains appear during gravity separation process. Usage of the jig group improves the shape of resultant separation curves. Due to this fact, in final concentrate, using two jigs with concentrate re-preparation 2 jigs, it is possible to gain a significantly greater production value than in the case of a single jig – especially in case of small demanded ash content. Increase of production value is especially meaningful in case of hard-dressed coal. Thus, if there are more jigs in preparation plant, the purposeful operation is to utilize them properly, using secondary preparation or recirculation of intermediate product.
The analyses in Section 3 have been conducted comparing the production value increases and the increases of operation costs in relation to reference layout with one jig. The results specified of effects prognoses in layouts under consideration allow to state that the usage of secondary preparation in second jig is economically profitable. From author’s studies results that one may obtain slightly larger production value [30] in systems with intermediate product recirculation. In group of other separator, it is possible to obtain more quantity of final concentrate of good demanded quality [32, 33, 34, 37].

One should mention that simulation prognoses presented here related to 8-20 mm grain class, at which preparation accuracy is the best one (the separation curve No 7 in figure 1 has the shape most approximate to the perfect one). While preparation smaller coal grains, the increase of production value in two jig systems is even larger.

This study, related to secondary preparation issues, is well inscribed into the domain of postulated improvement of preparation methods. Consideration of preparation in various jig layouts should be particularly essential in case of design or modernization tasks in coal preparation plants.

Possible to obtain – in the case of hard-dressed feed – increase of production value is worth of notice for production engineers in coal preparation plants. This may contribute to the improvement of efficiency level of dispatcher control of coal preparation technological systems.

Obtaionment of smaller minimum demanded ash content in concentrate is possible in jig system than in case of one jig system.

5. References

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