Development of innovative technologies for deep mineral processing

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Abstract. The rate of industrial development depends not only on the demand for products that are outdated in terms of quality, but also on the possibility of updating the quality indicators of the raw material mass, matching the demand dynamics of the raw materials quality with the indicators corresponding to the future tasks. The transition of the world economy and energy to a low-carbon development trajectory reduces the demand for Russian coal, and therefore the near future of the coal industry is associated with fundamental changes in the requirements for the quality and variety of marketable products. There is an urgent need for technological renewal in coal enrichment, restoration and further development of coal chemistry. The paper highlights the key problems and trends in the field of deep coal enrichment, reveals the methods used in the processing plants of Kuzbass. The proposed technology of deep mineral processing "Carbon-99", which received the support of the Skolkovo Innovation Center in 2021, is described. The Carbon-99 technology is a synthesis of technological solutions groups, which variety depends on the properties of the mineral groups included in a particular coal material: enrichment of rock mass cl. 2-200 mm, magnetic separation cl. 0-2 mm, enrichment of sludge masses-centrifugation cl. 0-0. 05 mm. It is shown that the proposed complex technology of deep coal enrichment will reduce the ash content in the concentrates of brown, coking and anthracite coals to 1-9%, and reduce the sulfur content by 30-70%. Reduction of moisture content in the coal mass, including dispersed materials. Also, to obtain concentrates of mineral groups extracted from the coal mass, without chemical reagents.

1. Introduction

In the complicated modern economic conditions, the search for ways to maximize the economic effect of the results of their activities becomes a relevant objective for enterprises. The solution of this problem takes on a special character for those of them whose sphere of activity is the enrichment of minerals. On the one hand, this is due to the global trend of reorientation of the raw materials model of the economy to the processing one; on the other, the specifics of mineral processing involves the implementation of a large number of sequential operations, when the effectiveness of one of them lays the foundation for the quality of the next one; on the third hand, for many enterprises, increasing the content of useful components in processed raw materials is a key direction for the intensification of technological processes.
Coal is a unique material that is used as fuel, raw materials for various industries, and a resource for extracting concentrates of rare elements. One of the areas of active discussion of modern researchers is the fact which method of enrichment ("wet" or "dry") is the most acceptable. Thus, from the point of view of A. M. Gerasimov and S. V. Dmitriev, the use of "wet" production technologies has many negative economic and environmental consequences, especially in the regions of Siberia and regions with arid climate [1]. Therefore, the authors proposed a technological scheme for mineral coal enrichment based on its thermochemical modification. B. Mandal, D. Pudasainee, V. Kurian, R. Gupta and other have a different point of view: in their view, the product quality and extraction with the "wet" method is better than with the dry method of enrichment and the former should be actively developed. But it is important to understand that wet cleaning is mainly used for metallurgical coals, whereas for energy coals there is a general tendency to use dry coal cleaning [2, 3]. It should be noted that many foreign researchers, when describing the methods of coal enrichment, place great emphasis on embedding carbon capture technology and reducing greenhouse gas emissions [4].

The currently existing methods of coal enrichment differ in a wide range of parameters, but the constant increase in the requirements of the consuming industries for the quality of coal products leads to a continuing interest in the development of new ones. These and many other features of the activities of enterprises engaged in the field of mineral processing determine the need to search for production-specific, cost-optimal, relevant to the trends and processes occurring in the industry, scientifically based and highly efficient technologies. In addition, it is important for processing enterprises that the technologies used meet the natural-geographical, climatic and geological features of the territory of their presence.

2. Identification of problems and trends in the field of deep coal processing

The discrepancy between the technological level and the quality of coal products to the requirements of the global coal market is an urgent problem of the industry. The fall in the cost of coal on the world market can be considered as a natural process associated with the imbalance between supply and demand in the competitive struggle with cleaner energy sources. The study of the coal market in Russia conducted by Alto Consulting Group company showed that 80% of all production is carried out in the Kansk-Achinsk, Kuzbass, and Pechersk basins [5], and the search for new coal formations is constantly underway. However, the increase in the production of high-ash coal will only worsen the situation on the market in the future. Considering the fact that the logistics transit is overloaded with coal with an ash content of 9-20%, a valuable mineral component containing a polymetallic mineral group and rare earth elements is sent abroad. High-quality Russian products with an ash content of less than 6% in the domestic and foreign markets are practically invisible, in contrast with foreign high-tech carbon-containing products in the form of a long range of lubricants, paints, fillers, sorbents, electrode mass, catalysts and other things [6].

Against the background of these problems new global trends in the field of deep coal enrichment are being formed:

- Strengthening of Russia's positions in the global coal market.
- Technological development of the industry and strengthening of the scientific and technical base of companies and research centers.
- Development of labor relations and corporate social responsibility of coal companies.
- Improving of professional training system of personnel for the coal industry.

3. Methods of coal enrichment at Kuzbass processing plants

Currently only in the Kemerovo region – Kuzbass there are 54 processing plants and units [7]. In addition to the Kuzbass enterprises themselves which develop and use existing coal enrichment technologies, scientific and educational institutions are working in this direction in the region (table 1).
Table 1. Key coal processing methods used at Kuzbass processing plants [8].

| Company name | Methods used |
|--------------|--------------|
| JSC «SUEK-Kuzbass» | Jigging |
| JSC HC «SDS-Coal» | Jigging, flotation, dense medium separation |
| JSC OUK «Yuzhukzbassugol» | Jigging, flotation |
| JSC «Sibuglemet» | Jigging, flotation, dense medium separation, spiral separation |
| PJSC «SouthernKuzbass» | Jigging, flotation, dense medium separation, spiral separation |
| JSC «Coalcompany«Kuzbassrazrezugol» | Flotation, dense medium separation, spiral separation |
| JSC «Stroyservice» | Jigging, flotation, dense medium separation |
| LLC «Processing plant «Prokopevskaya» | Jigging |
| JSC «Topprom» | Dense medium separation, spiral separation |
| LLC «Processingplant «Angersky» | Jigging, flotation |
| LLC «Coalcompany «Zarechnaya» | Dense medium separation, spiral separation |
| JSC «RaspadskayaCoalCompany» | Dense medium separation, spiral separation |
| JSC «Coal company «Northern Kuzbass» | Jigging, flotation, spiral separation |

The study of the disadvantages and advantages of existing technological solutions according to their main indicators has allowed to reveal the following differences (table 2).

Table 2. Quantitative indicators of key technological solutions in the field of coal processing.

| Indicator name | Pneumatic vacuum separation unit | «Wet» technologies for the enrichment of mining and coal raw materials |
|----------------|-------------------------------|---------------------------------------------------------------|
| Fractional composition of the enriched mass, mm | 13-100 | 0.5-200 |
| Energy costs, kW/t | 1.4-2.0 | 2.5-4 |
| Ash content of marketable products, % | from +5 | from +5 |
| Output of marketable products, % | 30-35 | 45-70 |
| Ash content of waste, % | +40 | 45-70 |

The presented technologies are characterized by the lack of the following features:

- Work at the same density index of coal and rock.
- Production of marketable products with reduced ash and sulfur values below the parent values.
- Extraction of mineral concentrates without chemical reagents in a separate stream using dry method.
- Extraction of toxic, mineral groups from enrichment waste using dry method.
- Deep processing of waste into construction and mineral concentrates.

4. Deep mineral processing technology “Karbon-99”

For several years the authors of the research have been working on the concept of a technology for deep enrichment of coal mass to produce a concentrate with an ash content of 1-6% without the use of chemical reagents, which in 2021 received the support of the Skolkovo Innovation Center. The
approach underlying the project includes 3 technologies that are basic for achieving high-quality indicators of coal enrichment in industrial volumes (figure 1)

![Types of technologies](image)

**Figure 1.** Types of technologies as a part of “Carbon-99”.

According to research, the existing technologies of coal enrichment use, as a rule, two main differences in the organic and mineral components (the difference in the densities of these parts and the difference in their surface properties-wettability). In addition to these differences, the proposed integrated technology for deep coal enrichment uses a significant difference in the friction properties and spectral-noise characteristics, geometric shapes of surface particles, magnetic susceptibility and specific conductivity. The proposed technology will allow the extraction of pyrite inclusions, minerals of the ferroaluminosilicate group, separation of vitrinite group, organic sulfur, alkaline earth compounds and sulfur-containing minerals from the carbon mass, as well as the separation of polymetallic mineral groups.

In terms of the first type of the technology, an automatic control system allows to control the ash content on the flow of the material going to the enrichment, including noise characteristics. There is an option that allows to control the quality of enrichment on the flow, due to the deviation of the actuator by feedback, according to the results of the analysis of noise characteristics. The automatic control system monitors the incoming and outgoing mass, humidity, volume, ash content of marketable products on the flow (according to load cells, capacitive and ultrasonic sensors, the spectrum of noise characteristics controlled on the flow is analyzed). At the exit from the processing plant, the indicators of coal, pyrite minerals, and rock varieties are similarly monitored. The operation principle of the ash content sensors is based on a two-stage analysis of the spectral noise characteristics of coal, rock, and pyrite before the enrichment process and after on the outgoing streams. The proposed technology is used for dry coal with a moisture content of no more than 7.5% for classes from +2 mm and higher.

In the second technology, the material crushed within 0.05-2mm is classified and sent for magnetic separation. The principle of the magnetic separator operation is based on the delta in the magnetic susceptibility of the minerals being enriched, followed by radial separation. For minerals that do not have magnetic susceptibility, an additional concentrating unit of magnetostatic separation is installed to separate mineral inclusions by resistivity. The magnetostatic separator can work independently with various mineral groups ranging in size from values less than a micron to 3 mm.

Settling centrifuge-classifier allows to implement several modes of operation in one unit: including counterflow and direct-flow mode. In the zone where the power is supplied through the feed pipe the counterflow mode of movement of the settled solid phase and the formed liquid phase – a centrate with non-settled solid particles is carried out. In the opposite part of the rotor a direct-flow mode of operation of a cascade classifier centrifuge is implemented, in which the settled fine particles of the solid phase and the clarified product move along the rotor in one direction, which contributes to the controlled clarification of the centrate in several cascades discharged from the centrifuge.

Deep enrichment of coal mass will allow Russian ore enrichment specialists to provide their industry with high-quality raw materials and compete in the world market of energy sources and high-
tech materials by reducing the ash content of products below the parent values in the range of 1-9%. One of the significant factors in the application of the "Carbon-99" technology is the reduction of the environmental load due to the extraction of sorption mineral groups from the coal mass, with the subsequent introduction of commercially attractive mineral concentrates into the enterprise's economy. As a result of deep processing of coal several products are being formed:

- Coal concentrate with an ash content of 1-9%.
- Mineral concentrate, which in contrast to the industrial product of existing technologies is characterized by an incomparably increased content of sorption mineral groups extracted from the coal mass (the material is of interest as a valuable ore concentrate).
- Deep enrichment tailings (of interest as a group of building materials).

Sludge coal washing discharges are the product of technological imperfections of the currently used technologies. By applying "Carbon-99" technologies to the processing of sludge discharges it is possible to change the situation in financial and environmental terms, extracting from the accumulated sludge mass for many decades in all fields of the country, carbon containing material with an ash content of 1 to 15%. With no additional mining and milling costs. To obtain concentrates of mineral groups of commercial interest in industry, to extract environmentally hazardous mineral groups. Significantly reduce the volume and financial maintenance of tailing dumps, hydraulic waste disposals, treatment of recycled and waste water. Additionally, to attract to the economy of the regions products of deep enrichment, mineral groups, both from dry waste and from pulp.

Speaking about the quantitative indicators of the “Carbon-99” technology the following values should be given (table 3).

**Table 3. Quantitative indicators of the «Carbon-99» technology.**

| Indicator name                              | Deep coal processing plant with extraction of valuable mineral and organic components |
|---------------------------------------------|-----------------------------------------------------------------------------------|
| Fractional composition of the enriched mass, mm | 0.001-200                                                                         |
| Energy costs, kW / t                        | 0.1                                                                               |
| Ash content of marketable products, %       | 1-6                                                                               |
| Output of marketable products, %            | 75-90                                                                             |
| Ash content of waste, %                     | 70-90                                                                             |
| The possibility of enriching dry rock mass   | yes                                                                               |
| The possibility of enriching wet rock mass   | yes                                                                               |

5. Summary
The approach underlying the "Carbon-99" technology is an awareness of a set of unsolved goals, economic and environmental problems: between the quality indicators of the industrial coal market and the increasing requirements for the quality of coal products in metallurgy, coke chemistry, coal chemistry, energy in the domestic and international markets, associated with insufficient technological equipment and, as a result, with low economic profitability of coal enterprises, environmentally hazardous marketable products and toxic production waste. "Carbon-99" is a technological tool that shifts the standards of requirements from the existing quality indicators and technological capabilities to the zone of quality indicators of 1-9%.

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