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ENERGY-EFFICIENT TECHNOLOGIES OF INTERGATED COAL AND MINING WASTE DEVELOPMENT IN THE MOSCOW COAL BASIN IN THE CONTEXT OF SECURE AND SUSTAINABLE SUPPLY OF RAW MATERIALS IN CENTRAL RUSSIA

A conceptual framework is provided for high-technology and energy-efficient production of nanomaterials and rare earths toward import substitution and technological independence of machine engineering and other industries in the central region of Russia. It is shown that there are prerequisites for meeting this challenge based on innovative technologies of integrated development of coal deposits and mining waste in the territory of the Moscow Coal Basin. A solution to the problem is an integrated approach to study and development of geotechnologies for high-level processing of coal and production waste based on underground gasification of lignite via filtration channels and a chemical geotechnology for extraction of useful components from ash residue recovered from underground mined-out area. The proposed approach is intended to create a background for implementation of projects fostering regional safety enhancement, primarily, in the field of mineral mining and in technosphere, and, later on, in the socio-economic environment.

Key words: *integrated coal mining, coal, mining and processing waste, underground coal gasification, energy efficiency nanomaterials, rare earths, Moscow Coal Basin, Tula Region.*

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Introduction

Science-based evaluation and high-tech and energy-efficient production of nanomaterials and rare metals towards sustainable import substitution and technological independence of machine building and other industry branches in Central Russia is one of the most critical challenges of this time. The analysis of mineral supplies base and the current technologies shows that meeting the challenge is possible based on innovative techniques of integrated development of coal reserves and mining waste in the Moscow Coal Basin [1–4]. At the same time, the modern approaches described in the new global research [18] devoted to the holistic view over the energy feedstock supply chains reveal the economic, political and social concern about technological efficiency of energy feedstock production and utilization, especially when it becomes increasingly difficult to get access to energy minerals [19]. In this connection, the relevance of R&D discussed in this article is "in flow" of the global trend toward regional security, including mineral resources and energy supply. The issue of secure and sustainable supply of raw materials in general and, specifically, in terms of coal supply in Russia is studied in detail in [23, 24].

Problem formulation

Problem formulation mineral resources are the part of the national wealth of Russia and the natural basis for economic growth in the country. Science-based technologies for development of natural mineral deposits and for mining waste management enable implementation of innovative capabilities of the mining and processing industry. The Moscow Coal Basin features a unique geographical position. This coal field lies in the territory of the Novgorod, Tver, Smolensk, Kaluga, Tula and Ryazan Regions. In-place coal reserves total 11 Bt. Economic resources make over 3.5 Bt. Until recently, the mineral wealth of the Tula Region was lignite of the Moscow Coal Basin where development started in 1853. During this time, the Tula Region has produced more than 21 billion 200 million tons of coal. Total area subjected to coal mining impact is round 12% of the territory of the Region. The similar situations are observed in Kuzbass and in the east of Donbass [5–7]. Hence, it is urgently needed to develop efficient innovative technologies for coal mining and mine waste management in the Moscow Coal Basin.

The scientific significance of this challenge consists in finding new patterns and improving exiting mechanisms of rational nature management when shaping energy-independent industrial clusters. Inside such territories, it is effectual to use innovative technologies of underground coal gasification, electric power generation and processing of ash residue and mining waste. This will allow materializing the ideology of the next-level environmental and industrial safety and will make it possible to formulate scientific principles of import substitution and technological self-sufficiency of the industry in Central Russia based on the integrated development of coal reserves and mining waste in the Moscow Coal Basin.

An objective of the studies is the scientific evaluation and development of geotechnologies for deep conversion of coal and waste of fuel and energy industry, underground mining and other productions through underground gasification of lignite and by using physicochemical geotechnology of ash residue recovery from mined-out voids after gasification in the Moscow Coal Basin. Reaching this objective is the backbone block of meeting the challenge discussed.

The scientific novelty of the objective is the integrated approach to investigation and development of geotechnolgies for deep conversion of coal and mining waste based on underground gasification of lignite in a filtration channel, physicochemical recovery of ash residue from mined-out voids and extraction of useful components. The confidence in reaching the objective and obtaining the planned results rests upon the huge amount of knowledge available on the discussed problem, highly skilled research staff and advanced equipment available at the Tula State University, as well as on effective cooperation with industry and on support from the Tula Region Authorities.

Foreign approaches to similar problems

On the whole, the challenges of integrated development of coal reserves and mining waste as well as marketable production from industrial refuse are of extreme concern in academic schools in Europe and USA. Of special interest is underground coal gasification and the resultant syngas processing. The emphasis is laid on energy-saving technologies. However, the areas of the research are narrow and never intersect. One area is coal mining waste processing and coal dressing with production of different materials from secondary mineral resources (China, USA and Canada). Underground coal gasification is studied in USA, China, South Africa, Poland and Australia. Judging by publications during the recent ten years, dedicated researches are undertaken in all areas within the discussed problem [8–11]. Nevertheless, the presented integrated approach to this problem has never been discussed abroad. The world scientific community explores mainly the areas of underground coal gasification, mining waste management and energy-efficient technologies of mineral processing.

As regards the problem under discussion, the key scientific rivals in the world are currently the academic schools in USA, Canada, Great Britain, Germany, Poland, China and South Africa. This inference is based on the analytical review of publications available in such periodicals as *International Journal Coal Geology*, *Energy Conversion and Management*, *Fuel*, *Procedia. Environmental Sciences*, *Journal of the Taiwan Institute of Chemical Engineers*, *Progress in Energy and Combustion Scienc*e and *Applied Energy* [9–14].

Proposals of the tula region's leading institutions

The Tula State University and Tula Research and Geological Survey ground the proposed methods and approaches on the present-day developments of the theory of gas filtration in porous absorbing media and the physical gas dynamics of reactive media, as well as on the thermal physics and mathematical modeling of mines. Recovery of useful components is based on recent findings of experimental physical chemistry and theory of chemical engineering plants and processes. The theoretical and applied results are subjected to experimental verification in laboratory and full-scale conditions.

Advisable work content for operational stage I:

1. Studies of geology and hydrogeology of coal reserves in the area of the Tula Region.

2. Generalization and systematization of the available data bases on geology, hydrogeology and actual reserves of lignite in the area of the Tula Region.

3. Analysis of ground water quality figures within mining leases of closed mines and geology of remaining reserves of closed open pit coal mines.

4. Analysis of geology, hydrogeology and commercial value of unexposed in-place reserves of lignite in the area of the Tula Region.

5. Substantiation and development of innovative geotechnology concept on integrated development of coal reserves of the Moscow Coal Basin.

As a result, a data base on geology and actual reserves of lignite in the Tula Region will be generated with electronic layouts of closed open pit and underground mines. The hydrogeological characteristic and qualitative indicators of groundwater composition will be obtained for the areas of mining leases of closed mines. The geological structure of the remaining reserves in closed open pit coal mines as well as the ground condition, hydrogeology and commercial value of unexposed in-place reserves of lignite in the Tula Region will be revealed. This information will allow creating a concept of an investment project on innovative geotechnologies for integrated development of coal deposits. The geotechnology of underground coal gasification and electric energy generation will be the energy platform for integrated subsoil management in the Tula Region.

Stage II is to be devoted to studying mechanisms of deliberate change of mining waste properties based on investigations specified below.

1. Classification of iron-bearing waste of mining, processing, fuel-and-energy and metallurgical industries on the ground of estimates of their physicochemical properties and usability as a source of Fe(II) and Fe(III) in formation of nanodispersed particles of magnetite [15].

2. Analysis of change in properties of iron-bearing mining waste (IBW) and investigation of deliberate change of properties and condition of waste rocks under chemical condensation and electrochemical dissolution.

3. Development of the technology of magnetite production from IBW.

4. Analysis of magnetic behavior of magnetite under effect of electromagnetic fields with varied parameters and the estimate of stability of magnetic properties of magnetite produced using different methods.

5. Investigation of mechanisms of deliberate change in properties of magnetite and substantiation of the technology design for production of ferrofluids in various dispersion media; examination of properties and efficiency of these fluids.

The expected results of Stage II include:

— classification of iron-bearing industrial waste as a secondary source of materials to produce ferrofluids; interrelation of composition and properties of IBW and the target scenario of their most rational use;

— mechanisms of formation of nanodispersed magnetite depending on effects exerted by physical fields on mineral constituetn of mining and processing IBW, and the mechanisms of change of mineral properties in production of ferrofluids by way of chemical condensation and electrochemical treatment;

— substantiation of potential increase in saturation magnetization of magnetite owing to elevated degree of dispersion of magnetite particles after treatment in electromagnetic plants with different inductance and frequency;

— evaluation of spectrum parameters for magnetic particles formed under electrochemical treatment;

— diffusion-based mathematical model of magnification of impurities on water surface and science-based parameters of adsorption systems of magnetized spegers of barium hexaferrite for purification of polluted water bodies and treatment of liquid effluents in mining and construction;

— methods meant for deliberate change of properties of mining and processing IBW under influence of thermal and electromagnetic fields with a view to producing cost-effective ferrofluids;

— technologies of integrated mineral mining and processing, with approval of their novelty by governmental patent expertise;

— securing of import substitution and technological self-sufficiency of machine engineering and other works using ferrofluids in central Russia.

Stage III aims to develop theory and scientific basis for generation of thermal and electric enegry in the course of underground combustion of coal, including:

1. Substantiation of physical model and mathematical description of coal combustion in filtration channel.

2. Mathematical model of heat-and-mass exchange under coal combustion in filtration mode and software package of simulation modeling of underground coal combustion.

3. Computational experimentation and determination of steady-state operating modes of underground heat-and-gas generator.

4. Creation of database on recuperative heat exchangers, gas-turbin and gas piston power plants and magnetohydrodynamic generators adaptable to underground heat and gas generators.

5. Conceptual designs of energy production using Underground heat gas producer–Local power plant system.

The Tula State University puts forward new technologies for integrated development of coal fields in the Tula Region: underground gasification of thin and medium-thick lignite beds and full-field development of lignite deposits [16, 17].

The layout of underground gasification of thin and medium-thick lignite (**Fig. 1**) includes vertical production wells 1 connected to horizontal production wells 2 drilled at the boundaries of a coal block at a spacing of 50–60 m. Between horizontal production wells 2, a chain of injection wells 4 spaced at 15–20 m is made. Between the vertical production wells along axis 6 drawn in perpendicular to coal bed strike line 7, the first injection well 5 is drilled. Wells 1 are connected with smoke exhauster 11. Power gas goes from smoke exhauster 11 to a consumer.

The layout of full-field lignite development (**Fig. 2**) contains drainage well 1, production wells 2, air injection wells 3, injection wells 4 to pump a dissolvent for ash and slag rsidue, wells 5 to pump out pregnatant solution to the surface and wells 6 for backfilling. The chains of the wells are spaced at 20–25 m in a coal block. Each chain includes 10–12 vertical wells drilled at distance of 15–20 m from one the other. The chain of drainage wells 1 is connected to water passage 7 that is coupled with water treatment unit 8. The chain of gas production wells 2 is connected with gas passage 9 coupled with smoke exhauster 10, which is switched to power gas purification unit 9 installed before local gas-fired plant 12. The chain of wells 5 to pump the pregnant solution to the surface is connected with pipeline 12 toward chemical engineering unit 14. Carbone dioxide accumulation unit 15 is coupled with power gas purification unit 11 and local gas-fired plant 12. Water treatment unit 6, power gas purification unit 11 and chemical engineering unit 14 are connected to the inlets of rejectable waste unit 16. Rejectable waste unit 16 and carbon dioxide accumulation unit 15 are linked with backfill preparation plant 17.

The full-scale trial of the technology was implemented in Kireevskaya Mine, Mosbassugol Company. A safety pillar at a shaft station was subjected to gasification. The safety pillar occurred at a depth of 65 m in unstable rock mass. The underground excavations at the shaft stations were drained. The pillar was framed by two underground openings that served as horizontal production wells 2. Vertical injection wells 4 were drilled in the center of the safety pillar, and the mine ventilation shaft functioned as vertical production wells 1. After ignition of coal and air-blast supply in the injection wells, the gas producer has reached steady-state operating conditions in 8 days.

The lower calorific value of power gas produced by air-blown gas generators is 3360–4200 kJ/m^2. Oxygen-steam gas supply has increased calorific value of power gas by 45–80%.

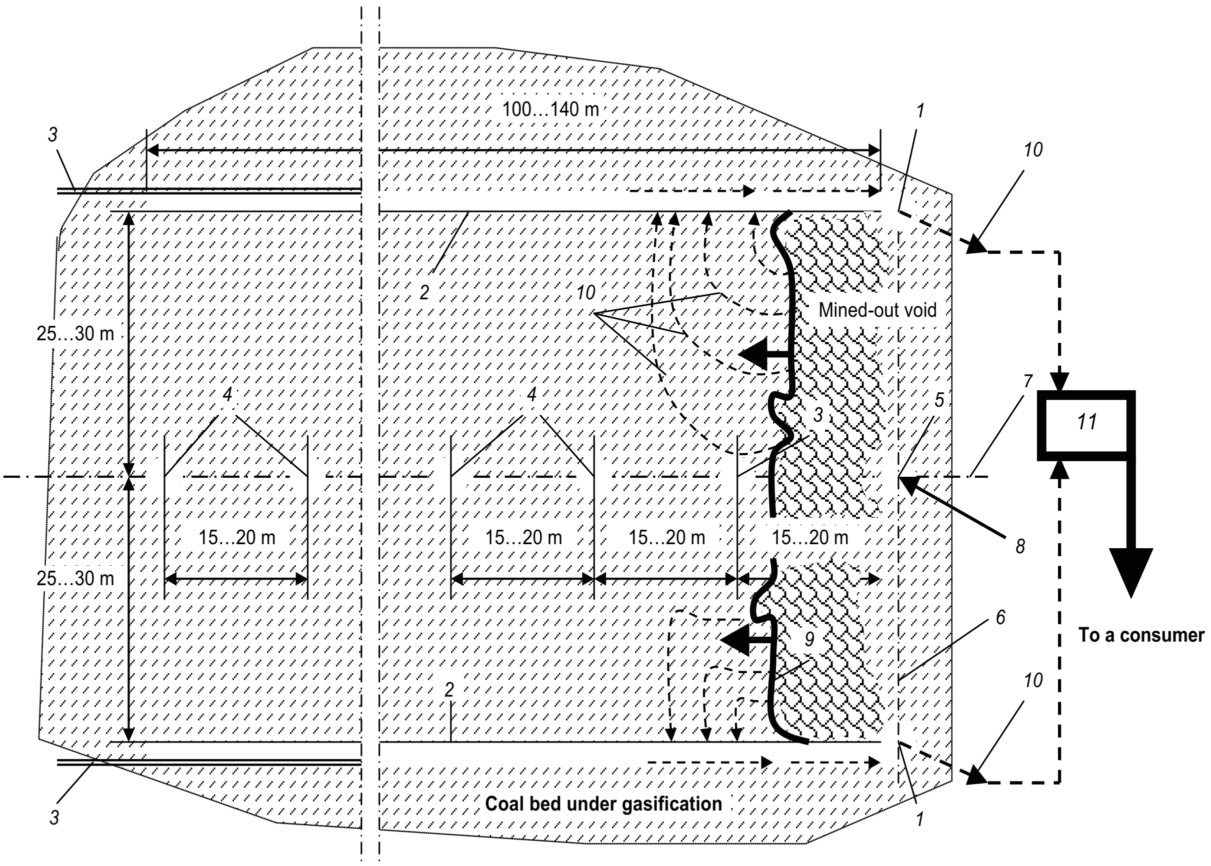

Fig. 1. Method of underground gasification of thin and medium-thick beds of lignite

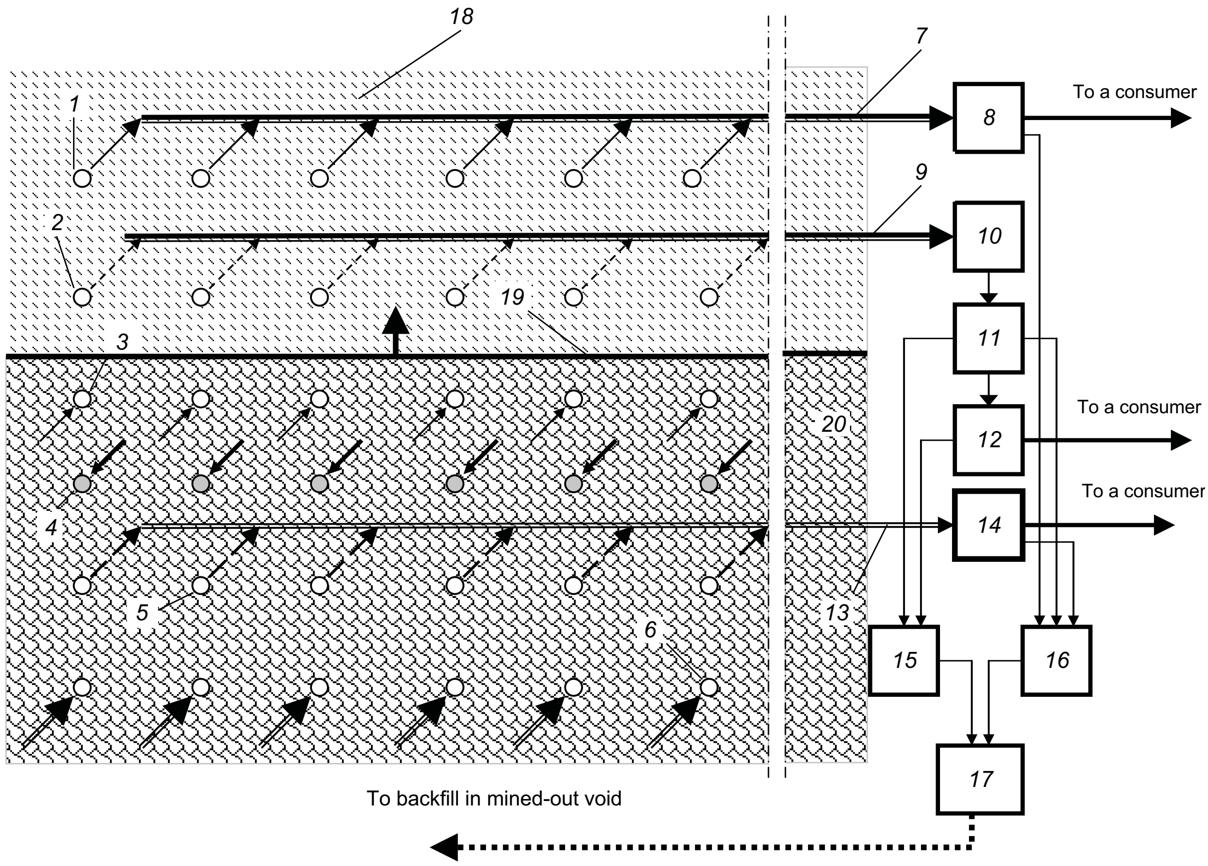

Fig. 2. Full-field developed of lignite deposit

From the evidence of interpretation of long-term observation results, the combustion face temperature should be maintained at a level of 550–700 °C by feeding an oxidizer at a flow rate of 20000–50000 m^3/h. The horizontal production wells should be 100–140 m long and drilled at the boundaries of a treated area in the coal bed, at the spacing of 50–50 m. It is advisable to drill the injection wells in the center of the gasification coal bed, at the spacing of 15–20 m.

In general, the observation data show that the proposed parameters of the technology design enable stable combustion at the fire face of the filtration channel and ensure increased calorific value of power gas by 45–80% in the course of underground gasification of thin and medium-thick beds of lignite at a depth of 30–100 m below the ground surface, in unstable rock masses.

Conclusion

The analysis of R&D undertaken at the Tula State University shows that the technologies of full-field coal development are within the trend of the global challenges, first, and are similar to the most successful foreign projects and even exceed them as regards a few specific parameters. At the same time, based on the actual data of full-field coal development in the mature economies (in terms of production of coalbed methane as an independent energy feedstock [20]), it is understood that these projects are low-profitable and long-term. Finally, the full-fledged science-based technological development is possible within the manufacturing economy and governmental monetary policy as illustrated by the model put forward by Academician Glaziev, e.g. [21, 22].

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