Synergistic approach as an innovative basis for obtaining a natural gas substitute

Pavlo Saik[1*], *Ella* Maksymova[2], *Vasyl* Lozynskyi[1], *Edgar* Cabana[3], and *Mykhailo* Petlovanyi[1]

[1]Dnipro University of Technology, Department of Mining Engineering and Education, 19 Yavornytskoho Ave., 49005, Dnipro, Ukraine
[2]Dnipro University of Technology, Department of Construction, Geotechnics and Geomechanics, 19 Yavornytskoho Ave., 49005, Dnipro, Ukraine
[3]Universidad Nacional de San Agustin de Arequipa, Institute of Renewable Energy Research and Energy Efficiency, 107 San Agustin St, 04000, Arequipa, Peru

Abstract. This paper studies the key problems of mining enterprises activity, which is mainly based on monofunctionality. A synergistic approach is described, which is a constituent basis for perspective performance of coal mines. The possibilities for profile reorientation of the coal mine operation as an enterprise for obtaining a natural gas substitute are analysed. The design peculiarities of a laboratory setup for studying the coal gasification processes (carbonaceous feed, various types of waste, etc.) are described that will form new approaches to implementation of the pilot units for producing the natural gas substitutes on the territory of coal mining enterprises, and combine them into a single mine technological chain. The developed setup, aimed to study the gasification processes, makes it possible to substantiate and determine the parameters of the carbonaceous feed gasification technology for obtaining the end product as a natural gas substitute.

1 Introduction

Currently, 11 state-owned coal mining enterprises (35 mines, of which three are in the phase of decommissioning) are under the jurisdiction of the Ministry of Energy and Coal Mining. Only two coal mining enterprises, such as PJSC Shahta Nadiya and SOE CC “Krasnolymanska” (one mine) are profitable. This situation leads to a decline in the mining industry, which provokes active processes of depopulation, deterioration of environmental conditions, an increase in unemployment, and the like [1, 2].

In fact, due to the lost access to the main oil and gas fields on the Black Sea shelf and a significant part of the coal deposits in the Eastern Donbass, restructuring of mines and reducing the cost of produced coal is an extremely urgent and strategic task. The mining industry prospective development is impossible without the introduction of innovative technical and technological solutions: modern approach for mining field planning [3-5] backfilling of gob area [6-9], reclamation and recultivation processes [10-12], control of

*Corresponding author: saik.nmu@gmail.com

mine ventilation [13-15], geomechanical stydy of rock mass behaviour based on rock properties stydy [16-19], ecological and environmental management [20, 21].

About 80% of all coal reserves occurs in thin and ultrathin seams. At the same time, the load on the stope faces is constantly growing. In the mines of the Western Donbass, during the longwall faces operation on these seams, the average load from one longwall face is about 2500-4500 t/day. Despite this, the processes of mining the coal from thin and ultrathin seams, in terms of their efficiency lead to a revision of the technologies for their development. A prominent representative of the mining sector, the coal region of Ukraine – Western Donbass with its main centres in the cities of Pavlohrad, Pershotravensk, Ternivka, is located in the Dnipropetrovsk region. Coal mining is performed by the private sector – PJSC “DTEK Pavlohradvuhillia” company. Despite the fact that the company continues investment in capital construction and production modernization even in difficult conditions, at the same time it is considering the possibility of decommissioning a number of mines [1, 22, 23].

Now the innovative effectiveness is an integral part of scientific and technological progress. Innovations contribute to a more complete needs satisfaction, an increase in the enterprise’s competitiveness in terms of product quality and production efficiency, organization and management of production at a modern level, as well as environmental protection and ensuring comfortable labour conditions [24, 25]. At the same time, the adjustment of innovative projects parameters is based on a refinement of the initial technical and economic objective, including the term of the project completion due to delays in the financing of its stages, violation of technologies when introducing innovations, delay in delivery of raw materials and other complications. In all cases of such violations, the resulting loss costs are added to the project costs.

Coal is an important strategic raw material for the global energy market. The fuel and energy complex of Ukraine, in particular the coal sector, is represented by mines which are in crisis [26-28]. At the same time, these mines are the main profile specialization of single-industry cities. According to the State Strategy for Regional Development for 2021-2027, dated August 5, 2020, the cities whose development is associated with the implementation of one production function belong to monofunctional. A demonstrative example of such monofunctional cities are the main centres of coal mining regions.

As indicated in the report materials [29]: “Despite the certain measures adopted and significant financial support from the state for two decades, the degradation of the industry is only increasing: the significance of one of the industries that ensures the energy security of the state is gradually being lost. Among the main reasons for unsatisfactory state of the industry is the lack of a systematic approach to the implementation of state policy in the coal industry. This indicates the imperfect and inefficient existing system of state support for the coal industry”.

Thus, the relevant ministries face operational objectives and tasks, which require an urgent and immediate solution, specified in the State Strategy for Regional Development for 2021-2027. (These include the tasks in the direction of “Restoration and development of territories, structural economic restructuring of the regions affected by the armed aggression of the Russian Federation against Ukraine”, p. 5; in the direction of “Socio-economic transformation of territories where coal mining and coal processing enterprises are in the process of shut down”, p. 1-5, p. 9-10).

As noted in the work [30], in the event of mines liquidation, the problem of ensuring the employment of the released labor force and supporting the infrastructure of the mine settlements arises. Therefore, the main task at this stage is to create new jobs. In order to solve it, the new small and medium enterprises can be established in the areas of closed mines or the new production processes can be developed for methane production from the mined-out space of non-functioning mines.

2 Literature review

In recent years, it has become important to use a synergistic approach to analyze economic phenomena and processes. It is based on the development of new principles for the formation of a complex technological innovation system from simpler elements with the use of their best features and advantages [31].

As noted by the author in the work [32], the synergetics emerged resulting from “interdisciplinary problems”: environmental, demographic, economic, food and other global problems of mankind have acquired such proportions that require the combined efforts of scientists from all branches.

The synergistic approach is based on the possibility of cooperation in complex systems, and it comparatively better describes the phenomena and events which take place in the context of globalization [33, 34]. The use of synergistic approach is extremely important in the format of prospective activity of single-industry cities. By involving the property complex of coal mines on the territory of single-industry cities, it is possible to organize and implement separate business projects from mono (coal mining) to multifunctionality (coal mining, coal gasification, processing of solid household waste, capturing of coal mine methane with further gas hydrate formation, etc.) [35-37].

In this case, coal is the main energy feedstock for obtaining a natural gas substitute. When analysing the trends in the fuel and energy complex development, the alternative fuels are quite clearly revealed today, in particular, biofuel, water-coal fuel, synthesis gas (SG), synthetic natural gas (SNG) and hydrogen [38]. At the same time, the process of quick re-equipment of a coal mining enterprise for production of a substitute for natural gas can be based on the introduction of gasification technologies [39]. Moreover, it is additionally necessary to consider the utilization of different waste types, in particular, organic waste, which is implemented at combined complexes, which include high-temperature units of utilization and purification.

In coal gasification (thermal destruction of carbonaceous feed, waste of various genesis), there are three main gases in the initial jet of the main combustible gases: carbon oxide (CO), methane (CH_4) and hydrogen (H_2) [40, 42]. The feed gas may also contain substantial amounts of other gaseous hydrocarbons (C_xH_x) [43, 44]. In this case, to improve the economic performance when introducing this technology on the territory of mining enterprises, the associated recovery of methane, contained in large quantities in the rock mass, is promising in the process of thermal destruction [45]. In fact, it refers to the creation of a new combined technology for mining the coal deposits from two well-known technologies – underground coal gasification and technology of methane recovery from coal seams [46].

Enterprises of underground gasification can be realized in two formats. The first includes hot water supply (HWS) enterprises, the product of which is gas for the production of heat and electricity at thermal power plants. The second includes the energy-chemical complex “HWS-TPP”, in the scheme of which technical and technological solutions are used, which increase the efficiency due to steam and gas installations and improve the ecological purity of the complex due to the processing of initial gasification products [47-49].The formation of the synergistic approach principles for obtaining a substitute natural gas, based on gasification technologies (thermochemical destruction), is characterized by the following common features:

– availability of the required source of transformation and appropriate technical support;

– using the resource, technological and organizational potential of enterprises involved in the exploitation and development of carbonaceous feed (preference is given to coal mines to be decommissioned);

– achieving joint interaction of fuel and energy sector with communal services for the full-factor raw materials attraction and the use of the obtained resources to preserve environmental components.

– determining the demand for the necessary energy products, based on the needs of the domestic and world markets;

Formation of new approaches to the potential development of coal mining enterprises in our time is becoming essential. This will make it possible to substantiate and predict the effectiveness of the proposed solutions regarding the development prospects of not only the coal enterprise, but also the region as a whole [50-52]. The main principle that should be laid into foundation, from a technological point of view, is the continuous system functioning. The predominant operating principle of such a system is cogeneration production of energy carriers based on underground coal gasification, accumulation systems and energy-biological processing.

The creation and development of a new enterprise model or the improvement of the existing one is associated with a number of solutions to complex technological problems and the possibility of their adaptation in various conditions of enterprise functioning. The model is a constituent part of the scientific worldview of the studied object, which, by grouping the common features of the given object, enables displaying its statistical and dynamic indicators [53, 54].

Before the formation of a gas generator model, it is necessary to assess the basic principles and permissible errors that will substantiate its adequacy. Rational principles and permissible errors, when constructing the models, make it possible to determine the basic patterns of the processes characteristic of a given model. In this case, it is possible to neglect the secondary factors influencing its formation. It is customary to distinguish between methods of mathematical and physical modelling, which are based on the principles of physical or mathematical similarity in scientific research.

Thus, the research purpose is to develop a laboratory setup for the study of coal gasification processes (thermochemical destruction of carbonaceous feed, waste of various genesis). This makes it possible to further study the potential of this type of raw material with the formation of new approaches to the pilot projects, developed on the territory of mining enterprises, with the use of a synergistic approach.

3 Methodology of research

Based on the analysis of domestic and international experience of coal gasification installations (thermochemical destruction of carbonaceous feed), the authors of this work have developed and constructed a laboratory setup for studying the above processes using the CAD software package (SolidWorks). This setup makes it possible to substantiate the operating parameters of the formed georeactor system both along the length of the burning front and the length of gasification column. In addition, due to the setup design features, it is supposed to study the "well – gas generator" technology.

Physical modelling makes it possible to perform the entire geotechnical process or its certain parts on a test bench set. This makes it possible to study the patterns of physical and chemical phenomena occurring in the model at minimal financial expenditures. However, there are some difficulties in transferring the obtained patterns to real conditions, since it is necessary to strictly observe the similarity requirements. When studying the underground gasification process, only an approximate physical modelling is possible within the framework of the classical similarity theory. The problem is not only in theoretical providing the similarity criteria equilibrium for the model and prototype, but also in the choice of materials which will be used for modelling the rock mass. According to the similarity theory, which allows determining the similarity criteria of various types and phenomena, it follows that physical modelling of underground gasification on equivalent materials is possible, because the equations describing physical-chemical processes in the model and in prototype are the same.

4 Result and discussion

The authors of this work describe their own project development to study the processes associated with obtaining a natural gas substitute. The setup was purchased with the support of the Ministry of Education and Science of Ukraine within the framework of establishing the Centre for Collective Use of Scientific Equipment "Innovation Geoenergy" (adopted by the Ministry of Education and Science of Ukraine, order No. 444 dated 02.08.2018) with the formation of a laboratory for thermochemical transformation technologies.

The proposed method for producing a natural gas substitute is based on gasification technology. The reproduction and research into gasification processes are effective through the setup completion with the formation of its main working systems. Fig. 1 shows the technological scheme of the coal gasification setup.

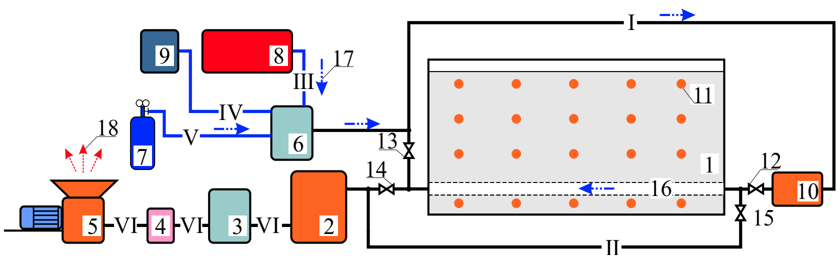

Fig. 1. Technological scheme of the setup for carbonaceous feed gasification (thermal destruction) of the coal gasification: 1 – metal case; 2 – sampling cooler; 3 – automated generator gas metering system; 4 – gas analyzer; 5 – smoke sucker; 6 – automated system for metering the blowing mixture consumption; 7 – oxygen cylinder; 8 – compressor; 9 – steam generator; 10 – blowing reagents distributor; 11 – thermocouples; 12, 13 – blowing pipeline valves; 14, 15 – gas discharging pipeline valves; 16 – reaction channel; 17 – direction of the blowing mixture movement; 18 – direction of the generator gas movement; I – pipeline for the blowing mixture supply at the "well – gas generator" technology; II – reverse pipeline; III – oxygen pipeline; IV – air pipeline; V – steam pipeline; VI – gas discharging pipeline.

The setup is based on four constituting segments:

1. Stand for research into gasification processes. This is a three-section metal box designed to study the gasification processes when modelling the extraction panel and using the "well – gas generator" technological scheme.

2. Blowing components supply system. It consists of blowing joints, a "well – gas generator" pipeline system, an air compressor, a steam generator.

3. Generator gases discharging system. It includes a reverse joint, gas discharging pipeline, cooler tank, smoke sucker.

4. Control and measuring equipment is represented by an automated system for metering the consumption of blowing and gas discharging mixtures, gas analyzers, thermocouples, a thermal imager and a pyrometer.

During the previous studies [55], it has been determined that the gas temperature at the outlet from the experimental gas generator is 435-550°C. This value of the generator gas temperature makes it impossible to determine in it the combustible gases qualitative composition using the available gas analyzer. Therefore, a cooling tank is additionally introduced into the gas discharging system, which not only provides cooling of the generator gas, but also makes it possible to perform sampling from the condensate formed during the research. The cooling tank design provides for a pipeline system assembled in it, while ensuring the throughput of the gas discharging pipeline.

When modeling the coal seam, a reaction channel is formed in it (16). To accelerate the coal seam ignition, it is covered with pieces of coal, and to quickly burn the reaction channel through, the operation of the compressor (8) and the smoke sucker (5) is synchronized. The beginning of the gasification process is controlled by a gas analyzer (4), which is set on the gas discharging pipeline (VI).

The coal gasification process occurs with a variation of blowing mixtures, supplied from an oxygen cylinder (7), a compressor (8) and a steam generator (9), respectively, through oxygen (III), air (IV) and steam (V) pipelines, through an automated system for metering the blowing mixture consumption (6), through the pipeline for supplying the blowing mixture at the "well – gas generator" technology (I) to the blowing reagents distributor (10), and further to the reaction channel (16). In this case, blowing pipeline valve (12) is open, and the gas discharging pipeline valve (15) is closed.

During gasification, the generator gas is discharged through the gas discharging pipeline (VI), through a sampling cooler (2), an automated generator gas metering system (3) and a gas analyzer (4) by a smoke sucker (5). The blowing pipeline valve (13) is closed, and the gas discharging pipeline valve (14) is open.

The resulting condensate is poured into a container through a tap hole built into the lower part of the sampling cooler (2) and sent to a laboratory for assessing the qualitative composition.

The reversing process occurs through a reverse pipeline. In this case, the gas discharging pipeline valve (14) is closed, the valves (15) and (12) are open.

The qualitative composition of the produced generator gas is controlled using an automated generator gas metering system (3) and a gas analyzer (4). The process of burning front advance is controlled by thermocouples (11) located along the perimeter on the side walls of the metal case (1).

A series of experimental studies performed makes it possible to orient the gasification process (thermal destruction) of carbonaceous feed to obtain gas mixtures of the required composition. However, given the current state of the fuel and energy complex, the production of hydrogen, synthesis gas and reducing gases has great prospects. Natural gas substitutes, being processed as chemical raw materials, should contain a minimum amount of oxidant (CO_2) and ballast (nitrogen), therefore the best process is gasification under pressure with steam-oxygen blowing.

A distinctive feature of the developed setup is the ability to study the "well – gas generator" technology. With this technology, the reaction channel is a cylindrical channel. Therefore, when formulating a mathematical description of the gasification process, it is necessary to use a cylindrical coordinate system. The input from the side of the blowing well is taken as the origin of coordinates (17). During the coal gasification process, the reaction zones move along the reaction channel length [56]. The channel dimensions will depend on the increment of seam roof caving and ash residue. The forced diffusion equation for axial symmetry of the reaction channel can be described by the equation:

$$W\frac{dk}{dz}=D\left(\frac{d^2k}{dr^2}+\frac{1}{r}-\frac{dk}{dr}\right)-\alpha k, \quad (1)$$

where W – average flow velocity directed along the axis of the channel; z, r – coordinates; k – oxygen concentration on the surface of carbon dioxide; α – reaction rate constant; D – diffusion coefficient.

The produced gas composition can be changed by varying the blowing mixture supplied to the underground gas generator. For example, the content of carbon monoxide in the produced gas can be increased by increasing the reaction temperature [57, 58]. The gas generator productivity is determined by a number of parameters (pressure, temperature, composition of the source material, which is gasified, the supply of reagents and the time of their contact in the reaction channel) [59-61]. This process can be performed in three main ways: in a stationary layer, in a fluidized layer and in a pulverized fuel flow.

It should be noted that the variety of the source product in the gasification of carbonaceous feed makes possible to obtain a different composition of the formed product:
– generator gas – heat of combustion – 3.8-4.6 MJ/m^3;
– synthesis gas for chemical technology – 10.9-12.6 MJ/m^3;
– reducing gas (for metallurgical and machine-building industries) – 12.6-16.8 MJ/m^3;
– domestic gas (heating) – 16.8-21.0 MJ/m^3;
– synthetic natural gas (combination gas) for long-distance transportation – 25.0-38.0 MJ/m^3.

When implementing the underground gasification process, the issues of obtaining a substitute for natural gas, reducing its losses during transportation, increasing the chemical and energy efficiency, and increasing the economical efficiency should be solved comprehensively.

5 Conclusions

The solution to the problems associated with the mining enterprises activity is to form a new approach to the development of their energy resources. Therefore, today the concept of "coal clean energy technologies" is gaining rapid and positive development. Its introduction makes it possible to reduce the negative impact on the environment and reduce the technogenic load on the coal-mining regions. A peculiarity characteristic of modern coal mining is in situ processing. Therefore, the perspective of developing environmentally friendly sources, based on alternative coal energy technologies, is obvious. An important stage in the underground gasification technology is to obtain high-quality end products with the possibility of further involvement in the country's energy balance. In addition, by forming technologically isolated underground gas generators, it is possible to maximize the energy potential of a mining enterprise, that is, to achieve its maximum efficiency, not excluding the conditions for ensuring environmental components. The developed setup, aimed to study the gasification processes, makes it possible to substantiate and determine the parameters of the carbonaceous feed gasification technology for obtaining the end product as a natural gas substitute.

This research was performed within the framework of scientific works and scientific-technical (experimental) developments of young scientists "Synthesis, optimization and parameterization of innovative technologies for mining the resources of gas-coal deposits" under the support of the Ministry of Education and Science of Ukraine (State registration No. 0119U000248).

References

1. Petlovanyi, M.V., Lozynskyi, V.H., Saik, P.B., & Sai, K.S. (2018). Modern experience of low-coal seams underground mining in Ukraine. *International Journal of Mining Science and Technology*, *28*(6), 917-923. https://doi.org/10.1016/j.ijmst.2018.05.014
2. Dunayevska, N. (2019). Coal research institute kept the power on in Ukraine. *Nature*, *568*(7752), 316-316. https://doi.org/10.1038/d41586-019-01206-6
3. Lozynskyi, V., Medianyk, V., Saik, P., Rysbekov, K., & Demydov, M. (2020). Multivariance solutions for designing new levels of coal mines. *Rudarsko Geolosko Naftni Zbornik*, *35*(2), 23-32. https://doi.org/10.17794/rgn.2020.2.3
4. Galiyev, S.Zh., Dovzhenok, A.D., Kol'ga, A.S., Galiyev, D.A., & Uteshov, E.T. (2019). Digitalization and the potential for improving the design and planning of mining operations in open cast mining. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *1*(439), 146-154.
5. Rysbekov, K., Toktarov, A., Kalybekov, T., Moldabayev, S., Yessezhulov, T., & Bakhmagambetova, G. (2020). Mine planning subject to prepared ore reserves rationing. *E3S Web of Conference*, (168), 00016. https://doi.org/10.1051/e3sconf/202016800016

6. Sotskov, V., Dereviahina, N., & Malanchuk, L. (2019). Analysis of operation parameters of partial backfilling in the context of selective coal mining. *Mining of Mineral Deposits*, *13*(4), 129-138. https://doi.org/10.33271/mining13.04.129
7. Kuzmenko, O., Petlyovanyy, M., & Heylo, A. (2014). Application of fine-grained binding materials in technology of hardening backfill construction. *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining*, 465-469. https://doi.org/10.1201/b17547-79
8. Kuz'menko, O., Petlyovanyy, M., & Stupnik, M. (2013). The influence of fine particles of binding materials on the strength properties of hardening backfill. *Annual Scientific-Technical Colletion – Mining of Mineral Deposits*, 45-48. https://doi.org/10.1201/b16354-10
9. Arslanov, M.Z., Mustafin, S.A.,, Zeinullin, A.A., Kulpeshov, B.S., & Mustafin, T.S. (2020). Model for determining classification of filling materials hardening. *News of National Academy of Sciences of the Republic of Kazakhstan*, *5*(443), 6-12. https://doi.org/10.32014/2020.2518-170x.98
10. Kalybekov, T., Rysbekov, K., Sandibekov, M., Bi, Y.L., & Toktarov, A. (2020). Substantiation of the intensified dump reclamation in the process of field development. *Mining of Mineral Deposits*, *14*(2), 59-65. https://doi.org/10.33271/mining14.02.059
11. Popovych, V., Stepova, K., Voloshchyshyn, A., & Bosak, P. (2019). Physico-chemical properties of soils in lviv volyn coal basin area. *E3S Web of Conferences*, (105), 02002. https://doi.org/10.1051/e3sconf/201910502002
12. Petlovanyi, M., Ruskykh, V., Zubko, S., & Medianyk, V. (2020). Dependence of the mined ores quality on the geological structure and properties of the hanging wall rocks. *E3S Web of Conferences*, (201), 01027. https://doi.org/10.1051/e3sconf/202020101027
13. Golinko, V., Yavors'ka, O., & Lebedev, Y. (2011). Substabtiation of the parameters of elements of mine vent systems while exploiting bedded deposits of horizontal occurence. *Technical and Geoinformational Systems in Mining*, 141-144. https://doi.org/10.1201/b11586-23
14. Bondarenko, V.I., Kharin, Ye.N., Antoshchenko, N.I., & Gasyuk, R.L. (2013). Osnovnye nauchnye polozheniya prognoza dinamiki metanovydeleniya pri otrabotke gazonosnykh ugol'nykh plastov. *Naukovyi Visnyk NHU*, (5), 24-30.
15. Khomenko, O., Kononenko, M., & Myronova, I. (2013). Blasting works technology to decrease an emission of harmful matters into the mine atmosphere. *Annual Scientific-Technical Colletion – Mining of Mineral Deposit*, 231-235. https://doi.org/10.1201/b16354-43
16. Cherniaiev, O.V. (2017). Systematization of the hard rock non-metallic mineral deposits for improvement of their mining technologies. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 11-17.
17. Abdiev, A., Mambetova, R., Abdiev, A., & Abdiev, Sh. (2020). Studying a correlation between characteristics of rock and their conditions. *Mining of Mineral Deposits*, *14*(3), 87-100. https://doi.org/10.33271/mining14.03.087
18. Malkowski, P., & Ostrowski, L. (2019). Convergence monitoring as a basis for numerical analysis of changes of rock-mass quality and hoek-brown failure criterion parameters due to longwall excavation. *Archives of Mining Sciences*, *64*(1), 93-118. https://doi.org/10.24425/ams.2019.126274
19. Dychkovskyi, R., Shavarskyi, Ia., Saik, P., Lozynskyi, V., Falshtynskyi, V., & Cabana, E. (2020). Research into stress-strain state of the rock mass condition in the process of the operation of double-unit longwalls. *Mining of Mineral Deposits*, *14*(2), 85-94. https://doi.org/10.33271/mining14.02.085
20. Gorova, A., Pavlychenko, A., & Borysovs'ka, O. (2013). The study of ecological state of waste disposal areas of energy and mining companies. *Annual Scientific-Technical Colletion – Mining of Mineral Deposits*, 169-172. https://doi.org/10.1201/b16354-29
21. Buzylo, V., Pavlychenko, A., Savelieva, T., & Borysovska, O. (2018). Ecological aspects of managing the stressed-deformed state of the mountain massif during the development of multiple coal layers. *E3S Web of Conferences*, (60), 00013. https://doi.org/10.1051/e3sconf/20186000013
22. Pivnyak, G.G., & Shashenko, O.M. (2015). Innovations and safety for coal mines in Ukraine. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 118-121.

23. Dychkovskyi, R., Vladyko, O., Maltsev, D., & Cabana, E.C. (2018). Some aspects of the compatibility of mineral mining technologies. *Rudarsko-Geološko-Naftni Zbornik*, *33*(4), 73-82. https://doi.org/10.17794/rgn.2018.4.7
24. Bondarenko, V., Svietkina, O., & Sai, K. (2017). Study of the formation mechanism of gas hydrates of methane in the presence of surface-active substances. *Eastern-European Journal of Enterprise Technologies*, *5*(6(89)), 48-55. https://doi.org/10.15587/1729-4061.2017.112313
25. Sadovenko, I.A., & Derevyagina, N.I. (2012). About activation potential of loess landslide massif. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 80-84.
26. Kirin, R., Hryshchak, S., & Illarionov, O. (2020). Features of legal support for the operation of small atypical Ukrainian coal mines under contractual conditions of a public-private partnership. *Mining of Mineral Deposits*, *14*(2), 128-137. https://doi.org/10.33271/mining14.02.128
27. Ma, Z., Pei, X., Yi, Y., Liu, Y., & Zhang, X. (2019). The impact of the ukraine crisis on the planning of russian-european natural gas pipeline projects. *Journal of Coastal Research*, (98), 392. https://doi.org/10.2112/si98-090.1
28. Shevchenko, S., Koval, A., Danylchenko, D., & Koval, V. (2020). Energy crisis and electricity reform of ukraine – first results. *IEEE KhPI Week on Advanced Technology*, (9250119), 526-529. https://doi.org/10.1109/KhPIWeek51551.2020.9250119
29. Rakhunkova palata. (2019). *Zvit Rakhunkovoi palaty za 2019 rik pro rezultaty audytu efektyvnosti vykorystannia koshtiv derzhavnoho biudzhetu 12.11.2019 No. 32-2*. Retrieved from https://rp.gov.ua/upload-files/Activity/Collegium/2019/32-2_2019/Zvit_32-2_2019.pdf
30. Serdiuk, O.S. (2012). Alternatyvni pidkhody do restrukturyzatsii vuhilnoi haluzi Ukrainy. *Naukovi pratsi NDFI*, *3*(60), 115-121.
31. Falshtynskyi, V.S., Dychkovskyi, R.O., Saik, P.B., Lozynskyi, V.H., & Cabana, E.C. (2017). Formation of thermal fields by the energy-chemical complex of coal gasification. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 36-42.
32. Virchenko, V. (2009). Synerhetychnyi pidkhid v ekonomichnykh doslidzhenniakh. *Visnyk Kyivskoho Natsionalnoho Universytetu im. Tarasa Shevchenka*, (110), 34-36.
33. Sribna, Y., Trokhymets, O., Nosatov, I., & Kriukova, I. (2019). The globalization of the world coal market – contradictions and trends. *E3S Web of Conferences*, (123), 01044. https://doi.org/10.1051/e3sconf/201912301044
34. Lahutin, V.D. (2019). *Teoretyko-metodolohichni transformatsii ekonomichnoi nauky u XXI st.* Kyiv: Kyivskyi natsionalnyi torhovelnoekonomichnyi universytet. https://doi.org/10.31617/k.knute.2019-05-29.010
35. Ovchynnikov, M., Ganushevych, K., & Sai, K. (2013). Methodology of gas hydrates formation from gaseous mixtures of various compositions. *Annual Scientific-Technical Colletion – Mining of Mineral Deposits*, 203-205. https://doi.org/10.1201/b16354-37
36. Sai, K., Malanchuk, Z., Petlovanyi, M., Saik, P., & Lozynskyi, V. (2019). Research of thermodynamic conditions for gas hydrates formation from methane in the coal mines. *Solid State Phenomena*, (291), 155-172. https://doi.org/10.4028/www.scientific.net/SSP.291.155
37. Bondarenko, V., Kovalevska, I., Astafiev, D., & Malova, O. (2018). Examination of phase transition of mine methane to gas hydrates and their sudden failure – Percy Bridgman's effect. *Solid State Phenomena*, (277), 137-146. https://doi.org/10.4028/www.scientific.net/ssp.277.137
38. Kong, Z., Dong, X., & Liu, G. (2016). Coal-based synthetic natural gas vs. imported natural gas in China: a net energy perspective. *Journal of Cleaner Production*, (131), 690-701. https://doi.org/10.1016/j.jclepro.2016.04.111
39. Lozynskyi, V.G., Dychkovskyi, R.O., Falshtynskyi, V.S., Saik, P.B., & Malanchuk, Ye.Z. (2016). Experimental study of the influence of crossing the disjunctive geological faults on thermal regime of underground gasifier. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 21-29.
40. Bhutto, A.W., Bazmi, A.A., & Zahedi, G. (2013). Underground coal gasification: From fundamentals to applications. *Progress in Energy and Combustion Science*, *39*(1), 189-214. https://doi.org/10.1016/j.pecs.2012.09.004

41. Dutta, S., Wen, C.Y., & Belt, R.J. (1977). Reactivity of coal and char. 1. in carbon dioxide atmosphere. *Industrial and Engineering Chemistry Process Design and Development*, *16*(1), 20-30. https://doi.org/doi:10.1021/i260061a004
42. Higman, C., & Van Der Burgt, M. (2003). *Gasification*. https://doi.org/10.1016/B978-0-7506-7707-3.X5000-1
43. Lozynskyi, V., Dychkovskyi, R., Saik, P., & Falshtynskyi, V. (2018). Coal seam gasification in faulting zones (heat and mass balance study). *Solid State Phenomena*, (277), 66-79. https://doi.org/10.4028/www.scientific.net/SSP.277.66
44. Ye, D.P., Agnew, J.B., & Zhang, D.K. (1998). Gasification of a south australian low-rank coal with carbon dioxide and steam: Kinetics and reactivity studies. *Fuel*, *77*(11), 1209-1219. https://doi.org/10.1016/S0016-2361(98)00014-3
45. Saik, P., Petlevanyi, M., Lozynskyi, V., Sai, K., & Merzlikin, A. (2018). Innovative approach to the integrated use of energy resources of underground coal gasification. *Solid State Phenomena*, (277), 221-231. https://doi.org/10.4028/www.scientific.net/SSP.277.221
46. Lazarenko, S.N., Trizno, S.K., & Kravtsov, P.V. (2010). Primenenie modifitsirovannoy tekhnologii podzemnoy gazifikatsii uglya dlya razrabotki vysokogazonosnykh ugol'nykh mestorozhdeniy. *Gornyy Informatsionno-Analiticheskiy Byulleten'*, (2), 354-357.
47. Falshtynskyi, V., Saik, P., Lozynskyi, V., Dychkovskyi, R., & Petlovanyi, M. (2018). Innovative aspects of underground coal gasification technology in mine conditions. *Mining of Mineral Deposits*, *12*(2), 68-75. https://doi.org/10.15407/mining12.02.068
48. Beshta, O.S. (2012). Electric drives adjustment for improvement of energy efficiency of technological processes. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 98-107.
49. Pivnyak, G.G., Sobolev, V.V., & Filippov, A.O. (2012). Phase transformations in bituminous coals under the influence of weak electric and magnetic fields. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 43-49.
50. Zhao, Y., Zang, L., Li, Z., & Qin, J. (2012). Discussion on the model of mining circular economy. *Energy Procedia*, (16), 438-443. https://doi.org/10.1016/j.egypro.2012.01.071
51. Bondarenko, V., Kovalevs'ka, I., & Ganushevych, K. (2014). *Progressive technologies of coal, coalbed methane, and ores mining*. London, United Kingdom: CRC Press, Taylor & Francis Group, 523 p. https://doi.org/10.1201/b17547
52. Wang, H., & Li, Z. (2020). Safety management of coal mining process. *IOP Conference Series: Earth and Environmental Science*, (598), 012005. https://doi.org/10.1088/1755-1315/598/1/012005
53. Adjiski, V., Despodov, Z., Mirakovski, D., & Serafimovski, D. (2019). System architecture to bring smart personal protective equipment wearables and sensors to transform safety at work in the underground mining industry. *Rudarsko Geolosko Naftni Zbornik*, *34*(1), 37-44. https://doi.org/10.17794/rgn.2019.1.4
54. Mustakhimov, A., & Zeynullin, A. (2020). Scaled-up laboratory research into dry magnetic separation of the Zhezdinsky concentrating mill tailings in Kazakhstan. *Mining of Mineral Deposits*, *14*(3), 71-77. https://doi.org/10.33271/mining14.03.071
55. Saik, P.B., Dychkovskyi, R.O., Lozynskyi, V.H., Malanchuk, Z.R., & Malanchuk, Ye.Z. (2016). Revisiting the underground gasification of coal reserves from contiguous seams. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 60-66.
56. Falshtyns'kyy, V., Dychkovs'kyy, R., Lozyns'kyy, V., & Saik, P. (2013). Justification of the gasification channel length in underground gas generator. *Annual Scientific-Technical Colletion – Mining of Mineral Deposits*, 125-132. https://doi.org/10.1201/b16354-22
57. Falshtynskyi, V., Dychkovskyi, R., Saik, P., & Lozynskyi, V. (2014). Some aspects of technological processes control of an in-situ gasifier during coal seam gasification. *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining*, 109-112. https://doi.org/10.1201/b17547-20

58. Dreus, A.Yu., Sudakov, A.K., Kozhevnikov, A.A., & Vakhalin, Yu.N. (2016). Study on thermal strength reduction of rock formation in the diamond core drilling process using pulse flushing mode. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (3), 5-10.
59. Pivnyak, G., Dychkovskyi, R., Bobyliov, O., Cabana, E.C., & Smoliński, A. (2018). Mathematical and geomechanical model in physical and chemical processes of underground coal gasification. *Solid State Phenomena*, (277), 1-16. https://doi.org/10.4028/www.scientific.net/ssp.277.1
60. Stańczyk, K., Kapusta, K., Wiatowski, M., Świądrowski, J., Smoliński, A., Rogut, J., & Kotyrba, A. (2012). Experimental simulation of hard coal underground gasification for hydrogen production. *Fuel*, *91*(1), 40-50. https://doi.org/10.1016/j.fuel.2011.08.024
61. Hu, Z., Peng, Ya., Sun, P., Chen, Sh., & Zhou, Yu. (2020). *Thermodynamic 1 equilibrium simulation on the synthesis gas composition in the context of underground coal gasification*. Preprint.