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Experimental Studies of the Effect of Design and Technological Solutions on the Intensification of an Underground Coal Gasification Process

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Abstract: This paper represents the results of experimental studies of physical modeling of the underground coal gasification process in terms of implementation of design and technological solutions aimed at intensification of a gasification process of thin coal seams. A series of experimental studies were performed in terms of a stand unit with the provided criteria of similarity to field conditions as well as kinetics of thermochemical processes occurring within a gas generator. Hard coal (high volatile bituminous coal) was selected as the raw material to be gasified, as that coal grade prevails in Ukrainian energy balance since it is represented by rather great reserves. Five blow types were tested during the research (air, air–steam, oxygen–steam, oxygen–enriched, and carbon dioxide and oxygen). As a result, the effect of tightness of a gas generator on the quantitative and qualitative parameters of coal gasification while varying the blow by reagents and changing the pressure in a reaction channel has been identified. Special attention was paid to the design solutions involving blow supply immediately into the combustion face of a gas generator. The experimental results demonstrate maximum efficiency of the applied gas generator design involving flexible pipelines and activator in the reaction channel and a blow direction onto the reaction channel face combined with blow stream reversing which will make it possible to improve caloricity of the generator gas up to 18% (i.e., from 8.4 to 12.8 MJ/m^3 depending upon a blow type). Consideration of the obtained results of physical modelling can be used with sufficient accuracy to establish modern enterprises based on the underground coal seam gasification; this will help develop more efficiently the substandard coal reserves to generate heat energy as well as power-producing and chemical raw material. The research conclusions can provide technical reference for developing a new generation of underground coal gasification technology.

Keywords: coal gasification; rocks; coal seam; material balance; heat balance; tightness; gas

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1. Introduction

Currently, different studies are being carried out analyzing deep coal processing aimed both at manufacturing of energy products for electric energy generation and obtaining valuable chemical products [1–3]. Use of coal to generate syngas, methanol, liquid fuel, and other deficit products is the tendency of special topicality [4–6]. That makes it possible to consider coal as a reliable alternative source of obtaining carbohydrate raw material, especially in terms of exhaustion of oil and gas reserves due to growing volumes of their consumption and low rates of additional exploration of oil-and-gas fields [7–11].

Currently, production of energetically valuable liquid fuel from coal is the industrially developed process; in this context, reactions of incomplete coal oxidation are quite often to have in surface gas generators [12,13]. A main disadvantage of surface gas generators is their high cost and considerable expenditures for coal extraction and transportation to the place of processing [14]. Underground coal gasification (UCG) is a prospective tendency of deep coal processing; that provides the reactions of incomplete coal oxidation in terms of underground conditions immediately within the place of coal seam occurrence—in an underground gas generator—with production of gas (after its corresponding surface-based processing), which is close to natural gas in its consumer properties [15,16]. Moreover, the gas of underground coal gasification may be the raw material for getting syngas, methanol, ammonia, carbamide, and other valuable chemical products [17–22]. At the same time, it is critically important to provide environmental safety during mining [23–27].

Underground gasification of solid fuel is an important tendency in the development of natural fuel deposits; it means underground fuel transformation into a combustible gas for its further energetic and technological use after its outlet to the earth's surface [28]. Main feature of underground coal gasification is that such mining method helps develop both off-balance and non-commercial coal reserves [29–32]. The non-traditional mining method of coal deposits opens new prospects in the development of coal seams with complicated mining and geological modes of occurrence. It combines extraction, dressing, and complex processing [33–35] with detailed study of rock mass behavior [36–41].

The essence of the technology of underground coal gasification is in drilling of wells from the earth's surface towards a coal seam by means of directed drilling, their linkage within a seam by one of the known techniques with further coal seam ignition, creation of the conditions for coal transformation right underground into a combustion gas, and removal of the produced gas through the wells onto the earth's surface [42–44].

Advantages of the mentioned technology are as follows: coal is not hoisted to the surface, there are no large rock volumes to be placed somewhere, the terrain integrity is not disturbed, there is no subsidence due to formation of underground voids, and there is no need in using additional chemical reagents that have negative impact on the environment [45–47]. Thus, all the technological operations of underground coal gasification are performed from the earth's surface without miners' underground operations. The technology belongs to so-called clean coal technologies, it is environmentally safe, and it can become a great alternative to extraction [48–52].

A process of underground coal gasification (UCG) consists of the primary chemical reactions within an oxidizing zone, a reaction channel of a gas generator [53]. A combustion (oxidizing) process in that zone is accompanied by the formation of carbon monoxides and dioxides. A reducing zone of a gas generator shows the processes accompanied by the secondary reducing reactions with the formation of gasification products [54,55]. A degree of coal transformation into gasification products depends on certain key conditions and parameters: ultimate composition, texture and structure of a coal seam and roof and floor rocks, hydrogeological conditions, pressure, temperature, composition of a blow mixture, directionality and duration of blow contact in space and time with a combustion face of an underground gas generator [56,57].

Currently, there is sufficient number of studies analyzing the features of design and technological solutions in terms of expediency of underground gas generator tightness [58–61], methods of supply and directionality of blow flows with the provided adaptivity and intensification of the processes of coal seam gasification [62–65] including controlled retracting injection point (CRIP) system [66,67], influence of mining and geological conditions of coal seam occurrence on the underground gasification process [68–72], and influences of underground coal gasification on the environment [46,58,73–76].

Application of different technical means, methods, and techniques as well as physical fields makes it possible to intensify the UCG process by effecting two objects: immediate coal mass and blow flows injected into the combustion face of an underground gas generator [77–82].

Tightness of the gas generator design is provided by injection-stowing operations within the deformed layers of the rocks enclosing the seam [83]. Stowing operations are performed with the consideration of changes in geomechanical parameters, parameters of a temperature field of the "rock mass—gas generator" system, changes in the advance rate of a combustion face of a gas generator, and increase in the gasified area in time and space [84–86]. While using injection stowing in terms of gasification of thin coal seams, ground subsidence is not more than 11–18% of the coal seam thickness [87].

Introduction of injection stowing of the deformed natural roof rock and the gasified space within the UCG stations in the underground gas generator design will ensure the mobility of a coal seam gasification process owing to the expansion of the area for the technology implementation. Artificial leak-tightening of a gas generator helps increase the criteria of controllability, compactness, environmental credentials, and safety of the process, which will allow performing the underground coal gasification process in the adapted modes of pressure and temperatures. That stipulates the growth of quantitative and qualitative indices of the UCG process since a set of factors, among which increased pressure in a reaction channel and features of the underground gas generator design are the key ones, results in the considerable losses of blow and generator gas during the coal seam gasification [88,89].

The research objective is to carry out the experimental modeling and study the effect of design and technological solutions, which influence immediately the degree of efficiency of the underground coal gasification process.

To reach the objective the authors, based on the experimental studies, strive to identify the effect of gas generator tightness on the quantitative and qualitative parameters of coal gasification (loss of blow and gas; changes in heat conductivity, temperature, and combustion heat as well as in the output of combustible generator gases and chemical products) in terms of blow variation by reagents and changing pressure in a reaction channel as well as to determine the effect of design and technical solutions for blow supply immediately onto the combustion face of a gas generator (loss of blow and gas, pressure, coal, advance rate and time that the main processes are achieving) depending on the type of gas generator design.

2. Materials and Methods

2.1. Determining the Sufficient Tightness of a Gas Generator

While substantiating the sufficient tightness of an underground gas generator, the following was considered:

(1) Permeability of the coal-overlaying thickness taking into account natural and artificial fractures of the coal-overlaying thickness without injection stowing of the deformed rocks is determined according to the formula (1):

$$K_{c.o.t} = \sum\nolimits_{i=1}^{n} \frac{k_p^i \cdot h_{r.l}^i \cdot P_{r.r}}{h_{r.c} \cdot P_{r.c}}, \tag{1}$$

where $K_{c.o.t}$ is coefficient of permeability taking into account natural and artificial fractures, of the coal-overlaying thickness before stowing operations: k_p^i is coefficient of permeability taking into account natural and artificial fractures of the rock layers of the roof before stowing operations; $h_{r.l}^i$ is thickness of rock layers of the roof, m; $P_{r.r}$ is pressure within the roof rocks, MPa; $h_{r.c}$ is thickness of reaction channel, m; and $P_{r.c}$ is pressure within the reaction channel of a gas generator, MPa.

(2) Permeability of the coal-overlaying thickness taking into account natural and artificial fractures of the coal-overlaying thickness after injection stowing of the deformed rocks is determined according to the formula (2):

$$K_{c.o.t.s} = \sum\nolimits_{i=1}^{n} \frac{k_{p.s}^i \cdot h_{r.l}^i \cdot P_{s.r.r}}{h_{r.c} \cdot P_{r.c}}, \tag{2}$$

where $K_{c.o.t.s}$ is coefficient of permeability taking into account natural and artificial fractures of the coal-overlaying thickness after stowing operations; $k_{p.s}^i$ is coefficient of permeability taking into account natural and artificial fractures of the rock layers of the roof after stowing operations; $h^i_{r.l}$ is thickness of rock layers of the roof, m; $P_{s.r.r}$ is pressure within the stowed roof rocks, MPa; $h_{r.c}$ is thickness of reaction channel, m; and $P_{r.c}$ is pressure within the reaction channel of a gas generator, MPa.

Coefficient of sufficient tightness of an underground gas generator $K_{t.u.g/g}$ with the consideration of the roof rock permeability during injection stowing and temperature effect on the mass under stowing is to be identified according to the formula (3):

$$K_{t.u.g/g} = \frac{K_{c.o.t.s} \cdot \beta_{e.m}}{K_{c.o.t}}, \quad (3)$$

where $K_{c.o.t}$ is coefficient of permeability taking into account natural and artificial fractures of the coal-overlaying thickness before stowing operations; $K_{c.o.t.s}$ is coefficient of permeability taking into account natural and artificial fractures of the coal-overlaying thickness after stowing operations; and $\beta_{e.m}$ is coefficient of temperature expansion of the mass under stowing.

2.2. Determining the Effect of Heat Exchange

A degree of the effect of convective heat exchange within the rocks enclosing a gas generator is determined by density, structure, and dimensions of the voids. General amount of heat (Q) transferred within a certain time period through a rock layer h_r is determined according to the formula (4):

$$Q = \left(\frac{\lambda_{eq}}{h_r} - \alpha_i\right) \cdot (T_1 - T_2), \quad (4)$$

where: α_i is coefficient of heat conductivity of the rocks; h_r is thickness of the rock layer; T_1 is initial temperature; T_2 is final temperature; and λ_{eq} is equivalent coefficient of heat conductivity of the rocks is determined according to the formula (5):

$$\lambda_{eq} = \lambda_r \cdot (1 - P)^3, \quad (5)$$

where: λ_r is coefficient of heat conductivity of the rocks, if there are no artificial fractures in the rocks (intact rock mass); P is value of natural and artificial fractures in the rocks.

Heat conductivity of the rocks is in cubic dependence on the rock porosity and fractures. The stowing of natural and technogenic voids within the deformed layers of the roof results in changes in heat conductivity from the convective to conductive one.

Density of the rock mass enclosing a gas generator decreases due to the effect of rock pressure, which experiences its changes in time and space along with the combustion face advance and stipulates the prevailing convective heat exchange within the roof rocks.

2.3. Experimental Studies

The studies were carried out to test the technological schemes of underground coal gasification, if the gas generator design is changed, i.e.:

- Gas generator design with stowing of the deformed thickness of the roof rocks and the gasified space;
- Gas generator design without stowing.

Apart from the tightness of a gas generator, technical solutions of the blow reagent supply into the combustion face were the subject of experimental identification of the optimal method of the gasification process performance. Following solutions of the blow reagent supply were tested:

- Without a flexible pipeline with the blow direction onto the reaction channel face;
- With flexible pipelines with the blow direction through perforated nozzles onto the reaction channel face;

– With flexible pipelines and activator in the reaction channel, with the blow direction onto the reaction channel face.

2.3.1. Experimental Stand Unit

The experimental stand unit is designed and patented at Dnipro University of Technology, and manufactured by Naftomash RMA under financial support of the Ministry of Education and Science of Ukraine.

A gas generator model consists of four systems (Figure 1):

– An experimental stand;
– A system of supply of separated and mixed blow mixture (blow reagents, see Section 2.3.3);
– A gas outlet system;
– A system of control and measuring equipment (temperature control and control of input and output gas mixtures).

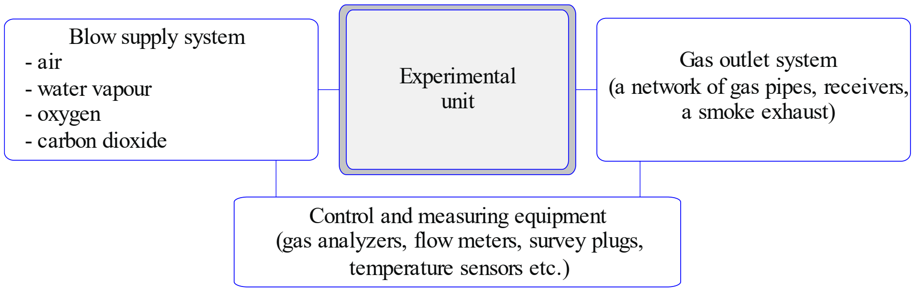


Figure 1. Technological scheme of a stand unit of underground coal gasification.

An experimental stand welded from sheet steel is a central link of the facility. There are holes for blow supply and generator gas outlet as well as ignition and control holes on the stand front [90,91]. A system of thermal sensors with signal converters equipped with the interface was used to identify the temperature field parameters. The reference shear detectors were used to control the coal mass state.

The coal rock mass was modelled in terms of the experimental unit according to the similarity criteria (see Section 2.3.5).

2.3.2. Ultimate and Technical Composition of Coal

Hard coal (high volatile bituminous coal) was selected as the raw material to be gasified. That coal grade prevails in Ukrainian energy balance as it is represented by rather great reserves. Table 1 shows proximate and ultimate analysis of the coal.

Table 1. Proximate and ultimate analysis of the coal.

Proximate Analysis					Ultimate Analysis				Combustion Heat (Q_r), MJ/kg	Coal Density (γ), g/cm^3
W^r, %	W^a, %	A^c, %	S^d, %	V^{daf}, %	C^{daf}, %	H^{daf}, %	O^{daf}, %	Nr, %		
1.7	2.2	38.2	1.3	37.0	80.7	6.3	6.8	4.9	24.6	1.45

The values shown in Table 1 are used to calculate the material and heat balance (see Section 2.3.4), being an indispensable part of research as the obtained results of calculations define the required amount of blow to be supplied into a gas generator.

2.3.3. Blow Reagents

The stand-based experimental studies were accompanied by changes in the parameters of blow reagents. Five basic previously tested blow types were used, i.e.:

I. Air blow (O_2—21%, N_2—79%);

II. Air–steam blow (O_2—21%, N_2—79%, H_2O_{steam});
III. Oxygen–steam blow (O_2—35%, N_2—65%, H_2O_{steam});
IV. Oxygen–enriched blow (O_2—35%, N_2—65%);
V. Carbon dioxide and oxygen (O_2—21%, CO_2—10%, N_2—69%).

A series of experimental studies was alternated by means of blow change. Each following change in blow mode was followed by the transfer to the air blow. A transition mode in terms of blow lasted one hour.

2.3.4. Material and Heat Balance

The material and heat balance are determined by physical rates of chemical reactions, technological efficiency of the process, and modes of blow mixture supply into the gasification zone [92]. To calculate the material and heat balance, the MT-Balance software was applied. The software product was developed at the Dnipro University of Technology [93,94].

During the calculation, the software uses not only the specified parameters of the ultimate and technical composition of the coal but also many physical values-constants as well as the values characterizing the initial state of the gasification process. The software algorithm makes it possible to obtain the following:

- Material balance of the oxidizing zone;
- Material balance of the reducing zone;
- Volumetric parameters of gas mixtures of a gas generator;
- Chemical and physical efficiency of the gasification process;
- Energy balance of the gasification process;
- Total energy of the oxidizing and reducing zones.

Identification of the material and heat balance with the help of underground gasification is a valid and convenient mechanism for obtaining quantitative and qualitative parameters of the blow mixture composition and gases outgoing from a gas generator. That allows simplifying considerably the data processing and helps obtain rapidly the final results with high degree of conformity.

2.3.5. Similarity Criteria

Modeling of the operating parameters of the process of underground coal gasification according to the criteria of similarity to field conditions are the important elements of the experimental data transfer into the field conditions as the performance of experiments in terms of ground stand units are aimed at simulation of the UCG processes taking into account geological and technological parameters [95,96].

The research was carried out in terms of the experimental stand unit to model a process of underground gasification taking into consideration the similarity criteria and the specified scale coefficients. Following expression is taken as the basis in terms of non-stationary seam gasification [97]:

$$\overline{T} = \frac{T - T_0}{T_{\max} - T_0} = f(H_0), \tag{6}$$

where T is current temperature, °C; $T_{\max}$ is maximum temperature, °C; T_0 is initial temperature, °C; H_0 is criterion of homochronicity (of time).

$$H_0 = \frac{v \cdot t}{x} = 1, \tag{7}$$

where v is gasifying rate, m/day; t is gasifying time, days; x is distance, m.

Generally, all similarity criteria, taking into consideration time, are called homochronicity criteria (*Ho*) since they are applied to identify a time conversion factor through a multiplier of other physical quantities. Hence, in terms of similarity of two or more systems, *Ho* (homochronicity criterion), *Fr* (Froude number), Eu (Euler's criterion), and *Re* (Reynolds number) have the same values for any similar points. In practice of similarity criteria use, it is expedient to reduce some of them to more convenient format helping determine directly values being a part of the criteria.

Thus, a conclusion concerning full nature-model similarity compliance makes it possible to calculate homochronicity criterion, i.e., constant temporal similarity within the processes. Comparison of modeling of working parameters of underground coal gasification helps obtain the following:

$$Ho = \frac{v \cdot t}{x} = \frac{v' \cdot t'}{x'}, \tag{8}$$

where v is actual displacement velocity of a material point, m/day; t is displacement time of the point, days; x is distance passed by the material point during t time, m; and v', t', x' are velocity, time, and path of a similar material point on the model, respectively.

To obtain the valid results of the modelling in terms of the experimental stand unit that would help get the data for field conditions, a group of similarity invariants, characterizing the gasification process, were considered [98]:

- Kinetics of chemical reactions;
- Gas dynamics and mass exchange of the oxidizing and reducing zones;
- Convective and conductive heat exchange.

Adherence to the abovementioned similarity invariants, representing the gasification kinetics, was obtained by the fact that the coal model was of the same grade and composition as the "field" coal.

Convectional temperature exchange takes place right within a contact of reactional zone expanding up to 2–4 thicknesses of the degassed seam. Then, enthalpy takes place at the expense of conductive rock heating. Temperature rise and its expansion deep in the rock mass last until origination of thermal stresses varying rock behavior while falling [99]. Based upon previous research carried out under the conditions of Western Donbas mines, it can be concluded that convectional enthalpy transfer was observed at greater distances than 6 m [100]. This situation is justified by the stratification cavities formation in the roof of an underground gasifier and the presence of pores and fractures in it. The degree of influence of heat exchange convection is determined by the presence of cavities in the rocks and their location, which in turn determines the thermal stress of the adjacent roof rocks.

The pressure in the underground gas generator model and the ultimate composition of a generator gas in the similarity scale meet the field conditions. According to the calculated data, air consumption during the air blow was 2.32 m^3/kg of coal; in case of blow enriched with oxygen, it was 1.89 m^3/kg of coal. The reaction channel length within the experimental stand is 1.5 m; thickness of the coal seam is 0.5 m. Taking into account the similarity criteria, a 1.5 m value of the reaction channel length corresponds to the reaction channel length of the underground gas generator being 30 m.

3. Results and Discussion

As a result of the stand-based experimental studies, the influence of tightness characteristics of a gas generator on the quantitative and qualitative parameters of coal seam gasification have been identified. Figure 2 demonstrates a graph of changes in losses of the blow supplied into a gas generator and the obtained generator gas in terms of changing pressure growth from 0 to 0.35 MPa.

The Graph demonstrates that stowing nonavailability starts impacting blow and generator gas losses in terms of minimum pressure change achieving maximum 32.5% values at 0.35 MPa pressure. In turn, at the same pressure value, stowing is only 15%. Hence, 17.5% (i.e., more than double) difference in blow losses has been identified depending upon various modes of preparation of gas generators.

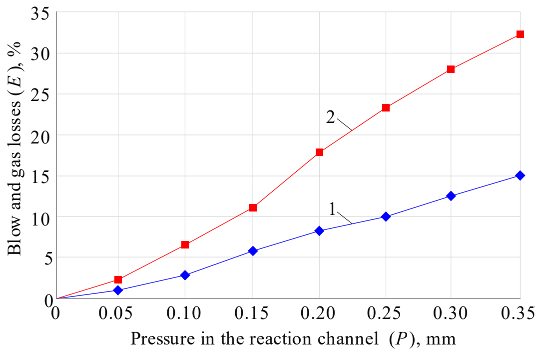


Figure 2. Dependence of blow and gas losses (*P*, %) in terms of pressure changes in an underground gas generator: 1—gas generator design with stowing of the deformed thickness of the roof rocks and gasified space; 2—gas generator design without stowing.

A gas generator design with stowing of the deformed thickness of the roof rocks and gasified space is characterized by $K_{t.u.g/g}$ = 0.032 coefficient of leak-tightness. At the same time, the tightness coefficient of a gas generator without stowing is $K_{t.u.g/g}$ = 0.214.

In terms of sufficient gas generator tightness ($K_{t.u.g/g}$ = 0.032), it is possible to ensure effective contact of blow and a combustion face of the reaction channel. In addition, heat capacity of the rocks enclosing a gas generator increases; heat efficiency of the reaction zones of a gas generator grows stipulating stability of material and heat balance of the coal seam gasification process.

Figure 3 shows the dependences of heat conductivity of the rocks around a gas generator on the temperatures emitting during gasification and tightness of a gas generator.

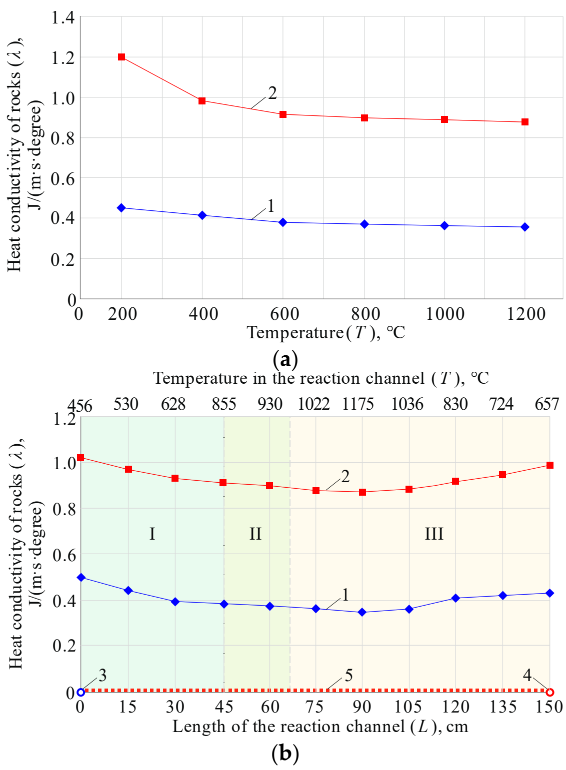


Figure 3. Dependences of heat conductivity of the rocks (λ) around a gas generator on the temperatures emitting during gasification and tightness of a gas generator: (**a**)—general conductivity of the roof rocks of a gas generator; (**b**)—heat conductivity of the roof rocks along the combustion face of a gas generator; 1—generator design with stowing of the deformed thickness of the roof rocks and gasified space; 2—generator design without stowing; 3—air-supply well; 4—gas-outlet well; 5—line of the combustion face of a gas generator; I—oxidizing zone; II—transition zone; III—reducing zone.

Increase in temperatures in the oxidizing zone of a gas generator and heat capacity of rock layers are observed throughout the reaction channel length, which is stipulated by heat losses in the rocks around the reaction channel. That happens at the expense of decreasing heat and temperature conductivity of the roof rocks. Heat-generating capacity of the oxidizing zone at the expense of artificial heat insulation of the rock mass provides efficient operation of the reducing zone, where endothermal reactions with heat absorption occur. Technogenic heat of the rock mass around a gas generator is rather considerable; correspondingly, in terms of its removal, it can be used in cogeneration plants.

Coal is gasified in terms of blow injection from the side of coal mass and gas removal from the gasified space. Along with the expanding degassed void, consumer features (calorific capacity) of gas are deteriorating as the gasification front is displacing gradually from the initial location to the gasification boundaries, leaving behind the gasified space, which is filled gradually with slugs, residual coal, and deposited rocks of the upper thickness. The fly ash is driven out of coal from an underground gasifier together with the generator gases. It is generally captured by particle filtration equipment before the flue gases reach the chimneys. Non-reacted coal ash is left in the mined-out space. The volume of non-reacted coal ash makes up 38–45% of the volume of the coal seam.

Figure 4 shows the results of analyzing the temperatures of gasification products at their output from the gas-outlet well and combustion heat of a generator gas of a thin carboniferous seam.

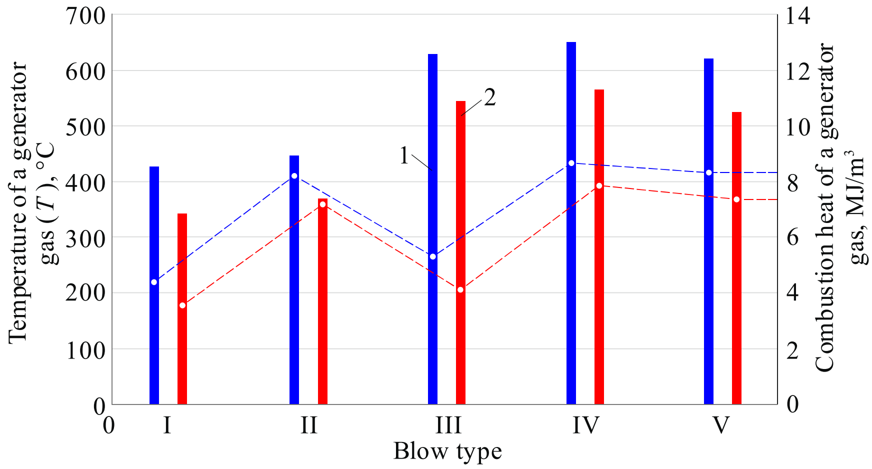
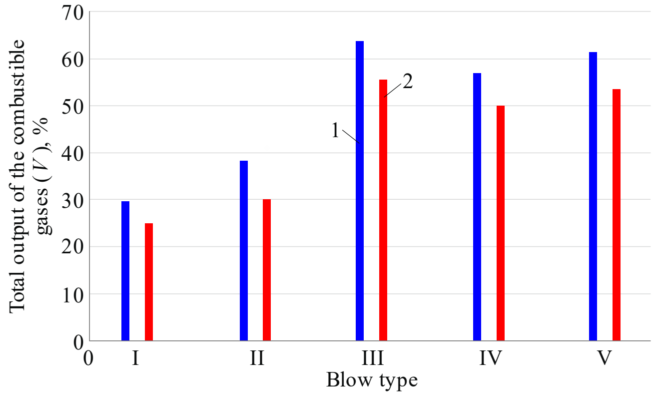
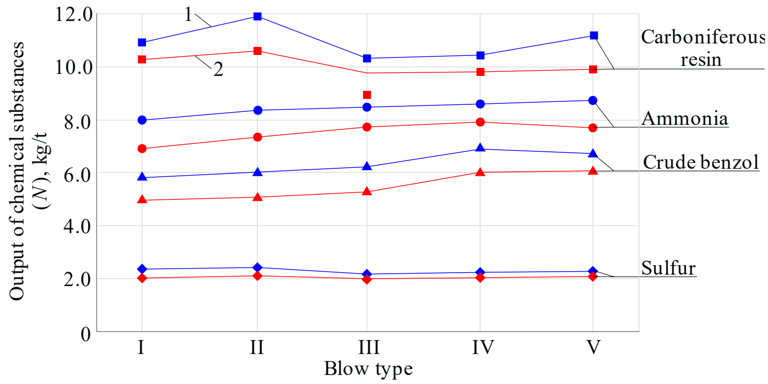


Figure 4. Dependence of changes in the temperature of coal gasification products (generator gas) at their output from a gas-outlet well and combustion heat of a generator gas upon the blow type and tightness of a gas generator: 1—generator design with stowing of the deformed thickness of the roof rocks and gasified space; 2—generator design without stowing; I—air blow (O_2—21%, N_2—79%); II—air-steam blow (O_2—21%, N_2—79%, H_2O_{steam}); III—oxygen-steam blow (O_2—35%, N_2—65%, H_2O_{steam}); IV—oxygen-enriched (O_2—35%, N_2—65%); V—carbon dioxide and oxygen (O_2—21%, CO_2—10%, N_2—69%).

The obtained results of stand-based experimental studies of design features of artificial tightness of a gas generator have made it possible to evaluate the quantitative and qualitative parameters of the output of coal seam gasification products taking into account mining-geological conditions, design features of a gas generator, and technological parameters of the gasification process (Figure 5).



(**a**)



(**b**)

Figure 5. Dependences of changes in the output of coal gasification products (generator gas) upon the blow type and tightness of a gas generator: (**a**)—output of combustible gases; (**b**)—output of chemical substances from a condensate; 1—generator design with stowing of the deformed thickness of the roof rocks and gasified space; 2—generator design without stowing; I—air blow (O_2—21%, N_2—79%); II—air-steam blow (O_2—21%, N_2—79%, H_2O_{steam}); III—oxygen-steam blow (O_2—35%, N_2—65%, H_2O_{steam}); IV—oxygen-enriched (O_2—35%, N_2—65%); V—carbon dioxide and oxygen (O_2—21%, CO_2—10%, N_2—69%).

Decreasing natural and artificial fractures of the layered roof rock thickness and the gasified space at the expense of increased tightness of a gas generator helps reduce migration of high-temperature UCG products into the roof and floor rocks. In turn, that will allow further expansion of the UCG application area in terms of thin coal seams occurring at shallow depths. The calculations have shown that preparation of underground gas generators with injection stowing of the roof rocks will make it possible to increase the gasified coal area by 1.6–1.8 times, the degree of coal seam gasification will grow by 7–12%, and the heat-generation gas capacity will go up to 18%.

At the same time, great attention should be paid to continuous supply of air mixture onto the combustion face of the gas generator's reaction channel as that creates stable pressure and activates heat-generation within the oxidizing zone of the reaction channel. That results in the balanced behavior of active zones of a gas generator and balanced kinetics of thermochemical reactions of the gasification process.

Having been developed and tested in terms a stand unit for simulation of the underground coal gasification process, the design and technical solutions aimed at blow supplying immediately onto the combustion face stipulate intensification of a gasification process of thin coal seams taking into account specific mining-geological conditions.

Consequently, three possible gas generator designs were to be analyzed as for the efficiency of a gasification process:

(1) Without a flexible pipeline for blow direction onto the reaction channel face (design A);
(2) With flexible pipelines for blow direction through perforated nozzles onto the reaction channel face (design B);
(3) With flexible pipelines and activator in the reaction channel, with blow direction onto the reaction channel face (design C).
(4) Figure 6 represents the results of a series of experiment studies.

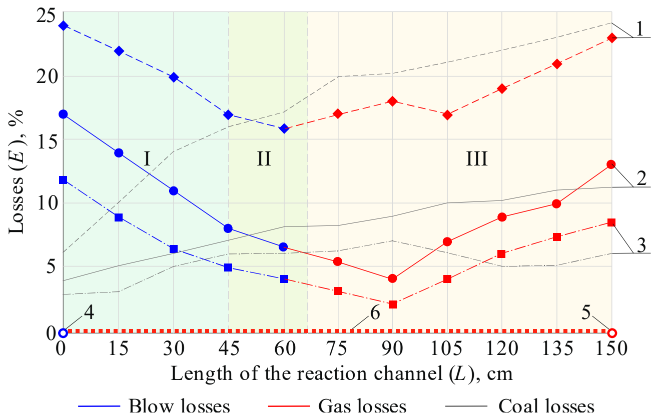


Figure 6. Dependences of the losses of blow, generator gas, and coal upon the gas generator design: 1—design A; 2—design B; 3—design C; 4—air-supply well, 5—gas-outlet well, 6–line of the combustion face of a gas generator; I—oxidizing zone; II—transition zone; III—reducing zone.

If a gas blow flows from the side of mass, gas outlet towards the gasified space is stimulated somehow by large volumes of that space, deformation, and rock caving into the gasification zone as well as the available excessive pressure in it.

Coal is gasified better around the blow well than around the gas-outlet well. Thus, this is the point with higher concentration of coal losses in terms of seam area and thickness. Moreover, it is stipulated not only by the unilateral direction of the blow flow but also by the fact that the advance of reaction zones of gasification along the channel length is accompanied by the deteriorating aerodynamic conditions, and finally there will be a moment when there is no sufficient length for the reaction zones.

Figure 7 summarizes analyses of the effects of different designs of a gas generator (A, B, and C) as for the blow supply into the reaction channel on the uniformity of the combustion face advance.

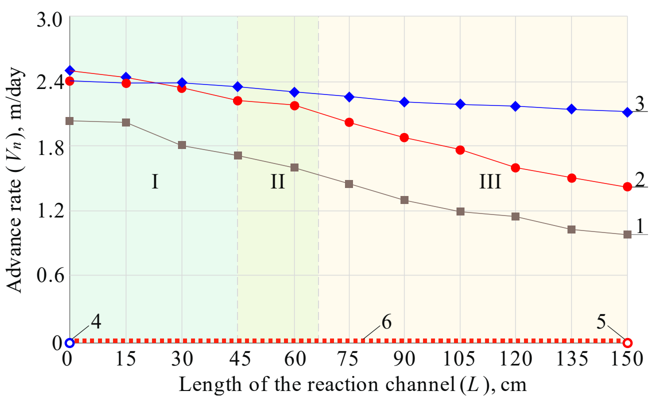


Figure 7. Dependences of the effect of different designs of blow supply into the gas generator's reaction channel on the uniform combustion channel advance depending on the gas generator design: 1—design A; 2—design B; 3—design C; 4—air-supply well, 5—gas-outlet well, 6—line of the combustion face of a gas generator; I—oxidizing zone; II—transition zone; III—reducing zone.

While analyzing Figure 7, it is possible to state the following: if coal seam is gasified involving the gas generator design with flexible pipelines and activator in the reaction channel as well as the blow direction onto the combustion face of a reaction channel (design C), there is no need in blow reverse as we can observe uniform advance of the gas generator's combustion face.

Involvement of the off-balance and abandoned reserves of thin and very thin coal seams into gasification in terms of using the designs and technological schemes of gas generators with the controlled flexible pipelines, perforated nozzles, and activators provides adaptive activation of the oxidizing and reducing processes with the controlled transition zone between them in the reaction channel of a gas generator. Control and controllability of a gas generator throughout the reaction channel length is ensured by the dosed, separate supply of a blow flow onto the combustion face into each active zone of the reaction channel. That results in the reduced losses of blow, generator gas, and solid fuel; it also stipulates uniform advance of active zones of the reaction channel's combustion face during the coal seam gasification.

Implementation of the abovementioned technological solutions in the gas generator designs and technological solutions of coal seam gasification will reduce considerably the time spent for the formation of a reaction channel and beginning of the mine gas generator's operation in active mode of coal gasification (Figure 8).

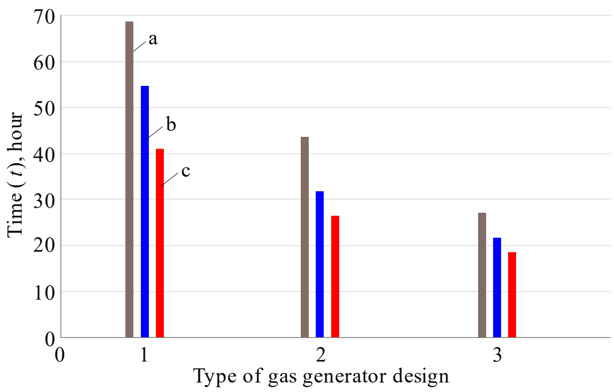


Figure 8. Effect of the gas generator design on the time of achieving the main processes: a—formation of the reaction channel of a gas generator; b—start of the gasification mode of a gas generator; c—reversing; 1—design A; 2—design B; 3—design C.

Consideration of geological structure, ultimate composition of a solid fuel, rocks of the roof and floor as well as the parameters of blow mode and its direction onto the combustion face according to the functional features of active zones of a reaction channel and design solutions of a gas generator stipulates adaptivity of the process of underground coal gasification to a concrete model of thin coal seam development in terms of using flexible pipes with perforated nozzles, or activator.

Control of the process of thin and very thin coal seam gasification with the help of flexible pipelines with blow direction through perforated nozzles onto the reaction channel face (scheme B) does not provide sufficiently effective activation of thermochemical processes within the active zones of a gas generator. In terms of oxidizing zone of the reaction channel, that design solution effects immediately the kinetics of chemical reactions and heat generation. The reducing zone is not affected immediately; thus, the reducing gasification processes proceed under the effect of gas products and heat generated within the oxidizing zone. Figure 8 demonstrates that design C helps reduce almost twofold the time for reaching the main processes, i.e., a gasification process experiences its intensification.

Disadvantages of the design are as follows: impossibility to control the oxidizing zone of a gas generator, nonuniform gasification of the combustion face of the reaction channel that influence negatively the quality of a thermochemical process as well as prolongs the time for preparation and formation of the reaction channel and reverse of blow flows.

Implementation of a perforated activator in the reaction channel of a gas generator to activate the underground coal gasification process ensures immediate effect on active zones of the combustion face; that helps control the active zones maintaining energy balance between the zones and selectivity of a gasification product, and increase quantitative and qualitative parameters of the process. Concerning disadvantages of design C, it can be mentioned that considerable mass of a perforated activator creates resistance during its displacement along with the advance of the gas generator's combustion face. Consequently, critical loads are formed on a flexible pipeline and its connection with the activator causing the need in limitation of the length of the gas generator's extraction pillar.

The obtained results of changes in generator gas output depending upon a blow type are correlated with a high convergence degree with earlier studies of underground coal gasification. Namely, numerous papers mention positive effect by oxygen-enriched blow [101–104] as well as oxygen and steam blow [104,105] on generator gas output indices. Essential effect by carbon dioxide blow has also been mentioned in [106–108]. Moreover, experimental results support confidently earlier studies with the use of similar coal [85]. No doubt, we cannot suggest full compliance of the research results since ultimate and technical analysis of the coal is not identical.

Comparative analysis of the results concerning blow stream reversing with studies by foreign researchers, described scrupulously in [109–111], prove the correctness of the selected tendency to intensify underground gasification process.

As for the comparison of the improved techniques, proposed by this paper, their effect on a gas formation process is incomparable with the similar studies. Nevertheless, we have propose to the studies alternative techniques of blow supply to fire mass of underground gas generator in addition to such popular systems as Controlled Retracting Injection Point (CRIP) [66,112,113], Movable Injection Point [114], Unfixed Pumping Points [115,116], and recently developed gasification agent injection tool for underground coal gasification [116].

The authors believe that further studies will concern analysis of underground gasification effect while degassing thin and very thin coal seams. Namely, determination of the influence of qualitative and quantitative composition of carbonous reagents on the gas formation efficiency within a reaction channel of an underground gas generator is meant. Moreover, a problem to analyze environmental component of a gasification process (among other things, formation of polluting gases and mercaptans and their expansion) remains a topical issue.

4. Conclusions

A series of experimental studies involving the gasification process modeling has helped substantiate the effect of technological and technical innovations in gas generator designs on the parameters of the coal seam gasification process.

Implementation of the designs of underground gas generators with stowing of the deformed roof rocks as well as the ones with the controlled active zones of a gas generator (especially while gasifying the abandoned balance and off-balance reserves of thin and very thin coal seams) provides adaptivity of the coal seam gasification process to specific mining-geological conditions.

A key feature of the innovative solutions of underground coal gasification, stipulating its economic expediency, is creation of favorable conditions for the directed blow supply into the reaction zone of coal mass from the variable points and keeps its contact with coal during the whole planned time of coal gasification.

Preparation of underground gas generators with injection stowing of the roof rocks will help reduce the prime cost of the produced coal by 23.5% owing to the following: area of the gasified coal increases by 1.6–1.8 times; degree of coal seam gasification grows by 7–12%. In this regard, maximum efficiency of underground gasification is achieved if a gas generator design involving flexible pipelines and activator in the reaction channel and blow direction onto the reaction channel face combined with blow stream reversing and oxygen blow use which will make it possible to improve caloricity of the generator gas up to 18% (i.e., from 8.4 to 12.8 MJ/m^3 depending upon a blow type).

Design technological schemes allows controlling efficiently a gas-generation process by directed blow supply and constant forcing of a blow flow against the combustion bed surface by means of combination of gas-blow flows (blow injection and exhaustion of gasification products) and by reversing the blow flows.

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