UDC 622.278.273.2

P. B. Saik[1], Cand. Sc. (Tech.),
R. O. Dychkovskyi[1], Dr. Sc. (Tech.), Prof.,
V. H. Lozynskyi[1], Cand. Sc. (Tech.),
Z. R. Malanchuk[2], Dr. Sc. (Tech.), Prof.,
Ye. Z. Malanchuk[2], Dr. Sc. (Tech.), Assoc. Prof.

1 – State Higher Educational Institution “National Mining University”, Dnipro, Ukraine, e-mail: saik.nmu@gmail.com
2 – National University of Water Management and Nature Resources Use, Rivne, Ukraine, e-mail: malanchyk@ukr.net

REVISITING THE UNDERGROUND GASIFICATION OF COAL RESERVES FROM CONTIGUOUS SEAMS

П. Б. Саїк[1], канд. техн. наук,
Р. О. Дичковський[1], д-р техн. наук, проф.,
В. Г. Лозинський[1], канд. техн. наук,
З. Р. Маланчук[2], д-р техн. наук, проф.,
Є. З. Маланчук[2], д-р техн. наук, доц.

1 – Державний вищий навчальний заклад „Національний гірничий університет“, м. Дніпро, Україна, e-mail: saik.nmu@gmail.com
2 – Національний університет водного господарства та природокористування, м. Рівне, Україна, e-mail: malanchyk@ukr.net

ХАРАКТЕРИСТИКА ПІДЗЕМНОЇ ГАЗИФІКАЦІЇ ЗАПАСІВ ВУГІЛЛЯ ЗБЛИЖЕНИХ ПЛАСТІВ

Purpose. Substantiating of contiguous coal seams coefficient during application of borehole underground coal gasification technology based on dependences of interstratial rocks subsidence on gasification duration.

Methodology. Using stand experimental research and methods of computer modeling we obtained the dependences of interstratial rocks subsidence in terms of their thickness change, alternating thickness of coal seams and duration of the gasification process. To reflect the geomechanical situation of rock mass around underground gasifier, license software Flac 5.00 was used. For data processing and building of synthesis dependences, the method of multiple regression using generally accepted data processing systems – Excel-2013 was used.

Findings. The obtained inequality allows setting the coefficient of contiguous coal seams during the application of underground gasification technology. Setting this factor makes it possible to assess mining and geo-logical conditions of coal seams occurrence with further rational order of their gasification. For values of contiguous coefficient 5.5–5.7, gasification of coal seams can be carried out both in ascending and descending sequence. In this case, there is no need to preserve the allowable distance between combustion faces on adjacent seams.

Originality. To determine the contiguous of coal seams, a mathematical mechanism was developed, whose effectiveness is confirmed by computer simulation of rock massif that contains an underground gasifier and by research on a special test bench installation. The difference between the results was less than 24 %.

Practical value. Dependence of interstratial rocks subsidence at changing duration of the gasification process describing the development of possible formation of gas-permeable cracks in interstratial rocks ensuring technological process was established. The obtained conditions of contiguous coal seams allow providing rational order of mine workings.

Keywords: *stand research, underground coal gasification, contiguous coal seams, coefficient of contiguity*

Introduction. In Donetsk and Lvivsko-Volynskyi coal basin the majority of reserves is located in contiguous coal seams. Analysis of domestic and international experience has shown that extraction of such reserves using conventional mining methods is uneconomical because of the negative manifestation of rock pressure in working faces. This situation greatly affects the cost of coal produced and mining accidents. It is possible to avoid this situation by improving conventional technologies of extraction, at least by changing the process of extraction. According to the opinion of leading specialists in the field of fuel and energy complex, this problem can be solved by implementing a radically new technology of development and processing of coal in place of its occurrence in a closed technological cycle – borehole underground coal gasification (BUCG). To carry out this technology, it is necessary to drill two boreholes toward the coal seams with subsequent linking. Then the coal seam must be ignited, which promotes creation a controlled combustion face with balanced oxidation and reduction zones. This makes it possible to obtain a mixture of combustible gases and then use them as a source of electricity and chemicals. In this way, the development of mining coal deposits for obtaining energy and innovation of the product in an environmentally closed cycle is classified as “Clean Coal Technology” (CCT) and “High Technologies” (HT).

Analysis of the recent research and publications. Over the last decade, the global energy market has shown growing interest in the technology of underground coal gasification, as evidenced by the number of developed projects and an increasing share of patents and security documents (according to Worldwide European Patent Office). New technological solutions of the process execution and new designs of gasifiers appear.

A team of researchers developed innovative technological solutions related to ensuring the effectiveness and efficiency of gasification technology application based on performed scientific and experimental study. A particularity of these technological solutions of coal seams gasification is that they are adapted to one productive horizon or the coal fields, where the works of minerals extraction have not been carried out. Therefore, it is necessary to consider a further possibility of expanding the technology for other coal seams. Today the question concerns a transfer of the results in terms of real mines, the creation of power and chemical complex of processing the received energy and chemical products. This requires the development of spatial representations of the state of the rock mass during the process of underground gasification and creation of efficient modes of operation [1], studying the balance of physical and chemical reactions [2], which will expand the use of the technology of borehole underground coal gasification and conduct rational management planning of mining, locating underground gasifiers with a focus on required final energy product. The technology of underground gasification of contiguous coal seams is being paid increasing attention due to reducing the volume of drilling operations and improving the productivity of a gasifier plant. Simultaneous extraction of coal reserves in contiguous seams results in a significant reduction of costs of the received final product.

In manuscript [3] the method of underground gasification of contiguous coal seams which involves their preliminary degassing through horizontal or inclined boreholes drilled on the upper and lower layers, is suggested. In the process of gasification, degassing of above layering strata of rocks is conducted. The period of degassing of the zone of upper layer discharge is regulated by changing the speed of combustion face advance along the bottom layer. Underworked coal seam and rock massif can completely give almost all methane only in unloading zone.

The period of gas recovery can be called a degassing interval. In the area of drainage, discharge efficiency is increased up to 78–88 %. The implementation of this method of gasification prevents drainage of methane into the atmosphere (if any) from rock massif around underground gasifier, and escape of combustible gases through underworked rock massif. During this technology, methane is viewed not as an independent energy product, but as an additional product of underground gasification gases.

While using the “UCG-methane” technology, proportion of methane in the initial combustible gas is increased to 26–44 %. This technology can increase the energy indicators of degassing gases from coal seams in the closed cycle and receive a comprehensive energy products and fertilizers. The downside of this technology is the low efficiency of degassing 15–20 % when the coal seam is intact. The occurrence of excess pressure in the gasifier leads to the escape of methane and gasifier gas on the Earth’s surface, polluting the atmosphere and hydrosphere.

Another variant of underground gasification of contiguous coal seams is a technology described in the paper [4]. This technology provides, firstly, gasification of upper layering coal seam, formation of a gathering collector in a goaf. Its hermetization is done from outside of the earth’s surface and gasification of other coal seams in ascending order. Methane outlet released from the rock massif, goes along degassing wells. The peculiarity of this gasification technology is that after creating a gathering collector other contiguous coal seams can be gasified in advance of each combustion face on the bottom layer relative to the top. The main disadvantages, as in the first case, can be low indicators of coal seams degassing process and the need for complex degassing of wells.

The closest technical solution of contiguous coal seams gasification is a method of underground gasification of solid fuels described in the paper [5]. The advantages of this technological scheme include reducing the cost of preparing and opening the coal seam, increasing the area of the gasifier, reducing air blast and gasification products escape. The following can be referred to as its disadvantages: the difficulty of breaking into layers of the coal seam and the inability to hold the opposite gasifier through design features of a vertical shaft.

Unsolved aspects of the problem. Analysis of the above technological solutions showed that the mechanism for setting conditions for coal gasification of contiguous seams has not been developed yet. The following restrictive factors have been hardly considered: structural change of the rock mass, thickness, the angle of the seam, the length of the combustible face and extraction pillar; occurrence of geological faults; the variation of parameters of the gasification process; design features of underground gasifier; different ways of managing rock pressure, etc. The authors of this work, see the need to investigate the effect of geometrical parameters of coal seams and changes in quality of the contiguous rocks on quality indicators of the gasification process as the primary task.

Presentation of the main research and explanation of scientific results. With interstratial rocks lowering, the probability of the vertical cracks formation in the rock massif increases [6]. It should be noted that during coal seam gasification the fracturing formation is related primarily to rock pressure. Uneven distribution of temperature field around underground gasifier is a secondary factor. During gasification of contiguous coal seams, forming of the vertical cracks is even more evident. These discontinuous formations turn into gas channels in the rocks. Vortices of blowing and gaseous mixtures of lower and upper underground gasifiers can occur there. This situation leads to destabilization of the whole system.

In undisturbed rock massif, natural cracks are under stresses caused by mining pressure and reservoir pressure of gas in the cavities of the cracks [7].

The possibility of formation of gas channels in interstratial rocks has been based on a subsidence on the coal bottom of the upper coal seam. The formation of vertical cracks is observed in the rock layers with horizontal deformation $\xi > 5$ mm/m [8]. Based on the study of the stress-strain state of the rocks of the main roof, a strain graph of the main roof depending on the size of subsidence was built (Fig. 1).

Analyzing this dependence (Fig. 1), we can conclude that the subsidence of the main roof by over 200 mm results in increase of vertical through-cracks ($\xi > 5$ mm/m). This makes it possible to predict the probability of formation of these cracks based on the values of coal bottom subsidence of the upper layer.

During the process of experimental research three models of rock and coal massif around ex-situ gasifier were formed. The transition from the model size to natural conditions occurred using the relevant similarity criteria. Thickness of the coal seam in each model was the same – 1.2 m. Thickness of interstratial rocks ranged from 3.6 to 6.6 m. Three layers represented interstratial rocks. Thickness of the first layer was 0.7 m, the second ranged from 2.3 to 5.3 m, and the third was 0.6 m. Modelled physical and geometrical parameters

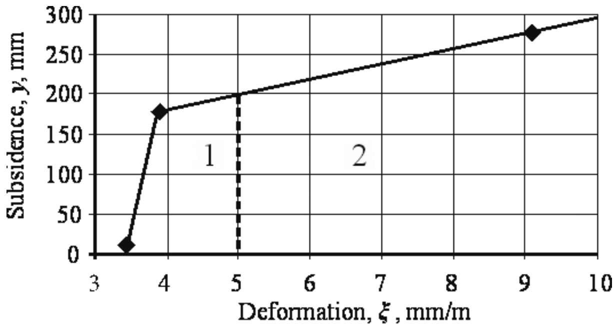


Fig. 1. Graph of behavior of the main roof depending on the size of subsidence:

1 – the zone in which there are no vertical through cracks formation; 2 – the zone of vertical through cracks formation

corresponded to geological conditions of selected areas of mine fields of SE "Lvivvuhillia".

Monitoring of the subsidence of interstratial rocks and their collapse was carried out for 18 measuring points (reference sensors) in three rows in terms of underground gasifier area. They were placed at the bottom of the upper coal seam (6), as shown in the technological diagram in Fig. 2.

The nature of the rocks subsidence in each model had both their own and common features.

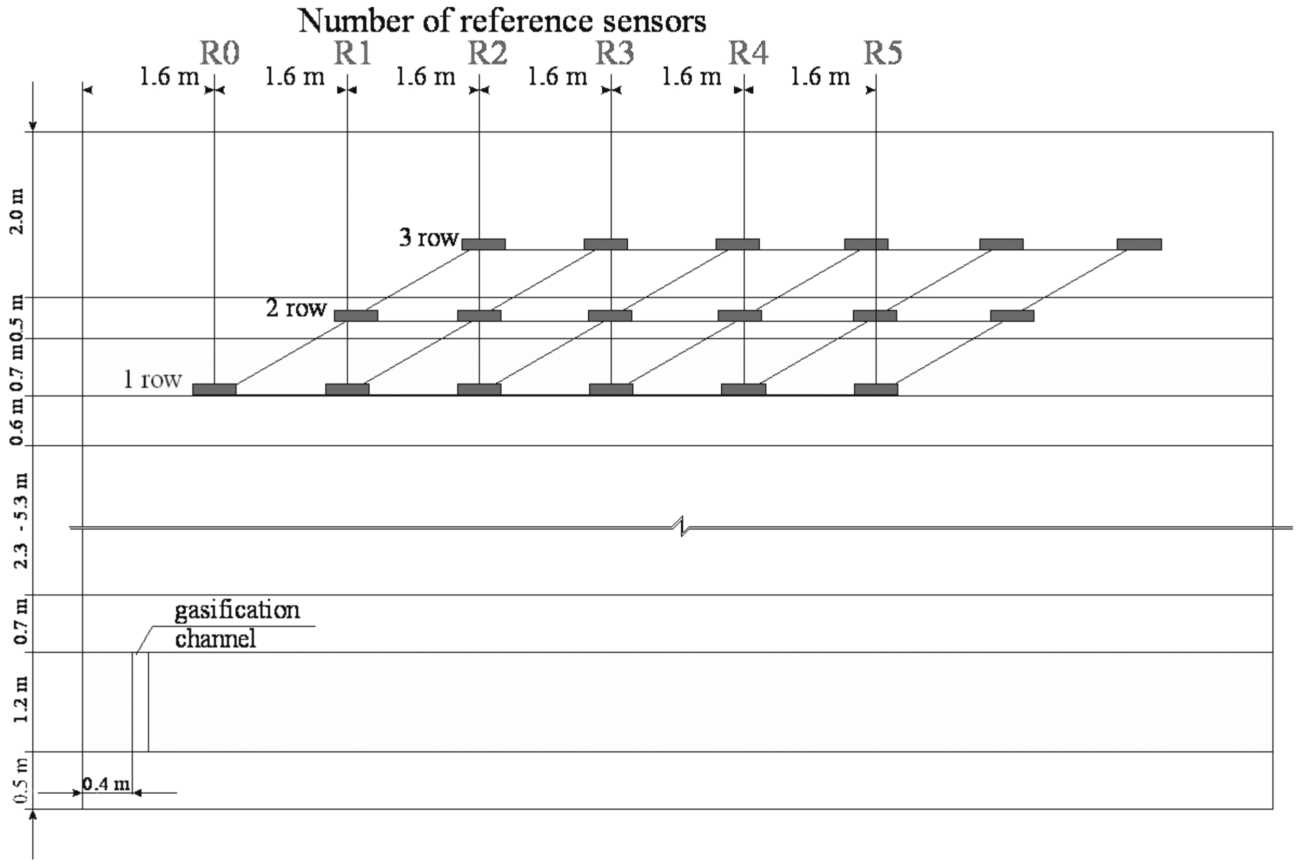


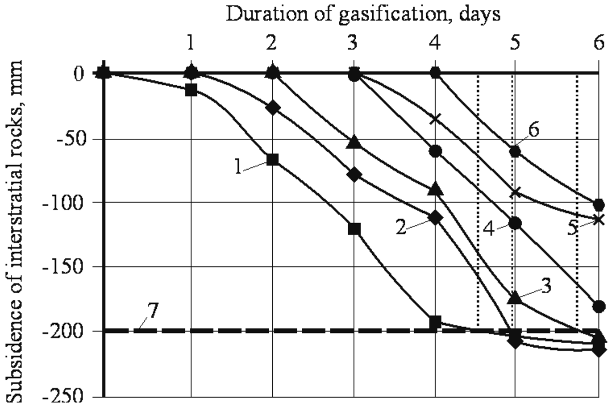
Fig. 2. Scheme of reference sensors installation:

1 – the bottom of lower coal seam 2; 3–5 – interstratial rocks; 6 – upper coal seam; 7, 8 – rocks of the roof of upper coal seam 6; 9 – reaction (gasification) channel; 10 – reference sensors

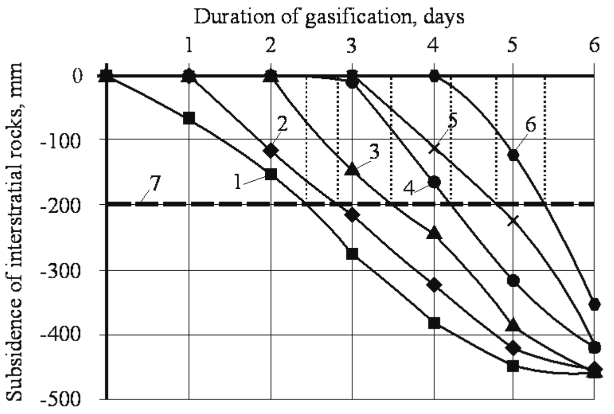
As a result of studies, dependences of rock layers subsidence with lithological differences were defined. These dependences were set using a measuring ruler and a system of optical sensors. With the transition to the full-scale gasification process, through the established scale factors, the distance between the reference sensors (R1–R6) equals 1.6 m. The distance to the first row of reference sensors along the length of the column gasification (R1) of man-made reaction channel (9) is equal to 1.2 m. During the research, we conducted gasification of the lower coal seam (2).

Fixation of subsidence that corresponds to natural conditions was held daily. Total observation time was 6 days. Dependencies of bottom subsidence at the top coal seam during variable thickness of interstratial rocks (3.6 and 6.6 m) and thickness of lower coal seam 1.2 m on the duration of the gasification process is shown in Fig. 3.

In this figure, horizontal line 7 shows a critical border of subsidence, below which the formation of through vertical cracks starts. The maximum subsidence of reference sensors with a thickness of interspatial rocks $h = 3.6$ m was observed on day 5 of gasification and made 0.46 m, $h = 5.4$–0.28 m, $h = 6.6$–0.21 m.



a



b

Fig. 3. Diagram of interstratial rocks subsidence with a thickness of 3.6 m (a) and 6.6 m (b) depending on the gasification duration:

1–6 – subsidence values of reference sensors; 7 – a critical border of subsidence, below which the formation of through vertical cracks occurs

The main feature during underground coal gasification is the presence of high temperatures in the combustion face > 1000 °C [9]. The values of temperature decrease with distance from the combustion face. At a distance of coal seam roof of 3.6 meters above combustion face, the maximum temperature is in the range of 200–300 °C, while in the rocks of the bottom at the same distance it is 53–82 °C. The degree of the roof rocks exposure to heat depends on blast pressure in the underground gasifier. With the pressure increasing from 0.15 to 0.35 MPa, the heat of roof rocks increases by 70–100 °C. This change in temperature is due to convection penetration of combustible gases mixture through artificial gas channels (vertical through cracks). This problem can be solved by using stoichiometric conditions for the dual fuel system [10].

The results of the research (Fig. 3) prove that provided the advance of the lower combustion face over the upper one, it should be before the area of formation of vertical through cracks. Based on the results the of bottom subsidence of the upper coal seam and the rate of combustion face advance, the dependence of the possible delay of upper combustion face on the lower one with variable interspatial rocks thickness was obtained (Fig. 4).

From the studies, it is clear that the maximum allowable distance of upper combustion face delay from the lower combustion face with the thickness of lower coal seam of 1.2 m changes under linear dependence and can be written as

$$L_{ek} = 1.55h - 2.93,$$

where L_{ek}. is the value of the combustion face delay of the upper coal seam with compared to the lower coal seam; h is the thickness of interstratial rocks.

In the area of SC "Lvivvuhillia" mines, the thickness of coal seams varies from 0.6 to 1.2 m, and the thickness of interstratial rocks reaches up to 28 meters. Therefore, for these parameters, given the technical and economic characteristics of experimental studies, the coefficient of contiguity of coal seams was analyzed using available information packets that form the basis of computer modeling.

During coal seams gasification, the space of gasification area increases, resulting in destruction of above

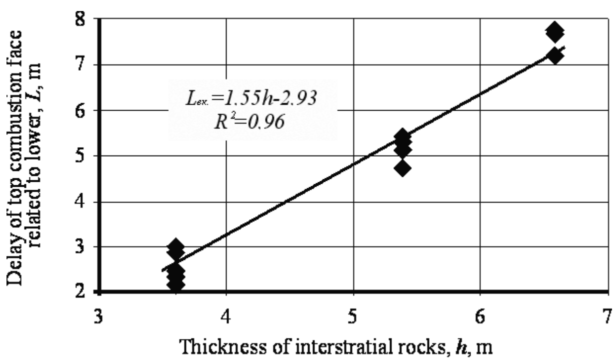


Fig. 4. Change dependency of the upper combustion face delay on the lower one under variable thickness of interstratial rocks

rock mass. A mechanism of rock mass destruction allows observing its subsidence in concrete span point.

During simultaneous gasification of contiguous coal seams, an important element is to establish the value of the first combustion face delay regarding the second one. Determining this value excludes mutual and simultaneous influence of the underground gasifier on interstratial rocks. The underground gasifier can work both in ascending and in descending sequence. The delay in the lower coal seam does not virtually affect the top coal seam, whereas delay in the upper coal seam can create substantial effect on blowing flow.

During our research, 27 models were processed using methods of computer simulation. As a result, graphs of top coal seam subsidence at different values of interstratial rocks were obtained. Fig. 5 shows received graphs of subsidence of upper coal seam at interstratial rocks with a thickness of 3.6 m and a thickness of the lower coal seam of 1.2 m.

Based on Fig. 5, primary rock subsidence of the upper coal seam occurs at point 1Y (x = 39, y = 33), in 0.2 days of gasification process. In 1.6 days, at a value of goaf of 3.5 m, subsidence value made 200 mm. This makes it possible to predict the position of the upper combustion face, provided its delay from the lower seam. Construction of models was performed until the maximum lowering of the bottom of the lower seam did not exceed 200 mm.

At the first stage of modeling with the thickness of coal seam of 1.2 m, a step of interstratial rock thickness was 0.2 m. The acceleration of the process of this model was increased by up to 0.4 m. With the coal seam thickness decreasing to 0.6 m, and interstratial rocks decreasing to 3.6 m, subsidence does not exceed 200 mm.

According to the results of computer simulation it was found that subsidence of rocks of the bottom of the upper coal seam > 200 mm was observed with the studied coal seam thickness of 1.2 m at the level of 6.9 m, 1.0–5.6 m, 0.8–4.4 m and at 0.6–3.4 m. This does not contradict the experimental research conducted in the laboratory. The discrepancy between the results of all kinds of research does not exceed 24 %.

Accordingly, we can get dependences in which we can assume when the coal seams are contiguous during underground gasification (Fig. 6). The main parameters that influence contiguity will be thickness of coal seams and interstratial rocks.

Consequently, during underground coal gasification coal seams can be related as contiguous under the inequality

$$\frac{h}{m} \leq 5.5-5.7,$$

where *h* is thickness of interstratial rocks, m; *m* is thickness of the lower coal seam, m.

The ratio $\frac{h}{m}$ reflects the contiguous coefficient of coal seams during underground coal gasification (k_c). For values of the coefficient $k_{c.} \geq 5.5$–5.7, gasification of coal seams can be conducted in descending and ascending sequence.

Research conclusions and recommendations for further research in this area. The study of si-

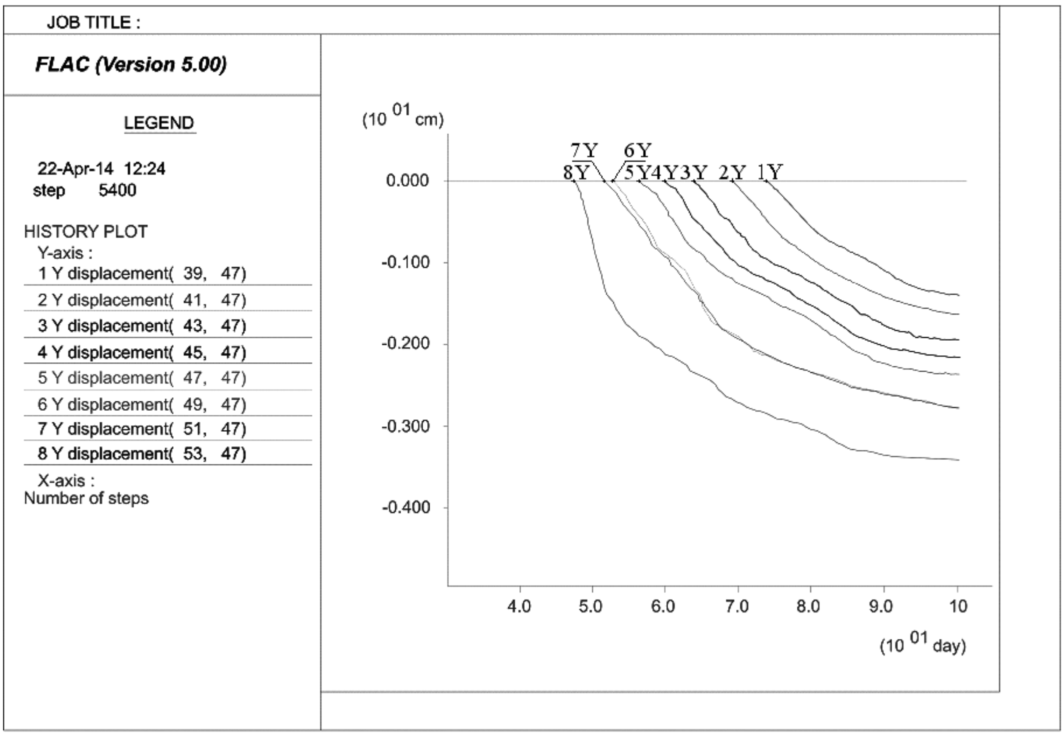


Fig. 5. Graphs of subsidence of the upper coal seam (Y, cm) depending on time (x, days) at interstratial rocks thickness of 3.6 m

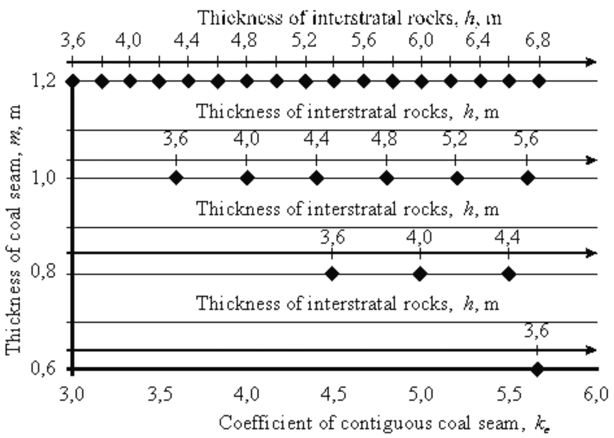


Fig. 6. Formation of data field for determination of contiguous coefficient of coal seams depending on interstratial rocks and coal seam thickness

multaneous multi-level gasifiers shows that existing approaches to determining the coefficient of contiguous coal seams during underground gasification require significant adjustments. Unfortunately, existing methods for determining the parameters used in the complex mechanized coal extraction are not suitable when applying the borehole underground coal gasification technology. Using experimental tests research and computer simulations, the authors, have attempted to establish the degree of influence of underground gasification gases in ascending and descending sequence of coal gasification. The basis of research was mining and geological conditions of mines SE "Lvivvuhillia".

According to the results of these studies, dependence that reflects the condition of coal seam being contiguous was obtained. Considering this dependence makes it possible to ensure the stable coal gasification process and avoid destabilization zones of thermochemical reactions in an underground gasifier.

References / Список літератури

1. Lozynskyi, V. H., Dychkovskyi, R. O., Falshtynskyi, V. S. and Saik, P. B., 2015. Revisiting possibility to cross disjunctive geological faults by underground gasifier, *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, No. 4, pp. 22–28.

2. Falshtynskyy, V., 2012. New method for justification of the technological parameters of coal gasification in the test setting. In: *Geomechanical Processes During Underground Mining – Proceedings of the School of Underground Mining*. CRC Press/Balkema, The Netherlands, pp. 201–208.

3. Trizno, S. K. and Lazarenko, S. N., 2007. *Sposob podzemnoy gazifikatsii svity ugol'nykh plastov*. Pat. 2307244 RF MPK E21V43/295.

Патент № 2307244 РФ МПК E21B43/295. Способ подземной газификации свиты угольных пластов / С. К. Тризно, С. Н. Лазаренко и др. – Опубл. 27.09.2007.

4. Trizno, S. K., Lazarenko, S. N. and Fedorin, V. A., 2009. *Sposob podzemnoy gazifikatsii svity krutykh i krutonaklonnykh ugol'nykh plastov*. Pat. 2347070 RF MPK E21V 43/295.

Патент № 2347070 РФ МПК E21B 43/295. Способ подземной газификации свиты крутых и крутонаклонных угольных пластов / С. К. Тризно, С. Н. Лазаренко, В. А. Федорин. – Опубл. 20.02.2009.

5. Falshtynskyi, V. S., Dychkovskyi, R. O. and Tabachenko, M. M., 2010. *Sposib pidzemnoyi hazyfikatsiyi potuzhnykh plastiv tverdoho palyva*. Ukraine. Pat. 50753 MPK E21V 43/00.

Патент № 50753 Україна, МПК E21B 43/00. Спосіб підземної газифікації потужних пластів твердого палива / В. С. Фальштинський, Р. О. Дичковський, М. М. Табаченко та ін. – Опубл. 25.06.2010.

6. Sakhno, S., Kobylianskyi, B. and Sakhno, I., 2016. Destruction of rocks by the non-explosive depleting compounds during mining. *Mining of Mineral Deposits,* No. 10(1), pp. 25–30.

7. Rakishev, B., Seituly, K. and Kovrov, O., 2014. Physical modeling geomechanical stability of opencast slopes and internal overburden dumps. In: *Legislation, Technology and Practice of Mine Land Reclamation*, pp. 583–588.

8. Savostianov, O.V., 2016. *Metody prohnozu heomekhanichnykh protsesiv dlia vyboru tekhnolohichnykh parametriv vidpratsiuvannia polohykh plastiv* [Methods for forecasting geomechanical processes for selecting technological parameters for working flat seams]. Dnipropetrovsk: NMU.

Савостьянов О.В. Методи прогнозу геомеханічних процесів для вибору технологічних параметрів відпрацювання пологих пластів: монографія / Савостьянов О.В. – Днепропетровск: НГУ, 2016. – 246 с.

9. Falshtynskyi, V., 2013. Justification of the gasification channel length in underground gas generator. In: *Annual Scientific-Technical Collection – Mining of Mineral Deposits 2013*, CRC Press/Balkema, The Netherlands, pp. 125–132.

10. Postrzednik, S., Przybyla, G. and Zmudka, Z., 2015. Main conditions and effectiveness of gas fuel use for powering of dual fuel IC self-ignition engine. *Transport Problems*, Vol. 10, Iss. 3, pp. 99–111.

Мета. Обґрунтування коефіцієнта зближення вугільних пластів при застосуванні технології свердловинної підземної газифікації, виходячи зі встановлених залежностей опускань міжпластових порід від тривалості газифікації.

Методика. Стендовими експериментальними дослідженнями та методами комп'ютерного моделювання встановлені залежності опускання міжпластових порід при змінній їх потужності та потужності вугільних пластів від тривалості процесу газифікації. Для відображення геомеханічної ситуації гірського масиву навколо підземного газогенератора застосовано пакет ліцензійної прикладної програми Flac 5.00. Для обробки даних та побудови узагальнюючих залежностей використано метод множинної регресії із застосуванням загальновизнаної системи обробки даних Excel-2013.

Результати. Отримана нерівність, що дає можливість встановлювати коефіцієнт зближення вугільних пластів при застосуванні технології підземної газифікації. Встановлення даного коефіцієнта дозволяє проводити оцінку гірничо-геологічних умов залягання вугільних пластів з подальшим раціональним порядком їх газифікації. При значеннях коефіцієнта зближення більших 5,5–5,7 газифікацію вугільних пластів можна проводити як у висхідному, так і низхідному порядках. При цьому не потрібно витримувати допустиму відстань між вогневими вибоями, що працюють на зближених пластах.

Наукова новизна. Запропоновано математичний механізм для визначення коефіцієнта зближення вугільних пластів, ефективність якого підтверджена комп'ютерним моделюванням стану гірського масиву, що вміщує підземний газогенератор, та дослідженнями на спеціальній стендовій установці.

Практична значимість. Встановлено залежності опускань міжпластових порід від тривалості газифікації, що характеризують утворення газопровідних каналів у породах міжпластя для забезпечення технологічності процесу. Отримана умова зближення вугільних пластів дозволяє проводити раціональний вибір порядку відпрацювання запасів вугілля.

Ключові слова: *стендові дослідження, підземна газифікація, зближені пласти, коефіцієнт зближення*

Цель. Обоснование коэффициента сближения угольных пластов при применении технологии скважинной подземной газификации, исходя из установленных зависимостей опусканий межпластовых пород от продолжительности газификации.

Методика. Стендовыми экспериментальными исследованиями и методами компьютерного моделирования установлены зависимости опускания межпластовых пород при изменении их мощности и мощности угольных пластов от продолжительности процесса газификации. Для отображения геомеханической ситуации горного массива вокруг подземного газогенератора применен пакет лицензионного приложения Flac 5.00. Для обработки данных и построения обобщающих зависимостей использован метод множественной регрессии с применением общепризнанной системы обработки данных Excel-2013.

Результаты. Полученное неравенство дает возможность устанавливать коэффициент сближения угольных пластов при применении технологии подземной газификации. Определение данного коэффициента позволяет проводить оценку горно-геологических условий залегания угольных пластов с последующим рациональным порядком их газификации. При значениях коэффициента сближения больше 5,5–5,7 газификацию угольных пластов можно проводить как в восходящем, так и нисходящем порядках. При этом не нужно выдерживать допустимое расстояние между огневыми забоями, которые работают на сближенных пластах.

Научная новизна. Предложен математический механизм для определения коэффициента сближения угольных пластов, эффективность которого подтверждена компьютерным моделированием состояния горного массива, вмещающего подземный газогенератор, и исследованиями на специальной стендовой установке.

Практическая значимость. Установлены зависимости опусканий межпластовых пород от продолжительности газификации, характеризующие образования газопроводных каналов в породах междупластья для обеспечения технологичности процесса. Полученное условие сближения угольных пластов позволяет проводить рациональный выбор порядка отработки запасов угля.

Ключевые слова: *стендовые исследования, подземная газификация, сближенные пласты, коэффициент сближения*

Рекомендовано до публікації докт. техн. наук І. А. Ковалевською. Дата надходження рукопису 15.01.16.