Jr. of Industrial Pollution Control 33(1)(2017) pp 1042-1047
www.icontrolpollution.com
Research Article

THE WAYS OF SAFETY IMPROVEMENT DURING THE OUTBURST-PRONE AND GAS-BEARING COAL SEAMS DEVELOPMENT

VLADIMIR BORISOVICH SOLOVIOV * AND ROSTISLAV DMITRIEVICH MAGOMET

Saint Petersburg Mining University, 199106, Saint Petersburg, 21 Line, 2, Russia

(Received 29 May, 2017; accepted 04 June, 2017)

Key words: Coal industry, Coal mining, Coal industry safety, Coal seam degassing, Coal industry trends, Human resources, Economical efficiency of the coal industry, Development strategies, Methane utilization

ABSTRACT

The state of industrial and labor safety is characterized by the fatality level per one thousand workers in mines. The present index has become lower as compared to the other industries, but the high accident risk remains. The methane explosion is one of the main reasons of the accidents, which necessitates the quality improvement of the mining personnel professional training; the prevention measures financing and the staff training in terms of the mining safety assurance; the equipment installation for safety improvement, including the equipment providing the appropriate pulverized-coal and gas conditions and more reliable conditions of the preliminarily deposits degassing and the mining plants airing. The safety problems have assumed great importance due to the gas and dust explosions which have become more frequent at the coal mines in recent times. The seam unloading and the preliminary degassing are among the methods of the problem solving. The undermining of the underlying seams by the degassing method (combustion) serves to the negative phenomena likelihood reduction.

INTRODUCTION

When analyzing the current state and the development trends of the coal industry in Russia (Smirnova and Soloviov, 1982; Soloviov, *et al*., 1995), the following basic components of the true picture should be considered:

the economic indexes of the industry and their variation influenced by the national and the external market factors;

the industrial safety indexes;

the coal industry reorganization dynamics and efficiency indexes (Monaghan, 2007; Belov, 2010; Vasyuchkov and Vorobev, 1997).

The deterioration in the operating conditions is the characteristic feature of the coal deposits development:

the yearly average growth of the mining depth constitutes 10-12 m;

with the depth increase, the gas content of the coal seams also increases (at the deep layers, it reaches 25-30 m^3/t),

there is an increase in significance of the contribution to the adjacent strata gas balance formation, the gas content of which in some cases equals to 4-6 m^3/t;

the outburst hazard increasing with the depth sufficiently complicates the coal seams mining (Kreinin, 2004; Karasevich, *et al*., 2009).

Due to the explosion hazard of the methane-air mixture, the coal seam methane is considered to be one of the major hazards during mining and a limiting factor of the modern high-performance equipment application (Komarov, 2012; Our News).

The problem of the safe technologies development for the underground mining is crucial for the modern mining enterprises, especially for the gas-bearing and outburst-prone seams (Karmanskii, 2009; Magomet and Mironenkova, 2014). The depletion of the mineral deposits accessible for the conventional production methods, the increase in the coal deposits mining depth, the increasing contribution of the coal in the

***Corresponding authors email: soloviev_vb@mail.ru**

national supply-demand balance, the increasing contribution of the nonconventional power sources, and the geothermal energy among them, as well as a number of other reasons permit to consider the new technologies development for the coal production and conversion as the particularly topical problem in modern times (Puchkov, *et al.*, 2009).

In this case, the comprehensive approach with the use of the nonconventional production technologies is assumed to be the most efficient approach (Arens, *et al.*, 2007; Dyadkin, *et al.*, 1993). The borehole power technology of the thermochemical coal seams conversion along with the in-situ gasification (combustion) based on the geotechnical methods principles suggested in the present paper is among the technologies mentioned above (Zorya and Kreinin, 2009a; Zorya and Kreinin, 2009b; Dyadkin, *et al.*, 1993). It allows for the efficient use of the coal and the surrounding rocks energy potential as well as the utilization of the valuable chemical elements associated with the coal seams (Dyadkin, *et al.*, 1994). The objective of the suggested technology is in the safety improvement as well as the ecological and economic efficiency improvement of the integrative development of the power and chemical resources of the coal deposits. The present objective is fulfilled by means of the fractional combustion of the unworkable protective seams with the purpose of the safe mining of the outburst-prone seams and the seams liable to rock-bumps of the coking and chemically valuable coals. The engineering concepts and techniques, typical for the all technology variants being different by the purposes, mark these technologies off from the existing methods of the coal deposits power development (Zoryn, *et al.*, 2009; Kornilov, 2004).

METHOD

The method suggested by the authors (Fig. 1) provides the safety and the high intensity of the underground mining of outburst-prone and gas-bearing seams, as well as the improvement of the integrated utilization comprehensiveness of the coal bearing strata energy resources.

Where: 1 is the outburst-prone and gas-bearing seam with the depth M_1; 2 is the unworkable protective seam with the depth M_2; 3 are the coal roadways, which prepare the extraction pillar of the outburst-prone and gas-bearing seam 1 with the length L_B; 4 are the vertical wells, drilled from the surface to the bottom of the protective seam 2; 5 is the mining complex for the outburst-prone and gas-bearing seam 1 mining; 6 is the roof caving zone of the outburst-prone and gas-bearing seam 1; 7 are the hydraulic fracturing cracks, formed from the wells in the seams 1 and 2; 8 are the drainage wells, drilled from the coal roadways 3; 9 are the flows of the high temperature gas-steam-smoke mixture being the seam 2 combustion products; 10 is the electric steam generating unit; 11 are the thermally insulated steam pipelines; 12 is the outburst-prone and gas-bearing seam 1 heat-up zone; 13 is the preliminary degassing zone of the seam 1; 14 are the flows of the water-air mixture; 15 is the heat exchanger – steam generating unit GPU; 16 are the interstratal air holes, drilled from the coal roadways 2 of the seam 1 to the seam 2 bottom; 17 are the injection nozzles above the holes 16 for water injection in the air flow 14; 18 is

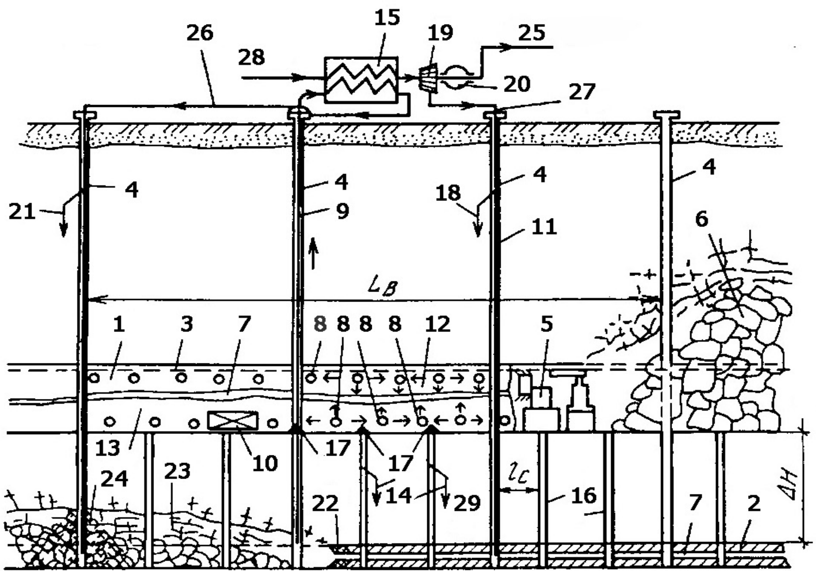

Fig. 1 Flow chart of the laser scanning device.

the power-generating steam flow of the supercritical parameters; 19 is the steam turbine; 20 is the electric power generator; 21 is the flow of the exhaust condensed steam and other liquefied gases; 22 is the combustion front of the protective seam 2; 23 is the roof caving zone of the protective seam 2; 24 is the underground storage zone; 25 is the electric energy; 26 is the steam-gas mixture; 27 is the steam; 28 is the water; 29 is the air.

The outburst-prone and gas-bearing seam 1 with the depth M_1, the high gas content g_1, the volumetric heat capacity C_T and the temperature T, as well as the protective seam 2 with the calorific capacity q_T, unsuitable for extraction due to the low (unworkable) depth M_2, are mined. The seam 1 is mined by the long pillars (L_B) and is prepared by the coal roadways 3 in case of the place length l_B being equal to the mining block length, equipped by the mining complex 5 with the complete roof caving 6. From the vertical wells 4 drilled from the surface along the coal roadways axis, dividing the long pillar in the mining blocks with the length L_C the hydraulic fracturing with the radius R=0.7 L_C is performed in both seams with the hydraulic fracturing cracks system 7, covering the whole extraction pillar area. The preliminary degassing of the seams sections, as they get close to the stope, is provided with the purpose of the increase in the output per face up to the capabilities of the mining complex 5 (for removal of the permissible air speed constraints based on the conditions of the mixture dilution up to the safe concentration of the methane, evolving from the broken coal). For this purpose, the drainage wells 8, connected to the vacuum pumping unit through the degassing pipeline (not shown), are drilled from the coal roadway 3 (or from both coal roadways from the opposite direction).

The outburst-prone and gas-bearing seam 1 heat-up to the temperature of 100ºC depending on the particular conditions can be performed by the following different methods (Fig. 1):

1) The use of the electric steam generating unit 10, which is connected to the wells 8 by the thermally insulated steam pipeline 11 in the heat-up zone 12, passing to the degassing zone 13;

2) The methane combustion in the boiler section of the mine (for g_1 >20 m^3/t not more than 30% of the methane captured during the deep seam degassing) with layering by the well 4 and the coal roadway 3 of the thermally insulated steam pipeline 11;

3) Generation of the steam with the high parameters (for instance, 550ºC and 25 MPa) from the heat exchanger – steam generating unit 15 of the GPU type by means of the recuperative heat exchange with the gas-steam-smoke combustion products 9 of the protective seam 2 in the combustion front 22 with the length l_0.

As opposed to the known in-situ coal gasification methods, the chemical energy of the complete coal oxidation in the process mentioned above is generally conversed to the latent heat of evaporation, as far as combustion is developed in the water-air medium (in the experiment of the coal combustion under the steam band and the water column the measured temperature values had reached 1300ºC). The water-air flow 14 is formed in the injection nozzles 17 above the vertical interstratal air holes 16 with the length ΔH, drilled from the coal roadway 3 of the outburst-prone and gas-bearing seam 1 with the interval l_C up to the intercrossing with the hydraulic fracturing cracks 7 of the seam 2.

For the protective seam 2 preparation for combustion after its completion by the wells 4 and 16, the filtration channels 25 are laid between the wells 16; in this case, the combustion front is created from the pair of channels mentioned above, and the length of the combustion front l_0 is determined by the suggested formula. The filtration flame front channeling is performed in the counter-flow mode, when using the compressed air from the of the mine compressor the filtration-air channels are formed with the length l_C and l_B correspondingly for the water-air mixture flows 14.

RESULTS

As far as the steam generated during combustion of the small fraction of the seam 2 resources with the gas-steam-smoke mixture 9 formation is enough for heat-up and thermal degassing of the outburst-prone and gas-bearing seam 1, the main power-generating steam flow of the supercritical parameters is directed from the GPU through the steam pipeline 18 to the turbine 19 of the electric power generator 20, and the flow 21 of the exhaust foul condensed steam from the GPU (in appropriate cases together with the other liquefied refuses) is directed through the pipeline and the exhausted well 4 to the underground storage zone 24 in the caving zone 23 in the burnt up section of the seam 2. The preceding and succeeding deformations and the crack formation in the interburden layers ensure the required protective effect for the safe mining of the outburst-prone and gas-bearing seam 1, eliminating the risk of the sudden outburst of coal and gas.

After the burnout of the protective seam 2 coal within the boundaries of the pillar (one combustion front can simultaneously operate in each block with the length L_C), and also in case of emergency, the dry powder-foam fire extinguishing units of the PPU type installed in the coal roadway in each block close to the self-swelling stoppings are switched on. When the inert gases fill the whole volume of the interstratal air holes 16 as well as the interstratal air connections l_C and l_B of the burnt-up section along the combustion fronts 22 the combustion process stops over a period of several minutes.

In case of the seam 1 gas-bearing capacity decrease to approximately 2-5 m^3/t, the main problem is solved due to the intense thermal vacuum degassing: the output per face can be increased to the value of 5000 tons per day. The supercritical parameters of the steam generated during the protective seam combustion ensure the high efficiency level of the turbine-generator, and the drastic reduction of the mining works amount as well as the exception of the coal transportation and storage, installation and maintenance of the boiler-room, ash and slag disposal areas, the gas and thermal outbursts prevention systems, according to preliminary estimates can reduce the total costs per 1 kW per hour of the power production more than by an order in case of the typical fuel consumption of approximately 320 g/h.

The flow 9 passes through the coal roadways 3, interstratal air holes 16 and the air connections l_C and l_B of the seam M_2 by means of the general shaft thermal depression, which in case of the temperature increase in the combustion front up to the values of 1200-1300ºC can be excessive and the air-flow resistances, installed in the wells 16, can be required.

The combustion front length l_0, covering the requirement of the heat-up of the mine section being LB · l_B in the area at the outburst-prone and gas-bearing seam 1 by ΔTºC by means of combustion at the seam 2 or the width of one panel in case of the length l_B, can be determined by the formula:

$$l_0 = C_T \Delta T M_1 L_B k_\lambda^2 / q_T M_2 \eta_C$$

where C_T is the coal specific heat capacity, kJ/kgºC;

M_1 is the depth of the outburst-prone and gas-bearing seam, m;

M_2 is the protective seam depth, m;

LB is the length of the extraction pillar of the outburst-prone gas-bearing seam, m;

ΔT is the heating value of the outburst-prone gas-bearing seam 1,ºC;

q_T is the calorific capacity of the protective seam, kJ/kg;

k_λ is the coefficient, considering the conductive heat losses to the surrounding rock, u.f.;

η_C is the coefficient, considering the incomplete burnout of the protective seam in terms of depth and area, u.f.

For instance, in case of C_T = 1.7 MJ/kgºC; q_T = 26.4 MJ/kg; L_B= 3000 m; L_C = 500 m; l_C = 50 m; l_B = 200 m; M_1 = 2.0 m; M_2 = 0.5 m; k_λ = 1.25; ΔT = 100ºC and η_C = 0.85, we will obtain l_0 = 100 m.

Hence, for the heat-up of the extraction pillar of the outburst-prone and gas-bearing seam 1 with the resources of approximately 1.5 million tons per 100ºC, it is sufficient to use the steam volume, generated during combustion of the off-spec coal of the protective seam 2 in one panel with the width l_0 = 100 m, which is 1/30 of the present seam resources in the mining section, remaining the bulk of the produced steam of the supercritical parameters (550ºC, 25 MPa) for the electrical energy production. The approximate calculation shows that in case of the simultaneous mining in each of six blocks of the mining section (L_C = 500 m) by one panel during approximately 2.5 years (it is the time of the present panel preparation and mining accepted on the basis of the in-situ coal gasification experience, being equal to 4800 years), the total amount of the power energy will be approximately 1 billion kW per hour in case of the rated average electrical power of the present type power system of approximately N_E = 60 MW, which is vastly superior to the total power of the owed drilling, pumping, steam generation and compressor units and it justifies the expected power efficiency of the suggested technology.

Assuming the methane desorption intensity growth in case of the coal temperature increase on the basis of the experimental data for ΔT = 100ºC, the seam gas-bearing capacity decrease from 22 to 2 m^2/t can be expected. It will permit to let through the stope working section 4 m^2 approximately 15-16 m^3/s of the air with the velocity of 4 m/s, that is it, will permit to provide the required dilution of the methane, produced in case of the daily output per face up to 5000 tons per day.

In addition to the main effect mentioned above, the methane removal of approximately 20 m^3/t for degassed resources of the mining section of the outburst-prone and gas-bearing seam 1 of approximately 1.5 million tons can be estimated as approximately 30 million m^3. In case of utilization of the present amount of methane, the steam volume with the total heat content of 720 million MJ can be obtained in the gas boiler house with the efficiency factor of 0.6, which is three times more than the heat energy consumption required for the seam heat-up by $\Delta T = 100^oC$ (244.8 million MJ).

DISCUSSION

When using the electric steam generating unit 10, the steam amount produced during the protective seam 2 combustion, required for the advanced underworking and unloading of the outburst-prone gas-bearing seam 1, can be completely used for the electrical energy generation. The seam 1 heat-up before its deep degassing can be implemented only by means of the removed methane utilization.

However, even the periodical infusion of the steam generated in the heat exchanger through the deep wells in the hydraulic fracturing cracks of the both seams is obviously reasonable in case of the steam pressure being just above the overburden pressure (for instance, 25 MPa as opposed to the total overburden pressure at the coal bearing strata depth of H=1 km, not exceeding 22-23 MPa).

CONCLUSION

The environmental efficiency of the suggested technology is defined by the integrated utilization of both coal and methane resources of the outburst-prone and gas-bearing seam 1, involvement into operation and utilization for production of the electrical energy of the non-commercial reserves the unworkable protective seam 2 off-spec coal, as well as the disposal of the foul condensed steam and other possible refuses by means of their running through the deep wells 4 in the mining section of the protective seam 2.

The underground operations safety achievement along with the stope high efficiency assurance is possible in case of the application of the integrated degassing systems: degassing of the coal rock mass and the mining section by the wells, drilled from the surface; degassing of the coal rock mass and the mining section from the section openings; the seam degassing by the wells drilled by plate from the section openings and further efficient utilization of the degassing methane.

The following four guiding principles can be assumed as the basic prospective lines of the coal industry development:

1. The resource-saving principle;
2. The social efficiency principle;
3. The environmental safety principle;
4. The economic efficiency principle.

REFERENCES

Arens V.Zh., Vertman A.A. and Khcheyan G.Kh. 2007. Novye podkhody k ispolzovaniyu nevostrebovannykh resursov tverdykh poleznykh iskopaemykh. [New Approaches to the Use of the Unclaimed Solid Minerals Resources]. Vestnik Rossiiskoi akademii estestvennykh nauk. 3.

Belov A.V., Zvonarev M.I, and Grebenyuk I.V. 2010. Patent na izobretenie No. 2381356 RF. Sposob podzemnoi gazifikatsii. [Patent RF on the Invention No. 2381356. The In-Situ Gasification Method]

Dyadkin Yu.D., Gendler S.G. and Smirnova N.N. 1993. Geotermalnaya teplofizika [Geothermal Thermal Physics], Saint Petersburg: Nauka. 256.

Dyadkin Yu.D., Smirnova N.N., Soloviov V.B. and Popova P T.V. 1994. Patent No. 2012791. Sposob podzemnoi gazifikatsii moshchnykh ugolnykh plastov" [Patent No. 2012791. The Method of the In-Situ Gasification of the High Coal Seams].

Dyadkin Yu.D., Soloviov V.B. and Smirnova N.N. 1993. Tekhnologiya termokhimicheskoi pererabotki ugolnykh plastov v komplekse s izvlecheniem geotermalnoi energii" [Thermochemical Conversion of the Coal Seams in Conjunction with the Geothermal Energy Generation], In Mezhdunarodnyi simpozium "Problemy geotermalnoi energii" [International Symposium "Geothermal Energy Problems"]. Saint Petersburg: SPbGGI.

Karasevich A.M., Kreinin, E.V. and Zorya, A.Yu. 2009. Patent No. 2359116. Sposob ekologicheski chistoi podzemnoi gazifikatsii glubokozalegayushchikh uglei. [Patent No. 2359116. Environmentally Friendly In-Situ Gasification Method of the Deep Coals].

Karmanskii A.T. 2009. "Issledovaniya mekhanizma desorbtsii metana pri nasyshchenii uglya dioksidom ugleroda" [Study of the methane desorption in case of the coal saturation by carbon dioxide]. *Zapiski gornogo instituta*. 183 : 285-288.

Komarov A. 2012. Proekt podzemnoi gazifikatsii uglya DTEK i Linc Energy: est li smysl?" [Project of the In-Situ DTEK and Linc Energy Coal Gasification: Is It Worthwhile?]. Retrieved March 8, 2017, from http://hvylya.net/analytics/economics/proekt-podzemnoy-gazifikatsii-uglya-dtek-i-linc-energy-est-li-smyisl.html.

Kornilov D.V. 2004. Est li budushchee u podzemnoi gazifikatsii uglei [The Future of the In-Situ Coal Gasification]. *Nauka v Sibiri*. 31-32 : 2467-2468.

Kreinin, E.V. 2004. Netraditsionnye termicheskie tekhnologii dobychi trudnoizvlekaemykh topliv: ugol, uglevodorodnoe syre. [Unconventional Thermal Technologies of the Hard-To-Recover Fuels Production: Coal, Hydrocarbon Crude], Moscow: IRC Gazprom Ltd. 302

Magomet, R.D. and Mironenkova, N.A. 2014. Tendentsii razvitiya toplivno-energeticheskogo kompleksa na primere ugledobyvayushchei otrasli [Development Tendencies of the Fuel and Energy Complex in the Context of the Coal Mining Industry], In Trudy Mezhdunarodnoi nauchno-tekhnicheskoi konferentsii "Innovatsii v sistemakh kontrolya, upravleniya, zashchit i monitoringa bezopasnosti v gornoi promyshlennosti" [Proceedings of the International Scientific and Technical Conference "Innovations in the Field of Mining Safety Control, Protection and Monitoring Systems"]. Katowice, Poland: EMAG, pp. 44-51.

Monaghan A. 2007. Kurs na ugol" [Coal Course]. *Pro et Contra*. 1(40)

"Nashi novosti" [Our News], Sonel Company. Retrieved March 8, 2017, from http://www.sonel.ru/ru/company/news/.

Puchkov L.A., Slastunov, S.V. and Kolikov, K.S. 2009. Problemy realizatsii kontseptsii metanobezopasnosti na ugolnykh shakhtakh Rossii [Implementation Problems of the Methane Safety Concept at the Coal Mines in Russia]. *Ugol*. 1 : 28-30.

Smirnova N.N. and Soloviov V.B. 1982. Otsenka teplopoter v kanale gazifikatsii [The Heat Losses Assessment in the Gasification Channel]. *Fizicheskie protsessy gornogo proizvodstva*. 12.

Soloviov V.B., Goncharov E.V. and Orlov T.V. 1995. Sposob podzemnoi pererabotki ugolnogo veshchestva. Patent No.14116 na izobretenie No. 1686885 [The Underground Coal Conversion Method Patent No. 14116 on the Invention No. 1686885.].

Vasyuchkov Yu.V. and Vorobev, B.M. 1997. Patent na izobretenie No. 2100588 RF. Sposob polucheniya elektroenergii pri besshakhtnoi uglegazifikatsii i/ili podzemnom ugleszhiganii. [Patent RF on the Invention No. 2100588. Electrical Energy Generation Method in Case of the Shaftless Coal Gasification and/or In-Situ Coal Combustion].

Zorya A.Yu. and Kreinin E.V. 2009a. Est sposob uvelicheniya doli ugolya v elektroenergetike" [There Exists the Way of the Coal Percentage Increase in the Power Industry]. *Ugol*. 4 : 53.

Zorya A.Yu. and Kreinin E.V. 2009b. Mozhet li podzemnaya gazifikatsiya ugolnykh plastov stat promyshlennoi tekhnologiei?" [Can the In-Situ Gasification of the Coal Seams Become the Industrial Engineering?]. *Ugol*. 3.

Zorya A.Yu., Kreinin E.V. and Lazarenko S.N. 2009. Novye vozmozhnosti" [New Opportunities]. *Ugol Kuzbassa*. 4.