DOI 10.18454/PMI.2016.6.803

UDC 622.324.5.004.14

GEODYNAMIC METHODS FOR ASSESSING METHANE DISTRIBUTION IN BITUMINOUS COAL DEPOSITS AND MEASURES TO INTENSIFY METHANE FLUXES DURING MINE GAS DRAINAGE

E.V.GONCHAROV, S.V.TSYREL
Saint-Petersburg Mining University, Saint-Petersburg, Russia

This paper explores states of methane within the coal bearing stratum and shows heavy dependency of the intrastratal gas migration on the forms of porous space and petrographic properties of coal. The adsorbed methane is found to be predominant in the coal of Kuznetsk Basin. Different forms of coal diffusion and filtration are described revealing their dependency on geological and thermodynamic conditions. The paper provides justification for the primary focus on geodynamic processes when designing gas drainage systems and applicability of morphometric methods and remote sensing data for their identification. The significance of researches into the processes activating exothermic reactions resulting in methane transition to free state is explained. The paper presents the results of using seismic-acoustic stimulation techniques as one of the practical approaches to addressing this issue.

Results of successful industrial testing have been compared with the results of numerical modelling of stress-strain state, which can also be managed through seismic-acoustic stimulation.

Key words: methane, coal beds, gas drainage, geomechanical and geodynamic processes, gas fluxes intensification.

How to cite this article: Goncharov E.V., Tsyrel S.V. Geodynamic methods for assessing methane distribution in bituminous coal deposits and measures to intensify methane fluxes during mine gas drainage. Zapiski Gornogo instituta. 2016. Vol. 222, p.803-808. DOI 10.18454/PMI.2016.6.803

Introduction. Today most accidents resulting in large loss of life not only in coal mining, but in the ore mining industry as a whole are caused by methane explosions and subsequent fires and ground collapses. Existing and recently offered gas drainage methods (N.V.Nozhkin, S.V.Slastunov, K.S.Kolikov, A.S.Seregin), various technological combinations of hydraulic fractures and simply an increased emphasis on compliance with ventilation standards have significantly reduced the number of accidents, but have not eliminated the problem. As evidenced by the last accident at ‘Severnaya’/Northern/ mine the methane explosions followed by long-lasting fires occur not only within seams partially drained without reduction in pressure, but also within underworked beds, in conditions most favourable for efficient gas drainage. Methane-related accidents, though much less frequent than in Russia, also occur at the mines in USA and China [16, 21, 23], where gas is drained for a long while before mining.

In order to improve efficiency of gas drainage techniques, basic information about methane states in coal beds and enclosing strata and patterns of its migration at different coal deposits shall be again analyzed. As is known, coalbed methane may be found in the form of autonomous methane deposits outside the developed coal basins or be the second after the coal energy bearing component in the coal beds of gas-coal deposits [1]. The coalbed methane may also form autonomous microdeposits either in the coal or in the strata enclosing multiple coal layers. While most reserves of methane are confined to the coal layers and interlayers and affect safety of mining operations. Bituminous coal deposits with high content of methane accessible for cost-effective extraction can be referred to coal and methane-coal deposits.

But in contrast to USA and Australia [24-25] in conditions of coal basins within Russia such deposits have not yet been found. Geological conditions of coalbed methane deposits are similar to that of purely methane deposits, but have a number of principal differences, due to which technology used to intensify methane fluxes at gas fields in Russia (and across the world) turns out to be low efficient.

DOI 10.18454/PMI.2016.6.803

Research methods. *Analysis of methane state in coal beds.* Obviously the first and the main reason of these differences is the state in which methane occurs in the coal bearing stratum. Content and state of methane in the coal beds first of all depend on the coal genetic type, petrographic composition and metamorphism grade (stage of phase transformations), as well as on the depth of occurrence and geodynamic conditions. Dependency between the methane state and metamorphism grade is shown in Table 1 [13, 14].

Table 1

Possible states of methane in coal beds

Stages of phase transformations	Methane state and content, %		
	Adsorbed (in supramolecular aggregates)	Absorbed	Free
2G-3G	30-40	15-35	15-40
4Zh-5K-60S	15-40	20-40	15-25
7-8T-9-10A	10-15	40-60	25-35

Metamorphism grade is not the only determinant of the methane state in coal beds, the same important role is played by the petrographic composition and structure. Methane of solid glance Donetsk and Kuznetsk coal is occurring within supramolecular aggregates; as a mobile phase (fluid) adsorbed on the inner surface of the coal; in the form of free gas dispersed in the closed or open interconnected cavities (pores and cracks).

Free methane and water-methane fluids in coal beds are found in cavernous-porous, fractured-porous, fractured, layered-fractured and layered cavities, with their content in Kuznetsk coals ranging from 3-5% to 12-15% of total methane reserves. Various forms of occluded methane form thin molecular films on the inner surfaces of the cavities. Occluded methane comprises over 40% of total methane content. Content of chemically nonbonded methane within pseudo-clathrates ranges from 5% to 20-30%. In total the average content of physically bonded methane in Kuznetsk coal is from 60% to 70%. Molecularly (chemically) bonded (adsorbed) methane in the amount of 5% to 10% is partially desorbed from the coal stratum subsequent to intensive avalanche-like processes of sudden releases and at low rate from the pieces of crushed coal with reduced pressure.

Analysis of methane migration patterns. Intrastratal migration of gases leading to formation of sheet microdeposits is minor and can be explained by presence of migration channels (permeable pores). Permeability of channels depends on their effective cross section: Knudsen – Folmer – Brownian pores have low efficiency in terms of possible motion paths for methane molecules; the Poiseuille free flow of gas is possible only with cross section of 100 microns and larger (Table 2) [14, 15] .

Analysis of gas pressure in coal beds and enclosing strata and its effect on migration patterns. Gas pressure in coal beds largely governs the free to bonded gas ratio. Concentration of free gas increases to its maximum of 10-15% at the following methane pressure in the coal beds at the depth of: 500-600 m – 4-6 MPa; 600-700 m – 6-8 MPa; 700-800 m – 7-9 MPa; 800-1000 m – 8-11 MPa and more than 1000 m – 9-14 MPa. Residual pressure in the stratum averages to 1.0-1.2 MPa [1, 15].

Pressure of gases in the coal bearing strata also depends on the depth, excluding zones of abnormally high pore pressure (AHPP). Highly important for assessment of reserves are the incidents of abnormally high pore pressure at the depth over 600-700 m. AHPP value may exceed the average pressure at the given depth manifold (by dozens and hundreds of times). AHPP is an indication of sharp increase in specific reserves of gas in local methane deposits (microdeposits) allowing for their efficient use [1, 7, 15, 17, 18, 20]. In underground mining AHPP zones are the primary source of powerful gas blows.

The role of pressure gradient for intrastratal gas flows outside the AHPP focus within the coal seam having no fractures is perceived only at small distances (portions and points of a meter). Only cracks and fractures extend the range of gas migration and contribute to occurence of releases of various intensity.

DOI 10.18454/PMI.2016.6.803

Table 2

Overview of fossil coal porous space with respect to gas generation properties

Cavity	Size, μm	Place, shape, peculiarities of manifestation	Correlation with gassiness. Motion patterns	Research methods
Cavity (pore) intra- and inter-aggregate space				
Molecular pores	0.0005-0.00007 and less	In molecular, macromolecular and intermolecular structures	With molecular binding, clathrate and occluded. Diffuse and molecular migration	Physical and chemical; Diffractometric; transmission electron microscopy
Folmer ultra-micropores	0.001-0.01	Elongated pores in the structure with predominantly surface processes	Predominantly occluded gas not released upon coal destruction	Physical and chemical, scanning electron microscopy (SEM), transmission electron microscopy (TEM), reflection electron microscopy (REM)
Knudsen meso-micropores	0.001-0.1	In unstructured vitrinite with equilibrium ratio of surface processes and viscous flow processes	Mostly occluded gas, released in avalanche-like processes with intensive dispersing	
Brownian	0.1-1.0	Pores of colloidal and crystalline vitrinite structure with predominant molecular motion	Lower portion of gas freely migrating within the gas bearing system of confined seam	Physical and chemical, SEM and optical microscopy
Poiseuille	1.0-10.0	In the structure of vitrinite fragments and in an unstructured mass. Viscous flow is predominant	Freely released gas	Physical and chemical, physical, scanning electron and optical microscopy
Micropores	Over 10	In the structure of fusinite, semi-fusinite, semi- and structural vitrinite	Gas not always freely released	Physical, physical and chemical, SEM and OM
Cavity interlayer, fracture and compound interaggregate space				
Fracture and interlayer space	Opening 0.01-10.0	Intersecting layered, intralayered and interlayered. Surface processes abate, viscous flow is predominant	From occluded to free gas	Physical, physical and chemical, REM and TEM, SEM and OM

Possibility to extract the occluded (but chemically nonbonded) gas depends on the motion patterns of its molecules: Knudsen – gliding over the surfaces of connecting channels with separation of molecules and formation or replacement of vacancies; Folmer – in the process of molecules collisions, gliding over the surfaces of channels, layer-by-layer migration, etc.; Brownian motion in the form of exchange of radicals. That's why when developing gas drainage and methane extraction methods the researchers shall not be limited only to Poiseuille processes and shall not ignore other migration patterns such as through thinner pores and even unhomogeneity of crystal lattice.

Nevertheless low intensity of diffusion and flows of various types through thin pores leads to low efficiency of extraction of molecular-bonded and occluded gas from the coal seam if the coal structure is not intensely affected. As evidenced by the laboratory and field studies the coal in its virgin undisturbed state has low permeability. The gas motion within the coal is driven by diffusion mechanism, and filtration process occurs in the system of natural 'cleavage' fractures governed by the Darsy law:

$$Q = S\frac{K_{np}}{\mu}\frac{\Delta(P + gh\rho)}{l},$$

where S is the cross section of the sample; P is the pressure on the free surface of the fluid, i.e. proportional to the pressure $\Delta P = (P + gh\rho)$ inducing fluid filtering through a porous medium with the path length l; μ is the viscosity of the fluid. While coal diffusion coefficient is extremely small – in normal conditions it is equal to 10^{-11} s/cm^2, and largely depends on local changes in temperature and type of dynamic exposure. A.N.Desyatkin [8] also highlights this by presenting results of laboratory and field studies, which show that in virgin undisturbed state the coal has low permeability.

 DOI 10.18454/PMI.2016.6.803

Research findings. The conducted studies reaffirmed the opinion of V.V.Kiryukov and his colleagues [13-15] on importance of petrographic studies of coal. In particular, the studies [13] have once again experimentally proven the conclusion that the methane-bearing capacity of coal depends on the content of vitrinite in coal, which has a large amount of micropores acting as collectors of occluded methane. Thus, the higher vitrinite content in coal is, the higher methane retention capacity the coal has. The fusinite (inertinite) content in coal correlates with the number of macropores and consequently the coal with higher inertinite content faster desorbs methane. The liptinite content in coal is characterized by small amount of occluded methane.

The conducted analysis demonstrated the importance of thorough examination of methane states and migration patterns at a certain coal field in order to decide on appropriate gas drainage methods and parameters.

For determining the coal methane retention capacity both direct and indirect methods can be used. Direct methods are based on examining core samples from the exploratory boreholes and extracting methane therefrom. Despite all its deficiencies (from a sparse network of wells to the methods of core sampling and research) this method is deemed standard, and key data on gassiness of coal deposits in Russia is based on the values obtained using this method [2, 3].

Unfortunately, there are few indirect indications of probable physical and technological solutions. Besides all methods, except for laboratory studies, used to asses in-situ (well-specific, seam-specific) indicators of methane retention capacity, gas permeability, gas recovery rate, methane diffusion have numerous drawbacks. Nevertheless in general terms provided regular organized complex monitoring it is possible to obtain data about gas content in mined seams (with account of flows, crossflows, mined-out spaces and adjacent seams), sufficient to solve most technological tasks. As concerns indirect methods for assessing gassiness, in particular, residual gas content and forecasting methane migration, the most insightful are the studies under the lead of O.V.Taylakov [21, 22].

Determination of the coal gassiness using indirect method is based on analysis of actual gas content in the mine workings and establishing the balance between the gas sources, including mined-out spaces, seams, adjacent interlayers and actually mined seams. In such context such terms as methane permeability and migration get vague. In the studies of O.V.Taylakov [4, 21, 22] a task of most accurate assessment of gassiness is solved with due regard to methane desorption in applying the mine corner, that ensures quasi-constant thermodynamic conditions during bed samples drilling out and processing methods addressing filtering processes (the Darcy's law) and diffusion (the Fick's second law). The use of methods like this helps to efficiently compare data on changes in stress-strain state simulated for a seam [6, 11, 17, 22, 23] with dynamics of changes in the seam gassiness.

It is extremely important to note that predominance of absorbed methane locked out in actually closed pores of the coal of Kuznetsk and other Russian fields, makes dependency of sorption on pressure, temperature, etc. an importance factor predetermining gas content in the mine workings. Initial increase in gas content leading to accidents is in most cases explained by the defects or failures of ventilation system, gas blows from the unidentified AHPP and releases from zones with accumulated free methane. But further emissions of large amounts of methane creating risk of accidents, first of all fires and explosions, are attributable to powerful processes of desorption upon temperature increase which may occur in relieved and unrelieved coal strata and coal lumps accumulated at the bottom holes and mined-out space. The heated coal interlayers and high-ash carbonaceous rocks may serve as methane sources in the roof and bottom of the high-risk seam, the same as adjacent parts of coal beds both unmined and mined. In addition methane locked out in fractures emerging as a result of main roof dinting and collapsing also has some role to play.

Conclusion. Thus, the most efficient method for draining the coal of Kuznetsk Basin, primarily in order to extract the occluded methane is heating. But high power consumption of the heating processes, low thermal diffusivity of coal and the danger of stimulating intense oxidation processes in coal constrain the use of thermal gas drainage methods.

Another method, which is safer and less power intensive [6, 19] is seismoacoustic excitation. But its use is subject to obtaining reliable information about state, petrographic composition and structure of coal, mining and gas pressure and general geodynamic situation. So far, the gas drainage using seismoacoustic and similar methods was carried out without any regard to the petrographic and geodynamic factors, or consideration thereof was only formal, which dramatically reduced efficiency of gas drainage activities. The authors propose a gas drainage method comparable with existing methods, but taking into account petrographic and geodynamic conditions of coal bed.

Seismoacoustic excitation method described in papers [4, 6, 7, 12, 18, 19] includes geodynamic zoning, identification of seam areas most optimal for gas drainage in the first turn with the use of seismoacoustic vibration transmitters AKSI, and development of gas drainage activities with account of changes in the stress-strain state of the seam. Seismoacoustic excitation leads not only to destruction of interpore partitions, but also to partial conversion of vibrational energy to heat energy and better conditions for methane desorption. While the value of complex of works for geodynamic zoning increases, as it allows to anticipatorily identify zones of block formations within rocks having tendency for more intense gas dynamics due to higher permeability, gassiness and more favourable conditions for gas drainage. These ideas became the core of the method developed and protected with patent, which helps to anticipatorily identify zones more optimal for methane extraction due to lower mining pressure (i.e. higher permeability) and maximum fracturing, where the probability of gas anomalies is the highest [17].

Acknowledgment. *The paper takes into account findings of research conducted jointly with Professor V.V.Kiryukov, of whom the authors keep the blessed memory.*

REFERENCES

1. Ajruni A.T. Prediction and prevention of gas-dynamic phenomena in coal mines. Moscow: Nauka, 1987, p. 310 [in Russian].

2. *Galazov R.A., Ajruni A.T., Sergeev I.V.* et al. Gas volumes of USSR coal mines: effective methods of artificial degassing of coal seams at greater depths. Moscow: Nauka, 1987, p. 200 [in Russian].

3. Ajruni A.T., Galazov R.A., Sergeev I.V. et al. Gas volumes of USSR coal mines. Integrated development of gas-bearing coal deposits. Moscow: Nauka, 1990, p. 213 [in Russian].

4. Goncharov E.V., Popov I.F. Equipment and technology of thermal-gas-chemical action at the intensification of oil-gas flowing in deviated wells drilled and flattens. *Vremja koltjubinga*. 2014. N 4(050), p. 68-69 [in Russian].

5. Goncharov E.V., Popov I.F., Shangaraeva L.A. Methods and thechiques of hydrocarbons extraction in the conditions of Russian coals and lignites. *Neft', gaz. Promyshlennost'*. 2014. N 3(53). p. 24-33 [in Russian].

6. Goncharov E.V., Tsyrel S.V., Zubkov V.V. Seismic-acoustic impact effectiveness of the intensification of the degassing of coal seams.Vestnik KUZGTU. 2016. N 1, p. 28-36 [in Russian].

7. Goncharov E.V., Rabota Je.N., V'junnikov A.A., Lodus E.V. Degassing seams outburst by thermal-acoustic impact. *Gornyj informacionno-analiticheskij bjulleten'*. 2009. Otdel'nyj vypusk. N 11, p. 49-65 [in Russian].

8. Desjatkin A.N. Identification of coal seams and evaluation of their commercial characterstics according to geological and geophysical studies of wells during methane extraction: Avtoref. dis…kand. geol.-min. nauk. Moscow: RGU nefti i gaza im. I.M.Gubkina, 2011, p. 22 [in Russian].

9. Zubkov V.V., V'junikov A.A. Degassing zones effective degassing during coal seams formation development. *Markshejderija i nedropol'zovanie*. 2015. N 2, p. 29-32 [in Russian].

10. Zubkov V.V., Zubkova I.A. Effective degassing zone calculation during beds development. *Markshejderija i Nedropol'zovanie*. 2013. N 3, p. 54-57 [in Russian].

11. Zubkov V.V., Zubkova I.A. Effective degassing zone calculation during beds development in faulting zones. *Markshejderija i Nedropol'zovanie*. 2013. N 5, p. 60-62 [in Russian].

12. Karmanskij A.T., Goncharov E.V. Increasing the productivity of oil wells by the influence of the bottomhole formation zone with thermal-gas-chemical liquids. *Neft', gaz. Promyshlennost'*. 2013. N 5(50), p. 22-25 [in Russian].

13. Kirjukov V.V., Novikova V.N. Nanospace and phase states of coal and coal bed methane problems. *Zapiski Gornogo instituta*. 2005. Vol. 163, p. 179-182 [in Russian].

14. Kirjukov V.V., Kushh O.A. Industrial and geological factors of development of coal-gas deposits in Donetsk region. Mezhvuz. sb. Ekaterinburg: Ur. gorno-geol. akademija, 1998. Iss. 8, p. 243-253 [in Russian].

15. Kirjukov V.V. Fuel and energy complex of Russia. Coal industry development perspectives. SPbGGI, St. Petersburg. 1997, p. 68 [in Russian].

16. Kuznecov S.V., Trofimov V.A. The nature and mechanism of gas-permeable zones formation in coal seams. *Fiziko-Tehnicheskie problemy razrabotki poleznyh iskopaemyh*. 1999. N 1, p. 21-27 [in Russian].

17. Jakovlev D.V, Shabarov A.N., Goncharov E.V. et al. Patent N 2136850 RF. Coal seams methane recovering method Opubl.10.09.99. Bul. N 25 [in Russian].

18. Shabarov A.N., Goncharov E.V., Talanov D.Ju., Karih V.A. Patent N 2322586 RF. The method of extracting methane from coal seams fields. Opubl.20.04.2008. Bul. N 11 [in Russian].

19. Shabarov A.N., Goncharov E.V., Karmanskij A.T. et al. Patent N 2328594 RF The method of gas-impulse processing of oil and gas wells and tools for its implementation. Opubl. 10.07.2008. Bul. N 19 [in Russian].

20. Goncharov E.V., Kiselev V.N., Guseva N.V. et al. Patent N 2450105 RF. The method of protection of ground objects from the effects of deformation processes initiated by the development of oil and gas fields. Opubl.10.05.2012. Bul. N 13 [in Russian].

21. Tajlakov O.V., Kormin A.N., Tajlakov V.O. Determination of residual gas content of coal seams based on macrotechnic desorption processess of filtration and methane diffusion to assess the effectiveness of the degassing. *Nauka i tehnika v gazovoj promyshlennosti*. 2014. N 1, p. 10-13 [in Russian].

22. Shabarov A.N., Goncharov E.V., Guseva N.V. Geomechanical aspects of sudden coal and gas blowouts and degassing of coal seams. *Markshejderskij vestnik*. 2015. N 1, p. 43-47 [in Russian].

23. Coalbed Methane Extraction: Detailed Study Report, United States Environmental Protection Agency, December 2010, p. 91.

24. Handbook on Coal Bed Methane Produced Water: Management and Beneficial Use Alternatives. U.S. Department of Energy National Petroleum Technology Office Bureau of Land Management, July 2003, p. 322.

25. Rice D. Coal bed Methane an untapped energy resource an environment concern. U.S. Geological Survey, Energy Resource Surveys Program, USGS Fact Sheet FS-019-97, 1992, p. 19-97.

***Authors*: E.V.Goncharov,** *Senior Research*, *goncharovbox@mail.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **S.V.Tsyrel,** *Doctor of Engineering Sciences*, *Chief Scientist*, *tsirel58@mail.ru* (*Saint-Petersburg Mining University*, *Saint Petersburg*, *Russia*).

The paper was accepted for publication on 30 September, 2016.