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Exploitation Technologies of Coalbed Methane in the Qinshui Basin of China

Y. J. Lu[a], *, J. X. Han[a], **, V. V. Shelepov[a], *, E. Yu. Makarova[a], ****, K. Li[a], *****, and J. Chu[a], ********

[a] *Department of Geology, Moscow State University, Moscow, 119234 Russia*
**e-mail: lhmsu@mail.ru*
***e-mail: pulinsd@qq.com*
****e-mail: shelepov_s@mail.ru*
*****e-mail: lenamakarova87@yandex.ru*
******e-mail: kaikaili@mail.ru*
*******e-mail: vladimirchujun@yandex.ru*

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Abstract—Coalbed methane (CBM) is a new environmentally friendly unconventional energy source of great promise for exploitation. The CBM resources in the Qinshui Basin are as great as 3.97×10^{12} m^3, i.e., 10.8% of the total coal gas resources of China. Compared to the main coal basins of the United States, Australia, Canada, and Russia, the Qinshui Basin is characterized by high metamorphism, high gas content, and low values of porosity and permeability, as well as by low formation pressure. The commercial exploitation of productive beds at the Qinshui Basin requires the use of efficient technologies of stimulation. Vertical wells with hydraulic fracturing (HF) predominate at the Qinshui Basin. The CO_2 injection, electric pulse, multistage HF, etc. technologies are used as well.

Keywords: coalbed methane, stimulation treatment of CBM, hydraulic fracturing, coal geology of China, Qinshui basin

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INTRODUCTION

Coalbed methane (CBM) is a natural gas that is generated and contained within coal beds. The formed methane is mainly adsorbed by the organic matter of coal. The remaining gas occurs either in a free state within the fractures and pores of coal or as a dissolved form in the water of the coal beds. CBM production may not only be of commercial efficiency but also would provide environmental protection and decrease excess power consumption. The CBM deposits in China are found at depths down to 2000 m and contain 36.8×10^{12} m^3 of gas accumulated in seven basins, including the Qinshui Basin. The methane resources of this basin equal 3.97×10^{12} m^3 or 10.8% of the total coal gas resources of China (Zhao and Tian, 2008). The Qinshui Basin is located in the east of Shanxi Province situated in the west of Northern China (Fig. 1). Commercial CBM production is carried out in the southern area of the Quinshui basin (Ye et al., 2009).

Stratigraphy. The coal-bearing part of the deposit is of Carboniferous–Permian age and is bedded on the weathered crust of Ordovician rocks and overlain with Mesozoic–Cenozoic rocks. The main productive layers are accumulated in the Taiyuan and Shanxi formations of Late-Carboniferous (C_3t) and Early-Permian (P_{1s}) ages, respectively (Fig. 2). The Benxi and Shixezi formations (C_{2b} and P_{2X}, respectively) are characterized by thin coal beds of no commercial value (Liu, 2007; Liu, 2012).

The Taiyuan formation consists of interbedding of fine-grained feldspar quartz sandstones, grey-black siltstones, argillites, limestones, and coal beds. The formation is characterized by the occurrence of layers of limestone and marl of a decreasing content upward in the section. The total thickness of the formation varies from 68.28 m in the south to 140.64 m in the north. The bottom of the Taiyuan formation is distinguished by sandstone of the K1 layer. The top is sandstone of the K7 layer, which is considered as the upper boundary of the formation.

The formations include from 4 to 14 coal beds nos. 16, 15, 13, 12, 11, 10, 9, 8, 7, and 6. The total thickness of the beds is within 0.4–19.4 m (6.36 m on average).

The Shanxi formation is presented by the alternation of fine-grained feldspar quartz sandstones, aleuric argillites, argillites, and coal beds. The profile

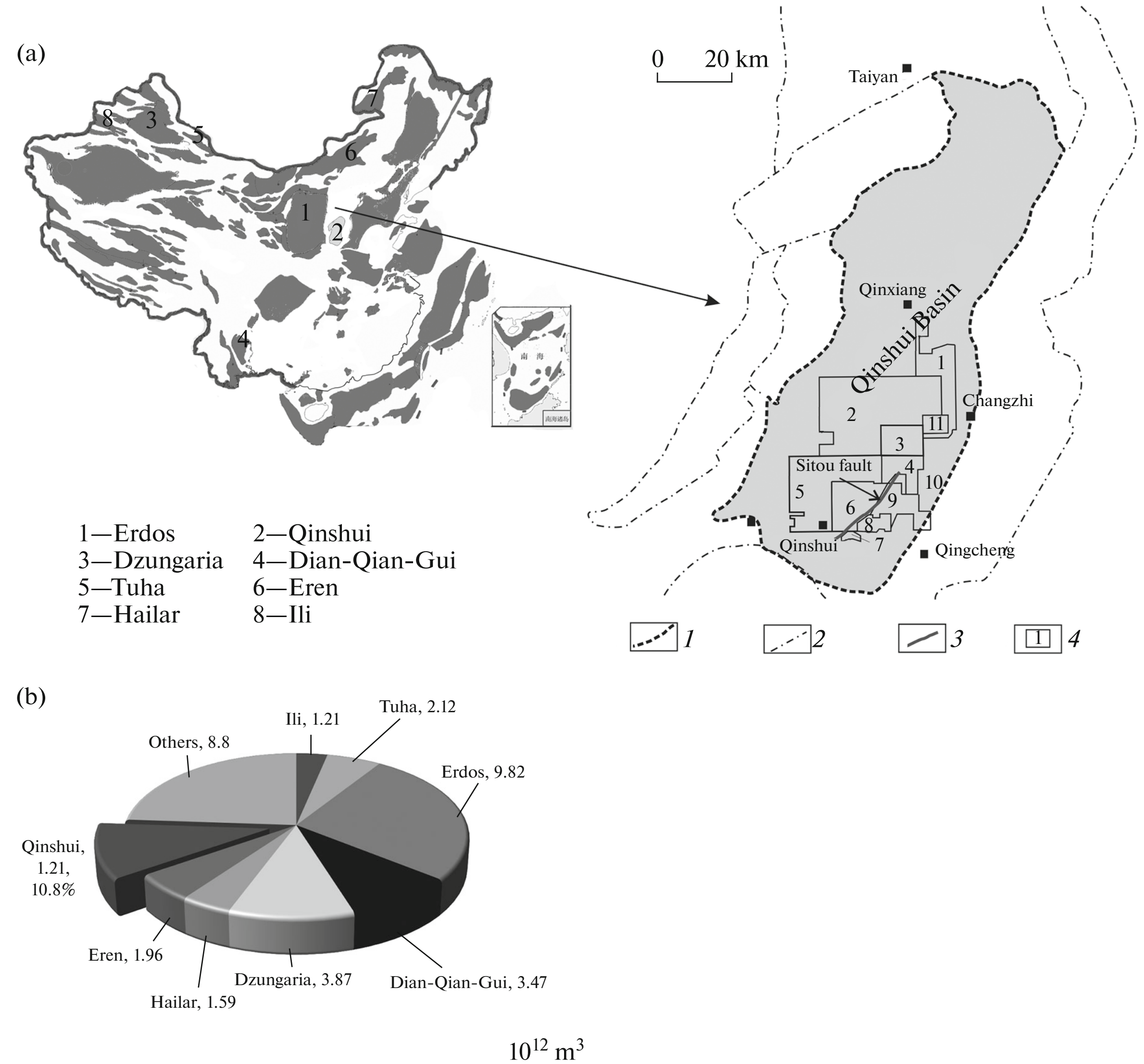

Fig. 1. The location of the Qinshui Basin in China: (a) (*1*), basin boundary; (*2*), structural element boundary; (*3*), fracture; (*4*), block (1) Xiadian; (2) Qinnan; (3) North Shizhuang; (4) South Shizhuang; (5) Mabi; (6) Zhengzhuang; (7) Daning; (8) Panzhuang; (9) Fanzhuang; (10) Zaozhuang; (11) Zhangzi and (b) the distribution of methane geological resources in coal basins of China.

contains neither layers nor seams of carbonate rocks. The total thickness of the formation ranges within 18.6–213.25 m (60.12 m on average); the thickness decreases from the north to the south. The bottom of the Shanxi formation conforms to the sandstone top of layer K8. The formation includes two to seven coal beds of various thicknesses and maturities; the productive beds are nos. 5–1 (bottom–up). The total thickness of the coal beds is 0.25–11.51 m (4.9 m on average).

The tectonics of the Qinshui Basin. The Qinshui Basin is a large synclinorium located between the Taihang and Lülyang elevations. The basin is characterized by quite a simple tectonics: the breaks presented mainly by faults are found exclusively at the edges. The mode of tectonics and the intensity of deformations are varied gradually from the center to the periphery of the basin. The inner part of the basin is characterized by secondary folds. The two wings of the synclinorium are quite symmetrical; the gradient of the western wing is relatively steep (~10–20°), while the eastern wing is flatter (~10°). The northern and southern parts of the basin are steeply rising.

Coal resources and quality in the Qinshui Basin. Coal bed 15 of the Taiyuan formation is among the exploited layers. The bed is mature and is 2.0–6.0 m in thickness (it is thicker in the north than in the south). The thickness of bed 15 varies in the south within 1.80–5.45 m (2.67 m on average), i.e., it is thinner than coal bed 3. The top of bed 15 consists of limestone of the K2 layer.

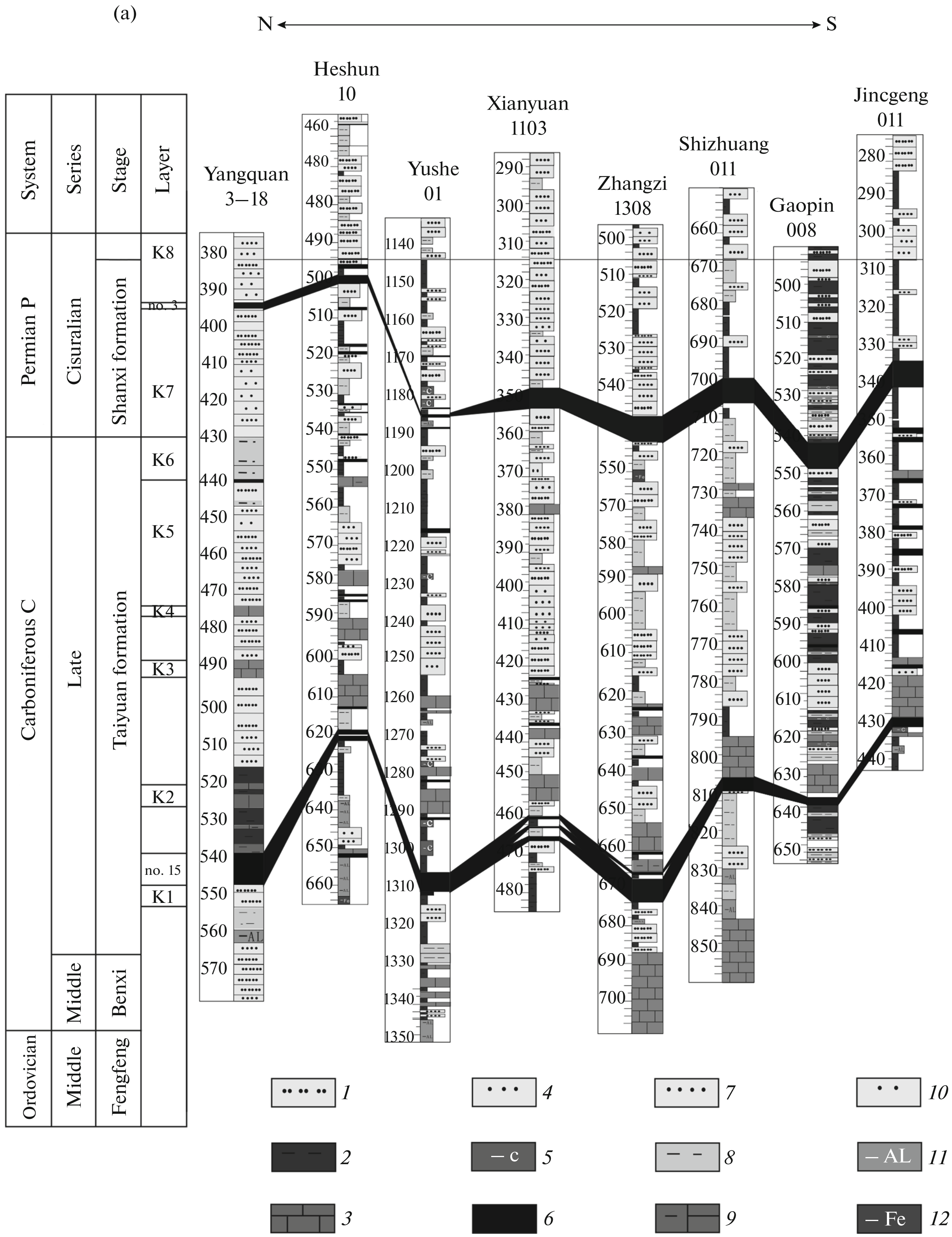

Fig. 2. Lithological columns of the Qinshui Basin: (a) the main beds, K1, K5, K6, K7, and K8, sandstone; K2, K3, and K4, limestone; nos. 3 and 15, coal beds; (*1*) siltstones; (*2*) argillites; (*3*) limestones; (*4*) medium-grained sandstones; (*5*) coaly argillites; (*6*) coal; (*7*) fine-grained sandstones; (*8*) argillite sandstones; (*9*) argillite limestones; (*10*) sandstones; (*11*) aluminous argillite; (*12*) sideritic argillite and (b) the location of wells over the basin: (*1*) wells and (*2*) the line of well locations.

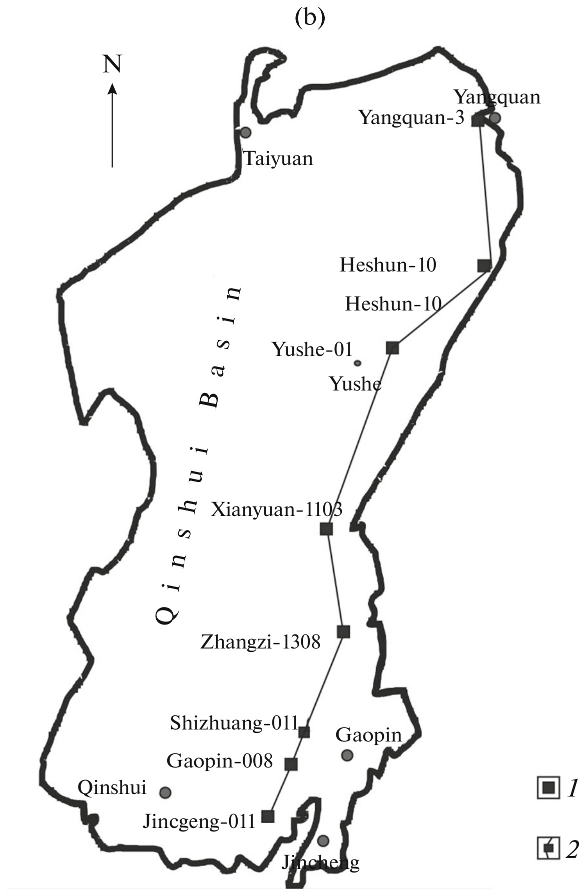

Fig. 2. (Contd.).

The coal bed 3 in the Shanxi formation is the main exploited layer. This bed is characterized by higher thickness compared to the others (0.53–7.84 m) and by widespread occurrence over the basin. The thickness of bed 3 is at a maximum in the southeastern area of the basin, with slight variations in the central and southern areas (5–7 m). The coal bed is characterized by a complicated structure with as many as five to six rock interlayers (usually two or three).

Bed 9 of the Taiyuan formation (which is as thick as 2–3 m in the north) is located between coal beds 15 and 3. The bed is thinner in the central and southern areas of the basin, which makes methane production in this layer unpromising. Thus, coal beds 3 and 15 of the Qinshui Basin are the main fields of coalbed methane production.

The Qinshui Basin is characterized by a high degree of coalification: the reflectivity of vitrinite (R_0) is varied from 0.83 to 6.95%. The maximum R_0 values were registered in the coal beds of the Shanxi formation from the Maojialing area in the northwest of the basin, which is related to the effect of magmatic bodies. This is a local feature; in general, the coals of the main productive beds 3 and 15 show similar degrees of transformation.

The coal ranks in the basin are situated in the following way: fat and coke coals (F and C, respectively) with R_0 within 0.9–1.5% prevail in the western part of the basin; the coals in the east are exhausted–baking (EB) and hard (H); the northern area is characterized by the prevalence of exhausted–baking (EB) and hard (H) coals, as well as of anthracite; and in the south, except for a small amount of hard coals (H), anthracites are mainly bedded. The central part of the basin contains mainly hard coals (H) and anthracites.

Characterization of methane–coal basins of the world. The coals of the Qinshui Basin were formed during the Carboniferous (C) and Permian (P) periods. The considered deposits in the coal bed 3 are similar in age to those of the Kuznetsk Basin in Russia and are much more ancient compared to the coal-bearing deposits in the basins of San Juan (United States), Alberta (Canada), and Surat (Australia).

Compared to the basins in other countries, the Qinshui Basin is characterized by small number of coal beds usable for methane production (Table 1) (Beaton et al., 2006; Gentzis and Bolen, 2008; Flores, 2014; Hui et al., 2013; Ji and Yang, 2007; Li et al., 2008; Li et al., 2014; Nurkowski, 1984; Storonskii, 2014; Thakur, 2017; 2013; Zolotykh, 2010). The main gas-productive beds are nos. 3 and 15. These beds show lower thickness compared to other basins but contain coals (preliminary anthracites) of high coalification.

The CBM-productive wells of the Qinshui Basin are mainly in the 300–1500 m depth range. It is significant that the average gas content in coal beds is high; however, the values of porosity and permeability may be low and decrease with depth. If a reservoir is located deeper than 800 m, the coal bed permeability is below 0.42 md (Ye et al., 2014).

Thus, the coal beds in the Qinshui Basin are usually characterized by low values of porosity and permeability, as well as by low formation pressure. The conditions as such make the commercially efficient gas production from the coal beds impossible without use of valid stimulation technologies.

The technology of CBM production at the Qinshui Basin. Various technologies of CBM production have been developed in the world due to the geological characteristics of specified basins. Thus, CBM in the United States is produced by the technology of cavity completion with an open coal face, as well as by using HF on an aqueous base with sand, HF on a gel base, repeated HF, and foamy HF. Technologies of CBM production that include multilayer HF, Mist-FracSM foamy HF, and the CobraFrac stimulation technology for horizontal holes to decrease the expense of CBM production were developed in Canada. In Australia, the drilling technologies for wells of middle and short radius (MRD and TRD, respectively) were developed, along with the technology of hydraulic jets in horizontal holes designed especially for coal beds with a high

Table 1. The geological characteristics of methane–coal basins in the world

Parameter	Countries and basins				
	Qinshui, China	San Juan, United States	Surat, Australia	Alberta, Canada	Kuznetsk Basin, Russia
Geological resources of methane, 10^{12} m^3	3.97	2.38	0.10	15.6	13.1
Age of coal-bearing deposits	C–P	K	J	J–K	C–P
Total thickness of productive beds, m	5–16	~30	20–40	6–20	~30
Gas presence, m^3/t	3.9–38.7	2.8–17	1–8	14.9–21.4	10.0–27
Porosity, %	1.15–7.69	1.0–3.0	6.0–9.0	9.5–22.3	8.44–16.05
Permeability, md	0.0003–82.8	1–60	1–1600	10–500	0.01–10
R_o, %	0.9–4.3	0.3–1.2	0.3–0.75	0.3–0.8	0.72–2.2
Depth, m	300–1500	168–1220	200–800	200–800	300–1200

gas content, various levels of water saturation, and high formation pressure.

At present, CBM in the considered basin is produced using vertical wells, mainly by the stimulation technologies of HF with active water, fracturing with a liner of cross-linked gel, foamy HF, HF with a pure liquid, repeated HF, ECBM (Enhanced Coal Bed Methane Recovery) stimulation, electric impact, etc.

Hydraulic fracturing using active water. The active water for fracturing contains a definite amount of chemical additives (KCl, surfactants etc.). When using HF, active water is injected through the casing pipe into the coal bed. The liquid volume is within 150–1000 m^3. Quartz sand is used as a proppant at the volume of 10–100 m^3 for a single layer. The concentration of quartz sand must be 247.5 kg/m^3 or less; the rate of the mixture injection varies from 5 to 8 m^3/min (Lu et al., 2016).

Active water for fracturing has a number of advantages: the low manufacturing cost, a moderate level of bed contamination, easy preparation of the reactants, etc. The technology of hydraulic fracturing with active water is the most applicable in China; however, the low transportability of sands within the bed requires a higher rate of liquid injection. A large volume of water consumption may cause an unreasonable elongation of a hydraulic fracture. A low content of sand results in deficient conductance of liquid and gas within the coal bed during exploitation (Ye et al., 2016).

Hydraulic fracturing with a linear gel. The main reactants of linear gels are water and thickeners. The jelly-like gel is prepared from water and a thickening liquid with the addition of cross-linking and breaking agents. A linear (or cross-linked) gel has good ability to transfer sand, low losses of liquid, the ability to form long fractures, etc. However, the gel is poorly breakable for low temperature coal beds, which results in quite a high level of a bed contamination, therefore this technology is rarely applied in coal beds (Tang et al., 2000).

Hydraulic fracturing with a pure liquid. A pure fracturing liquid consists mainly of surfactants of low molecular masses that pollute coal beds slightly and have a high ability to transfer sands. This technology is rarely used at coal deposits because of its high cost.

A pure liquid to be tested for fracturing the coal beds in the Hancheng district (Shanxi province) was selected at the China United Coalbed Methane Co., Ltd. Hydraulic fracturing was successfully performed and had good results at three wells of eight coal beds (Li et al., 2012).

Foamy hydraulic fracturing. The liquid for foamy HF consists of outer and inner phases (gaseous and liquid, respectively). The outer phase is usually either nitrogen or carbon dioxide; the liquid phase consists commonly of a foaming agent, a foam stabilizer, and a base liquid. A liquid of less than 52% foam content may be used as a system for increasing the power of the withdrawal of the fracturing liquid and is usually applied at the final HF stage (after the liquid). Liquid with a 52–96% foam content, i.e., foamy liquid, has the required characteristics for hydraulic fracturing. The permeability of the coal bed is low and is more sensitive to the injected liquids; thus, the foaming agent, the foam stabilizer, and the base liquid play a decisive role in polluting the coal bed. The liquids usually contain macromolecular additives that cause considerable damage to the beds. The use of foamy liquid for fracturing offers the great advantage of its high capacity to transfer sands and easy withdrawal out of the bed. However, the disadvantages include high cost and the complexity of describing its true characteristics.

At present, the foamy HF with nitrogen has been applied at no less than 11 wells; HF with carbon dioxide is still rarely used at the methane–coal deposit in the south of the Qinshui Basin (Sun et al., 2011; Wu et al., 2012).

Repeated fracturing of the bed. Repeated HR means the technology of fracturing a bed two or more times in old wells with low oil and gas flow. One may usually distinguish small-scale repeated fracturing to remove blockages and large-scale fracturing to form new fractures. Repeated HR in coal beds may increase the initial conductance of a fracture and the gas recovery.

Repeated HF in the Qinshui Basin has been carried out at more than ten wells with good results: the methane production increased by factors of 3–10 (Zhang et al., 2010). The use of repeated HF solves the problem of short fractures that occurs under primary HF, as well as that of the low conductance of the fractures caused by plugging with coal grains (Zhang et al., 2016).

CO_2–ECBM stimulation. The key mechanism of the CO_2–ECBM technology is the kinetic process of CO_2 adsorption and CH_4 displacement in coal beds. Moreover, this technology offers the advantage of promoting CO_2 burial in geological structures and increasing the recovery ratio of methane, which results in additional commercial benefits.

Based on research data, the China United Coalbed Methane Co., Ltd. carried out tests in the Qinshui Basin. In the course of testing, CO_2 was injected in succession into two wells, on average 201.4 t for each. The results showed that the bulk of the CO_2 was adsorbed by the coal bed; the well productivity and methane recovery ratio were considerably increased. At the same time, the aim of CO_2 burial was attained (Ye et al., 2012).

In general, this technology is rarely used in China because of its imperfections and high cost. However, companies and specialists are optimistic about the CO_2–ECBM technology and are confident of its rapid development.

Electric impact. This technique is based on the use of the energy of a high-voltage discharge in a liquid medium. Under the electric discharge, a channel of through conductivity is formed between two electrodes in a liquid, with subsequent widening into a collapsing low-temperature plasma cavity, which generates blast and compression waves. The blast wave that propagates within the near-well zone causes the destruction of mudding formations (Veselkov, 2007).

The use of this technology may result in the appearance of fractures and the removal of blockages within a coal bed, thereby improving the filtration and increasing the flow of gas. The technology is characterized by a short time cycle and quite a low cost, whereas it is limited by the small range of pulse pressure and significant requirements for the selection of wells.

To increase gas recovery, the technologies of multihole drilling, of a cavity with an open coalface, and of the drilling of a U-shaped well at the sites of high permeability were successfully tested at the Quinshui Basin.

CONCLUSIONS

The Qinshui Basin is promising for exploitation owing to its great CBM resources. The geological characteristics of the coal beds in the basin are different from those for the basins in other countries; thus, most of the efficient technologies of CBM production in the United States, Canada, and Australia are not applicable to the CBM recovery at the Qinshui Basin.

Due to the geological characteristics of coal beds in the Quinshui Basin, a new technology was developed in China. The technology consists in hydraulic fracturing with active water; this is the main technique of CBM production in this basin. At present, the technology of foamy HF is applied at the areas of low formation pressure and secondary HF is carried out for old wells and those of decreased productivity. The use of the CO_2–ECBM and electric impact technologies is having favorable results.

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