Advances in Geo-Energy Research

Vol. 2, No. 1, p. 34-42, 2018
www.astp-agr.com

Original article

Coalbed methane recovery from multilateral horizontal wells in Southern Qinshui Basin

Shenggui Liu[1], Songlei Tang[1], Shunde Yin[2,3]*

[1]*Institute of Mechanics & Architecture, China University of Mining & Technology (Beijing), Beijing 100083, P. R. China*

[2]*Department of Civil and Environmental Engineering, University of Waterloo, ON N2L 3G1, Canada*

[3]*Department of Petroleum Engineering, University of Wyoming, WY 82071, USA*

(Received January 11, 2018; revised January 25, 2018; accepted January 26, 2018; available online January 30, 2018)

Citation:
Liu, S., Tang, S., Yin, S. Coalbed methane recovery from multilateral horizontal wells in Southern Qinshui Basin. *Advances in Geo-Energy Research*, 2018, 2(1): 34-42, doi: 10.26804/ager.2018.01.03.

Corresponding author:
*E-mail: shunde.yin@uwaterloo.ca

Keywords:
Coalbed methane
multilateral horizontal well
methane emissions
gas recovery
Southern Qinshui Basin

Abstract:
Since 2006, more than 80 multilateral horizontal wells have been drilled in Panzhuang block, Southern Qinshui Basin. In this paper, 6 typical wells in a region are selected as an example. The thickness of coal, gas content, reservoir pressure, permeability, burial depth, and reservoir pressure conditions are analyzed. The practice shows that production by multilateral horizontal well declines from 43,111 m^3/day per well in the 2^{nd} year to 25,126 m^3/day per well in the 4^{th} year. The numerical simulation result shows that the lateral interference forms in Well QNP05 after two years of gas production, and the gas content is reduced to less than 8 m^3/t within the controlled region after six years. The area of gas content was less than 8 m^3/t after eight years of gas production is about 3.2 km^2, which is about 76% of the controlled area of the six multilateral horizontal wells. The results indicate that multilateral horizontal wells contribute to high production rates at potentially profitable levels and can also serve as an effective tool for a high-rank CBM field drainage.

1. Introduction

Commercial exploitation of coalbed methane (CBM) as a natural gas resource is an important milestone in the history of the global oil and gas industry (Flores, 1998). Since the 1970's, coalbed methane has been determined to be an economically viable energy source in America (Tim, 2012). Investigations have focused on understanding its origin, occurrence, distribution, availability, producibility and recoverability (Flores, 1998; Cui et al., 2004). In China, the number of CBM producing wells has increased significantly due to safer mining practices and a need for additional energy reserves throughout the past decade (Robinson, 2004; White et al., 2005). From 2005, China has gradually expanded its investment in the development of coalbed methane fields, and by June 2012, the number of drilled CBM wells has grown to 11,000, among which more than 4,100 are producing wells (Qin et al., 2013).

Poor permeability and low reservoir pressure are the two major reservoir deficiencies that result in the failure of the conventional vertical wells to achieve high productivity (Wang et al., 2017). Horizontal wells drilled from both the surface and from internal mine workings provide the opportunity for higher levels of methane recovery in less time compared to traditional vertical wells (Diamond, 1977; Steven, 2011), while costs for horizontal holes range from only 1 to 4 times as much (Gentzis, 2009; Palmer, 2010). The coal in Qinshui Basin generally has a low permeability range from 0.1 to 3.0 mD (Cai and Liu, 2011), and the performance of anthracites in Qinshui basin are superior to most of other basins referenced in China, The first multilateral horizontal well was completed in December 2004 to extract methane from coal seams prior to mining in the Daning coal mine in Southern Qinshui Basin, China (Liu et al., 2011). Because of the high productivity and the relatively low price, approximately 200 multilateral horizontal wells are drilled presently. Performance of six multilateral horizontal wells with lateral branches spaced from 100 to 150 m Southern Qinshui Basin is studied by comparative approach, and results shown in this study indicate that multilateral horizontal wells contribute to high production rates at potentially profitable levels and can also serve as an effective tool for a high-rank CBM field drainage.

https://doi.org/10.26804/ager.2018.01.03.

2. Reservoir characterization

(1) Reservoir geometry

There are two target seams in this study. The upper seam (#3) is 200-650 m deep and 75 m above the lower seam (#15). Both seams are in very good lateral continuity due to little heavy tectonic disturbance, and each individual seam is in a stable distribution of average thickness of 5.5 m and 2.5 m respectively (Yao and Wang, 2009). Adjacent seams occur only sporadically with a thickness no more than 1m are #7 and #9 between them and #2 above them, but they are not suitable for CBM production. It is also illustrated by Fig. 2 that coals in this area are generally located in the slope of the southern part of Qinshui Basin. Dip of this monocline stratum averages $3^{\circ}\sim6^{\circ}$.

Over 80% of the macerals is vitrinite, of which reflectance is about 2.2%∼4.5%, categorizing the coal as anthracite (Su et al., 2005). Porosity attributed to orthogonal cleats and porous volume in coal matrix is 2%∼6%, featuring high gas storage capacity and coal matrix shrinkage potential.

In short, the reservoir in Southern Qinshui Basin is of a nature with moderate depth, stable thickness, lateral continuity, gently dipping, little disturbance, and blocky integrity, which is very favorable for CBM production.

(2) Coal geomechanical properties

Tests on coal strength, strain, and compressibility indicate that the target coal seams in Southern Qinshui Basin are strong and stress sensitive. The uni-axial compressive strength of the #3 coal seam is 10∼20 MPa, and Poisson's ratio is up to 0.42.

(3) Stress condition

The stress gradient in southern Qinshui Basin is (1.6∼1.3 Mpa/100 m). This low degree of stress gradient favors gas flow.

(4) Reservoir pressure

The in-situ injection/fall-off tests in southern Qinshui Basin indicate that the reservoir is under saturated with a pressure gradient less than 0.65 MPa/100 m.

(5) Diffusivity and Permeability

As established from desorption tests, sorption time of #3 coal seam is about 8-10 days; the diffusion coefficient is therefore around $0.372\times10^{-7}\text{m}^2/\text{d}$ (under its original reservoir pressure condition).

According to an injection/fall-off well test, the permeability of the No. 3 coalbed reservoir varies in the range of 0.02 to 3.61 mD. Although the difference of the permeability of the main coal seam is significant, the distribution of permeability in the block shows an increasing trend from north to south in the Southern Qinshui Basin (Fu et al., 2001).

(6) Gas content and isotherm characters

Direct desorption and isotherm tests on samples have been conducted to obtain gas content information as well as gas storage capability known as one of the isotherm characteristics. Average gas contents in the proposed blocks are as high as 16-22 m^3/t for #3 coal seam and 15-24 m^3/t for #15 coal seam (Jin and Zhao, 2010).

Isotherm test provides such data for checking coal sorption ability over pressure-drop under a given temperature. The two parameters, Langmuir Volume (VL, m^3/t,) and Langmuir Pressure (VP, MPa), calculated from the isotherm curve are 25-50 m^3/t (air-dry basis) and 2.3-3.5 MPa (Liu, 2006; Lv and Tang, 2012). These results indicate that the target reservoir in the proposed area constitutes a huge gas storage capacity.

However, if multilateral horizontal wells are not implemented, the portion of gas recoverable is very limited, as it is difficult to draw down the bottom hole pressure below 1.6 MPa, and due to the under-saturated nature. The original gas content is well below its capacity, thereby only a small part of the gas could be produced unless the pressure drop could be quickly extended to far field at a very low level.

3. Reservoir parameter of multilateral horizontal wells

Coalbed methane is a major cause for outbursting or explosions worldwide and a coalbed with methane content greater than 9 m^3/t is considered to be coal and gas outburst prone (Campoli et al., 1985). For the purpose of drainage of CBM from #3 coal seam, six multilateral horizontal wells have been drilled since 2006. The major goal was to reduce gas content from 20 m^3/t to less than 8 m^3/t in the first mining block projected to mine 6-8 years later. Six multilateral horizontal wells named QNP01, QNP02, QNP03, QNP04, QNP05 and QNP06 were drilled, and the main bore and lateral branch patterns are shown in Fig.1. The multilateral horizontal wells QNP02, QNP04 have one main bore and several lateral branches, and the other wells have two main bores and several lateral branches, all lateral branches being spaced at 100 to 150 m.

The multilateral horizontal wells QNP01, QNP02 and QNP05 are located in the Houjiashan Syncline and the other wells are located in the Mashancun Anticline as shown in Fig. 2.

Reservoir properties for the multilateral horizontal well site are described in Table 1 which exhibit good potential of gas deliverability. The burial depth and coal thickness are 260-302 m and 5.5-5.8 m, respectively. The borehole lengths in the coal seam of multilateral horizontal wells are between 3,318-6,225 m. The drainage area of the six multilateral horizontal wells is 4.2 km^2.

4. Degasification performance of multilateral horizontal well

(1)Production simulation of multilateral horizontal well

In this study, CBM-Sim reservoir modeling software was used. CBM-Sim incorporates a three-dimensional, dual porosity simulator which simulates fluid flow through coal to a producing wellbore. For the purpose of this study, a single gas component sorption model was utilized, assuming pure methane in the coal seam.

Reservoir modeling parameters were obtained from CBM exploration well Pan2, as outlined in Table 2, the permeability is 2.2 mD, burial depth is 300 m, initial reservoir pressure is 2.8 Mpa, Langmuir volume is 38.6 m^3/t, Langmuir pressure is 2.5 Mpa, desorption time is 6.14 days, water saturation is 81% and coal thickness is 6.0 m. According to the obtained

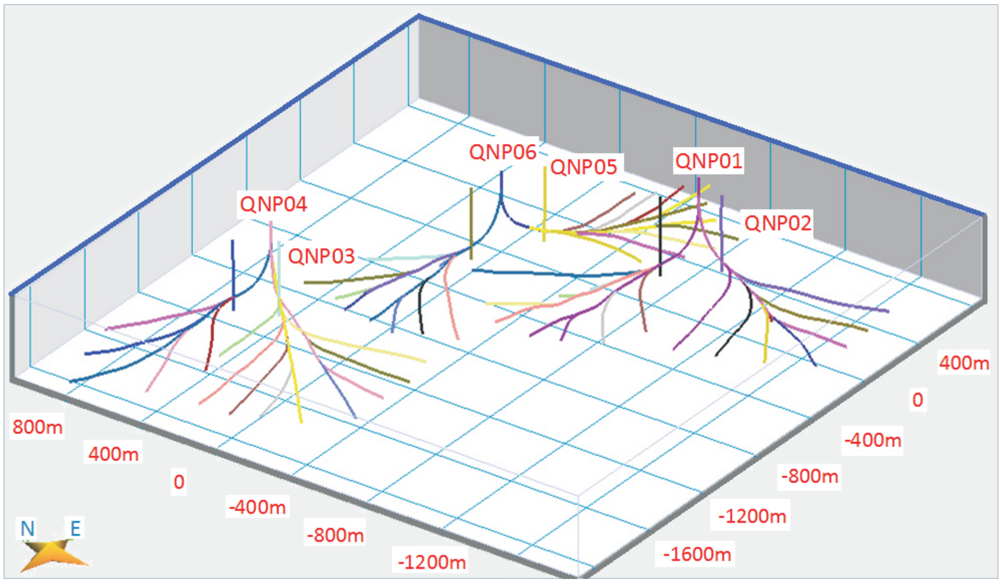

Fig. 1. Main bore and lateral branch patterns.

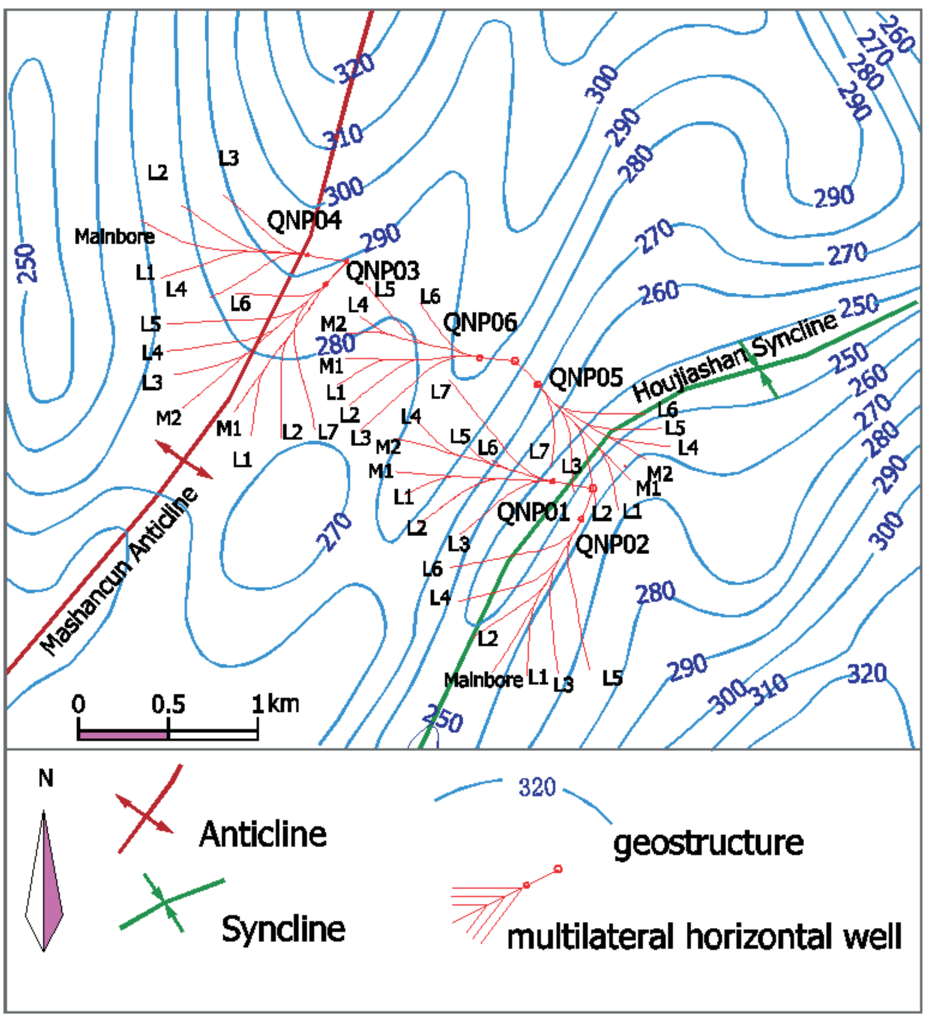

Fig. 2. Geostructure map of multilateral horizontal well control region.

Table 1. Reservoir parameter description for the well site.

Well ID	Burial depth (m)	Coal thickness (m)	Borehole length in coal seam (m)	Drainage area (km^2)
QNP01	302	5.8	4,879	0.72
QNP02	280	5.7	4,919	0.75
QNP03	243	5.5	6,225	0.85
QNP04	246	5.7	3,318	0.59
QNP05	280	5.5	5,183	0.66
QNP06	260	5.8	4,344	0.63

Table 3. Reservoir parameters of the horizontal wells.

Well ID	gas content (m^3/t)	permeability (mD)	reservoir pressure (MPa)
QNP01	20.6	1.6	2.75
QNP02	21.2	2.2	2.74
QNP03	19.2	1.4	1.99
QNP04	19.5	1.1	2.09
QNP05	20.2	2.5	2.41
QNP06	19.8	1.0	2.26

Table 2. Coal reservoir data used in the models.

Parameter	Data
Permeability (mD)	2.2
Burial depth (m)	300
Initial reservoir pressure (MPa)	2.8
Gas content (m^3/t)	19.1
Bulk density (kg/m^3)	1,430
Langmuir volume (m^3/t)	38.6
Langmuir pressure (Mpa)	2.5
Desorption time (days)	6.14
Temperature (°C)	18.0
Coal thickness (m)	6.0
Water saturation (%)	81

Langmuir coefficients, depth, pressure gradient, and initial gas content, the coal is undersaturated. Simulation region is 4,375 m $\times$ 4,000 m, and is discretized into 175×160 finite difference elements. Based on the actual main bores and lateral branches of the six multilateral horizontal wells, the control area is 4.2 km^2. Reservoir parameters used in history matching are outlined in Table 3.

Distribution diagram for coalbed methane recovery (Fig. 3) is analyzed: after two years, the coalbed methane recovery rate reaches 15% within the single well control region; after three years, recovery rate exceeds 30% within the single well controlled region; after five years, recovery rate exceeds 40% within the single well controlled region; after ten years, recovery rate exceeds 65% within the single well controlled region. Thus, gas recovery rate is proportional to the pressure drop rate of a horizontal well. For the sake of releasing CBM well productivity fully, pressure drop zone should be extended adequately in the drainage process. Gas recovery rate is proportional to pressure drop rate of the horizontal well. The zone around the boreholes is about 0.4 km^2 with gas content reduced to 8 m^3/t after two years of gas production, and the lateral interference appears in Well QNP05 with a lateral branch interval of less than 100 m. The zone is about 1.2 km^2 with gas content less than 8 m^3/t after four years of gas production. The area is about 2.1 km^2 with gas content less than 8 m^3/t after six years of gas production, and gas content is less than 8 m^3/t within the well QNP05 control region. Well interference with other wells has occurred. The area with gas content less than 8 m^3/t after eight years of gas production is about 3.2 km^2, and that is about 76% of the controlled area of the six multilateral horizontal wells.

(2)Vertical well performance

There are totally 150 wells drilled in the Panzhuang block for the purpose of CBM development, and all have been tested to identify their single well production capacity. Continuous geometry and strong geomechanical nature of the seam made it straightforward for all the operators to complete the holes with casing followed by perforating the #3 coal seam and then hydro-fracturing for reservoir stimulation.

Among these wells, production from 45 wells is more than 5,000-9,000 m^3/d at peak rate and more than 4,000 m^3/d at stable rate. Production from 72 wells is more than

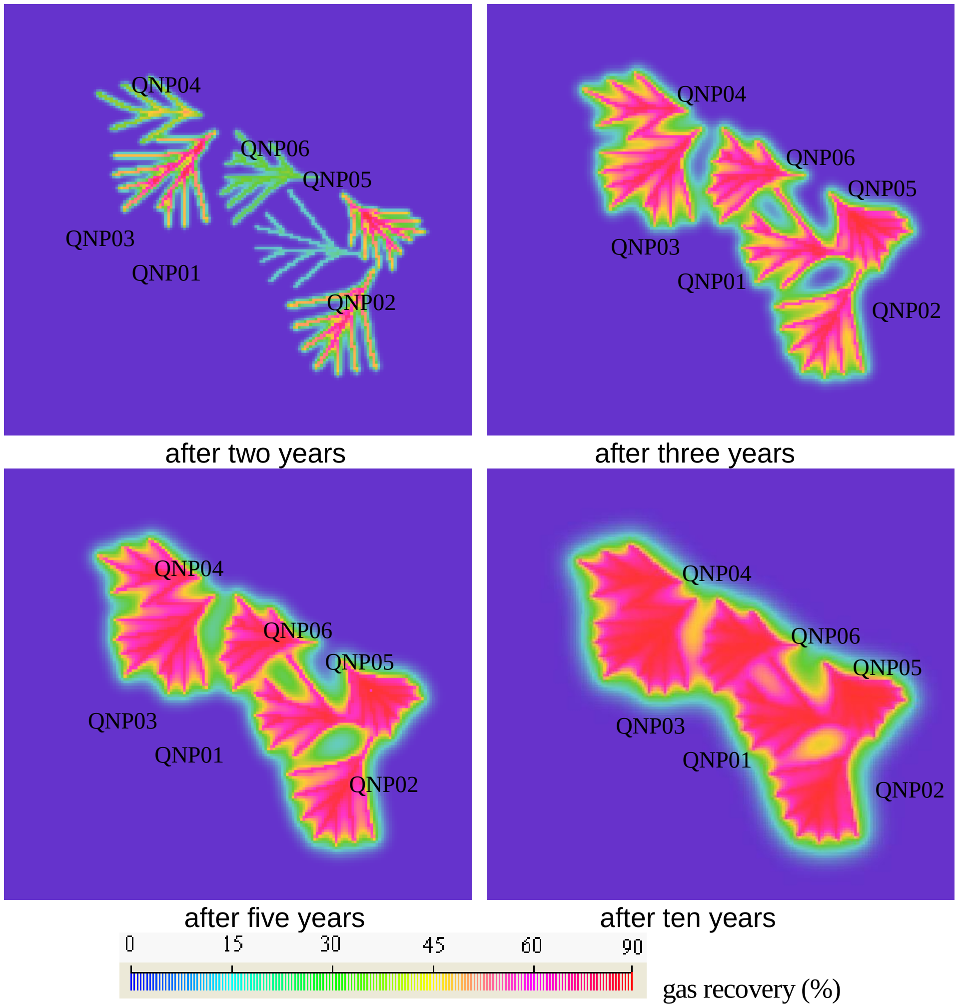

Fig. 3. Accumulative gas production of the multilateral horizontal wells.

3,000-5,000 m^3/d at peak rate and more than 2,500 m^3/d at stable rate, and other wells deliver less than 2,500 m^3/d of gas. However, reservoir damage from drilling flushing, misoperation of hydro-fracturing, and inappropriate dewatering arrangements would lead to low production rate. Full insight into all the details of such historical data could provide us a better understanding of the reservoir potential. Based on these analyses, we would suppose that gas at a rate of 2,800 m^3/d and water at a rate of 1-6 m^3/d are the average levels of deliverability of vertical hydro-fracturing well.

PH55 is taken as an example to reveal the gas production capacity of the vertical well. PH55 started to produce gas after 20 days' drainage. Critical desorption pressure is 1.97 MPa. Stabilized gas production will be obtained when bottom hole pressure is reduced to 1.02 MPa. Steady gas production is 2,000$\sim$7,100 m^3/d as shown in Fig. 4. The average water saturation rate in the drilling area is 95%, average gas content is 21 m^3/t, average coal thickness is 6.1 m, average pressure gradient is 0.77 MPa/100m. Controlled area of the vertical well is 0.09 km^2, regional resource abundance is 16.7 million m^3/km^2, accumulated gas production in all four years is 5.1461×10^6 m^3, and recovery rate is 30.7%. Gas production and recovery rate are outlined in Table 4.

(3)Multilateral horizontal well performance

Production enhancement of multilateral horizontal wells in coal seams is attributed to accelerated pressure drop through long-stretched wellbores and enhanced flow conductivity of the coal.

Figs. 5 and 6 show the first 48 months of average gas production for the six multilateral horizontal wells. Gas production begins after 2-3 months of water production, when the flowing BHP reaches the critical desorption pressure. Water production also begins to decline at this time, and the wells become pumped off after 12-16 months. This trend is typical for producing wells in Southern Qinshui Basin. Gas production peaks after 9-12 months. For Wells QNP02 and QNP05, the maximum gas production is more than $80,000$ m^3/d. For Well QNP01, average gas production rate declines from $43,111$ m^3/day in the 2^{nd} year to $25,126$ m^3/day in the 4^{th} year. Compared to the vertical wells in this basin, multilateral horizontal wells led to much more gas production.

QNP01 well is taken as an example to reveal the gas producing capacity of multilateral horizontal well. QNP01 started to produce gas after 2 months' drainage. The critical desorp-

Table 4. Production data statistics of the well PH55.

year	Daily gas production (m^3/d)	Accumulated gas production (m^3)	recovery rate (%)
1	1,474	537,839	3.2
2	4,411	2,147,676	12.8
3	5,006	3,975,034	23.7
4	3,208	5,146,135	30.7

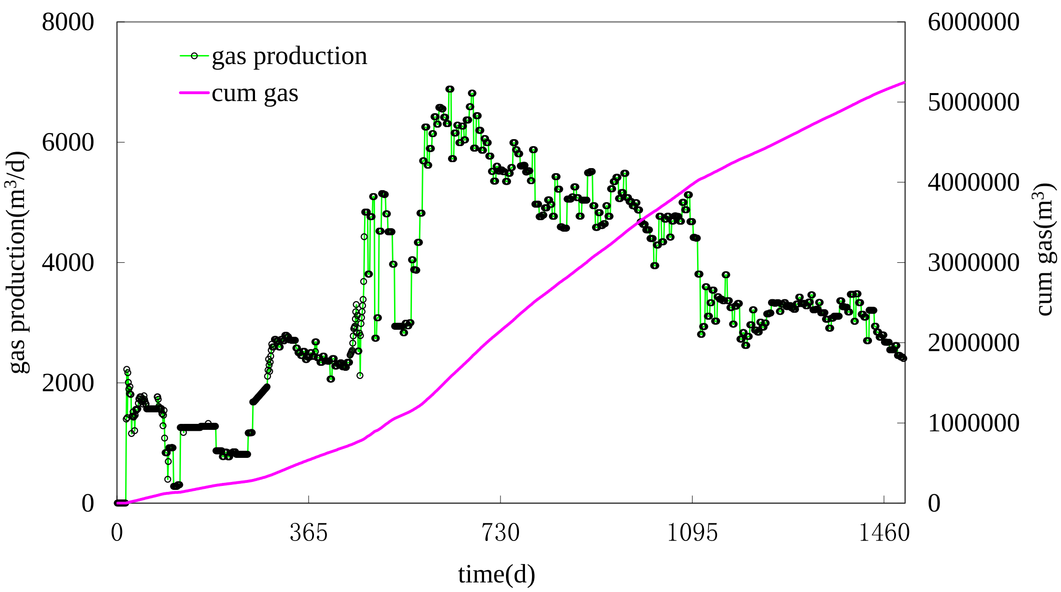

Fig. 4. Gas production of the well PH55.

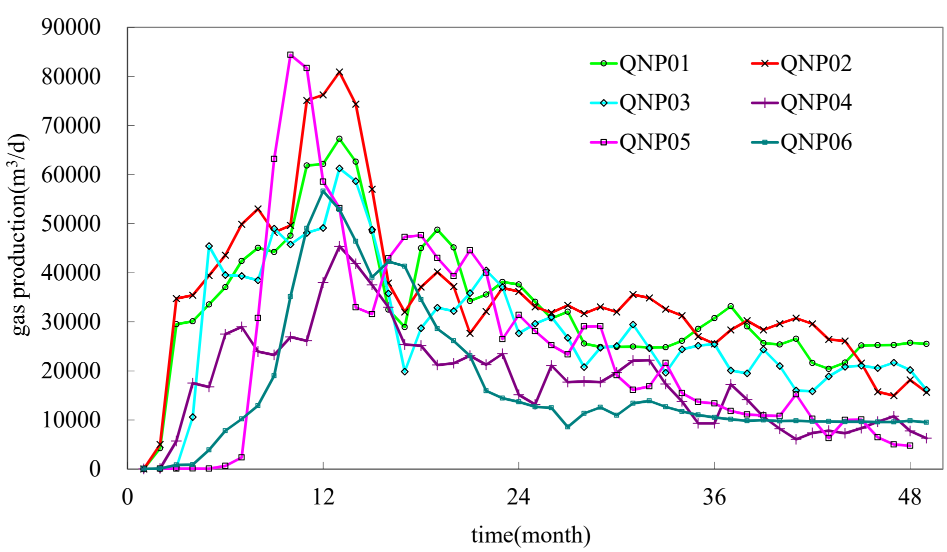

Fig. 5. Average gas production of the multilateral horizontal wells.

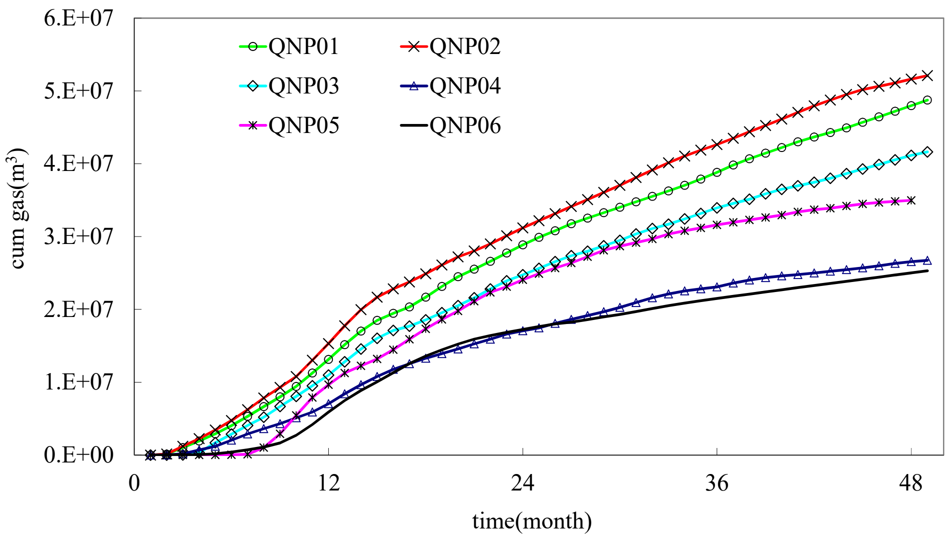

Fig. 6. Accumulative gas production of the multilateral horizontal wells.

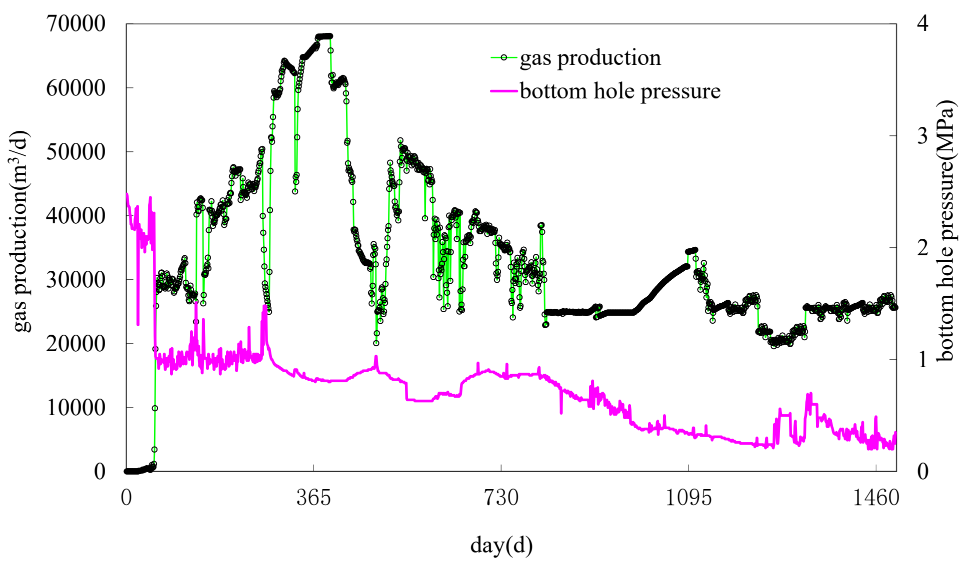

Fig. 7. Gas production of the horizontal well QNP01.

Table 5. Production data of the horizontal well QNP01.

year	Daily gas production (m^3/d)	Accumulated gas production (m^3)	recovery rate (%)
1	36,883	13,462,295	12.9
2	43,111	29,197,947	27.9
3	27,704	39,309,958	37.6
4	25,126	48,480,789	46.3

tion pressure is 2.06 MPa. stabilized gas production will be obtained when bottom hole pressure is reduced to 0.95 MPa. The steady gas production is $2.1 \times 10^4 \sim 6.8 \times 10^4$ m^3/d as shown in Fig. 7. The average water saturation rate within the Controlling area is 90%, average gas content is 20 m^3/t, average coal thickness is 6.1 m, and average pressure gradient is 0.76 MPa/100m. Controlled area of the vertical well is 0.6 km^2, regional resource abundance is 1.1×10^8 m^3/km^2, accumulated gas production in all four years is 4.848×10^7 m^3, and recovery rate achieve 46.3%. Gas production and recovery rate are outlined in Table 5.

5. Discussion

Well group development is commonly used in CBM exploitation. It presents effective well interference, enlarges pressure-drop area and expedites depressurization. Simulation based on engineering data has been done in this paper, the recovery rate curve in different stages indicates:

(1) In the 2nd year of drainage, each branch well of QNP02, QNP01 and QNP05 multilateral horizontal wells exhibits synergistic pressure-drop effect.

(2) In the 3rd year of drainage, every single well of multilateral horizontal wells exhibits intense well interferences, recovery rate in the controlling area of each single well reaching 35%.

(3) In the 5th year of drainage, well interferences in the horizontal wells get further strengthened, recovery rate in the controlling area of each single well reaching 55%.

(4) In the 10th year of drainage, well interferences in the horizontal wells get fully demonstrated. Reservoir pressure drops down to 0.5 Mpa, and recovery rate of each single well in the controlling area exceeds 75%.

6. Conclusion

Both theoretical analysis and preliminary data indicate CBM wells in Southern Qinshui Basin have abundant gas production potential. Much better than vertical hydro-fracturing technology, multilateral horizontal wells reach the seam with a group of lateral sections connected to the vertical wellbore leaving no out-of-reach poor permeable coal in the reservoir. This results in a nearly homogeneous drainage volume in the wellbore covered area. Therefore, a high and stable production rate can be achieved from multilateral horizontal well designs and spacing, as practiced in Southern Qinshui Basin.

The numerical simulation results show that the lateral interference has formed in Well QNP05 after two years of gas production, and the gas content was reduced to less than 8 m^3/t within the controlled region after six years. The area of gas content less than 8 m^3/t after eight years of gas production is about 3.2 km^2, which is about 76% of the controlled area of the six multilateral horizontal wells. This practice by drilling multilateral horizontal wells to produce CBM gas in Panzhuang block before mining has demonstrated great potential in producing profits. Moreover, the multilateral horizontal well network is designed to serve as a “multi-purpose” and “long-life” drainage facility, guaranteeing a much safer mining environment.

Gas content, reservoir pressure and permeability are the critical factors that influence the recovery rate of a coal reservoir. Gas production curve of wells in Panzhuang block is controlled by resource abundance, reservoir pressure and permeability. Practical production data and simulation data demonstrate that gas production curve of multilateral horizontal wells in Panzhuang block is distinguished by early peak and long duration.

Acknowledgments

This project is supported by the National Natural Science Foundation of China (41472130).

References

Cai, Y.D., Liu, D.M., Yao, Y.B., et al. Geological controls on prediction of coalbed methane of No. 3 coal seam in Southern Qinshui Basin, North China. Int. J. Coal Geol. 2011, 88(2-3): 101-112.

Campoli, A.A., Trevits, M., Molinda, G.M. Coal and gas outbursts: Prediction and prevention. Coal Min 1985, 22(12): 42-44.

Diamond, W.P., Oyler, D.C., Fields, H.H. Report of Investigations 8277: Directionally controlled drilling to horizontally intercept selected strata. Pa. US Bureau of Mines, Upper Freeport Coalbed, Green County, pp. 1-20.

Flores, R.M. Coalbed methane: From hazard to resource. Int. J. Coal Geol. 1998, 35(1-4): 3-26.

Fu, X.H., Qin, Y., Li, G. An analysis on the principal control factor of coal reservoir permeability in Central and Southern Qinshui Basin. Coal Geology & Exploration 2001, 7(1): 45-52. (in Chinese)

Gentzis, T., Deisman, N., Chalaturnyk, R.J. A method to predict geomechanical properties and model well stability in horizontal boreholes. Int. J. Coal Geol. 2009, 78(2): 149-160.

Jin, Y., Zhao, Y. Disscusion of geological factor on gas content of coal seam in Qinshui Basin. West-China Exploration Engineering 2010, 12: 55-58. (in Chinese)

Liu, S.G. Study on the coal-bed gas reservoir forming conditions and production enhancing mechanism of multiple laterals horizontal well in Qinshui Basin. China University of Mining and Technology (Beijing), 2006, 89: 57-68. (in Chinese)

Liu, S.G., Hao, N., Li, H.F. Proceedings of the 20th International Symposium on Mine Planning and Equipment Selection: Practice of coalbed methane drainage by drilling multilateral horizontal well in coal mine. Almaty, pp. 1413-1428.

Lv, Y.M., Tang, D.Z., Xu, H., et al. Production characteristics and the key factors in high-rank coalbed methane fields: A case study on the Fanzhuang Block, Southern Qinshui Basin. Int. J. Coal Geol. 2012, 96: 93-108.

Palmer, I. Coalbed methane completions: A world view. Int. J. Coal Geol. 2010, 82(3-4): 184-195.

Qin, Y., Yuan, L., Cheng, P. Scenario prediction for the mid-term and long-term coalbed methane production scale of surface drilling wells in China. Acta Petrolei Sinica 2013, 34(3): 71-80. (in Chinese)

Robinson, J., Kadatz, B., Wong, S., et al. ECBM micro-pilot test in the anthracitic coal's of the Qinshui basin, China: Field results and preliminary analysis. The 3rd International Workshop on the Prospective Roles of CO2 Sequestration in Coal Seam, 2004, pp. 33-44.

Spindler, G.R., Poundstone, W.N. Experimental work in the degasification of the Pittsburgh coal seam by horizontal and vertical drilling. Sco. Min. Eng. AIME 1960, 220: 37-46.

Steven, A., Kramer, D., Michael, K. A numerical study on optimization of multilateral horizontal wellbore patterns for coalbed methane production in Southern Shanxi Province, China. Int. J. Coal Geol. 2011, 86(4): 306-317.

Su, X.B., Lin, X., Liu, S., et al. Geology of coalbed methane reservoirs in the Southeast Qinshui Basin of China. Int. J. Coal Geol. 2005, 62(4): 197-210.

Tim, A.M. Coalbed methane: A review. Int J. Coal Geol. 2012, 101: 36-81.

Wang, H.T., Guo, J.J., Zhang, L.H. A semi-analytical model for multilateral horizontal wells in low-permeability naturally fractured reservoirs. J. Pet. Sci. Eng. 2017, 149: 564-578.

White, C.M., Smith, D.H., Jones, K.L., et al. Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery-a review. Energy Fuels 2005, 19(3): 659-724.

Yao, H., Wang, X. Coalbed Methane Reservoir Characteristic in Soutern Qinshui Basin. Beijing, China Coal Industry Publishing House, 2009. (in Chinese)

Ye, J.P. Proceedings of the 2011 Chinese coalbed methane academic symposium: China coalbed methane industry development report. Xiamen, Fujian, pp. 3-9.