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Research on Fracturing Optimization of Coalbed Methane Wells Aiming at Economic Benefit—A Case Study of Liulin Block

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Abstract: Hydraulic fracturing is an essential technology in the development of coalbed methane reservoirs. Hydraulic fracturing can create a highly conductive fracture in the reservoir and increase its permeability. At present, the focus of coalbed methane reservoir fracturing optimization is gradually shifting to the fracturing scale. In the current development process, more and more coalbed methane blocks try to increase the fracturing scale to increase the gas production of coalbed methane wells. Field tests show that gas production of coalbed methane wells will increase to a certain extent with the increase of fracturing scale. However, the increase in the scale of fracturing also increases its cost. Therefore, the most economical fracturing scale is not necessarily the optimal fracturing scale for gas production. The field test usually pays more attention to the gas production effect, but the development of a coalbed methane field should pay more attention to the economic benefit, and the optimization of fracturing should take the economic benefit as the goal. Taking economic benefits as the starting point, this paper uses fracturing simulation to calculate the fracture extension under different geological conditions and different fracturing scales. It also uses numerical simulation to calculate the gas well productivity under different fracture extension conditions. The economic evaluation model was established to calculate the economic benefits under different fracturing scales, and the optimal fracturing scale was obtained. Finally, the typical maps of fracturing optimization under different geological conditions are formed. The optimization method of fracturing scale integrating economy, fracturing, and gas reservoir is realized. The research results have been successfully applied to the optimization scheme of Liulin block development, and very good results have been achieved. Because this method is targeted at different geological conditions, it can be used to guide the fracturing optimization of other coalbed methane blocks and has very important significance for the development and optimization of coalbed methane reservoirs.

Keywords: coalbed methane; production forecast; fracturing simulation; economic evaluation; fracturing scale optimization

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1. Introduction

Coalbed methane is methane gas adsorbed in coal seams. Coalbed methane is a dangerous gas that can easily cause an explosion during the development of coal mines. At present, coalbed methane can be extracted from the ground for human use. Hydraulic fracturing is an important technology that has increased the production of coalbed methane during the development of coalbed methane reservoirs. The history of coalbed methane development shows that fracturing technology can economically and effectively improve the permeability of reservoirs and increase the production of coalbed methane wells. The fracturing scale has an important effect on the productivity of fractured wells. Li Shuguang et al. believe that fracturing has brought a breakthrough in the development of deep No. 8 coal in the Daning-Jixian block, but the production capacity of test wells varies greatly, and the main controlling factors of production capacity are unclear, which seriously restricts the coalbed methane development process. To solve this problem, 28 typical evaluation indicators are selected from geological conditions, fracturing construction, and drainage and production systems. The sensitivity analysis of post-fractured productivity of coalbed methane wells is carried out by using the grey correlation method, and corresponding technical countermeasures are proposed [1]. In order to explore the influence mechanism of the hydraulic fracturing effect of coalbed methane vertical wells on the productivity effect of gas wells, Ma Daibing et al., taking the Haishiwan mining area in Yao-Jie, Gansu Province as an example, focused on the fracturing reform effect of coal reservoirs in the form of vertical well development and its impact on productivity. The research results show that too short effective fracturing fractures in coal reservoirs are the main reason for the rapid decline of gas well production. It is suggested that the hydraulic fracturing of coal reservoirs in the later stage should increase the amount of fracturing fluid injected, appropriately increase the fracturing fluid displacement, reduce the proppant sand ratio, and focus on preventing fracturing fluid filtration loss and preventing the formation of sand removal wedge [2]. Taking coalbed methane wells in Qinshui Basin as an example, Li Quanzhong et al. studied the influence of fracturing scale on the typical drainage and production indicators by analyzing the typical drainage and production indicators of coalbed methane wells and explored the mechanism of the influence of different fracturing scale on the typical drainage and production indicators. The results show that the production of coalbed methane wells after fracturing mainly depends on the energy and channel conditions of coal reservoirs. The cumulative water production, the cumulative water production before casing pressure, and the flowback rate of coalbed methane wells are independent of the fracturing scale, while the cumulative gas production and average gas production of coalbed methane wells are related to the fracturing scale. With the increase of fracturing scale, the cumulative gas production and average gas production increase, but when the fracturing scale exceeds a certain value, the overall cumulative gas production and average gas production decline [3]. Sun Han Sen believes that fracturing technology is the key to the efficient development of coalbed methane production technology, which is of great significance for vigorously developing coalbed methane and realizing the goal of carbon neutrality in China. It is suggested to clarify the fracture initiation and expansion mechanism of coal seam, develop new composite fracturing technology and diversified fracturing liquid system of coal seam, develop intelligent fracturing of coal seam gas, and improve the intelligent level of coal seam gas development and fracturing [4].

With the introduction of fracturing technology into the development of coalbed methane, a lot of optimization and improvement have been carried out. Based on a large number of domestic and foreign data and theoretical and experimental data, Ma Pinghua et al. studied the effects of intra-layer horizontal principal stress difference coefficient, inter-layer minimum horizontal principal stress difference, rock mechanics parameters, internal fracture pressure difference coefficient of coal and rock, and rock interface properties on the formation and propagation of hydraulic fractures. According to the fracturing and production data of the field, the influences of ground stress condition, fracturing technology, construction fluid amount, sand addition amount, fracturing fluid system, fracturing perforation interval, and secondary fracturing technology on production are analyzed. Through optimization, reasonable fracturing technology methods and parameters for the Hancheng mining area in the southeast margin of the Ordos Basin are proposed, and good results have been achieved in practical application [5]. In order to scientifically optimize the fracturing process of coalbed methane wells, Liu Huihu et al., taking the southern Qinshui Basin as an example, discussed the main factors affecting the fracturing effect of coalbed methane wells based on engineering data and fracture monitoring data and proposed a fracturing process optimization scheme with the premise of ensuring the fracturing effect of coalbed methane wells and taking into account the distribution of coal seam in-situ stress [6]. In order to improve the poor fracturing and drainage effect of horizontal wells in Shizhuang Block, Ji Yong et al. analyzed the monitoring and interpretation of microfracture fracturing of coalbed methane vertical wells in Shizhuang Block and concluded that the important factor leading to the poor drainage effect was that only about 10% of the proppant actually acted on the coal seam during fracturing and reconstruction. In order to make fracturing construction more effective in coal seams, a new idea of artificially inducing horizontal fractures was proposed, and the feasibility of the technology was verified through laboratory tests and fracture morphology mechanism studies [7]. Cong Richao et al. put forward a new idea of developing coalbed methane by using supercritical CO_2-shaped energy fracturing technology. This technology uses high-pressure supercritical CO_2 to crack coal dynamically and achieves multiple and continuous injections of high-pressure supercritical CO_2 in combination with the process of "shaped energy impact + oil casing co-injection", so as to generate a complex fracture network of a certain scale in the reservoir that is not controlled by in-situ stress. With no water, environmental protection, safety, high efficiency, and other technical advantages. The feasibility of developing coalbed methane by supercritical CO_2 polymer fracturing has been verified through research, which provides a new idea for the efficient development of coalbed methane and the integration of CO_2 geological storage [8]. In order to solve the difficulty of extracting coal seams with low permeability and high gas, Wang Zedong et al. proposed the pressure relief and permeability enhancement technology of coalbed methane liquid two-phase composite fracturing through theoretical analysis based on existing research results. The coal seam is cracked by relying on high-pressure acid and high-pressure lye injected into the drilling hole, and high-pressure CO_2 gas is generated by liquid reaction to play the role of displacement and permeability enhancement. The ground stress field and gas pressure field of the coal seam after fracturing and anti-reflection are reduced and homogenized, and the extraction efficiency is improved [9]. Yao Hongsheng et al. recognized that the lack of fracture-controlled reserves caused by small reservoir reconstruction volume is one of the main reasons for the low production of coalbed methane wells. They took the low-producing gas wells with short stable production periods and abundant remaining reserves in the south Yanchuan coalbed methane field in the southeast margin of Ordos Basin as the research object and carried out field tests of multiple fracturing efficiency enhancement development technology with the main characteristics of increasing displacement by steps, gradually increasing the amount of pre-fluid, and adding proppant in combination. After the application of this technology, the fracture length increases by three times, the fracture shape changes from a single fracture to a complex fracture network, and the reservoir reconstruction volume is effectively expanded. Through multiple combinations and sand addition, the fracture network is effectively supported, and efficient diversion channels are established in deep coal reservoirs. The double breakthrough of daily average production and final cumulative production has been achieved, which proves that multiple fracturing efficiency enhancement development technology can improve the complexity of fracture networks in deep coal reservoirs and achieve effective support and efficient flow diversion [10]. Li Guishan et al. studied fracturing processes suitable for deep coalbed methane well development, including hydraulic sand-jet fracturing, continuous tubing bottom-seal driven fracturing, "hydraulic sand-jet perforating + large-discharge combined fracturing" and "multi-cluster directional perforating + bridge plug combined staged fracturing" technologies, which were applied in the deep coalbed methane development process of Hengling block in Heshun. The results show that this technology can significantly increase the reservoir reconstruction volume, increase the contact area between fractures and reservoirs, and enhance the ability of the reservoir to supply liquid and gas to fractures and wells. This technology can be used as the main fracturing technology for deep coalbed methane horizontal wells [11]. Huang Zhongwei et al. developed a supporting sand control technology for directional multi-stage and multi-cluster fracturing by hydraulic jet in view of the common phenomenon of sand and pulverized coal production in the process of coal seam gas well discharge and shutdown. By adopting the "anti-gravity method", the technology realizes the accurate orientation of sand-blasting perforating nozzles in horizontal wells and integrates sand-blasting perforating, hydraulic sealing and volumetric fracturing; it can effectively control sand while increasing production. It provides new technical support and stimulation direction for the efficient development of coalbed methane horizontal wells [12]. In order to explore and study the economical and efficient stimulation technology applicable to coalbed methane wells, Fan Yao used the successful experience of pre-acid fracturing technology of conventional oil and gas reservoirs for reference and conducted an evaluation experiment of pre-acid improving fracturing effect. Combined with macro observation, X-ray diffraction analysis, and scanning electron microscopy—energy spectrum, he compared and analyzed the changes in mineral composition and content before and after the experiment. The mechanism and applicable conditions of coal seam stimulation with pre-acid fracturing technology are studied. The experimental results show that pretonic acid can improve the connectivity between coal reservoir holes and fractures, greatly reduce the damage of fracturing fluid itself to the coal seam, and the transformation effect is remarkable [13]. Aiming at the problem of low production of coalbed methane wells, Kong Peng analyzed the causes of low production and put forward the nitrogen foam secondary fracturing transformation technology, which used its technical characteristics of low filtration loss, high sand carrying, high flow back and low pollution to carry out secondary transformation of wells with poor initial fracturing effect and coal blockage to improve gas production of a single well. Field application test results show that the secondary fracturing reconstruction with nitrogen foam has a smooth construction process and a significant production increase effect, and the average daily gas production per well has increased by more than 1000 square meters [14]. In order to realize the low-cost and efficient development of coalbed methane, Li Junfeng proposed the uncemented L-type segmented fractured horizontal well in coal seam to strengthen the exploitation of coalbed methane based on the characteristics of 3# coal seam and 15# coal seam in Zhengzhuang Coalfield. The research has formed four core key technologies of "high quality, fast and safe" drilling and completion, rapid drag jetting of coiled tubing with bottom seal combined with staged fracturing, "large displacement, large fluid volume, medium-sand ratio" active water fracturing stimulation and fine production control of L-shaped horizontal wells. The large-scale development and application in the Zhengzhuang gas field have achieved a double breakthrough in coalbed methane development technology and high gas production [15]. Taking the northern Changzhi area of Qinshui Basin as an example, Shen Penglei analyzed four kinds of hydraulic fracturing technology and the application effect of deep coalbed methane wells. In view of the advantages and disadvantages of the process technology, a new technology of conventional tubing pressure fracturing was independently developed. Based on the conventional tubing fracturing technology, the technology installed a pressure stabilizer in the wellhead and underground tubing to control the pressure inside and outside the tubing during the fracturing process and optimized the lifting and lowering procedure with a wire rope fishing device, so as to realize the hydraulic fracturing operation with pressure. The fracturing construction curve of this technology is mainly stable pressure type, which can form continuous and straight fracturing fracture channels and reduce reservoir damage. Microseismic monitoring showed that the technique was used to fracture both wings up to 70 m long. The daily gas output of the test well is more than 4000 square meters. At the same time, operating costs are saved, and fracturing efficiency is improved [16]. Taking the No. 5 coal seam in Daning-Jixian Block as the research object, Li Xuejiao proposed the use of indirect fracturing technology to improve the development effect of coalbed methane. By carrying out research on compressibility evaluation of coal seam fracturing, hydraulic fracturing numerical simulation, and field test, Li Xuejiao established the process flow of staged fracturing of horizontal wells in soft coal seams with low permeability crushing and revealed the law of hydraulic fracture expansion under this technology. The results show that compared with coal stratification, the brittleness and immersion of waste separation are better, and the compressibility is higher. Fracturing in the dirt can communicate the upper and lower coal seams, greatly reduce the construction pressure and fracture extension pressure, reduce the coal powder output, good fracture extension, and significantly increase production [17]. In order to explore the fracturing characteristics of coalbed methane wells in Tunlan Block, Li Hongyu et al. took the No. 2 coal seam in Tunlan Block, Xishan, Taiyuan as the research object and studied the fracturing characteristics of coal seam from a multi-scale perspective through geological cataloging of coalbed methane wells, macroscopic characteristics description of coal samples and CT scan analysis. The research results show that fracturing significantly increases the width and number of fractures in coal samples, and the pore fractures in fractured coal are more developed [18]. The fracturing fluid system can maintain a long foam half-life under formation pressure and has good foaming ability and foam stability. The fracturing fluid system can maintain high viscosity and has good rheological properties after a long time shearing at high temperatures. Compared with the conventional nitrogen foam fracturing liquid system, the new nitrogen foam fracturing liquid system has better sand carrying capacity, lower filtration loss, and lower coal core permeability damage rate and can meet the needs of coalbed methane reservoir fracturing construction [19]. Taking the south Yanchuan coalbed methane field as the research object, Yao Hongsheng et al., aiming at the problems of deep coalbed methane reservoir reconstruction difficulties and short supporting fractures, optimized the fracturing system based on the applicability analysis of reservoir fracturing reconstruction, carried out key research on key technologies of integrated geological engineering reservoir reconstruction, developed "low density and long migration" proppant, and achieved good fracturing effects. It provides a new idea for deep coalbed methane development [20]. Taking the Longtan Formation coal seam in the southeast Chongqing area as the research object, Fang Dazhi completed the fracturing construction of the NY1 well by optimizing the fracturing technology based on the liquid system of drag-reducing water fracturing, and according to the technical ideas of large displacement, low sand ratio, slasher type, and different particle size composite sand addition. During the fracturing process of the NY1 well, the construction pressure was stable, no sand plugging was observed, and the gas production in the later production process remained above 2800 cubic meters, indicating the successful implementation of the fracturing process, which has certain guiding significance for the theoretical research and practical development of ultra-deep coalbed methane wells [21]. Yao Hongsheng et al. chose Nanchuan Block in southeast Chongqing as the research object. Based on seismic, drilling, logging, analysis, and testing data, they analyzed the geological conditions of coalbed methane in the Longtan Formation, optimized the geological sweet spot, proposed targeted fracturing technology, and applied it to field research practice. An effective fracturing reform idea with the core of strong transformation scale, large particle size support, and multiple rounds of construction was proposed, and it was successfully applied in well D1, with a stable daily gas output of more than 6200 cubic meters per directional well, achieving a major breakthrough in coalbed methane exploration in southeast Chongqing [22].

In the process of fracturing optimization and improvement, researchers have always focused on the fracturing scale. On the one hand, increasing the fracturing scale can increase the degree of reservoir reconstruction and thus increase the gas production of coalbed methane wells. However, the increase in frac scale also brings with it an increase in development costs. How to develop gas reservoirs under optimal economic conditions has always been the focus of scholars' research. Lu Haibing et al. developed the coal seam fracturing optimization design software based on the theory of coal seam fracturing optimization design, combined with the structure and characteristics of coal seam fracturing, and based on the hydraulic fracturing mechanic's principle. The software used numerical algorithms to calculate the geometry of dynamic fractures and calculated the proppant migration distribution in fractures based on the Stokes particle subsidence migration formula [23]. In order to effectively optimize the fracturing process of coalbed methane wells in the Dafosi Gas field in the Binchang Mining area, Ma Dongmin et al. conducted statistical analysis on the gas production situation and fracturing construction parameters of 24 coalbed methane vertical wells in the gas field, studied the impact of fracturing construction of coalbed methane vertical wells on their productivity, and analyzed and compared the fracturing construction parameters of gas wells with good productivity. It is found that under the condition of the same geological factors in the coal reservoir, the main engineering parameters affecting the fracturing effect include construction displacement, fracturing fluid amount, sand addition strength, and sand ratio [24]. Chen Hongfei et al. optimized the basic parameters of staged fracturing such as proppant, fracturing fluid, number of fracturing stages, interval between stages, fracturing fluid volume and sand volume by means of coal and rock permeability damage experiment, fracture conductivity experiment and numerical simulation, etc. According to the optimized results, they designed single-well fracturing and achieved good results [25]. In order to increase the reconstruction volume of the coal reservoir and improve the recovery rate of coalbed methane, Wu Xiuping has optimized the fracture spacing based on the fracture-induced stress field of horizontal well-staged fracturing by using numerical simulation methods. The results show that the horizontal induced stress difference produced by the pre-fracturing fractures in horizontal wells increases at first and then decreases with the increase of the fracture distance, resulting in the shift and even reversal of the maximum horizontal principal stress. The maximum horizontal principal stress turning Angle after the induced stress field is superimposed, and the corresponding optimal fracturing stage spacing is optimized. In this way, the segmented spacing can be arranged to ensure that the spacing is as small as possible, and normal fracture expansion can be formed to form multiple effective parallel main fractures, realize volume cutting of coal reservoirs, and improve the fracturing and stimulation effect of coal reservoirs [26]. In order to optimize the fracturing parameters of horizontal wells under different coal seam conditions, Zhu Weiping et al. established a seepage model considering the characteristics of gas desorption and gas-water two-phase flow, which was solved by PEBI mesh and finite volume method. According to the permeability and thickness characteristics of the coal seam, four types of coal reservoirs are divided, and corresponding mechanism models are established, and then the cumulative gas production and pressure field under different fracturing parameters of horizontal wells are simulated and calculated. It is found that the properties of coal seam greatly affect the optimal values of horizontal section length, fracture half-length, and fracture spacing of multi-stage fractured horizontal wells [27]. Based on the proppant index method and considering the dynamic fracture permeability after fracturing, Zhao et al. established a mathematical model of fracture parameter optimization related to the fracture scale. The optimum fracture parameters under the optimal fracturing scale were obtained by double iterative solution, and the optimum fracture parameters were plotted under different permeability and fracturing scales. The calculation results show that the larger the fracturing scale, the better there is an optimal scale. The non-Darcy flow in the fractured fracture of a coal seam reduces the optimal joint length and increases the optimal joint width [28]. Ren Fei et al. studied the effects of different fracture numbers, fracture lengths, fracture spacing, and flow conductivity on the productivity of coalbed methane horizontal wells under the change of a single index after fracturing in the middle block of the east wing of the Qinshui Depression by numerical simulation. The orthogonal test method was used to quantitatively study the main and secondary sequence and the significant degree of the effects of different fracture parameters on the productivity of fractured horizontal wells. Furthermore, the optimal fracture parameter combination of coalbed methane horizontal wells in the study area is determined to provide a reference for the optimal fracturing design of coalbed methane horizontal wells in the initial stage [29]. Xiong Wenxue et al. established a complete hydraulic parameter optimization design method for fracturing fractures in vertical wells of coalbed methane reservoirs by considering the non-Darcy turbulence effect and the characteristics of gas and water two-phase flow in fractures near the fracturing zone, combined with the restriction conditions of net pressure constraint and minimum fracture width constraint in hydraulic fracturing fractures. On the basis of the conventional gas reservoir material balance method, the production performance prediction model based on the coalbed methane reservoir material balance method is established, and the production performance of fractured vertical wells is predicted. The results show that the non-Darcy turbulence effect has a significant impact on productivity in vertical wells. Turbulence in highly permeable coal reservoirs reduces the effective permeability of proppant to reduce fracture conductivity, which has a great negative impact on the productivity of gas wells. High-permeability coal reservoirs are prone to short and wide fracture geometry, while low-permeability coal reservoirs are prone to long and narrow fracture geometry [30]. In order to study the influencing factors of fracturing parameters in the development of coalbed methane horizontal wells, Zhang Yongnian aimed at coalbed methane reservoir conditions in Qinduan Block, based on numerical simulation method and orthogonal experimental design, adopted range analysis. The effects of fracture number, fracture length, fracture spacing, flow conductivity, fracture distribution rule, and fracture shape combination on the productivity of fractured horizontal wells in this coalbed methane block were studied [31]. In order to increase the output of a single deep coalbed methane well, Yuan Junhong designed horizontal wells and their fracturing parameters from the perspective of optimizing fracturing parameters of U-shaped horizontal wells based on regional structural characteristics, coal seam thickness, gas content, and hydrogeological characteristics [32]. Based on the coalbed methane geological characteristics of well ZZ01 in Zhaozhuang coalfield, Wang Jing conducted an in-depth study on the optimization of staged fracturing parameters of horizontal wells by using numerical simulation methods from three aspects of productivity, coal mine safety, and economic benefits, and finally obtained the best fracturing fracture parameters. The research results provide guidance for the optimization of staged fracturing engineering of coalbed methane horizontal wells in the future [33]. Based on the structural characteristics and complexity of the coal seam itself, Wu Bailie established a geometric fracturing model for coalbed methane wells and proposed the corresponding solution based on the basic theory of coal seam fracture expansion and the knowledge of fluid mechanics, linear elastic fracture mechanics, rock mechanics, and computational mathematics. Field application shows that fracturing coal seams with shallow burial depth and large filtration loss needs to be carried out with large displacement. The filtration will reduce the geometrical dimensions of fractures in three directions. The elastic modulus of the coal seam and Poisson's ratio have the same influence on the fracture geometry, but the degree is different. Increasing the stress difference between the barrier layer and the coal seam is conducive to obtaining the long and wide seam. Large displacement can increase the length and width of cracks, but it is necessary to control the height of cracks. During the coal seam fracturing construction, the stress difference between the barrier layer and the coal seam is artificially increased, and the adoption of large-displacement fracturing is conducive to obtaining artificial fractures with high conductivity [34]. Through continuous theoretical research and field tests, Geng Tiexin gradually established a set of parameters optimization methods suitable for fracturing coalbed methane wells in the eastern Daqing basin. This method mainly includes geological condition evaluation, coal and rock characteristics analysis, fracture network fracture theory research, measure layer and fracturing process optimization, fracturing fluid formulation research, proppant optimization, construction parameter simulation post-compression effect evaluation, etc. [35]. Based on seepage theory and rock mass mechanics theory, Zhang Wenyong built a mathematical model of fracture morphology and a productivity prediction model and optimized perforation parameters, fracturing fluid volume, sand ratio, and other pumping parameters [36]. Taking the Shizhuang South block in Qinshui Basin as the target, Huang Ningman proposed that induced steering fractures are not easily produced by secondary fracturing, and temporary plugging agents should be used to promote the steering of secondary fracturing fractures to improve the production effect of secondary fracturing. The numerical simulation method of the gas reservoir and fracture simulation method is used to optimize the fracture parameters and construction parameters of secondary fracturing [37]. Based on the physical properties of coal reservoirs, Li Ruoxiang established a three-dimensional elastic finite element model considering the fluid-structure coupling of porous media and the stress concentration at the radial borehole and studied the fracture characteristics of coal seam radial wells during fracturing. The effects of radial hole diameter, length, number, azimuth Angle, and ground stress difference on the initiation pressure, initiation location, and direction of the fracture are clarified. It is found that the radial hole has a strong guiding effect on the initial extension direction of the fracture [38]. Relying on Daning Block in Qinshui Basin and its LDP-XX well, Guo Zhiqi explored the adaptability of staged multi-cluster densely fractured horizontal wells to coal reservoir geological conditions and, based on this, developed the theory and technology of optimal design of staged multi-cluster densely fractured horizontal wells [39]. Through laboratory experiments, Song Shuai analyzed the damage mechanism of different types of fracturing fluids to high-grade coal rocks and then developed a low-damage fracturing fluid system on this basis. Numerical simulation was used to optimize fracture parameters and construction parameters of horizontal well-staged fracturing [40]. In view of the frictional pressure loss of coiled tubing, the energy that can be delivered to the working face of these dry coalbed methane wells is limited. Karen uses nitrogen to release energy during fracturing to form downhole pressure pulses, thereby generating an order of magnitude change in the available energy at the fracture surface and fracturing the reservoir with this energy. At present, the method has been applied in the Horseshoe Canyon in the western Canadian sedimentary basin [41].

Based on the research of gas reservoirs and productivity evaluation, this paper evaluates gas reservoir productivity under different fracturing effects. Combined with fracturing simulation and economic evaluation, the economic cost and fracturing effect of different fracturing scales are evaluated. Forming a typical fracturing optimization map under different geological conditions. The integrated optimization method of economy, fracturing, and gas reservoirs is realized.

2. Introduction to Exploration and Development of Liulin Block

The Liulin block is located in the eastern part of the Ordos Basin. It belongs to the Jinxi fold in western Shanxi Province (Figure 1). The tectonic deformation range in the study area is small, mainly due to the transitional characteristics of the basin margin structure. The whole structure in the study area is simple, and the stratum uplift is small. The main marker layer and coal seam in the Liulin block are relatively stable [42]. The coal-bearing strata in the Liulin block are the Shanxi Formation and Taiyuan Formation, with an average thickness of 145.25 m. The coal seams inside the coal-bearing strata in Liulin Block are divided into 14 layers, and the average thickness of the coal seams is 12.7 m. The average thickness of the exploitable part of the coal seam is 10.49 m. The main development strata of the Liulin block are the No. 3 coal seam, No. 4 coal seam, and No. 5 coal seam in the Shanxi Formation, and No. 8 coal seam and No. 9 coal seam in the Taiyuan Formation. There are a variety of aquifers distributed in the Liulin block, which are mainly Ordovician karst fissure aquifers and Carboniferous aquifers in the order from bottom to top. The lowest position is represented by the Triassic sandstone fissure aquifer (Figure 2) [43].

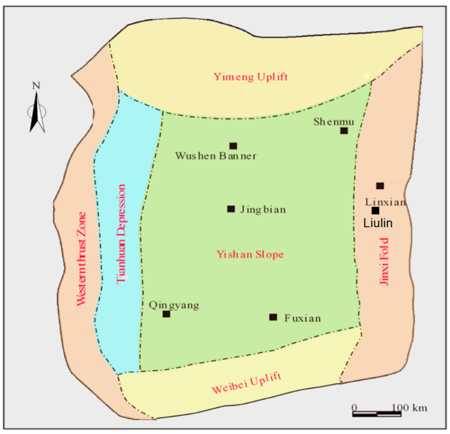


Figure 1. Structure diagram of Liulin block.

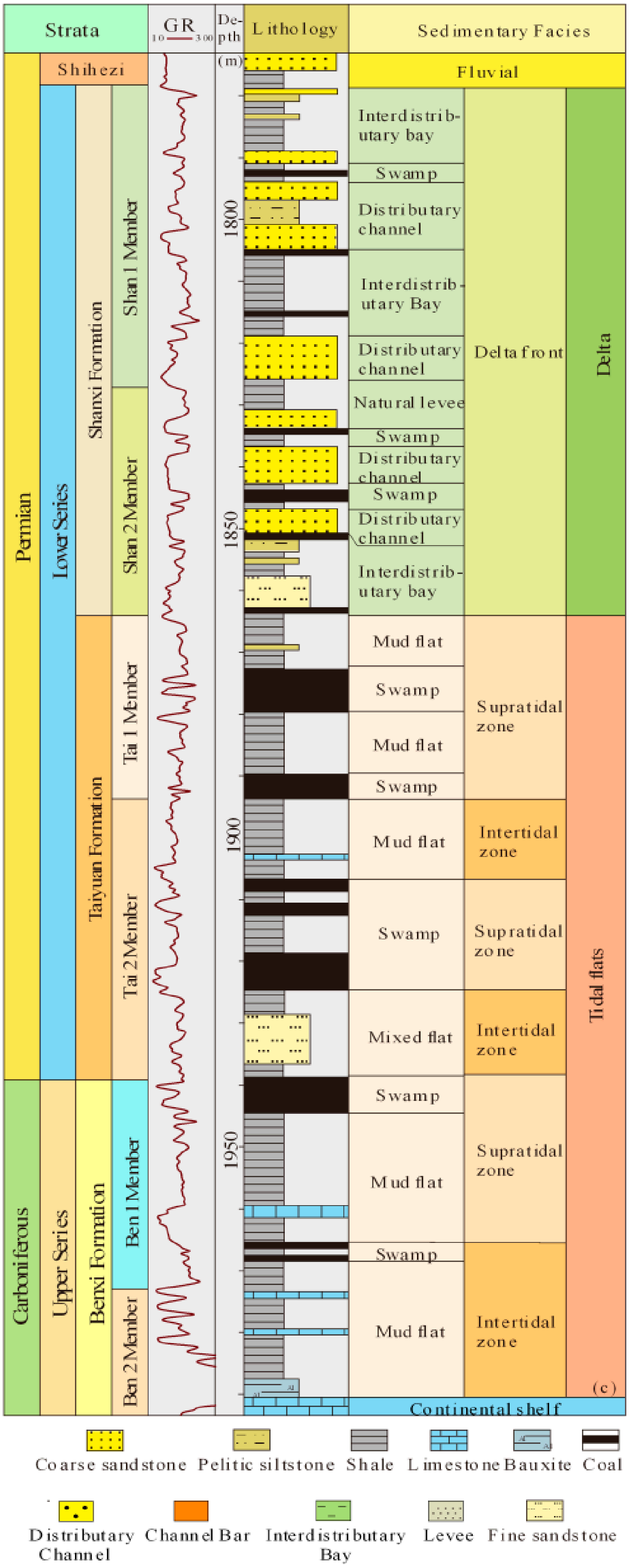


Figure 2. Vertical stratification diagram of Liulin block.

Production wells began to be put into operation in Liulin Block in 2010. Before 2018, the block was in the stage of national science and technology major special research. The capital investment at this stage mainly comes from the support of major national projects. From 2018 to 2019, the block will be in the pilot test stage, and the main task is to carry out pilot tests based on the research results of major national science and technology projects. 2020 will be the production capacity construction stage of the block and officially enter the large-scale development stage. The block will enter the adjustment phase from 2021 (Figure 3). Currently, the wells that came on stream between 2010 and 2021 have largely been shut down. This study takes this part of the shut-in as well as the research object. The well was modified with current fracturing technology to release the production capacity.

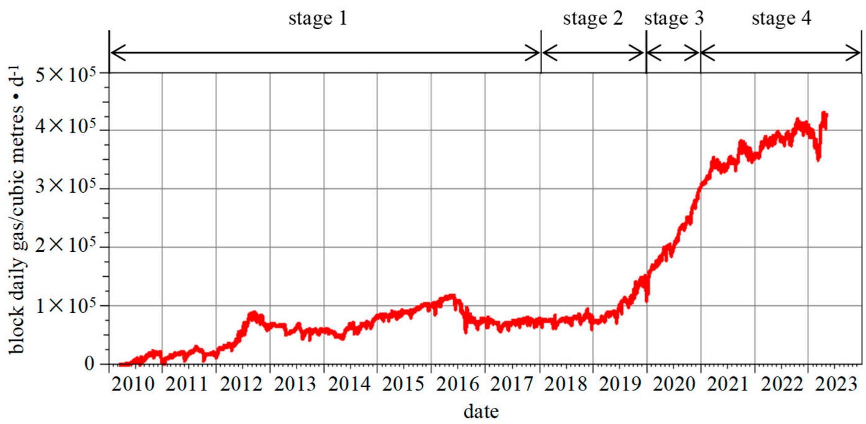


Figure 3. Production stage division of Liulin block. NOTE: stage 1 is the research stage of major national science and technology projects. stage 2 is the pilot test stage. stage 3 is the stage of capacity construction. stage 4 is the development adjustment phase.

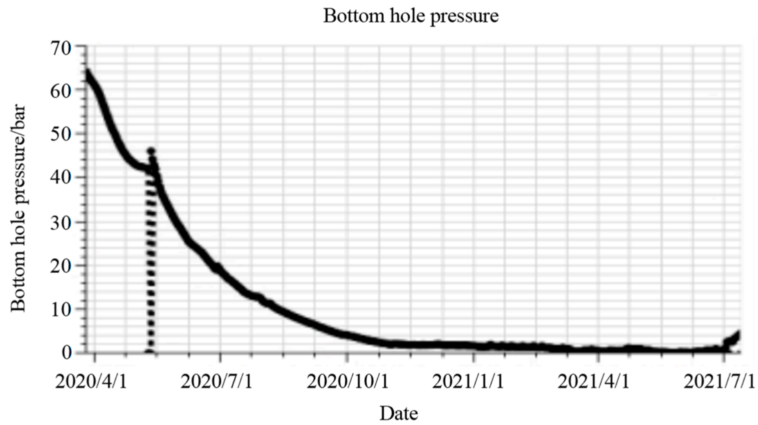
3. Block Numerical Simulation Research

There are 138 wells shut down in the research stage of national science and technology major projects, involving a total of 882 layers of exploitation. It is necessary to select layers with economic value for development. Firstly, it is necessary to conduct numerical simulation studies on representative wells to evaluate the productivity of the block and determine the main controlling factors of the productivity of the block.

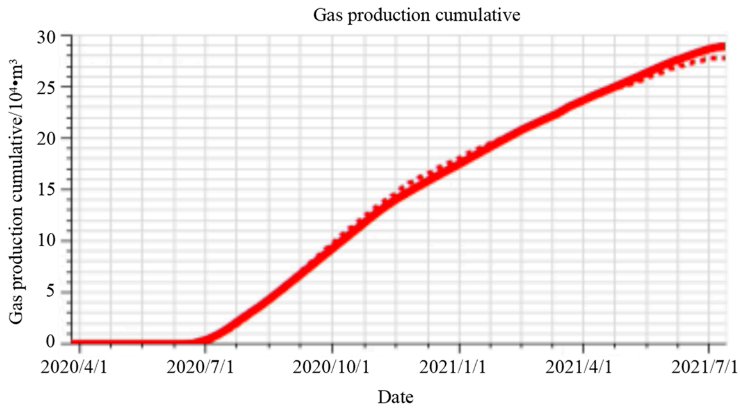
Well A, located in the northeast of the study area, produces continuously and is less affected by the production system. The production data of well A can better reflect the real properties of the reservoir. PETREL RE numerical simulation software (The software version used in this study is version 2021.3.0) is used to simulate the production process of well A, and the geological parameters of the reservoir around well A are determined by historical fitting. The historical fitting effect of well A is shown in Figure 4. The geological parameters around well A are shown in Table 1.

Table 1. Historical fitting parameters of well A.

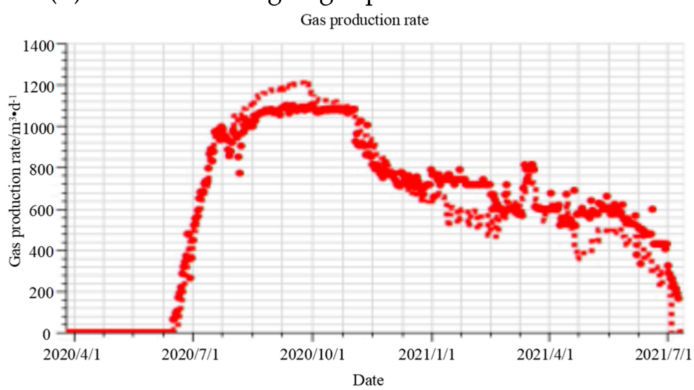
Parameters	Unit	Value
Thickness	(m)	5.1
Gas Content	(m^3/t)	12.3
Density	(cm^3/g)	1.4
Permeability	(mD)	0.02
Porosity	(%)	1.2
Formation Pressure	(MPa)	6.69
Langmuir Volume	(m^3/t)	20.49
Langmuir Pressure	(MPa)	1.76
Fracture Half-Length	(m)	60



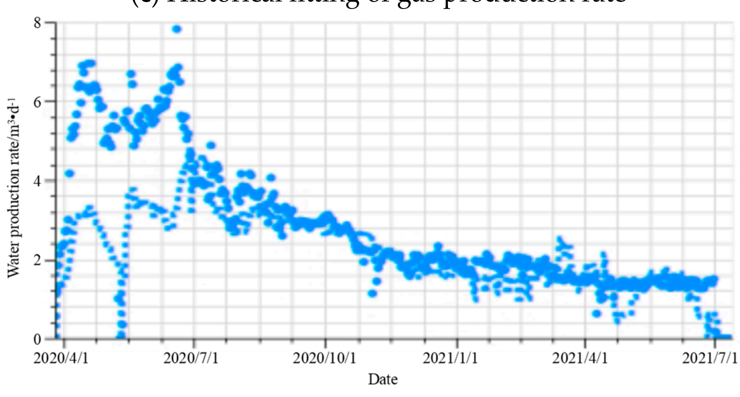
(**a**) Historical fitting of bottom hole pressure



(**b**) Historical fitting of gas production cummulative



(**c**) Historical fitting of gas production rate



(**d**) Historical fitting of water production rate

Figure 4. Historical fitting of well A numerical simulation.

The numerical model of well A is used to analyze the factors influencing productivity. According to the numerical simulation results obtained, the gas content increased from 12.5 m^3/t to 13.5 m^3/t, and the average gas production increased from 420 m^3/d to 590 m^3/d, with no significant increase (red box in Figure 5).

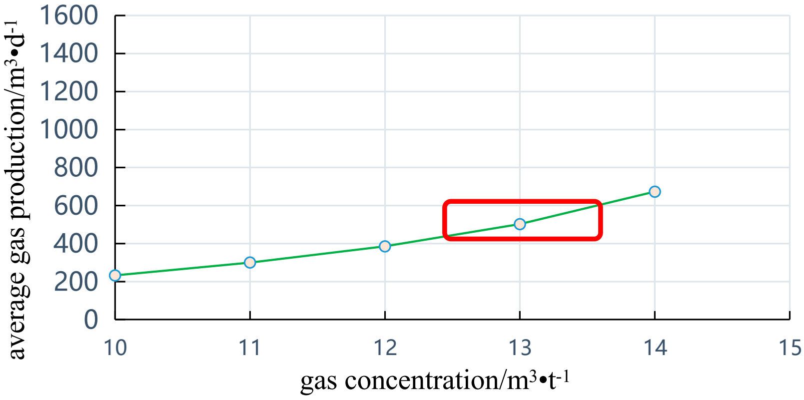


Figure 5. Average gas production at different gas concentrations (numerical simulation).

The numerical model of well A was used to analyze the factors affecting productivity. According to the numerical simulation results obtained, the thickness of well A increased from 2 m to 6 m, and the average gas production increased from 200 m^3/d to 600 m^3/d, with a significant increase effect (Figure 6).

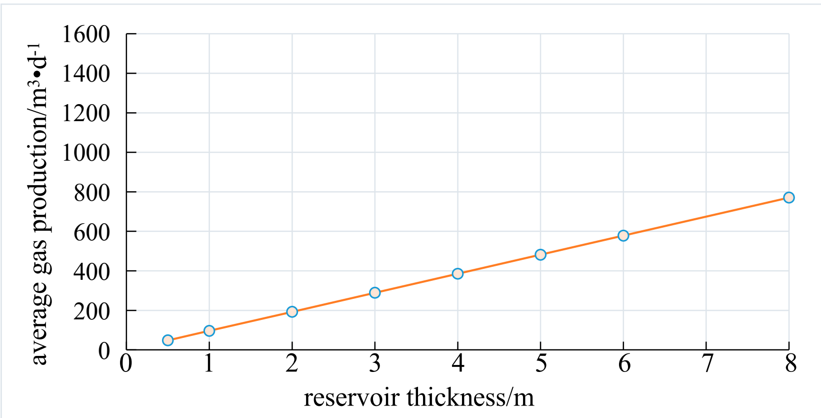


Figure 6. Average gas production at different thicknesses (numerical simulation).

Under the same geological conditions, optimizing the fracturing scale can effectively increase the production of coalbed methane wells by more than two times. The results of numerical simulation and dynamic analysis show that there is a significant positive correlation between fracturing scale and gas production (Figure 7). Increasing the fracturing scale can further improve the production of coalbed methane wells. However, increasing the fracturing scale also increases the fracturing cost and requires further optimization of the fracturing scale. Therefore, there must be an optimal fracturing scale and corresponding fracture length to achieve the optimal economic benefits.

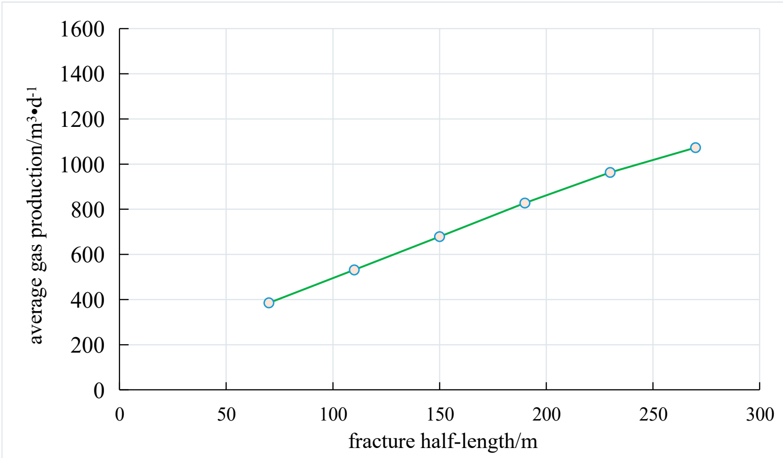


Figure 7. Average gas production at different fracture lengths (numerical simulation).

In order to obtain the fracturing limit of the coal reservoir in the Liulin block, it is necessary to calculate the fracturing curve shape of all fractured wells. According to the shape of the fracturing pressure, the fracturing curve can be divided into four types. A stable fracturing curve indicates stable fracturing pressure. The downward fracturing curve represents a slow drop in fracturing pressure during the fracturing process. The sand difficulty fracturing curve represents a sharp increase in fracturing pressure in a short period of time. The fluctuating fracturing curve indicates that the fracturing pressure is unstable and fluctuates greatly during the fracturing process. The upward fracturing curve indicates that the fracturing pressure remains at a large value for a long time during the fracturing process. The statistical results show that 46% of the fracturing wells in the Liulin block belong to a stable fracturing curve, 22% belong to a downward fracturing curve, and 2% belong to an upward fracturing curve, and the three types account for 70% of the total number of wells (Figure 8). This result indicates that the coalbed methane reservoir in the Liulin block has the potential to increase the fracturing scale.

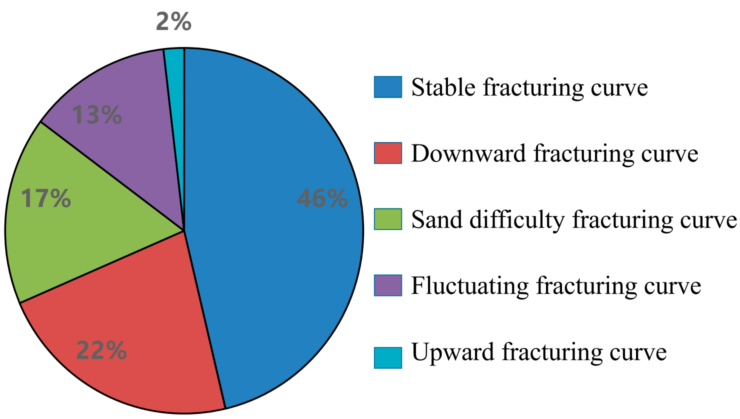


Figure 8. Statistical diagram of fracturing pressure curve type in Liulin block.

In order to determine the sensitivity of thickness, gas content, and fracturing scale (represented by fracture length in numerical simulation) to production, an orthogonal experimental design with three factors and four levels was used to analyze the sensitivity of the main controlling factors of production in Liulin block. From the results of the orthogonal test, the correlation coefficient of thickness reaches 705, which is the highest among the three parameters, indicating that thickness has the greatest influence on yield in the south of Liulin Block. The higher the thickness, the higher the gas production. When reservoir conditions are comparable, the ratio of fracturing scale to production can be up to three times (Table 2).

Table 2. Orthogonal experimental parameter.

Parameters	Gas Content (m^3/t)	Thickness (m)	Fracture Half-Length (m)	Average Gas Production (m^3/d)
Experiment 1	11	2	70	149
Experiment 2	11	6	270	1329
Experiment 3	14	2	270	779
Experiment 4	14	6	70	1009
Correlation factor	155	705	475	

It can be seen from the numerical simulation that the thickness is the main controlling factor of the production of the old well in the southern Liulin block, and the higher the thickness, the higher the gas production. Due to the small variation range of gas content in the whole study area, the effect of gas content on production is not obvious. When the reservoir conditions are similar, the fracturing scale has a great influence on the production.

4. Productivity Controlling Factors Analysis of Fracturing Parameters

In order to eliminate the interference of geological production factors on fracturing parameters, the normalized peak gas production was used as the objective function to conduct a multi-factor correlation analysis. Normalized peak gas production is defined as the ratio of actual peak gas production to the characteristic coefficient of productivity. The productivity characteristic coefficient is the ratio of gas content multiplied by reservoir thickness to reservoir depth.

For vertical wells, normalized peak gas production has a strong positive correlation with reconstruction intensity and a general positive correlation with displacement and effective average water production; a strong positive correlation with liquid volume, sand volume, and average sand ratio; a general positive correlation with bottom-flow pressure and a general negative correlation with effective average water production (Figure 9). For horizontal wells, normalized peak gas production has a strong positive correlation with effective average gas production. In contrast, both have a strong positive correlation with reconstruction intensity and a strong negative correlation with pre-fluid proportion and rupture pressure, which are not affected by horizontal section orientation, horizontal section length, single section length, and displacement (Figure 10).

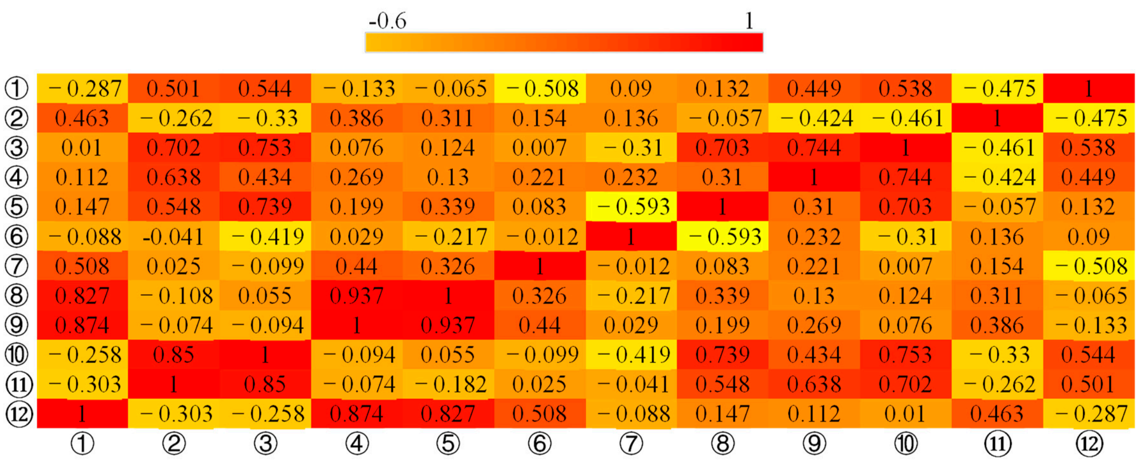
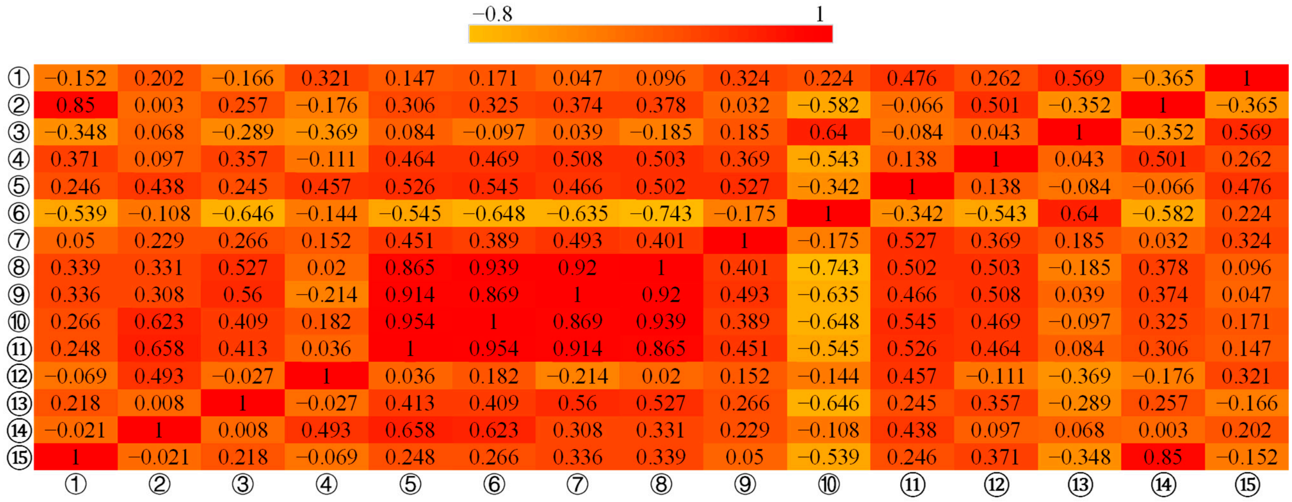


Figure 9. Correlation analysis results of influencing factors of vertical well productivity engineering in Liulin block. The serial numbers in the figure represent the parameters as follows: ① See gas well bottom flow pressure, ② Average daily water production, ③ Average daily gas production, ④ Daily gas production during stable production period, ⑤ Average sand ratio, ⑥ Prefluid ratio, ⑦ Displacement, ⑧ Sand strength, ⑨ Liquid strength, ⑩ Sand dosage, ⑪ Liquid dosage and ⑫ Normalized peak daily gas production.



	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮
①	−0.152	0.202	−0.166	0.321	0.147	0.171	0.047	0.096	0.324	0.224	0.476	0.262	0.569	−0.365	1
②	0.85	0.003	0.257	−0.176	0.306	0.325	0.374	0.378	0.032	−0.582	−0.066	0.501	−0.352	1	−0.365
③	−0.348	0.068	−0.289	−0.369	0.084	−0.097	0.039	−0.185	0.185	0.64	−0.084	0.043	1	−0.352	0.569
④	0.371	0.097	0.357	−0.111	0.464	0.469	0.508	0.503	0.369	−0.543	0.138	1	0.043	0.501	0.262
⑤	0.246	0.438	0.245	0.457	0.526	0.545	0.466	0.502	0.527	−0.342	1	0.138	−0.084	−0.066	0.476
⑥	−0.539	−0.108	−0.646	−0.144	−0.545	−0.648	−0.635	−0.743	−0.175	1	−0.342	−0.543	0.64	−0.582	0.224
⑦	0.05	0.229	0.266	0.152	0.451	0.389	0.493	0.401	1	−0.175	0.527	0.369	0.185	0.032	0.324
⑧	0.339	0.331	0.527	0.02	0.865	0.939	0.92	1	0.401	−0.743	0.502	0.503	−0.185	0.378	0.096
⑨	0.336	0.308	0.56	−0.214	0.914	0.869	1	0.92	0.493	−0.635	0.466	0.508	0.039	0.374	0.047
⑩	0.266	0.623	0.409	0.182	0.954	1	0.869	0.939	0.389	−0.648	0.545	0.469	−0.097	0.325	0.171
⑪	0.248	0.658	0.413	0.036	1	0.954	0.914	0.865	0.451	−0.545	0.526	0.464	0.084	0.306	0.147
⑫	−0.069	0.493	−0.027	1	0.036	0.182	−0.214	0.02	0.152	−0.144	0.457	−0.111	−0.369	−0.176	0.321
⑬	0.218	0.008	1	−0.027	0.413	0.409	0.56	0.527	0.266	−0.646	0.245	0.357	−0.289	0.257	−0.166
⑭	−0.021	1	0.008	0.493	0.658	0.623	0.308	0.331	0.229	−0.108	0.438	0.097	0.068	0.003	0.202
⑮	1	−0.021	0.218	−0.069	0.248	0.266	0.336	0.339	0.05	−0.539	0.246	0.371	−0.348	0.85	−0.152

Figure 10. Correlation analysis results of influencing factors of horizontal well productivity engineering in Liulin block. The serial numbers in the figure represent the parameters as follows: ①Average daily water production, ② Average daily gas production, ③ Pressure drop, ④ Bursting pressure, ⑤ Average sand ratio, ⑥ Prefluid ratio, ⑦ Displacement, ⑧ Sand strength, ⑨ Liquid strength, ⑩ Sand dosage, ⑪ Liquid dosage, ⑫ Average fracturing stage length, ⑬ Horizontal bearing, ⑭ Length of horizontal section and ⑮ Normalized peak daily gas production.

In summary, the main controlling factors of productivity of vertical well/directional well are liquid strength, sand strength and average sand ratio. The main controlling factors of horizontal well productivity are the strength of used fluid, the strength of sand addition and the proportion of pre-fluid.

5. Establishment of Block Fracturing Simulation Model

1. Determination of ground stress direction.

The maximum horizontal ground stress direction of the target block can be determined roughly 20 degrees to 60 degrees southeast by combining the results of the wall caving judgment and the fracture morphology monitoring.

2. Calculation of ground stress and rock mechanics parameters.

A one-dimensional geomechanical model is established based on logging data such as acoustic waves and gamma rays, including the establishment of rock mechanics parameter profile, the establishment of mud shale index, the establishment of normal compaction curve, the calculation of formation pore pressure and three-dimensional geostress, etc., and the calculation results are further corrected by the formation pressure, formation rupture pressure and minimum geostress gradient obtained by small fracturing tests.

3. Research on multi-parameter collaborative fracturing simulation.

Based on the results of reservoir geomechanical characteristics, the typical fracturing model of the target block is established. Further combined with the results of multi-parameter productivity control factor analysis. A numerical simulation scheme for fracturing scale optimization under different fracturing intensities and different discharge rates was established. Combined with the on-site fracturing contract, the fracturing costs corresponding to different fracturing schemes can be calculated (Table 3).

Table 3. Summary of fracturing scale optimization scheme design in Liulin Block.

Serial Number	Sand Strength m^3/m	Liquid Strength m^3/m	Displacement m^3/min	Net Fluid Volume m^3	Sand Volume m^3	Expense Ten Thousand Yuan
1	20	225	6	900	80	29
2			8			29
3			10			31
4	30	337.5	6	1350	120	41.5
5			8			41.5
6			10			43.5
7	40	450	6	1800	160	54
8			8			54
9			10			56
10	50	562.5	6	2250	200	66.5
11			8			66.5
12			10			68.5
13	60	675	6	2700	240	79
14			8			79
15			10			81

6. Research on Optimization of Block Fracturing Scale

Combined with fracturing effect prediction, gas production prediction, and economic evaluation model, the fracturing scale suitable for economic development under different geological conditions is studied (Figure 11).

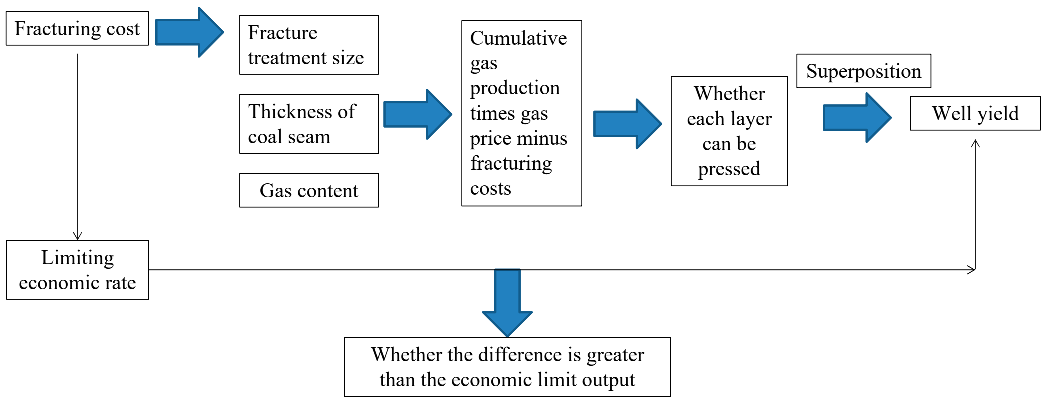


Figure 11. Fracturing well selection optimization program.

Based on the fitted geological model, the cumulative gas production from different thickness, gas content and fracturing scale to 2030 was evaluated. A total of 200 numerical simulation models with 5 gas content, 8 fracture lengths and 5 reservoir thicknesses were established to obtain cumulative gas production under different gas content, different reservoir thicknesses and different fracturing scales (Figure 12).

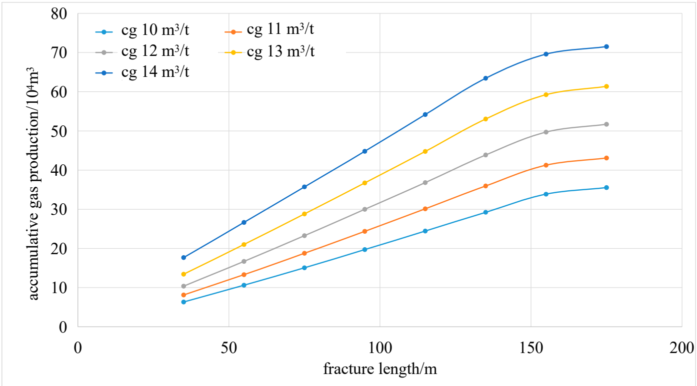


Figure 12. Cumulative gas production under different gas content and fracture length. Note: cg in the picture represents the gas content of the coal reservoir.

When the fracturing scale is small, the cumulative gas production can not meet the fracturing cost, and it is not economical. With the increase of the fracturing scale, the cumulative gas production increases, and the fracturing cost increases at the same time; there is an optimal fracturing scale, which makes the economic benefits optimal (Figures 13 and 14).

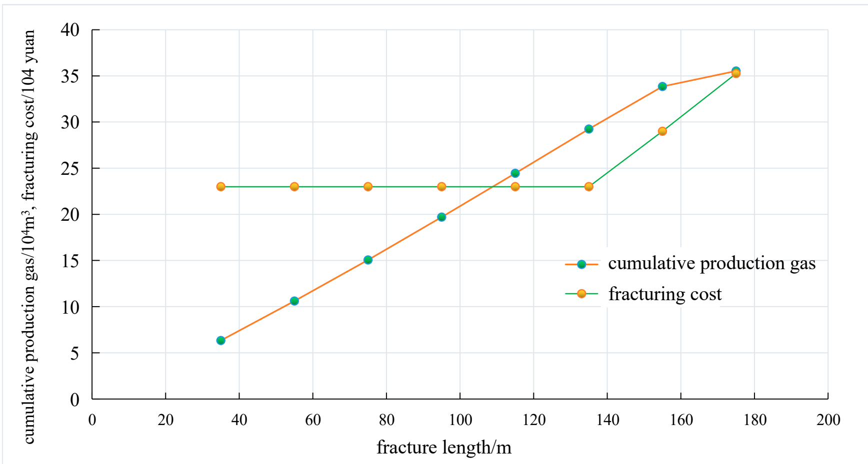


Figure 13. Cumulative gas production and fracturing cost under different fracture lengths.

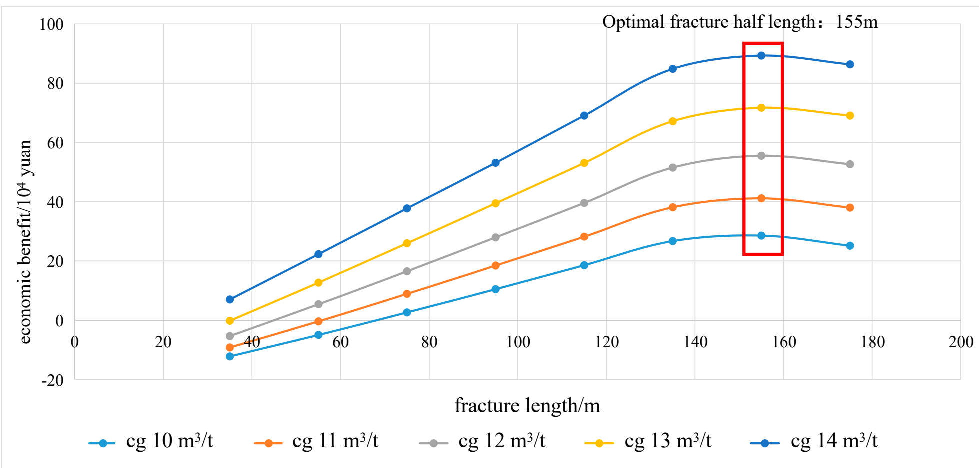


Figure 14. The economic benefit under different gas content and fracture half-length. Note: Economic benefit is the selling price of cumulative gas production minus fracturing costs and production costs.

Due to the complex distribution of coal seams in Liulin Block, No. 3 coal, No. 4 coal, and No. 5 coal are called the upper coal group in the process of analysis, and No. 8 coal, No. 9 coal, and No. 10 coal are called the upper coal group. For the upper coal group, the overall development effect is good; when the gas content is greater than 9 m^3/t, the thickness is greater than 0.5 m, and it can be economically developed (meet the fracturing cost). For the lower coal group, when the gas content is less than 12 m^3/t, and the thickness is less than 0.5 m, the cumulative gas production cannot meet the fracturing cost. When the thickness is small, the fracturing simulation shows that the fracturing fracture length is proportional to the amount of fluid used and the amount of sand added, and the fracturing fracture length is obviously related to the amount of fluid used and the amount of sand added. Therefore, even if the fracturing cost increases with the increase of the fracturing fracture length, the fracture length also increases significantly. Therefore, the larger the fracturing scale, the greater the gas production, the better the benefit, and the longer the optimal fracture length (Red circles in Figures 15 and 16).

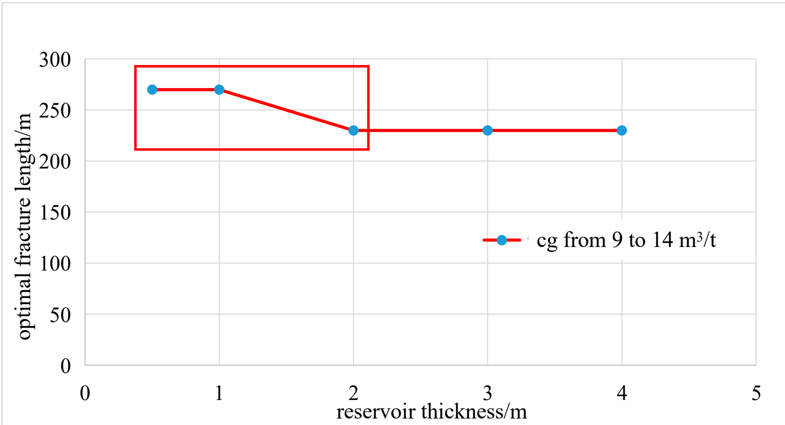


Figure 15. Chart of optimal fracture length of upper coal group.

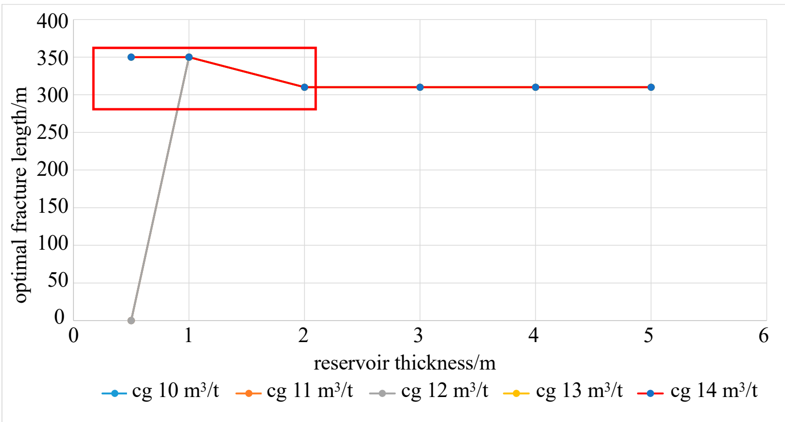


Figure 16. Diagram of optimal fracture length of lower coal group.

Based on the results of fracturing zone screening, the overall economy of a single well is evaluated. The well and layer selection process is as follows:

1. The wells and corresponding formations that can be re-fractured at present are sorted out;
2. Determine whether the formations can be fractured under the optimal fracturing scale;
3. The gas production of the corresponding formation of a single well is compared with the cost of secondary fracturing of a single well to determine whether a single well is compressible.

7. Conclusions

1. In the process of fracturing reform of coalbed methane reservoir, the strength of liquid, sand addition strength, and the average sand ratio have a great influence on the fracturing effect of vertical wells, and the ratio of liquid use strength, sand addition strength, and pre-fluid has a great influence on the fracturing effect of horizontal wells. The production factors of vertical and horizontal Wells can be obtained by analyzing the correlation of peak gas production with geological normalization. For vertical Wells, the correlation coefficients between the peak gas production and the intensity of sand addition and liquid use reach 0.827 and 0.847, which are the two highest parameters among all the parameters. In third place is displacement, which has a correlation coefficient with peak gas production of 0.508. For horizontal Wells, the correlation coefficients between peak gas production and rupture pressure, sand addition strength, and liquid used strength are 0.371, 0.339, and 0.336, respectively. These three parameters are the main parameters affecting horizontal well production. Because the data of horizontal Wells are relatively few, the correlation of horizontal wells as a whole is less than that of vertical wells.
2. When the thickness is small, the fracture extension effect is significantly correlated with the fracturing scale. Therefore, the longer the optimal fracture length is under this condition, the lower the optimal fracture length will be when the thickness increases. Through numerical simulation analysis, it was found that the gas content of the target well increased from 12.5 cubic meters per ton to 13.5 cubic meters per ton, and the peak annual average gas production increased from 420 cubic meters per day to 590 cubic meters per day. The increase effect was not obvious, and the detailed relationship curve is shown in Figure 5. The target well thickness increased from 2 m to 6 m, and the peak annual average gas production increased from 200 m cubic meters per day to 600 cubic meters per day, with a significant increase effect. See Figure 6 for a detailed correlation curve. There is a significant positive correlation between fracturing scale and gas production. Increasing the fracturing scale can further increase the production of coalbed methane Wells. See Figure 7 for a detailed relationship curve.
3. Large-scale fracturing will increase the fracture extension effect, but it will also increase the fracturing cost. In optimizing the fracturing scale, it is necessary to comprehensively consider the fracturing scale and fracturing cost. The comparison between Figures 11 and 13 shows that, without considering economic benefits, the cumulative gas production increases with the increase of fracture half-length, in which case it is difficult to determine the optimal fracture half-length (Figure 11). When the economic benefit is taken into account, the relationship between the crack half-length and the economic benefit is first positively correlated and then becomes positively correlated when the crack half-length reaches 155 m, and the optimal crack half-length is easily obtained as 155 m (Figure 13). It is more accurate to optimize fracture length considering economic benefit.

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