Method and Application of Reducing Pressure and Increasing Production in Nanometer Porous Coal Seam

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Objectives: In order to deeply analyze the feasibility of reducing pressure and increasing production of coalbed methane wells in nano-porous coal seams and clarify the principle of well selection. Methods: The sensitivity of bottom hole flowing pressure to coalbed methane production is analyzed by establishing productivity equation in stable production period of coalbed methane wells. Combined with the numerical simulation method, the drainage and production effect of L-1 well in the Block A is simulated after reducing the flowing pressure at the bottom of the well. Results:The results show that for CBM wells that have been put into production, the effect of increasing the production can be achieved by reducing the bottom hole flowing pressure, and when the bottom hole flowing pressure is large, reducing the bottom hole flowing pressure can obtain a larger increase in gas production. The cumulative gas production of Well L-1 can be increased by 110×104m3 compared with the previous measures, and the increase rate can reach 85%.Conclusion: Combining with the pressure-reducing and increasing production wells in the Block A, the applicable conditions for pressure-dropping and increasing production to increase the production of CBM wells are proposed, that is, continuous and stable drainage and production, and there is a certain height of liquid column between the moving liquid level and the coal roof before operation.

Keywords:coal bed methane; reducing blood pressure and increasing production; productivity equation; enhanced oil recovery
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Coal has complex and developed pore structure, rich and diverse pore structure and pore morphology, forming a large number of crisscross network structure. According to the pore structure, the pores above 1000nm are called macropores, those between 100nm and 1000nm are called mesopores, those between 10nm and 100nm are called transitional pores, and those below 10nm are called micropores. Small angle X-ray scattering (SAXS) is a method to obtain pore structure parameters of coal samples through X-ray penetration testing. This technology is widely used in the research field of nano pore structure of nano materials and porous materials. Through this technology, the complexity of coal seam pore structure can be realized more comprehensively.

Because most of the coalbed methane exists in the form of adsorption, the main method of exploiting coalbed methane is to reduce the formation pressure, which is different from conventional natural gas in the aspects of reservoir forming mechanism, occurrence state, distribution law and exploration and development mode [1-3]. From the point of view of coalbed methane production, compared with conventional natural gas, the problem of low single well production of coalbed methane wells is very prominent[4-6]. There are many main control factors that affect the production of a single well of CBM, including geological conditions, engineering technology, and drainage control[7-11]. Based on the influencing factors of CBM wells, it is aimed at improving the production and recovery of CBM single well. Some solutions have also been proposed at home and abroad.

Conventional oil and gas reservoirs are often developed by water injection to enhance oil recovery, but coalbed methane storage belongs to nano pores, with extremely low permeability, so it is difficult for water to be effectively injected. And coalbed methane belongs to adsorption gas, which can be desorbed into free gas when the pressure is reduced, so it can be recovered. Therefore, water injection / polymer injection development is not suitable for coal reservoir.

For example, by injecting carbon dioxide and nitrogen, the recovery ratio of coalbed methane can be improved [12-14]. The principle of carbon dioxide enhanced recovery ratio is that the adsorption capacity of coal matrix to carbon dioxide is stronger than methane, and the injection of carbon dioxide can displace methane in matrix. The mechanism of enhanced oil recovery by nitrogen is that the adsorption capacity of methane is stronger than that of nitrogen. When nitrogen is injected, the pressure of methane phase can be reduced, so that the production pressure difference of methane can be increased without reducing the total pressure in coal seam. Therefore, for nano-scale pores, although it is feasible to increase production by gas injection in theory, there is no breakthrough in this method at present。

The improvement of hydraulic fracturing technology is also the research direction to improve the recovery of coalbed methane[15], but these methods are mostly applicable to newly commissioned wells. At present, most CBM blocks in China have been put into production on a large scale, and there is a low average production of single wells. Therefore, research on improving the recovery of coalbed methane has more important significance and effect on this background.

Because coalbed methane belongs to adsorption gas, bottom hole flowing pressure and formation pressure are more sensitive to coalbed methane production[16], this paper makes an in-depth study on depressurization and stimulation technology of coalbed methane well, and demonstrates the feasibility and well selection principle of depressurization and stimulation technology from theory, numerical simulation and practical application effect.

METHODS

Assuming that in a mean, isothermal, and equal-thickness circular formation, a central coalbed methane well produces at a constant output in a small time step. At this time, it is considered that a stable seepage state is reached. Then the stable seepage differential equation can be expressed as:

$$\frac{1}{\mathrm{r}}\frac{\mathrm{d}}{\mathrm{dr}}\left(\mathrm{r}\frac{\mathrm{d}\widetilde{\mathrm{P}}}{\mathrm{dr}}\right) = 0 (1)$$

(1) The equation is a second order ordinary differential equation:

$$\widetilde{\mathrm{P}} = \mathrm{C}_1 \ln \mathrm{r} + \mathrm{C}_2 (2)$$

Where $\widetilde{P}$ is the pressure function:

$$\widetilde{\mathrm{P}} = \int \rho \mathrm{dP} + \mathrm{C}\ (3)$$

Substitute the following boundary conditions:

At the shaft wall:

$$\mathrm{r} = \mathrm{r_w} \qquad \widetilde{\mathrm{P}} = \widetilde{\mathrm{P}}_\mathrm{w}\ (4)$$

At the outer boundary:

$$\mathrm{r} = \mathrm{r_e} \qquad \widetilde{\mathrm{P}} = \widetilde{\mathrm{P}}_\mathrm{e}\ (5)$$

Because the coalbed methane is adsorbed gas, only when the pressure is lower than the critical desorption pressure, the coalbed methane desorbs into free gas, while the strata outside the desorption range have no gas movement. Therefore, in formula (5), $\widetilde{P}_e$ is the critical desorption pressure, and r_e is the desorption radius.

Find out:

$$\mathrm{C}_1 = \frac{\widetilde{\mathrm{P}}_\mathrm{e} - \widetilde{\mathrm{P}}_\mathrm{w}}{\ln\frac{\mathrm{r_e}}{\mathrm{r_w}}} \mathrm{C}_2 = \widetilde{\mathrm{P}}_\mathrm{w} - \frac{\widetilde{\mathrm{P}}_\mathrm{e} - \widetilde{\mathrm{P}}_\mathrm{w}}{\ln\frac{\mathrm{r_e}}{\mathrm{r_w}}} \ln \mathrm{r_w}\ (6)$$

Substituting C1 and C2 into (2) to obtain the expression of the pressure function:

$$\widetilde{P} = \widetilde{P}_e - \frac{\widetilde{P}_e - \widetilde{P}_w}{\ln\frac{r_e}{r_w}} \ln\frac{r_e}{r} (7)$$

In order to find the output Q, Darcy's law is used. Because it is a gas seepage, the volume flow will change with pressure. However, in the case of steady seepage, the mass flow is constant, which is equal to the cross-section multiplied by the mass flow rate, namely:

$$M = \frac{2\pi Kh(\widetilde{P}_e - \widetilde{P}_w)}{\mu \ln\frac{r_e}{r_w}} (8)$$

After substituting the pressure function into equation (8), the expression of volume flow rate of plane radial flow gas well under standard condition is obtained:

$$Q = \frac{\pi Kh}{\mu} \frac{T_a}{P_a \bar{z} T_f} \frac{P_e^2 - P_w^2}{\ln\frac{r_e}{r_w}} (9)$$

In the formula,

H: formation thickness;

K: shear permeability;

Q: Gas production of gas wells under standard conditions;

μ: gas viscosity;

Ta: temperature under standard conditions;

Tf: formation temperature;

Pa: pressure under standard conditions;

Z: compression factor.

Since the boundary pressure Pe in the mathematical model is selected as the critical desorption pressure, the desorption range has not been extended to the well spacing range. At this time, the desorption range of the CBM well continues to expand, there is continuous desorption gas supplement, and the gas production is relatively stable. Therefore, the productivity prediction model It is suitable for predicting the gas production of CBM wells in the stable production stage.

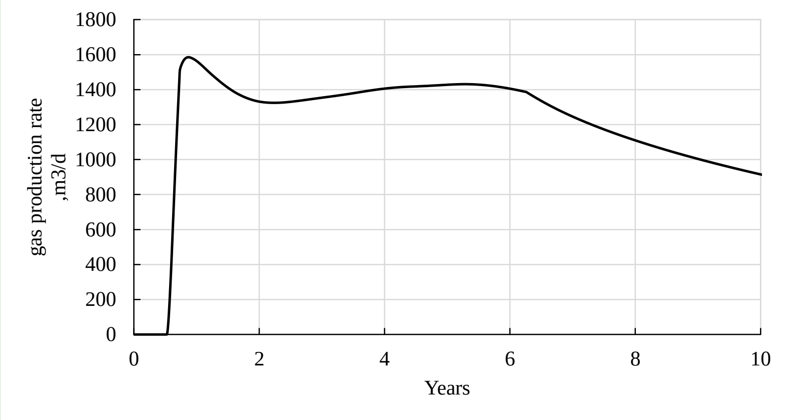
In order to verify the applicability of the productivity prediction model, firstly, the differences between the productivity prediction model and commercial numerical simulation software are compared. Through the statistics of the geological parameters of the existing drainage wells in the target block, the thickness, porosity and initial pressure are all measured values. Permeability, gas content and critical desorption pressure are calculated according to the production data, and the above parameters are averaged to establish a typical CBM geological model suitable for the target block. The design basic model parameters are shown in the table 1. Based on the model parameters, productivity model and numerical simulation software are used to predict CBM production.

Table 1
The Parameter of the Typical Model

Well control area	300m×300m	Thickness	6m
permeability	1X10-3μm2	Porosity	5.82%
Gas content	17.2m3/t	Initial pressure	6.0Ma
Critical desorption pressure	2.2MPa	Bottom hole pressure	0.2Ma

The above geological model is simulated by commercial numerical simulation software. The drainage system is controlled at the moving liquid level drop rate of 3m/d during the drainage and pressure reduction stage, that is, the bottom hole flow pressure is controlled at a drop rate of 0.03MPa/d, after the gas is seen The descending speed of the liquid surface becomes 0.1m/d. The simulation results are shown in the Figure 1. The CBM well enters a stable production period after going through the drainage depressurization stage and the production rise stage, and the gas production during the stable production period is about 1350m3/d.

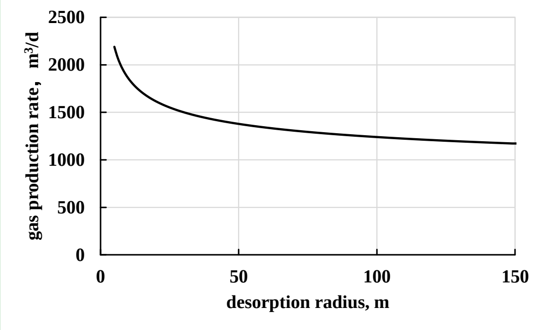
Figure 1
The Results of Gas Production Curve in a Block With Numerical Simulation



The productivity prediction model is used to calculate the coalbed methane production under the same geological parameters. It can be seen from formula (9) that after the geological parameters are determined, the gas production of coalbed methane wells is mainly related to the desorption radius, and the larger the desorption radius, the smaller the daily gas production. This is because the larger the desorption radius is, the smaller the pressure drop and desorption gas distributed to each grid with the same water production will be. However, from the calculation results, it can be seen that the decrease of gas production is small, and it basically stays in the stable production stage.

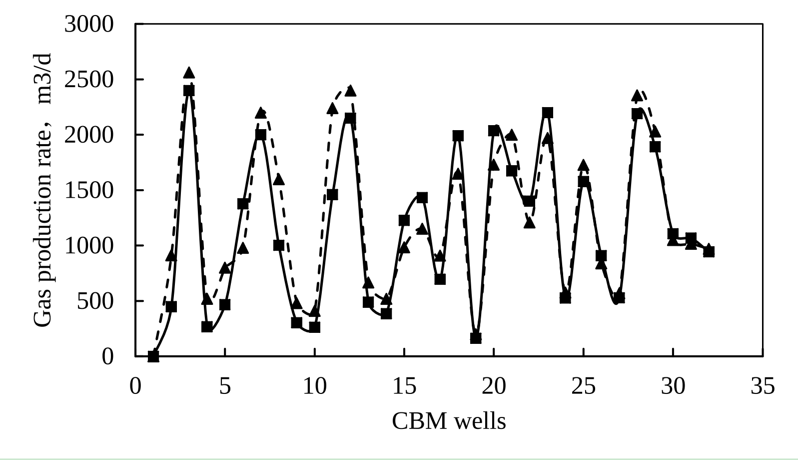
In order to facilitate the comparison, the daily gas production with desorption radius of 70m is selected. The results show that the gas production in stable production period calculated by the theoretical model is about 1400m3/d (Figure 2). The error with the numerical simulation results is within a reasonable range, and it is considered that the derived productivity prediction model is in good agreement with the numerical simulation.

Figure 2
The Result of Single Well Productivity With Theoretical Calculation



In addition, 33 wells with stable drainage system, high production time rate, and gas production in the Block A were selected for single-well production calculation. The calculation parameters are selected based on actual well test data, where the viscosity is 0.013mPa·s, the well diameter is 0.1m, and the permeability is between 0.25mD-3.74mD based on the interpretation of the CBM well test. The coal seam thickness is determined according to the actual test data of each well, and the critical desorption pressure and bottom hole pressure are obtained from the actual production data. The critical desorption pressure is the bottom hole flowing pressure at gas breakthrough. The calculation results are shown in the Fig 3.

Figure 3
The Contrast Between the Theoretical Result and Actual Gas Production

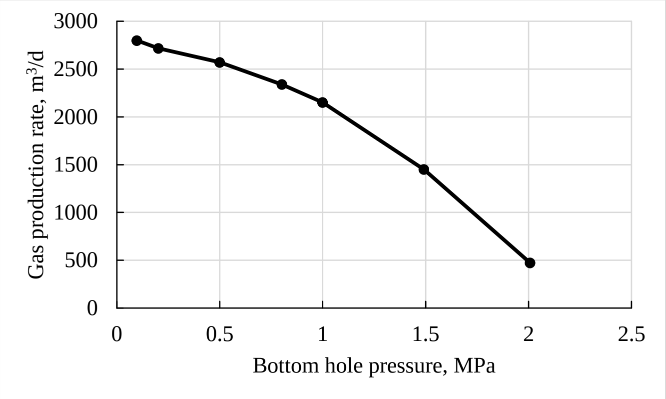


The results show that the prediction results of 85% of the wells are in good agreement with the actual production data, the average error is 10%, and the minimum error can be within 3%, which can be used to predict the gas production of CBM wells. There are two main reasons for the poor gas production prediction of some wells (15%). One is that the current understanding of coal seam permeability is not clear, which can not truly describe the underground permeability. Second, there are some errors in bottom hole flowing pressure measurement.

From the productivity equation, it can be seen that permeability, coal seam thickness, critical desorption pressure and bottom hole flowing pressure all have certain influence on the productivity of coalbed methane wells. However, the first three belong to the properties of coal seam itself, so it is difficult to achieve the goal of increasing production by changing the existing technology. Although the artificial fracturing technology can increase the permeability to a certain extent, it is only near the coalbed methane well, and the secondary fracturing will not only increase the cost, but also have higher risks, so it is unlikely that the permeability of coal seam will be adjusted after putting into production. Therefore, bottom hole flow pressure has become one of the important parameters of CBM wells to increase and stabilize production. Reducing bottom hole flow pressure can increase gas production of CBM wells. The method of deepening pump hang-up is usually used on site to further reduce bottom hole flow pressure.

The calculation results show that the gas production increases with the decrease of bottom hole flowing pressure, and the increasing range is smaller and smaller (Figure 4). That is to say, when the bottom hole flowing pressure is large, a larger increment of gas production can be obtained by reducing the bottom hole flowing pressure.

Figure 4
The Relation Curve Between Yield and Bottom Hole Pressure



On the other hand, in the nano pores, coalbed methane mainly exists in the coal seam as adsorption state. At present, it is mainly developed according to the mechanism of "drainage depressurization desorption diffusion seepage". In the study of coalbed methane desorption, the single molecular layer adsorption kinetics theory, namely Langmuir isothermal adsorption theory, is mostly used. The adsorption and desorption characteristics of coal seam have an important influence on the development of coalbed methane. Through the study of curvature variation characteristics of coalbed methane desorption (adsorption) curve, the influence of depressurization measures on gas production is clarified.

Under certain conditions of temperature and adsorbate, the adsorption of coal to gas can be described by the Langmuir equation:

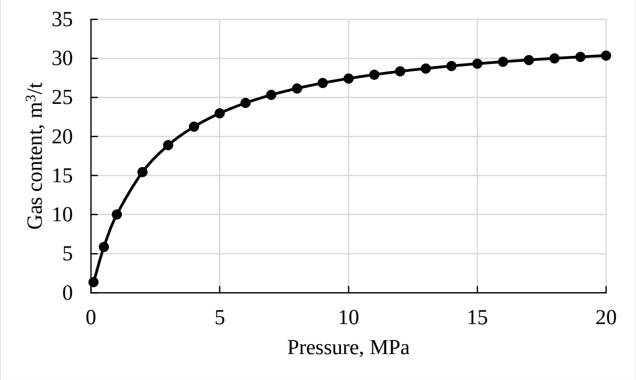
$$V = \frac{V_L P_L}{P + P_L}$$

In the formula: V——Adsorption gas volume

V_L——Range Volume
P_L——Lang's pressure
P——Reservoir pressure

Taking Block A as an example, the LAN's volume is 34m3/t and Lanshi pressure is 2.4Mpa. The Langer curve of this block can be obtained as shown in the Figure 5.

Figure 5
Isothermal adsorption curve of block A



It can be seen from the Figure 5 that as the formation pressure gradually decreases, the amount of adsorbed gas gradually decreases, that is, the adsorbed gas is slowly desorbed into free gas. In the initial stage of desorption, if the formation pressure is 4MPa, the desorption speed is relatively slow. As the pressure drops further, the desorption speed of the adsorbed gas gradually increases.

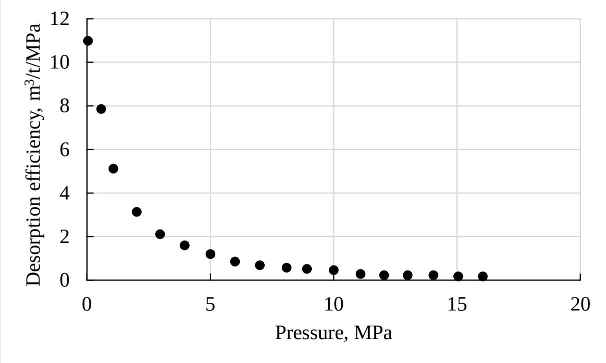
In order to quantitatively characterize the desorption rate of adsorbed gas, the concept of coalbed methane desorption efficiency is introduced, that is, the desorption amount per ton of coal under unit pressure drop. According to the Langmuir equation, the desorption efficiency of coalbed methane can be expressed as the first derivative of coalbed methane adsorption capacity

$$\eta = \frac{V_L P_L}{(P+P_L)^2} (4.3\text{-}1)$$

Where: η -- desorption efficiency

The Figure 6 shows the relationship between the desorption efficiency of coalbed methane in nano-scale pores and formation pressure. The results show more clearly that with the decrease of formation pressure, the desorption speed of coalbed methane is gradually accelerated, the desorption gas volume is gradually increased, and the final recovery degree is continuously increased.

Figure 6
Relationship Between the Desorption Efficiency And Formation Pressure



Taking block A as an example, assuming that the critical desorption pressure is 4MPa and the initial gas content is 20m3 / T, when the final average formation pressure is 1MPa, the remaining adsorption gas in the coal seam is 9.4m3/t, and the recovery degree is 52.9%. If further depressurization is carried out at this time, the final average formation pressure is 0.5MPa, and the remaining adsorbed gas in the coal seam is 5.5m3/t, and the recovery degree is 77.8%. Therefore, the depressurization and stimulation measures greatly improve the gas production and recovery factor of coalbed methane.

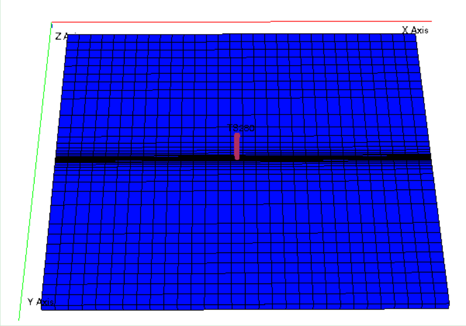
Numerical Simulation Verification of Depressurization and Production Increase

Block A is located in the southeast of Qinshui Basin, under the jurisdiction of Jincheng City, Shanxi Province, and is one of the blocks with high exploration degree of coalbed methane in China. As a whole, it is a monoclinic structure with NE strike and northwest inclination. The 3# coal of Shanxi Formation and the 15# coal of Taiyuan Formation have moderate buried depth, large thickness and high gas content, which are the main strata of coalbed methane exploration and development, and are mainly concentrated in the development of 3# coal seam at present, so this paper takes 3# coal as the research target.The 3# coal seam has a buried depth of 600-900m, the thickness is mainly between 4.0-8.0m, with an average of about 6.0m, and the measured gas content is between 2.34-19.16m3/t. The CBM wells in this block are arranged in a 300m×300m well pattern, and the current average gas production rate is 1263m3/d.

On July 26th, 2010, the No.3 coal seam of Well L1 was opened and mined side by side, and gas production began on October 7th, 2010. At present, the peak gas production of this well is 2356m3/d, and the average daily gas production is 1426 m3/d. Since the bottom hole flow pressure of the L1 well continues to drop gently, the drainage time rate is 95%, the drainage system is well controlled, and the gas production and water production are at the average level of the block, this well is selected as a representative of block A CBM wells and establish ideal numerical models.

The ideal numerical model is established by ECLIPSE numerical simulation software. According to the actual test data, the hydrocarbon gas of coalbed methane wells in this area is CH4, without C2+ and other components. The fluids in this model are defined as methane and water, which are calculated by black oil model. According to the well spacing of L1 well and the coal seam thickness (6m), a numerical model with the size of 300m×300m×6m is established, and the boundary of the model is a closed boundary. The grid steps in the X direction are all 10m, and in the Y direction, in order to simulate artificial fractures, the grid is densely processed around the coalbed methane well, and the simulated artificial fracture grid step is 0.1m. The actual artificial fracture width is 2.3mm, the conductivity is 250mD•m, and the fracture permeability is set in the model to be 250mD•m/0.1m=2500mD. One layer of grids is set in the Z direction, and the grid step length is 6m. As shown in Figure 7, the CBM well is located in the center of the model.

Figure 7
The Numerical Model of L1



The reservoir parameters used in the numerical model are all from the actual test parameters of well L1, as shown in Table 2. The fracture half length and fracture conductivity are simulated by fracturing software, the Langmuir pressure and Langmuir volume are obtained by laboratory test, the critical desorption pressure is determined by bottom hole flow pressure when gas breakthrough occurs, and the gas content of the well can be obtained by combining with Langmuir curve. However, the permeability and porosity of coal seam have not been measured and tested in this well. The permeability and porosity of coal seam cleavage in the initial model may not be consistent with the actual stratum, and the matrix permeability in the model is 0.

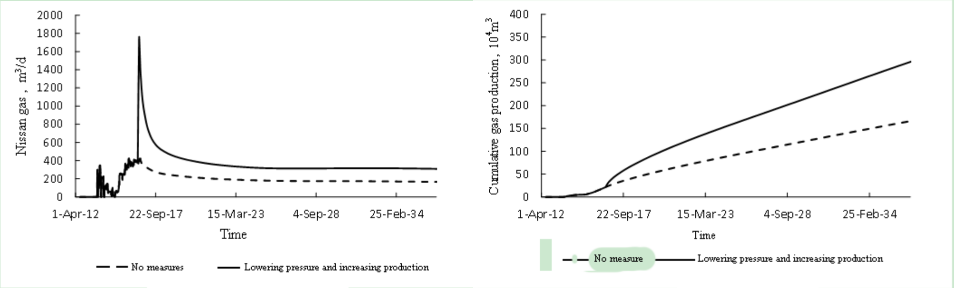
Table 2
The Fitting Formation Parameters of L1

Parameter	Parameter value	Parameter	Parameter value
Formation thickness	6.0m	Cuttings permeability	1mD
Porosity	5%	Formation pressure	5.0MPa
Half-length crack	70m	Fracture conductivity	250mD•m
Lang pressure	2.29MPa	Lang volume	30.37m3/t
Gas content	17.2m3/t	Critical desorption pressure	2.2MPa

Through the numerical simulation research, the historical fitting method is used to verify and modify the model parameters. Finally, the historical fitting of multiple production indicators makes the single-well numerical model closer to the actual geological conditions of the gas reservoir, and more accurately reflects the distribution of underground gas and water. And the law of migration. In this paper, the method of determining the production volume is used to fit the gas production, water production, and bottom hole pressure of a coalbed methane well. The fitting results are better. After fitting, the cleat permeability is 2.5mD and the porosity is 3%.

Through this model, the L-1 well was used to numerically simulate the pressure reduction and stimulation measures, and the bottom hole flow pressure was reduced to 0.3 MPa. After the pressure drop, the changes in the well's daily gas production and cumulative gas production were compared and analyzed.

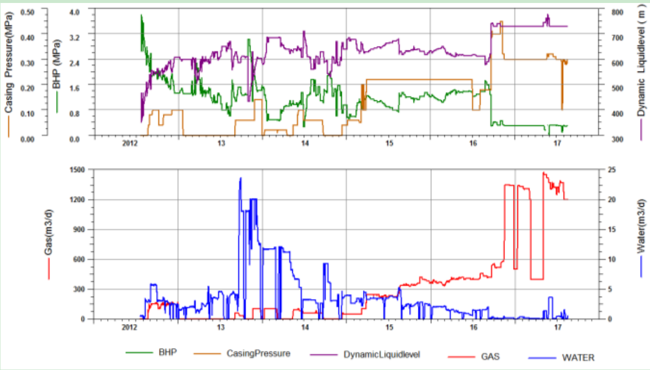
Figure 8
The Contrast of Development Effect Between No Measures and Increase Production



The comparison results show that after reducing the bottom hole flowing pressure, the peak daily gas production of L-1 well can reach 1800m3 / D, which is 3 times higher than that before the measures, and the daily gas production during the stable production period is 300m3 / D, which is 2 times higher than that before the measures (Figure 11). It is estimated that the cumulative gas production in 20 years (2032) will be 246 × 104m3, 110% higher than before × 104m3, an increase of 85%.

According to the prediction results, on November 17th, 2016, the pump hanging measures were deepened for well L-1, and the pump suction port was lowered to 10m below the coal floor. After the well was re-opened, the daily gas production of well L-1 reached 1470m3/d, and as of August, 2017, the daily gas production was 1200m3/d, which was consistent with the expected results (Figure 9).

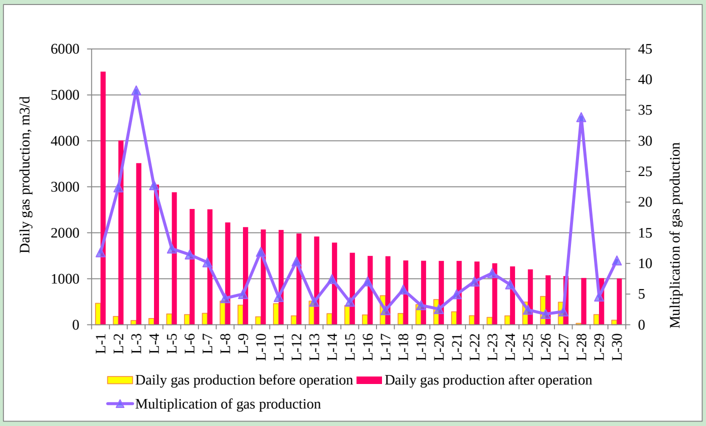
Figure 9
The Actual Production Curve After Increase Production Measures



RESULTS

Among the wells with depressurization and stimulation measures in Block A, the output of 30 wells increased to more than 1000m3 / d after operation, and the daily gas production after lifting was 1007-5504m3 / D, which was 2-38 times of that before operation. The output of 21 wells increased by more than 5 times, accounting for 70%. The change of well production after depressurization and stimulation is shown in Figure 10.

Figure 10
The Contrast of Production Before and After Increase Production Measures



In addition to the influence of coalbed methane adsorption characteristics, continuous and stable drainage and drainage sources are also the factors that need to be considered whether the pressure reduction and production increase measures can increase production.

Continuous and Stable Drainage

The operation well with good effect has good production continuity, and the production rate is 76% - 100%, with an average of 96%. The production rate of 43% (13 wells) is more than 99%, 73% (22 wells) is more than 95%, and 83% (25 wells) is more than 90%.

In addition, it can be seen from the measure wells that the time of stable production before stable gas production accounts for a large proportion of gas production time. The stable production time before reducing pressure and increasing production was 290 ~ 944 days, with an average of 688d days. Stable production time accounts for 55% ~ 97% of gas production time, with an average of 76%. Stable gas production is 61~560m3/d, with an average of 332m3/d, mostly concentrated in 200 ~ 400 m3/d.

The stable production characteristics and the production time rate show that these wells do little damage to the reservoir during the early drainage process, ensure the unblocked seepage channel, obtain effective drainage in the early production stage, and ensure the effective expansion of the pressure drop funnel.

Early Gas Breakthrough and Low Water Production

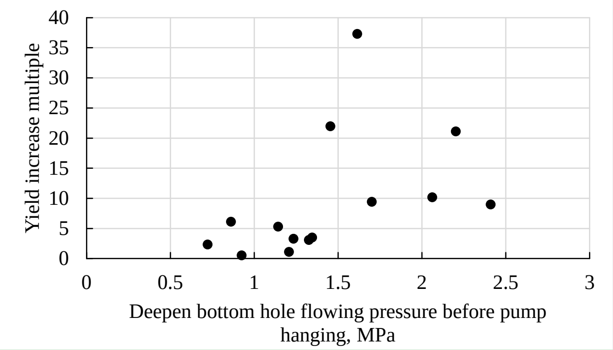
It can be seen from the effective measure wells that most wells have the characteristics of short production time and small cumulative water production before gas breakthrough. The gas breakthrough time of 30 wells is 2 ~ 157 days, and the average gas breakthrough time is 55 days, and only 4 wells have been put into production for more than 100 days. The average water production of a single well is 0.6~7.92m3/d, with an average of 2.08m3/d. Early gas generation and low water production indicate that the discharged water is coalbed water, and the temporary reserve ratio is high, and coalbed methane is easy to desorb.

Bottom Hole Flowing Pressure Before Operation

Before depressurizing and increasing production, the distance between the dynamic liquid level and the coal seam roof is 60 ~ 217 m, with an average of 108m, mostly concentrated in 60 ~ 150 m. The dynamic liquid level is above the roof of coal seam, which indicates that there is a certain height of liquid column and there is room for lowering the flowing pressure at the bottom of the well. At the same time, the height of dynamic liquid level is limited, which indicates that the coal seam has been effectively depressurized in the early stage and has a certain pressure relief area. The bottom hole flowing pressure also reflects this phenomenon. Before operation, the bottom hole flowing pressure was 0.68 ~ 2.38 MPa, with an average of 1.3MPa.

A number of depressurization-increasing production wells in the Block A are selected for illustration, as shown in Figure 11, which is a comparison diagram of bottom hole flow pressure before operation and production growth multiple after operation. The results show that the greater the bottom hole pressure before operation, the greater the production growth multiple, which is the same as the above research results. And for the target area, in order to obtain a better stimulation effect, it is recommended to select a coalbed methane well with a bottom hole flow pressure greater than 1.3 MPa before the pressure reduction and stimulation operation.

Figure 11
The Relation Curve Between Production Increase and Bottom Hole Pressure Before Measures



DISCUSSION

The productivity prediction equation of CBM well in stable production period is established, and the sensitivity analysis of bottom hole flowing pressure is carried out. The results show that the gas production of CBM well increases with the decrease of bottom hole flowing pressure, and the increase range is smaller and smaller. That is to say, when the bottom hole flowing pressure is large, a larger increment of gas production can be obtained by reducing the bottom hole flowing pressure.

The pressure reduction and production increase of L-1 well are simulated by numerical simulation method. The results show that the cumulative gas production is estimated to be 246×104m3 after 20 years (2032), which is 110×104m3 higher than that before the measures, and the growth rate can reach 85%.

Under the continuity of drainage and production and a reasonable drainage system, wells that can greatly increase daily gas production after pressure drop and increase production operations need to meet the following conditions: 1) Continuous and stable drainage, stable gas production, and a production time rate of 90 %the above. 2) The reservoir pressure is appropriate, there is a certain height of liquid column between the moving liquid surface and the roof of the coal seam, and the bottom hole flow pressure before operation is higher than 1.3 MPa.

Human Subjects Approval Statement

This paper did not include human subjects.

Conflict of Interest Disclosure Statement

None declared.

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