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Numerical Simulation Research of Coal-bedded Methane Well Output and the Application Analysis

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Abstract: A numerical simulation of coal-bed gas wells is an effective method to determine the estimation prospects of coal-bed gas ground output, production preferences, and recovery assessments, and follows the model selection, data entry, sensitivity analysis, history matching, and production forecasting simulation steps of conventional numerical simulations regarding oil and gas reservoirs. In the present study, a coal-bed methane non-equilibrium pseudo-steady sorption-diffusion model of a coal-bed gas well output, which was combined with a coal-bed gas flow equation, was used to establish a mathematical model of coal-bed gas migration. Then, based on this model, the #3 coal-bed gas well of the southern Qinshui Basin was set as an example. COMET3 software was used to simulate the numerical simulative solution, and to analyze the air changes and water production. The results showed that, based on the dual porosity in a single permeability model of the coal-bed gas flow mechanism, the unknown variables P_g and S_g in the mathematical model of the gas and water transport were derived. Then, through the history matching of the gas and water data obtained by the COMET3 software, and the coal reservoir P_g and S_g parameter dynamic characteristics analysis, it was concluded that after discharge and the mining of the well for a period of 40 days, the coal-bed gas output began to transition from a single-phase flow of water, to an unsaturated single-phase flow. This accurately described the output process of the #3 coal-bed gas well of the southern Qinshui Basin, and provided theoretical guidance for the reasonable coal-bed gas mining of the next stage.

***Keywords:** coal-bedded methane; recovery mechanism; mathematical model; numerical simulation*

1. Introduction

Coal-bed gas is a type of high calorific value, and a clean new energy which causes less pollution. The development and utilization of the rich CBM resources in China could make up for the deficiency in conventional energy sources. However, most of the coal-bearing basins in China have experienced multiple tectonic movements. The coal seam structure is complicated, and the heterogeneity of the coal reservoir is strong. However, the permeability is generally low, and the coal reservoir is very sensitive to formation pressure, which results in the development of coal-bed gas to be very slow. Therefore, an accurate analysis of the basic principles of coal-bed gas, which was established based on a reasonable set of coal-bed gas well output mathematical models, is of particular importance. The production process using a mathematical model, which was a reasonable combination of a coal reservoir numerical simulation, can describe the CBM well during the all of the stages.

Luo Zujiang[1] established a three-dimensional mathematical model of the #3 CBM gas output in coal-beds in the Qinshui Basin. Zhang Xianmin [2] took into consideration the coal matrix shrinkage impact of the coal-bed wells of the CAPE mining simulation and prediction. A mathematical model and numerical analysis of the development of a coal seam gas branch well was conducted by Li Na et al. [3]. Also, based on the existing models from the United States, Wu Xiaodong [4] established a mathematical model of non-equilibrium quasi steady well bottom flow in a vertical well.

Chen Jingang et al. [5] used COMET2 coal-bed gas numerical simulation software, utilized a piecewise fitting method of coal-bed gas well gas production, along with the water production process of historical fitting and correction, and then continued the discussion to rank the coal reservoirs' permeability during dynamic mining changes. Li Weikang et al. [6] established a coal layer hydraulic cutting, gas pumping, solid-fluid coupling mathematical model in order to study the stress and gas pressure fields of coal, and the amount of gas drainage variations following hydraulic bedding cutting. Yi Xinbin [7] established the optimization criterion for completion and stimulation measures, which was based on permeability grading, through a numerical simulation in order to calculate the cumulative gas production analysis, and the final selection of the most appropriate method of completion stimulation. Yang

Xinle et al.[8] explored the impact of coal-bed gas production after the steam heating a coal seam, as well as the establishment of a low permeability coal-bed gas heat injection process, methane seepage heat-flow-solid multi-physics coupling mathematical model, and the process of a mining methane seepage numerical simulation law. Feng Qihong [9] established a seam with an adjacent layer of a sandstone gas co-mingled dimensional gas-dynamic mathematical model, and a numerical model of water flow, combined with the geological data mining of Hancheng, and then launched a coal-bed gas adjacent laminated sandstone numerical simulation analysis of the mining conditions and significant influence factors. Li Guoqing et al. [10] used the same permeability, stress sensitivity, and consideration of cleat compression rate of change S-D permeability model and a different higher-order structure of coal-bed gas well drainage numerical model to study the early strength. Jin Yi et al. [11] used a Lattice Boltzmann Method to simulate the coal-bed gas migration process, and analyzed the end face of the fractal dimension, absolute roughness, and relative roughness the CBM transport features, introducing a new split-infiltration equation with a numerical analysis value simulation of the relationship between the permeability. Jiang Rui et al. [12] used a numerical simulation under different coal seam dip angle horizontal well production process pressures and gas saturation distributions, post-productions, and U-shaped horizontal wells, and put forward their recommendations. However, there are few reports available regarding the mathematical model of the mechanism of coal-bed gas production.

Fanhui Zeng [13] considered the non-uniform flow distribution and the variable mass linear flow in the fractures of a fractured horizontal well, results show that the daily output of fractured horizontal wells decreases rapidly from a high value at the beginning of production and then remained steady at a constraint of bottom hole pressure. Jalal M. Jalil[14] used the numerical simulation and experimental study, the pipe spacing is optimized. Li Mengxia[15] shows that gas-lift is one of the most widely used artificial lift methods in oil fields to increase oil recovery, and study the parameter sensitivity of the gas-lift unloading process.

In this study, for the analysis of the coal seam gas flow mechanism, along with the coal bed gas output process, a universally recognized expression of coal-bed gas wells throughout the production process of gas was used. A water transport shift double-single permeability model [16,17] was adopted, based on the analysis of the gas well production model of the coal-bed gas non-equilibrium quasi steady state adsorption diffusion coal-bed gas [18]. Then, based on the basic equation of a coal-bed gas flow mechanism, a mathematical model was established to meet the actual migration of the coal-bed gas. On the basis of this model, COMET3 simulation software was used to describe the process of coal-bed gas well bottom hole flow, and to guide the development of the coal-bed gas. Also, based on the mathematical model of the coal-bed gas seepage flow, combined with the actual coal reservoir in Qinshui Basin coal-bed gas well, along with the engineering parameters and a certain period of gas and water drainage data and so on, used the COMET3 inversion of the coal reservoir's parameters. The history of the coal reservoir drainage data fitting established a reasonable system of scheduling a coal-bed gas development program.

2. Basic principles of coal bed gas production

A coal seam is a typical dual porosity media with coal matrix micro-pores. The coal matrix pores of coal-bed gas have a strong adsorption capacity, and approximately 70 to 95% of the methane gas is affected by physical adsorption on the inner surface of the coal matrix [19]. A coal seam and the contained coal bearing strata generally contain water. The coal seam gas needs to drain to the groundwater for the coal seam gas output to provide initial power. At the beginning of the exploitation of coal-bed gas in the dehydration treatments, drainage, and pressure reduction process for the production of coal-bed gas, the induced accelerated coal-bed gas is desorbed from the surface of the coal matrix pores, as well as by matrix and micro pore diffusion to the fracture. According to the Darcy flow through a fractured flow shaft, the change of coal-bed gas from a high energy potential direction to a low energy potential direction is a continuous migration [20].

2.1. Coal bed gas flow mechanism

Coal-bed gas mainly exists in the micro pores of a coal matrix in an adsorption state, and the adsorption of coal to gas is non-selective and reversible. With the development of groundwater in a coal reservoir and fracture system, the pressure of a coal reservoir rock system begins to decrease. When the reservoir pressure is reduced to the coal seam under critical desorption pressure, the coal-bed gas adsorbed on the surface of the coal matrix is desorbed from the micro pore surface, and enters into the coal seam fracture system [21]. The desorption and adsorption are inverse processes. Therefore, the desorption characteristics of the coal-bed gas can be described by Langmuir's isothermal adsorption theorem as follows:

$$C(p) = V_L p / (p_L + p) \tag{1}$$

Where, p is the fluid pressure in the cleat, MPa; $C(p)$ represents the concentration of the gas inside the matrix equilibrium conditions, m^3/t; V_L is the Langmuir volume, m^3/t; and P_L is the Langmuir pressure, MPa.

The desorption concentration is higher on the desorption surface, and the concentration is lower in the fracture space. Under the concentration gradient, the coal-bed gas is diffused from the micro fracture system to the crack space along the pore. The entire process of the coal-bed gas diffusion is controlled by the distance of the coal-bed gas migration from the matrix to the crack, the concentration of coal-bed gas, and the intrinsic diffusion of the coal matrix. For the coal seam gas available, Fick's first law of diffusion into cracks by diffusion can be expressed as follows:

$$q_m = aA_m D\left[C - C(P)\right] \tag{2}$$

Where, q_m represents the amount of diffusion, m^3/d; C is the average gas concentration in the substrate, m^3/t; D is the diffusion coefficient, 1/d; a represents the cylindrical radius, m ; and A_m is the surface area of the matrix block unit, m^2.

Following the coal-bed gas diffusion through the micro pores in the coal, the coal-bed gas and the water in the coal-bed produce a mixed phase flow in the cleat system. The gas and water two phase media in the slit can flow in the form of a seepage flow, and gas and water flow through the pressure drop of the fracture system along the coal seam. According to Darcy's law, the flow rate of the gas and water phase can be expressed as follows [21]:

Gas phase：

$$V_g = -KK_{rg}\left(\nabla P_g - e_g g \nabla h\right) / \mu_g \tag{3}$$

Liquid phase：

$$V_w = -KK_{rw}\left(\nabla P_w - e_w g \nabla h\right) / \mu_w \tag{4}$$

Where, V is the seepage velocity, cm/s; K is the absolute permeability of the coal seam, 10^{-3}um^2; K_r represents the fluid relative permeability, 10^{-3}um^2; μ stands for the fluid viscosity coefficient; P is the coal seam fluid pressure, MPa; e represents the fluid density, m^3/t; g is the acceleration of gravity, m/s^2; h is the buried depth, m; and subscripts w, g represent the water and gas, respectively.

2.2. Production process of coalbed methane

The coal-bed gas reservoir is a type of pressure closed gas reservoir, which is different from conventional natural gas, as the drainage and pressure reduction are the main methods of coal-bed gas well drainage. The pressure differences between the well bore and coal seam are formed by the pumping of water into the well bore. Therefore, the groundwater in the coal seam wellbore flow eventually forms a head centered at the wellbore pressure drop funnel [22]. With the prolonging of mining time, the pressure drop funnel gradually becomes expanded and extended along the radial direction of the shaft. Three different drainage areas of coal-bed gas can be formed in the coal bed gas well. The inner layer is the two phase flow zone of the effective gas supply area. The middle layer is the effective desorption zone of the coal-bed gas, and the outermost layer is a single phase water seepage zone. In order to improve the production of coal-bed gas wells, the area of the two-phase flow must be improved.

During the physical process, in combination with the coal seam and the division of the drainage area of coal-bed gas well, the coal-bed gas production experienced three stages, as shown in Fig. 1. The first was the under saturation stage. With the downward pressure on the coal seam near the wellbore, the coal-bed gas desorption had not yet begun, and there was only water output. Also, near the wellbore, there was a single-phase water flow only. When the reservoir pressure further declined, the coal seam gas began to be desorbed from the surface of the pores, and the fracture system formed discontinuous bubbles which obstructed the flow of water. The relative permeability decreased, and the fissure water entered a non-saturated single-phase flow phase. As the near wellbore pressure in the coal reservoir became further reduced, a large amount of coal-bed gas desorption diffusion entered into the fracture system, and the water formed a Darcy gas-water two-phase flow. In the wellbore pressure funnel, under the action of the coal seam gas over a certain time period of continuous output, the three stages of the production of the coal-bed gas in time and space were a continuous process.

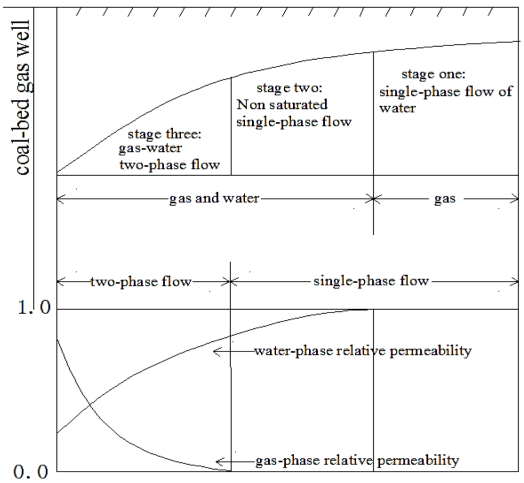

Fig. 1 *Schematic diagram of the three coal-bed methane output stages*

3. Establishment of the mathematical model

In the above analysis of the coal seam gas flow mechanism and the CBM production process, both Chinese and international researchers generally agree that, in the double-single permeability model, which is combined with the basic control equation of coal bed gas flow, a mathematical model which is in accord with the actual migration of the coal-bed gas can be established. This model describes the process of the bottom whole flow, and guides the development of the coal-bed gas.

3.1. Basic assumptions

(1) A coal reservoir has a special double porosity via a coal matrix pore system and a double cleat system composed of a single permeability.

(2) A coal reservoir can be compressed, and the isotropic medium.
(3) In the original state, a coal seam becomes 100% water saturated, and does not contain free or dissolved gases.
(4) Water is a slightly compressible fluid, which ignores the amount of dissolved gas.
(5) The free gas is regarded as real gas.
(6) The pore diameter of a coal matrix is small, and water cannot enter. Therefore, it only contains an adsorption state, free state gas, and other gas phases.
(7) In a fissure water flow stage, which is governed by Darcy's law, the cracks in the gas diffusion for a non-equilibrium quasi steady process obey Fick's first law of diffusion.
(8) The processes of desorption, diffusion, percolation, and output of coal-bed gas are isothermal.

3.2. Mathematical model

According to the basic equation of the coal-bed gas flow mechanism, the double single permeability model was as follows:

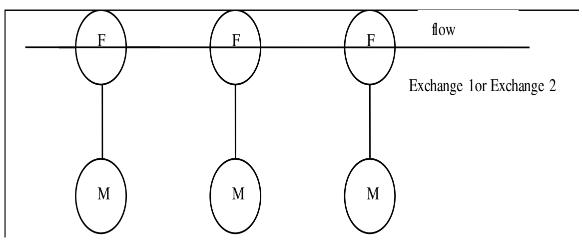

Fig. 2 *Principles of dual porosity and single permeability model*

Where M is the stroma; F represents the cracks; Exchange 1 is the gas channeling between the matrix and the fracture; and Exchange 2 is the air gap to large gap gas diffusion.

The double-single permeability model and the basic equation of the gas and water movement [23-25] establish a mathematical model to meet the actual migration of the coal-bed gas. The expression of the gas flow is as follows:

$$\nabla.\left[b_g M_g\left(\nabla p_g+\gamma_g \nabla Z\right)+R_{sw} b_w M_w\left(\nabla p_w+\gamma_w \nabla Z\right)\right]_f$$
$$+q_m+q_g=\frac{\partial}{\partial t}\varphi\left(b_g s_g+b_w s_w R_{sw}\right)_f \tag{5}$$

Where, b_g and b_w are the volumetric factor of the gas and water, respectively, m^3/m^3; S_g and S_w represent the gas and water saturation in the coal seam fracture system, respectively, kg/m^3; $\nabla\cdot$ is the divergence operator; ∇ is the gradient operator; R_{sw} represents the dissolved gas water ratio; Z is the elevation, m; q_g stands for the gas production, m^3; φ is the effective porosity, dimensionless; M_g and M_w represent the molar mass of the gas and water, respectively, g/mol; P_g and P_w are the gas and water pressure in the fracture system, respectively, MPa; and γ_g and γ_w represent the gas and aqueous phases, respectively, MPa/m.

The expression of water migration is as follows:

$$\nabla.\left[b_w M_w\left(\nabla p_w+\gamma_w \nabla Z\right)\right]_f+q_w$$
$$=\frac{\partial}{\partial t}\varphi\left(b_w s_w\right)_f \tag{6}$$

Where, q_w represents the water generation, m^3; and $M_n=k_f k_m/\mu_n$, n is the gas or water, a type of phase state mobility.

The matrix system desoption equation is as follows:

$$C(p)=V_L p/(p_L+p) \tag{7}$$

The following is the matrix system diffusion equation:

$$\partial V_m/\partial t=V_E\left(p_g\right)-V_m/\tau \tag{8}$$

The capillary pressure equation is as follows:

$$p_{cgw}=p_g-p_w \tag{9}$$

Eq. 10 is the saturation equation as shown below:

$$s_g+s_w=1.0 \tag{10}$$

The initial condition is as follows:

$$p_w\big|_{t=0}=p_i; s_g\big|_{t=0}=s_{gi}; s_w\big|_{t=0}=s_{wi}; V_m\big|_{t=0}=V_{mi} \tag{11}$$

Where, P_i is the original pressure of the coal cleat system, MPa; S_{wi} represents the original water saturation of the coal cleat system; S_{gi} is the original gas saturation of the coal cleat system; P_{cgw} represents the capillary pressure value, MPa; V_{mi} is the volume concentration of the raw gas in the coal matrix (standard), m^3/m^3; t is the coal-bed gas desorption time, s; and P is the average reservoir pressure, MPa.
In general, within the coal-bed gas reservoir numerical simulation in the constant pressure boundary, the constant bottom hole pressure (the well's dynamic liquid level position), gas and water production formula is as follows:

$$q_g=\frac{2a\pi k_f k_{rg}\Delta z\left(p_{fg}-p_{wf}\right)}{u_g b_g\left[\ln\left(r_e/r_w\right)+s\right]\Delta v}$$
$$q_w=\frac{2a\pi k_f k_{rw}\Delta z\left(p_{fw}-p_{wf}\right)}{u_w b_w\left[\ln\left(r_e/r_w\right)+s\right]\Delta v} \tag{12}$$

Where, Δz is the net thickness of the coal reservoir, m; a represents the unit conversion factor; P_{wf} is the bottom hole flowing pressure, MPa; P_{fw} represents the grid water pressure, MPa; P_{fg} is the grid gas pressure, MPa; Δv represents the unit cell volume; u_g is the gas viscosity, Pa.s; u_w is the water viscosity, Pa.s; s represents the skin factor; r_w is the wellbore radius, m; and r_e is the effective wellbore radius, m.

The expression of K_f and P_{wf} in the gas and aqueous phase production formula is as follows:

$$k_f = \sqrt{k_{fx}k_{fy}}\,,\, p_{wf} = 2\int_{p_0}^{p_{wf}} \frac{p_{wf}}{u_g z} dp_{wf} \tag{13}$$

Where, k_{fx} and k_{fy} represent the penetration of the cleat system in different directions, md; and z is the depth of the well head to the middle of the coal seam, m.

In the synthesis of the above basic equation, types (5) and (6) of the obtained gas and water contain the unknown variables Pg and Sg, which shift to Eqs. (14) and (15). The numerical simulation of the mathematical model of sorting out the unknown variables P_g and S_g, along with the back results in the change of reservoir pressure and gas saturation within the reservoir with the corresponding changes, can be used to solve the method and numerical simulation method, respectively. In the process, the coal-bed gas in P_g and S_g changes in value. This can be compared and analyzed in order to guide the production of the coal-bed gas well. However, the premise is that the other relevant basic parameters in the numerical model can be measured in the laboratory or through field drilling. Testing the well and other technical means can be used to obtain the case. Then, based on the derived equation of the gas and water transport, using the numerical simulation software COMET3, the two parameters can be used as independent variables in the simulation process. According to the changes of these two variables, the other variables can be derived as follows;

$$\begin{aligned}&\nabla.\left\{b_g\, k_f k_m/u_g\left[\nabla P_g+\gamma_g\nabla Z\right]+R_{sw}b_w\, k_f k_m/u_w\left[\nabla\left(P_g-P_{cgw}\right)+\gamma_w\nabla Z\right]\right\}_f \\ &+\alpha A_m D\left[C-V_L p/\left(p_L+p\right)\right]+a\frac{2\pi\sqrt{k_{fx}k_{fy}}k_{rg}\Delta z\left(p_{fg}-p_{wf}\right)}{u_g b_g\left(\ln\frac{r_e}{r_w}+s\right)\Delta v} \\ &=\frac{\partial}{\partial t}\left[\varphi b_g S_g+\varphi b_w R_{sw}\left(1-S_g\right)\right]_f\end{aligned} \tag{14}$$

$$\begin{aligned}&\nabla.\left\{b_w k_f k_m/u_w\left[\nabla\left(P_g-P_{cgw}\right)+\gamma_w\nabla Z\right]\right\} \\ &+a\frac{2\pi\sqrt{k_{fx}k_{fy}}k_{rw}\Delta Z\left(p_{fw}-p_{wf}\right)}{u_w b_w\left(\ln\frac{r_e}{r_w}+s\right)\Delta v} \\ &=\frac{\partial}{\partial t}\varphi\left[b_w\left(1-S_g\right)\right]_f\end{aligned} \tag{15}$$

4. Application of numerical simulation technology for coal-bed gas reservoirs in the Jincheng mining area

In the southern Qinshui Basin, the No. 15 coal of the Shanxi group and the No. 3 coal of the Taiyuan group have coal seams with large thicknesses and stable structure. This area is considered to be the most promising for coal-bed gas exploration and development in China. The depths of the coal seams buried deep in the formation of the Shanxi group are 500 and 600 m. The coal-bed thickness is between 5 and 7 m, with an average thickness of 6 m. The Taiyuan Coal Group No. 15 is a relatively stable seam, which is buried at between 450 and 600 m. The average thickness is 3 m, with a pressure coefficient of less than 0.8, and is classified as an under pressure coal reservoir. With the increase of the depth of coal seam mining, the reservoir pressure has shown a trend of further increase. The coal reservoir gas content has become higher, generally in the 10 to 20 m^3/t range, with low permeability in the reservoir, which is generally 0.1×10^{-3} to $6.7\times10^{-3}um^2$, and usually not more than $2\times10^{-3}um^2$. The coal reservoir heterogeneity is strong, with the addition to a small amount of large and middle holes. The pores of the coal seams contain very few large and middle-sized holes, and based on the micro hole and transition pores, the effective porosity ranges from 1.15 to 7.69%, and are usually not more than 5%. The numerical simulation of the coal-bed gas well production follows the steps of the numerical simulation of the oil and gas reservoir. This usually includes a model selection, data entry, sensitivity analysis, and the history and productivity prediction of five links.

In regards to the history matching and fitting choice of the southern Qinshui Basin #3 coal-bed gas wells, the influence of the parameter variation on the COMET3 simulation was analyzed. The actual data of the drainage for a 60-day period were selected. Coal seam #3 was objectively chosen, and the simulation area was defined as a 5.2 × 5.1 km^2 region with the well as the center, descartes coordinate grid simulation grid, a unit grid area of 100 m × 100 m, with a grid number of 50 × 50. Combined with the introduction of the geological model, the numerical simulation grid is as shown in Fig. 3. Also, combined with the southern Qinshui Basin, the actual coal reservoir and engineering parameters basic data set was as follows: the coal storage layer initial gas content was 17.85 m^3/t; crack initial water saturation was 1kg/m^3; coal reservoir temperature was 210℃; fracture porosity was 4.32; X, Y direction of the fracture permeability was 5.32 md; direction of Z was 0; Langmuir volume was 45.83 kg/m^3; Langmuir pressure was 3.32 MPa; methane adsorption was 10.24 days, not considering the capillary pressure and matrix shrinkage effect, and the gas was assumed to be a methane single component. Based on the above coal reservoir and engineering parameters, a simulation using the block center wells of the No. 3 coal-bed gas wells was conducted. The basic parameter data are shown in Tables 1 and 2.

Table 1. *Basic parameters of the #3 Jin well*

Parameter	*Thickness of coal seam/m*	*Coal seam temperature/℃*	*Adsorption time/d*	*Fracture water saturation /Kg.m^{-3}*	*Fracture porosity /%*	*Fracture permeability/md*		
						Kx	**Ky**	**Kz**
Numerical value	5.8	21	17.85	1	4.32	5.32	5.32	0

Table 1. *Basic parameters of the #3 Jin well (to be continued)*

Original pressure of coal seam/Mpa	*critical desorption pressure/Mpa*	*Original gas content in coal seam/m^3·t^1*	*Langmuir volume/kg·m^{-3}*	*Langmuir pressure/Mpa*
14.5	3.8	17.85	45.83	3.32

Table 2. *List of relative permeability*

Water saturation	*Relative permeability of water*	*Gas relative permeability*	*Water saturation*	*Relative permeability of water*	*Gas relative permeability*
0.45	0.00	0.95	0.75	0.25	0.28
0.50	0.04	0.87	0.80	0.36	0.20
0.55	0.06	0.75	0.85	0.48	0.15
0.60	0.09	0.59	0.90	0.60	0.10
0.65	0.13	0.48	0.95	0.76	0.05
0.70	0.18	0.37	1.00	0.94	0.02

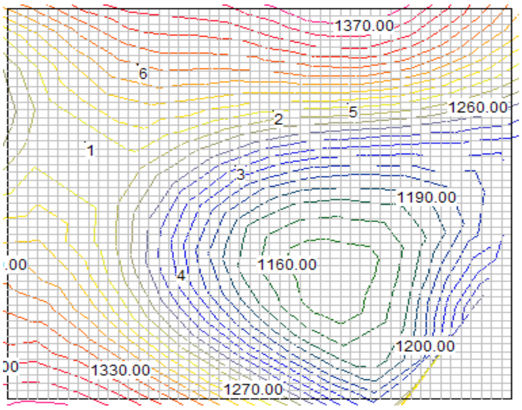

Fig. 3 *Mesh divided during the numerical simulation based on the geological model*

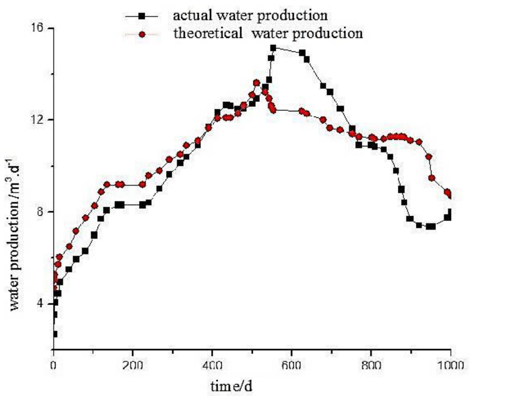

Fig. 4 *History matching graph of the daily water production of the #3 Jin well*

4.1. History matching of the gas and water production

The southern Qinshui #3 well's actual production history was matched with the historical daily gas and water production data. According to the base curve and analog output 2D graphical results, as well as the later adjustment of the coal seam gas row mining process in the absolute permeability of the fracture, the fracture porosity and adsorption time of the gas-water relative permeability of coal reservoir layer's basic and engineering parameters were obtained. On the basis of these, the history fitting curve of the actual drainage of the coal-bed gas wells, and the fitting results were obtained, as shown in Figs. 4 and 5:

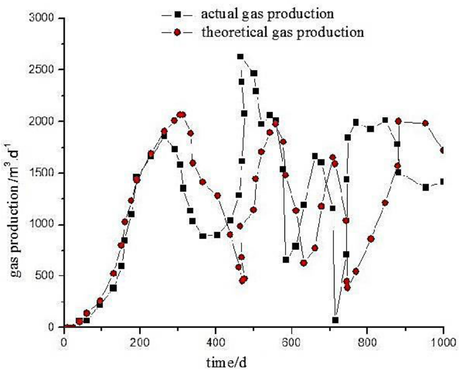

Fig. 5 *History matching graph of the daily gas production of the #3 Jin well*

The following results could be seen from the historical fitting: there were constant adjustments in the layer gas drainage process parameters, based the fracture permeability, fracture porosity, adsorption time, and so on. Therefore, the measured and simulated curves were as close as possible for the improvement of the fitting of the precision values. The coal-bed gas wells fitting result was improved after the completion of the trial mining period. In the cases of the coal reservoir experiencing saturation, with the decline in the coal seam near the wellbore pressure, the coal-bed gas desorption had not yet started. During the process of producing only water output for 40 days, as seen through the fitting chart, with the further decline of the reservoir pressure, and the coal-bed gas desorption from the surface of the pore, the coal bed gas production began to gradually increase during the first stage. Therefore, the gas production was well fitted, and the simulations were more reasonable.

4.2. Coal reservoir parameter analysis

Following the successful matching of the historical data, the simulation operation recorded the dynamic change characteristics of the coal reservoir parameters during the course of the historical mining. The COMET3 output coal reservoir pressure dynamic characteristic change plan was used, as shown in Fig. 6.

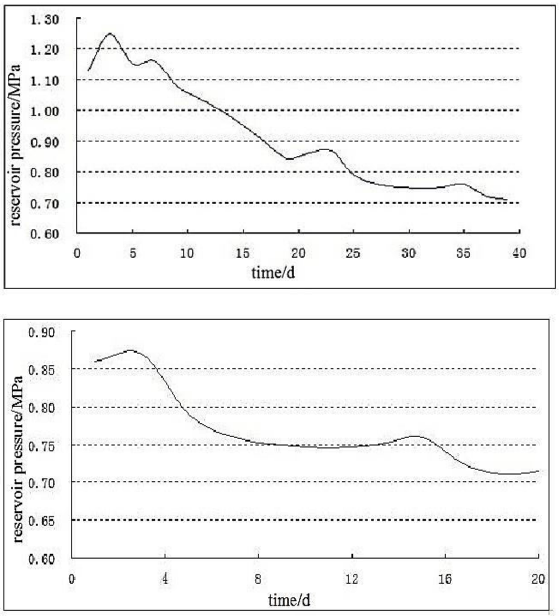

***Fig. 6** Simulation output of the dynamic changes in the coal reservoir pressure*

In the parameter correction calculation following the identification, during the 60-day testing of the trial mining coal reservoir parameters, the well had been in a state of dynamic change. As shown in Fig. 6, the process changes during the 60 days of production could be divided into two different stages. The first stage was the production process up to 40 days. It can be seen in the first phase diagram that, although the reservoir pressure around the wellbore began to decline due to the critical desorption pressure being lower than the reservoir pressure during the period up to 40 days, the water output of the coal-bed gas desorption had not yet started. Also, the single phase flow of the water near the wellbore, as well as the pressure around the wellbore, had only slightly changed. After 40 days, the production began to enter the second phase, and the simulation process began to produce gas. As can be seen from the second phase variations shown in Fig. 6, the critical desorption pressure of the coal-bed gas was higher than the reservoir pressure. The desorption of the coal-bed gas started from the pore surface, and spread to the fracture system. Following 60 days of production, as shown in the second phase of the simulation plane illustrated in Fig. 6, it can be seen that the pressure changes around the wellbore were larger. The dynamic variation characteristics of the gas saturation in the coal reservoir is shown in Fig. 7.

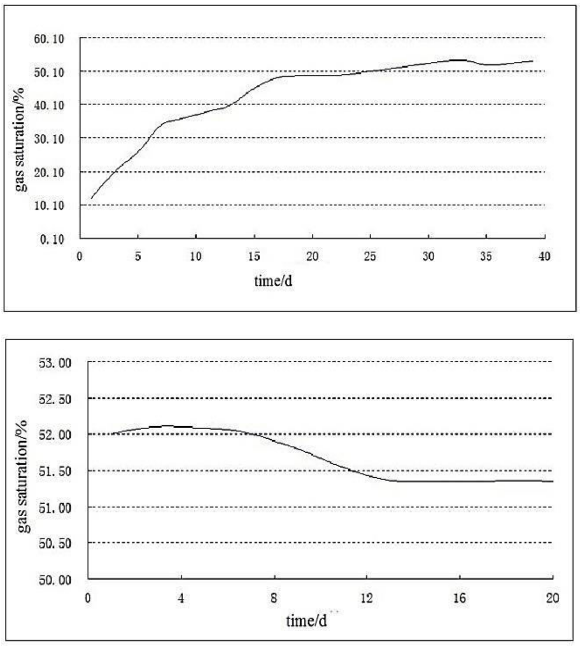

***Fig. 7** Simulation output of the dynamic changes in the coal reservoir gas saturation*

Also, as shown in Fig. 7, the coal-bed gas saturation value during all the stages of the production had been in a dynamic state. From the two different stages of the mining process shown in Fig. 7, it can be seen that the variations of the production values for the 40-day period were significantly less than the value of the production after the 40-day period. Through the analysis of the simulation results, the following could be concluded: During the test production during the period of up to 40 days, the wellbore experienced only water output. This was the first stage of the output coal-bed gas single-phase water flow stage, and the amount of coal-bed gas desorption increased while the production test was conducted. The coal-bed gas reservoirs around the wellbore saturation value showed an increasing trend, and the coal-bed gas production was gradually transitioning to the second stage of the output of coal-bed gas, or the non-saturated water flow stage. As the production continued, the output of the coal-bed gas entered the stage of a gas and water two-phase flow, and it was expected in the next period of time that the production of coal-bed gas wells would enter a stage of stability and high yield, which would be maintained for a long period of time.

5. Conclusions

In this study, the #3 coal-bed gas well of the southern Qinshui Basin was set as an example. Based on the analysis of the mechanism of the coal-bed gas flow, and by using the coal-bed gas and water movement in the double-porosity single-permeability model, which was combined with the basic equation of the flow mechanism, a set of mathematical models describing the actual migration of the coal-bed gas was set up. This was used to guide the entire process of coal-bed gas well production. The following conclusions could be drawn from the results:

(1) In this study, a mathematical model was set up to meet the actual migration of the coal-bed gas, based on the principle of coal-bed gas well production, along with the analysis of the process of coal-bed gas well output desorption, diffusion, and percolation, and based on a double-single permeability model combined with the basic equation of the coal-bed gas flow mechanism. Then, derived from the case of the gas and water transport equation with the two unknown variables P_g and S_g, and when the relevant parameters were known, the equation was able achieve a solution.

(2) Using the historical data of the testing in a coal-bed gas well, and based on the basic equation of a coal-bed gas flow mechanism, a drainage hole seepage model with a single permeability was used. Then, the COMET3 reservoir simulation software test data of history fitting analyzed the production process of the reservoir parameters and dynamic characteristics. The results showed that the 40-day period following the production of the coal reservoir exceeded the critical desorption reservoir pressure, and a large amount of coal-bed gas began to be desorbed and transported into the output near the wellbore. The coal-bed gas production moved from a single-phase flow of water to a transition phase, and then to an unsaturated water phase.

(3) For the transportation of coal-bed gas, and the production of a coal-bed gas shift model simulation involving coal reservoir and engineering parameters, reasonable mathematical and geological models need to be established in order improve the accuracy of the simulation, and to also provide technical support and theoretical guidance for the reasonable drainage of coal-bed gas wells.

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