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Research Article

Productivity Prediction Research of Fractured Horizontal Wells for Low Permeability Gas Reservoirs

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Abstract: In order to effectually resolve the problems as embarrassing solving and cumbersome calculation in design and simulation of hydraulic fracturing in coal petrography, the productivity prediction analysis software of horizontal wells has been developed in this study based on the object-oriented visual programming environment. The analysis software can determine the rock mechanics parameters, the distribution of crustal stress and the coalbed methane production, which can greatly improve the work efficiency of the engineering staff. The software has better applicability and can provide a foundation for the analysis of CBM productivity prediction. The results show that: simulation analysis is of high precision, can satisfy the actual engineering needs. Fracture number and half-length have a greater impact on fracturing horizontal well production; moreover, crack width almost has no influence on production.

Keywords: Fracture geometry parameters, fractured horizontal well, low permeability gas reservoir, production prediction, seepage near-wellbore

INTRODUCTION

The permeability of coal seams in China is low with mostly less than 50 mD. Almost all coalbed methane wells with the gas production above 1000 m^3/d are reformed by hydraulic fracturing during the past 20 years of coalbed methane exploration and development process (Archer and Roland, 2001). Hydraulic fracturing can effectively ameliorate flow channel, improve coal rock diverting capacity and increase productivity, which has become the effective measure of CBM exploration. Moreover, it has caused universal attention and special research of domestic and foreign experts and scholars. The cracks of hydraulic fracturing are closely related to the strata structure, rock mechanics property and ground stress (Clarkson *et al*., 2011; Keim *et al*., 2011). Fracturing crack simulation analysis belongs to an important subject of hydraulic fracturing technology research field. Meanwhile, the fracturing effect is directly related to the production capacity of coalbed methane well (Maricic *et al*., 2008). Economic and effective fracturing should connect mutual-disconnected cracks in the original fractures, broaden the original cracks and effectively accelerate the pressure decrease and transmission during the process of discharge and mining, so as to achieve the purpose of efficient production. In case of hydraulic fracturing operation failure, it will cause the destruction of coal seam pressure system, the abandon of coalbed methane well and significant economic loss. Therefore, hydraulic fracturing crack simulation analysis has become the key problem on coal rock fracture design, construction and production forecast.

This study analyzes CBM horizontal well production and studies sensitive factors. The results can not only provide the fundamental basis for resource evaluation and fracturing stimulation plans, but also have important practical significances for exploration and development of coalbed methane wells.

THEORETICAL BASES

Mechanical parameters: Coal seam is quite different from conventional sandstone reservoir with complex physical and mechanical properties, which has many crack and pore systems of a high degree of uncertainty. Therefore, coal reservoir physical and mechanical parameters on hydraulic fracturing of coal rock have always been one of the hottest issues in the international engineering research. It can not only provide references for productivity prediction after hydraulic fracturing, but also be the most important information on the destruction rule of coal rock strain and stress.

- **Elasticity modulus:** Elastic modulus is an important performance parameter in engineering, can be considered as measure index of rock to

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produce elastic deformation. The bigger the value is, the greater the stress to have elastic deformation:

$$E = \left(\frac{\rho}{\Delta t_s^2}\right)\left(\frac{3\Delta t_s^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}\right) \tag{1}$$

- **Poisson's ratio:** It is the elastic constant of rock deformation. Different rock materials have quite different values of Poisson's ratio. Poisson's ratio plays an important role on crack size, which is also the important parameter of confirming vertical fracture pressure:

$$\nu = \frac{1}{2}\left(\frac{\Delta t_s^2 - 2\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}\right) \tag{2}$$

- **Shear modulus:** It stands for the rock's ability to resist shear strain. The greater the rock, the more difficult it is to produce shear deformation:

$$G = \frac{\rho}{\Delta t_s^2} \tag{3}$$

- **Bulk modulus:** It can be defined as the pressure required producing unit relative volume contraction:

$$K = \rho\left(\frac{3\Delta t_s^2 - 4\Delta t_p^2}{3\Delta t_s^2 \Delta t_p^2}\right) \tag{4}$$

where,
E = Elasticity modulus, MPa
ρ = For rock density, kg/m^3
Δt_s = Transverse wave offset time, $\mu s/m$
Δt_p = Longitudinal wave offset time, $\mu s/m$
ν = For Poisson's ratio
G = Shear elasticity, MPa
K = Bulk modulus, MPa

Layered ground stress model: Three assumptions are used in the model, namely:

- The far field pore pressure value is constant
- The stratum is linear porous elastomer
- The lateral strain is zero:

$$\begin{cases} \sigma_v = \int_0^H \rho(h)gdh + p + \frac{\nu}{1-\nu}\sigma_{gH\max} + \frac{\alpha E(T-T_0)}{1-2\nu} \\ \sigma_h = \frac{\nu}{1-\nu}\int_0^H \rho(h)gdh + p + \frac{\nu}{1-\nu}\sigma_{gH\max} + \frac{\alpha E(T-T_0)}{1-2\nu} \\ \sigma_H = \frac{\nu}{1-\nu}\int_0^H \rho(h)gdh + p + \sigma_{gH\max} + \frac{\alpha E(T-T_0)}{1-2\nu} \end{cases} \tag{5}$$

where,
H = The vertical depth, m
g = The gravity acceleration, m/s^2

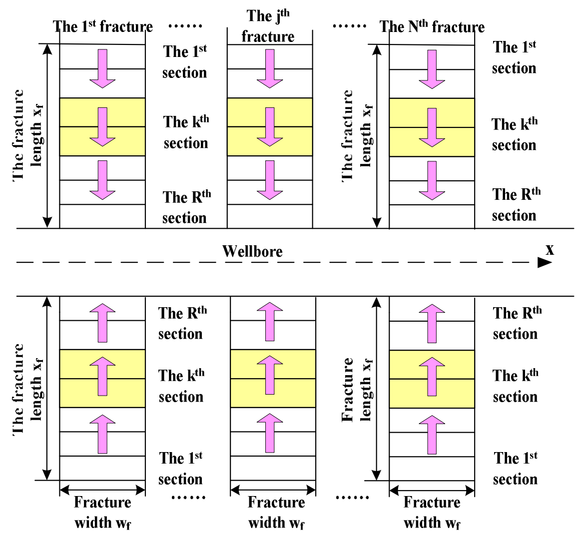

Fig. 1: Diagram of fracture segmentation parameters

σ_v, σ_h, σ_H = The vertical stress, horizontal minimum and maximum principal stresses respectively, MPa
T, T_0 = The original temperature and formation temperature in production process, K
α = The linear expansion coefficient, 1/K
p = Formation pore pressure, MPa
$\sigma_{gH\max}$ = The maximum horizontal constitution stress, MPa

Seepage near-wellbore and productivity prediction model: It has the following assumptions:

- Fluid is single-phase and incompressible Newtonian fluid; the flow of the whole system is an isothermal process.
- Fractured horizontal well only goes through one reservoir with the same thickness.
- Cracks distribute symmetrically by horizontal wellbore, the fracture height is the thickness of reservoir.

Assume that the production length of fractured horizontal well is L, which can be divided into M parts with ΔL of each section. The half-length of crack is x_f which can be divided into R parts (number from crack tip to wellbore) with Δx_f of each section. Fracture section parameter diagram is shown in Fig. 1. The flows in each infinitesimal horizontal section and infinitesimal rectangular crack are infinite diversion with uniform flow distribution. Each micro horizontal well section or micro crack can be equivalent to a vertical well.
Equivalent borehole diameter of infinitesimal crack:

$$r_{wf,jk} = 0.223\Delta x_f \tag{6}$$

Equivalent borehole diameter of infinitesimal horizontal well section:

$$r_{we,i} = \Delta L \cdot \exp\left\{-1.75 + \frac{h\beta}{\Delta L}\ln\left[\frac{\pi r_w}{h}(1+\beta)\sin\frac{\pi z_{w,i}}{h}\right] + \frac{2\beta^2 h^2}{\Delta L^2}\left(\frac{1}{3} - \frac{z_{w,i}}{h} + \frac{z_{w,i}^2}{h^2}\right)\right\} \quad (7)$$

According to the theory of potential superimposition, the potential of any point $W(x, y, z)$ can be written as below:

$$\Phi(x,y,z) = \frac{1}{4\pi\Delta L}\sum_{i=1}^{M}(q_{w,i}\ln r_{we,i}) + \sum_{j=1}^{N}\left[\frac{1}{4\pi\Delta x_f}\sum_{k=1}^{2R}(q_{f,jk}\ln r_{wf,jk})\right] + C \quad (8)$$

where, $r_{wf,\,jk}$ is the equivalent borehole diameter of the k^{th} infinitesimal section of the jth crack, m; $r_{we,\,i}$ stands for the equivalent borehole diameter of the i^{th} infinitesimal section of horizontal well, m; h is the thickness of coal seam, m; β stands for coefficient of permeability anisotropy; r_w is the wellbore diameter, m; $z_{w,\,i}$ is the distance between the i^{th} infinitesimal section and coal seam bottom, m; N is the crack number; $q_{w,\,i}$ stands for production per unit length of the i^{th} infinitesimal section, $m^3/d/m$; $q_{f,\,jk}$ is the flow rate per unit length of the k^{th} infinitesimal section of the j^{th} crack, $m^3/d/m$; C is undetermined constant, MPa.

Taking special points along the equivalent vertical sidewall and the supply boundary, the relations between bottom-hole pressure and flow rate are:

$$p_e - p_{wr,i} = \frac{\mu}{2\pi hk}\left[\sum_{i=1}^{M}\Delta L q_{w,i}\ln\frac{r_e}{r_{wa,wi}} + \sum_{j=1}^{N}\sum_{k=1}^{2R}\Delta x_f q_{f,jk}\ln\frac{r_e}{r_{fjk,wi}}\right] \quad (9)$$

$$p_e - p_{fr,jk} = \frac{\mu}{2\pi hk}\left[\sum_{i=1}^{M}\Delta L q_{w,i}\ln\frac{r_e}{r_{wi,fjk}} + \sum_{j=1}^{N}\sum_{k=1}^{2R}\Delta x_f q_{f,jk}\ln\frac{r_e}{r_{fst,fjk}}\right] \quad (10)$$

where, $p_{wr,\,i}$ is casing pressure of the i^{th} infinitesimal section along the horizontal well, MPa; μ is fluid viscosity, mPa.s; k stands for reservoir permeability, mD; r_e is reservoir supply radius, m; $r_{wa,\,wi}$ is the distance between the centre of the i^{th} infinitesimal section and the a^{th} infinitesimal section along the wellbore, m; $p_{fr,\,jk}$ is casing pressure of the k^{th} infinitesimal section of the j^{th} crack, MPa; $r_{fjk,\,wi}$ is the distance between the centre of the i^{th} infinitesimal well section and the centre of the k^{th} infinitesimal section of the j^{th} crack, m; $r_{wi,\,fjk}$ is the distance between the centre of the k^{th} infinitesimal section of the j^{th} crack and the centre of the i^{th} infinitesimal well section, m; $r_{fst.\,fjk}$ stands for the distance between the centre of the k^{th} infinitesimal section of the j^{th} crack and the centre of the t^{th} infinitesimal section of the s^{th} crack, m.

When the fracture fluids go towards the wellbore, the flow can be treated as one dimensional linear flow. The pressure drop of the k^{th} infinitesimal section of the j^{th} crack can be written as:

$$\Delta p_{f,jk} = \frac{\Delta x_f \mu q_{ft,jk}}{k_f w_f h} \quad (k < R) \quad (11)$$

$$\Delta p_{f,jk} = \frac{\Delta x_f \mu q_{ft,jk}}{2k_f w_f h} \quad (k = R) \quad (12)$$

where,

k_f = Fracture permeability, mD
w_f = For fracture width, m
$q_{ft,\,jk}$ = The section flow rate of the k^{th} infinitesimal section of the j^{th} crack, m^3/d

Based on the momentum and mass conservation principle, the pressure drop of the i^{th} infinitesimal section of the fractured horizontal well is:

$$\Delta p_{w,i} = \left(\frac{32\rho_i q_{w,i} q_{wt,i}}{\pi^2 D^4} + \frac{32\rho_i f_{t,i}}{\pi^2 D^5}q_{wt,i}^2 + \rho_i g\cos\theta_i\right)\Delta L \quad (13)$$

Where, $\Delta p_{w,\,i}$ is the pressure drop of the i^{th} infinitesimal section of fractured horizontal well, MPa; ρ_i stands for mixed fluid density of the i^{th} infinitesimal section along the horizontal well, kg/m^3; $q_{wt,\,i}$ is the section flow rate of the i^{th} infinitesimal section of horizontal well, m^3/d; D is the wellbore diameter, m; θ_i is the hole deviation angle of the i^{th} infinitesimal section of horizontal well,^{o}; $f_{t,i}$ is the friction coefficient between the i^{th} infinitesimal section of horizontal well and pipe wall; g is gravitational acceleration, m/s^2.

According to the pressure continuous principle, the pressure of fluid flow at the wellbore in the reservoir should be equal to the pressure at the wellbore in the borehole, furthermore, the pressure of fluid flow at crack wall in the reservoir should be equal to the pressure of fluid flow at crack wall in the crack. Therefore, we can obtain CBM horizontal well production prediction model.

ANALYSIS OF COMPUTING RESULTS

We take L7 well of Shengli oil field to illustrate the application of the software. The block has medium coal rank with buried depth of 420 m. Three-dimensional wellbore trajectory is shown in Fig. 2 with the horizontal length of 470 m. The basic parameters of stratum and L7 well are written in Table 1; moreover, the basic parameters of cracks are shown in Table 2.

Table 1: Basic parameters of stratum and L7 well

Effective thickness/m	8	Horizontal length/m	470
Permeability/mD	0.4	Gas drainage radius/m	220
Supply pressure/MPa	5.6	Gas viscosity/(mPa·s)	0.012
Flowing bottom hole pressure/MPa	0.7	Formation temperature/°C	80
Wellbore radius/m	0.1	Distance to the bottom of formation/m	4
Anisotropy coefficient	1/3	Wall relative roughness	0.01

Table 2: Basic parameters of crack

Fracture number	3	Fracture width/m	0.005
Fracture half-length/m	65	Fracture permeability /mD	112

Table 3: Calculation result list of production and fracture number

Fracture number	2	3	4	5	6	7
Production/(m^3/d)	1301.196	1956.412	2596.408	3219.188	3824.755	4413.947

Table 4: Calculation result list of production and fracture half-length

Fracture half-length/m	50	65	80	95	110	125
Production/(m^3/d)	1539.888	1956.412	2354.594	2735.690	3100.838	3451.073

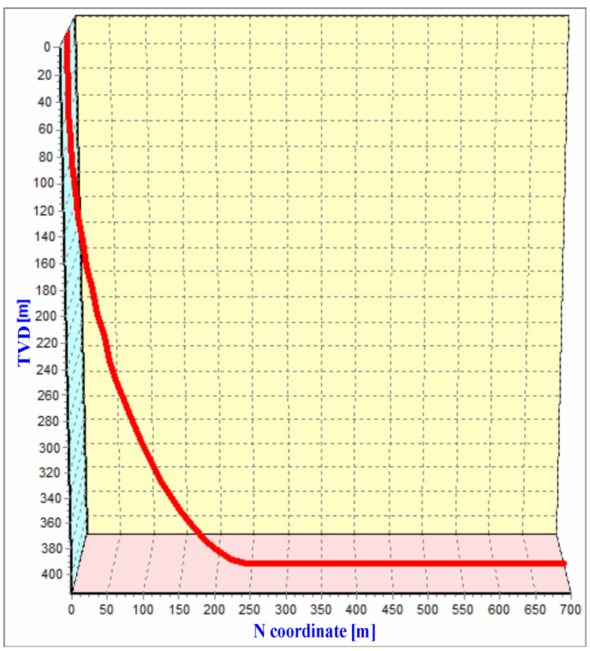

Fig. 2: Wellbore trajectory graph

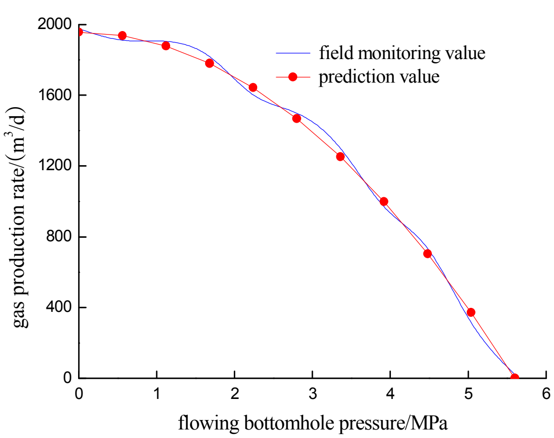

Fig. 3: The comparison diagram of prediction production and monitoring value

Under the condition of different bottom hole flowing pressures, the comparison diagram of prediction production of L7 fractured horizontal well and the monitoring value is shown in Fig. 3. Prediction results are in good agreement with field monitoring value with the average error around 7%, which can meet the engineering accuracy requirements.

The following studies the effects of fracture parameters on fractured horizontal well production.

Fracture number: Taking the values in Table 1 and 2 as the basic parameters, the results are shown in Table 3 when well bottom pressure difference of 2.8 MPa. With the increasing of fracture number, coalbed methane production of fractured horizontal well improves gradually. Crack number has a great influence on production.

Fracture half-length: Coalbed methane production increases with crack half-length increasing. Based on production well bottom hole flowing pressure of 2.8 MPa, Production and fracture half-length relationship table is shown in Table 4. Coalbed methane production increases from 1154.916 m^3/d to 1467.309 m^3/d when crack half-length increases from 50 m to 65 m with a raise of 27.05%. The production increases from 2051.768 m^3/d to 2325.629 m^3/d when crack half-length increases from 95 m to 110 m with a raise of 13.35%. Fracture half-length has a great influence on fractured well production.

Fracture width: With the change of well bottom flowing pressure, fractured horizontal well production value list is shown in Table 5.

Based on Table 5, the production increases with increasing fracture width, but the rise is small. Based on production well bottom flowing pressure of 2.8 MPa, coalbed methane production increases from 1467.309 m^3/d to 1509.922 m^3/d when crack width increases from 5 mm to 10 mm with a raise of 2.9%. The

Table 5: Calculation result list of production and fracture width

Bottom hole flowing pressure/MPa	Pressure difference/MPa	Production/(m^3/d) Fracture width 5 mm	Fracture width 10 mm	Fracture width 15 mm	Fracture width 20 mm	Fracture width 25 mm	Fracture width 30 mm
0.000	5.600	1956.412	2013.229	2041.977	2060.993	2075.076	2086.078
0.560	5.040	1936.848	1993.097	2021.557	2040.383	2054.325	2065.217
1.120	4.480	1878.155	1932.700	1960.298	1978.553	1992.073	2002.635
1.680	3.920	1780.335	1832.038	1858.199	1875.504	1888.319	1898.331
2.240	3.360	1643.386	1691.112	1715.261	1731.234	1743.063	1752.306
2.800	2.800	1467.309	1509.922	1531.483	1545.745	1556.307	1564.559
3.360	2.240	1252.104	1288.466	1306.865	1319.036	1328.048	1335.090
3.920	1.680	997.770	1026.747	1041.408	1051.106	1058.288	1063.900
4.480	1.120	704.308	724.762	735.112	741.958	747.027	750.988
5.040	0.560	371.718	382.514	387.976	391.589	394.264	396.355
5.600	0.000	0.000	0.000	0.000	0.000	0.000	0.000

production increases from 1531.483 m^3/d to 1545.745 m^3/d when crack width increases from 15 mm to 20 mm with a raise of 0.93%. Above all, crack width has no obvious effect on improving fractured horizontal well production.

CONCLUSION

- According to the example of L7 well, the results indicate that the results simulated by the software basically coincide the measuring value with the average error of 7%. The software has better applicability and can provide a foundation for the analysis of CBM productivity prediction.
- Fracture number and fracture half-length have a greater influence on the production of fractured horizontal well. However, crack width has no obvious effect on improving fractured horizontal well production. In order to improve horizontal well production, we should increase fracture number and fracture half-length.

REFERENCES

Archer, R.A. and H.N. Roland, 2001. The Green element method for numerical test analysis. Proceeding of the Annual Technical Conference and Exhibition. October 1-4, 2000, Dallas, Texas, pp: 9.

Clarkson, C.R., M. Rahmanian and A. Kantzas, 2011. Relative permeability of CBM reservoirs: Controls on curve shape. Int. J. Coal Geol., 88(4): 204-217.

Keim, S.A., K.D. Luxbacher and M. Karmis, 2011. A numerical study on optimization of multilateral horizontal wellbore patterns for coalbed methane production in Southern Shanxi Province, China. Int. J. Oil Gas Coal Technol., 86(4): 306-317.

Maricic, N., S.D. Mohaghegh and E. Artun, 2008. A parametric study on the benefits of drilling horizontal and multilateral wells in coalbed methane reservoirs. Reserv. Eval. Eng., 11(6): 976-983.