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Sensitivity analysis on borehole effective extraction radius variation based on multiple linear regression model

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Abstract

To investigate effects of multiple factors on effective extraction radius of gas drainage borehole, a mathematical gas-solid coupling model is developed. Impacts of original gas pressure, borehole diameter, extraction time and initial coal permeability on effective extraction radius are qualitatively studied by adopting Comsol Multiphysics analysis. Furthermore, with the effective extraction radius as index, orthogonal experimental design analysis on multiple factors' effects is conducted. Quantitative multiple linear regression model between effective extraction radius and each influencing factor is established by using SPSS method, with fitted correlation coefficient being 0.858. Extreme difference analysis and multiple regression analysis show that the significance of factors' effects on effective extraction radius could be ranked as (from largest to smallest): initial coal permeability, original gas pressure, borehole diameter. There is no multicollinearity. Meanwhile, the distribution of residuals is normal, indicating that the constructed multiple linear regression model has good validity and reliability, which could provide references for gas extraction borehole design and real-time optimization of gas extraction parameters.

Keywords: Multiple linear regression model; Effective extraction radius; Sensitivity analysis; Coal permeability

1. Introduction

Coal resource plays an important role in world's industrial energy development[1]. It accounts for the majority in many countries' energy structure[2, 3]. Coal seam gas is a clean gas stored in coal. Large amount of coal seams have low permeability, thus are difficult for gas extraction, which poses a serious threat to mine safety and production. Gas-related incidents are irreversible and cause huge damage[4]. The most effective way to control gas-related hazards is gas extraction[5]. Gas extraction could not only reduce mining hazards but also enable the use of clean resource, as well as reduce greenhouse gas emissions[6, 7]. In gas extraction practice, effective extraction radius is a significant parameter which could accurately reflect effectiveness of extraction.

In recent years, related researchers have conducted many investigations on gas extraction using boreholes. Chen et al[8] studied effect of different numbers of boreholes on coal seam gas pressure change and effective extraction area by using a 3D numerical simulation method. Sun et al[9] analyzed advantages and disadvantages of current methods for testing the effective extraction radius of boreholes. They proposed a combination method of actual measurement and simulation to accurately determine effective extraction radius of in-seam boreholes. Li et al[10] carried out a study on evolutionary characteristics of surrounding plastic zone during drilling boreholes with different diameters. Liu et al[11] simulated effects of negative pressure, borehole diameter and borehole length on effective extraction radius of directional long boreholes by establishing a coal-gas coupling model considering Klinkenberg effect. Fang et al[12]further explored the differences in gas pressure distribution and factors affecting effective extraction radius by adopting Hudi

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coal mine in Qinshui basin as a research object. Yang et al[13] proposed a gas extraction radius determination method combining pressure drop method and gas flow method, as a response to insufficient gas extraction radius issue under complex conditions. Liu et al[14] used gas pressure variations at monitoring points around borehole to reflect degree of disturbance between boreholes and to determine most efficient drilling arrangement pattern for gas extraction. Zou et al[15] combined theoretical derivation and numerical simulation to obtain effective extraction radius. At the same time, they conducted field measurements to verify theoretical result. Liu et al[16] proposed a new effective extraction radius determination index for slotted boreholes. They verified the reliability and validity of this method by examining extraction index and residual gas content in coal. Du et al[17] studied gas migration characteristics in gas-bearing coal, and established a coupling gas flow model based on regarding coal as pore-fracture dual medium. The purpose is to reasonably arrange gas extraction boreholes to improve drainage efficiency.

It could be seen that many previous studies focus on effect of a single factor on gas extraction performance. Synergistic impacts of multiple factors on gas extraction needs to be further quantitatively determined. In this study, based on gas-solid coupling model and COMSOL software, gas extraction process is analyzed. Through combining orthogonal experimental design and SPSS analysis method, influence of multi-factor interaction on effective extraction radius is studied, including significance of influence of each factor. A multiple linear regression model between effective extraction radius and multiple factors is developed. Research results are expected to provide reference for design of gas extraction boreholes in coal mines.

2. Theoretical fundamentals

2.1. Coal deformation control equation

Regarding coal as matrix-fracture media, the effective stress law is introduced[18], which could be expressed as:

$$\sigma_{ij}^{e} = \sigma_{ij} - \left(\beta_f p_f + \beta_m p_m\right)\delta_{ij} - k\varepsilon_s \ldots\ldots..(1)$$

Where, σ_{ij}^{e} is effective stress (MPa), σij is regarded as total stress (tensile one being as positive direction), δ_{ij} is Kronecker delta tensor, p_f is fracture gas pressure (MPa), p_m is matrix gas pressure (MPa), K is bulk modulus MPa, $K=E/3(1-2v)$, ε_s is the ultimate adsorption strain, $\varepsilon_s=\varepsilon_L p_m/(P_L+p_m)$. ε_L is Langmuir volume strain constant. β_f and β_m is the Biot effective stress coefficient corresponding to fractures and pores, respectively[19]. β_f and β_m are as follows:

$$\beta_f = 1 - \frac{K}{K_m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

$$\beta_m = \frac{K}{K_m} - \frac{K}{K_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3)$$

Where, Km, Ks are bulk modulus of coal matrix and bulk modulus of coal skeleton, MPa, $Km=Em/3(1-2v)$, $Ks=Km/[1-3\phi m(1-v)/2(1-2v)]$; Em is elastic modulus of coal matrix, MPa; ϕm is matrix porosity.

Simultaneous equations (1) (2) (3), we could obtain:

$$Gu_{i,ji} + \frac{G}{1-2v}u_{j,ji} - \beta_f p_{f,i} - \beta_m p_{m,i} - K\varepsilon_s + F_i = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(4)$$

Where, G is shear modulus MPa, G = E / 2 (1 + v), E is elastic modulus of coal, MPa; v is Poisson's ratio; F_i is volume force, MPa; u_i， u_j (j = 1,2,3) is displacement component, m.

2.2. Gas diffusion equation

In gas extraction process, the dynamic balance of gas pressure in coal seam is constantly broken. Difference of gas migration velocity between fracture and matrix system causes matrix gas pressure being greater than fracture gas pressure. Matrix gas diffuses into the fracture system[19]:

$$Q_s = \mathrm{D}\sigma_c(c_m - \rho_g) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

Where, Q_s is gas diffusion flux per unit volume of coal matrix, kg/(m^3·s), D is diffusion coefficient, m^2 /s, σ_c is matrix shape factor, m^{-2}; c_m is matrix gas density, kg/m^3;ρ_g is fracture gas density, kg/m^3.

According to ideal gas state equation, it could be obtained:

$$c_m = \frac{M_c}{RT} p_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$p_g = \frac{M_c}{RT} p_f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$M_c$is molar mass of methane (kg/mol), while R is universal gas constant (J / (mol · K)).

The total amount of gas stored in unit coal matrix volume is

$$m_m = \frac{V_L p_m}{p_{m+P_L}} \rho_c \rho_{gs} + \phi_m \frac{M_C}{RT} P_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$\rho_{gs} = \frac{M_c}{V_M} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

According to the law of conservation of mass:

$$\frac{\partial m_m}{\partial \mathrm{t}} = -\frac{M_c \sigma_c D}{RT} \left(p_m - p_f\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Control equation of dynamic change of adsorbed gas pressure in matrix could be obtained by simultaneous equations (8), (9), (10) :

$$\frac{\partial p_m}{\partial \mathrm{t}} = -\frac{V_M \sigma_c D\left(p_m - p_f\right)(p_m + p_L)^2}{V_L RT \rho_c + \phi_m V_M (p_m + P_L)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

2.3. Gas seepage equation

After borehole extraction breaks balance of gas pressure in coal seam, gas in the matrix enters fracture system through diffusion. For unit volume of coal, according to law of conservation of mass[20], it could be obtained:

$$\rho \frac{\partial}{\partial \mathrm{t}}(\phi_f \rho_g) = -\nabla(\rho_g V) + Q_s(1 - \phi_f) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where, V is gas seepage velocity in fracture, which conforms to Darcy's law. After balance of coal seam gas pressure is broken, control equation of dynamic change of fracture-free gas pressure is as follows[21].

$$\phi_f \frac{\partial p_f}{\partial \mathrm{t}} + p_f \frac{\partial \phi_f}{\partial \mathrm{t}} = \nabla\left(\frac{k_e}{\mu} p_f \nabla p_f\right) + \sigma_c D (1 - \phi_f)(p_m - p_f) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

2.4. Equations of porosity and permeability

For coal being matrix-fracture duplex medium, dual-pore poroelastic theory[22-24] is more applicable to study change of fracture porosity with effective stress [21].

$$\frac{\phi_f}{\phi_{f0}} = 1 + \frac{1}{M \phi_{f0}} \left[\beta_f\left(p_f - p_{f0}\right) + \beta_m (p_m - p_{m0})\right] + \frac{\varepsilon_L}{\phi_{f0}}\left(\frac{K}{M} - 1\right)\left(\frac{p_m}{P_L + P_m} - \frac{p_{m0}}{P_L + p_{m0}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Relationship between permeability and fracture porosity of coal conforms to cubic law[25]:

$$\frac{k}{k_0} = \left\{\frac{\phi_f}{\phi_{f0}}\right\}^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Where, $k_0$is the initial permeability of coal, m²; k is absolute permeability of coal, m².

3. Numerical model establishment

According to parameters of targeted coal seam, a two-dimensional geometric model with a size of 40m ×35m is established. Thickness of the coal seam is 5m. A gas extraction borehole is drilled in the middle of model. Borehole diameter is 94mm, as shown in Fig. 1. Bottom of the model is a fixed boundary, while the whole model could subside. Boundary on the left and right sides are roller support. The top is the constant load boundary, with overlying load being 18 MPa. In the initial conditions, coal seam is in free stress state. All external boundaries of the model are non-permeable boundaries for gas. Model grid includes 1431 domain units and 105 boundary units. Grid division around the borehole is dense, while grid division in other areas is relatively sparse. Initial coal porosity is 0.06. Gas density is 0.716kg/m³. Dynamic viscosity of gas is 1.8×10^{-5} Pa·s. Roadway boundary pressure is 0.1013MPa while the negative pressure of extraction is 13 kPa.

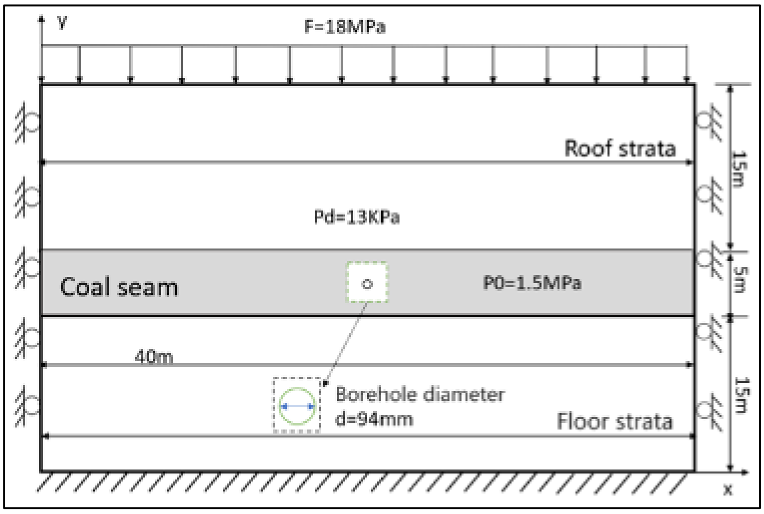

Figure 1 Numerical simulation model

4. Results analysis and discussion

According to prediction method of coal and gas outburst threat area (GB/T25216-2010), the critical value of gas pressure for judging whether coal seam has outburst danger is 0.74 MPa. Therefore, during gas extraction, the area with gas pressure being smaller than 0.74 MPa is regarded as effective extraction area. In addition, for coal seams with original gas pressure less than 0.74 MPa, Article 190 of the Coal Mine Safety Regulations points out that after implementation of coal seam gas pre-drainage, the outburst prevention effect of gas drainage area must be tested. The gas content after drainage should be 30% lower than gas content before drainage. In this study, where the residual gas pressure being less than 0.74 MPa is defined as the effective extraction area. Meanwhile, the radius of this area is called effective extraction radius.

4.1. Effect of extraction time on effective extraction radius of borehole

To investigate relationship between extraction time and effective extraction radius, a parameter combination of 94 mm diameter, 13 kPa negative pressure, and 1×10^{-17} m² initial coal permeability is used for simulation analysis. It could be seen from Fig. 2 that after a certain period of extraction, gas pressure in coal seam presents an elliptical distribution centered on the borehole. Gas pressure gradually increases from the borehole wall to the outside. With increasing extraction time, effective extraction radius gradually increases. In the case of specific extraction time, the farther the distance from borehole center, the lower the gas pressure decrease ratio. Effective extraction radius reaches 0.32 m after 100 days of extraction, 0.68 m after 300 days of extraction, 1.06 m after 500 days of extraction, and 1.61 m after 700 days of extraction.

In the early stage of gas extraction, gas pressure changes obviously. With the increase in extraction time, downward trend of gas pressure gradually becomes smaller. This is because gas extraction amount in early stage of extraction is large. However, with the progress of extraction, gas pressure in coal continues to decrease. Affected by increase in effective stress, the fracture opening reduces. Thus permeability decreases. Gas pressure reduction rate gradually becomes small. It should be noted that continuous extraction will lead to shrinkage of coal matrix, increasing permeability again. However, gas content in later stage of extraction is less than that in the early stage. So it will not generally bring a significant increase in gas extraction amount.

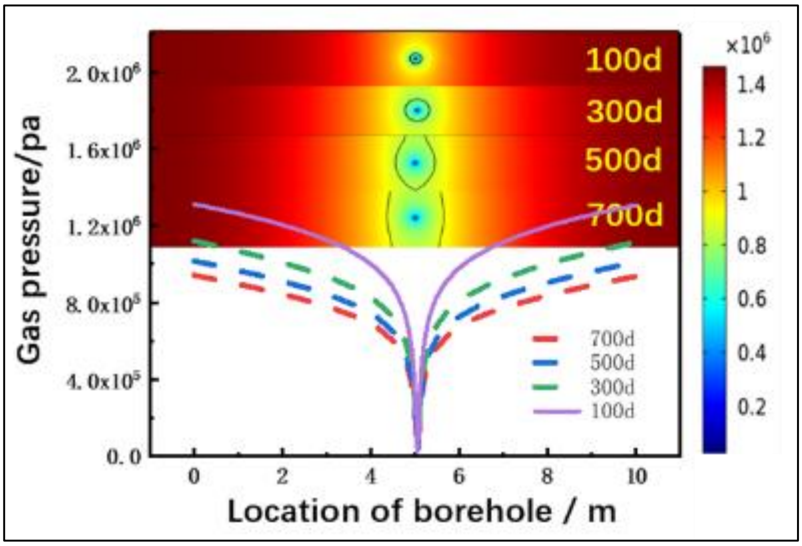

Figure 2 Gas pressure changes at different extraction times

4.2. Effect of initial coal permeability on effective extraction radius of borehole

In the process of gas extraction, decrease in pore pressure, shrinkage effect of coal matrix, compression of coal skeleton and change of effective stress will both lead to continuous permeability change. Real-time relationship between permeability and extraction radius is a typical grey system, which is difficult to study quantitatively[26]. Therefore, this paper studies influence of permeability on effective extraction radius from perspective of initial coal permeability before gas extraction. The initial coal permeability $1\times10^{-18}m^2$,$1\times10^{-17}m^2$ and $3\times10^{-17}m^2$, respectively. Variation of effective gas drainage radius with time in different initial permeability conditions is analyzed, as shown in Fig. 3.

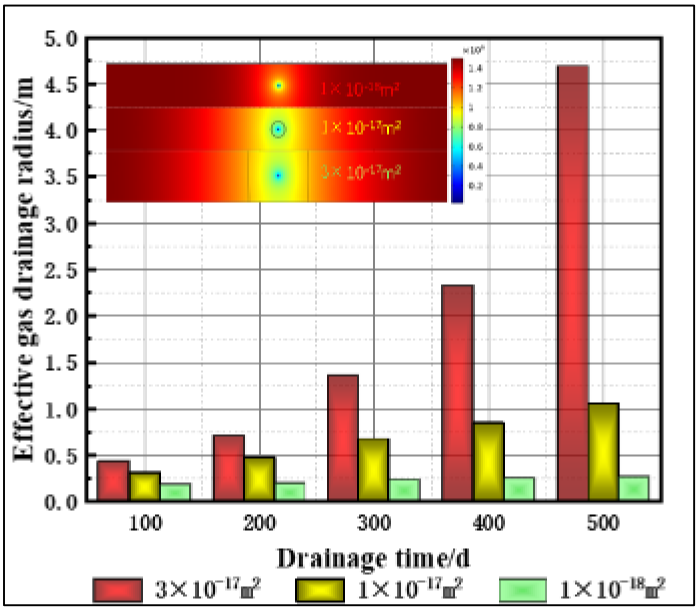

Figure 3 Variation of effective drainage radius with time affected by initial coal permeability

Fig. 3 shows that effective extraction radius of underground gas extraction increases with rising initial permeability of the coal seam, and extraction radius rises with extension of extraction time. Initial coal permeability has a significant influence on effective extraction radius. Increasing permeability shows an obvious effect on improving effective extraction radius. Meanwhile, this effect is more significant with longer extraction time. For example, when extraction time is 100d, the extraction radius corresponding to those three initial permeability of 1×10^{-18} m^2, 1×10^{-17} m^2, and 3×10^{-17} m^2 are 0.19 m, 0.32 m, and 0.44 m, respectively. In contrast, while extraction time is 500 d, the corresponding extraction radius of those three permeability values increase to 0.27 m, 1.06 m, and 4.69 m, respectively. For permeability being 1×10^{-18} m^2, the extraction radius increase ratio is about 0.42. But when permeability being 3×10^{-17}m^2, the extraction radius increase ratio is approximately 9.66, indicating a big difference with 0.42.

4.3. Effect of original gas pressure on effective extraction radius of borehole

The greater the original gas pressure of coal seam, the higher the risk of coal and gas outburst during coalmining, and the more difficult it is to extract gas to safe-mining level. To investigate effect of original gas pressure on effective extraction radius of borehole, initial coal permeability is set as 1×10^{-17} m^2, with original gas pressure being 1.5 MPa, 2 MPa, and 2.5 MPa, respectively. Fig. 4 is change of effective extraction radius with extraction time under different original gas pressure conditions. It could be concluded that under those three gas pressure conditions, effective extraction radius is 0.48 m, 0.27 m, and 0.21 m, respectively at 200 d of gas drainage. Keeping the extraction time same, with the increase in original gas pressure, effective extraction radius becomes smaller. Fundamental reason for this phenomenon is that in gas extraction process, although gas around borehole is gradually extracted, high-pressure gas farther from borehole continues to flow to borehole. When the original gas pressure is greater, pressure gradient is also bigger. Therefore, gas around borehole is more easily and quickly replenished from gas far away from borehole, resulting in a slow decrease in gas pressure around borehole. Thus effective extraction radius becomes smaller and it takes longer to extract gas to safe-mining level [27].

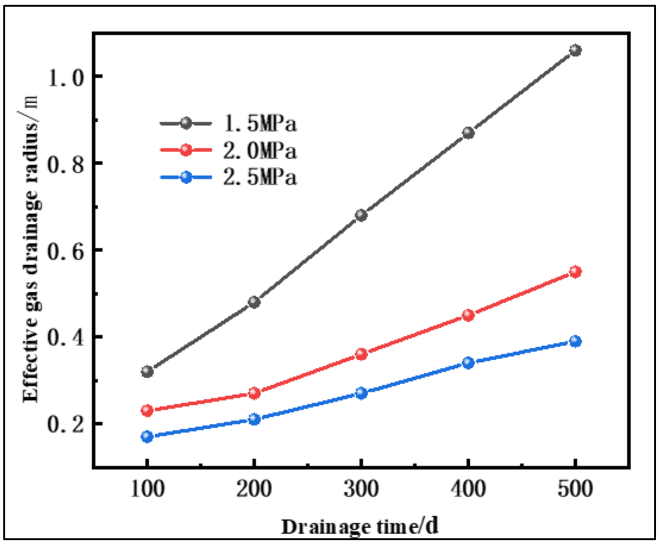

Figure 4 Change of effective extraction radius under different original gas pressure conditions

4.4. Effect of borehole diameter on effective extraction radius of borehole

To analyze influence of different borehole diameters on effective extraction radius, three diameter values of 54 mm, 94 mm and 134 mm are selected, which are controlled within a reasonable range[28-30].

It could be seen from Fig. 5 that when diameter changes from 54mm, 94mm to 134mm, effective extraction radius increases. The longer the extraction time, the greater the increase level. For example, when extraction time being 100 days, effective extraction radius of Φ134 mm borehole is 0.22 m larger than that of Φ54 mm borehole. When the time is 500 d, the differences increases to 0.52 m. Meanwhile, it could also be seen from displacement cloud diagram in Fig. 5 that as diameter of borehole increases, the displacement around borehole will also increase. However, when the diameter borehole reaches 500 mm (in reality, such a large borehole is generally not used, here only for reflecting influence of diameter on displacement around borehole), a large displacement occurs around borehole. Actually, when diameter increases to 134 mm, the growth rate of effective extraction radius begins to slow down. Therefore, it is concluded that when diameter is small, effective extraction radius increases with rising diameter value. But for diameter, it is not the bigger the better. This is because, on the one hand, increase in effective extraction radius caused by bigger diameter gradually becomes limited. On the other hand, with continuous increase of diameter, borehole is prone to deformation, collapse, cracking and other phenomena, which result in higher requirements for borehole sealing and stable protection, particularly, the super-large boreholes.

In summary, gas extraction time, original gas pressure, initial coal permeability, borehole diameter both affect effective gas extraction radius. In normal conditions, the longer the extraction time, the larger the effective extraction radius. Effective extraction radius is negatively correlated with original gas pressure. The smaller the original gas pressure, the better the extraction effect. Effective extraction radius increases with growing initial permeability of coal seam, and the increasing effect are significant. When borehole diameter is small, effective extraction radius increases with the increase in diameter value. However, it is not that the larger the diameter, the better. When borehole diameter is too large, effective extraction radius increases limitedly. But the difficulty and cost of borehole drainage method are significantly improved due to large diameter value.

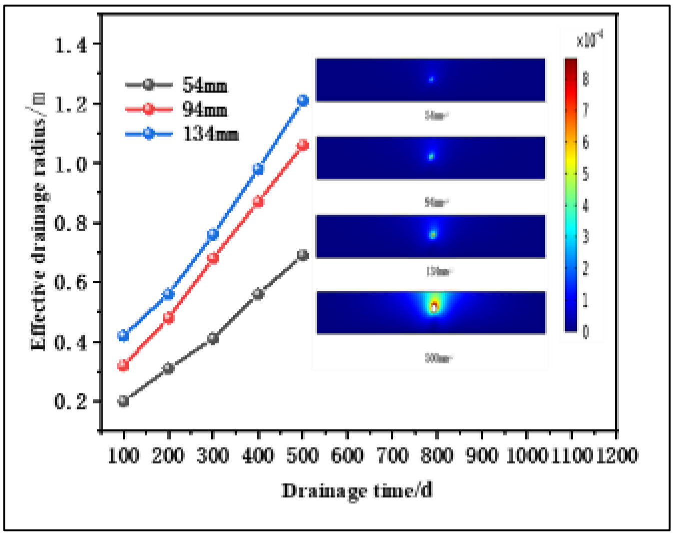

Figure 5 Variation of effective extraction radius and displacement around borehole affected by different borehole diameters

5. Multiple linear regression analysis based on orthogonal experimental design

Qualitative relationships between each influencing factor and effective extraction radius are discussed in above-mentioned study. To further quantitatively investigate effects of related factors, including original gas pressure, initial coal permeability and borehole diameter, on effective extraction radius. Orthogonal design test analysis is conducted. Each factor takes three levels, as shown in Table 1. $L_9 3^{(4)}$ orthogonal table is adopted. The test number is not test sequence. To eliminate error interference, the test arrangement is carried out randomly.

Table 1 Numerical simulation scheme and results of orthogonal test

Serial number	**Original gas pressure (A)/MPa**	**Initial permeability (B)/m²**	**Borehole diameter (C)/mm**	**Effective gas drainage radius /m**
1	1.5	1×10^{-18}	54	0.205
2	1.5	1×10^{-17}	94	1.037
3	1.5	3×10^{-17}	134	3.466
4	2	1×10^{-18}	94	0.217
5	2	1×10^{-17}	134	0.673
6	2	3×10^{-17}	54	1.197
7	2.5	1×10^{-18}	134	0.194
8	2.5	1×10^{-17}	54	0.137
9	2.5	3×10^{-17}	94	1.448

5.1. Sensitivity Analysis of influencing factors

In general, without considering interaction between factors, the greater the level change of each influencing factor, the greater the influence of this factor. Through range analysis, influence degree of each factor on the judgment index could be obtained.

Table 2 Analysis of orthogonal test results

Factor	Original gas pressure(A)	Initial permeability (B)	Borehole diameter (C)
K1	4.708	0.764	1.687
K2	2.087	1.995	2.702
K3	2.075	6.111	4.481
k1	1.569	0.225	0.562
k2	0.696	0.665	0.901
k3	0.692	2.037	1.494
R	-0.878	1.782	0.338

In the Table 2, Ki (i=1,2,3) is the sum of test results corresponding to each factor.

$$ki=Ki/s \quad \ldots\ldots\ldots\ldots(16)$$

Where, s is the number of occurrences of each level on any column. Thus ki represents arithmetic mean of test results obtained at any factor level i.

R is the range, which characterizes influence of factor levels in the column on evaluation index. The larger the range, the greater the effect of this factor on effective extraction radius.

According to results of range analysis in above Table, the absolute value of range of each influencing factor is RB > RA > RC in descending order. This indicates that the effect significance of each factor is ranked as initial permeability > original gas pressure > borehole diameter.

5.2. Multiple linear regression prediction model

Assuming that there is a statistical linear correlation between system variable y and several independent variables x_1, x_2,..., x_k. Hypothesis 1: the selected samples are independent; Hypothesis 2: All samples do not have multicollinearity; Hypothesis 3: Residuals are normally distributed. A multiple linear regression equation could be established to describe linear relationship between dependent variable and multiple independent variables. The model is expressed as:

$$y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4+\ldots\ldots+b_kx_k+\varepsilon \quad \ldots\ldots\ldots\ldots (17)$$

Where, y is dependent variable; x_1-x_k is independent variable; b_0 is regression constant; b_1-b_k is regression coefficient; ε is random error.

Effective extraction radius of gas drainage is taken as the dependent variable, while original gas pressure, initial coal permeability and borehole diameter are regarded as independent variables. x_1, x_2, and x_3 represent borehole diameter, initial coal permeability and original gas pressure, respectively. b_1, b_2 and b_3 are regression coefficients of the corresponding variables.

Table 3 Regression coefficient and significance test

Model coefficient	Non-normalized coefficients		Standardized coefficient	T	Significance	Colinearity statistics	
	B	Standard error	Beta			allowable error	VIF
Constant	17.380	3.651		4.761	0.005		
Borehole diameter	0.012	0.005	0.379	2.250	0.074	1.000	1.000
Initial permeability	0.916	0.207	0.746	4.425	0.007	1.000	1.000
Original gas pressure	-0.976	0.414	-0.398	-2.359	0.065	1.000	1.000

Dependent variable: effective extraction radius

It could be seen from Table 3 that non-standardized regression coefficient of borehole diameter is 0.012 > 0. The regression coefficient test result t = 2.25. And the corresponding significance level Sig = 0.074, which is not far greater than 0.05. The significance is within acceptable range. It shows that borehole diameter positively affects effective extraction radius, i.e. the larger the diameter, the bigger the extraction radius. For initial permeability, non-standardized regression coefficient is 0.916 > 0, The regression coefficient test result is t = 4.425. While corresponding significance level is Sig = 0.007 < 0.05, indicating that initial permeability significantly affects extraction radius, that is, the greater the initial permeability, the larger the extraction radius. Meanwhile, the non-standardized regression coefficient of original gas pressure is -0.976 < 0. The regression coefficient test result t = -2.359. Corresponding significance level Sig = 0.065, that is close to 0.05. The significance is within an acceptable range, indicating that original gas pressure negatively affects extraction radius. Because the non-standardized coefficient measurement units of those three factors are different, the absolute value of normalized partial regression coefficient is adopted to compare contribution rate of three parameters to extraction radius. Absolute values of three-factor standard coefficients are 0.756 > 0.398 > 0.379. Thus contribution rate of three parameters to extraction radius could be ranked as initial permeability > original gas pressure > borehole diameter, which is consistent with above range analysis results. The constant b_0 = 17.38, the regression coefficient of borehole diameter b_1 = 0.012, the regression coefficient of initial permeability b_2 = 0.916, while the regression coefficient of original gas pressure b_3 = – 0.976. Based on above testing, regression coefficient is statistically significant. The multiple linear regression model is obtained:

$$y=17.38+0.012x_1+0.916x_2-0.976x_3 \quad (18)$$

5.3. Regression model test

5.3.1. Test of goodness of fit

Stepwise regression analysis was conducted to obtain R^2, adjusted R^2 and Durbin-Watson parameter, etc, as shown in Table 4.

Table 4 Multiple linear regression model fitting parameters

Model	R	R^2	Adjusted R^2	Standard error estimation	D-W
1	0.926[a]	0.858	0.773	0.506933	2.27

a. Prediction variables: original gas pressure, initial permeability, borehole diameter.

Fitting degree R^2 represents fitting effect of regression equation on sampling observation points. In the closed interval of 0 and 1, the closer R^2 is to 1, the better the fitting effect is. The closer to 0, the worse the fitting effect. It could be seen that R^2 = 0.858 indicates the predictive variable could explain 85.8 % of dependent variable condition, i.e. 85.8 % of extraction radius changes is related to predictive variables of original gas pressure, initial permeability and borehole diameter. R^2 is close to 1, meaning the goodness of fit is good. There is a very close linear correlation between extraction radius and original gas pressure, initial permeability and borehole diameter.

5.3.2. Analysis of variance

Table 5 shows significance test results of the established model. F value is 10.070, while significance value is 0.015, being larger than 0.005. This reflects that regression model between borehole diameter, initial permeability of coal seam, original gas pressure and effective extraction radius are significant.

Table 5 Significance test of multiple linear regression model

Model	Quadratic sum	df	Mean square	F	Significance
Regression	7.763	3	2.588	10.070	0.015[b]
Residual error	1.285	5	0.257		
Total	9.048	8			

b. Dependent variable: effective extraction radius.

5.3.3. Independence test

Based on Table 4, result value of Durbin-Watson is 2.27. In statistics, if the Durbin-Watson value is not in the range of 1.5-2.5, the independent variables are not independent with each other. There is good autocorrelation. Since $1.5 < 2.27 < 2.5$, so parameters in this study are independent with each other and there is no autocorrelation, which proves the first hypothesis of multiple linear regression model.

5.3.4. Multicollinearity test between variables

It could be seen from Table 3 that tolerance and variance expansion factor VIF of those three factors are all 1. In statistics, VIF > 10 indicates that there is multicollinearity between variables. Since 1 being far less than 10, there is no multicollinearity between three independent variables. These three parameters are essentially very different, which proves that second hypothesis of multiple linear regression model is established.

5.3.5. Residual distribution test

Fig. 6 and Fig. 7 are standard P-P diagram and scatter plot of regression standardized residuals. Fig.6 reflects that all sampling points are distributed around asymptote. Data and the model are matched, indicating that residuals obey normal distribution. Fitting effect of multivariate linear regression equation is good. Fig. 7 shows that distribution of sampling points is irregular and scattered, revealing residuals are random and there is no heteroscedasticity. This proves third hypothesis of multiple linear regression model.

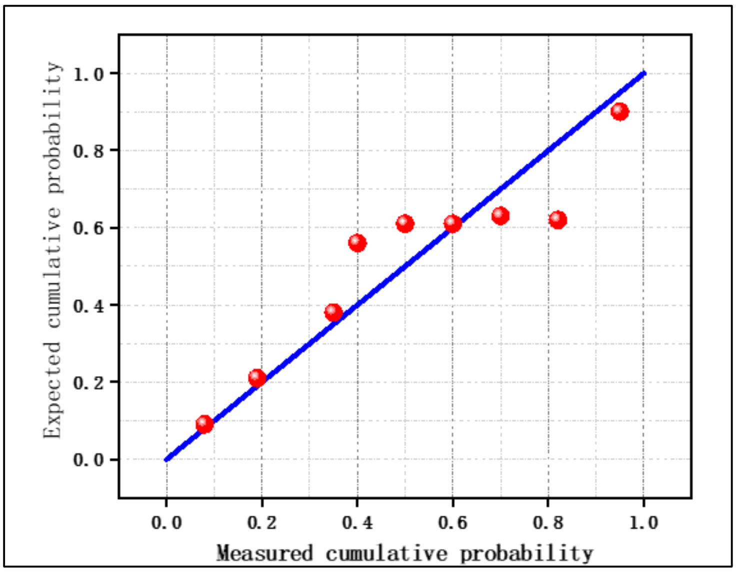

Figure 6 p-p plot of regression standardized residuals

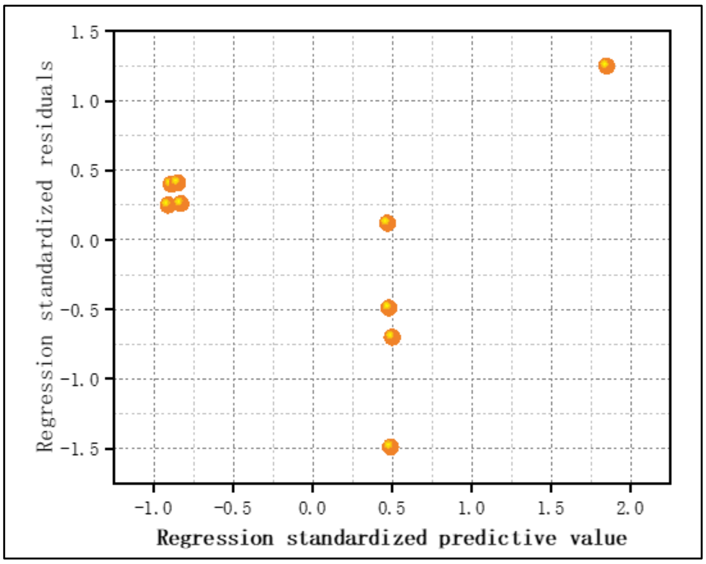

Figure 7 Scatter plot of regression standardized residuals

Therefore, based on above analysis of multiple linear regression model, it is concluded that borehole diameter, initial permeability of coal seam, original gas pressure are three main factors affecting effective gas extraction radius. There is no multicollinearity. The residual distribution is a normal distribution. The fitted multiple linear regression model is effective and reliable.

6. Conclusion

- In the process of gas extraction, gas pressure presents an elliptical distribution centered on borehole, which gradually increases from borehole wall to farther positions. In the early stage of gas extraction, gas pressure changes obviously. With the increase in extraction time, the trend of pressure declining gradually becomes smaller. Initial coal permeability positively affects effective extraction radius. This effect is more significant with increase in extraction time. For same extraction time, the larger the original gas pressure, the smaller the effective extraction radius. With the increase in borehole diameter, effective extraction radius increases. Also, the longer the extraction time, the greater the rising effect.
- Range analysis and multiple regression analysis consistently show that contribution rate (from large to small) of initial permeability, original gas pressure and borehole diameter to effective extraction radius is initial permeability, original gas pressure, borehole diameter. Multiple linear regression model between effective extraction radius and those three factors is $y = 17.38 + 0.012x_1 + 0.916x_2 - 0.976x_3$, with fitting correlation coefficient being 0.858. Prediction test shows that initial permeability, original gas pressure, and borehole diameter are independent. Residual distribution is normal distribution. This indicates multiple linear regression model's validity and reliability.

In real gas drainage practices, each related parameter should be reasonably selected according to engineering conditions and cost factors. It is not that the larger the parameter value is, the better, e.g. borehole diameter. With increasing mining depth, gas content and gas pressure gradually increase, and coal permeability further decreases. Effective influence radius of gas extraction is getting smaller and smaller. It is more difficult to reach the safety standard. Based on results in this study, effect of permeability on gas extraction is the most significant. Therefore, it is recommended to take measures (e.g. protective-layer coalmining, hydraulic slotting, etc.) to achieve efficient gas extraction in stress-relief and permeability-enhancement coal seam.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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