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Determination of Gas Well Productivity by Logging Parameters

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Abstract

The prediction and evaluation of reservoir productivity is a comprehensive index of the dynamic characteristics of gas reservoirs, which can provide a reasonable basis for the design and rational distribution of gasfield development plan. Proration of gas well is an important procedure in the development process, Absolute open flow as a key indicator of rational production of gas well. It is very important to determine the absolute open flow of the gas well. The Permian in Ordos Basin is a typical tight sandstone gas reservoir. The paper analyses correlation relations between different logging parameters and absolute open flow, and get the four parameters, porosity, permeability, storage coefficient（the product of porosity and effective thickness）with better correlation relations and effective thickness with best correlation relation by combining a large amount of gas logging data and static logging data and means of linear regression analysis, Then on the basis of this, a new empirical formula for calculating the absolute open flow of gas wells is obtained by using the method of multiple linear regression. The example shows that the result of this method is reasonable and reliable and the method can provide scientific basis for the prediction of natural gas absolute open flow of tight sandstone gas reservoirs.

Keywords: gas well productivity, logging parameters, multiple linear regression, tight sandstone gas reservoirs, Permian, absolute open flow

1. Introduction

Tight sandstone gas reservoir is an important component of unconventional oil and gas in our country at present, which has great exploration and development potential (Kang et al., 2016). Ordos Basin is a typical tight sandstone gas reservoir, the main river - delta facies sandstone, the main producing layer for Taiyuan, Shanxi and Shihezi group, reservoir average porosity is 7.8%, the average permeability is 0.63mD, The radius of the roar is less than 1μm, the reservoir is characterized by low porosity and low permeability, heterogeneity is strong, production forecasting more difficult (Yang et al., 2015; Lu et al., 2015). The absolute open flow rate is considered as an important parameter to evaluate the productivity of gas wells. Generally the result is got through the system test, isochronal test, modified isochronal test, single point test and other productivity test method calculation (Lu et al., 1998). The absolute open flow rate is an important parameter to evaluate the productivity of gas well. It is usually calculated by means of systematic well test, isochronal test, modified isochronal test, single point test and other productivity test methods (Gou, 2004, 2005). The production capacity test theory requires that the gas well test reach a stability condition. The production capacity test theory requires that the gas well test reach the relative stability condition. The productivity equation and the absolute open flow rate error of the heterogeneity low permeability gas well are determined, and the tight sandstone gas reservoir with low porosity and low permeability reaches the pressure stability. And the time required achieving stable pressure in tight sandstone reservoirs with low porosity and low permeability will take very long. System test, isochronal test, modified isochronal test are to be conducted at least four working systems of the production and pressure data test (Wang et al., 2010; Yang et al., 2012; Yan et al., 2013). The method will cost time and increase the economic cost. And different work system will inevitably affect the production of gas wells in the process.

The previous studies used the logging data to evaluate the gas well productivity semi-quantitative and quantitative evaluation methods (Shao et al., 2007). Gray correlation analysis is used to analyze the correlation and neural network method (Yan et al., 2007; Luo et al., 2006). Multivariate regression analysis was used to analyze the unrestricted flow, which was more convenient than the BP neural network, and could reflect the correlation between the parameters and the absolute open flow (Wang et al., 2006; Hu et al., 2010). In this paper, a large number of static logging data and dynamic test gas data are combined to determine the absolute open flow of gas wells by multiple linear regression method. The logging data is obtained before the formation is reconstructed, which can reflect the physical and objectivity of reservoir physical property and oil and gas content; and the test gas data can truly reflect the gas-bearing property of the reservoir. The method can reduce the operational risk, save the cost, improve the economic efficiency, and can be used as a new method to calculate the absolute open flow.

2. Method

2.1 One-dimensional Linear Regression Analysis

In order to establish an ideal model of absolute open flow forecasting, the selection of influencing factors is very important. In the Shenmu gas field of the Ordos Basin, the reservoir heterogeneity is strong and the reservoir fractures are not developed due to the interaction of sea-land alternation and digenesis. The main reservoir spaces are intergranular pores and dissolution pores. The Shenmu block develops the braided delta deposition, so the factors such as porosity and permeability, pore throat structure, gas saturation and thickness all have influence on gas well productivity (Cai et al., 2007). In this paper, the reservoir thickness, porosity, permeability, reservoir effective thicknesses are selected, and the storage capacity (the product of porosity and effective thickness) is introduced. The thickness and effective thickness of the reservoirs are important parameters in evaluating the reservoir, which are related to the reserves and abundance of the reservoir. When the porosity of the reservoir is the same, the bigger the porosity is, the stronger the seepage capacity is, and the porosity will directly influence the productivity of the gas well. The storage factor is the product of porosity and effective thickness and is an important indication of the ability of a well to contain the fluid. Permeability reflects the ability of fluid flow in the reservoir, which is an important factor affecting gas well productivity.

In order to analyze the influence of parameters on the absolute open flow, the Spearman correlation method is used to analyze the parameters. The Spearman rank correlation coefficient is a nonparametric property (independent of distribution) that measures the correlation between two variables, X and Y, in the range [-1, +1]. The sign of the Spearman rank correlation coefficient represents the positive and negative correlations of the two variables X and Y. If the Spearman rank correlation coefficient is positive, it indicates that Y increases as X increases, whereas Y decreases as X increases. When the Spearman rank correlation coefficient is 0 that means Y does not vary with X. The Spearman rank correlation coefficient is numerically close to ± 1 indicating that the two variables X and Y are close to monotonic increasing or decreasing strictly. When the rank correlation coefficient is calculated, the data xi and yi are ordered from large to small, and the position of the data after ordering is defined as a, b, then a and b are the ranks of the variables xi and yi, as di = a-b. When two same values are presented in the same column of data, the order of the two values is specified to be the same. According to the basic data analysis, if the data exist in the same rank, you should use the same rank correlation coefficient calculation method, the correlation coefficient is:

$$\rho_s = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \tag{1}$$

Cohen (1988) and other scholars put forward the correlation coefficient of the size of the criterion to determine the relevance of variables (Table 1)

Table 1. Criteria for judging relevance

Corelation	Negative Value	positive value
uncorrelated	-0.09~0.0	0.0~0.09
low correlation	-0.3~-0.1	0.1~0.3
Medium correlation	-0.5~-0.3	0.3~0.5
significant correlation	-1.0~-0.5	0.5~1.0

2.2 Correlation Analysis of Absolute Open Flow

According to the test data of Permian in the Ordos Basin, the data of wells in the Permian system in the 25 test gas results are selected (Table 2). Calculating reservoir thickness, effective thickness, porosity, storage capacity and permeability and absolute open flow of the Spearman correlation coefficient in the SPSS software and then analyze the Correlation of the parameters with the absolute open flow.

Table 2. Multiple Regression Analysis of the Basic Data

Well Number	Reservoir Thickness (m)	Effective Thickness (m)	Porosity （%）	Storage Coefficient （Φ*h）	Permeability (mD)	Absolute Open Fl ow (10^4m^3/d)
1	11.9	6.2	7.66	47.49	1.31	3.8018
2	10.2	4.1	7.74	31.73	0.75	2.5399
3	8.9	8.9	24.35	31.73	0.83	5.8489
4	7.2	5.4	7.11	38.39	2.78	3.4036
5	11.8	8.5	10.52	89.42	1.62	7.9283
6	5.1	2.3	6.73	15.47	0.67	2.5031
7	7.3	7.3	7.81	56.94	0.38	4.0454
8	6.9	6.9	7.64	52.71	1.03	3.4367
9	2.7	2.7	5.63	15.20	0.81	2.4582
10	15.8	15.8	7.49	43.44	1.72	8.1154
11	3.9	2.2	9.43	20.74	2.17	2.6108
12	8.7	5.9	9.43	20.74	2.57	5.3948
13	7.0	4.4	10.65	46.86	1.84	4.2067
14	5.8	5.8	6.07	46.66	1.01	3.2245
15	9.0	9.0	7.12	64.08	3.11	6.1441
16	6.9	6.9	7.51	51.81	2.44	4.6321
17	5.6	5.0	9.17	45.85	1.01	4.2818
18	11.9	2.5	8.62	21.52	0.15	3.4929
19	3.3	3.3	8.32	27.39	1.91	2.2009
20	8.3	2.5	6.34	15.85	0.54	2.0976
21	2.6	2.6	11.23	29.19	0.82	1.2173
22	6.2	3.2	7.06	22.59	1.06	1.5486
23	7.4	4.8	6.51	31.23	0.96	1.7535
24	10.2	5.2	10.01	50.05	1.07	1.0012
25	18.1	4.0	7.27	29.08	0.36	0.4355

The results of the rank correlation coefficient of the calculated parameters and the absolute open flow rate are represented in Table 3.

Table 3. Rank correlation coefficient table

Parameters	Reservoir Thickness	Effective Thickness	Porosity	Permeability	Storage Coefficient
Absolute Open Flow	0.27	0.782	0.301	0.324	0.486

It can be seen from the table that the Spearman correlation coefficients of all factors and absolute open flow are positive, indicating a positive correlation with the absolute open flow. The effective thickness has a significant correlation with the absolute open flow, and the permeability, porosity and storage capacity are medium correlated. The correlation between the reservoir thickness and the absolute open flow is 0.27, which is low correlation. The coefficient of correlation between the storage capacity and the absolute open flow is 0.486, which is bigger than the correlation coefficient 0.31 between the porosity and the absolute open flow. The storage capacity is the product of the porosity and the effective thickness. The results shows that the combination of logging parameters in an appropriate way can improve the correlation with the absolute open flow.

Scatter plot analysis was performed on the reservoir thickness with the lowest correlation between absolute open flow and the highest effective reservoir thickness. The relationship between the reservoir thickness and the absolute open flow shows the data points are scattered and the tendency fitting is poor. The correlation coefficient R2 is 0.43, indicating that the correlation degree is low. There is a positive correlation between the absolute open flow rate and the effective thickness, the correlation coefficient R2 is 0.74, the value is close to 1, and the correlation degree is high. Removing the reservoir thickness, choose four better parameters of the four correlation coefficients, and then use multiple linear regression method to establish an absolute open flow calculation model.

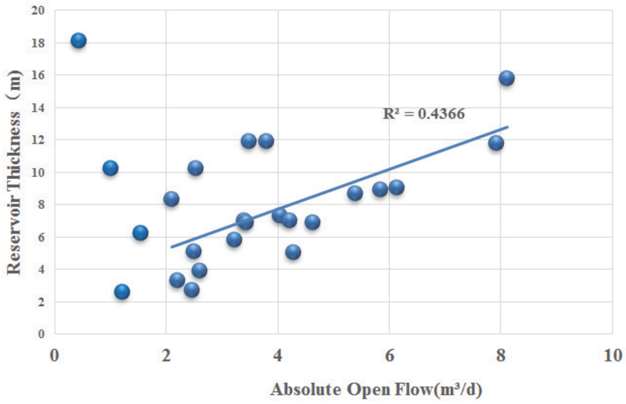

Figure 1. Catter diagram of reservoir thickness and absolute open flow

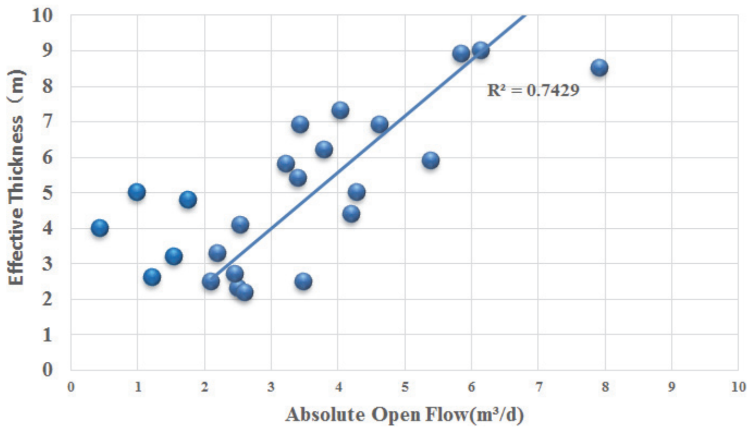

Figure 2. Cattering diagram of effective thickness and absolute open flow of gas layer

2.3 Multiple Linear Regression Analysis Model

The multiple linear regression equation is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \quad (2)$$

The regression coefficients in the multiple linear regressions can be estimated by the least squares method. Residual sum of squares is calculated as:

$$SSE = \Sigma (y-\hat{y})^2=0 \quad (3)$$

$\hat{y}$ is the estimation of the sample. According to the principle of the minimum value calculation, we know that the residual sum of squares SSE is a minimum. And when the partial derivatives of SSE to $\beta_0, \beta_1, \cdots \beta_k$ are zero, SSE takes the minimum value.

Make a partial derivation of SSE and $\beta_0, \beta_1, \cdots \beta_k$, and make it equal to zero, we can gain a formulation $k+1$.

$$\frac{\partial SSE}{\partial \beta_i} = -2\sum (y-\hat{y}) = 0 \quad (4)$$

$$\frac{\partial SSE}{\partial \beta_0} = -2\sum (y-\hat{y})x_i = 0 \tag{5}$$

Multiple linear regression regression degree test needs to use the determination coefficient R^2, R^2 said independent variable dependent linear correlation degree, $0 \le R^2 \le 1$, the value closer to 1, the higher the regression equation fitting. It is defined as:

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} = 1 - \frac{\sum (y-\hat{y})^2}{\sum (y-\bar{y})^2} \tag{6}$$

SSR is the sum of squares of regressions, SSE is the sum of squares of the residuals, and SST is the sum of squared deviations of the total deviation.

The size of the constant coefficient R^2 is affected by the number x of the independent variable k. When the number of independent variables increases, it will cause the regression of the sum of squared SSR increases, while R^2 increases. However, increasing the number of independent variables caused by R^2 increase can not represent the degree of fit, so by modifying k, to exclude the number of independent variables in the regression equation between the different degree of fitting, the number of independent variables to fit the excellent Degree of influence.

The modified method is: the original formulation of the numerator denominator, respectively, divided by their degrees of freedom, becomes the mean square error ratio, adjusted for R^2:

$$\bar{R}^2 = 1 - \frac{SSE/(n-k-1)}{SST/(n-1)} = 1 - \frac{SSE}{SST} \bullet \frac{n-1}{n-k-1} = 1-(1-R^2)\frac{n-1}{n-k-1} \tag{7}$$

From F statist the high degree of fit, F statistic is more significant, F statistic formulation is:

$$F = \frac{R^2/k}{(1-R^2)/(n-k-1)} \tag{8}$$

3. Results

When the number of independent variables is large, with the help of SPSS software, enter the appropriate dependent variable and independent variables, can be quickly calculated. Four parameters, such as effective thickness, storage capacity (Φ * h)), permeability and porosity, are input into the SPSS regression model in turn, and the following parameters are obtained.

Table 4. Model summary

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
volue	0.833	0.695	0.634	0.643

R is a complex correlation coefficient, indicating that all independent variables in the model and the dependent variable between the linear regression relationship between the size of the larger R indicates that the more close to the linear regression relationship. The coefficient of determination R^2 is equal to 0.695, the revised R^2 is 0.634, the greater the value, the better the model fitting effects. The standard error reflects the accuracy of the model, the smaller the standard error, the better the fitting effect of the model.

Table 5. Analysis of variance

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	65.999	4	16.500	11.377	.000[a]
Residual	29.004	20	1.450		
Total	95.003	24			

The results of regression analysis are listed in the table: the sum of squares of regression, the degree of freedom of regression, the probability of significance, and so on. The probability of significant test of regression equation is 0, less than the level of significance0.05, indicating that the coefficient is not equal to 0 at the same time, the explanatory variables and explanatory variables of the linear relationship is significant. A linear equation can be established with the model has statistical significance.

Table 6. Regression coefficient table

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std.Error			
Constant	-0.127	0.689		-0.184	0.856
Effective Thickness	0.409	0.111	0.621	3.680	0.001
Porosity	0.006	0.006	0.132	0.981	0.005
Storage Coefficient	0.020	0.018	0.179	1.134	0.027
Permeability	0.446	0.355	0.166	1.258	0.036

The unrestricted flow regression formulation obtained from the regression coefficient table:

Absolute open Flow = -0.127 + 0.4093 × Effective Thickness + 0.006×Porosity + 0.02 × Storage Capacity + 0.446 × Permeability

4. Discussion

In order to make sure the reliability and the range of error of the formulation, the tested gas and well logging data of 29 wells in the Ordos basin were selected as the tested data. The established empirical formulation was used to calculate the absolute open flow rate, and the results were compared with the productivity test Calculated results.

Table 7. Comparison of results of productivity test and model calculation

Well Number	Effective Thickness (m)	Porosity （%）	Storage Coefficient （Φ*h）	Permeability (mD)	Productivity test ($10^4m^3/d$)	Model calculation ($10^4m^3/d$)	Relative Error（%）
1	1.8	10.3	18.54	1.94	2.2044	1.9070	13.49
2	15.4	8.2	123.35	1.18	11.4671	9.2130	19.66
3	4.7	8.6	40.42	0.52	2.6536	2.8872	8.80
4	4.2	8.6	36.12	0.15	3.4924	2.4317	30.32
5	3.1	10.1	31.31	0.70	2.9287	2.1399	26.93
6	11.5	10.7	123.05	5.13	11.6154	9.3897	19.12
7	4.0	8.2	32.80	2.36	2.0152	3.2668	62.11
8	21	5.7	119.70	0.79	12.9195	11.2425	12.98
9	4.3	7.0	30.10	5.42	8.9775	4.6930	47.72
10	15.5	6.8	105.40	1.02	10.2452	8.8162	13.95
11	6.6	7.5	49.50	0.30	3.8263	3.7412	1.55
12	3.5	8.2	28.70	0.98	2.0929	2.3648	12.99
13	4.8	7.7	36.96	1.18	10.13263	3.1479	68.93
14	4.1	7.7	31.57	0.75	2.5391	2.5620	0.91
15	5.5	7.2	39.60	2.18	8.4808	3.9300	53.66
16	5.2	7.1	36.92	2.78	3.4036	4.0207	18.13
17	6.3	4.8	30.43	0.20	3.7385	3.1765	15.03
18	1.8	7.8	14.06	1.94	2.2042	1.8025	18.22

19	3.8	6.6	25.08	0.24	1.8384	2.0754	12.89
20	16.0	5.7	91.20	0.76	12.9127	8.6142	33.28
21	15.5	6.8	105.40	1.02	10.2429	8.8162	13.90
22	4.7	7.9	37.13	0.23	3.2962	2.6879	18.30
23	2.4	6.9	16.56	0.30	1.2453	1.3610	9.29
24	4.0	9.3	37.20	1.10	2.4917	2.7994	12.35
25	2.5	4.5	11.25	5.58	3.1278	3.6362	16.25
26	6.3	9.1	57.27	0.35	6.4594	3.8057	41.08
27	8.9	6.5	58.12	10.95	10.4438	9.5999	8.08
28	6.4	5.4	34.30	0.48	3.3181	3.4229	3.16
29	2.1	8.0	16.88	0.26	1.2453	1.2338	0.93

To examine the accuracy of the model, a reasonable range of error is discussed. The range of relative error is less than 10%, considering the simulation result is pretty good. The range of relative error is between 10% and 20%, considering the simulation result is good. The range of relative error is between 20% and 30%, considering the simulation result is in medium level. The range of relative error is more than 30% considering the simulation result is poor. The model is not very ideal. Analyze the table of the calculated result and presented in Table8

Table 8. Statistical results of model calculation

Range of Relative Error	Model Effects	Well Number	The Proportion
＜10%	pretty good	7	24%
10%~20%	good	14	48%
20%~30%	medium	2	6.8%
＞30%	poor	6	20.6%

By comparing the results of the model calculation with those of the productivity test results, the calculation accuracy of the model can be seen visually.

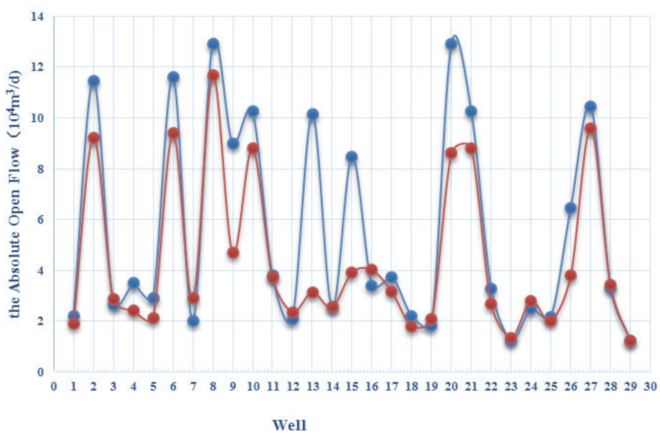

Figure 3. Comparison between model calculation results (red) and productivity test results(blue)

From the simulation result analysis table (Table 9), we can see that the established calculation model has high prediction accuracy. If the relative error is less than 20%, it is considered that the simulation effect of the model is better. The calculated result of the empirical formulation is close to the absolute open flow value obtained by the productivity test and the coincidence rate is up to 72% degree. From the comparison of the calculated results (Fig 3), it can be seen that the obtained empirical formula has high prediction accuracy with the range of $2 \times 10^4 \sim 4 \times 10^4 m^3/d$, and the prediction precision is up to 90.9%. The accuracy of the absolute open flow is larger than $8 \times 10^4 m^3/d$, but it is still within the acceptable range. According to previous studies, tight sandstone gas reservoirs need to be fractured and their productivity is affected by the half-length of fractures. As the length of fractures increases, the open-flow capacity of gas wells increases to a certain extent. The reasons for the large errors of some wells are analyzed, and the crack half-length explained by the pressure recovery test of the wells with irresistible flow of more than $8 \times 10^4 m^3/d$ and the wells with absolute open flow of less than $4 \times 10^4 m^3/d$ are also compared. And get the following table. It is found that the half-length of the fracture is larger than that of the smaller error, and the empirical formula is affected by the degree of fracturing. When the degree of fracturing is large, it will influence the calculation accuracy of empirical formulation

Table 9. Fracture half-length analysis table

Well	Fracture half-length（m）	Relative Error（%）	Well	Fracture half-length（m）	Relative Error（%）
7	60.5	62.11	23	13	9.29
9	54.6	47.72	14	18.5	0.91
15	42	53.66	11	23.8	1.55
26	46.8	41.08	8	35.2	12.98

Analyze the error, the following circumstances will cause the error becomes larger.

(1) The open mode of production layer. The fracturing thickness is less than the effective thickness and is not fully open.

(2) The effect of well heterogeneity. Parts of the stratigraphic litho logy mutation, sandstone pinch or local cracks are developed. Fracturing degree is too wide. Crack half-length is too wide, or crack width is too wide.

Acknowledgments

The multiple linear regression analysis of the Upper Paleozoic Permian series logging and well logging data in the eastern Ordos basin is used to obtain the new prediction method of the absolute open flow. The results are as follows:

(1) There is a positive correlation between the absolute open flow rate of gas well and the porosity, permeability, storage capacity and effective thickness of the reservoir. The correlation between the absolute open flow and the effective thickness is the largest, and the correlation between reservoir thickness and absolute open flow is low.

(2) In this paper, the correlation of effective thickness and the largest unrestricted flow is the largest. As a result, the definition of the effective thickness plays an important role of the calculation the accuracy of unrestricted flow.

(3) Combining logging parameters in an appropriate method can improve the correlation with absolute open flow, such as the correlation of the reservoir coefficient (the product of porosity to the effective thickness) to the absolute open flow rate is greater than the correlation between porosity and absolute open flow.

(4) The results present that the accuracy of the empirical formula is 76%, which provides a new method for predicting the productivity of the Permian reservoir in the eastern Shenmu gas field. The new method has been applied to the prediction of reservoir productivity. The advantages are benefits for logging data calculation, saving time and improving economic efficiency. And it can be considered as an important non-stop supplement of production capacity test flow calculation.

(5) The obtained empirical formulation has high prediction accuracy in the range of $2 \times 10^4 \sim 4 \times 10^4 m^3/d$, and the prediction precision is up to 90.9%. The accuracy of the formulation is lower than that of the unconfined flow value of more than $8 \times 10^4 m^3/d$, and the accuracy of the formulation is affected by the degree of fracturing.

(6) Absolute open Flow = -0.127 + 0.4093 × Effective Thickness + 0.006×Porosity + 0.02 × Storage Capacity + 0.446 × Permeability, the method can provide scientific basis for the prediction of natural gas absolute open flow of tight sandstone gas reservoirs. At the same time, it provides a new method for predicting the productivity of tight sandstone, make full use of logging data, combined with multiple linear regression.

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