FEASIBILITY ANALYSIS AND OPTIMAL DESIGN OF THE ACIDIZING OF COALBED METHANE WELLS

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ABSTRACT

Plugging is a prominent cause of reduced production in coalbed methane (CBM) wells. In this thesis, the feasibility analysis and optimal design of the acidizing of CBM wells to remove the plugging are researched. First, X-ray diffraction analysis shows that the plugging contains acid-soluble minerals and a field case indicates that the acidizing effect is positively correlated with the content of acid-soluble minerals. Inspired by this, the author analyzes influencing factors of the content of acid-soluble minerals. Well logging parameters (DEN, AC, GR) are selected to establish a neural network model to predict the content of the acid-soluble minerals. Furthermore, the feasibility criterion of the acidizing of CBM wells is proposed. Then a forward model and a parameters inversion algorithm are proposed to diagnose the plugging. The multi-solution problem of parameters inversion is solved by the Gauss-Marquardt (G-M) algorithm based on the stochastic initial value and maximum probability. Combining this method with the present numerical model, the author presents an optimal design to optimize the volume and injection rate of the acid. Meanwhile, by experimental study, the author proposes a new acid formulation. Finally, the results are applied in the field to confirm the feasibility of the acidizing. The findings show that acidizing is an effective stimulation technology for specific CBM wells and the feasibility analysis and the optimal design can improve this effect.

Keywords: Coalbed methane; plugging; acidizing; feasibility analysis; optimal design.

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DEDICATION

To my parents for their love, patience, and support during my graduate studies.

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NOMENCLATURE

B	Formation volume factor, dimensionless
C	Wellbore storage coefficient, m^3/Pa ;
C_{i1}	Comprehensive compressibility of the inner region, Pa^{-1}
C_{i2}	Comprehensive compressibility of the outer region Pa^{-1}
h	Thickness of the coal seam, m
k_0	Initial permeability, m^2
k_1	Permeability of the inner region, m^2
k_2	Permeability of the outer region, m^2
k_d	Permeability of the damage region, m^2
p_1	Pressure of the inner region, Pa
p_2	Pressure of the outer region, Pa
p_i	Pressure at the initial condition, Pa
p_w	Bottom hole pressure, Pa
q	Flow rate, m^3/s
r	Radius, m
r_d	Damage radius, m
r_w	Wellbore radius, m
r_f	Radius of the inner region, m
R	Radius of the outer region, m
S	Skin factor, dimensionless

t	Production time, s
α	Experimental constant, dimensionless
μ_1	Fluid viscosity of the inner region, Pa s
μ_2	Fluid viscosity of the outer region, Pa s
ϕ_0	Initial porosity, dimensionless
ϕ_1	Porosity of the inner region, dimensionless
ϕ_2	Porosity of the outer region, dimensionless
ϕ_d	Porosity of the damage region, dimensionless

CHAPTER 1 INTRODUCTION

1.1 Review

Coalbed methane (CBM) is an unconventional natural gas resource. The development of CBM has great social and economic benefits in alleviating the shortage of conventional oil and gas supply, ensuring the safe production of coal, protecting the atmospheric environment, and improving the energy structure.

Coalbed methane has been well developed in United States, Canada, Australia, China, India, and the United Kingdom. Among these countries, the United States was the first country to succeed in commercializing CBM. Canada has made the fastest progress in commercializing CBM. Australia and China recently started exploiting CBM. Both countries rapidly increasing their development of CBM product. Although the conditions and policies of CBM resources in different countries are different and the development of the CBM industry is also different, each country faces some common problems.

The low gas production rate of the single CBM well is one problem faced by all countries, and this problem needs to be solved urgently. For example, China is rich in CBM resources. The geological resources of CBM up to the depth of 2000 meters are about $36.81 \times 10^{12} \text{m}^3$, which is equivalent to conventional natural gas resources. In recent years, China has increased investment in the CBM industry and given policy support, but the results of large-scale development and rapid capacity building are far

from achieving the desired results. As of December 2017, China has put about 11500 vertical CBM wells into operation. The average single well gas production is only 800 m³/d, and 300 horizontal CBM wells has also been put into operation. The average single well gas production is only 6000 m³/d.

The reasons for the low gas production rate in CBM wells are complex. Coal seam plugging is one of prominent reasons for reducing the production of CBM wells. Coal seam plugging causes a reduced permeability of the coal seam, a smaller drainage pressure range, and a decreased gas production and water production. Thus, the overall production of CBM wells is reduced. Sometimes, wells are even scrapped. In the CBM Hancheng block(H block) in China, 936 wells CBM wells were put into operation before December 2017, but most of the CBM wells are now plugged to different degrees. Of them, 96 wells are plugged seriously. The daily gas and water production levels of these 96 CBM wells were high at an early time, but they decreased sharply after 30 days. After 150 days, the daily gas and water production rates of these 96 CBM wells were nearly zero.

Coal seam plugging is caused by two factors: (1) during the process of drilling, fracturing, and drainage, the pulverized coal, which occupies the seepage channel in the coal seam, is not easily discharged from the coal seam and wellbore, and (2) the pulverized coal mixed with other substances from the coal seam, cap layer, underburden, and gangue adheres to the flow channel and becomes more difficult to discharge. With the continuous production of CBM wells, increasingly more blockage

substance is generated. Part of the blockage is discharged from the wellbore, while the rest of the blockage gathers in the coal seam around the wellbore.

In order to remove the plugging, various technologies (Palmer et al., 1993; Ni et al., 2012; Keshavarz et al., 2016; Teng et al., 2016; Xu et al., 2017) such as acidizing, repeated fracturing, cavity completion, high energy gas injection, and electric pulse have been explored and tested in the field. The effect of these technologies has been partly good and partly poor, and it has changed with the area. Therefore, an effective coal seam plugging removal method is required.

1.2 Problem statement

In order to develop an effective coal seam plugging removal method, conventional oil and gas reservoir stimulation including fracturing and acidizing (Harry O. McLeod, 1984; Fadele et al., 2000; Zimmermann et al., 2011; Shafiq and Mahmud, 2017) is considered to be used in CBM wells. Hydraulic fracturing has become an effective and common method for CBM production (Palmer, 2010; Soliman et al., 2012; Zheng et al., 2013; Zhou et al., 2015; Li et al., 2018), but acidizing is rarely used in CBM production, and few reports about the acidizing of CBM wells have appeared in the literature. The reason for this is that acid has no chemical reaction with coal. Accordingly, it is generally believed that acidizing in CBM production will not achieve the desired effect and the acidizing of CBM wells is not feasible. This view has been validated in some field trials, but other field tests of the acidizing of CBM wells have

shown that acidizing greatly improves production. Therefore, the feasibility of the plugging removal technology of the acidizing of CBM wells is unclear.

If the plugging removal technology of acidizing is feasible, the optimal design including parameters in operation and acid formulation should be completed before acidizing is carried out. The optimal design will enhance the acidizing effect: thus, the feasibility criterion will be fixed. Therefore, feasibility analysis and optimal design are closely related, and the study of each part will provide technical support for improving CBM production.

1.3 Research objectives and scope

The main objectives of this thesis are the feasibility analysis of the acidizing of CBM wells, the optimization design of the acidizing of CBM wells, and the application of feasibility analysis and the optimal design in the field. The feasibility analysis and optimization design will be based on establishing the corresponding model and solving the model. Then the judgment criteria and optimization scheme are put forward for the CBM layer. This judgment criteria and optimization scheme are confirmed by subsequent field operation. Typical wells will be discussed in detail in this thesis. The research scope of this thesis is as follows:

(1) Feasibility analysis of the acidizing of CBM wells

The X-ray diffraction experiment shows that the feasibility of the acidizing of CBM wells is related to the content of acid soluble minerals. Considering the cost and convenience of implementation, well logging data and a neural network are used to

predict acid soluble content instead of X-ray diffraction. The corresponding criteria for determining the feasibility of the acidizing of CBM wells in the H block are put forward.

(2) Optimal design of the acidizing of CBM wells

Based on the existing acidizing numerical model, a forward model of the acidizing of CBM wells is established. The improved G-M algorithm based on maximum probability and random initial value is used to inverse the parameters. According to the corresponding constraint condition, the volume of acid and the injection rate of acid are optimized. Meanwhile, because of optimization design, the corresponding criteria has been improved.

(3) Field case

A typical H082 well is selected as an example. The background information is introduced, and then the feasibility of acidizing, the diagnosis of plugging, the optimal design, and the acidizing effect are elaborated. The results of application confirm the results of the feasibility analysis and the optimal design.

1.4 Methodology

In order to fulfill the proposal presented in Section 1.3, a series of experiments and modeling were carried out for the study and a series of field applications was conducted for verification. To analyze the feasibility of the acidizing of CBM wells, an X-ray diffraction experiment and a neural network node debugging experiment were carried out. To optimize the design of the acidizing of CBM wells, the forward model acidizing of CBM wells based on the existing numerical acidizing model was established, and

the G-M algorithm was improved to include inverse parameters based on the maximum probability and random initial value. Both the experimental results and the conclusions of the modeling are confirmed by field application.

1.5 Thesis outline

This thesis is composed of five chapters. Chapter 1 contains the research background of this thesis. Based on the research topic, the corresponding objective, scope, and methodology of this study are also mentioned in this chapter. Chapters 2 and 3 discuss the feasibility analysis and the optimization design of CBM acidizing in detail. These two chapters contain the literature review, experimental introduction, experimental procedure descriptions, model establishment, model solution, result analysis, and summary. Chapter 4 is the field application of the results of Chapters 2 and 3. The application confirms the conclusions in Chapters 2 and 3. Chapter 5 summarizes the previous chapters and provides recommendations for the future development of the acidizing of CBM wells.

CHAPTER 2 FEASIBILITY ANALYSIS OF THE ACIDIZING OF COALBED METHANE WELLS

2.1 Introduction

Acidizing is a technology that injects acid into pores and fractures of formation under reservoir rock breakdown pressure. Its purpose is to dissolve solid particles produced during drilling, completion, and workover so as to relieve reservoir damage, dredge the flow channel, and improve the productivity of oil and gas wells.

Although acidizing is used to increase the production of conventional oil and gas reservoirs, it is seldom used to increase the production of CBM wells, and there is almost no literature on the acidizing of CBM wells. As there is no chemical reaction between acid and coal, it is generally believed that acidizing will not achieve the desired effect in increasing the production of CBM wells. This view has been verified in some field tests, but other field tests have achieved good results. Therefore, the feasibility of the acidizing of CBM wells is not clear, and it is the primary issue studied in this thesis.

The feasibility of the acidizing of CBM wells is closely related to the effect of the acidizing of CBM wells (i.e. daily water production and daily gas production after acidizing). Therefore, the key to studying the feasibility of the acidizing of CBM wells is the prediction method of the acidizing effect. From the theoretical research point of view, the prediction method can be divided into two parts: (1) the prediction method

of the acidizing effect based on numerical simulation, and (2) the prediction method of the acidizing effect based on statistical analysis.

2.1.1 Prediction method of the acidizing effect based on numerical simulation

Many numerical simulation models have been developed to simulate the acidizing process in conventional oil and gas reservoirs. Generally speaking, the numerical simulation models for acidizing can be divided into two categories. The first category describes the pore structure changes after complex three-dimensional space acid injection by introducing the pore size distribution function from the microscopic perspective, which mainly includes the capillary model (Schecher and Gidley, 1969) and the slow reaction model (Williams and Whiteley, 1971). The second category determines the content of soluble minerals, the dissolution rate of the minerals, and the relationship between permeability and porosity by experiment. It describes the principle of acid-rock reaction macroscopically. This kind of model mainly includes the lumped parameter model (McCune et al., 1975), the distributed parameter model (Hekim and Fogler, 1980), and the heterogeneous model (Hill and Rossen, 1994).

The acidizing of CBM wells has its own specialty. The numerical simulation model that is suitable for acidizing in a conventional reservoir cannot be directly to predict the effect of the acidizing of CBM wells. In fact, the CBM reservoir mainly depends on adsorption. When the pressure of the coal seam falls under the desorption pressure, the CBM is separated from the surface of micro-pores and diffused into fractures through the matrix and micro-pores. Then it flows into the wellbore through fractures.

Moreover, the numerical simulation needs to input accurate parameters. Incorrect input parameters will inevitably get the wrong numerical simulation results, so it is very difficult to study the feasibility of the acidizing of CBM wells by using the prediction method of the acidizing effect based on numerical simulation.

2.1.2 Prediction method of the acidizing effect based on statistical analysis

Compared with the numerical simulation method, it is easier to realize the prediction of the acidizing effect of CBM wells by means of statistical analysis. For example, in the selection of conventional oil and gas reservoir fracturing, qualitative description is applied as the criteria for selecting wells and layers in fracturing (Economides and Nolte, 2001), and it is usually revised by statistical analysis during operation. In order to quantify the selection of fractured wells, some methods such as the grey correlation method (Xie et al., 2005), distance discriminant (Li et al., 2015), fuzzy comprehensive evaluation model (Jin et al., 2004), and neural network model (Lu et al., 2009) are used to predict the fracturing effect of conventional oil and gas reservoirs.

The statistical analysis method (such as the neural network model) requires a large number of field application samples. At the same time, the factors affecting the acidizing effect of CBM wells are complex, so it is very difficult to study the feasibility of coalbed methane acidification by using the prediction method of the CBM acidification effect based on statistical analysis.

2.2 Feasibility criteria

2.2.1 Correlation between the acidizing effect and the content of acid soluble minerals

The effect and feasibility of acidizing are different for different kinds of plugging. In order to evaluate the acidizing effect, the recovery rate of permeability (i.e., the formation permeability after acidizing divided by the initial formation permeability) should be measured theoretically. However, for the field case, the daily water/gas production recovery rate (i.e. the highest daily water/gas production after acidizing divided by the initial daily water/gas production) is used to measure the effect since using the value of the field production data instead of the value of calculations is more objective. The daily water recovery rate is the foremost factor while the daily gas production recovery rate is a minor factor, because it takes a long time for gas to recover and other factors influence gas production.

In the CBM H block in China, the acidizing field tests of 8 CBM wells were carried out in the previous period (three years before this research), and the effect was partly good and partly poor. In order to determine the reasons for the differences in the acidizing effect on CBM wells, the authors conducted experiments. Table 2.1 shows the mineral content of the plugging in the 8 CBM wells analyzed by X-ray diffraction.

From Table 2.1, although coal has no chemical reaction with acid, the mineral content of plugging is complex and varied. Within the table, except gypsum and barite, other 7 types of minerals can react with acid. In fact, the plugging mineral components

are different from coal because the plugging is formed by pulverized coal mixed with other material from the coal seam, overburden, underburden, and coal seam gangue.

The correlation between the acidizing effect of these 8 CBM wells and the mineral content of the plugging material is analyzed. The content of the plugging material is the sum of the content of 7 types of minerals except gypsum and barite. It can be seen from Fig. 2.1 that, although the correlation between the acidizing effect and each mineral content is not strong, if the dolomite, siderite, hematite, silicate, and other minerals which can react with the acid (the acid-soluble plugging mineral content) are accumulated, the acidizing effect is strongly correlated with the acid-soluble plugging mineral content.

It can also be seen from Fig. 2.1 that the acidizing effect is positively correlated with the acid-soluble plugging mineral content in weight. An new solid acid is used in this acid test which will be illustrated in detail in Chapter 3.5. In fact, the acid does not react with pulverized coal, but it can react with acid-soluble minerals. Therefore, acidizing reduces the volume of plugging and its ability to adhere to the flow channel which promotes the discharge of the plugging. Anyway, the higher the acid-soluble plugging mineral content, the better the acidizing effect.

Table 2.1 The analysis result of X-ray diffraction

Well	Quartz	Feldspar	Calcite	Dolomite	Gypsum	Barite	Siderite	Hematite	Clay
no.	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
1	18.88	2.97	0.77	6.83	22.37	21.86	7.53	17.53	1.26
2	9.80	1.17	1.96	1.17	43.95	25.32	3.49	8.20	4.94
3	20.24	2.11	12.22	21.18	1.43	8.22	7.56	23.56	3.48
4	3.82	1.04	1.42	1.58	29.67	58.38	0.55	2.07	1.47
5	25.54	3.88	9.86	17.93	0.16	2.50	8.93	27.73	3.47
6	9.82	2.93	13.82	10.59	16.97	11.97	7.72	22.66	3.52
7	2.77	4.05	0.95	1.21	35.78	21.24	19.59	9.65	4.76
8	34.18	1.12	14.75	1.36	7.09	11.46	7.83	19.31	2.90

Fig. 2.1 The correlation between the content of acid soluble minerals in the plugging and the acidizing effect

2.2.2 Preliminary feasibility criteria

Using linear regression, according to the linear relationship between the acidizing effect and the acid-soluble plugging mineral content, it can be determined that, in the H block, if the acid-soluble plugging mineral content is more than 80%, then the acidizing effect is good. If the acid-soluble plugging mineral content is between 40% and 80%, the acidizing effect is modest. If the acid-soluble plugging mineral content is less than 40%, the acidizing effect is poor. Inspired by this, for the H block, this thesis presents the preliminary CBM acidizing feasibility criteria in Table 2. According to this criterion, in these 8 CBM wells, the acidizing effect of two CBM wells (25.0%) was obvious, the acidizing effect of three CBM wells (37.5%) was modest, and the acidizing effect of three CBM wells (37.5%) was poor. Overall, the average daily water production recovery rate of these 8 CBM is 51.3%, which belongs to the modest effect. It should be indicated that, for different regions, depending on the different conditions and exploitation strategy, the feasibility criteria will be changed.

It should be pointed out that the preliminary feasibility criterion is based on the early 8 CBM wells. The problem is that the size of sample is small and the research is not extensive. Nevertheless, it is the foundation of further precise feasibility analysis. Based on Table 2.2, in the H block, the acidizing feasibility criteria were identified as wells with an acid-soluble plugging mineral content of more than 80%. This criterion is based on the condition and policy in H block. For other region, the criterion is different. Except for special reasons (e.g., sometimes based on validation

considerations or sometimes in terms of overall operation, etc.), the later selection of CBM wells are in accordance with this feasibility criteria.

Table 2.2 The preliminary feasibility criteria of acidizing

The content of acid soluble mineral	Judgment	Acidizing suggestion
<40%	Poor effect	No
40%—80%	Modest effect	No
>80%	Obvious effect	Yes

2.3 Influencing factors of acid soluble minerals

In order to apply the above feasibility criteria, it is necessary to know the content of acid soluble mineral of the plugging. Considering the cost, it is impossible to carry out X-ray diffraction analysis of the plugging for every CBM well. Meanwhile, it may not be possible to obtain an experimental sample of the plugging in the field. Thus, to conduct a feasibility analysis of acidizing, we must find another way to predict the acid soluble mineral content of the plugging.

2.3.1 Theoretical analysis

In order to establish the model, we first analyze the factors affecting the content of acid soluble minerals of plugging. Because the plugging is formed by pulverized coal mixed with other material from the coal seam, overburden, underburden, and coal seam gangue, the well logging parameters of the coal seam, overburden, underburden, and coal seam gangue are considered influencing factors.

In log interpretation, the longitudinal wave time difference when an acoustic wave propagates in rock is measured by compensated acoustic logging (Lai et al., 2018). The shear wave time difference when the acoustic wave propagates in rock can generally be obtained from full-wave logging. When shear wave logging data are not available, the shear wave time difference is calculated by using density (DEN) ρ_b and longitudinal wave time difference (AC) in logging data according to the empirical relationship between the shear wave and longitudinal wave, as shown in Eq. (2.1):

$$\Delta t_s = \frac{\Delta t_p}{(1 - 1.15 \frac{1/\rho_b + (1/\rho_b)^3}{e^{1/\rho_b}})^{1.5}} \quad (2.1)$$

If the shear wave logging data can be measured in the field, known as the shear wave time difference Δt_s , the following formula can be used to match it:

$$\Delta t_s = \frac{\rho_b \Delta t_p^2}{a_t \Delta t_p + b_t \rho_b + c_t} \quad (2.2)$$

In this formula, a_t , b_t , c_t are conversion parameters which are different in different regions. The conversion parameters can be obtained by matching the existing shear wave data and then the shear wave time difference data can be obtained more precisely and accurately.

The formulas for calculating the dynamic Poisson's ratio γ_d and dynamic elastic modulus E_d of rocks (Anderson et al., 1973) are as follows:

$$\gamma_d = \frac{\Delta t_s^2 - 2\Delta t_p^2}{2(\Delta t_s^2 - \Delta t_p^2)} \quad (2.3)$$

$$E_d = (\frac{\rho_b}{\Delta t_s^2}) (\frac{3\Delta t_s^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}) \times 10^9 \quad (2.4)$$

The elastic parameters calculated by the logging method are dynamic parameters. According to the mechanism of stress formation, the occurrence and action of underground rocks, especially in the aspects of in-situ stress amplitude, loading speed, and rock deformation, are closer to the static test conditions. The dynamic Poisson's ratio γ_d and the dynamic elastic modulus E_d are transformed into static Poisson's ratio γ_s and static elastic modulus E_s by linear regression

$$\gamma_s = a_\gamma + b_\gamma \gamma_d \quad (2.5)$$

$$E_s = a_E + b_E E_d \quad (2.6)$$

where a_γ and b_γ are the conversion parameter of Poisson's ratio and a_E and b_E are the conversion parameter of elastic modulus.

The tensile, compressive, and shear strength of rock reflect the characteristics of rock under various pressures, which mainly comes from the mechanical experiment of the core. Based on the statistical relationship between the uniaxial compressive strength of rock and elastic modulus and the statistical relationship between the uniaxial compressive strength of rock and the clay content of rock (Deere and Miller, 1966), using the gamma value (GR) in logging data and calculated static elastic modulus E_s , tensile strength is calculated according to the following formula:

$$I_{sh} = \frac{GR - GR_{\min}}{GR_{\max} - GR_{\min}} \quad (2.7)$$

$$V_{sh} = \frac{2^{2^* I_{sh} - 1}}{2^2 - 1} \quad (2.8)$$

$$S_t = E_s (a_s + b_s V_{sh}) \quad (2.9)$$

where a_s and b_s are the conversion parameters of tensile strength.

In conclusion, from well logging interpretation, the acid soluble mineral of the plugging is closely related to rock property, rock components, and rock strength where the rock property and rock components are characterized by natural gamma (GR) and the rock strength is measured by rock density (DEN) and acoustic interval transit time (AC). Therefore, within all well logging parameters, GR, DEN, and AC of the coal

seam, overburden, and underburden, respectively (ignoring the coal seam gangue), are selected as main influencing factors of the acid soluble mineral of the plugging.

2.3.2 Verification of influencing factors using field data

The above analysis requires field data to be proven. In the H block, we collect the plugging data of 35 CBM wells (excluding the data from the 8 CBM wells tested in previous research). By X-ray diffraction, we obtain the acid soluble minerals in the plugging. Meanwhile, we obtain the GR, DEN, and AC of the coal seam, overburden, and underburden, respectively. The data from these 43 wells are shown in Table 2.3. The correlation between the acid soluble minerals in the plugging and these 9 well logging parameters are shown in Fig. 2.2. From Fig. 2.2, the absolute values of correlation coefficient between these 9 parameters and the acid soluble minerals of the plugging are all more than 0.8, which indicates that they have a strong correlation.

Table 2.3(a) The data of the acid soluble minerals of DEN, AC, and GR in the coal seam

No.	DEN	AC	GR	Acid soluble
	(g/cm ³)	(μs/m)	(API)	mineral content
	Coal seam			(%)
1	1.43	413	30	55.77
2	1.45	421	27	30.73
3	1.45	290	62	90.35
4	1.31	413	28	11.95
5	1.46	322	74	97.34
6	1.45	330	36	71.06
7	1.42	389	34	42.98
8	1.46	321	39	81.45
9	1.45	301	72	91.25
10	1.32	392	36	25.31
11	1.50	310	50	85.52
12	1.34	425	26	15.07
13	1.41	375	55	62.77
14	1.49	322	47	63.36
15	1.48	395	48	61.38
16	1.52	365	94	93.49
17	1.44	381	36	43.36
18	1.59	290	102	98.26
19	1.41	403	35	44.20
20	1.46	327	59	75.82
21	1.40	395	37	45.96
22	1.52	336	45	67.23
23	1.47	315	59	78.33

Table 2.4(a) continued The data of the acid soluble minerals of DEN, AC, and GR of the coal

seam				
No.	DEN (g/cm ³)	AC (μs/m)	GR (API)	Acid soluble mineral content (%)
Coal seam				
24	1.45	402	36	52.29
25	1.53	301	67	85.84
26	1.38	398	32	36.22
27	1.44	366	41	58.55
28	1.46	329	46	66.52
29	1.43	338	39	57.16
30	1.53	313	96	95.27
31	1.41	322	55	64.55
32	1.51	325	92	93.50
33	1.44	359	63	86.38
34	1.43	347	58	72.79
35	1.41	377	39	42.50
36	1.45	341	60	75.63
37	1.46	326	65	83.50
38	1.42	345	51	61.92
39	1.39	396	37	41.38
40	1.49	320	88	95.45
41	1.45	304	41	78.35
42	1.43	338	39	52.22
43	1.51	365	91	94.73

Table 2.5(b) The data of the acid soluble mineral of DEN, AC, and GR of the overburden

No.	DEN	AC	GR	Acid soluble
	(g/cm ³)	(μs/m)	(API)	mineral content
	Overburden			(%)
1	2.25	150	73	55.77
2	2.21	282	66	30.73
3	2.68	126	106	90.35
4	2.14	292	38	11.95
5	2.60	128	140	97.34
6	2.40	180	66	71.06
7	2.37	267	58	42.98
8	2.49	102	80	81.45
9	2.59	117	126	91.25
10	2.25	257	39	25.31
11	2.60	126	82	85.52
12	2.21	277	47	15.07
13	2.38	166	56	62.77
14	2.37	141	88	63.36
15	2.37	243	77	61.38
16	2.45	115	156	93.49
17	2.38	198	59	43.36
18	2.55	105	174	98.26
19	2.41	214	76	44.20
20	2.53	236	82	75.82
21	2.39	206	78	45.96
22	2.39	145	90	67.23
23	2.47	210	81	78.33

Table 2.6(b) continued The data of the acid soluble mineral of DEN, AC, and GR of the overburden

No.	DEN	AC	GR	Acid soluble
	(g/cm ³)	(μs/m)	(API)	mineral content
	Overburden			(%)
24	2.28	192	71	52.29
25	2.36	138	93	85.84
26	2.40	290	52	36.22
27	2.36	197	66	58.55
28	2.37	142	85	66.52
29	2.38	184	49	57.16
30	2.62	125	148	95.27
31	2.42	204	61	64.55
32	2.57	112	139	93.50
33	2.40	160	160	86.38
34	2.58	228	85	72.79
35	2.36	211	72	42.50
36	2.49	156	81	75.63
37	2.56	149	96	83.50
38	2.44	217	63	61.92
39	2.40	198	71	41.38
40	2.48	172	166	95.45
41	2.53	137	69	78.35
42	2.43	163	72	52.22
43	2.46	171	159	94.73

Table 2.7(c) The data of the acid soluble mineral of DEN, AC, and GR of the underburden

No.	DEN	AC	GR	Acid soluble
	(g/cm ³)	(μs/m)	(API)	mineral content
	Underburden			(%)
1	2.32	188	62	55.77
2	2.03	295	51	30.73
3	2.76	130	115	90.35
4	1.96	350	36	11.95
5	2.54	145	145	97.34
6	2.31	168	90	71.06
7	2.34	206	55	42.98
8	2.36	201	138	81.45
9	2.51	159	140	91.25
10	2.08	295	33	25.31
11	2.42	170	125	85.52
12	1.99	356	53	15.07
13	2.39	154	81	62.77
14	2.48	133	91	63.36
15	2.51	210	80	61.38
16	2.52	112	196	93.49
17	2.33	212	54	43.36
18	2.59	148	182	98.26
19	2.44	204	43	44.20
20	2.46	206	94	75.82
21	2.43	213	46	45.96
22	2.46	138	92	67.23
23	2.45	183	98	78.33

Table 2.8(c) continued The data of the acid soluble mineral of DEN, AC, and GR of the

underburden				
No.	DEN (g/cm ³)	AC (μs/m)	GR (API)	Acid soluble mineral content (%)
24	2.35	181	60	52.29
25	2.52	153	118	85.84
26	2.17	286	65	36.22
27	2.43	165	76	58.55
28	2.42	133	88	66.52
29	2.42	152	74	57.16
30	2.56	135	165	95.27
31	2.43	165	85	64.55
32	2.53	151	147	93.50
33	2.35	160	128	86.38
34	2.27	210	96	72.79
35	2.35	227	44	42.50
36	2.31	197	103	75.63
37	2.47	137	105	83.50
38	2.46	178	83	61.92
39	2.32	209	41	41.38
40	2.59	125	150	95.45
41	2.31	183	112	78.35
42	2.33	181	61	52.22
43	2.57	158	173	94.73

Fig. 2.2(a) The correlation between DEN and the acid soluble mineral of the plugging in the coal seam

Fig. 2.3(b) The correlation between AC and the acid soluble mineral of the plugging in the coal seam

Fig. 2.4(c) The correlation between GR and the acid soluble mineral of the plugging in the coal seam

Fig. 2.5(d) The correlation between DEN and the acid soluble mineral of the plugging in the overburden

Fig. 2.6(e) The correlation between AC and the acid soluble mineral content of the plugging in the overburden

Fig. 2.7(f) The correlation between GR and the acid soluble mineral of the plugging in the overburden

Fig. 2.8(g) The correlation between DEN and the acid soluble mineral of the plugging in the underburden

Fig. 2.9(h) The correlation between AC and the acid soluble mineral of the plugging in the underburden

Fig. 2.10(i) The correlation between GR and the acid soluble mineral of the plugging in the underburden

2.4 Prediction method

Then, based on research and verification, we propose a method to predict the acid soluble minerals in the plugging with the artificial neural network (ANN). In this thesis, we chose the BP network, which is the most common ANN today. The BP network is a supervised training technique that sends input values forward through the network and then computes the difference between the predicted result and the corresponding desired result from the training data. The error is then propagated backward through the net, and the weights are adjusted. The process stops when the predicted results are the best approximate of the desired results (Bhatt and Helle, 2002). Three-layer BP networks with two hidden layers are proposed here. The Levenberg-Marquarac (L-M) algorithm is used for its fast convergence speed (Burney et al., 2004).

2.4.1 Establishment of the artificial neural network (ANN)

In the neural network model for predicting the acid soluble minerals in the plugging, there are 9 nodes in the input layer which are the GR, DEN, and AC of the coal seam, overburden, and underburden, respectively, and one node in the output layer, which is the acid soluble mineral of the plugging. According to experience, the number of nodes in the hidden layer is generally 8 to 15. After testing, we apply two hidden layers and each hidden layer has 12 nodes. Therefore, the model for predicting the acid soluble minerals in the plugging is determined as $9 \times 12 \times 12 \times 1$, which is shown in Fig. 2.3.

Finally, we use 43 samples in Table 3 to train and validate the ANN model. We divide the samples into two sets: one for training and the other one for validation. For

example, we randomly select 37 samples (in Table 3, except Nos. 6, 10, 19, 25, 30, and 42) to train. The average accuracy of matching is 99.17%. The left 6 samples are used to validate the accuracy of the prediction. The average accuracy of the prediction is 90.24%. We conduct 10 tests like the above training and validation. For all, the average accuracy of prediction is more than 85%.

Fig. 2.11 The structure of the ANN

2.4.2 Application and verification of the ANN

Finally, we use the 43 samples in Table 2.3 to train and verify the established ANN model. We divide the samples into two sets: one for training and the other for verification. The first set is a random selection of 37 samples (the ones listed in Table 2.3, except for Nos. 6, 10, 19, 25, 30, and 42). This set is used for model training and matching. The average matching accuracy rate is 99.17%. The second set is comprised of the remaining 6 samples, and it is used to verify the accuracy of the prediction results. The prediction results are shown in Table 2.4. The average accuracy rate is 90.24%.

For another example, the first set is randomly selected 35 samples (the ones listed in Table 2.3 except Nos. 3, 11, 17, 22, 27, 31, 36, and 39) for model training and matching. The average accuracy of the matching results is 99.36%. The second set is the remaining 8 samples, which is used to verify the accuracy of the prediction results. The prediction results are shown in Table 2.5. The average accuracy rate is 90.03%.

We have carried out similar training and verification a total of 10 times. The accuracy of the all prediction results are more than 85%. Therefore, it is accurate to predict the content of acid soluble minerals by the ANN.

Table 2.9 The comparison between the prediction value of the ANN of the content of acid soluble minerals and actual value of the content of acid soluble minerals (6 samples)

No.	Actual value of content of acid soluble minerals	Prediction value of content of acid soluble minerals	Relative error
	(%)	(%)	(%)
6	71.06	75.52	6.28
10	25.31	28.91	14.22
19	44.20	39.26	11.18
25	85.84	77.13	10.15
30	95.27	89.76	5.78
42	52.22	46.49	10.97

Table 2.10 The comparison between the prediction value of the ANN of the content of acid soluble minerals and the actual value of content of acid soluble minerals (8 samples)

No.	Actual value of content of acid soluble minerals	Prediction value of content of acid soluble minerals	Relative error
	(%)	(%)	(%)
3	90.35	83.26	7.85
11	85.52	75.83	11.33
17	43.36	45.17	4.17
22	67.23	74.61	10.98
27	58.55	50.27	14.14
31	64.55	71.50	10.77
36	75.63	85.31	12.80
39	41.38	44.59	7.76

2.5 Chapter summary

(1) The X-ray diffraction experiment shows that the coalbed plugging contains acid soluble material.

(2) The field case of coalbed acidizing shows that the acidizing effect is related closely to the content of the acid soluble material.

(3) After analyzing the influencing factors of content of acid soluble mineral, based on the logging data (GR, AC, DEN) of the coal seam, cap layer, and underburden, respectively, a neural network model for predicting the content of acid soluble material in the plugged region was established.

(4) A feasibility criterion is proposed to determine the selected work of the acidizing of the coal layer.

CHAPTER 3 PLUGGING DIAGNOSIS AND OPTIMAL DESIGN

3.1 Introduction

The optimal design of acidizing should be done before acidizing is carried out in the field, because the result of the optimal design will affect the acidizing effect and the feasibility of the acidizing. The design mainly includes optimization of the acid formula, the acidizing process, the acid volume, and the acid injection rate.

For conventional oil and gas reservoirs, the optimization of the acidizing operation parameters sets the acidizing effective radius greater than or equal to the damage radius, and it sets the damage zone permeability greater than or equal to the initial permeability as the constraint condition. It is difficult to remove reservoir damage, dredge flow channels, and improve oil and gas well productivity with less acid. Meanwhile, excessive acid not only causes waste, but it also may cause secondary damage. The damage radius and skin factor are usually obtained by well testing. The formulas for calculating the permeability and porosity of the damage zone are as follows:

$$k_d = k_0 \left(\frac{\ln(r_d / r_w)}{S + \ln(r_d / r_w)} \right) \quad (3.1)$$

$$\phi_d = \phi_0 \left(\frac{k_d}{k_0} \right)^\alpha \quad (3.2)$$

However, the development of CBM follows a low-cost strategy, and it is also limited for other reasons. Well testing interpretation in CBM wells is seldom carried out, so the two parameters (damage radius and skin factor) needed to optimize the

acidizing operation are unknown. Therefore, we need to diagnose the range (damage radius) and the degree of plugging (skin factor) first.

3.1.1 Parameters forward model

The forward model of parameters is to establish the corresponding physical model and mathematical model according to the actual situation and plugging characteristics of the coal seam. By using these models, the pressure can be calculated with known parameters such as the plugging range (damage radius) and the plugging degree (skin coefficient). In fact, if the coal seams are divided into plugged and non-plugged areas, the coal seams are similar to conventional composite reservoirs (Stanislav et al., 1992; Kuchuk and Tarek, 1997; Yang et al., 2005; Xu et al., 2015), which can be solved by establishing mathematical models and solving mathematical models.

3.1.2 Parameters inversion

Parameters inversion is the inverse problem of parameters forward modeling. That is, the pressure is taken as known by the actual measured pressure, and the parameters such as plugging range (damage radius) and plugging degree (skin factor) are obtained. We try to solve the above optimization model by the Newton method (Rosa and Horne, 1983), the Gauss-Marquardt algorithm (Rosa and Horne, 1983; Nanba and Horne, 1992; Barua et al., 1988), the Least Absolute Value approach (Rosa and Horne, 1995), the synthetically using the Step-by-Step Least Linear Square Method and Sequential Quadratic Programming (Guo et al., 2005), and the genetic algorithm (Yin et al., 1999).

Although the above automatic matching method can be used for reference, for the parameters inversion problem of coal seam plugging diagnosis, the selection of the optimization algorithm and the solving of the multi-solution are the challenge of this research.

3.1.3 Optimization of construction parameters

The optimization of acidizing construction parameters is based on the effective radius of acid being greater than or equal to the damage radius and the damage zone permeability being greater than or equal to the initial permeability. The foundation is the acidizing numerical simulation model. As mentioned earlier, for conventional oil and gas reservoirs, acidizing numerical simulation models mainly include the capillary model (Schechter and Gidley, 1969), slow reaction model (Williams and Whiteley, 1971), lumped parameter model (McCune et al., 1975), distributed parameter model (Hekim and Fogler, 1980), heterogeneous model (Hill and Rossen, 1994), and geochemical models (Sevougian et al., 1992; Liu et al., 1997; Chen et al., 1997; Kalia and Glasbergen, 2010). For the acidizing of CBM wells, considering the commonness between the acidizing of CBM wells and the acidizing of conventional oil and gas wells, the numerical simulation model of the acidizing of CBM wells can be selected from the above model, but the constraint condition should be connected with the parameters inversion results of the diagnosis of the plugging.

3.1.4 Optimization of acid component

For the acidizing of conventional oil and gas wells, acids can be roughly divided into five categories (Economides and Nolte, 2001; Shafiq and Mahmud, 2017; Leong and Mahmud, 2018):

- (1) Inorganic acids: including hydrochloric acid, fluoroboric acid, phosphoric acid, hydrochloric acid + hydrofluoric acid (mud acid).
- (2) Organic acids: formic acid and acetic acid.
- (3) Solid acids: amino sulfonic acid and chloroacetic acid.
- (4) Multi component acids: including hydrochloric acid + organic acid mixture, hydrochloric acid + hydrofluoric acid + organic acid mixture.
- (5) Retarded acids: including gelling acid (thickening acid), chemical retarded acid, and emulsified acid.

For carbonate reservoirs, hydrochloric acid, organic acid, emulsified acid, gelling acid (thickening acid), and phosphoric acid are the main types of acid. Among these, hydrochloric acid and organic acid are commonly used and the most efficient.

For sandstone reservoirs or reservoirs with high clay mineral content, the acid types are mainly mud acid and fluoroboric acid. The mud acid mainly dissolves the clay composition and plug in the formation, and the effect of the removal of plugging is good. However, due to the rapid reaction between hydrofluoric acid and minerals and the solubility of mud acid being very strong, hydrofluoric acid is rapidly consumed near the wellbore. The action time is short and the action distance is limited.

Fluoroboric acid is a kind of retarded acid. It can hydrolyze slowly to hydrofluoric acid, and its reaction rate is lower than that of conventional mud acid. Therefore, it can penetrate the reservoir deeply before the acid is exhausted. In addition, fluoroboric acid can also cause the chemical agglomeration of clay particles. The agglomerated particles are cemented, which limits the migration of particles caused by the increase of the flow rate after treatment. Therefore, fluoroboric acid can control the movement of particles in water sensitive formations.

Acetic acid and formic acid are both organic acids. They can be used to acidify sandstone reservoirs. Hydrofluoric acid or fluoroboric acid can also be added to organic acid and hydrochloric acid to dissolve clay components and plugging materials. The plugging removal effect of this combination is better. Hydrochloric acid and organic acid are commonly used acid types. The solubility of organic acid is lower than that of hydrochloric acid and mud acid. Adding organic acid can better control the reaction rate of acid rock and inhibit or retard corrosion.

3.2 Forward model for plugging diagnosis

The acidizing of CBM wells not only has generality with the acidizing of conventional oil/gas wells, but it also has specialty, so the model and solution of the acidizing of CBM wells can be inspired by the model and solution of the acidizing of conventional oil/gas wells. The goal is to remove the plugging of the coal seam. Therefore, the first step of the optimal design is to diagnose the plugging degree and plugging range of the coal seam.

3.2.1 Physical model

According to the actual situation of the CBM reservoir, the coal seam is divided into a plugging area and non-plugging area, which is represented by the inner area (zone 1) and the outer area (zone 2), respectively. The physical model is shown in Fig.

3.1. In order to meet the modeling requirements, it is assumed that the plugging area and the non-plugging area are homogeneous and isotropic porous media. The gas-water flow is simplified as the single-phase flow of the mixed fluid, and the change of the fluid viscosity compression coefficient in the two regions is neglected.

In fact, compared with conventional oil and gas reservoirs, the radius of the inner zone in the physical model is the radius of the damaged zone and the permeability of the inner zone is the permeability of the damaged zone (Peacock et al., 2017). The permeability of the outer zone is the permeability of the initial formation. The porosity of the inner zone is the porosity of the damaged zone, and the porosity of the outer zone is the porosity of the initial formation.

The range and the degree of plugging are used to describe the plugging of the coal seam, which is characterized by the ratio of the plugging radius and the permeability ratio, respectively. The plugging radius refers to the radius of the plugged zone (inner zone), which describes the extent of the coal seam plugging. The permeability ratio refers to the ratio of the permeability of the plugged region (inner zone) to the permeability of the unplugged area (outer zone), which is

$$M_{12} = \frac{k_1}{k_2}. \quad (3.3)$$

The permeability ratio describes the degree of the plugging of the coal seam. When the permeability ratio is larger than or equal to 1, it indicates there is no plugging in the coal seam. When the permeability ratio is less than 1, the coal seam is plugged. The smaller the permeability ratio, the more serious the coal seam is plugged.

Fig. 3.1 Physical model

3.2.2 Establishment of flow model

The parameters forward model is established on a mathematical model of fluid flow, which represents the actual situation and the plugging characteristics of the coal seam. Using this model, the known parameters (plugging radius and permeability ratio) are used to obtain the bottom-hole pressure. In fact, the parameters forward model is for parameters inversion (that is, bottom-hole pressure is known to obtain parameters). Because the parameters inversion process needs to induct the parameter forward model repeatedly, the parameters forward modeling should be quick in terms of calculation speed and stable in terms of calculation results.

To establish the mathematical flow model, the following dimensionless quantity is introduced:

$$p_{wD}(t_D) = \frac{(p_i - p_w)k_1 h}{0.001842qB\mu}, \quad (3.4)$$

$$t_D = \frac{3.6k_1 t}{\phi_1 \mu C_i r_{wa}^2}, \quad (3.5)$$

$$C_D = \frac{C}{2\pi\phi_1 C_i h r_{wa}^2}, \quad (3.6)$$

$$r_{wa} = r_w e^{-S}, \quad (3.7)$$

$$r_{fD} = \frac{r_f}{r_{wa}}, \quad (3.8)$$

$$r_{eD} = \frac{r_e}{r_{wa}}, \quad (3.9)$$

$$\omega_{12} = \frac{\phi_1}{\phi_2}. \quad (3.10)$$

According to the radial flow model, the corresponding differential equations, their initial conditions, and their boundary conditions are obtained by establishing the flow model and the connection conditions of the two regions, respectively, for the plugged and unplugged areas of the coal seam:

Inner region:

$$\frac{1}{r_D} \frac{\partial}{\partial r_D} (r_D \frac{\partial p_{1D}}{\partial r_D}) = \frac{\partial p_{1D}}{\partial t_D} \quad (1 \leq r_D \leq r_{fD}). \quad (3.11)$$

Outer region:

$$\frac{1}{r_D} \frac{\partial}{\partial r_D} (r_D \frac{\partial p_{2D}}{\partial r_D}) = \frac{\omega_{12}}{M_{12}} \frac{\partial p_{2D}}{\partial t_D} \quad (r_{fD} \leq r_D \leq R_D). \quad (3.12)$$

Initial conditions:

$$p_{1D}(r_D, t_D = 0) = 0, \quad (3.13)$$

$$p_{2D}(r_D, t_D = 0) = 0, \quad (3.14)$$

$$p_{1D}(r_{fD}, t_D) = p_{2D}(r_{fD}, t_D). \quad (3.15)$$

Inner boundary condition:

$$\left[C_D \frac{dp_{wD}}{dt_D} - r_D \frac{\partial p_{1D}}{\partial r_D} \right]_{r_D=1} = 1, \quad (3.16)$$

$$p_{wD} = \left[p_{1D} - S \frac{\partial p_{1D}}{\partial r_D} \right]_{r_D=1}. \quad (3.17)$$

Outer boundary condition:

$$p_{2D}(r_D \rightarrow \infty, t_D) = 0, \quad (3.18)$$

The connection condition for the two regions is:

$$\left. \frac{\partial p_{1D}}{\partial r_D} \right|_{r_D=r_{fD}} = \frac{1}{M_{12}} \left. \frac{\partial p_{2D}}{\partial r_D} \right|_{r_D=r_{fD}}. \quad (3.19)$$

3.2.3 Solution of flow model

For the above differential equations (Eqs. (3.11) and (3.12)), taking the Laplace transform to t_D , we can obtain:

$$\frac{1}{r_D} \frac{d}{dr_D} \left(r_D \frac{d\bar{p}_{1D}}{dr_D} \right) = u \bar{p}_{1D} \quad (1 \leq r_D \leq r_{fD}), \quad (3.20)$$

$$\frac{1}{r_D} \frac{d}{dr_D} \left(r_D \frac{d\bar{p}_{2D}}{dr_D} \right) = \frac{\omega_{12}}{M_{12}} u \bar{p}_{2D} \quad (r_{fD} \leq r_D \leq R_D). \quad (3.21)$$

Equations (3.20) and (3.21) are Bessel equations of zero-order deformation. The general form of solution can be given as:

$$\bar{p}_{1D}(r_D, u) = C_1 K_0(r_D \sqrt{u}) + C_2 I_0(r_D \sqrt{u}) \quad (3.22)$$

$$\bar{p}_{2D}(r_D, u) = C_3 K_0(r_D \sqrt{Nu}) + C_4 I_0(r_D \sqrt{Nu}) \quad (3.23)$$

where, C_1, C_2, C_3, C_4 are arbitrary constants.

According to the definite condition, C_1, C_2, C_3, C_4 are determined. The bottom hole pressure can be obtained as:

$$\bar{p}_{wD} = \frac{1}{u} \cdot \frac{1 + S \cdot B_1}{B_1 + C_D u (1 + S \cdot B_1)} \quad (3.24)$$

$$B_1 = \frac{\sqrt{u}}{f_1(\sqrt{u})} \frac{f_{KI1}(\sqrt{u}) - B_2}{f_{KI0}(\sqrt{u}) + B_2} \quad (3.25)$$

$$B_2 = \frac{f_{KI0}(r_{fD} \sqrt{u}) + f_{KI1}(r_{fD} \sqrt{u}) \cdot B_3}{B_3 - 1} \quad (3.26)$$

$$B_3 = \frac{f_I(r_{fD} \sqrt{B_4 u})}{f_I(r_{fD} \sqrt{u})} \cdot \frac{f_{KI0}(r_{fD} \sqrt{B_4 u})}{-f_{KI1}(r_{fD} \sqrt{B_4 u})} \cdot \frac{M_{12}}{\sqrt{B_4}} \quad (3.27)$$

$$B_4 = \frac{\omega_{12}}{M_{12}} \quad (3.28)$$

where,

$$f_{KI0}(x) = \frac{K_0(x)}{I_0(x)}, \quad (3.29)$$

$$f_{KI1}(x) = \frac{K_1(x)}{I_1(x)}, \quad (3.30)$$

$$f_1(x) = \frac{I_0(x)}{I_1(x)}. \quad (3.31)$$

Finally, the above analytic solution is arranged to obtain the Laplace image function of dimensionless bottom hole pressure:

$$\bar{p}_{wD}(u) = \frac{1}{u} \cdot \frac{1 + A_1 S}{A_1 + C_D u (1 + A_1 S)} \quad (3.32)$$

where,

$$A_1 = \sqrt{u} \cdot \frac{K_1(\sqrt{u}) - A_2 I_1(\sqrt{u})}{K_0(\sqrt{u}) + A_2 I_0(\sqrt{u})} \quad (3.33)$$

$$A_2 = \frac{K_0(r_{fD} \sqrt{u}) I_1(r_{fD} \sqrt{u}) + A_3 K_1(r_{fD} \sqrt{u}) I_0(r_{fD} \sqrt{u})}{(A_3 - 1) I_0(r_{fD} \sqrt{u}) I_1(r_{fD} \sqrt{u})} \quad (3.34)$$

$$A_3 = \frac{M_{12}}{\sqrt{\omega_{12}/M_{12}}} \cdot \frac{I_1(r_{fD} \sqrt{u})}{I_0(r_{fD} \sqrt{u})} \cdot \frac{A_4 I_0(r_{fD} \sqrt{u \omega_{12}/M_{12}}) + K_0(r_{fD} \sqrt{u \omega_{12}/M_{12}})}{A_4 I_1(r_{fD} \sqrt{u \omega_{12}/M_{12}}) - K_1(r_{fD} \sqrt{u \omega_{12}/M_{12}})} \quad (3.35)$$

$$A_4 = \frac{K_1(r_{eD} \sqrt{u \omega_{12}/M_{12}})}{I_1(r_{eD} \sqrt{u \omega_{12}/M_{12}})} \quad (3.36)$$

In these equations, I_0 and I_1 are the first type of virtual volume Bessel function of the 0th order and first order, respectively; and K_0 and K_1 are the second type of the virtual volume Bessel function of the 0th order and first order, respectively.

3.2.4 The numerical inversion of Laplace transform

By Eq. (3.32), the dimensionless bottom hole pressure can be solved by the Stehfest numerical inversion method (Stehfest H., 1970). The Stehfest numerical inversion method for obtaining the original function $f(t)$ using the Laplace image function $\bar{f}(z)$ is based on the following formula:

$$f(t) = \frac{\ln 2}{t} \sum_{j=1}^N V_j \bar{f}(z) \quad (3.37)$$

where,

$$z = \frac{j \ln 2}{t} \quad (3.38)$$

$$V_j = (-1)^{j+\frac{N}{2}} \sum_{k=\lceil \frac{j+1}{2} \rceil}^{\min(j, \frac{N}{2})} \frac{k^{\frac{N}{2}+1} (2k)!}{(\frac{N}{2}-k)! (k!)^2 (j-k)! (2k-j)!} \quad (3.39)$$

N must be an even number, and the selection of the value of N is very important, as it directly affects the accuracy of the calculation results. The results show that $N = 6, 8$, and 10 in most cases (otherwise, the accuracy of the calculation results will be significantly reduced). After practice and comparison and considering the speed of calculation and other factors, $N = 8$ is obtained (Abate J. et, 1995).

The bottom-hole pressure in the Laplacian space is calculated according to the Stehfest numerical inversion method, and then the bottom-hole pressure values in real space are obtained.

Table 3.1 The value of N and V_j

N	6	8	10
V_j	$V_1 = 1$	$V_1 = -\frac{1}{3}$	$V_1 = 0.083$
	$V_2 = -49$	$V_2 = 48\frac{1}{3}$	$V_2 = -32.083$
	$V_3 = 366$	$V_3 = -906$	$V_3 = 1279$
	$V_4 = -858$	$V_4 = 5464\frac{2}{3}$	$V_4 = -15623.67$
	$V_5 = 810$	$V_5 = -14376\frac{2}{3}$	$V_5 = 84244.18$
	$V_6 = -270$	$V_6 = 18730$	$V_6 = -236957.5$
		$V_7 = -11946\frac{2}{3}$	$V_7 = 375911.7$
		$V_8 = 2986\frac{2}{3}$	$V_8 = -340071.7$
			$V_9 = 164062.5$
			$V_{10} = -32812.5$

3.3 Solution of parameters inversion of plugging diagnosis

3.3.1 Model of optimization

The diagnosis of the plugging of the coal seam is a parameters inversion problem. As mentioned earlier, the plugging of the coal seam is described by the range and the degree of plugging: specifically, by the plugging radius and permeability ratio. To simplify expression, the parameters (the plugging radius and the permeability ratio) are written in the form of vectors, which are

$$\alpha = (r_f, M_{12}) = (\alpha_1, \alpha_2) \quad (3.40)$$

Parameters inversion is the inverse problem of the parameters forward model. In fact, using the parameters forward model (3.32) and the known parameter α , the bottom-hole pressure can be calculated. The objective function of the parameters inversion model can be taken as the square sum of deviance of the calculated bottom-hole pressure values and the actual measured bottom-hole pressure values, which is

$$F(\alpha) = \sum_{i=1}^n (p_w^{cal}(\alpha, t_i) - p_w^{obs}(t_i))^2 = \sum_{i=1}^n f_i^2(\alpha) \quad (3.41)$$

where $p_w^{cal}(\alpha, t_i)$ is the bottom-hole pressure using the parameter forward model (3.32) to calculate; $p_w^{obs}(t_i)$ is the actual measured bottom-hole pressure; t_i is the actual time point for each actual measurement; and n is the total number of actual measured time points.

Therefore, the parameter inversion process of diagnosing plugging of the coal seam is to adjust parameter α , so that when the optimal solution α^* is obtained, the

calculated bottom-hole pressure is best matched with the actual measured bottom-hole pressure, which is the minimized value of the objective function (3.41). Thus, it is expressed as an optimization model as follows:

$$F(\alpha^*) = \min_{\alpha} F(\alpha) \quad (3.42)$$

3.3.3 Comparison and verification of inversion algorithm

For the above optimization model, we try the Newton method (Rosa and Horne, 1983), the Gauss-Marquardt algorithm (Rosa and Horne, 1983; Nanba and Horne, 1992; Barua et al., 1988), the Least Absolute Value approach (Rosa and Horne, 1995), the synthetically using the Step-by-Step Least Linear Square Method and Sequential Quadratic Programming (Guo et al., 2005), and the genetic algorithm (Yin et al., 1999). We compare and verify the Newton method, the G-M algorithm, the LAV approach, the SLLSM-SQP, and the GA.

The indicators of comparison and verification are the calculation time and the correct rate. The verification method and the correct standard are designed to randomly take a set of the hypothetical value β' of the fracture parameter β to use the model to calculate the bottom-hole pressure. The calculated bottom-hole pressure data are set as the measured bottom-hole pressure data. Then, the automatic matching method is used to find the optimal solution β^* . Finally, it is judged whether the optimal solution obtained is correct: that is, if $\beta^* = \beta'$ (in this thesis, the specific condition is that the average relative error of the four parameters is less than 1%). If so, then the optimal

solution obtained by the verification algorithm is correct. Otherwise, the verification of the optimal solution obtained by the algorithm is incorrect.

In the above verification method, for each automatic matching method, we set 9 hypothetical values for the plugging radius and the permeability ratio, so these two parameters are combined into 81 sets of hypothetical values β' . For each set of β' , we find the optimal solution β^* and judge whether the optimal solution obtained is correct or not. Through the calculation time and the correctness of the optimal solution of these 81 sets, the average calculation time and correct rate of this automatic matching method are counted.

Fig. 6 shows the average calculation time and the correctness of the optimal solution of these five automatic matching methods. From the figure, the accuracy of these five automatic matching methods is low in which the highest accuracy rate is 45.68%, and the lowest accuracy rate is 20.99%. In fact, these automatic matching methods are all local optimization algorithms. The matching result depends on the initial value. In the iterative process, the local optimal solution is incorrectly considered as the global optimal solution. This multi-solution is a common problem of all optimization methods.

The difference of the calculation time of the five automatic matching methods is large. The calculation time of the G-M algorithm is the shortest (3.16s). The calculation time of the GA is the longest (23.70s). Because the correct rate of the optimal solution

for the G-M algorithm is 37.04%, the G-M algorithm has the highest automatic matching efficiency.

Fig. 3.2. The calculation time and correct rate of the five automatic matching methods

3.3.3 Improved algorithm of parameters inversion

We select the Gauss-Marquardt (G-M) algorithm. This algorithm has the advantages of the Newton method and the gradient method, which is a common method to solve the problem of the nonlinear match. In order to solve the problem of the parameters inversion of the plugging of the coal seam, five steps are required:

Step 1. Assignment: The initial value of the inversion parameter $\alpha^{(0)}$, the initial value of the damping factor λ_0 (as 0.01), the adjustment factor of the damping factor γ (as 10) and accuracy ε (as 10^{-4}).

Step 2. $k = 0$, $\lambda = \lambda_0$.

Step 3. $\tau = -1$, $\lambda = \lambda \gamma^\tau$.

Step 4. $f(\alpha^{(k)}) = (f_1(\alpha^{(k)}), f_2(\alpha^{(k)}), \dots, f_n(\alpha^{(k)}))^T$, $F(\alpha^{(k)}) = (f(\alpha^{(k)}))^T f(\alpha^{(k)})$,

$$J = \begin{pmatrix} \frac{\partial f_1(\alpha^{(k)})}{\partial \alpha_1} & \frac{\partial f_1(\alpha^{(k)})}{\partial \alpha_2} \\ \frac{\partial f_2(\alpha^{(k)})}{\partial \alpha_1} & \frac{\partial f_2(\alpha^{(k)})}{\partial \alpha_2} \\ \vdots & \vdots \\ \frac{\partial f_n(\alpha^{(k)})}{\partial \alpha_1} & \frac{\partial f_n(\alpha^{(k)})}{\partial \alpha_2} \end{pmatrix}. \quad (3.43)$$

Step 5. To calculate $P_k = -(J^T J + \lambda E)^{-1} (J^T f(\alpha^{(k)}))$, $\alpha^{(k+1)} = \alpha^{(k)} + P_k$,

$f(\alpha^{(k+1)}) = (f_1(\alpha^{(k+1)}), f_2(\alpha^{(k+1)}), \dots, f_n(\alpha^{(k+1)}))^T$, $F(\alpha^{(k+1)}) = (f(\alpha^{(k+1)}))^T f(\alpha^{(k+1)})$.

Step 6. If $F(\alpha^{(k+1)}) > F(\alpha^{(k)})$, then $\tau = \tau + 1$, $\lambda = \lambda \gamma^\tau$, and turn to Step 5.

Step 7. If $\|J^T f(\alpha^{(k)})\| > \varepsilon$, then $k = k + 1$, and turn to Step 3, else the optimal solution of $\alpha^* = \alpha^{(k)}$.

where E is the unit matrix and $\|J^T f(\alpha^{(k)})\|$ is the module of vector $J^T f(\alpha^{(k)})$.

The above algorithm has been validated. The process is as follows: α' is a random value of parameter α . The bottom-hole pressure is calculated by the parameter forward model (3.32). Then the calculated bottom-hole pressure is set as the actual measured bottom-hole pressure, and the G-M algorithm is used to obtain the optimal solution α^* . Obviously, if $\alpha^*=\alpha'$, the optimal solution is correct. Otherwise, the optimal solution obtained by the verification algorithm is wrong. For the convenience of statistics, the number of the theoretical verification is 100. The results of the theoretical verification show that the G-M algorithm achieves an accuracy of 37% for the optimal solution. The main reason for the error is that the objective function is a highly non-linear function in which the local optimal solution is considered the global optimal solution. This multi-solution problem is a common problem for all optimization methods.

To solve the problem of the multi-solution, this thesis proposes a G-M algorithm based on stochastic initial and maximum probabilities. The multi-solution is because local optimal solutions seem to be the global optimal solution in the conventional G-M algorithm. Although we may obtain different local optimal solutions based on different initial values, the global optimal solution occurs in the largest probability within all optimal solutions. The specific method is: firstly, a large number of initial values are randomly generated (considering the calculation of the workload and the calculation time, 500 sets of random initial value are used). Then, for each initial value, the G-M algorithm is used to obtain the optimal solution. Finally, the global optimal solution is the solution with the largest probability of occurrence.

For this new algorithm, we carried out theoretical verification. The results of theoretical verification show that the accuracy of the optimal solution is 93%, and the multi-solution problem is solved. Meanwhile, from the calculation point of view, each theoretical verification requires an average time of 825 minutes on personal computers. It is estimated that each set of random initial parameters requires an average time-consumption of 1.65 minutes, and each parameter requires less than 0.01 seconds.

3.4 Optimization of construction parameters

The acidizing of CBM wells has generality with the acidizing of conventional oil/gas wells so some of the present numerical acidizing models can be used directly including the temperature calculation model, the acid concentration distribution model, the mineral concentration distribution model, the acid effective radius calculation model, the acid effect prediction model, and the parameters determination method (Liu et al., 1997; Chen et al., 1997; Nitika and Gerard, 2010). Using these models, we can calculate the effective radius of acid L_f and the permeability of the coal seam after acidizing, and then calculate the permeability ratio after acidizing M_{12} .

The acidizing of CBM wells has its own specialty. The objective is to remove the plugging in the coal seam so that the permeability of the plugged area recovers its initial permeability. In other words, the conditional constraint is:

$$L_f \geq r_f \text{ and } M_{12} \geq 1 \quad (3.44)$$

It can be seen that the optimal method of the acidizing of CBM wells is based on the existing acidizing numerical model so that the acid volume and the acid injection rate are optimized. The process is shown in Fig. 3.2.

Fig. 3.3 Process of optimal design

3.5 Optimization of acid formulation

In the acidizing of conventional oil/gas wells, the common acids are hydrochloric acid (HCl), mud acid (hydrochloric acid mixed with hydrofluoric acid (HF)), and these two acid systems mixed with other chemical additives (Economides and Nolte, 2001; Shafiq and Mahmud, 2017; Leong and Mahmud, 2018). In the H block, we used mud acid in the test of the earliest 8 CBM wells. The formulation of mud acid is:

However, because of the safety hazards, high cost, and complex manufacture of liquid acid, we consider developing solid acid in this thesis.

3.5.1 Type of acid

We select solid sulfonic acid ($\text{NH}_2\text{SO}_3\text{H}$), solid ammonium hydrogen fluoride (NH_4HF_2), and liquid acetic acid (CH_3COOH) as the basic component of the acid system. The reason is that (1) the combination of $\text{NH}_2\text{SO}_3\text{H}$ and CH_3COOH help dissolve calcareous cement and ferruginous cement; (2) the acid stays at a low PH value in the formation, so it helps inhibit the generation of sediment of ferric hydroxide ($\text{Fe}(\text{OH})_3$); (3) CH_3COOH helps stabilize iron ions and slow down the reaction rate of acid; and (4) although there is no HF in this acid system, in favor of the ion-exchange between clay minerals in the coal seam and $\text{NH}_2\text{SO}_3\text{H}/\text{NH}_4\text{HF}_2$, HF is slowly generated to remove the plugging of quartz, feldspar, calcite, dolomite, and clay.

Except for the basic component of acid, we select solid 2-Butyne-1,4-diol ($\text{C}_4\text{H}_6\text{O}_2$) and liquid formaldehyde (HCHO) as corrosion inhibitors and solid ammonium chloride

(NH₄Cl) as the anti-swelling agent. We do not select potassium chloride (KCl) as the anti-swelling agent, because when potassium ion exists, HF reacts with clay to generate the sediment of potassium fluorosilicate (K₂SiF₆).

3.5.2 Acid formulation

After test and optimization, based on low cost, safety, convenience, and other factors of the H block, we design the acid formulation as:

The concentration of amino sulfonic acid, ammonium hydrogen fluoride, and acetic acid in the above solid acid formula is determined by the corrosion test. The process is: firstly, acid is prepared as the acid formulation. Then, 5g plugging of each well are added into the acid. After two hours, the leftover plugging is filtered, washed, dried, and weighed. Finally, the dissolution rate is measured.

Figure 3.3 is the correlation between the dissolution rate of solid acid to the plugging of three CBM wells and the concentration of sulfonic acid. From Fig. 3.3, it can be seen that, when the concentration of sulfamic acid is less than 4%, the corrosion rate increases rapidly. When the concentration of sulfamic acid is more than 4%, the corrosion rate increases slowly, so 4% sulfamic acid is a reasonable choice.

Figure 3.4 is the correlation between the dissolution rate of solid acid to the plugging of three CBM wells and the concentration of ammonium hydrogen fluoride. From Fig. 3.4, it is evident that the corrosion rate increases rapidly when the concentration of ammonium hydrogen fluoride is less than 4%. When the concentration

of ammonium hydrogen fluoride is more than 4%, the corrosion rate increases slowly, so 4% ammonium hydrogen fluoride is a reasonable choice.

Figure 3.5 is the correlation between the dissolution rate of acetic acid to the plugging of three CBM wells and the concentration of solid acid. From Fig. 3.5, it can be seen that, when the concentration of acetic acid is less than 2%, the corrosion rate increases rapidly. When the concentration of acetic acid is more than 2%, the corrosion rate increases slowly, so 2% acetic acid is a reasonable choice.

The concentration of formaldehyde and butynediol in a solid acid formulation is determined by the corrosion tests. This experiment is in the oven under 303.15K to simulate the coal seam temperature. The process is as follows: firstly, acid is prepared as the acid formulation. Then, the N80 metal piece, which has already been weighed and its area measured, is put into the acid. After two hours, the metal piece is filtered, washed, dried, and weighed. Finally, the corrosion rate is measured.

Figure 3.6 is the correlation between the corrosion rate of solid acid to the N80 metal piece and the concentration of formaldehyde. From Fig. 3.6, it is evident that the corrosion rate decreases rapidly when the formaldehyde concentration is less than 1%, and it decreases slowly when the formaldehyde concentration is more than 1%, so 1% formaldehyde is a reasonable choice.

Figure 3.7 is the correlation between the corrosion rate of solid acid to the N80 metal piece and the concentration of butynediol. It can be seen from Fig. 3.7 that the corrosion rate decreases rapidly when the concentration of butynediol is less than 1%,

and it decreases slowly when the concentration of butynediol is more than 1%, so 1% butynediol is a reasonable choice.

In the solid acid formulation, the concentration of ammonium chloride is determined by X-ray diffraction analysis. After the plugging powder was treated with clay stabilizer, the interfacial spacing was obtained by X-ray diffraction analysis. The results can be used to evaluate the clay stabilizer.

Table 3.2 shows the interfacial spacing of plug powder from three CBM wells treated with different concentrations of ammonium chloride. From Table 3.2, when the concentration of ammonium chloride is less than 1%, the interfacial spacing decreases rapidly. When the concentration of ammonium chloride is more than 1%, the interfacial spacing decreases slowly, so 1% ammonium chloride is a reasonable choice.

Fig. 3.4 The correlation between the dissolution rate of solid acid to plugging of three CBM wells and the concentration of sulfonic acid

Fig. 3.2 The correlation between the dissolution rate of solid acid to the plugging of three CBM wells and the concentration of ammonium hydrogen fluoride

Fig. 3.3 The correlation between the dissolution rate of solid acid to the plugging of three CBM wells and the concentration of acetic acid

Fig. 3.4 The correlation between the corrosion rate of solid acid to the N80 metal piece and the concentration of formaldehyde

Fig. 3.5 The correlation between the corrosion rate of solid acid to the N80 metal piece and the concentration of butynediol

Table 3.2 The results of the interfacial spacing experiment of plug powder from three CBM wells treated with different concentrations of ammonium chloride

Ammonium chloride (%)	The interfacial spacing of plugging of the first CBM well	The interfacial spacing of plugging of the second CBM well	The interfacial spacing of plugging of the third CBM well
	(Å)	(Å)	(Å)
0	22.24	20.79	22.57
0.5	17.47	16.97	18.04
1.0	12.93	12.35	13.28
1.5	12.71	12.18	13.05
2.0	12.68	12.12	12.81
Initial powder	12.51	11.85	12.66

3.5.3 Analysis and comparison of the test of acid

We select the plugging of 10 CBM wells in the H block to conduct the dissolution test of this new solid acid. The results are shown in Table 3.3.

From Table 3.3, the highest dissolution rate is 61.93%. The lowest one is 20.65%. The average is 47.85%. These results indicate that the new acid can react with the plugging, so the acidizing of CBM wells is feasible.

Besides, we use the weight loss of the tested piece to conduct a corrosion test. The results are shown in Table 3.4. The average corrosion rate is $2.56 \text{ g/h}\cdot\text{m}^2$.

To compare the mud acid and new solid acid, we conduct the dissolution test and corrosion test of the mud acid as well. The results are shown in Tables 3.5 and 3.6. From Tables 3.5 and 3.6, the average corrosion rate of the mud acid is 35.82% and the average corrosion rate for the N80 metal piece is $4.66 \text{ g/h}\cdot\text{m}^2$. It can be concluded that, compared with the mud acid, the dissolution rate of the new solid acid is increased by 33.60% and the corrosion rate is decreased by 45.01%. Besides, the cost is also decreased by 25%.

Table 3.3 The results of the dissolution test with the plugging of 10 CBM wells and new solid acid

No.	The weight before dissolution (g)	The weight after dissolution (g)	Dissolution rate (%)
1	5.0123	2.7389	45.36
2	5.0327	2.2659	54.98
3	5.0436	2.4441	51.54
4	5.0206	2.3524	53.15
5	4.9997	1.9033	61.93
6	4.9876	3.9576	20.65
7	5.0268	2.7068	46.15
8	5.0347	2.1241	57.81
9	4.9926	2.4318	51.29
10	4.9953	3.2156	35.63

Table 3.4 The results of the corrosion test with the N80 metal piece and new solid acid

No.	Time (h)	Area of metal piece (m ²)	The weight before corrosion (g)	The weight after corrosion (g)	Corrosion rate (g/h·m ²)
1	2	0.001373	10.5393	10.5322	2.58
2	2	0.001379	10.5337	10.5267	2.54

Table 3.5 The results of the dissolution test with the plugging of 10 CBM wells and mud acid

No.	The weight before	The weight after	Dissolution rate
	dissolution (g)	dissolution (g)	(%)
1	5.0022	3.4187	31.66
2	5.0061	2.7381	45.30
3	5.0047	2.8935	42.18
4	5.0025	2.8103	43.82
5	4.9947	2.6727	46.49
6	5.0063	4.3556	13.00
7	4.9977	3.3143	33.68
8	4.998	2.9467	41.04
9	5.0038	3.0133	39.78
10	5.0038	3.9434	21.19

Table 3.6 The results of the corrosion test with the N80 metal piece and mud acid

No.	Time (h)	Area of metal piece (m ²)	The weight before corrosion (g)	The weight after corrosion (g)	Corrosion rate (g/h·m ²)
1	2	0.001387	10.6631	10.6501	4.69
2	2	0.001382	10.5856	10.5728	4.63

3.6 Chapter summary

- (1) A parameters forward model for plugging diagnosis is established.
- (2) A parameter inversion algorithm for plugging diagnosis is proposed.
- (3) The Gauss-Marquardt algorithm based on stochastic initial and maximum probabilities is used to solve the multi-solution problem.
- (4) Based on the present numerical acidizing model, in order to make the effective radius of the acid greater than or equal to the plugging radius and to make the permeability of the plugged region greater than or equal to the initial permeability, the optimal design of acidizing is proposed.
- (5) By experiment and optimization, a new acid formulation is obtained. For the H block, the average dissolution rate is 37.82%. It also indicates the feasibility of the acidizing of CBM wells.

CHAPTER 4 APPLICATION AND ANALYSIS

4.1 Field case

4.1.1 Well information

In this part of the study, the H082 well in the H block is selected as an example. Its data is shown in Table 4.1, and its yield is shown in Fig. 4.1. This well was produced after fracturing treatment. The highest daily water production was 7.15 m³/d and the highest daily gas production was 1489.6 m³/d. However, in the process of fracturing and production, a large amount of pulverized coal was produced. Plugging occurred when the pulverized coal mixed with other material from the coal seam, overburden, underburden, and coal seam gangue. The daily water production decreased to 0.20m³/d on the 291th day, and the daily production of gas decreased to 0 m³/d on the 231st day. Within this time, since the wellbore was plugged, this well had a workover on the 193th day. After the 292th day, the well stopped producing and then a feasibility analysis of acidizing, the optimal design, and preparation for acidizing was conducted. On the 312th day, the well produced again.

Table 4.1 The basic data of Well H082

Parameter	Value
Depth, m	647
Thickness, m	5
Temperature, K	303.15
Pressure at the initial condition, Pa	6.2×10^6
Wellbore radius, m	0.108
Radius of the outer region, m	175
Porosity of the inner region, dimensionless	0.046
Porosity of the outer region, dimensionless	0.046
Permeability of the outer region, m^2	1.35×10^{-15}
Fluid viscosity, Pa s	1×10^{-3}
Formation volume factor, dimensionless	1
Wellbore storage coefficient, m^3/Pa	1000
Comprehensive compressibility, Pa^{-1}	3×10^{-9}

Fig. 4.1 The production of Well H082

4.1.2 Feasibility analysis

X-ray diffraction analysis showed that the acid soluble mineral content was 87.02% (the data has been shown in No. 25 of Table 3) while the acid soluble mineral content predicted by the ANN was 87.02%, so the prediction error was 1.33%. According to the feasibility criteria, Well H082 is feasible for acidizing.

4.1.3 Plugging diagnosis

Because there was a workover on the 193th day of work, the available data is from the first 192 days of pressure data. To distinguish between different uses, this thesis divides these data into two groups. For example, choosing measurement time points $n = 120$, the first set is the first 120 days of data for parameter inversion and pressure fitting. The second group is the 121th day to the 192th day of data, which is used to verify the accuracy of the inversion results.

The results are based on the inversion results of the previous 120 days. The pressure values from the 121th day to the 192th day are calculated by using the parameters forward model (9). The calculated values are compared with the actual values of the second set in Fig. 4.2.

It can be seen from Fig. 4.2 that the average error of the pressure data for matching is 7.21% and the average error of the pressure data for verification is 4.28%. The diagnostic result is that the plugging radius is 1.37 m and the permeability ratio is 0.24.

Fig. 4.2 The pressure matching and verification of Well H081

4.1.4 Optimal design

In order to remove the plugging of the coal seam, the optimal design is used to optimize the parameters of the well acidizing. When the injection rate is $1.2 \text{ m}^3/\text{min}$ and the time is 65 min, the effective radius of the acid is 1.46 m and the permeability ratio is 1.01, as shown in Fig. 4.3, which achieves the goal of removing the plugging of the coal seam (the effective radius of the acid is greater than the plugged radius, and the permeability of the plugged area is greater than the initial permeability). Therefore, the optimized volume of the acid is 78 m^3 and the optimized injection rate is $1.2 \text{ m}^3/\text{min}$.

Fig. 4.3 The change of the effect radius of acid and the permeability ratio of Well H082 with time

4.1.5 Acidizing effect

The well was acidized on the 312th day. The daily water production increased rapidly after acidizing. The highest daily water production reached 7.35 m³/d. The daily water recovery rate was 102.80%. The daily gas production was recovered and steadily controlled. At present, the daily production rate is 2367 m³/d and the daily gas recovery rate has reached 158.01%. Therefore, not only from the results of theoretical calculation, but also from the results of practical production, the feasibility and effect of the acidizing of CBM wells can be confirmed.

4.2 Discussion and results

4.2.1 Overall situation

The above models and methods (the feasibility criteria and the optimal design) are applied in 26 CBM wells in the Hancheng block of China, as shown in Fig. 4.4. The H082 well is one of the representative CBM wells.

The average daily water production recovery rate of the 26 CBM wells is 84.5%. The acidizing effect on these wells is good (the daily water recovery rate is more than 80.0%). From the feasibility criteria, the acidizing effect of 19 CBM wells (73.1%) is obvious, the acidizing effect of four CBM wells (15.4%) is modest, and the acidizing effect of three CBM wells (11.5%) is poor. Compared with the earlier 8 CBM wells, it can be seen from Figs. 1 and 9 that the average daily water production recovery rate increased from 51.3% to 84.5%, so the acidizing effect was greatly improved.

Furthermore, the coincidence rate of the feasibility criteria is not high. According to Table 2.2 and Fig. 4.4, it can be seen that the actual results of 13 CBM wells confirms the prejudgment, so the coincidence rate is 50.0%. In detail, the acidizing effect of 10 CBM wells in the prejudgment is obvious, while the effect of 9 CBM wells in the field is obvious. Thus, the coincidence rate of these 10 CBM wells is 90.0%. The acidizing effect of 11 CBM wells in the prejudgment is modest while the acidizing effect of only one CBM well in the field is modest, so the coincidence rate of these 11 wells is 9.1%. The effect of the remaining 10 CBM wells in these 11 CBM wells is upgraded to obvious, accounting for 90.9%. The acidizing effect of 5 CBM wells in the prejudgment is poor, while the acidizing effect of three CBM wells in the field is poor, so the coincidence rate of these five CBM wells is 60.0%. The effect of the remaining two CBM wells in these five wells is upgraded to modest, accounting for 40.0%.

Fig. 4.4 The correlation between the content of acid soluble minerals in the plugging and the acidizing effect (based on 26 CBM wells)

4.2.2 Improvement of feasibility criteria

The reason for the low coincidence rate of the feasibility criteria is that the criteria was proposed based on the early 8 CBM wells, which is a very small sample. Moreover, due to the application of optimal design, the acidizing effect of the later 26 CBM wells is greatly improved. The feasibility of CBM wells improved remarkably. Therefore, the feasibility criterion of the acidizing of CBM wells should be fixed, as shown in Table 4.2.

Comparing Table 4.2 to Table 2.2, the number of CBM wells which can be recommended for acidizing is increased because of the optimal design. It should be pointed out that this feasibility criterion is based on the H block. It can be used in other regions at an early time, but it will be adjusted depending on different conditions and exploitation strategies.

Table 4.2 Fixed feasibility criterion of the acidizing of CBM wells

Acid soluble mineral content	Judgment	Acidizing suggestion
<40%	Poor effect	No
40%—55%	Modest effect	No
>55%	Good effect	Yes

4.3 Chapter summary

(1) Field application confirms the feasibility and effect of the acidizing of CBM wells.

(2) Acidizing is an effective stimulation technique for some specific CBM wells depending on the content of the acid soluble material in the plugging.

(3) The feasibility diagnosis and optimal design are important to improve the acidizing effect of CBM wells.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

(1) The X-ray diffraction experiment shows that the coalbed plugging contains acid soluble material, and the field case of coalbed acidizing shows that the acidizing effect is related closely to the content of the acid soluble material.

(2) After analyzing the influencing factors of the content of acid soluble mineral, based on the logging data (GR, AC, DEN) of the coal seam, cap layer, and underburden, respectively, a neural network model for predicting the content of acid soluble material in the plugged region is established. A feasibility criterion is proposed to determine the selected work of the acidizing of the coal layer.

(3) A parameters forward model for plugging diagnosis is established. A parameter inversion algorithm for plugging diagnosis is proposed. The Gauss-Marquardt algorithm based on stochastic initial and maximum probabilities is used to solve the multi-solution problem.

(4) Based on the present numerical acidizing model, in order to make the effective radius of the acid greater than or equal to the plugging radius and to make the permeability of the plugged region greater than or equal to the initial permeability, the optimal design of acidizing is proposed.

(5) By experiment and optimization, a new acid formulation is obtained. For the H block, the average dissolution rate is 37.82%. It also indicates the feasibility of the acidizing of CBM wells.

(6) Field application confirms the feasibility and effect of the acidizing of CBM wells. Acidizing is an effective stimulation technique for some specific CBM wells (depending on the content of the acid soluble material in the plugging). The feasibility diagnosis and optimal design are important to improve the acidizing effect of CBM wells.

5.2 Recommendations

(1) The feasibility criteria in this thesis can only be directly used in the H block. For other regions, this feasibility criteria can be used as preliminary feasibility criteria. After testing several wells in the region, a new feasibility criterion which can directly be used in the region should be developed.

(2) Except for well logging data, other parameters can also influence the content of acid soluble minerals in the plugging. These parameters can be added into the ANN model to increase the accuracy of prediction.

(3) A more effective optimal algorithm can be developed to solve the multi-solution problem and improve the accuracy and speed of calculation.

(4) A new acid formulation can be developed to ensure the safety of acidizing a well, improve the dissolution rate and corrosion rate, and reduce the cost.

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