

Development and Application of Foam Drainage System Optimization Software

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Abstract: This study proposes an intelligent decision-making method based on the combination of time series prediction and multi-dimensional evaluation, aiming at the key issues of foam drainage agent dosage control and injection system optimization in foam drainage gas production process of shale gas wells. By constructing a time-series prediction model for gas well production parameters, accurate fitting of dynamic production data such as gas production and gas yield can be achieved; And through the fuzzy comprehensive evaluation model, threshold clustering is used to ultimately obtain the optimal foam drainage system. Based on the above theoretical framework, the foam drainage system optimization software system was developed, and the software operation flow chart, user interface, and functional design considerations are provided. Finally, the software was used to optimize the actual foam drainage system of a shale gas well. The application results show that the software is simple to use, has relatively complete functions, and can provide the optimal bubble discharge system, which has promotional value.

Keywords: Shale gas; Evaluation of Bubble Drainage System; Time series prediction; Fuzzy comprehensive evaluation; Threshold clustering.

1. Introduction

During the process of oil extraction, water is produced along with natural gas and enters the middle and late stages of extraction. In the middle and late stages of extraction, the accumulation of liquid in gas wells will lead to a significant decrease in production capacity. Foam drainage gas production technology refers to the use of foam agent to separate water and natural gas, so that natural gas can escape from the water smoothly. It is widely used in natural gas exploitation. However, it is difficult to master the proportion and injection volume of foam agent, which requires experienced operators to operate, greatly affecting the exploitation efficiency. Therefore, it is necessary and practically valuable to develop a bubble discharge system optimization software. [1-5]

The current mainstream optimization method for bubble discharge system is based on time series models to predict the trend of water production changes. Although it has achieved certain results, significant shortcomings remain: (1) only focusing on a single water production indicator, ignoring the coupling effect of multiple parameters such as casing pressure, oil pressure, and water gas ratio; (2) The evaluation cycle is based on months, which cannot meet the needs of refined dynamic regulation; (3) Lack of an integrated software platform; on-site applications still rely on discrete computing tools. It is worth noting that existing commercial software generally suffers from problems such as vague algorithmic principles, one-sided evaluation dimensions, and inefficient human-computer interaction, making it difficult to support real-time decision-making under complex working conditions.

Looking at the current development of similar professional software, there are problems such as unclear software algorithms and principles, inadequate consideration of bubble rating evaluation, unrefined user interfaces, limited functionality, and inability to accurately optimize foam

drainage systems. The following will take the foam drainage system optimization software developed by the author as an example to illustrate its design ideas and implementation process. [6-14]

2. Research on Software Design Principles and Algorithms

2.1. Steps for optimizing the foaming effect

The steps for optimizing the foam effect are shown in Figure 1. Firstly, based on the production data before single well bubble discharge, a set of prediction models including ARIMA (Differential Autoregressive Model), Autoformer (Sequence Autoencoder Model), and Time Decomposition Model (STL Decomposition and Prophet Combination) are constructed. The optimal prediction model is selected through the cross validation ($MAPE \leq 8.3\%$) to dynamically simulate future production data under non-bubble discharge conditions; Secondly, the predicted data are compared with the actual foam production data, and the dynamic change rate of parameters such as gas production and water production are calculated as $\delta = |P_{act} - P_{pred}| / P_{actual} \times 100\%$, forming a difference feature matrix. Then, the weights of each parameter are determined, and a 5-level fuzzy evaluation standard is established; Finally, the comprehensive evaluation index is input into the clustering model, and the initial centroid is optimized using the K-means++ algorithm. The dynamic optimization interval is divided using the contour coefficient SSE criterion to generate an optimal bubble ranking system library that includes factors such as injection gradient and frequency period. The entire process achieves closed-loop optimization from data-driven prediction to intelligent decision support, with a modular design of the technical framework, ultimately resulting in the optimal bubble filling system.

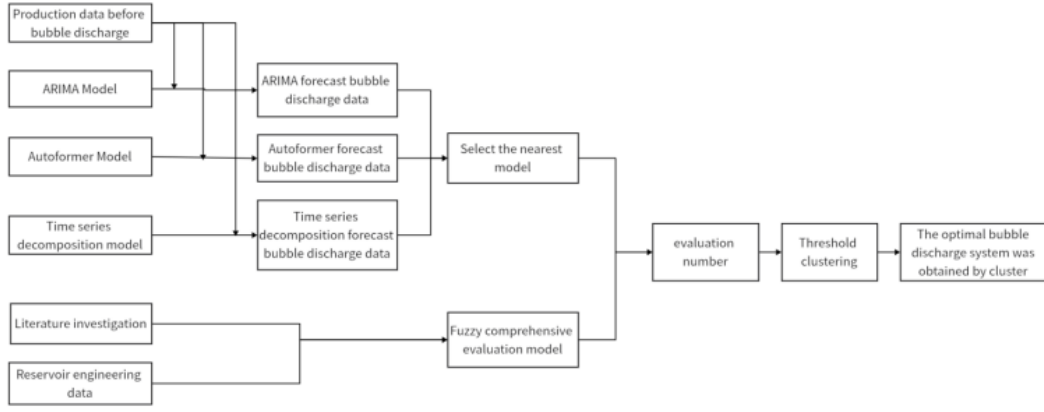


Figure 1. Flowchart of Optimization Algorithm for Bubble Discharge System

2.2. Time series model evaluation criteria

Using the production data of a single well before foam discharge as the input parameters for the time series prediction model, ARIMA model, Auto former model, and Prophet model were used to predict the casing pressure data after foam discharge of the well.

In order to seek the optimal time series prediction model with strong generalization ability, mean absolute error (MAE) and mean square error (MSE) are used as indicators to measure the performance of the prediction model. Both of these indicators are used to evaluate the model's fit to real data, and smaller MAE and MSE values typically indicate better predictive performance of the model. Taking the bubble discharge dataset of casing pressure from a specific well as an example, the mathematical formulas for MAE and MSE are as follows.

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (1)$$

$$MSE = \sum_{i=1}^n (y_i - \hat{y}_i)^2 \frac{1}{n} \quad (2)$$

In the formula, n is the number of time series days for the well. y_i is the true value of the Production data of the i -th day of bubble discharge casing pressure in the well. \hat{y}_i is the predicted value of the production data for the i -th day of bubble discharge casing pressure in the well.

Table 1. Comparison Table of Accuracy of Various Models

time series model	MAE	MSE
Prophet model	0.39	0.35
ARIMA model	0.62	0.45
Autoformer model	0.81	1.15

2.3. Time series model selection results

Select 17 wells, targeting N209H2-3, N209H2-1, N209H14-1, N209H14-2, N209H14-3, N209H14-4, N209H14-5, N209H3-1, N209H3-2, N209H3-3. Comparing the accuracy of Prophet model, ARIMA model, and Autoformer model on the test set using casing pressure production data from 17 wells as representatives, the results are shown in the following figure.

Figure 2 shows that the Prophet model performs well in terms of computational accuracy, while the ARIMA model and Autoformer model perform poorly in terms of computational accuracy. Therefore, this study chose the Prophet model.

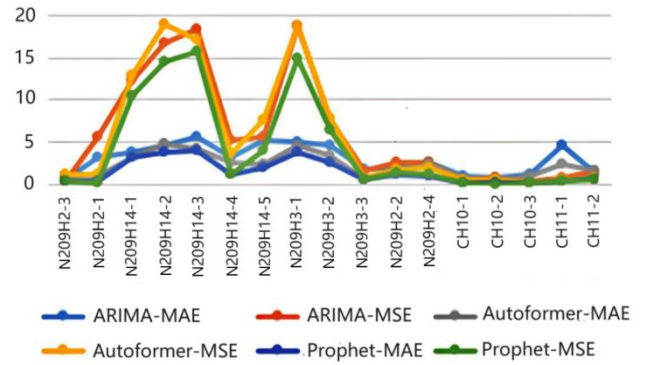


Figure 2. Comparison of Calculation Accuracy of Various Time Series Models

Taking the N209H2-3 well as an example, the comparison chart of the true and predicted oil casing pressure curves after bubble drainage using various time series models is shown below.

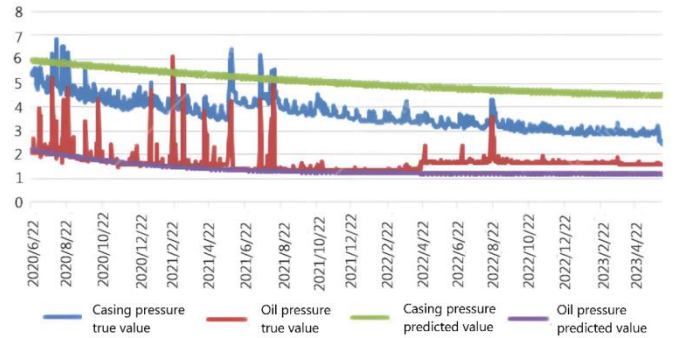


Figure 3. Comparison chart of true and predicted oil sleeve pressure curves

2.4. Fuzzy comprehensive evaluation

Based on the fuzzy comprehensive evaluation system of foam drainage gas production effect established by literature research, four core indicators were screened out through principal component analysis: daily gas production change rate (ΔG), daily water production change rate (ΔW), oil pressure change rate (ΔP) and casing pressure change rate (ΔC). By combining Analytic Hierarchy Process (AHP) to determine weights and conducting consistency tests with $CR < 0.1$, a fuzzy evaluation model is established to ultimately obtain comprehensive evaluation results. The construction flowchart is shown in Figure 4.

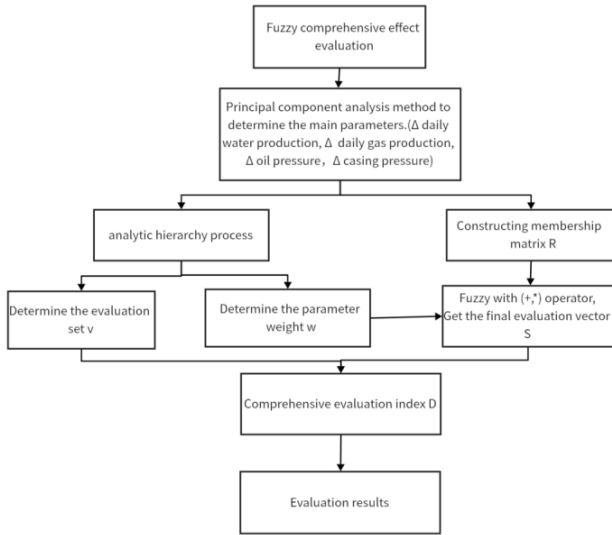


Figure 4. Flow Chart for Constructing Fuzzy Comprehensive Evaluation Model

2.4.1. Determine the evaluation set

In order to divide the boundaries of each evaluation indicator into different levels and facilitate the establishment of a membership matrix for evaluation indicators, this method sets the evaluation levels that can be selected for evaluation indicators, forming a fuzzy set of comments.

Define five evaluation levels in set V_r , with corresponding evaluation level branch vectors $V_j = (90, 70, 50, 30, 10)$. Based on the fuzzy evaluation method, the evaluation level is first determined as shown in Table 2.

Table 2. Judging set

Value range	V_j	V_r
[100,80]	90	very good
[80,60]	70	good
[60,40]	50	better
[40,20]	30	general
[20,10]	10	differ from

2.4.2. Establish a membership matrix

This study uses linear analysis to construct a membership matrix R to quantify the degree of membership of each evaluation indicator to the evaluation set V_j . For this purpose, it is necessary to establish scientifically reasonable grading boundaries for each indicator. Taking the change rate index of casing pressure as an example: Firstly, all time series data are processed using the bubble method to determine the maximum and minimum values of the index. Subsequently, the interval is equally divided into five levels to form evaluation boundary values. In this evaluation system, the maximum change rate corresponds to the "excellent" level, while the minimum change rate represents the "poor" level. The other three levels correspond to "good", "moderate", and "average" in order. For other production parameter indicators, this linear equal division method is also used to determine their grading limits, thereby ensuring the consistency and comparability of the evaluation system.

2.4.3. Establish a membership matrix

In order to qualitatively and quantitatively determine the importance of different evaluation indicators for drainage and gas production effects, the Analytic Hierarchy Process (AHP)

was used to determine the weights of bubble drainage effects.

Next, normalize the data to obtain weights $W = \{w_1, w_2, \dots, w_n\}$, of which, The importance of w_i as an evaluation indicator, $\sum_{i=1}^n w_n = 1, i=1, 2, \dots, n$.

2.4.4. Synthesize the final evaluation result

Firstly, the $(+, *)$ operator is used to fuzzy synthesize the weight W and matrix R to obtain the final evaluation vector S ; Then, based on the evaluation set V and evaluation vector S , the comprehensive evaluation index D can be obtained from the following equation; Finally, based on the value range of D , the evaluation index corresponding to the evaluation set is determined to obtain the evaluation result.

$$S = W \cdot R = (s_1, s_2, \dots, s_j) \quad (3)$$

$$D = S \cdot V = \sum_{j=1}^n (s_j \cdot v_j) \quad (4)$$

2.5. Threshold clustering to obtain the optimal bubble sorting system

In response to the optimization problem of bubble discharge system, this study proposes an optimization method that combines fuzzy comprehensive evaluation and threshold clustering, based on the basic principle that the bubble discharge system exhibits similarity under similar working conditions (see Figure 5 for the specific process). The implementation process of this method mainly includes the following three steps: firstly, applying the threshold clustering algorithm to analyze historical production data, identifying and extracting representative clustering center points, which represent typical bubble discharge systems under different working conditions. Secondly, calculate the distance between the predicted data of the optimized working condition and each cluster center point, and select the bubble system corresponding to the cluster center point with the smallest distance as the candidate system scheme for this working condition. This method fully utilizes historical empirical data to ensure the feasibility of the optimization plan. Finally, a fuzzy comprehensive evaluation is conducted on all candidate schemes, and the bubble ranking system with the highest evaluation index is selected as the optimal scheme by comparing the evaluation indices of each scheme. This method not only ensures the scientific nature of optimization results, but also improves the reliability of decision-making.

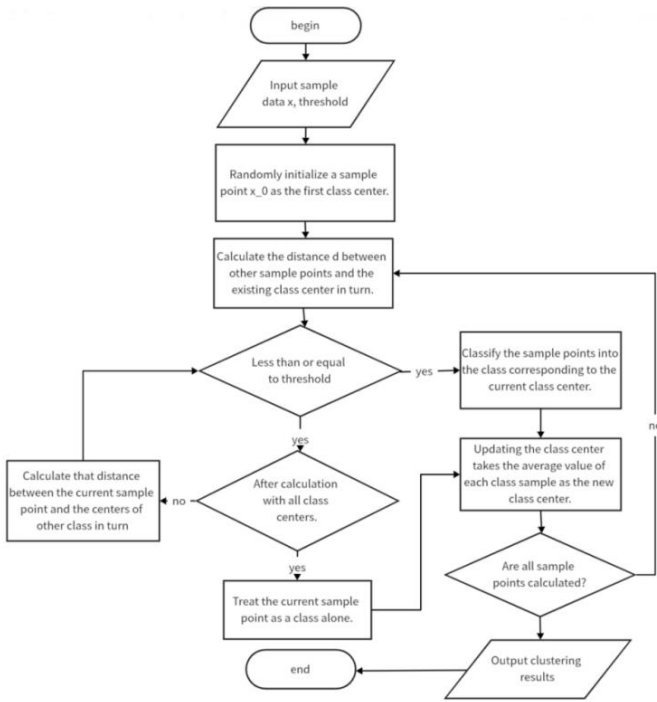


Figure 5. Flowchart of Threshold Clustering Algorithm

3. Software Design and Implementation

3.1. Software functional framework design

Based on the concept of application software engineering, the author designed and implemented bubble scheduling optimization software using the Spring Boot+Vue framework in the Windows environment. The operation and running process are shown in Figure 6.

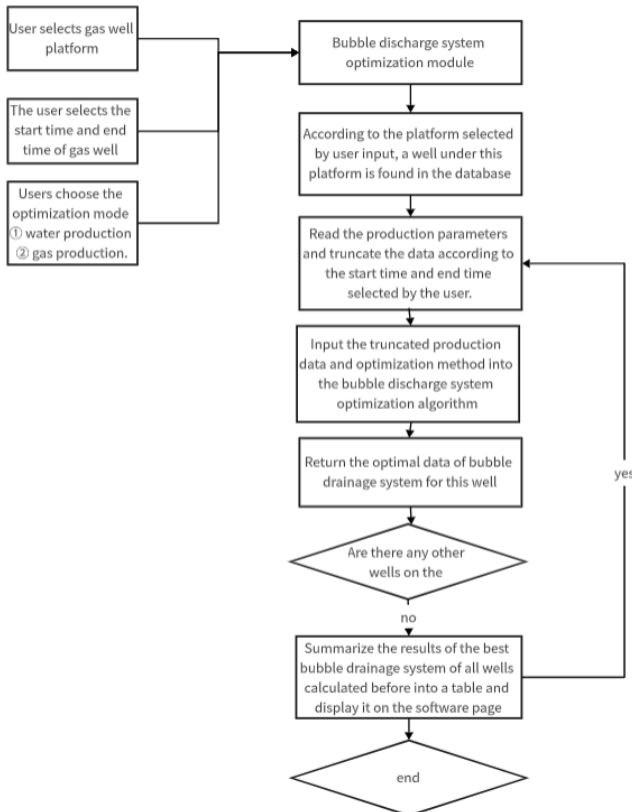


Figure 6. Flow Chart of Optimizing Bubble Scheduling System Software Usage

3.2. Software operation interface

Foam drainage system optimization software is shown in Figure 7 and Figure 8

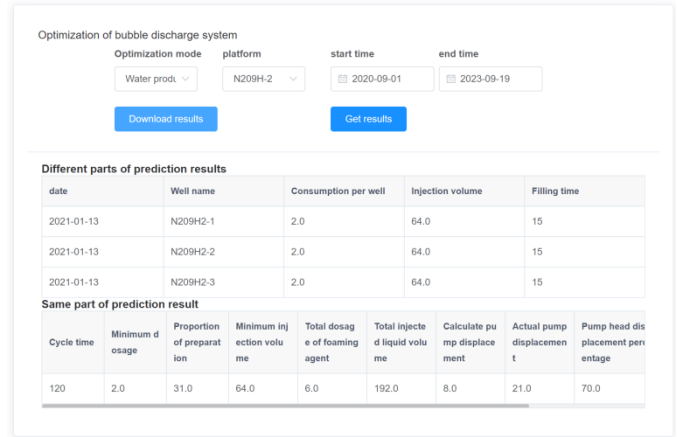


Figure 7. Optimization Results of Bubble Drainage System



Figure 8. Gas Well Bubble Discharge Diagram

3.3. Notes on Software Design

In the software design process, in order to facilitate users and increase practical functions, several issues need to be noted:

In order to facilitate user input of parameters, the design and implementation should consider the ability to read data in batches from Excel or input data one by one from the interface. And the software supports one-click export of input parameters, calculation results, and analysis charts to Excel/PNG/JPG image formats, ensuring data traceability, reusability, and meeting cross platform collaboration requirements

For the convenience of users to intuitively view the imported production parameter data, the software should be able to draw production curve charts based on the data. In addition, for further analysis, a triangle chart of gas wells and a bubble chart of daily gas water gas ratio have been added. The software also provides interactive operation functions such as chart scaling, multi-layer overlay, and data annotation.

4. Application examples and analysis

The foam drainage system optimization software is used to optimize the foam drainage system of Well N209H2-3, and the evaluation index division limits are shown in Table 3.

Selecting data from a certain period of time in the well for the calculation shown above, the final evaluation results are shown in Table 4.

Taking the N209H2-3 well as an example, this well had unperforated data before June 22, 2020, and data that had

already been soaked from June 22, 2020 to June 6, 2023. First, the unperforated data was used to predict the soaked data, and then threshold clustering was performed on the soaked data based on the rate of change and evaluation index of the four parameters. Finally, the optimal soaked system was obtained

by following the steps of the aforementioned algorithm. The following table shows the comparison between the predicted optimal soaked system and the actual system on that day (the second line in the table is predicted, and the third line is actual).

Table 3. Boundaries for Dividing Evaluation Indicators

Production parameter change rate	Very good	Good	Better	General	Differ from
Δ sleeve pressure	0.71	0.47	0.23	-0.01	-0.24
Δ Oil pressure	0.20	-0.04	-0.28	-0.52	-0.75
Δ daily gas production	36.33	27.04	17.76	8.47	-0.81
Δ daily water production	11.42	8.34	5.26	2.18	-0.90

Table 4. Final evaluation results

Change rate				Evaluation index D	Evaluation level vr
casing yield	oil yield	Daily gas yield	Daily water yield		
0.05	0.09	0.04	-0.9	45	better
0.08	0.08	-0.01	0.24	47.82	better
0.07	0.08	-0.03	-0.13	46.90	better
0.05	0.08	-0.04	0.13	47.19	better
0.04	-0.17	0.08	0.26	38.65	general
0.03	0.04	0.06	-0.86	43.30	better
0.05	0.08	0.03	-0.65	45.43	better

Table 5. Optimal Bubble Discharge System

Change rate		Dosage of treatment agent	Dilution ratio	....	Stop injection time	Evaluate	
Casing yield	....					index	result
0.28	....	3	23	....	96	64.9	good
0.38	....	4	14	....	100	44.8	better

5. Conclusion

In summary, this study proposes the following innovative solutions to address the technical bottlenecks in gas well bubble discharge optimization and completes engineering verification: (1) constructing a multi parameter collaborative analysis framework, introducing a fuzzy comprehensive evaluation model to quantify the weights of various indicators, and combining a threshold clustering algorithm to achieve dynamic partitioning of bubble discharge effects from daily accuracy to daily accuracy; (2) Designing a modular visual interface that integrates core functions such as production data prediction and bubble chart drawing, liquid accumulation height prediction, and bubble discharge system optimization. Compared to traditional methods, this software has significant advantages in prediction accuracy, parameter coverage, and ease of operation. (3) The software can predict the oil casing pressure data after foaming based on the data before foaming, with high accuracy, and can find the optimal foaming system for the well.

According to the application results, the software has a high accuracy in predicting production data after gas well bubbling, and has a good optimization effect and high accuracy in the bubbling system. The software has significant value for promotion and application.

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