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Evaluation of Factors Influencing Energy Consumption in Water Injection System Based on Entropy Weight-Grey Correlation Method

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Abstract

In order to determine the importance of influencing factors of energy consumption in oilfield water injection systems, the distribution of energy loss in the water injection system was analyzed, the factors affecting the energy consumption of the water injection system were determined, and an evaluation index system for the energy consumption of the water injection system was established. This indicator system covers all links and all energy loss nodes of the energy loss of the water injection system, thereby an evaluation model for influencing factors of energy consumption in water injection system based on entropy weight - grey correlation method was built. Use the entropy weight method to get the ranking of the importance of energy consumption indicators; use the gray correlation method to determine the correlation between each water injection system and energy consumption factors. The application results show that the entropy weight-grey correlation method proposed in this paper can effectively obtain the importance of the energy consumption factors of the oilfield water injection system, and provide scientific guidance for the daily management and targeted optimization of the water injection system.

Keywords: oilfield water injection system; main controlling factors of energy consumption; evaluation index; entropy weight method; grey correlation method

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1 Introduction

Oilfield water injection is an important means to replenish energy into strata in oilfield development process so as to improve oilfield recovery ratio [1]. At present, the power consumption of the water injection system accounts for about 33% ~ 56% of the total power consumption of the oil field [2]. Therefore, it is essential to evaluate the energy consumption of water injection system and find out the influencing factors resulting in high system energy consumption, so that the operating efficiency of water injection system can be improved [3].

In recent years, researches on the influencing factors and evaluation of water injection system energy consumption including: Peng et al. studied methods to improve the operation efficiency of water injection systems, and the influencing factors of energy consumption, and established an oilfield water injection system optimization control mathematical model [4]; Lei et al. established a comprehensive evaluation model for ground systems and digital dynamic statistics [5]; Zhou et al. established a reasonable index system and evaluation method that reflect the energy efficiency of the water injection system according to the characteristics of Xinjiang oilfields [6]; Tan et al. established an energy consumption model using association rules and chaotic time series, and studied the relationship between energy consumption factors in the water injection system [7] and so on. However, the above scholars did not give a clear statement on the importance of the factors affecting the energy consumption of the water injection system.

When determining the importance of energy consumption influencing factors, the entropy weight-grey correlation method can be used, which can solve the sorting problem of influencing factors. Wang et al. applied the gray correlation analysis method to the analysis and research of pipeline corrosion influencing factors in the oilfield water injection system [8]; Nan et al. used the improved entropy weight-grey correlation method to determine the key factors that have a significant impact on the reliability of power supply in the power supply area [9]; Zhang et al. reasonably evaluated the workshop's manufacturing capacity in combination with entropy weight method and grey relational analysis method [10]; Jia et al. analyzed the island earthquake emergency response capacity of different island counties based on the entropy weight method-grey correlation analysis method [11]; Liu et al. used entropy weight-improved grey correlation method to study the influence of 12 risk factors on tunnel collapse, and determine the risk assessment of highway tunnel collapse [12]. Therefore, the entropy weight-grey correlation analysis method has been applied in many fields, and has achieved good analysis and evaluation results, but it has not been applied in the analysis of the importance of the energy consumption factors of the oilfield water injection system. For this reason, this paper establishes a water injection system energy consumption evaluation index system, and uses the entropy weight-grey correlation method to determine the importance of the factors affecting the water injection system energy consumption.

2 Determination of Energy Consumption Composition and Evaluation Index of Water Injection System

2.1 Analysis of Energy Consumption Composition in Water Injection System

To analyze the composition of the energy consumption of the water injection system, the starting point is to analyze the process flow of the water injection system, and then to clarify the energy flow direction of the system, to find out the nodes of energy loss in the system, and to finally classify the influencing factors of the energy loss nodes [13].

Oilfield water injection system is a continuous closed hydraulic system which consists of water source, water injection station, water distributing station and water injection pipe network [14]. Its structure is shown in Fig. 1.

It can be seen from Figure 1 that when the water injection system is operating, the incoming water from the water source is pressurized by the water injection station and then enters the water distribution room through the water injection main line and the water injection branch line. After the pressure is adjusted by the valve in the water distribution room, it finally flows into the water injection well [15]. Therefore, the water injection system is that supplies water to each water distribution station, and each water distributing station is connected

Fig. 1 Structure of water injection system.

to multiple wellheads, to form a complex water injection system with large area [16].

In the entire water injection process, the power input to the water injection system is recorded as the total input energy of the system, and the water energy output to the water injection well is recorded as the output energy of the system, that is, the effective energy [17]. During the energy transfer process of the water injection system from input to output, the loss of system energy is mainly distributed in the seven nodes of the two components, and the energy flow of the water injection system is shown in Figure 2 [18].

Fig. 2 Energy flow diagram of water injection system.

It can be seen from Figure 2 that the energy loss link of the water injection system is divided into two parts, namely the water injection pump station part and the water injection pipe network part. Among them, the water injection pump station part contains 3 loss nodes: engine loss, water injection pump loss, and differential pressure loss at pump line; The water injection pipe network part contains 4 loss nodes: trunk loss, throttling loss at water distributing station, single-well line loss, and wellhead loss. From the above analysis, it can be seen that the influencing factors that affect the energy consumption of the water injection system are more complicated. In order to facilitate further analysis, they are classified into three categories: equipment factors, pipe network factors and stratigraphic factors [19–22], as shown in Figure 3.

Among them, device and pipe network are subjective factors, including the operating efficiency of water injection pump, engine and pipe network and the water injection pipe network techniques, they can improve operating efficiency through optimization and modification; strata is an objective factor, It reflects the energy that the entire water injection system must provide to meet the objective requirements of injection-production balance, such as the required water injection pressure and water injection volume [23]. As a result, we could only analyze the reason of energy consumption in water injection system and its improvement direction from

Fig. 3 Influencing factors of energy consumption in water injection system.

subjective factors, namely device factors and pipe network factors.

2.2 Determination of energy consumption evaluation index for water injection system

On the basis of clarifying the distribution of energy loss in the water injection system and the factors affecting the energy consumption of the water injection system, the energy consumption evaluation index of the water injection system will be determined.

The determined energy consumption evaluation index of the water injection system should cover all links of the energy loss of the water injection system, and it should be a comprehensive set of system indicators that reflect not only the equipment factors of the system, but also the pipe network factors of the system. The energy consumption evaluation index system of the oilfield water injection system is shown in Table 1.

Table 1 Energy consumption index system for water injection system.

System link	Energy loss node	Energy consumption index	Test parameter
Pump A ₁	Engine loss B ₁	Power factor C ₁	Active power D ₁ , reactive power D ₂ , power factor D ₃
	Water injection pump loss B ₂	Unit efficiency C ₂	Pump inlet pressure D ₄ , outlet pressure D ₅ , outlet flow D ₆
	Differential pressure loss of pump line B ₃	Differential pressure of pump line C ₃	Station outlet pressure D ₆
Pipe network A ₂	Trunk loss B ₄	Trunk pressure loss C ₄	Trunk pressure D ₈
	Throttling loss of water distributing station B ₅	Valve control of water distributing station C ₅	Oil pressure of water distributing station D ₉
	Single-well pipeline loss B ₆	Single-well pipeline pressure loss C ₆	Wellhead pressure D ₁₀
	Wellhead loss B ₇	Wellhead valve control C ₇	Wellhead flow D ₁₁

Table 1 presents four parts of content, namely system link, energy loss node, energy consumption index, and test parameter.

(1) System link: Two components of energy loss, namely pump A₁ and pipe network A₂.

(2) Energy loss node: it is the 7 loss nodes of the two components in the system link, there are 3 items in the pump A₁: engine loss B₁, water injection pump loss B₂, differential pressure loss of pump line B₃. Pipe network A₂ are 4 items: trunk loss B₄, throttling loss of water distributing station B₅, single-well pipeline loss B₆, wellhead loss B₇.

(3) Energy consumption index: According to the energy loss node of pump A₁, the corresponding energy consumption index is determined to be 3 items: power factor C₁, unit efficiency C₂, differential pressure of

pump line C_3 . Determined by the energy loss node of pipe network A_2 . The corresponding energy consumption indicators are 4 items: trunk pressure loss C_4 , Valve control of water distributing station C_5 , single-well pipeline pressure loss C_6 , wellhead valve control C_7 , a total of 7 energy consumption indicators.

(4) Test parameters: 11 parameters need to be tested in order to obtain energy consumption indicators, as shown in Table 1.

3 Establish the evaluation model of entropy weight-grey correlation method

Based on the evaluation index system of water injection system energy consumption factors established in Table 1, this paper will use the entropy weight-grey correlation method to determine the comprehensive evaluation model of water injection system energy consumption factors. Entropy can reflect the disorder degree of a system, and the index entropy value can indicate the information quantity contained in the system, that is to say, the smaller is entropy value is, the larger its weight will be [24]. Established on basis of objectively measured data, the grey correlation method figures out how proximate the evaluation indexes of each energy consumption influencing factor of each water injection system is to the optimal ideal system energy consumption level [25]. For this reason, the entropy weight-grey correlation method can be used to study the importance of factors affecting energy consumption of water injection systems.

The implementation steps of the entropy weight-grey correlation method of the water injection system are as follows:

(1) Select several water injection systems, and obtain the test parameters in Table 1 according to GB/T 33653-2017 Energy Consumption Test and Calculation Method for Oilfield Production System [26], and calculate their energy consumption indicators.

(2) Construct the energy consumption index of each system as an evaluation index matrix X , and normalize the index after standardizing the index values in the matrix.

(3) Calculate the entropy value E_i of the energy consumption index, and then obtain the entropy weight w_i of the energy consumption index of the water injection system through data processing, thereby obtaining the weight ratio of the energy consumption index of the water injection system.

(4) According to the gray correlation method, taking the evaluation index matrix X constructed in (2) as the comparison sequence, and then selecting a set of optimal system energy consumption index parameters in the water injection system as the reference sequence, constructing the matrix $[x_0(k), x_j(k)]$, and normalizing the index values;

(5) By calculating the gray correlation coefficient of the water injection system, and further combining with the entropy weight w_i of the energy consumption index in (3), the gray correlation degree of each water injection system is obtained, and the ranking result of the influence degree of the energy consumption index on the water injection system is finally determined.

3.1 Energy consumption index entropy weight method

The value of energy consumption index corresponding to the energy consumption influencing factors of each water injection system in the oil field is different, and the degree of influence on the water injection system is also different, and their proportions are also different. Hence, it is crucial to determine the weight of each evaluation index scientifically and reasonably. The calculation steps are as below:

(1) Construct an evaluation index matrix X

First, collect the test parameters of each water injection system in an oil field over the years, and calculate its energy consumption index, and then construct the energy consumption index of each system as an evaluation index, and list them as matrix X as below.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Where: $X = [x_{ij}]_{m \times n}$, $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$.

(2) Standardize the index value

As the selected energy consumption indexes from each water injection system are in different units, so this index matrix is handled by dimensionless method.

$$\text{Positive index: } y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (2)$$

$$\text{Negative index: } y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (3)$$

Where: y_{ij} is the standardized energy consumption index value of water injection system.

(3) Normalize the index value

To normalize the standardized index matrix, figure out the proportion p_{ij} of the j th water injection system in the i th influencing factor:

$$p_{ij} = \frac{y_{ij}}{\sum_{j=1}^n y_{ij}} \quad (4)$$

(4) Calculate the entropy value

Figure out the entropy value E_i of the i th influencing factor index:

$$E_i = -\frac{1}{\ln n} \sum_{j=1}^n p_{ij} \ln p_{ij} \quad (5)$$

Where: in case that $p_{ij} = 0$, the define $\lim_{p_{ij} \rightarrow 0} p_{ij} \ln p_{ij} = 0$.

(5) Calculate the entropy weight

Figure out the entropy weight w_i of the i th influencing factor index:

$$w_i = \frac{1 - E_i}{\sum_{i=1}^m (1 - E_i)} \quad (6)$$

Where, it satisfies $\sum_{i=1}^m w_i = 1$.

3.2 Systematic grey relational analysis

Select a water injection system with the optimal value of energy consumption in the oilfield water injection system as the reference sequence, and use the data in formula (1) as the comparison sequence to form a matrix, and then normalize the data sequence to index values to obtain the water injection system The correlation with energy consumption indicators, The larger the correlation is, the higher they are correlated to each other. Thereby, the evaluation condition of energy consumption influencing indexes for water injection system can be distinguished. The calculation steps of grey correlation analysis method are as below:

(1) Determine the analysis series

According to the index system with determined data, the data of water injection system with optimal energy consumption is taken as the reference series $\{X_0(k)\}$, expressed as $X_0(k) = \{X_0(1), X_0(2), \dots, X_0(m)\}$, ($k = 1, 2, \dots, m$). The data series of n evaluated water injection systems are taken as the comparison series $\{X_j(k)\}$, expressed as: $X_j(k) = \{X_j(1), X_j(2), \dots, X_j(m)\}$, ($j = 1, 2, \dots, n, k = 1, 2, \dots, m$). The reference series and comparison series form the following matrix $[x_0(k), x_j(k)]$:

$$[x_0(k), x_j(k)] = \begin{bmatrix} x_0(1) & x_1(1) & L & x_n(1) \\ x_0(2) & x_1(2) & L & x_n(2) \\ M & M & O & M \\ x_0(m) & x_1(m) & L & x_n(m) \end{bmatrix} \quad (7)$$

(2) Normalize the index value

In order to simplify the calculation of evaluation indexes, the evaluation index values of each water injection system are normalized. $X'_j(k)$ is the normalized data series, in which, $(j = 0, 1, 2, \dots, n, k = 1, 2, \dots, m)$.

(3) Work out the correlation coefficient

The correlation coefficient is a dispersal measure to reflect how proximate the comparison series of selected water injection systems is to the reference series (i.e. target value) of water injection system with the optimal energy consumption, which is expressed as $\varepsilon_{0j}(k)$.

$$\varepsilon_{0j}(k) = \frac{\min_k \min_k |X'_0(k) - X'_j(k)| + \rho \max_j \max_k |X'_0(k) - X'_j(k)|}{|X'_0(k) - X'_j(k)| + \rho \max_j \max_k |X'_0(k) - X'_j(k)|} \quad (8)$$

Where: ρ is the distinguishing coefficient, $\rho \in [0, 1]$, generally set as $\rho = 0.5$.

(4) Calculate correlation degree

The information of correlation coefficient is dispersed and not easy to analyze. In order to make the obtained evaluation results to fit the actual situation, the weight obtained by using entropy weight method is integrated with the correlation coefficient, then the entropy weight - grey correlation is:

$$r_{0j} = \sum_{k=1}^m w_k \cdot \varepsilon_{0j}(k), \quad j = 1, 2, L, n, k = 1, 2, L, m \quad (9)$$

(5) Rank the correlation degree

According to the rank of correlation degree, the ranking results of evaluation indexes of influencing factors for selected water injection systems are obtained.

4 An oil field application case analysis

Using the above-established evaluation index system for energy consumption influencing factors of the water injection system, and based on the entropy weight-grey correlation method analysis method given, taking five water injection systems in an oil field as an example to, determine the importance of the energy consumption influencing factors of each system.

For example, to determine the importance of the energy consumption factors of five water injection systems in an oil field, first collect basic information about the operation of each system as shown in Table 2.

In Table 2, System (Optimum) is the current optimal water injection system selected, which is taken as the optimal energy consumption reference system, and System I to System V are the systems that need to be analyzed.

Then obtain the test parameters of five water injection systems, such as: active power D_1 , outlet pressure D_5 , outlet flow D_6 , truck pressure D_8 , etc., and calculate the energy consumption indicators of each water injection system. See Table 3 for statistics.

4.1 Energy consumption index entropy weight method calculation results

The energy consumption index of the five systems in Table 3 is constructed as an evaluation index matrix by formula (1):

Table 2 Basic information of an oilfield water injection system.

Research system	Water injection qty/m ³ /d	System ef- ficiency/%	Water injection well/head	Pump unit/set
System(Optimal)	8925.36	67.01	61	4
System I	19247.76	49.44	108	7
System II	3924.00	63.01	47	3
System III	7995.26	67.48	55	4
System IV	15826.08	42.85	83	6
System V	5216.40	46.92	36	5

Table 3 Energy consumption index of an oilfield water injection system.

Energy consumption index	System (Optimal)	System I	System II	System III	System IV	System V
Power factor C_1	0.93	0.83	0.95	0.75	0.91	0.70
Pump unit loss C_2 /%	20.18	15.26	14.59	34.92	20.91	16.96
Differential pressure of pump line C_3 /%	4.14	4.15	1.95	2.01	1.83	6.11
Trunk pressure loss C_4 /MPa	0.39	1.57	2.18	0.51	0.15	0.57
Valve control pressure loss C_5 /MPa	3.42	3.39	7.73	2.00	2.93	2.33
Single-well pipeline pressure loss C_6 / MPa	0.22	0.43	0.67	0.51	0.81	0.21
Wellhead valve control C_7 /%	0.00	0.01	0.22	0.02	0.07	0.13

$$X = \begin{bmatrix} 0.83 & 0.95 & 0.75 & 0.91 & 0.70 \\ 15.26 & 14.59 & 34.92 & 20.91 & 16.96 \\ 4.15 & 1.95 & 2.01 & 1.83 & 6.11 \\ 1.57 & 2.18 & 0.51 & 0.15 & 0.57 \\ 3.39 & 7.73 & 2.00 & 2.93 & 2.33 \\ 0.43 & 0.67 & 0.51 & 0.81 & 0.21 \\ 0.01 & 0.22 & 0.02 & 0.07 & 0.13 \end{bmatrix} \quad (10)$$

According to the evaluation index matrix in formula (10), the index values are standardized and normalized by formulas (2)~(6), and the entropy value of each energy consumption index is calculated, and the entropy weight is obtained, thereby determining the weight of the energy consumption index Sort, as shown in Table 4.

Table 4 Weight of energy consumption index of an oilfield water injection system.

Energy consumption index	Entropy weight	Weight rank
C_1	0.0000160	6
C_2	0.9831032	1
C_3	0.0060623	3
C_4	0.0010549	4
C_5	0.0096778	2
C_6	0.0000752	5
C_7	0.0000105	7

For this reason, the importance of energy consumption indicators is ranked by the entropy weight method:

unit efficiency C_2 > valve control of water distributing station C_5 > differential pressure of pump line C_3 > trunk pressure loss C_4 > single-well pipeline pressure loss C_6 > power factor C_1 > wellhead valve control C_7 .

4.2 System grey correlation method calculation results

According to the energy consumption index parameters in Table 3, the evaluation index matrix $[x_0(k), x_j(k)]$ of the system is constructed by formula (7)

$$[x_0(k), x_j(k)] = \begin{bmatrix} 0.93 & 0.83 & 0.95 & 0.75 & 0.91 & 0.70 \\ 20.18 & 15.26 & 14.59 & 34.92 & 20.91 & 16.96 \\ 4.14 & 4.15 & 1.95 & 2.01 & 1.83 & 6.11 \\ 0.39 & 1.57 & 2.18 & 0.51 & 0.15 & 0.57 \\ 3.42 & 3.39 & 7.73 & 2.00 & 2.93 & 2.33 \\ 0.22 & 0.43 & 0.67 & 0.51 & 0.81 & 0.21 \\ 0 & 0.01 & 0.22 & 0.02 & 0.07 & 0.13 \end{bmatrix} \quad (11)$$

The gray correlation coefficients of the energy consumption indicators of the system are calculated by formula (8), as shown in Table 5.

Table 5 Grey correlation coefficient of an oilfield water injection system.

Energy consumption index	System I	System II	System III	System IV	System V
C_1	0.9621	0.9922	0.9337	0.9922	0.9168
C_2	0.9258	0.9166	0.8064	0.9883	0.9502
C_3	0.9997	0.4669	0.9244	0.9186	0.9297
C_4	0.9848	0.3385	0.9985	0.9969	0.9977
C_5	0.9996	0.3615	0.9813	0.9935	0.9856
C_6	0.9914	0.3447	0.9881	0.9761	0.9996
C_7	1.0000	0.3334	0.9999	0.9997	0.9994

The gray correlation degree of the water injection system calculated by formula (9) is shown in Table 6:

Table 6 Grey correlation degree of water injection system in an oil field.

	System I	System II	System III	System IV	System V
Relevancy r_{0j}	0.9271	0.9078	0.8090	0.9879	0.9505
Rank	3	4	5	1	2

It is known from above calculation that, the order of the energy consumption influence degree of the five water injection systems obtained by the gray correlation method is as follows: system IV > system V > system I > system II > system III.

4.3 Model establishing results and analysis

From the above analysis results, it can be seen that there are 7 influencing factors in the energy consumption of the water injection system. The order of their importance is as follows: pump unit loss > valve control pressure loss > differential pressure loss of pump line > trunk pressure loss > single-well pipeline pressure loss > power factor loss > wellhead loss.

After clarifying the importance of the influencing factors of the water injection system, it provides scientific guidance for the daily management and optimization of the water injection system. In particular, the pump

unit loss and pipe network pressure loss have a greater impact on the system energy consumption. Through targeted system optimization, the energy consumption caused by the pump unit and pipe network pressure can be minimized; and the wellhead valve control loss importance is the lowest, therefore, its impact on the water injection system can be ignored.

5 Conclusions

(1) The distribution of energy loss in the water injection system was analyzed, the factors affecting the energy consumption of the water injection system were determined, and the energy consumption evaluation index system of the water injection system was established. This indicator system covers all links and all energy loss nodes of the water injection system. It has determined 7 energy consumption indicators and 11 test parameters, so that it fully reflects the energy consumption of each link of the water injection system and the operating status of the system.

(2) Established an evaluation model of energy consumption influencing factors of water injection system based on entropy weight-grey correlation analysis method, and determined the main influencing factors of energy consumption of oilfield water injection system. Using the entropy method to get the ranking of the importance of energy consumption indicators: unit efficiency C_2 > valve control of water distributing station C_5 > differential pressure of pump line C_3 > trunk pressure loss C_4 > single-well pipeline pressure loss C_6 > power factor C_1 > wellhead valve control C_7 . The gray correlation method can be used to determine the correlation between each water injection system and energy consumption factors.

(3) Through application examples, the results show that the entropy weight-grey correlation method proposed in this paper can effectively obtain the importance of the energy consumption factors of the oilfield water injection system, and provide scientific guidance for the daily management and targeted optimization of the water injection system.

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