Construction of a digital intelligent evaluation platform for energy consumption of large oilfield water injection systems

Yan Ruan¹*, Xuliang Zhang¹, Junfeng Ning¹

¹School of Electronic Engineering, Xi’an Shiyou University, Xi’an 710065, China
*1439315078@qq.com

Abstract—With the development of oilfield water injection systems becoming more and more complex, relying on artificial experience to judge the efficiency of energy consumption and the status of the system more difficult. Based on hydraulic theory and matrix theory, establish the characteristic equations of the node unit, pipeline unit and auxiliary unit of the water injection system, and use the flow balance to form the overall matrix equation of the water injection system. Established a theoretical model of water injection system simulation, based on this, build a digital intelligent evaluation platform for water injection system energy consumption. In this way, it simulates the production operation status of the water injection system under theoretical conditions and compares it with the actual production operation data, so as to accurately analyze and evaluate the current status of the water injection system's pipe network energy consumption and the operating efficiency of the branch pipe network energy consumption of each water injection station. The intelligent analysis and evaluation of energy consumption of the water injection pipe network system has been realized, and the optimization and transformation goals have been defined. It has played a significant role in promoting the realization of digital and intelligent oilfield water injection systems.

1. Introduction

At present, domestic oil fields generally adopt water injection development methods to ensure oil layer pressure and supplement formation energy, increase oil production speed and recovery rate, and realize stable and high production of crude oil. The proportion of energy consumption of water injection systems in the process of water transmission and distribution is increasing. After the development of my country's land and eastern oilfields to the middle and late stages, water injection power consumption has accounted for more than 30% of oilfield production costs, and effective work only accounts for 50% to 55% [1-2]. And with the gradual progress of oilfield development and construction, the oilfield is entering the development stage of high water-cut and ultra-high water-cut periods. The amount of water injection will increase significantly, and the total energy consumption of water injection will rise sharply. Consumption reduction and governance are urgent.

As the oilfield enters the late stage of exploitation, the pipeline network system is constantly being renovated and updated, and the efficiency and energy consumption of the water injection system are judged by human experience only with large errors. Therefore, the oilfield urgently needs a convenient, fast and reliable water injection energy consumption evaluation method. Based on this, a digital intelligent management platform for energy consumption of the water injection system was constructed to better help oilfield water injection managers to analyze the energy consumption of the existing water injection system and implement optimization and transformation measures to achieve the purpose of energy saving and consumption reduction for the oilfield.
2. Theoretical foundation

2.1. Basic structure of water injection system

The water injection system is generally composed of basic units such as water injection station, water injection pipe network, water distribution room, and water injection well [1]. The main equipment in the water injection station is the water injection pump and the motor that drives the water injection pump. The water injection pipe network is mainly composed of pipelines, valves, tees and elbows.

2.2. Mathematical model of pipeline and node unit

According to the finite element analysis method, the water injection pipeline network can be divided into pipelines and node units, and the pipeline units are connected by the node units. In the state of constant flow, conforming to the laws of conservation of energy and mass, the pipeline unit i is shown in Figure 1, and the nodes connected to the pipeline unit are k and j.

![Figure 1 Pipeline unit](image)

The energy equation of tube element i [3-4]:

$$\Delta H^i = H_k - H_j$$ (1)

Where $\Delta H^i$ is the pressure loss of pipeline unit i, in meters; $H_k$ is the pressure of node k, in meters; $H_j$ is the pressure of node j, in meters.

If it is stipulated that water flows from k to j, then $H_k > H_j$, the following formula:

$$\Delta H^i = \frac{q'^{2}}{2\alpha } L$$ (2)

Where $L$ is the length of tube element i, in meters; $\overline{K}^i$ is the flow coefficient; $q$ is the flow of tube element i, in cubic meters per second; $\alpha$ is a constant coefficient.

The calculation formula of the flow coefficient in formula (2) is:

$$\overline{K}^i = \frac{\pi d^{8/3}}{10n}$$ (3)

Where $d$ is the inner diameter of the tube element, in meters; $n$ is the tube roughness coefficient. Generally, water injection pipelines are old steel pipes, usually $n=0.013$.

The flow of nodes in the water injection pipe network satisfies the law of conservation of mass, that is, inflow equals outflow, as shown in Figure 2. $U_i$ is the water supply of the node, $q_{ij}$ and $Q_i$ are the water consumption of the node.

![Figure 2 Schematic diagram of the flow balance of node i](image)

For node i, the flow balance equation is satisfied:

$$u_i - Q_i - \sum_{j \in I_i} q_{ij} = 0, \quad i=1,...,N$$ (4)

Where $N$ is the total number of nodes in the pipe network; $I_i$ is the set of node numbers connected to node i.
The relationship between the pressure drop of the pipeline unit and the flow rate of the pipeline unit can be obtained by formula (2):

\[ q_{ij} = s_{ij} \text{sgn}(H_i - H_j)\left|H_i - H_j\right|^\alpha \]  

(5)

In the formula, \( s_{ij} = \left(\frac{K_{ij}^2}{L_{ij}}\right)^\alpha \); \text{sgn} is the symbolic function.

2.3. Establish unit equation

Equation (5) provides a method for calculating the flow rate using the pressure loss between the two nodes of the pipeline unit \( i \), and specifies that the pipeline flow rate is positive when water flows from node \( k \) to node \( j \), that is, \( H_k > H_j \). Suppose that \( q_{ik} \) is the node flow of unit \( i \) connected to node \( k \), and \( q_{ij} \) is the node flow of unit \( i \) connected to node \( j \). If it is assumed that the flow out of the node is positive, then:

\[ \begin{align*}
q'_{i} &= K^i \Delta H = K^i (H_k - H_j) \\
q'_{j} &= -K^j \Delta H = -K^j (H_k - H_j)
\end{align*} \]  

(6)

Express the element equation in matrix form as:

\[ \begin{bmatrix}
q'_{k} \\
q'_{j}
\end{bmatrix} = K^i \begin{bmatrix}
+1 & -1 \\
-1 & 1
\end{bmatrix} \begin{bmatrix}
H'_{k} \\
H'_{j}
\end{bmatrix} \]  

(7)

2.4. Establish simulation model of water injection pipe network system

Equation (7) is a simple matrix equation. For a complex pipe network, due to the interconnection between units, each node must satisfy the flow balance equation (5), written as:

\[ \sum_{j \in i} q_{ij} = C_i \]  

(8)

According to formula (8), the flow balance equation of node 3 in Figure 3 can be written as:

\[ q_3^2 + q_3^3 = C_3 \]  

(9)

Figure 3  Schematic diagram of water injection network

On node 3, there are two units ② and ③ connected to it. Considering that the flow from the node is positive, there are:

\[ \begin{align*}
q_3^2 &= -K^2 (H_2 - H_1) \\
q_3^3 &= +K^3 (H_3 - H_4)
\end{align*} \]  

(10)

Substituting formula (10) into formula (9), we get:

\[ -K^2 H_2 + (K^2 + K^3) H_3 - K^3 H_4 = C_3 \]  

(11)

For each node of the injection pipe network can be balanced as shown in equation (11) formula, putting the flow balance equations of all nodes together constitutes the overall equations of the pipe
network system, that is, the simulation model of the pipe network system. For the pipe network system shown in Figure 3, the overall system equations constructed by it are as follows:

\[
\begin{bmatrix}
K^1 & -K^1 & 0 & 0 \\
-K^1 & K^1 + K^2 & -K^2 & 0 \\
0 & -K^2 & K^3 + K^4 & -K_3 \\
0 & 0 & -K^4 & K^4
\end{bmatrix}
\begin{bmatrix}
H_1 \\
H_2 \\
H_3 \\
H_4
\end{bmatrix} = \begin{bmatrix}
C_1 \\
C_2 \\
C_3 \\
C_4
\end{bmatrix}
\]

3. results & discussion

3.1. Digital Intelligent Evaluation Platform for Energy Consumption of Water Injection System

Based on the simulation theoretical model of water injection system established in the previous section, a digital intelligent evaluation platform for energy consumption of oilfield water injection system is constructed. The platform integrates water injection system data management, energy consumption analysis and evaluation, and optimization and transformation plans. It is a comprehensive human-computer interaction operation platform. The platform architecture is shown in Figure 4, which is mainly divided into two major modules, data management and water injection pipeline network energy consumption analysis and evaluation. Data management also includes system production data and static data of pipe network parameters to realize pipe network topology modeling and system simulation operation. The energy consumption analysis and evaluation of the water injection pipeline network includes the measured energy consumption analysis and evaluation and the theoretical energy consumption analysis and evaluation to analyze the energy consumption theory and the actual measurement results of the pipeline network. In addition, the comprehensive energy consumption analysis and evaluation of the pipe network analyze the theoretical and measured deviation values of the pipe network energy consumption, and finally, based on the energy consumption analysis, the system optimization and transformation plan is given.

![Figure 4 Architecture of a digital intelligent evaluation platform for energy consumption of oilfield water injection systems](image)

According to the platform architecture, GUI programs are written on the MATLAB platform to realize the human-computer interaction interface of the oilfield water injection system energy consumption digital intelligent evaluation platform. The main interface is shown in Figure 5. The function catalog includes data management, energy consumption analysis and evaluation, and optimization and transformation.
Taking the water injection system of an oil field as an example, the energy consumption analysis and evaluation module of the water injection system energy consumption digital intelligent evaluation platform is used to evaluate the operation of the pipeline network. The platform first automatically generates the pipe network topology of the water injection system, as shown in Figure 6. The water injection system belongs to a branched pipe network. The central location is a water injection station, which is connected to various water injection main lines, and the water injection wells are connected to the main line to realize water injection.

Based on the operating data of the oilfield pipeline network, the simulation analysis of 7 water injection stations is carried out. According to the theoretical model established above, the theoretical pressure of each water injection station can be calculated, and the measured value can be obtained from the pipeline network operating data. See Table 1 for the relative deviations between theoretical and measured pressures of the pipelines of each water injection station.

| Water injection station number | Water injection station pressure/MPa | Relative deviation/% |
|-------------------------------|------------------------------------|---------------------|
|                               | Measured value | Theoretical value   |                     |
| 1                             | 14.00          | 13.65               | 2.50                |
| 2                             | 14.28          | 14.12               | 1.12                |
| 3                             | 13.80          | 13.15               | 4.71                |
| 4                             | 15.70          | 15.53               | 1.08                |
| 5                             | 17.64          | 16.41               | 6.97                |
| 6                             | 31.16          | 30.11               | 3.37                |
| 7                             | 19.74          | 19.65               | 0.46                |
It can be seen from Table 1 that the measured pressures of the water injection stations 3, 5, and 6 have relatively high relative deviations from the theoretical pressures, indicating that the overall energy consumption of the three water injection stations is relatively high, and it is judged that the water injection pipelines are blocked and fouled. Have a greater potential for energy savings.

For a given water injection pressure at a water injection station, the pressure at each water distribution node directly reflects the energy consumption level of the water injection trunk line. The relative deviations of the theoretical and measured pressures of each branch of the No. 3 water injection station are shown in Table 2.

Table 2  The relative deviation between the theoretical and actual pressure of each water injection pipeline in the No. 3 water injection station

| Water injection branch | Water distribution room | Pressure of water distribution room/MPa | Relative deviation [%] | Average relative deviation [%] |
|------------------------|-------------------------|-----------------------------------------|-------------------------|-------------------------------|
|                        |                         | Measured value                          | Theoretical value       |                               |
| Route 1                | 3#                      | 10.95                                   | 13.15                   | 16.73                         | 11.41                         |
|                        | 2#                      | 12.35                                   | 13.15                   | 6.08                          |                               |
| Route 2                | 14#                     | 13.14                                   | 13.14                   | 0.00                          | 2.44                          |
|                        | 13#                     | 12.93                                   | 13.13                   | 1.52                          |                               |
|                        | 7#                      | 12.42                                   | 13.12                   | 5.34                          |                               |
|                        | 12#                     | 12.92                                   | 13.12                   | 1.52                          |                               |
|                        | 6#                      | 12.62                                   | 13.12                   | 3.81                          |                               |
| Route 3                | 21#                     | 11.54                                   | 13.14                   | 12.18                         | 9.13                          |
|                        | 20-1#                   | 12.34                                   | 13.14                   | 6.09                          |                               |
| Route 4                | Single well 1           | 11.45                                   | 13.15                   | 12.93                         | 11.03                         |
|                        | Single well 2           | 11.95                                   | 13.15                   | 9.13                          |                               |

The results in Table 2 show that the overall energy consumption of Route 1 and Route 4 is relatively high, indicating that the pipeline is blocked and scaled seriously. The optimization and transformation plan of the water injection system is to physically or chemically clean the pipe network of No. 1 and No. 4 trunk lines to reduce the pressure loss of the water injection pipeline and improve the efficiency of the water injection system.

4. conclusions

In view of the characteristics of the water injection pipe network system of large oilfields, based on hydraulic theory and matrix theory, the characteristic equations of each unit of the water injection system are established, and the overall matrix equation of the water injection system is formed by the flow balance. A simulation theoretical model of the water injection system was established, and a digital intelligent evaluation platform for energy consumption of the water injection system was developed based on this. In this way, the production operation status of the water injection system under theoretical conditions is simulated and compared with the actual production operation data. It can accurately analyze and evaluate the energy consumption status of the water injection system's pipe network and the operating efficiency of the energy consumption of the branch pipe network of each water injection station. Through this platform, realize the diagnosis and analysis of the energy consumption problem of the water injection pipe network system, find out the existing problems in the water injection pipe network and propose optimization measures, which play an important role in reducing the energy consumption of the water injection system and improving the production and operation efficiency of the water injection system.

Acknowledgment

This paper is financially supported by Shaanxi Province Technology Innovation Guidance Special Fund (Project NO.2017CGZH-HJ-08).
References

[1] Wei Lixin, Liu Yang, Sun Hongzhi. Optimization of operation scheduling of multi-source oilfield water injection system[J]. Petroleum Drilling and Production Technology, 2007(03):59-62+123-124.

[2] Song Qi, Zhuang Jianquan, Luo Jiangtao, Zheng Chunxing. Oilfield water injection pipeline network problem diagnosis and energy saving potential prediction[J]. Petroleum Industry Technical Supervision, 2018, 34(10): 32-35.

[3] Wang Hanxiang, Yang Dewei. Hydraulic calculation of surface branch pipe network for water injection in oilfield[J]. Journal of China University of Petroleum (Edition of Natural Science), 2010, 34(01): 125-128+133.

[4] Chang Yulian, Gao Sheng, Guo Junzhong. Simplification technology and calculation method of water injection pipe network system model[J]. Acta Petrolei Sinica, 2001(02): 95-100+125.

[5] Ren Yongliang, Chang Yulian, Xing Baohai, Gao Sheng, Zhang Ruijie, Wang Jing. Establishment and Solution of Hydraulic Model of Oilfield Water Injection String[J]. Journal of System Simulation, 2007(07): 1468-1470+1526.