The research on the operation mode and parameter selection method of large-scale water injection pipeline network

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Abstract

Due to the complexity of the large-scale water injection pipe network system and the difficulty of manual analysis, it is impossible to guarantee the optimal operation mode scheme selected. At present, there are still gaps in the research on the judgment of its optimal operation mode. Through the calculation and evaluation of a large amount of water injection system data, the selection method of the optimal operation mode of the water injection system is determined, and it is found that the selection of the optimal operation mode is closely related to the pressure distribution characteristics of the individual wells of the entire water injection system, and five discriminant rules for the optimal operation mode of the water injection system are formed based on these characteristics; the mathematical model for determining the mode and the optimal method of operating parameters is given, and the pipeline network simulation system automatically generates the pipe network topology diagram; the optimal operation mode of the water injection system is developed; Intelligent judgment software can modify its operating parameters according to needs, change operating modes, easily simulate the energy consumption in various modes of operation, adjust and find the optimal operation plan of the water injection pipe network. Application examples show that the judgment rules of the optimal operation mode of the water injection system and the optimization method of operating parameters can be used as an effective means for selecting the optimal operation plan for a large-scale water injection pipeline network.

Keywords Water injection pipeline network · Optimal operation mode · Discriminant rules · Boost mode · Partial pressure mode

Introduction

In the process of oilfield development, water injection is a way to increase production by maintaining formation pressure, ensuring high and stable crude oil production, and increasing the rate of crude oil production (White et al. 2020; Wang et al. 2019). In the water injection system, energy consumption roughly includes the energy consumed during the operation of the water injection

pump motor and the energy consumed in the water injection pipe network during the water injection process (Zhou et al. 2019). Among them, the water injection pipe network alone consumes 20–40% of the energy of the entire water injection system (Gao et al. 2020). In order to improve the operating efficiency of the water injection system and reduce the production energy consumption of the water injection system, research on efficient water injection technology and energy saving of the water injection system is an important subject of oilfield development (Ruan et al. 2018a; Zhang et al. 2017; Zhou et al. 2018).

One of the main factors affecting the energy consumption of the water injection pipe network is the operation mode of the water injection pipe network. The early operation mode was relatively simple, that is, the single-pipe multi-well water distribution process mode. Due to the large difference in the formation permeability of each water injection single well, the demand for the incoming water pressure is different, and the difference between the height and the low can even reach more than 10 MPa (Megapascal), but the outlet

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pressure of the water injection pumping station is a constant maximum demand value, which leads to some serious energy consumption loss of the water injection system, and the efficiency of the entire system is much lower than the normal value (Ruan et al. 2018b; Zhou et al. 1998). In order to reduce the loss rate of the pipe network, many scholars have carried out research in this area. It can be traced back to Yongshou Zhong's proposal in 1987 to carry out a pressurized water injection mode test for water injection wells in ultra-low permeability layers. Field practice and analysis can show that the cost of water injection was reduced (Zhong and Liu 1987); the partial pressure water injection mode was first adopted by Daqing Oilfield in 1993. After the pressure method, successful experience has been obtained (Gao et al. 2019; Zhou 1993); in recent years, Xiaolan He (2013) proposed to add a single-well booster device to the injection process to increase the water injection pressure and reduce the outlet pressure of the pumping station (He 2013); Gao et al. (2016) proposed to assume a partial pressure point and try to calculate the minimum useful power output of the water injection station to determine the partial pressure point, then achieve partial pressure water injection (Gao et al. 2016); Wenjuan Wu (2017) implemented single-well boost control for under-injection wells (Wu 2017); Chuang Duan, etc., (2020) applied partial pressure water injection technology to Zhuangxi Oil Production Plant (Duan 2020), etc. So, when is the pressurized water injection mode chosen? The choice of partial pressure water injection mode is a new problem. There is no unified understanding at present; the operating parameters of the definite mode are also established through trial calculations and manual experience. There is no clear set of parameter optimization methods, especially for large oil fields with complex water injection system, which is difficult to determine the optimal water injection scheme.

optimal operation mode of the water injection system, gives the judgment rules of the optimal operation mode of the water injection system, the mathematical model for determining the mode and the optimization method of operating parameters. The pipeline network simulation system automatically generates the pipeline network topology diagram; the intelligent judgment software for the optimal operation mode of the water injection system is developed, which can easily simulate the energy consumption under various modes of operation to adjust and find the optimal operation of the water injection network mode and parameters.

General idea of research work

Water injection pipe network operation mode

Oilfield water injection pipeline network usually adopts the traditional single-pipe multi-well water distribution process mode. In order to reduce the loss rate of the pipeline network, part of the water injection system can be optimized and transformed into a partial pressure injection process mode or partial pressure water injection process mode, thereby improving the efficiency of water injection system pipeline network (Zheng et al. 2013; Wang et al. 2018).

Booster water injection mode

The booster water injection mode is shown in Fig. 1a. The booster water injection mode is a process in the traditional water injection technology in which the headwater is pressurized by the water injection station, and then it is pressurized for the second time by the booster pump process

Fig. 1 Operation mode of water injection pipe network

Based on the calculation and evaluation of a large amount of water injection system data (Bo et al. 2021; Gao et al. 2018), this paper determines the selection method of the

before it reaches the water injection well from the water distributing room. This mode is suitable for water injection systems with individual high-pressure water injection wells

or local high-pressure blocks in the water injection system (Yang 2014).

Partial pressure water injection mode

The partial pressure water injection mode is shown in Fig. 1b. In the water injection system, there will be water injection wells with similar water injection pressures. Combine these water injection wells with similar water injection pressures together and establish an independent water injection system. By this method, the water injection system is divided into multiple subsystems with different water injection pressures. The water injection pressure of these subsystems is close to the pump pressure, which reduces the pressure difference between the pump pipes and improves the efficiency of the water injection system (Cheng et al. 2012; Dong et al. 2016).

For a large old oilfield, according to different well conditions and energy consumption of the pipe network system, different operation modes are selected, and the operation mode is adjusted with the changes in the production process, so that the entire water injection system can operate at the most efficient and economical optimal state.

General research ideas

The selection of the optimal operation mode is based on GB/T33653-2017 "Test and Calculation Method for Energy Consumption of Oilfield Production System" (GB, T33653-2017) to calculate the energy consumption of the current operating system, such as: water injection system efficiency, pipe network loss rate, and valve control pressure loss. According to GB/T31453-2015 "Monitoring Code for Energy Conservation of Oilfield Production Systems" (GB, T31453-2015), it evaluate whether the above calculation results meet the requirements of the monitoring specifications. If it meets the requirements, the model is optimal, and if it does not meet the requirements, it needs to be optimized.

The evaluation results of a large amount of data show that the current single-tube multi-well water distribution process mode may be the optimal mode, or it may need to be adjusted to meet the monitoring specifications, while the current operating boost mode and partial pressure mode basically meet the monitoring specifications. For those who do not meet the requirements, only need to optimize the parameters without adjusting the operating mode. Therefore, the selection of the optimal operation mode only needs to select the single-tube multi-well water distribution process mode that does not meet the requirements of the monitoring specification.

The method of choice is when the single-pipe multi-well water distribution process mode does not meet the requirements of the monitoring specifications, the preferred

boosting mode is considered from the perspective of investment cost to optimize, and it is the best if it can meet the requirements of the specification. Otherwise, the partial pressure water injection mode with large investment is selected to optimize, so as to finally meet the requirements of the monitoring specification. The overall research route is shown in Fig. 2.

Formation of discriminant rules for optimal operation mode of pipeline network

In the process of evaluating whether the system meets the requirements of monitoring specifications, through the actual investigation and comparative analysis of a large number of oilfield water injection systems, we find that the selection of optimal operation mode is closely related to the pressure distribution characteristics of each single well of the whole water injection system, and the following five discrimination rules of optimal operation mode are gradually formed.

In the actual investigation and comparative analysis of a large number of oilfield water injection systems, we found that the selection of the optimal operation mode is closely related to the pressure distribution characteristics of the individual wells of the entire water injection system.

Fig. 2 Overall research route

Fig. 3 Statistical drawing of pressure distribution of water injection wells in 1# water injection system

Fig. 4 Statistical drawing of pressure distribution of water injection wells in 2# water injection system

For example, the formation of rule 1: an oilfield 1# water injection system has a pump outlet pressure of 15.33 MPa, and a single-tube multi-well water distribution process is adopted. The statistical drawing of the pressure distribution of water injection wells is shown in Fig. 3.

It can be seen from Fig. 3 that there are 109 wells in the 1# water injection system, of which 98 wells are concentrated near the outlet pressure of the pump, accounting for 89.9% of the total number of wellheads in the system. Determined by the above-mentioned optimal operation mode selection method, when the well pressure is concentrated near the pump outlet pressure and accounts for more than 70% of the total wellheads, it meets the requirements of the monitoring specification. Therefore, a system with such characteristics is considered to be the pressure of the water injection well. The distribution is reasonable, and the system process does not need to be optimized. For this reason, a rule is formed, which is defined as rule 1.

For example, the formation of rule 2: a pump outlet pressure of 2# water injection system in an oilfield is 14.1 MPa, and a single-tube multi-well water distribution technology mode is adopted. The statistical drawing of the pressure distribution of water injection wells is shown in Fig. 4.

It can be seen from Fig. 3 that there are 35 wells in the 2# water injection system, of which 28 wells are concentrated in the middle pressure range, accounting for 80% of the total number of wellheads in the system, and only 6 wells have pressures in the range of 9–15 MPa, close to the pump outlet pressure. According to the above selection method, this type of water injection system needs to be optimized through the boost mode to meet the requirements of the monitoring specification. Therefore, it is recommended that systems with such characteristics adopt the boost mode optimization. For this reason, another rule is formed, which is defined as rule 2.

In the same way, after a large number of calculations and the characteristic comparison analysis with the actual pressure distribution map, rules 3, 4, and 5 are gradually formed and defined. The final corresponding optimal operating mode judgment rules are as follows:

Rule 1: If more than 70% of the water injection well pressure in the system is distributed near the outlet pressure of the pump in the pressure profile, it is considered that the current pressure distribution of the water injection well is reasonable and the system process does not need to be optimized;

Rule 2: When the pressure of more than 70% of the water injection wells of the water injection system is concentrated in the middle of the entire pressure distribution chart, and only a small number of water injection wells are distributed near the pump outlet pressure, this type of system is recommended to use the boost mode to optimize;

Rule 3: The pressure of the water injection well is more evenly dispersed in the interval of the pressure distribution diagram. This type of system is recommended to use the partial pressure water injection mode to optimize;

Rule 4: The system has been optimized for booster mode or partial pressure water injection mode, then the current system process does not need to be optimized. If the valve control pressure loss is greater than 3 MPa, parameter optimization is required;

Rule 5: Small displacement water injection system, such as the displacement below 20m³/h, the energy consumption is less than 200 kW (Kilowatt), then the current water injection system technology does not need to be optimized.

On the one hand, these five discriminating rules can conveniently guide the adjustment of the on-site operation mode. In practical applications, only according to the characteristics of the measured pressure distribution map at the wellhead can be used to determine whether the existing mode is optimal or how to adjust it; on the other hand, it is

necessary to establish a knowledge base and lay the foundation for the development of intelligent judgment software for optimal operating mode.

Mathematical model under certain mode and optimization of operating parameters

After determining the optimal mode, how to determine the optimal operating parameters is a problem to be further studied, such as which wells need to be pressurized in the pressurization mode, and the determination of the partial pressure point of the partial pressure mode. For this reason, it is necessary to establish relevant calculation models and optimize the parameters.

Mathematical model of traditional process mode and energy consumption calculation

The confirmed traditional single-pipe multi-well water distribution technology model and its mathematical model combined with the pipe network water conservancy calculation method in our previous research (Bureerat and Sriworamas 2013; Chang et al. 2001; Cafaro and Grossmann 2021; Kappos and Economides 2004) established the overall equations of the pipe network system as follows:

$$\begin{bmatrix} K^1 & 0 & \dots & 0 & 0 \\ 0 & K^2 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & 0 \\ 0 & 0 & \dots & K^{n-1} & 0 \\ 0 & 0 & \dots & 0 & K^n \end{bmatrix} \cdot \begin{bmatrix} (q^1)^2 \\ (q^2)^2 \\ \vdots \\ (q^{n-1})^2 \\ (q^n)^2 \end{bmatrix} = \begin{bmatrix} \Delta H^1 \\ \Delta H^2 \\ \vdots \\ \Delta H^{n-1} \\ \Delta H^n \end{bmatrix}$$

Abbreviated as:

$$K \cdot Q^2 = \Delta H \quad (1)$$

where: ΔH -Pipeline pressure loss vector; K -Characteristic matrix of pipe network; Q -Pipe flow vector.

A pipe network simulation system has been developed, and the system automatically generates a pipe network topology diagram of a water injection system, as shown in Fig. 5.

The traditional process mode does not require optimal parameters, and the system energy consumption value is directly calculated by the above model;

System total input power:

$$N_u = \frac{\sum_{i=1}^n [(p_{\text{Pout}} - p_{\text{Pin}}) \cdot G_p]_i}{3.6} \quad (2)$$

Fig. 5 Pipe network topology diagram of traditional process mode

where: N_u -System total input power, kW; p_{Pout} -Water injection pump outlet pressure, MPa; p_{Pin} -Water injection pump inlet pressure, MPa; G_p -Water injection pump flow, m^3/h ; n -The total number of water injection pumps tested in the water injection system.

Energy loss rate of water injection pipe network:

$$\varepsilon_{\text{pv}} = \frac{\sum_{i=1}^n [(p_{\text{Pout}} - p_0) \cdot G_p]_i - \sum_{j=1}^m [(p_{\text{Vout}} - p_0) \cdot G_w]_j}{3.6 \sum_{i=1}^n N_u} \times 100\% \quad (3)$$

where: ε_{pv} -Energy loss rate of water injection pipe network, %; p_{Vout} -Pressure after wellhead valve of water injection well, MPa; p_0 -Base pressure, 0.1 MPa; G_w -Wellhead flow of water injection well, m^3/h ; m -The total number of water injection wells tested in the water injection system.

The valve control pressure loss is:

$$p_v = \frac{\sum_{j=1}^m (p_g \cdot G_w)_j - \sum_{j=1}^m (p_p \cdot G_w)_j}{\sum_{j=1}^m G_w_j} \quad (4)$$

where: p_v -Valve control pressure loss, MPa; p_g -Water injection main line pressure of water injection system, MPa; p_p -Oil pressure in water allocating station, MPa.

On the one hand, the calculation results indicate the current energy consumption status of the system. On the other hand, it also confirms that the currently selected mode meets the requirements of the monitoring specification, which is the optimal mode.

Mathematical model and parameter optimization of boosting mode

The mathematical model of the confirmed boosting mode is based on Eq. (1) of the pipe network mathematical model of the traditional process mode, adding the number of booster pump units, and the increased input energy is:

$$N_{P2} = \sum_{X=1}^R \frac{(P_X - P_{Pout1})}{3.6\eta_P} \cdot Q_X \quad (5)$$

where: N_{P2} —The sum of the input power of the booster pump, kW; P_X —Injection pressure of the Xth injection well, MPa; P_{Pout1} —The outlet pressure of the water injection pump station after the water injection system boosting transformation, MPa; η_P —Booster pump unit efficiency, %; Q_X —Wellhead flow rate of X water injection well, m³/h; R—Number of booster wells.

The method of optimizing operating parameters in boosting mode is as follows:

- (i) Determining the number of booster wells: First, according to the judgment rule 2, there are a small number of water injection wells whose pressure is distributed near the pump outlet pressure, and the number of these small water injection wells is set as the number of booster wells R.
- (ii) Determination of the outlet pressure of the pumping station: Since the R wells close to the pressure of the pumping station are pressurized, the outlet pressure of the pumping station can be reduced to meet the pressure requirements of the R + 1th well.
- (iii) According to the mathematical model of the boosting mode and the determined operating parameter values, the pipe network simulation system generates the topology of the boosting mode pipe network, as shown in Fig. 6.

Fig. 6 Topology diagram of pipe network in boosting mode

(iv) Calculate the energy consumption values of the boost mode by formulas (2–4), and then, evaluate whether these energy consumption values meet the standards by the aforementioned monitoring specifications. Otherwise, modify the R value to $R \pm 1$, adjust the outlet pressure value of the pump station and calculate the energy consumption value again, until an optimized plan that meets the monitoring specifications is obtained. What needs to be explained is that it is sufficient to meet the monitoring specifications, and do not demand the lowest energy consumption indicators, otherwise the investment in manpower and material resources will be increased.

The process of the optimization method of the boost mode parameters is shown in Fig. 8a.

Mathematical model and parameter optimization of partial pressure mode

It is known that the partial pressure mode is composed of two parts: a high-pressure process and a low-pressure process. The processes belong to the single-tube multi-well water distribution process mode. Therefore, the mathematical model of the traditional process mode pipe network mathematical model Eq. (1) can be used.

The selection of the operating parameters of the partial pressure mode is mainly to determine the partial pressure point of the high- and low-pressure process, that is, to determine the output pressure required by the high-pressure process and the low-pressure process, respectively. The preferred method is as follows:

- (i) From Rule 3, it can be seen that the pressure of the water injection wells of the water injection system using the partial pressure mode is more evenly dispersed in the interval of the pressure distribution diagram, and the pressure of the well located in the middle of the interval is selected as the partial pressure point P. The original process trunk line is used as the high-pressure process line, and the outbound pressure value remains unchanged; add a low-pressure process line, and the outbound pressure is the sum of the partial pressure point pressure P and the pressure loss of the low-pressure process trunk line, and hang the water distribution room and well which will be less than the low-pressure process outbound pressure to the low-pressure process trunk line.
- (ii) According to the mathematical model of the partial pressure mode and the determined partial pressure point P value of the high- and low-pressure process, the partial pressure mode pipe network topology diagram can be generated by the pipe network simulation system, as shown in Fig. 7.

Fig. 7 Pipe network topology diagram in partial pressure mode

(iii) Calculate the energy consumption value of the partial pressure mode by formulas (2–4), and then, evaluate whether these energy consumption values meet the standard by the monitoring specification; otherwise, modify the partial pressure point value P to $P \pm 0.5$, and calculate the above energy consumption value again, until an optimized plan that meets the monitoring specifications is obtained. In the same way, do not demand the lowest energy consumption index.

The flow of the method for selecting the parameters of the partial pressure mode is shown in Fig. 8b.

An oilfield A# water injection system application case

Based on the above-established optimal operation mode judgment rules and parameter selection methods, etc., using MATLAB engineering software, an intelligent judgment software for the optimal operation mode of the water injection system is developed. The software contains a knowledge base of rules to first determine the operating mode that should be adopted for each water injection system. After the mode is determined, the optimal operating plan is determined based on its mathematical model and operating parameter optimization method.

Fig. 9 A# water injection system current program operation results

Fig. 8 Flow chart of optimization of operating parameters

☒ **Booster water injection mode** ☐ Partial pressure water injection mode

Number of pressurized wellheads: 12 Operation

Pump outlet pressure: 12.14 MPa

Partial pressure point wellhead pressure: MPa Operation

Output pressure of high-pressure: MPa

Output pressure of low-pressure: MPa

Energy consumption of the optimized scheme

Total system input: 2276.84 kW

Loss rate of water injection pipe network: 29.20 %

Valve control pressure loss: 2.70 MPa

Fig. 10 A# water injection system boost mode operation results

☐ Booster water injection mode ☒ **Partial pressure water injection mode**

Number of pressurized wellheads: Operation

Pump outlet pressure: MPa

Partial pressure point wellhead pressure: 10 MPa Operation

Output pressure of high-pressure: 13.00 MPa

Output pressure of low-pressure: 11.14 MPa

Energy consumption of the optimized scheme

Total system input: 1984.28 kW

Loss rate of water injection pipe network: 21.97 %

Valve control pressure loss: 1.13 MPa

Fig. 11 A# water injection system partial pressure water injection mode operation results

Take an oilfield A# water injection system as an example. The system has 84 wells and the pump outlet pressure is 13.5 MPa. At present, the traditional single-tube multi-well water distribution technology mode is adopted. Import the relevant test data into the mode discrimination software. The discrimination software displays the pressure distribution statistics of the water injection wells and various data of the energy consumption of the current scheme as shown in Fig. 9. At the same time, based on the knowledge base of the rules, it is intelligently judged that the A# water injection system should be optimized by the boost mode, and various data showing the energy consumption of the optimized scheme are shown in Fig. 10.

Therefore, it is convenient to compare the energy consumption before and after optimization. The system can also randomly modify the number of pressurized wellheads in the figure, and obtain the operating effect of the system when different pressurized wellheads are set.

Through the numerical evaluation of the energy consumption in Fig. 9 and Fig. 10, it is confirmed that the A# water injection system meets the requirements of the monitoring specification after the optimization of the boost mode.

The judgment software also has the function of changing the operating mode. For example, in Fig. 10, the partial pressure water injection mode can be selected, and the partial pressure point wellhead pressure can be set. The optimized operating result of the partial pressure water injection mode of the A# water injection system is shown in Fig. 11. The wellhead pressure at the partial pressure point can also be modified randomly.

Comparing the operating results of Fig. 10 and Fig. 11, although the energy consumption of the partial pressure mode in Fig. 11 is lower, the investment cost is much greater than that of the booster mode in Fig. 10. As mentioned above, the optimization scheme only needs to meet the monitoring specifications. The consumption index is the lowest.

With the intelligent judgment software of the optimal operating mode, a satisfactory operating scheme can be easily selected. Before the application of the determined scheme, a feasibility assessment of the oilfield is required. It is necessary to judge whether the determined operation scheme is feasible according to the on-site implementation conditions and oilfield investment intensity. Otherwise, select the operation mode again to modify the operating parameters until the final satisfactory optimal operation scheme of the water injection pipe network is obtained.

Conclusion

It is found that the selection of the optimal operation mode of the water injection system is closely related to the pressure distribution characteristics of the individual wells of the entire water injection system. The characteristics of the measured pressure distribution map are used to determine whether the existing model is optimal or how to adjust. The optimization of the boosting mode parameters is mainly to determine the number of boosting wells R and the outlet pressure value of the pumping station. The number of boosting wells is adjusted by a step size of 1, and the outlet pressure of the pumping station meets the target pressure value of the $R + 1$. The optimal parameter of partial pressure mode

is mainly the determination of the partial pressure point P value of the high- and low-pressure process. The pressure of the well located in the middle of the pressure distribution graph interval is selected as the partial pressure point P , and the step length is adjusted to 0.5. The water injection system software was developed for determining the optimal operation mode and parameter optimization. The software can intelligently determine the optimal operation mode of the water injection network, modify the operating parameters, change the operation mode, conveniently simulation run various modes of system energy consumption situation, adjust and find the optimal operation plan of the water injection pipe network.

Based on the above research work, it is suggested to further study the method of obtaining a large number of basic data and reliability analysis of water injection system, so as to ensure the accuracy of optimal operation mode discrimination and parameter optimization.

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Declarations

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Data availability The authors make sure that all data and materials as well as software application or custom code support their published claims and comply with field standards.

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Human or animals rights This article does not contain any studies with human participants or animals performed by any of the authors.

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