Optimization Algorithm Study of Operation Energy Consumption in Water Flooding System

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Abstract. Oilfield flooding is one of the methods which replenish energy to stratum, improve the recovery factor of oil exploitation in the development of oilfield. The energy consumption of water injection is also part of the total energy consumption. Oilfield flooding is one of the methods which with the great mass oilfields that in China have entered the later development period, the cost of oil exploitation is rising, and the water injection in the same way. It is an effective way to reduce the cost of water injection by using computer technology to optimize operation control of oil field water injection system. Water injection system analyzed in this paper is suitable by combining multiple centrifugal pump and frequency converter in the composition of water injection station as the water system, optimization mathematical model is established for water injection system, using c++ optimization software is compiled, selects the improved constrained variable dimension method was used to solve the model, the optimization result is applied to a production plant of daqing oilfield water injection system. After adopting the optimized pumping measures, the system efficiency is increased by 1.8% when meeting the water injection requirements, and the operation cost is saved by about 10,000 RMB per day, which reduces the production cost of the oilfield.

1 Introduction

Water injection is a very important method in oilfield development. It can effectively supplement formation energy and play an active role in improving oil recovery and ensuring high and stable production.[1] The water injection system is mainly responsible for pumping, transporting, pressurizing, throttling and injecting the injected water, which consumes a large amount of energy during operation. Especially as the oilfield enters the period of high-water-cut development, the water injection volume increases greatly and the water injection power consumption increases greatly.[2] It is predicted that the water injection power consumption of daqing oilfield increases by 0.78*10⁸kw·h on average annually, and the water injection power consumption has accounted for more than 40% of the total power consumption of oilfield production.[3] It is urgent to improve management level and control system operation cost.

Generally, the water injection system for large oil fields is the joint supply of water injection pipe network from multiple water injection stations. Each water injection station is equipped with multiple high-pressure water injection pumps, and several pumps are opened...
according to the demand of water injection in the system. In addition, 1-2 reserve pumps are also provided. The water injection process is as follows: the water is pumped out from the water injection station through the water injection pipe network to the water distribution room, and sent to the end water injection well through the water distribution room according to the injection pressure of the injection well and the pressure of the injection flow distribution.\[4\] The multi-station water injection system is a typical complex non-linear system. As each pump station influences each other, the adjustment of its operation parameters is difficult to determine accurately. In the actual operation, each oil field basically relies on experience and multiple attempts to determine an applicable pumping scheme, which often leads to high pressure of pipe network and increase of water injection cost due to the need to guarantee water injection requirements.\[5\] The optimization of operation cost of water injection system is to determine the opening scheme of each water injection pump and corresponding operation parameters on the premise of known pipe network system structure and water injection requirements, so as to reduce the operation cost of water injection. That is, in the case of fixed investment, to minimize operating costs and improve the economic benefits of oilfield development and construction.

2 Establishment of operation cost optimization model for water injection system

For the convenience of research, the following parameters are uniformly specified:

- $U_m$ — Outgoing flow of the M water injection station, $m^3/s$;
- $U_{mk}$ — The flow rate of the K pump in the M water injection station, $m^3/s$;
- $P_m$ — The discharge pressure of the M water injection station, $P_a$;
- $P_{mk}$ — The outlet pressure of the K pump in the M water injection station, $P_a$;
- $\eta_{pmk}$ — Efficiency of the K pump in the M water injection station;
- $\eta_{emk}$ — Efficiency of the K pump motor in the M water injection station;
- $\alpha$ — Unit conversion coefficient, constant;
- $f$ — The target function, the power consumption, kw·h;
- $\delta_{mk} = \begin{cases} 0 & \text{The k pump in the m station is closed} \\ 1 & \text{The k pump in the m station is open} \end{cases}$
- $M$ — Total number of waterflood stations;
- $K_m$ — Number of water injection pumps in the m station;
- $P_i$ — The pressure at the ith node in the pipe network, $Pa$;
- $N$ — Total number of nodes in the network;
- $h_{ij}$ — Pressure drop in pipe section between node i and j, $Pa$;
- $q_{ij}$ — The flow rate through the segment ij, $m^3/s$;
- $\text{Sgn}(a) = \begin{cases} +1 & a \geq 0 \\ -1 & a < 0 \end{cases}$ sign function;
- $Q_i$ — The water consumption of node i, if it is a water injection well, is equal to the injection flow; If is the intermediate node, then is 0, $m^3/s$;
- $S_{ij}$ — Specific resistance coefficient of segment ij;
- $K_{ij} = 1 / S_{ij}$ Friction coefficient of segment ij;

2.1 Objective function

The optimal energy consumption for operation of oilfield water injection system is the minimum total energy consumption, i.e. the minimum electricity consumption, on the premise of satisfying the injection pressure and injection flow of each injection well. The water consumption of each injection well in the system (i.e. the injection flow distribution) is known, the water consumption of each intermediate node is 0, and the following
optimization objective mathematical model is established with the pressure and flow rate of each injection station as optimization variables:

$$
\min f (U, P) = \alpha \sum_{m=1}^{M} \sum_{k=1}^{K_m} \delta_{mk} d_{mk} P_{mk} / \eta_{p_j/p_{esj}}
$$

(1)

2.2 Constraint condition

2.2.1 Pipe network node flow balance constraints

The optimal scheme of water injection system must be physically realizable, that is, the optimized scheme must satisfy various inherent constraints in the system. For any node I in a water-injection pipe network with $N$ nodes, the flow to that node at any time and time interval must be equal to the flow out of that node, and there must be a balance between them. There are at most three types of flow in and out of a node: The flow of pipeline adjacent to the node is $q_{ij}$; When the node is water injection well, the amount of water is $Q_i$. When this node is the water supply $U_i$ of the node where the water source is. These quantities have the following relations:\(^6\):

$$
U_i - Q_i - \sum_{j \in i} s_{ij} sgn(p_i - p_j) |p_i - p_j|^\frac{1}{\alpha} = 0 \quad i, j = 1, 2, \ldots, N; \ i \neq j
$$

$$
\dot{h}_{ij} = p_i - p_j = k_{ij} q_{ij}^\alpha
$$

$$
sgn(p_i - p_j) = \begin{cases} +1 & \text{when } p_i - p_j \geq 0 \\ -1 & \text{when } p_i - p_j < 0 \end{cases}
$$

(2)

where: $i$ is the set of node labels adjacent to node $i$; $\alpha$ is a constant: When the pipe flow rate is greater than 1.2m/s, take $\alpha=2$, otherwise $\alpha=1.8$.

$N$ equations can be listed according to equation (2), but it can be proved that only $n-1$ of them are independent of each other. Therefore, it is necessary to determine a reference node as a known quantity in advance and obtain the reference point of other node values. Generally, the pressure value of a test point should be selected for this reference point.

2.2.2 End node pressure constraint

The water injection system must guarantee its service quality, that is, the pressure value of all injection Wells should meet the geological injection requirements:

$$
p_i \geq p_i^{\min} \quad i = 1, 2, \ldots, N
$$

(3)

where: $p_i^{\min}$ is the minimum pressure requirement of the node $i$, and if the node is the injection well, it is the injection pressure of the well. If it is not a water injection well, there is no such requirement.

2.2.3 Water injection pump capacity constraints

The models of water injection pumps in each water injection station are different, and the water injection pumps shall meet the requirements of maximum and minimum discharge, that is:

$$
U_{mk}^{\min} \leq U_{mk} \leq U_{mk}^{\max} \quad i = 1, 2, \ldots, M \quad k = 1, 2, \ldots, K_m
$$

(4)
2.2.4 Water discharge from water injection station is limited

For the water injection volume of each water injection station, the discharge volume of each water injection station should be satisfied due to the restriction of water supply, sewage reinjection, electricity consumption and other factors.

\[ U_{m_{\min}} \leq \sum_{k=1}^{K_m} U_{mk} \leq U_{m_{\max}} \quad m = 1, 2, \ldots, M \]  

In the formula, \( U_{m_{\max}} \) and \( U_{m_{\min}} \) are the upper and lower limits of the outbound flow of the \( m \) injection station respectively.

2.2.5 Centrifugal pump parameter constraints

Large water injection systems generally use high pressure centrifugal pumps. The flow \( u \) of centrifugal pumps and the head \( p \) are not independent from each other, and there is a nonlinear correspondence between them \(^7\):

\[ p = a_0 - a_1 u^2 \] \hspace{1cm} (6a)

\[ \eta_p = b_0 - b_1 (u - u_0)^2 \geq \eta_{p_{\min}} \] \hspace{1cm} (6b)

In the formula, \( a_0, a_1, b_0, b_1 \) are fitting coefficients, which generally need to be obtained through testing; \( \eta_p \)—Efficiency of centrifugal pump, \%; \( \eta_{p_{\min}} \)—Allowable minimum pump efficiency; \( u_0 \)—The rate of centrifugal flow at the highest efficiency point, constant.

3 Optimization model solution

It can be seen from the above mathematical models and constraints that the operation cost optimization of oilfield waterflooding system is a complex nonlinear system optimization problem with equality and inequality constraints. For such optimization problems, the feasibility of using the Constrained Variable Metric method (cvm01) is given in literature \(^8\). To do this, need to modify the above constraint because for one a large water injection system, if according to the type (2) ~ (6), there are thousands of equality and inequality constraints, to so many with equality constraints and inequality constraints, continuous and integer variables of large, complex nonlinear optimization problem, using general CVM01 or other basic methods cannot solve it, appropriate measures must be taken.\(^3\).

3.1 Simplify the constraint conditions

The simplification of constraint conditions can be divided into pipe network simplification and "dimension reduction" operation of pumps, and the simplification of pipe network can be divided into two steps.

The first step is to divide the water injection pipe network into water injection main line and water injection branch line, water injection branch line is connected with water injection well or water distribution room. The flow distributed along the injection branch line is all simplified as the flow from the node of the injection main line. The injection pressure of the injection well gradually accumulates the head loss according to the reverse direction of the water flow until the main node, which can greatly reduce the constraints of equations and inequalities determined by equations (2) and (3) \(^4\).

The second step is to simplify several continuous water nodes in the same specification of water injection trunk into a virtual water node. The water demand of the virtual node is the sum of the water amount of the simplified actual node, and the water head pressure is to simplify the node with the maximum pressure required. At the same time, the pipe defined by the simplified node is reduced to a virtual pipe segment, which has all the physical characteristics of the original pipe segment.
For the "dimension reduction" operation of the pump, it is mainly to discard a number of pumps that do not participate in optimization. According to the optimization mathematical model (1), each pump is an optimization variable in the optimization calculation of the water injection system. In this way, for some water injection systems, the number of pumps may reach more than 50. For this reason, "dimension reduction" operation is needed, that is, some pumps are not considered in the process of optimization. The rule of exclusion should be: ① Spare pump in every station; ② Pumps in each station with higher unit consumption; ③ The power of the whole system is relatively high. It should be noted that the "dimensionality reduction" operation should be based on the water and pressure constraints of each station and the entire system. In general, after the above operations, the number of optimization variables can be reduced by about 1/3, thus accelerating the optimization process and reducing the configuration requirements of the computer [3].

With this simplification, the constraint conditions can be reduced to anywhere from a few dozen to a few hundred.

### 3.2 Two-layer hierarchical iteration—constrained variable-scale optimization

The optimization model of operation cost of water injection system shows that the second order continuous derivation of equations (1) and (2) exists. The minimum must exist. It is assumed that the Jacobi matrix of equality and inequality constraint is full rank at the minimum point, and Lagrange multiplication subindex \( \lambda \) (i is the node number) is non-zero, which can meet the condition for the establishment of the sub-problem of the constraint variable scale method [8].

Water injection system after the constraint of transformation, the number of equality and inequality constraints is still sometimes a lot, therefore, the optimization problem can be decomposed into two layers of hierarchical structure, and the optimization of the water injection system is divided into two layers of optimization, first of all, according to the characteristics of the water injection system and the system load situation, determine the optimal pressure and flow rate of the water injection station, then optimization of scheduling. Specific process is: on the second floor, give a set of pump and water injection station in advance of the initial pressure constraint condition of initial flow, injection pumps, with the constrained variable metric method to optimize the flow of the injection pumps and other operating parameters, and then sent to the first floor, traffic to provide to the optimization, solution of equations (2), it is concluded that the pressure of each node (i = 1, 2, ..., n), then the pressure of each water injection station is determined by equation (3), and then the pressure constraint conditions of the water injection station and the flow rate of the water injection pump are adjusted, which is then transferred to the second layer of the algorithm. So far as the cycle meets the requirements, the reasonable pumping scheme and the optimal operation parameters are obtained. Figure 1 is the block diagram of the calculation program. The specific algorithm is as follows.

![Figure 1. Two-layer hierarchical structure of the algorithm.](image)
According to production practice, set the initial point \( u(0) = (u_1, u_2, \ldots, u_M)^T \) that satisfies equation (5). And the detection step length \( \bar{a} = (\alpha_1, \alpha_2, \ldots, \alpha_M)^T \) and calculation accuracy \( \varepsilon \) are determined according to the size of pump discharge. Let the number of iterations \( k = 0 \).

1. Solve equations, calculate \( p(0) \), calculate the objective function \( f(u(0), p(0)) \);
2. Let \( \alpha = \bar{a} \);
3. \( i = 0, \overline{u}^{(0)} = u^{(0)} \);
4. Calculate trial point \( \overline{u}^{(i)} = (\overline{u}_1, \ldots, \overline{u}_i + \alpha_i, \overline{u}_{i+1}, \ldots, \overline{u}_{M-1}, \sum_{j=1}^{M-1} Q_j - \sum_{j=1}^{M-1} \overline{u}_j - a_i)^T \);
5. To determine whether \( \overline{u}^{(i)} \) satisfies equation (5), if it satisfies (5) to rotate (7), otherwise to rotate (9) to continue calculation;
6. From the given \( p^{(i)} \), solve the equations, calculate \( \overline{p}^{(i)} \), and then calculate the objective function \( f(\overline{u}^{(i)}, \overline{p}^{(i)}) \).
7. Is it true that \( f(\overline{u}, \overline{p}) < f(u, p) \)? If established, let \( \overline{u} = \overline{u}, f(\overline{u}, \overline{p}) = f(\overline{u}, \overline{p}) \), turn (13), otherwise turn (9) to continue calculation;
8. Calculate trial point \( u^{(i)} = (u_1, \ldots, u_i - a_i, u_{i+1}, \ldots, u_{M-1}, \sum_{j=1}^{M-1} Q_j - \sum_{j=1}^{M-1} u_j + a_i)^T \);
9. To determine whether \( u^{(i)} \) satisfies equation (5), if it satisfies rotation (11), otherwise, turn (13) to continue calculation;
10. From the given \( u^{(i)} \), solve the equations, calculate \( p^{(i)} \), calculate the target function \( f(u^{(i)}, p^{(i)}) \);
11. Is it true that \( f(u^{(i)}, h^{(i)}) < f(u, h) \)? If established, let \( u = u^{(i)}, f(u, p) = f(u^{(i)}, p^{(i)}) \), turn (13), otherwise turn (5) to continue calculation;
12. Is it true that \( i \) is equal to \( M-1 \)? If established, the probe process ends; otherwise, set \( i = i + 1 \) and return (5) to continue calculation.
13. Is it true that \( u^{(m-1)} \neq u^{(0)} \)? If the detection process is successful, turn (16) or turn (15) to continue calculation;
14. Is it true that \( a_i \leq \varepsilon \)? If it is true, the calculation results will be output and the calculation process will end. Otherwise, \( \alpha = \alpha / 2 \), the calculation will continue until (4).
15. Let \( \overline{u}_i = u_i^{(m-1)} + \lambda (u_i^{(m-1)} - u_i^{(0)}) \), \( \overline{u} = (\overline{u}_1, \overline{u}_2, \ldots, \sum_{j=1}^{M-1} q_j - \sum_{j=1}^{M-1} \overline{u}_j) \);
16. Is \( \overline{u} \) satisfied with formula (5) and \( f(\overline{u}, \overline{p}) < f(u^{(m-1)}, p^{(m-1)}) \)? If so, let \( u = \overline{u}, k = k + 1, \alpha = \beta \alpha \) turn (17) to continue to calculate.

4 The calculation example

As shown in figure 2, there are 9 water injection stations, 26 water injection pumps and 958 water injection Wells in a water injection system in daqing. 70,000 cubic meters of water are injected into the underground every day. After simplification, the system model becomes a quadratic programming problem with 26 variables, 92 equality constraints and 103 inequality constraints, both continuous variables and 0-1 variables. CVM01 is used for programming calculation. Firstly, the production data of a certain day is extracted, and the current operation of the water injection system is shown in table 1. According to the type (1) ~ (6) establish apricot north oilfield water injection system operation parameters optimization mathematical model, the gradient evaluation way choice parsing and gradient method (central difference may be adopted, and there is no much impact), the algorithm convergence precision is 0.0001, the gradient evaluation way of control variables take 1, quadratic programming subroutine initial values for automatically generated by the
program according to the requirements. The objective function calculates the initial value and takes the current production data.

Figure 2. Pipe network diagram of a water injection system in daqing.

The above optimization method is used for optimization, and the optimized operation results are obtained by more than ten minutes calculation on the computer with the main frequency of Intel 2.4G and memory of 2G, as shown in table 1.

Table 1. Compares the optimization results with the current operation data of the system.

| Name of water injection station | Pump no. | current drive pump | optimized pump on |
|--------------------------------|----------|--------------------|-------------------|
| Pump water volume (m³/d)       | Pump pressure (MPa) | Pipe pressure (MPa) | Pump pipe differential pressure (MPa) |
| Apricot18note 3#               | 6295     | 15.60              | 15.10             | 0.50 | 6015 | 16.90 | 15.57 | 1.33 |
| Apricot23note 1#               |          |                    |                   |      | 6598 | 15.88 | 15.80 | 0.08 |
| Apricot23note 2#               | 6635     | 16.10              | 15.70             | 0.40 | 6313 | 16.22 | 15.80 | 0.04 |
| Apricot23note 3#               | 6814     | 16.30              | 15.70             | 0.60 |      |       |       |     |
| Apricot16note 2#               | 2291     | 16.60              | 15.60             | 1.00 |      |       |       |     |
| Apricot16note 4#               | 2702     | 16.50              | 15.60             | 0.90 | 2506 | 16.91 | 15.40 | 1.51 |
| Apricot16note 1#               | 5182     | 15.60              | 15.50             | 0.10 |      |       |       |     |
| Apricot19note 2#               |          |                    |                   |      | 5654 | 16.32 | 15.56 | 0.76 |
| Apricot19note 3#               | 5797     | 15.80              | 15.50             | 0.30 |      |       |       |     |
| Apricot19note 2#               | 8820     | 17.00              | 16.20             | 0.80 | 9200 | 17.39 | 16.40 | 0.99 |
| Apricot17note 3#               | 8809     | 17.00              | 16.20             | 0.80 | 8995 | 17.34 | 16.40 | 0.94 |
| Apricot21note 2#               | 6546     | 16.70              | 15.50             | 1.20 |      |       |       |     |
| Apricot21note 3#               |          |                    |                   |      | 7311 | 15.67 | 15.56 | 0.11 |
New apricot 9
deep notes
1#  5203  16.40  16.00  0.40  5119  16.09  15.89  0.20
New apricot 9
deep notes
2#  5639  16.09  15.89  0.20
Apricot19note 2#
7454  15.80  15.70  0.10  9199  15.88  15.71  0.17

| Current operating index | Optimized operating index |
|-------------------------|---------------------------|
| System water volume: 72548 m3/d | System water volume: 72549 m3/d |
| System electricity consumption: 445792 kW*h | System electricity consumption: 432353 kW*h |
| Average pump efficiency: 75.49% | Average pump efficiency: 76.74% |
| Pipe network efficiency: 78.60% | Pipe network efficiency: 79.69% |
| System efficiency: 59.26% | System efficiency: 61.10% |
| Operating cost: 44.58 ten thousand yuan /d | Operating cost: 43.24 ten thousand yuan /d |
| Number of pumping stations: 12 sets | Number of pumping stations: 11 sets |

Optimize the difference between the operating index and the current operating index

| System water volume: 0 m3/d | System efficiency: 1.84 % |
| Pipe network efficiency: 1.09 % | Average pump efficiency: 1.25 % |
| System electricity consumption: -13439 kW*h | Operating cost: -1.34 ten thousand yuan /d |

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It can be seen from table 1 that, after optimizing the pump parameters, the system can save 13,000 kW*h per day and save about 13,000 kW/day and 4.8 million yuan per year of operating electricity after meeting the same water injection and water injection conditions, which not only greatly reduces the operation cost, but also improves the management efficiency.

5 Conclusion

The operation cost optimization of water injection system is a very complex problem, which involves a lot of data, such as the physical data of the pipe network, the injection distribution data of water injection wells, etc. The correctness of these data directly affects the adjustment calculation results of the pipe network, and is more likely to affect the convergence of CVM01 algorithm. Many calculations show that if there are many data errors, the calculation cannot converge. Under normal circumstances, CVM01 algorithm can calculate the optimization problem with the number of variables around 70 and the number of constraints no more than 200. Beyond this range, it often fails to converge. In addition, the length of calculation time and the accuracy of the results also have a lot to do with the configuration of the computer. After reasonable simplification and field data processing, CVM01 can be used to solve the optimization problem of water injection system operation cost.

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