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A Method for Optimising Pump Configuration and Operation in Oilfield Water Injection Network

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Some oilfields in China encounter operating problems on water injection pipeline networks. Due to the unreasonable planning of the pipeline, water cannot be transported to the end of the pipeline and injected into the wells. Also, a large amount of water is repeated transported. This paper aims to deal with the above issues by proposing a method of using pipeline pumps to pressurise the water injection pipeline network, which can improve the water supply capacity of the pipeline network, and reduce the energy consumption of water injection. The pipeline pump has the characteristics of convenient installation, compact structure, and wide application range. To effectively utilise the pipeline pump in the water injection network, a pipeline pump boosting optimisation model is developed, taking the lowest cost of the pump and operating energy consumption of the water injection system as the objective function, and considering the constraints of water injection, pipeline network hydraulics and pump operation. An oilfield in China is studied as an example, the results show that the proposed model can optimise the pump installation position and operations. The operating cost was reduced by 184 k CNY, and the total annual cost was saved by 154 k CNY. The maximum water injection increment can reach 4,700 m^3/d, which improves the water supply capacity of the water injection pipe network, and the needs of oilfield water injection planning can be satisfied.

1. Introduction

Although the surface water injection pipeline network can meet the basic water transport requirement, the larger oil field has a long distance between the water source and water sink. The outlet pressure of the central process facility shall not exceed the maximum pressure of the pipeline. Therefore, there will be problems such as failure to inject water at the end and high transport cost. At the same time, considering the high energy consumption of the pipeline network and the increasing demand for water injection planning in the future, it is necessary to optimise the locations where pumps should be installed in the pipeline network. The pipeline pump has the characteristic of convenient installation. Using pipeline pump is a good choice to pressurise the pipeline network and improve the water supply capacity of the pipe network.

Pipeline pump refers to a centrifugal pump with water inlet and outlet on the same straight line. It looks like a section of pipeline, which can pressurise the liquid and be directly installed on the pipeline without constructing a pump station. The vertical pipeline pump is shown in Figure 1. The pipeline pump is a centrifugal pump with a special structure. There are some advantages of pipeline pumps that make them superior to other oilfield pumps. These advantages include compact structure, small footprint, easy installation and maintenance, high operation stability (Yuan et al., 2013), a wide range of applications, and they can be installed anywhere in the pipeline.

In previous research, Sokolov and Barakhtenko (2020) developed a general dynamic programming algorithm, which can optimise the diameter of pipeline and the parameters of pump and valve. Halilovic et al. (2021) compared three methods of combining heat pump and energy system optimization model. Based on engineering practice, Johns et al. (2020) developed a hybrid evolutionary algorithm to optimise the design and operating

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strategy of water system. Wang et al. (2018) presented a mixed integer linear programming (MILP) model which can optimise the gathering and water injection pipeline networks simultaneously. For water transportation system of the oilfield, a MILP model is developed to minimise total transport and pump operating costs (Wang et al., 2019). Zheng et al. (2019) proposed a mixed-integer nonlinear programming (MINLP) model to optimise the pressurisation scheme of coal bed methane. Liao et al. (2018) proposed a MILP model to optimise the detailed scheduling of multi-product pipelines considering the pump operation constraints. There is a lack of relevant research on the system modelling of pipeline pumps to optimise the operating strategy of water injection systems. To fill this gap, this paper develops a water injection pump boosting optimisation model by investigating the equipment of the oilfield water injection system to optimise the water injection pump locations and operating conditions.

Figure 1: Vertical pipeline pumps

2. Optimisation model

In this paper, an optimisation model of pipeline pump pressurisation is developed. The goal of the model is to minimise the pump cost and operating cost of the water injection system. Related equations are shown in Eq.(1) to Eq.(3). Based on meeting the requirements of water injection, the constraints of water injection volume, pipe network hydraulic, and water injection pump operation are introduced into the model. Finally, the location and operating strategy of the pump in the water injection pipe network are decided.

$$f = \sum_i \sum_j c_{i,j}^p + \sum_i \sum_j c_{i,j}^o,\ \forall i \in N_S, j \in N_E \tag{1}$$

$$c_{i,j}^p = \frac{p^c}{T^{life}} \cdot B_{i,j}^p,\ \forall i \in N_S, j \in N_E \tag{2}$$

$$c_{i,j}^o = \frac{OCP_{i,j} \times p^{elc} \times 24 \times 350}{\eta^P \eta^E},\ \forall i \in N_E, j \in N_S \tag{3}$$

In the problem of optimizing water injection network operating parameters, the main constraints that need to be considered include hydraulic balance constraints, flow and pressure drop constraints, pump pressurisation restrictions, and pressure restrictions of water injection system.

2.1 Hydraulic balance constraints of node

For any node in the water injection pipeline network, according to the law of conservation of mass, the flow into the node must be equal to the flow out of the node. This requirement is modelled as Eq.(4).

$$\sum_{j \in N} Q_{j,i} - \sum_{j \in N} Q_{i,j} = q_i,\ \forall i \in N \tag{4}$$

For the three common types of nodes in the water injection system, the value of q_i is as follows:
1) For the nodes of water injection station, q_i = u, and is the total water injection volume of the water injection station;
2) For the nodes of water injection well, q_i = Q, and is the injection flow rate for water injection well;
3) For water distribution nodes or intermediate nodes, q_i = 0.
In the process of hydraulic calculation of pipe network, the node hydraulic balance constraint is taken as the termination condition of iterative calculation, so there is no need for human intervention in the operation of the whole algorithm.

2.2 Flow and pressure drop constraints of pipeline section

Pipeline section flow pressure drop restriction means that the flow and pressure of all pipeline sections in operation conforms to the actual hydraulic calculation results, including:
Flow constraints:

$$Q_{i,j} \le M \cdot D_{i,j}^p,\ \forall i, j \in N \tag{5}$$

$$Q_{i,j} \le M\left(B_{i,j}^{N} + B_{i,j}^{P}\right),\ \forall i,j \in N \tag{6}$$

$$B_{i,j}^{N} + B_{i,j}^{P} = 1,\ \forall i,j \in N \tag{7}$$

Eq.(7) means that there is only one choice between the inlet and outlet nodes of the pipeline section for pressurisation or no pressurisation.
Pressure drop constraints:

$$h_f = \lambda \frac{L}{d}\frac{v^2}{2g} \tag{8}$$

$$h_f = \frac{8\lambda_{i,j}}{g\pi^2 d_{i,j}^5} L_{i,j} Q_{i,j}^2,\ \forall i \in N_S, j \in N_E \tag{9}$$

$$p_i - p_j \ge \phi_{i,j} L_{i,j} Q_{i,j}^A + M\left(B_{i,j}^N - 1\right),\ \forall i \in N_S, j \in N_E \tag{10}$$

$$p_i - p_j \le \phi_{i,j} L_{i,j} Q_{i,j}^A + M\left(1 - B_{i,j}^N\right),\ \forall i \in N_S, j \in N_E \tag{11}$$

2.3 Pump pressurisation restriction

If a water injection pump needs to be installed between nodes i and j in the water injection system, there must be a positive pressure difference between the pump inlet and outlet, that is:

$$p_i - p_j \ge -\Delta p_{i,j} + M(B_{i,j}^P - 1),\ \forall i \in N_S, j \in N_E \tag{12}$$

$$p_i - p_j \le -\Delta p_{i,j} + M(1 - B_{i,j}^P),\ \forall i \in N_S, j \in N_E \tag{13}$$

2.4 Pressure restriction of water injection system

In order to ensure that the operating pressure of the system is within the allowable range, the maximum and minimum pressure limits of the pipeline network system are given to ensure that the pipeline section does not exceed the pressure and the pump inlet does not under pressure, that is:

$$p_i^{\min} \le p_i \le p_i^{\max},\ \forall i \in N \tag{14}$$

3. Case analysis

A water injection pipeline network of a large-scale oilfield in China is studied as an example. The water injection pipeline network has four central process facility. The central process facilities are equipped with centrifugal pumps which pressurize and pump the water into the pipeline network. Then the water is delivered to transfer stations for water injection. At present, the central process facilities can satisfy the water injection demand of the existing water injection pipeline network. According to the actual operating conditions of the site, to ensure that the water supply of the pipe network has sufficient pressure, the outlet pressure of the Central process facilities is set to the maximum pressure of 0.8 MPa, which causes a certain amount of energy waste. The MILP model developed in this paper can optimise the outlet pressure of the joint station, which also reduces the energy consumption.
There are 60,665 constraints, 13, 636 binary decision variables and 19,113 continuous decision variables in this case. Using Python with Gurobi solver to solve this MILP model, the optimization problem can be solved in a few seconds. The optimization results provide the configuration and operating scheme of pipeline pump, and provide a reference for designers.

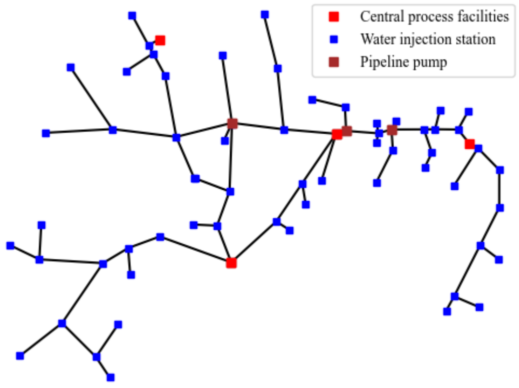

Figure 2: Configuration scheme of pipeline pump (the outlet pressure is 0.8 MPa)

Figure 2 shows the installation position of the pipeline pump obtained by optimisation model when the outlet pressure of the central process facilities is 0.8 MPa. Table 1 and Table 2 are the optimised operating strategies of pipeline pumps and central process facilities.

Table 1: Operating scheme of pipeline pump (the outlet pressure is 0.8 MPa)

pump station	Pump 1	Pump 2	Pump 3
Pump inlet pressure (MPa)	0.24	0.23	0.46
Pump outlet pressure (MPa)	0.39	0.73	0.68
Power (kW)	10.00	22.18	14.17
Flow (m^3/h)	258.75	162.50	241.25

Table 2: Operating scheme of central process facilities (the outlet pressure is 0.8 MPa)

Central process facilities	NO. 1	NO. 2	NO. 3	NO. 4
Pump inlet pressure (MPa)	0.71	0.38	0.10	0.10
Pump outlet pressure (MPa)	0.80	0.80	0.80	0.40
Power (kW)	10.00	19.52	96.85	1.59
Flow (m^3/h)	430.83	170.83	450.42	15.00

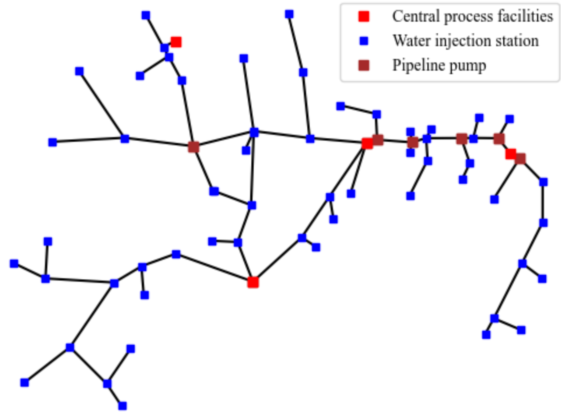

Figure 3: Distribution map of the original water injection pipeline network in the oil field

Table 3: Operating scheme of pipeline pump (the outlet pressure is not controlled)

Pump station	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5	Pump 6
Pump inlet pressure (MPa)	0.22	0.20	0.20	0.21	0.31	0.20
Pump outlet pressure (MPa)	0.71	0.40	0.48	0.41	0.71	0.47
Power (kW)	10.0	20.79	21.59	10.0	17.99	10.0
Flow (m^3/h)	75.83	374.58	282.92	191.67	162.50	135.00

Table 4: Operating scheme of central process facilities (the outlet pressure is not controlled)

Central process facilities	NO. 1	NO. 2	NO. 3	NO. 4
Pump inlet pressure (MPa)	0.64	0.36	0.10	0.10
Pump outlet pressure (MPa)	0.77	0.71	0.34	0.44
Power (kW)	15.0	16.25	40.04	1.74
Flow (m^3/h)	430.83	170.83	450.42	15.0

Table 5: Comparison and analysis of optimization results

Cost (10^4 CNY)	Energy consumption of operation	Pipeline pump	Annual
The outlet pressure is controlled	201.55	15	204.55
The outlet pressure is not controlled	183.15	30	189.15

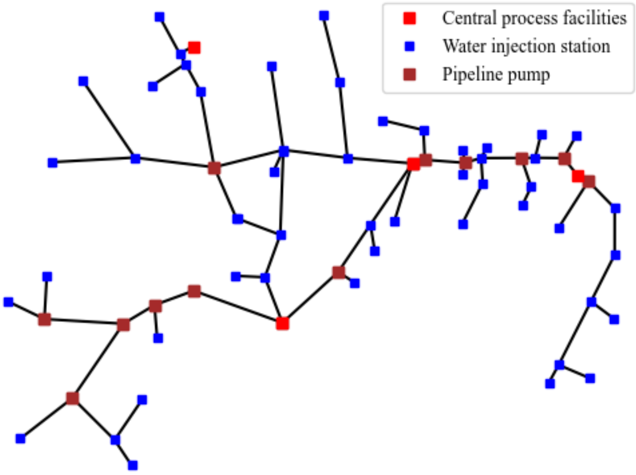

Figure 4: Optimised position of pipeline pump when the water injection volume is increased

Then, based on the existing water injection demand, without controlling the outlet pressure of the central process facilities, the installation position of the pipeline pump is shown in Figure 3, and the operating plan of the pipeline pump and the Central process facilities is obtained. Although the purchase cost of the pipeline pump is higher compared to the first case, due to the decrease of the outlet pressure, the load of the central process facilities is reduced, and the flexibility of the water supply is improved. In addition, the operating energy consumption has been reduced by 184 k CNY, and the total annual cost has been saved by 154 k CNY due to the reduction of pump outlet pressure and the reduction of electricity bill, as shown in Table 5.

Although the central process facilities can meet the water injection demand currently, the pipeline system may cannot meet the water injection demand at the end of the pipeline in the next three years. This is because water injection demand will increase based on the future water injection plan of the oilfield. So, it is necessary to add boosting points in the pipeline network. According to the water injection requirements, the transportation system of the pipeline network is optimised. The installation positions of the pipeline pump are shown in Figure 4.

To satisfy the water demand of the central process facility and avoid overpressure in the pipeline, 12 pressure boosting pumps were installed to pressurise the pipeline network which can guarantee the water demand of the end of pipeline network. After installing the pipeline pump, the operating energy consumption is 3.63 M CNY, and the total annual cost is 3.75 M CNY. The results show that the maximum water injection increment can reach 4,700 m^3/d, which improves the water supply capacity of the water injection pipe network, and the needs of oilfield water injection planning can be satisfied.

This model can optimise the pump installation position and operating strategy. The application of pipeline pumps can improve the water supply capacity of the surface water injection pipeline network to satisfy the demand of the water injection planning of this oilfield.

4. Conclusions

This paper presents a method to optimize the configuration and operation of pumps, and applies this method to the water injection network of oil field. More interestingly, this paper proposes a new type of pressurization equipment - pipeline pump. Because of its special structure, the pipeline pump can be installed at any position of the pipeline. Combining it with the optimization method can give better play to the effect of pressurization. The objective function of the optimization model is to minimize the pump cost and operation cost of the water injection system, and the constraints such as water injection volume, pipe network hydraulics and pump operation are considered. Finally, it is verified by a case of an oil field in China. The results show that without controlling the outlet pressure of the combined station, the operating cost is reduced by 184 k CNY, and the total annual cost is saved by 154 k CNY. It not only brings economic benefits, but also improves the water injection capacity of the pipe network. The operation and configuration strategy of pipeline pump calculated according to this model can provide some reference for oilfield workers. In the future, it can be combined with the automatic pipeline collection function to make an intelligent pipeline pressurization skid, which can automatically collect water volume, pressure, water quality and operating data while pressurizing the pipe network, so as to realize unattended.

Nomenclature

Sets

$i, j \in N$ – Set of node number

$i \in N_E$ – Set of pipeline node at the back end of pipeline pump

$j \in N_S$ – Set of pipeline node at the front end of pipeline pump

Continuous Parameters

$d_{i,j}$ – Inside diameter of pipe between nodes i and j, m

f – Total cost of water injection system, 10^4 CNY/y

g – Acceleration of gravity, m/s^2

h_f – Calculation formula of pipeline friction, -

$L_{i,j}$ – Pipe length from node i to j, m

M – Large value that can be set to the maximum flow, -

$OCP_{i,j}$ – Pump power, kW

p^{elc} – Electricity price, CNY/kWh

$p_i^{\max}$ – The maximum allowable pressure of the pipeline network system, MPa

$p_i^{\min}$ – The lowest pressure allowed by the pipeline network system, MPa

q_i – The water injection volume of node i，m^3/s

T^{life} – Depreciation period, y

v – Liquid velocity, m/s

η^P – Efficiency of pump, %

η^E – Efficiency of pump motor, %

$\lambda_{i,j}$ – Hydraulic friction coefficient of pipeline between nodes i and j, -

$\phi_{i,j}$ – The friction coefficient between pipeline section i and j, -

Binary variables

$B_{i,j}^N$ – Binary variable, 1 means no pump is installed between nodes i and j

$B_{i,j}^P$ – Binary variable, 1 means that the pump is installed between nodes i and j

$D_{i,j}^p$ – Binary variable, 1 means that there is a pipeline connection between i and j, and 0 means that there is no pipeline connection between i and j

Positive continuous variables

$c_{i,j}^o$ – Pump operating cost, 10^4 CNY/y

$c_{i,j}^p$ – Annual value of pump purchase and installation costs, 10^4 CNY/y

p^c – Pump purchase and installation costs, 10^4 CNY/y

p_i – Pump inlet pressure between pump installation nodes i and j, MPa

p_j – Pump outlet pressure between pump installation nodes i and j, MPa

$\Delta p_{i,j}$ – Pressure increase of pump installation node i, j, MPa

$Q_{i,j}$ – Flow between pipeline nodes i and j，m^3/s

$Q_{i,j}^A$ —The square of the flow of pipe sections i and j, (m^3/s)^2

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