Optimization of Long-distance Oil Pipeline Production Operation Scheme

Liming Gu*
Daqing Oilfield Storage and Transportation Sales Branch Research Institute, Daqing, China

*Corresponding author e-mail: 7471352@qq.com

Abstract. XX oil pipeline is responsible for transporting crude oil from XX to XX refinery. According to the actual operating conditions of the pipeline, it is known that the pipeline operation scheduling plan is manually formulated based on experience, resulting in a large amount of waste of fuel energy and electrical energy. In order to improve the economic benefits of pipeline operation and reduce system energy consumption, it is of great practical significance to optimize the pipeline operation scheduling scheme. In order to reduce the deviation between theoretical calculation and actual data, the total heat transfer coefficient and hydraulic friction coefficient of the pipeline are corrected and fitted according to the principle of least square method, which effectively improves the accuracy of the calculation method. Take the minimum total energy consumption cost of the entire pipeline as the objective function, take the outbound temperature and pump combination scheme of the entire pipeline as the decision variables, and take the inbound temperature, outbound temperature, flow rate, heating furnace heat load, and pump unit characteristics as constraints. Conditions, the establishment of the XX oil pipeline production operation scheduling program optimization mathematical model. The model is an optimization design problem including discrete variables and continuous variables, which is solved by dynamic programming according to the structural characteristics of the model. The optimization results show that energy consumption in winter and summer has been reduced by 23% and 18%, respectively.

1. Introduction

The XX buried oil pipeline transports XX crude oil. The pipeline has a total length of 199.73km, a pipe diameter of φ377×6.4mm, and a buried depth of 1.5m. The designed transportation capacity is 2 to 3 million tons per year. It is Operate by heating and airtight conveying mode. The outlet pressure of the first station of the XX oil pipeline is generally 6.0~7.5MPa, while the outlet pressure of the first station is only 3.0~5.0MPa. The excess pressure is throttled by the pump outlet valve, causing a certain amount of waste of electricity. At the same time, the actual operating temperature of the pipeline is relatively high, which makes the fuel consumption of the heating furnace very large. Therefore, in order to save energy and reduce consumption, and reduce the oil transportation costs of pipeline systems and energy-consuming equipment, it is necessary to optimize the oil pipeline production and operation scheduling plan, so as to obtain the optimal oil transportation equipment operation combination mode and production operation scheduling plan to achieve Long-term safe and efficient operation of pipelines.
In this paper, combined with the technological process of the XX oil pipeline, a mathematical model for the optimization of the pipeline operation scheme is established and the solution method is given.

2. Establishment of mathematical model

The purpose of the optimization of the XX oil pipeline operation plan is to determine the optimal opening plan of the equipment under the premise of ensuring the completion of the transportation task, so as to minimize the production and operation cost of the system. Pipeline production and operation costs include heat energy costs and power energy costs. The optimization mathematical model can be described as:

$$\min F = e_1B + e_2W$$

Include

$$B = \sum_{i=1}^{n} \sum_{k=1}^{n_{fi}} \delta_{ik} G_{jk} c_y \left( T_{out,f,i} - T_{in,f,i} \right) t$$

$$W = \sum_{j=1}^{m} \sum_{k=1}^{m_{jk}} \eta_{jk} P_{jk} Q_{j,k} H_{j,k} t$$

S.t

$$\sum_{k=1}^{m_{jk}} \gamma_{jk} Q_{j,k} = Q, k = 1,\ldots,m_{pj}$$

$$Q_{min,k} \leq Q_{j,k} \leq Q_{max,k}, k = 1,\ldots,m_{pj}$$

$$H_{min,k} \leq H_{j,k} \leq H_{max,k}, k = 1,\ldots,m_{pj}$$

$$Q_{min,k} \leq Q_{j,k} \leq Q_{max,k}, k = 1,\ldots,n_{pj}$$

$$P_{min} \geq P_{min}$$

$$T_{in,f,i} \geq T_{min,i}, i = 1,\ldots,n$$

$$T_{out,f,i} \leq T_{max,i}, i = 1,\ldots,n$$

Where $F$ is the total energy consumption cost of crude oil transportation, yuan; $e_1$ is the price of fuel oil, yuan/kg; $B$ is the total fuel consumption of the heating furnace in the heating station (or heat pump station) of the pipeline, kg/h; $e_2$ is the price of electricity, yuan/kW·h; $W$ is the total electrical energy consumed by the pump units in the heat pump stations of the pipeline, kW·h; $\delta_{ik}$ is the opening status of the $k$-th heating furnace in the $i$-th heating station (or heat pump station), and 0 is taken as Turn off the furnace, 1 means start the furnace; $n$ is the number of heating stations (or heat pump stations) across the pipeline; $n_{fi}$ is the number of heating furnaces in the heating station (or heat pump station); $G_{jk}$ is the $k$-th heating station of the $i$-th heating station (or heat pump station) The mass flow rate of the heating medium of the furnace, kg/h; $c_y$ is the specific heat of the heating furnace being heated crude oil, kJ/(kg·℃); $T_{in,f,i}$ is the heating furnace inlet temperature of the $i$-th heating station (or heat pump station), that is, the crude oil enters the station Temperature, ℃; $T_{out,f,i}$ is the outlet temperature of the heating furnace of the $i$-th heating station (or heat pump station), that is, the outlet station temperature of crude oil, ℃; $Q_{jw}$ is the low calorific value of fuel oil, kJ/kg; $T_{rk}$ is the $i$-th heating station (or heat pump) Station) The fuel oil entering temperature of the $k$-th heating furnace, ℃; $c_r$ is the specific heat of fuel oil, kJ/(kg·℃); $T_0$ is the ambient temperature, ℃; $c_0$ is the specific heat capacity of fuel oil at ambient temperature, kJ/(kg·℃); $\eta_{jk}$ is the $i$-th heating station (or
heat pump station) ) Thermal efficiency of the k-th heating furnace; \( \gamma_{pk} \) is the on-state of the k-th pump in the j-th heat pump station, taking 0 to turn off the pump and 1 to turn on the pump; m is the number of heat pump stations across the pipeline, including the first station and the second station; \( m_y \) is the number of pumps in the heat pump station; \( p_0 \) is the density of the crude oil heated by the heating furnace, kg/m³; \( Q_{pk} \) is the flow rate of the k-th pump in the j-th heat pump station, m³/s; \( H_{pk} \) is the head of the k-th pump in the j-th heat pump station, m; \( \eta_{pk} \) is the pump efficiency of the k-th pump in the j-th heat pump station; \( \eta_{ek} \) is the motor efficiency of the k-th pump in the j-th heat pump station; \( t \) is the operating time of the equipment, h; \( Q_{minpk} \) is the lowest of the k-th pump in the j-th heat pump station Delivery flow, m³/s; \( Q_{maxpk} \) is the highest delivery flow of the k-th pump of the j-th heat pump station, m³/s; \( H_{minpk} \) is the minimum lift that the kth pump of the j-th heat pump station can provide, m; \( H_{maxpk} \) is the jth heat pump The maximum head that the k-th pump of the station can provide, m; \( n_{sy} \) is the number of heating furnaces in the heating station (or heat pump station); \( P_{Ein} \) is the inlet pressure at the end of the pipeline, MPa; \( [P_{min}] \) is the lowest allowable entry pressure at the end of the pipeline, MPa; \( [T_{min}] \) is the lowest allowable entry temperature of crude oil, which is generally about 3°C higher than the freezing point of crude oil; \( [T_{max}] \) is the highest allowable exit temperature of crude oil exiting the station , °C; \( n \) is the number of heating stations (or heat pump stations) in the whole pipeline; formula (4) is the constraint of planned delivery; formula (5) and (6) are the constraint of pump working capacity; formula (7) is the heating capacity constraint of the heating furnace; equation (8) is the pressure constraint of the end of the pipeline; equation (9) is the temperature constraint of crude oil entering the station; equation (10) is the temperature constraint of crude oil exiting the station.

The objective function is the total energy consumption cost of the entire pipeline per unit time. The first term in the expression is the heat consumption cost of the entire pipeline within \( t \), and the second term is the power consumption cost of the entire pipeline within \( t \).

3. Solving method of mathematical model

In the XX oil pipeline optimization mathematical model, the outbound temperature of oil products is a continuous variable, and the pump combination is a discrete variable. Therefore, the optimization problem is a mixed variable nonlinear optimization problem. According to the structural characteristics of the model, a two-stage hierarchical optimization method is used to decompose the original optimization model into two sub-models, an outbound temperature optimization model and a pipeline optimal pump and tube matching model, and the two are solved by iteration.

3.1. Method to Solve the Problem of Oil Transportation Temperature Optimization

The optimization problem of oil pipeline is carried out under a certain combination of pump and pipe. In the pump pipe decoupling process, the inherent connection between the two optimization problems is artificially cut off, breaking the overall coupling characteristics of the model. In order to ensure that the optimal solution of the original model is obtained, the oil delivery temperature must be within a certain allowable range. Choose within the range. However, due to the discrete nature of the pump combination, when the oil delivery temperature of each station changes within a certain allowable range, the corresponding optimal pump combination will remain unchanged.

The oil transportation temperature optimization sub-problem is a non-linear programming problem. In order to simplify the solution process, starting from the physical background of the model, further transformations, decompositions and simplifications are made according to its structural characteristics. In the process of solving, the pressure variable can be eliminated after processing, and the direct method of nonlinear programming is used to solve the problem. But first, the penalty function method needs to be applied to transform the model into an unconstrained problem, and then the direct method is applied to solve the problem. In this paper, the Powell directional acceleration method is used to solve the problem. A large number of calculations show that the algorithm has a high solving efficiency. Generally, it can converge to a local optimal point after 2 rounds of iteration.

3.2. Solving method of pump combination optimization problem

After the optimal oil delivery temperature is obtained from the oil delivery temperature optimization sub-problem, the optimal pump combination and pipeline optimal matching sub-problem is essentially
a full range of optimal pump assembly problems. Since the number of pump combinations in the whole line is exponentially related to the number of pumps configured, the optimal pump combination problem in the whole range is generally a large-scale combination optimization problem. The combination optimization problem needs to be solved by the implicit enumeration method and the dynamic programming method.

The basic idea of the dynamic programming method is to use a network shortest path model to describe the optimal matching problem of the entire pipeline. According to the number and performance of oil pumps in each station of the pipeline, a variety of feasible pump combinations can be enumerated across the pipeline, and the optimal pump combination can be found on the basis of a given oil temperature. Since there are many pump combinations in each station, the heuristic deep search method is used in the process of establishing and solving the network shortest path model, which effectively improves the efficiency of the search algorithm.

The algorithm frame is shown in Fig.1.

![Solution steps of pipeline optimization model](image)

**Figure.1.** Solution steps of pipeline optimization model

4. Example calculation

Analyzing the actual operating data of the XX oil pipeline for many years, it can be seen that the pipeline has the most energy costs in January in winter, and the least energy costs in July in summer. Therefore, take the delivery plan of 251t/h on February 15, 2009 and 297t/h on August 15 as examples for optimization calculation. The optimization results are shown in Table 1 to Table 3. It can be seen from Table 1 and Table 2 that the parameters have been optimized under the conditions of meeting the
minimum allowable operating parameters, the oil temperature has been significantly reduced, and the savings in thermal energy consumption and power consumption costs are shown in Table 3.

**Table 1** Comparison of production parameters before and after the optimization of the operation plan when the output on February 15th is 251t/h in winter

|                      | Incoming station temperature/°C | Outbound temperature/°C | Incoming pressure/MPa | Outbound pressure/MPa |
|----------------------|---------------------------------|-------------------------|-----------------------|-----------------------|
|                      | raw data                        | Optimize                | raw data              | Optimize              |
| First stop           | 64.70                           | 64.10                   | 64.01                 | 0.08                  |
| Zhongyi Station      | 46.60                           | 61.30                   | 51.31                 | 3.51                  |
| Zhonger Station      | 47.30                           | 61.60                   | 53.22                 | 1.93                  |
| Last stop            | 46.50                           | —                       | —                     | 0.30                  |

**Table 2** Comparison of production parameters before and after the optimization of the operation plan when the transportation volume is 297 t/h on August 15th in summer

|                      | Incoming station temperature/°C | Outbound temperature/°C | Incoming pressure/MPa | Outbound pressure/MPa |
|----------------------|---------------------------------|-------------------------|-----------------------|-----------------------|
|                      | raw data                        | Optimize                | raw data              | Optimize              |
| First stop           | 60.60                           | 60.20                   | 60.11                 | 0.10                  |
| Zhongyi Station      | 46.80                           | 52.99                   | 2.92                  | 2.85                  |
| Zhonger Station      | 48.50                           | 49.57                   | 1.76                  | 1.46                  |
| Last stop            | 45.50                           | —                       | —                     | 0.30                  |

**Table 3** Comparison of costs before and after optimization

| month      | capacity t/h | Power consumption / (kw·d⁻¹) | Fuel consumption / (kg·d⁻¹) | Total cost / (yuan·d⁻¹) | saving % |
|------------|--------------|------------------------------|-----------------------------|--------------------------|----------|
| raw data   | Optimize     | raw data                     | Optimize                    | raw data                 | raw data |
| February   | 251          | 23040                        | 10379                       | 65097                    | 50125    | 23       |
| August     | 297          | 15800                        | 8822                        | 52884                    | 43365    | 18       |

5. Conclusion

With the goal of minimizing the production and operating costs, the outbound temperature and pressure as design variables, and the equipment workload as constraints, a mathematical model for the optimization of the Qingha oil pipeline production and operation plan was established. According to the structural characteristics of the model, the dynamic programming method is used to solve the problem.

The production and operation plans of the XX oil pipeline in February and August were optimized. Compared with the optimization before, the operation energy consumption cost was reduced by 23% and 18%, respectively, and the effect was significant.

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