INTRODUCTION
Most of the crude oil produced in China's oilfields is of high viscosity and easy to coagulate, which makes heating transportation a common way of crude oil transportation. In the heating and conveying process pipeline system, in addition to the oil pump set that provides pressure energy to the oil flow to overcome the friction loss and the difference in elevation, the conveying temperature should also be increased through the heating device to maintain the lowest oil temperature in the pipeline above the freezing point, thus effectively preventing the condensing pipe accident. The transmission equipment mainly consumes electricity and fuel, which makes the continuous operation pipeline become a large energy consumer, especially the pipeline with long transmission distance and low transmission capacity. Only heating self-consumption accounts for 1%-3% of the transmission capacity, even higher.1

At present, there are many problems in oil and gas pipelines, including the mechanism of oil mixing, flow noise, and particle deposition.2-10 The energy consumption of the...
hot oil pipeline system is also the focus of many scholars' research. Through a lot of literature research, we can set the energy consumption of the pipeline system in the following two directions:

1. Improving the equipment of hot oil pipeline system

Using new energy-saving equipment to replace the old equipment can greatly reduce the energy consumption of the hot oil pipeline system. Among them, the most representative is the application of frequency conversion technology in the oil pump unit,\textsuperscript{11} because each oil pump in the long-distance pipeline oil pump unit has a long operation time and large power consumption, which greatly increases the transportation cost of oil and gas resources. At present, power frequency fixed-speed motors are mostly used in oil pump units of long oil pipelines in China, which have good operating results, high operating efficiency, and strong reliability and safety. However, the flexibility of the power frequency constant speed motor is not enough, and it cannot change the power frequency according to the flow of the long-distance pipelines. Even when the flow of long-distance pipeline is small, the operation speed of the motor still remains at the initial setting state, lacking great flexibility, which is not conducive to improving the operational efficiency of the long-distance pipeline oil pump unit.\textsuperscript{12,13} Of course, in addition to the improvement of the oil pump, there are some other improvements in the process equipment. This paper summarizes the process equipment and technical improvements of the oil pipeline system, as shown in Table 1.

2. Improvement of the operation plan for the hot oil pipeline system

Reducing energy consumption by improving the operation scheme of the hot oil pipeline system is currently the most studied method. With the continuous development of mathematics and computer science, the continuous updating of artificial intelligence technology and intelligent optimization algorithms makes the process of solving many engineering problems simple, and the solution is better. At present, computer technology has been applied in many fields to obtain optimal solutions, such as microgrid, solar energy, and renewable energy.\textsuperscript{24-32} Many scholars have also proposed

| Improved equipment or technology | Advantages | Application results | Reference |
|---------------------------------|------------|---------------------|-----------|
| Drag reducer                    | Ability to reduce manual operations | Increase the output of petroleum products and save energy | Guan et al 2008\textsuperscript{14} |
| Circulating water mixing process simulation tester | Improving energy efficiency provides new technologies and reliable methods | Equipment meets energy-saving goals | Wang et al 2010\textsuperscript{15} |
| A new type of heating furnace | Most of the sand in the heavy oil can be removed before it flows into the furnace | To achieve energy conservation and environmental protection, extend service life and reduce costs and materials | Feng et al 2012\textsuperscript{16} |
| Variable frequency drive and Hydraulic Coupler | Ability to increase operating characteristics and increase cost-efficiency | The criteria to select options for the rotational speed of pump rotors regulating are formulated | Belkin et al 2015\textsuperscript{17} |
| Vacuum furnace dilution effect and uniform temperature perturbation | Increase the water speed in the heat exchange tube | It can effectively extend the fouling time and maintenance period of boiler pipes. | Jia et al 2016\textsuperscript{18} |
| Harmonic adjustment variable speed drive | Allows operators to install and retrofit generators with more suitable sizes | Save energy/fuel and reduce emissions and maintain good power quality | Hoevenaars et al 2017\textsuperscript{19} |
| High-temperature heat pump replaces traditional heater | It can provide high-temperature hot water to heat crude oil | It can replace the traditional heating furnace and reduce energy consumption | He et al 2017\textsuperscript{20} |
| Frequency control technology | The output power of the motor is effectively matched with the pipe flow, which reduces energy consumption | The centrifugal oil pump load can be saved by 20%-50% through speed control. | Liu et al 2018\textsuperscript{21} |
| Turbo expander and solar collector | The energy of the system can be calculated through fluctuations in thermodynamics and economic parameters | Realized the best design of the system | Barone et al 2019\textsuperscript{22} |
| Replacing expander with a turboexpander | The use of gas turbine outlet gas and the waste heat of the turboexpander helps to recover energy | Improve the energy efficiency of the system | Golchoobian et al 2019\textsuperscript{23} |
different solutions in the hot oil pipeline system, as shown in Table 2.

As can be seen from Tables 1 and 2, first of all, new equipment will gradually replace old equipment in the future, especially the application of variable frequency pumps in hot oil pipeline systems. Secondly, it is also extremely important to use optimization algorithms to optimize the model. This method can reduce the waste of resources in the empirical method and improve the operation efficiency of the pipeline system. Although there is a lot of research results in these two aspects, there are very few studies combining these two methods. This paper innovatively introduces the speed of the variable frequency pump as one of the optimization variables in the hot oil pipeline model and uses three intelligent optimization algorithms, genetic algorithm, particle swarm optimization, and simulated annealing algorithm, to solve the model. The article introduces in detail the treatment process of the variable frequency pump and the establishment process of the optimization model, which provides guidance significance for the improvement of the hot oil pipeline in the future.

The rest of the article is arranged as follows: In the second part, the paper introduces in detail the treatment method of

| Algorithm name | Optimization object | Results and conclusions | Reference |
|----------------|---------------------|------------------------|-----------|
| Ant colony optimization (ACO) | Optimization of natural gas pipeline transportation | It shows that the ACO is an interesting way for gas pipeline operation optimization | Chebouba et al 2009\cite{33} |
| GA and MILP | Network scheduling optimization | This work is helpful to develop a tool for the effective utilization of the pipeline network | Paulo et al 2013\cite{34} |
| Particle swarm optimization and differential evolution algorithm | Energy consumption optimization of the heated oil pipeline | The data error of pipeline operation and energy costs are reduced | Zhou et al 2015\cite{35} |
| ACO and GA | Monitoring oil pipelines | The buffer and sensing percentages in GA are higher than those in ACO | Elnaggar et al 2015\cite{36} |
| Genetic algorithm(GA) | Energy optimization of oil pipelines | The proposed optimal scheme can reduce the energy consumption of the simulated pipeline by 5%-9% | Liu et al 2015\cite{37} |
| MC-GPSO, MC-LPSO, MC-FIPSO, and MC-SLPSO | Optimal design of subsea oil pipelines. | It shows that MC-SLPSO is more suitable for solving subsea pipeline optimization problems | Zhang et al 2017\cite{38} |
| An improved particle swarm algorithm(IPSO-RBFNN) | Oil and gas pipeline defect recognition. | This method has higher recognition accuracy for pipelines | Zhang and Yu, 2018\cite{39} |
| Ant colony optimization (ACO) | Scheduling optimization of product oil pipelines | A self-learning algorithm is proposed for detailed optimal scheduling for a product oil pipeline | Zhang et al 2018\cite{40} |
| Genetic Algorithm and Back Propagation Neural Network (GA-BPNN) | Prediction of the apparent viscosity of crude oil | The GA-BPNN model is applicable to the apparent viscosity prediction of various crude oils | Zhang et al 2019\cite{41} |
| Genetic simulated annealing hybrid algorithm | Optimal design of gathering pipeline system | Optimization models for the phased development of old oilfields are proposed | He et al 2019\cite{42} |
| Improved Machine Learning Algorithms | Natural gas supply optimization | The algorithm is very suitable for the optimization of the natural gas supply system | Qiao et al 2019\cite{43} |
| A heuristic algorithm | Energy consumption optimization of natural gas pipelines | The method greatly reduces the optimization time and the calculation is accurate | Liu et al 2019\cite{44} |
| GA, PSO, and SA | Energy consumption optimization of natural gas pipelines | the method reduces the production energy consumption of related pipelines by 33.77% | Liu et al 2019\cite{45} |
| Tabu search algorithm | Energy optimization of subsea pipelines | The proposed optimization scheme greatly reduces the energy consumption of subsea pipelines | Peng et al 2019\cite{46} |
| BPNN, RBFNN, and GRNN | Energy optimization of heated oil pipelines | Reduction of related simulated pipeline energy consumption by 10.75% | Zhang et al 2020\cite{47} |
the variable frequency pump and the detailed process of the mathematical model of the oil pipeline, including the thermal calculation, hydraulic calculation, energy consumption calculation, and the basic information of the objective function of the pipeline system. In the third part of the article, the basic parameters and actual operating data of the simulated pipeline are given. In the fourth part, we compare the pressure change, temperature change, and energy consumption calculation of the three algorithms with the actual scheme and give the optimal scheme under the three algorithms, respectively, and draw the relevant conclusions in the fifth part.

2 | MODELS AND METHODS

The crude oil pipeline system is a complex system that contains multiple parts, each of which has a mutual influence. This complex system mainly includes the pipeline itself, the station yard, the crude oil transported in the pipe, and the relevant external environment that has an important impact on the pipeline system. Therefore, before the calculation of the system, it is necessary to simplify the complex pipeline system into available abstract mathematical expressions. This paper is mainly based on the following assumptions:

1. The conveying medium flows stably in the pipe.
2. Single-phase (liquid phase) homogeneous flow of conveying medium in the pipe.
3. The temperature of the conveying medium in the pipe is constant along the radial direction, and only the change of the axial temperature is considered.

The structural diagram of the oil pipeline of the fourth line of Qingtie is shown in Figure 1, in which all the pump combinations are in series, and the mode of three in use and one for standby is adopted. In addition, the model building is mainly based on the following formula.

2.1 | Inverter pump processing

2.1.1 | Treatment method of frequency conversion pump

There are some frequency conversion pumps in Qingtie’s four-line pipeline system, and the characteristics of the pump are changed by the change of the speed of the frequency conversion pump. According to the actual experience on the spot, the calculation accuracy of the characteristic curve of the variable frequency pump using the similarity theorem is not ideal. In this paper, the least square method is used to return the performance of the oil pump to be described as a polynomial. We define the flow-head and flow-power of the oil pump with the frequency converter as the relationship between Equations (1) and (2).

The flow-head relationship fitting equation of the inverter pump is as follows:

\[ H = A Q^2 + B Q + C Q + D x^2 + E x + F \]  
(1)

The flow-power relationship fitting equation of the oil pump is as follows:

\[ P = a Q^2 + b Q + c Q + d x^2 + e x + f \]  
(2)

in which: \( H \) — Head of variable frequency pump, m; \( P \) — Power of variable frequency pump, kW; \( x \) — Temperature of the conveying medium in the pipe.

The coefficient of the fitting equation of the relationship between flow and power to be described as a polynomial. We define the flow-head and flow-power of the oil pump using the similarity theorem is very good results, such as the regression model of the ternary cubic polynomial in (3).

\[ y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_1^2 + b_5 x_2^2 + b_6 x_3^2 
+ b_7 x_1 x_2 + b_8 x_1 x_3 + b_9 x_2 x_3 + b_{10} x_1^3 + b_{11} x_2^3 \]  
(3)

At the same time, Equation (3) can be replaced by appropriate variables to transform the nonlinear topic into a linear problem. The transformation method is (4).

\[ \begin{align*} 
x_1' &= x_1, x_2' = x_2, x_3' = x_3, x_4' = x_1^2, x_5' = x_2^2, x_6' = x_3^2, 
x_7' &= x_1 x_2, x_8' = x_1 x_3, x_9' = x_2 x_3, x_{10}' = x_1^3, x_{11}' = x_2 x_3^2 
\end{align*} \]  
(4)

After the transformation, the regression model becomes a multiple linear regression model, namely formula (5):

\[ y = \beta_0 + \beta_1 x_1' + \beta_2 x_2' + \beta_3 x_3' + \beta_4 x_4' + \cdots + \beta_{11} x_{11}' \]  
(5)
The unknown constant (that is, the formula coefficient) $\beta_0, \beta_1, \beta_2, ..., \beta_{11}$ is called the regression model coefficient. If $n$ sets of data are known and the $i$th set is $(y_i, x_{i1}, x_{i2}, ..., x_{11})$, then the linear regression model can be expressed as:

$$
\begin{align*}
    y_1 &= \beta_0 + \beta_1 x_{11} + \beta_2 x_{21} + \beta_3 x_{31} + \cdots + \beta_{11} x_{111} + \varepsilon_1 \\
    y_2 &= \beta_0 + \beta_1 x_{12} + \beta_2 x_{22} + \beta_3 x_{32} + \cdots + \beta_{11} x_{112} + \varepsilon_2 \\
    &\vdots \\
    y_n &= \beta_0 + \beta_1 x_{1n} + \beta_2 x_{2n} + \beta_3 x_{3n} + \cdots + \beta_{11} x_{11n} + \varepsilon_n
\end{align*}
$$

(6)

where $\varepsilon$ represents the random error term. Regression analysis is used to calculate the regression coefficient (formula coefficient) of the multiple linear regression models with the objective of minimizing the square sum of random errors. Expressed as a matrix:

$$
y = X\beta + \varepsilon
$$

(7)

in which:

$$
y = \begin{bmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n
\end{bmatrix},
X = \begin{bmatrix}
x_{11} & \cdots & x_{111} \\
x_{12} & \cdots & x_{112} \\
\vdots & \ddots & \vdots \\
x_{1n} & \cdots & x_{11n}
\end{bmatrix},
\beta = \begin{bmatrix}
\beta_0 \\
\beta_1 \\
\varepsilon_1 \\
\beta_2 \\
\varepsilon_2 \\
\vdots \\
\beta_{11} \\
\varepsilon_n
\end{bmatrix}
$$

(8)

In the multiple linear regression problem, a large amount of data needs to be processed, and many advanced mathematical bits of knowledge such as linear algebra and statistics are involved, which needs to be solved with the help of computer software. Equation (4) can be solved with $\beta = \text{regress}(y, X)$ in MATLAB based on the regression algorithm. In MATLAB, the regression function returns the least squares fitting solution of $y = X\beta$.

### 2.1.2 Treatment results of variable frequency pump

Qingtie four-line pipeline adopts a closed conveying method, and the pumps of each pump station are connected in series. The coding method is a combination of frequency conversion speed coding, such as 2400-2800-2300. The relevant parameters of the oil pumps at each station are shown in Table 3.

As shown in Table 3, only station 1, station 3, station 5, station 6, and station 7 have inverter pumps. Among them, station 1 and station 7 are the same type of oil pumps, station 3 and station 5 are the same type of oil pumps, and station 6 is another kind of oil pump, so this calculation only needs to fit three oil pumps.

1. Inverter pumps at station 1 and station 7

The characteristic equation was obtained by using the least square regression method, and the pressure head curve and power curve of the speed-regulating pump at stations 1 and 7 were fitted, as shown in Figure 2.

It can be seen from Figure 3 that the fitting method used in this paper has high precision, with the error of the pressure head fitting within 5% and the power fitting error within 5%, which can well fit and calculate the characteristic curve of the variable speed pump. The fitting results are shown in Equations (9) and (10).

Pressure head equation:

$$
H = 213.9 - 0.1892 \times rs + 0.001575 \times Q + 7.122 \times 10^{-4} \times rs^2 - 7.935 \times 10^{-6} \times rs \times Q - 5.961 \times 10^{-5} \times Q^2
$$

(9)

| Station number | The number of pumps | Displacement (m³/h) | Head (m) | The motor power (kW) | The number of frequency conversion pumps |
|---------------|---------------------|--------------------|----------|----------------------|------------------------------------------|
| 1             | 3                   | 3100               | 210      | 2000                 | 1                                        |
| 2             | /                   | /                  | /        | /                    | /                                        |
| 3             | 3                   | 3100               | 220      | 2300                 | 1                                        |
| 4             | 3                   | 3100               | 220      | 2300                 | /                                        |
| 5             | 3                   | 3100               | 220      | 2300                 | 1                                        |
| 6             | 3                   | 3100               | 220      | 2300                 | 1                                        |
| 7             | 3                   | 3100               | 210      | 2000                 | 1                                        |
| 8             | 0                   | /                  | /        | /                    | /                                        |
| 9             | 0                   | /                  | /        | /                    | /                                        |

**TABLE 3** Relevant parameters of each oil pump
Power equation:
\[
P = 2536 - 2.325 \times rs - 0.2646 \times Q + 0.0005761 \times rs^2
+ 0.0002787 \times rs \times Q - 5.684 \times 10^{-4} \times Q^2
\]  
(10)

2. Inverter pumps at station 3 and station 5

The characteristic equation was obtained by using the least square regression method, and the pressure head curve and power curve of the speed-regulating pump at stations 3 and 5 were fitted, as shown in Figure 3.

It can be seen from Figure 3 that the fitting method used in this paper has high precision, the fitting error of the head is within 5%, and the fitting error of the power is within 5%, which can well fit the characteristic curve of the variable speed pump, and the fitting results are shown in formula (11) and (12).

Pressure head equation:
\[
H = 233.9 - 0.2058 \times rs + 0.006203 \times Q + 7.578 \times 10^{-4} \times rs^2
- 9.808 \times 10^{-6} \times rs \times Q - 4.98 \times 10^{-5} \times Q^2
\]  
(11)

Power equation:
\[
P = 2624 - 2.4 \times rs - 0.2959 \times Q + 0.000595 \times rs^2
+ 0.0002922 \times rs \times Q - 5.446 \times 10^{-4} \times Q^2
\]  
(12)

3. Inverter pump at station 6

The characteristic equation was obtained by using the least square regression method, and the pressure head curve and power curve of the station 6 speed-regulating pump was fitted, as shown in Figure 4.

It can be seen from Figure 6 that the error of pressure head fitting is within 5%, and the error of power fitting is also within 5%, which can well fit and calculate the characteristic curve of the variable speed pump. The fitting results are shown in Equations (13) and (14).

Pressure head equation:
\[
H = 229.3 - 0.1978 \times rs + 0.01381 \times Q + 1.072 \times 10^{-3} \times rs^2
- 0.00006503 \times rs \times Q - 2.152 \times 10^{-5} \times Q^2
\]  
(13)

Power equation:
\[
P = 4140 - 4.07 \times rs - 0.1218 \times Q + 0.001072 \times rs^2
+ 0.00006503 \times rs \times Q - 2.152 \times 10^{-4} \times Q^2
\]  
(14)

2.2 | Establishment of the optimization model

1. Establish the objective function

There are two main energy consumption in the operation of crude oil pipeline: (a) power consumption of pump unit;
(b) fuel consumption of heating furnace. In this paper, the lowest energy consumption of the pipeline system is taken as the objective function.

\[
\min F = S_p + S_h
\]  \hspace{1cm} (15)

in which: 
- \( F \) — Pipeline energy consumption, kgce;
- \( S_p \) — Power consumption, kgce;
- \( S_h \) — Fuel consumption, kgce.

where power consumption \( S_p \) can be expressed as:

\[
S_p = \sum_{i=1}^{N_p} \frac{GH_i g t_{pi}}{1000 \eta_{pi} \eta_{ei}} \times \omega_1
\]  \hspace{1cm} (16)

in which: 
- \( N_p \) — The number of pump stations in operation in a piping system;
- \( G \) — The mass flow of crude oil in the pipe, kg/s;
- \( \omega_1 \) — Electricity conversion standard coal coefficient, 0.1229 kgce/(kW h);
- \( H_i \) — Head provided by pump station \( i \), m;
- \( g \) — Acceleration constant of gravity, 9.8 m/s\(^2\);
- \( t_{pi} \) — Running time of pump station number \( i \), h;
- \( \eta_{pi} \), \( \eta_{ei} \) — Mechanical efficiency and motor efficiency of the pump station numbered \( i \).

Fuel consumption \( S_h \) can be expressed as:

\[
S_h = \sum_{i=1}^{N_h} \frac{Gc(T_{outi} - T_{ini}) \eta_{hi} \eta_{hi}}{q \eta_{hi}} \times \omega_2
\]  \hspace{1cm} (17)

in which: 
- \( N_h \) — The number of heating stations in operation in the pipeline system;
- \( G \) — The mass flow of crude oil in the pipe, kg/s;
- \( \omega_2 \) — Oil conversion standard coal coefficient, 1428.6 kgce/t;
- \( c \) — Specific heat capacity of the heated medium, kJ/(kg \( ^\circ \text{C} \));
- \( T_{ini}, T_{outi} \) — Inlet and outlet temperature of heating station number \( i \); 
- \( t_{hi} \) — Running time of heating station number \( i \); 
- \( \eta_{hi} \) — Heating efficiency of the heating station; 
- \( q \) — Low heating value of fuel, kJ/kg.

2. Optimization variables

In order to accurately simulate this process, the combined opening method of the pump units of each pumping station, the speed of the variable frequency pump, and the outbound temperature of the heating station are used as the optimization variables of the hot oil pipeline.

\[
X = (C_{pi}, r_{si}, T_{outi})
\]  \hspace{1cm} (18)

in which: 
- \( C_{pi} \) — Pump unit combination mode of the \( i \)th pump station; 
- \( r_{si} \) — Speed of variable frequency pump of the pump unit in the \( i \)th pumping station; 
- \( T_{outi} \) — the Outbound temperature of heating station number \( i \).

3. Constraint conditions

4. (a) Inbound pressure constraint

The inlet suction pressure of the pump shall be greater than the allowable cavitation allowance of the pump, and the inlet pressure of the pump station shall be greater than the allowable minimum inlet pressure.

\[
H_{ini} > H_{ini, min}
\]  \hspace{1cm} (19)

in which: 
- \( H_{ini} \) — Inlet head of the \( i \)th pumping station, m; 
- \( H_{ini, min} \) — Allowable minimum inlet head of the \( i \)th pumping station.

(b) Outbound pressure constraints

The head provided by the pump station shall not be less than the head required for normal oil transportation and shall meet the strength requirements of the pipeline, that is, the outbound pressure shall not exceed the maximum pressure of the pipeline.

\[
H_{dmax} > H_{outi}
\]  \hspace{1cm} (20)

in which: 
- \( H_{outi} \) — The outbound head of the \( i \)th pump station, m; 
- \( H_{dmax} \) — Maximum working head of pipeline, m.

(c) Pipe hydraulic restraint

When calculating the pipeline friction, first calculate the Rayleigh number (here, it is assumed that the fluid is Newtonian fluid).

\[
Re = \frac{\rho d V}{\mu} = \frac{d V}{\nu} = \frac{4Q}{\pi d v}
\]  \hspace{1cm} (21)
in which: \(Re\)—Reynolds number; \(\rho\)—Fluid density, kg/m\(^3\); \(d\)—Inside diameter of the pipe, m; \(V\)—Flow rate of fluid in the pipeline, m/s; \(\mu\)—Dynamic viscosity, Pa s; \(Q\)—Volume flow of fluid in the pipeline, m\(^3\)/s.

When the Rayleigh number is calculated, the friction loss along the path can be calculated by the following formula.

\[
h_f = \frac{\lambda}{d} \frac{V^2}{2g}
\]

(22)

in which: \(h_f\)—Friction loss along the line, m; \(L\)—Length of pipe, m; \(d\)—Inside diameter of the pipe, m; \(V\)—Flow rate of fluid in the pipeline, m/s; \(g\)—Acceleration constant of gravity, 9.8 m/s\(^2\); \(\lambda\)—Friction coefficient.

At the same time, in order to make the calculation of the variable speed pump more convenient, the speed is used as a variable to fit the curve of the least square method, and the pressure head curve equation of the relationship between flow and head, and the corresponding data of each station are obtained.

\[
H = AQ^2 + BQ + CQrs + Drs^2 + Er + F
\]

(23)

in which: \(H\)—Head of oil pump, m; \(Q\)—Flow of the oil pump, m\(^3\)/s; \(rs\)—Speed of oil pump, L/min; \(A, B, C, D, E, F\)—The coefficient of the fitting equation of the relationship between flow and head, and the corresponding data of each station are shown in Table 4.

At the same time, the head provided by the pump station must not be less than the pressure loss of the pipeline between the pump stations.

\[
H_i \geq h_f + h_{mi} + h_{rp} + \Delta Z_i
\]

(24)

in which: \(h_f\)—Friction between pump stations, m; \(h_{mi}\)—Local friction between pumping stations, m; \(h_{rp}\)—Friction between heating stations, m; \(\Delta Z_i\)—Height difference between starting and ending points, m.

(d) Outbound oil temperature constraints

In a hot oil pipeline system, if the outbound temperature of crude oil is too low, important physical parameters of the crude oil may deteriorate, such as viscosity, yield value, and a “condensation accident” is likely to occur. If the outbound temperature is too high, the change in viscosity with increasing temperature after the temperature of the crude oil exceeds a certain value will be very small and very uneconomical, so the temperature needs to be controlled within a suitable range.

\[
|T_{out, \text{min}}| \leq T_{out} \leq |T_{out, \text{max}}|
\]

(25)

in which: \(T_{out, \text{max}}\)—The maximum outbound temperature of the \(i\)th hot station, °C; \(T_{out, \text{min}}\)—The minimum outbound temperature of the \(i\)th hot station, °C.

(e) Incoming oil temperature restriction

The temperature of oil entering the station shall be higher than the specified value to prevent the shutdown of the condensate pipeline.

\[
T_{in} \geq |T_{in, \text{min}}|
\]

(26)

in which: \(T_{in}\)—Incoming temperature of heating station number \(i\), °C; \(T_{in, \text{min}}\)—Minimum inlet temperature of the \(i\)th hot station, °C.

The distribution of temperature drop along the pipeline is calculated by the Sukhov formula, which is as follows.

\[
T_L = (T_0 + b) + [T_R - (T_0 + b)]e^{-at}
\]

(27)

\[
a = \frac{KgD}{GC} \quad b = \frac{Ggj}{K\pi D}
\]

(28)

in which: \(T_L\)—Oil temperature L meters from the start of the pipeline, °C; \(T_0\)—The ground temperature of buried pipeline environment, °C; \(T_R\)—Oil temperature at the beginning of the pipeline, °C; \(G\)—Mass flow in the pipeline, kg/s; \(c\)—Specific heat capacity of oil at average temperature, J/kg °C; \(K\)—Total heat transfer coefficient of the pipeline; \(i\)—Hydraulic slope of the pipeline; \(g\)—Acceleration constant of gravity, 9.8 m/s\(^2\);

(f) Heating furnace thermal load constraint

If the heat load of the heating furnace exceeds the rated value, safety accidents may occur. If the heat load is low, the efficiency will be very low.

\[
Q_{r, \text{min}} \leq Q_{ri} \leq Q_{r, \text{max}}
\]

(29)

| The station number | \(A\) | \(B\) | \(C\) | \(D\) | \(E\) | \(F\) |
|--------------------|------|------|------|------|------|------|
| Station 1 and station 7 | \(-5.961 \times 10^{-5}\) | 0.001575 | 7.935 \times 10^{-6} | 7.122 \times 10^{-4} | \(-0.1892\) | 213.9 |
| Station 3 and station 5 | \(-4.98 \times 10^{-5}\) | 0.006203 | 9.808 \times 10^{-6} | 7.578 \times 10^{-4} | \(-0.2058\) | 233.9 |
| Station 6 | \(-2.152 \times 10^{-5}\) | 0.01381 | 6.503 \times 10^{-5} | 1.072 \times 10^{-3} | \(-0.1978\) | 229.3 |
in which: $Q_{r_{\min}}$—Minimum heat load of the heating furnace, kJ/kg; $Q_{r_i}$—Thermal load of the $i$th heating station, kJ/kg; $Q_{r_{\max}}$—Rated heat load of the heating furnace (maximum heat load), kJ/kg.

(g) Pump power constraints

The speed is used as a variable of the power curve equation to fit the curve with the least square method. The power curve equation of the variable speed pump is as follows:

$$P = aQ^2 + bQ + cQrs + drs^2 + ers + f$$ (30)

in which: $P$—Power of oil pump, kW; $Q$—Flow of the oil pump, m$^3$/h; $Q_{r}$—Speed of oil pump, L/min; $a$, $b$, $c$, $d$, $e$, $f$—The coefficient of the fitting equation of the relationship between flow and power, and the corresponding data of each station are shown in Table 5.

There is a certain power limit for the pump in the pump station, and the limit conditions are as follows:

$$P_{\min} \leq P_i \leq P_{\max}$$ (31)

in which: $P_{\min}$—The minimum power allowed by the pump, kW; $P_i$—Power of the $i$th pumping station, kW; $P_{\max}$—Maximum power allowed by the pump, kW.

(h) Variable speed pump speed restriction

The speed of the variable speed pump shall run within a certain range, and its speed restriction is:

$$rs_{\min} \leq rs_i \leq rs_{\max}$$ (32)

in which: $rs_{\min}$—The minimum allowable speed of the pump, L/min; $rs_i$—Rotation speed of frequency conversion pump in the $i$th pumping station, L/min; $rs_{\max}$—The maximum speed allowed by the pump, L/min.

2.3 | Optimization algorithm

This article is based on MATLAB software programming, calling the optimization solver, using the genetic algorithm (GA), particle swarm algorithm (PSO), simulated annealing algorithm (SA) to solve the model.

1. Genetic algorithm (GA)

Based on the optimization model of the crude oil pipeline, according to the characteristics of the genetic algorithm, the optimization variables are coded to form the fitness function of the genetic algorithm. In the evolution process, the population size is 120, the crossover probability is 0.9, the mutation probability is 3%, and the termination criterion is the maximum evolution algebra 300. The flow of the solution step is shown in Figure 5.

2. Particle swarm optimization (PSO)

According to the characteristics of the particle swarm algorithm and the optimization model of the energy consumption of the pipeline operation, the optimized variables are coded to form the fitness function of the particle swarm algorithm. The particle number is 40, the particle length is 42, the maximum speed is 15% of the variation range of each dimension variable, and the acceleration coefficient is 2.0. The flow of the solution step is shown in Figure 6.

3. Simulated annealing algorithm (SA)

According to the characteristics of the simulated annealing algorithm and the optimization model of the energy consumption of the pipeline, the optimized variables are coded to form the objective function of the simulated annealing algorithm. The initial temperature is 100, the end temperature is 0.001, and the cooling factor is 0.98. The flow of the solution step is shown in Figure 7.

### Table 5 | Pump power fitting coefficient of each station

| Station number | $a$         | $b$       | $c$       | $d$       | $e$       | $f$       |
|----------------|-------------|-----------|-----------|-----------|-----------|-----------|
| Station 1 and | $-5.684 \times 10^{-4}$ | $-0.2646$ | $0.0002781$ | $0.0005761$ | $-2.325$ | $2536$    |
| station 7      |             |           |           |           |           |           |
| Station 3 and  | $-5.446 \times 10^{-4}$ | $-0.2959$ | $0.0002922$ | $0.000595$ | $-2.4$    | $2624$    |
| station 5      |             |           |           |           |           |           |
| Station 6      | $-2.152 \times 10^{-4}$ | $-0.1218$ | $0.00006503$ | $0.001072$ | $-4.07$   | $4140$    |
2 heating stations, and 1 final station. The whole line is equipped with 24 heating furnaces and 18 oil pumps, among which 1 oil pump is equipped with a speed regulation device in each of the 4 heat pump stations, and the pipeline station model is shown in Figure 8. In addition, the design throughput from 1 station to 3 stations is $1650 \times 10^4$ t/a, and the design throughput from 3 stations to 6 stations is $2000 \times 10^4$ t/a, and the design throughput from 6 stations to 9 stations is $1500 \times 10^4$ t/a.

### 3.2 Actual pipeline operation scheme

In order to better compare with the optimized scheme, this paper collected the actual operation data of the pipeline system in January 2018, as shown in Table 6.

The heat transfer coefficient $K$ and the ground temperature between stations are shown in Table 7, where the arithmetic average of the natural ground temperature at the ends of each pipe section is taken as the natural ground temperature along the pipe section.

### 4 RESULTS AND DISCUSSION

#### 4.1 Comparative analysis of optimization schemes

In the second part, this paper establishes the hot oil pipeline model of the study case and takes the pump combination mode, pump speed, and heating station temperature as the optimization variables, so it can be known that the pump speed, inlet, and outlet temperature and pressure in the new optimization scheme must be changed. In this part, we also mainly analyze these aspects.

1. Pipe inlet and outlet pressure analysis

To achieve the ideal pressure solution is to reduce the consumption of pressure energy, that is, to reduce the outbound pressure and increase the inbound pressure as much as possible, but this is only an ideal situation. In the actual optimization scheme, the inlet and outlet temperature, pump speed, and other factors are involved. Here, this paper pays
more attention to the analysis of the pressure drop between stations or the whole pipe section. The greater the pressure drop, the better the performance in reducing pressure energy consumption. Therefore, the pressure changes of the actual scheme and the three optimization schemes are compared as shown in Figure 9.

As shown in Figure 9, the pressure change trend of the optimization scheme and the actual scheme is similar. It can be clearly seen from the figure that the inlet pressure of the actual operation scheme is low in most cases. However, it is also difficult to find out which scheme has less pressure energy consumption only based on the curve in the figure, because the outbound pressure of various schemes is not consistent. Here, we can calculate the total pressure drop of the pipe segment by using the relevant data of each pump station, among which the total pressure of the scheme obtained by genetic algorithm (GA) is 0.34 MPa lower than the actual scheme, the total pressure of the scheme obtained by particle swarm optimization (PSO) is 0.65 MPa lower than the actual scheme, and the total pressure of the optimized scheme by simulated annealing method (SA) is 0.72 MPa lower than the actual scheme. It can be seen that the simulated annealing algorithm is better in reducing the pressure energy, and the genetic algorithm has a lower pressure reducing ability.

2. Temperature analysis of pipe inlet and outlet

Because the crude oil transported by this pipeline is easily condensable and highly viscous crude oil, the excessive temperature will cause excess heat consumption, and condensate accidents may occur if the temperature is too low. Figure 10 shows the temperature change of the inlet and outlet between stations.

Different from the pressure change of the inlet and outlet, although a few optimized outlet temperatures increase, it is obvious from Figure 10 that the outlet temperatures of the three optimized schemes are mostly smaller than the outlet temperatures of the actual schemes, and the inlet temperatures generally have little difference. It shows that all three schemes have a better ability to reduce heat consumption. In addition, the total temperature drop of the entire pipe section is also calculated in this paper. Compared with the actual scheme temperature drop, the temperature of the genetic algorithm (GA) optimization scheme decreased by 2.43°C, the particle swarm algorithm (PSO) optimization scheme decreased by 2.63°C, and the simulated annealing algorithm (SA) optimization scheme decreased by 2.13°C. Therefore, the optimization scheme obtained by the particle swarm algorithm can reduce heat consumption more.
3. Energy consumption forecast

Energy consumption is the main content of this study, which is mainly divided into electricity consumption and oil consumption. Here, the oil consumption and electricity consumption of each station are converted into standard coal units for better analysis and calculation of energy consumption. Compare the actual operation scheme with each optimization scheme, as shown in Figure 11.

It can be seen from Figure 11 that the energy consumption of the actual scheme is significantly higher than the energy consumption of the three optimized schemes. Compared

![Block diagram of the simulated annealing algorithm](image-url)
with the actual scheme, the total energy consumption of the scheme obtained by the genetic algorithm optimization was reduced by 7.57%, the power consumption was reduced by 7.00%, and the fuel consumption was reduced by 7.86%; The total energy consumption of the solution obtained by particle swarm optimization was reduced by 7.84%, the power consumption was reduced by 7.48%, and the fuel consumption was reduced by 8.01%. The total energy consumption of the solution obtained by the optimization of the simulated annealing algorithm was reduced by 6.01%, the power consumption was reduced by 7.19%, and the fuel consumption was reduced by 5.44%. It can be seen that the optimization solution solved by the particle swarm algorithm has the lowest production energy consumption, so it is the optimal solution.

### Table 6: Actual operation scheme of the pipeline system

| Station number | Number of pumps | Rotating speed (rpm) | Inbound temperature (°C) | Outbound temperature (°C) | Inbound pressure (MPa) | Outbound pressure (MPa) |
|----------------|-----------------|----------------------|---------------------------|--------------------------|-----------------------|-------------------------|
| No. 1          | 3               | 2890                 | 43.78                     | 46.52                    | 0.46                  | 5.63                    |
| No. 2          | 2               | 2956                 | 38.79                     | 42.01                    | 1.23                  | 3.91                    |
| No. 3          | 2               | 2890                 | 36.64                     | 41.42                    | 1.56                  | 4.25                    |
| No. 4          | 2               | 2441                 | 37.09                     | 40.54                    | 1.75                  | 5.51                    |
| No. 5          | 2               | 2375                 | 36.40                     | 43.41                    | 1.29                  | 5.15                    |
| No. 6          | 2               | 2987                 | 35.73                     | 42.16                    | 2.22                  | 5.59                    |
| No. 7          | 2               | 2987                 | 35.73                     | 42.16                    | 2.94                  | 2.80                    |
| No. 8          | 2               | 2987                 | 35.73                     | 42.16                    | 3.6                   | 2.3                    |
| No. 9          | 2               | 2987                 | 35.73                     | 42.16                    | 0.36                  | 0.36                    |

*Note: Monthly total energy consumption: 6 124 567.26 kgce. Electricity consumption: 2 001 131.13 kgce. Thermal energy dissipation: 4 123 436.13 kgce.*

### Table 7: Heat transfer coefficient K and ground temperature between stations

| Pipe section between stations | $K$ (W/m² K) | Ground temperature (°C) |
|-------------------------------|--------------|-------------------------|
| Station 1 to station 2        | 0.993        | 0.03                    |
| Station 2 to station 3        | 0.971        | 0.3                     |
| Station 3 to station 4        | 1.270        | -0.05                   |
| Station 4 to station 5        | 1.548        | 0.2                     |
| Station 5 to station 6        | 1.586        | 1.1                     |
| Station 6 to station 7        | 1.310        | 1.9                     |
| Station 7 to station 8        | 1.374        | 1.3                     |
| Station 8 to station 9        | 1.359        | 1.1                     |

### Figure 8: Pipeline and station model

### Figure 9: Comparison of inlet and outlet pressure
Based on the comparison of the pressure, temperature, and energy consumption of each inlet and outlet above, it is found that although the solution of particle swarm optimization algorithm does not show optimality in reducing the pressure drop of the pipeline, the difference between the solution and the maximum pressure drop is not large, so the optimization solution of particle swarm optimization algorithm is better. In addition, the paper also presents the optimal solutions of the three optimization algorithms as shown in Tables 8-10.

### 4.2 Comparative analysis of optimization algorithms

In the previous section, we compared the optimization schemes and found that the solution based on particle swarm optimization was better. But in order to find a better optimization algorithm, its performance is also very important, that is, the efficiency of the algorithm. According to the optimization case in this paper, the optimization calculation is carried out for the working conditions of 8 months in 2018. Taking the working conditions of January as an example, the iterative convergence diagram is shown in Figure 12.

It can be seen from Figure 12 that the genetic algorithm converges in about 40 generations and takes 87.97 seconds. The particle swarm algorithm converges in about 40 generations and takes 32.89 seconds; The simulated annealing algorithm converged before 400 generations and takes 261.45 seconds. Among the three algorithms, the particle swarm algorithm had the least calculation time, and the convergence algebra was similar to the genetic algorithm.

In order to better compare the performance of the three algorithms to solve the model in this paper, eight working conditions of the Qingtie line are calculated, which are collected in different months of 2018, and the final energy consumption calculated by the three algorithms is shown in Figure 13.

### Table 8 The solution obtained by the genetic algorithm

| Station number | Number of pumps | Rotating speed (rpm) | Inbound temperature (°C) | Outbound temperature (°C) | Inbound pressure (MPa) | Outbound pressure (MPa) |
|----------------|-----------------|----------------------|--------------------------|--------------------------|------------------------|------------------------|
| No. 1          | 3               | 2890                 | 43.78                    | 44.70                    | 0.46                   | 5.66                   |
| No. 2          |                 |                      | 38.87                    | 40.27                    | 4.35                   | 4.20                   |
| No. 3          | 2               | 2207                 | 36.02                    | 40.12                    | 2.01                   | 5.19                   |
| No. 4          | 2               | 2890                 | 35.73                    | 41.72                    | 1.53                   | 4.35                   |
| No. 5          | 2               | 2162                 | 36.00                    | 42.38                    | 2.02                   | 5.77                   |
| No. 6          | 2               | 2947                 | 36.13                    | 42.75                    | 1.07                   | 5.02                   |
| No. 7          | 2               | 2644                 | 35.20                    | 42.21                    | 2.01                   | 5.33                   |
| No. 8          |                 |                      | 35.63                    | 41.21                    | 2.74                   | 2.68                   |
| No. 9          |                 |                      | 35.49                    |                          | 0.28                   |                        |

Note: Monthly total energy consumption: 5 660 856.93 kgce. Electricity consumption: 1 861 465.2 kgce. Thermal energy dissipation: 3 799 391.73 kgce.
Analyzing Figure 13, we can draw the following conclusion: When the three algorithms solve the 8-month working condition, the particle swarm optimization algorithm finds the most optimal solutions and recommends the particle swarm optimization algorithm to solve the model from the aspect of optimal solution quality. In addition, the completion time of the three algorithms is shown in Figure 14. As shown in Figure 14, by comparing the solution time of three algorithms in different months, it is obvious that the particle swarm optimization algorithm has more advantages in solution time. From the aspect of optimization efficiency, particle swarm optimization is also recommended to solve the model.

5 | CONCLUSIONS

Based on the MATLAB 2019a programming software, this paper uses Qingtie four-line oil pipeline as a practical case to study the steady-state optimization of the oil pipeline.

1. For hot oil pipelines with variable frequency pumps, the variable frequency pumps can be considered in the modeling of hot oil pipelines and processed using least squares.
2. In this paper, the optimization model of the hot oil pipeline is established, which considers the actual situation of the oil pipeline. The frequency conversion pump model, the heating furnace model, the pipeline thermal, and hydraulic model are introduced into the optimization model, which can calculate the pump speed and the outbound temperature of the oil pipeline system. It conforms to the actual situation of the project and has certain instructive for the field operation.

3. The intelligent algorithm should be used to solve the pipeline model to get the optimal scheme of the pipeline so as to reduce energy consumption and improve the operating efficiency of the pipeline system. Among the three algorithms used in this paper, the particle swarm optimization algorithm has advantages both in solving speed and optimization results, which can reduce energy consumption by 7.84%.

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CONFLICT OF INTEREST
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS CONTRIBUTIONS
Enbin Liu: Methodology; software; validation; supervision; writing – review & editing. Peng Yong: Software; validation; investigation; writing – review & editing. Yang Yi: Software; formal analysis; writing – review & editing. Liuxin Lv: Software; validation; formal analysis. Weibiao Qiao: Methodology; formal analysis. Mohammadamin Azimi: Methodology; investigation.

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