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Optimization Design of Industrial Water Supply Pump Station Considering the Influence of Atmospheric Temperature on Operation Cost

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ABSTRACT Pump type selection at a pump station affects not only the hardware investment but also the operating efficiency. The influence of atmospheric temperature on water consumption was not considered in existing studies. This article considers the uncertainty of water consumption caused by temperature as well as the configuration and operation schedule of the pump station under various working conditions. The purpose of the present paper is to achieve the minimum annual investment and operation cost of the pump station. Taking a steel plant as an example, this article analyzes the possible working conditions of cooling water in the plant, establishes the annual minimum cost objective function of the optimal design, and sets the constraint conditions. The decision variables include the selection of overall pump type and optimal operation of the pump station under different working conditions. Finally, the mathematical model of the optimal design of a water supply pump station is given. The results show that when considering the influence of temperature on water consumption, the annual comprehensive cost is reduced, the optimization effect is obvious, and a good practical effect is achieved.

INDEX TERMS Water supply pump station, temperature, uncertain conditions, optimization design.

I. INTRODUCTION

In recent years, due to the acceleration of industrialization and the increase in industrial water consumption, water resource shortages have been further aggravated. Therefore, domestic and foreign scholars have paid much attention to the optimization design of water supply pump stations. For this design, in the late 1990s, In [1], Hirrel (1989) proposed a graphical method to select a water pump. First, the water consumption curve is established for water users, and the flow and head of the pump are determined according to the change in water consumption. The pump selected by this method is more suitable for a certain period of operation of a water supply system or a fixed water supply pump station, but it is not suitable for a complex water supply system, especially when there are both constant speed pumps and speed regulating pumps in the system. In [2], Ulanicki *et al.* (1993) used an optimization enumeration method to optimize the pumps. This method sets a number of constraint conditions on the pumps, and each constraint condition selects all the pumps that meet this condition in the Statistics table of water pump information once. Only the pumps that meet all constraints are included in the optimization results. This method can find the optimal solution, but the calculation time is too long. In [3], Moradi-Jalal *et al.* (2003) used water pump frequency conversion for agricultural irrigation and compared the results with an original pump operation analysis. They found that pump frequency conversion to reduce the speed of the pump can improve its efficiency. The specific optimization process refers to the arrangement of the pump model, the number of units and the operation schedule to minimize the design operation cost under a given demand flow condition. In [4], Ormsbee and Lansey (1994) proposed a dynamic programming algorithm to select the optimal combination of pumps. The objective function of this algorithm includes both energy consumption and peak flow phase. In terms of optimal

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pump station operation, Pezeshk *et al.* (1994) proposed a method suitable for online control, the ASA (adaptive search algorithm) [5]. The ASA shortens the solution time by searching for the global optimal solution with the system characteristic coefficient to obtain a near-optimal starting state. The pump and pipe characteristic coefficients are updated once per cycle, and a new set of optimal pumps is added to create a new and more efficient pump combination. The advantage is that it can be solved in real time and can handle large and complex systems. The disadvantage is that this method does not produce a global optimal solution because the objective function is nonconvex. In [6], Keith W. Little (1989) developed mixed integer linear programming on the basis of predecessors. He built an optimization model relevant to the use time arrangement. The objective function of the model specifies the operating hours of each pump or combination of pumps to minimize the total energy consumption (including commercial energy, demand consumption and generator operation consumption). The model constraints meet the average, maximum and minimum water demand and corresponding water supply system head requirements. In [7], C. Yuan (2000) applied the fuzzy set theory, combined with comprehensive consideration of energy consumption and water quantity, constructed the fuzzy mathematical model of the optimal operation of the water supply pump station, gave the membership function of energy consumption and water quantity, and established the model of real-time control. Up to now, with the development of optimization algorithms, heuristic optimization algorithm is the main algorithm in pump station optimization technology. Researchers use some heuristic algorithms such as the ant colony algorithm to solve the problem of pump selection and scheduling in pump station design. In [8], Giacomello *et al.* (2013) used linear programming to solve the pump scheduling problem. In [9], Hashemi (2014) used the ant colony algorithm to optimize the operation cost and scheduling time of a speed regulating pump. In [10], Zhang *et al.* (2019) proposed an optimal scheduling method based on station skipping, in which the use of one or more pumping stations can be reduced and the allocation of the gross head to other stations is optimized. For energy saving and longer service life, a parallel pump system was supplied, with the valves and rotational speed controls approximating the system's operating conditions closer to the designed conditions for different consumer loads. The developed optimization model employs a genetic algorithm (GA) aiming at the pumps' maximum efficiency [11]. In [12], Y.Yuan (2013) combined the optimization design of pump station with the characteristics of the ant colony algorithm, took the minimum cost as the objective function, took the total flow as the constraint condition, and used the ant colony search method to solve the model, which proves that the algorithm has high practical value in the optimization design of pump station. In [13], Lai *et al.* (2020) established an optimization model for parallel pump systems with the aim of reducing the pump system power consumption and improving the reliability by fixing pumps' off-design operation. The particle swarm optimization method is adopted to solve the optimization problem, aiming at minimizing the total power consumption of the pump system. But there is still a large development space for theoretical research of the optimal design, and few researchers consider the influence of atmospheric temperature on the water consumption of the water supply pump station. However, the atmospheric temperature is related to water consumption, which has not been considered in the past, so the optimal design scheme is not very suitable for the actual situation, and the operation cost is generally high.

II. OPTIMIZATION DESIGN MODEL OF A WATER SUPPLY PUMP STATION

The optimal design of a pump station refers to a design that meets the flow and head requirements of the water supply process, considering the overall investment of the pump station as well as the depreciation and maintenance cost and operation loss under different working conditions [14]–[16], The total selection scheme of a pump station and the operation scheme of pumps under different working conditions are given. The process of establishing the optimization model of a pump station includes selecting the decision variables reasonably, analyzing the decision variables, establishing the objective function and analyzing the constraints. In existing studies, the influence of air temperature on the cooling water demand was not considered, so the result was that the optimal design would not be suitable for the actual situation. For this problem, the following will be a specific analysis.

A. ANALYSIS OF THE INFLUENCE OF AIR TEMPERATURE ON WATER CONSUMPTION UNDER WORKING CONDITIONS

Production conditions determined by product varieties and production planning are also affected by temperature. The temperature mainly affects the flow demand of the system. This article takes the cooling water system of a steel plant as the research object, which is the most commonly used cooling water system in industrial production. In the production process, there are two working conditions: coarse steel and fine steel. Under these two working conditions, the working hours of the water supply system and the water supply flow will be different. The specific value can be obtained according to the annual output and steel varieties. Most existing studies did not consider the impact of temperature on the water demand of working conditions or simply divided the working conditions into summer and winter working conditions. Through our research, we found that such division is relatively rough and does not fully conform to the actual situation. Figure 1 shows the temperature change of J city in one year. It can be seen that the temperature in summer is higher than that in winter. However, there are also differences of 10-20°C in temperature performance every day. Therefore, we can use T1, T2…, etc. so all temperatures are divided into $T_n + 2$ sections. In these sections, the cooling water flow demand is not the same under

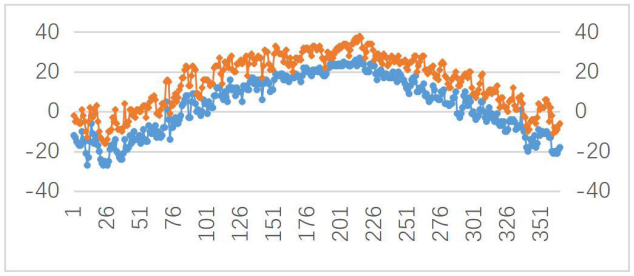

FIGURE 1. Temperature change of J City.

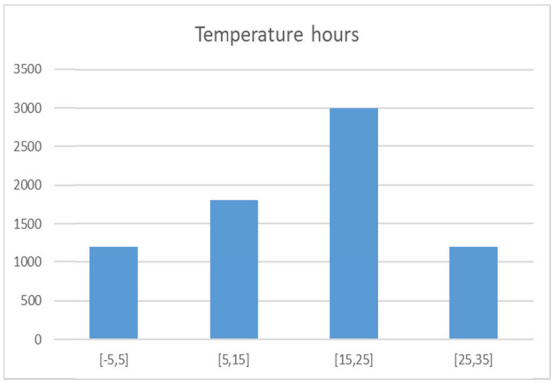

FIGURE 2. Statistical diagram of the temperature range.

the same working conditions, which is positively related to the ambient temperature.

The cooling tower of an air conditioning system is taken as the research object by Duan *et al.* [17]; the temperature of cooling tower water increases with the increase in the wet bulb temperature in the air. In [18], Liu used a numerical simulation method to study the comprehensive influence of environmental parameters on cooling water temperature drop. The influence of ambient temperature on the cooling water temperature drop cannot be ignored. Under certain conditions, the cooling water temperature drop will increase by 2°C-3°C for every 10°C rise in air temperature. In [19], Yang *et al.* (2013) took the cross flow tower as the research object, established the mathematical model through SPSS software according to the actual data, and obtained the linear regression equation between the influencing factors of the cooling tower and the outlet water temperature under certain conditions. The results showed that the inlet water temperature and the ambient temperature had a greater impact on the outlet water temperature.

The multivariate linear equation is

$$t_{out} = 0.331 + 0.43t_s + 0.552t_{in} + 0.001Q_{in} - 0.013G_{in} + \varepsilon \quad (1)$$

where t_{out} is the water outlet temperature of the cooling tower, t_s is the wet bulb temperature of the air around the cooling tower, t_{in} is the water inlet temperature of the cooling tower, Q_{in} is the water inlet volume of the cooling tower, and G_{in} is the air inlet volume of the cooling tower.

TABLE 1. Water supply conditions.

Condition	Water consumption under standard working condition	Working hours (h)	Actual water consumption (m^3/s)
condition 1	240	60*24	200-256
condition 2	450	240*24	400-495

TABLE 2. Water supply condition of a pump station considering the influence of air temperature.

Condition	Temperature (°C)	Actual water consumption (m^3/s)	Working hours (h)	Water consumption under standard working condition (m^3/s)
condition 1	-5--5	94-114	240	105
condition 2	5–15	117-140	360	128
condition 3	15–25	148-185	600	168
condition 4	25–35	210-256	240	240
condition 5	-5--5	181-213	960	197
condition 6	5–15	220-264	1440	242
condition 7	15–25	280-346	2400	315
condition 8	25–35	400-495	960	450

This article introduces a formula $Q = cm\Delta T$, where Q is the heat absorbed (or released), c is the specific heat capacity of the material, m is the mass of the object, and ΔT is the change of temperature after the heat absorption (or release). ΔT is $t_{in} - t_{out}$, the specific heat of atmospheric water is 4.2kJ/kg°C; when Q is a constant value, the rated inlet water temperature of the cooling tower is 36°C, and the outlet water temperature is 26°C. When the heat exchange is the same, and the temperature changes, the following equation is used:

$$4.2*10^3*m_1*|t_{out1} - t_{in}| = 4.2*10^3*m_2*|t_{out2} - t_{in}| \quad (2)$$

The relationship between working water consumption and ΔT can be obtained.

According to this, we divide the working condition of the environment temperature according to the temperature distribution and regard - 5°C, 5°C, 15°C, and 25°C as the temperature dividing points. Figure 2 shows the annual temperature of J city through interval statistics.

The water supply condition of the pump station is shown in Table 1. When considering the influence of temperature on the water demand of the pump station, the water supply condition of the pump station is calculated according to the divided temperature range according to formula (2), and the results are shown in Table 2.

B. ANALYSIS OF DECISION VARIABLES

In the design of a pump station, there are two parts, one is the selection of integral pump and the other is the optimal

operation of pump station under different working conditions. In the selection of an integral pump station, the main decision variables are the model of constant speed pumps, the number of constant speed pumps of the selected model, the model of variable speed pumps, the number of variable speed pumps of the selected model, the number of constant speed pumps under different working conditions, the number and frequency of variable speed pumps, etc.

C. OBJECTIVE FUNCTION

In this article, the configuration and operation of the pump station are combined [20], and the investment and operation are considered at the same time. The optimization objective function is established as follows with the minimum annual cost including capital construction investment, depreciation, maintenance and operation [21] as the objective:

$$\begin{aligned} \min Z &= M_Z + \sum_{j=1}^{m} \rho_j G_j \\ M_Z &= \Big(\sum_{i=1}^{N_d+N_{bd}} T_{di} P_{di} + \sum_{i=1}^{N_t} T_{ti} P_{ti} \Big) \Big(\frac{q(1+q)^y}{(1+q)^y - 1} + f \Big) \\ G_j &= \Big(\sum_{i=1}^{m_{dj}} s_{dij} \frac{\rho g Q_{dij} H_{ij}}{1000 \eta_{ij}} + \sum_{i=1+m_{dj}}^{m_{dj}+m_{tj}} s_{tij} \frac{\rho g Q_{tij} \eta_{ij} H_{ij}}{1000 \eta_{ij} \eta_N} \Big) \times t \times c \end{aligned} \tag{3}$$

The objective function is the annual operation cost of the water supply pump station, including the investment cost M_z and the electricity cost under all working conditions $\sum_{j=1}^{m} \rho_j G_j$. The investment cost takes into account the equipment purchase cost, loan interest q and maintenance rate f, and uses the method of equal principal and interest repayment to calculate. The equipment purchase cost includes the purchase cost of all types of constant speed pumps and all types of speed regulating pumps. The power of all pumps multiplied by the operation time t, and the unit price of electricity C is equal to the electricity cost. The pump power of a constant speed pump can be expressed as $\rho gQH/1000\eta$. The pump power of a speed regulating pump can be expressed as $\rho gQnH/1000\eta n_N$.

D. CONSTRAINT ANALYSIS

The specific constraints in the design of pump station are as presented below.

Due to the limited plant area, the total floor area of the water pump is smaller than that of the total pump room, and the water pump is allowed to be placed to restrict the flow as follows:

$$\sum_{i=1}^{N_d+N_{bd}} T_{di} S_{mi} + \sum_{i=1}^{N_t} T_{ti} S_{mi} \le S_{\max} \tag{4}$$

Flow restriction, specifically including the working flow of the selected pump after parallel connection under each working condition, shall meet the water flow requirements under this working condition. In addition, in order to ensure the safe and efficient operation of the pump, the flow requirements of the pump shall be considered as follows:

$$\begin{aligned} Q_{\min j} &\le \sum_{i=1}^{N_{dj}} s_{dij} Q_{dij} + \sum_{i=N_{dj}+1}^{N_{dj}+N_{tj}} s_{tij} \frac{Q_N n_{ij}}{n_N} \le Q_{\max j} \\ Q_{\min} &\le Q_i \le Q_{\max} \quad (i = 1, 2, 3 \ldots\ldots N_d) \end{aligned} \tag{5}$$

TABLE 3. Symbol meaning table.

Symbol	QUANTITY	Symbol	QUANTITY
M_z	investment cost	f	maintenance rate
ρ_j	weight value of the j-th working condition	y	investment period (year)
G_j	electricity cost of the j-th working condition	m_{dj}	type of constant speed pump under the j-th working condition
m	m working conditions	s_{dij}	number of the i-th constant speed pump under the j-th working condition
N_d	types of constant speed pump	m_{tj}	type of speed regulating pump under the j-th working condition
N_{bd}	types of standby constant speed pump	s_{tij}	the number of the i-th pump under the j-th working condition
s_{bd}	Number of standby constant speed pump	Q_{bd}	Flow of standby pump
N_t	types of speed regulating pump	Q_{dij}	flow rate of the i-th constant speed pump under the j-th working condition
T_{di}	number of type i-th constant speed pump	H_{ij}	head of the i-th pump under the j-th working condition
T_{ti}	number of the i-th speed regulating pump	η_{ij}	efficiency of the i-th pump under the j-th working condition
S_{mi}	Floor area of water pump	$S_{\max}$	Maximum pump room area
P_{di}	cost of type i-th constant speed pump	n_{ij}	rotation speed of the i-th pump under the j-th working condition
P_{ti}	cost of the i-th speed regulating pump	t	annual operation time of water pump
q	bank rate	C	the unit price of electricity
n_N	Rated speed	n_i	Speed of the i-th speed pump
η_i	Efficiency of the i-th speed pump	$\eta_{\max}$	Maximum efficiency
ρ	Density of medium	g	Acceleration of gravity
$Q_{\min}$	Minimum flow	$Q_{\max}$	Maximum flow
H_{st}	Net head	N_{dj}	types of constant speed pump under j-th working condition
Q_N	Rated flow	N_{tj}	types of speed pump under j-th working condition
S	Resistance coefficient		

Head Restraint: In this article, the combination of pumps is only the parallel combination of pumps, so the head of each pump should meet the head requirements of the water supply pump station and not exceed the maximum head that the pump itself can give:

$$\begin{aligned} H_{ij} &\le H_{\max} \\ H_{ij} &= H_{st} + SQ^2 \end{aligned} \tag{6}$$

The requirements for the number of standby pumps are mainly determined according to the importance of water supply and annual utilization hours, and the requirements shall meet the normal maintenance requirements of the unit. Generally, for important water supply pump stations, when there are three or less working pumps, one standby pump shall be set, and when there are more than three working pumps, two standby pumps shall be set, as follows:

$$\begin{aligned} s_{bd} &= 1 \quad (\sum_{i=1}^{N_d+N_{bd}} T_{di} + \sum_{i=1}^{N_t} T_{ti} \le 3) \\ Q_{bd} &= Q_{ij\max} \quad (\sum_{i=1}^{N_d+N_{bd}} T_{di} + \sum_{i=1}^{N_t} T_{ti} \le 3) \\ s_{bd} &= 2 \quad (\sum_{i=1}^{N_d+N_{bd}} T_{di} + \sum_{i=1}^{N_t} T_{ti} > 3) \\ Q_{bd} &= Q_{ij\max} \quad (\sum_{i=1}^{N_d+N_{bd}} T_{di} + \sum_{i=1}^{N_t} T_{ti} > 3) \end{aligned} \tag{7}$$

To avoid overheating when the speed is too low, the regulating range of the speed is restricted as follows:

$$0.5n_N \le n_i \le n_N \quad (i = 1, 2, 3 \ldots\ldots N_t) \tag{8}$$

To restrict efficiency, the pump can work in the high efficiency area and avoid the energy waste caused by the inefficient operation. The specific restrictions are as follows:

$$\eta_i \ge 0.9\eta_{\max} \quad (i = 1, 2, 3 \ldots\ldots N_d + N_t) \tag{9}$$

III. MODEL UNCERTAINTY ANALYSIS

In this article, the optimal design of a pump station under different working conditions of cooling water is considered. The working condition flow is uncertain, and the upper and lower limits of equation (5) above are uncertain. The flow parameters of a certain working condition and the current flow of the pump are not accurate, and there is a possible value range. Therefore, it is expressed as an interval number and treated as follows:

$$\begin{aligned} \left[Q^L_{\min j}, Q^R_{\min j}\right] &\le \sum_{i=1}^{N_{dj}} S_{dij} Q_{dij} + \sum_{i=N_{dj}+1}^{N_{di}+N_{tj}} S_{ij} \frac{Q_{Ni} n_{ij}}{n_{Ni}} \\ &\le \left[Q^L_{\max j}, Q^R_{\max j}\right] \end{aligned} \tag{10}$$

According to the time statistics of the annual interval of the atmospheric temperature in a certain place, due to the different weather conditions every year, the statistical results will fluctuate in a certain range, as reflected in the above formula (3), and the value of the operation time under each working condition has a certain range, which is processed into the following form:

$$\mathrm{G_j} = (\sum_{i=1}^{m_{dj}} s_{dij} \frac{\rho g Q_{ij} H_{ij}}{1000\eta_{ij}} + \sum_{i=1+m_{dj}}^{m_{dj}+m_{tj}} s_{tij} \frac{\rho g Q_{ij} \eta_{ij} H_{ij}}{1000\eta_{ij}\eta_N}) \times [\mathrm{t_j^L}, \mathrm{t_j^R}] \times c \tag{11}$$

$$\mathrm{G}_j^L = (\sum_{i=1}^{m_{dj}} s_{dij} \frac{\rho g Q_{ij} H_{ij}}{1000\eta_{ij}} + \sum_{i=1+m_{dj}}^{m_{dj}+m_{tj}} s_{tij} \frac{\rho g Q_{ij} \eta_{ij} H_{ij}}{1000\eta_{ij}\eta_N}) \times \mathrm{t_j^L} \times c \tag{12}$$

$$\mathrm{G}_j^R = (\sum_{i=1}^{m_{dj}} s_{dij} \frac{\rho g Q_{ij} H_{ij}}{1000\eta_{ij}} + \sum_{i=1+m_{dj}}^{m_{dj}+m_{tj}} s_{tij} \frac{\rho g Q_{ij} \eta_{ij} H_{ij}}{1000\eta_{ij}\eta_N}) \times \mathrm{t_j^R} \times c \tag{13}$$

The production condition is the overall demand design, but there may be some changes in the actual production to show the uncertainty. In the optimization model, the uncertainty is mainly reflected in the coefficient of each condition in the optimization objective function. The influencing factors are the original operation plan and the annual temperature statistics, and there is also a fuzzy value range, expressed as follows:

$$\begin{aligned} \rho_j &= [\rho_1^L, \rho_1^R][\rho_2^L, \rho_2^R] \\ \rho_j^L &= \rho_1^L \rho_2^L, \quad \rho_j^R = \rho_1^R \rho_2^R \end{aligned} \tag{14}$$

$$\min Z = M_Z + \sum_{j=1}^{m} [\rho_j^L, \rho_j^R][G_j^L, G_j^R] \tag{15}$$

A. TRANSFORMATION OF PARAMETER UNCERTAINTY

The uncertainty optimization problem began with the work of Bellman and Zadeh [22] and Zadeh [23]. In the past, people usually use a random programming or fuzzy programming method to describe the uncertainty problem. However, whether it is the probability distribution function of random process or the membership function of fuzzy mathematics, it is not easy to determine. More often, only the value range of these uncertain parameters is obtained, which leads to the interval number optimization problem [24].

Many scholars have put forward different methods for the comparison of interval numbers, which can be roughly divided into two categories: one is the ranking method based on interval order relations, which can determine the size of interval numbers qualitatively through the defined order relations; the other is the ranking of interval numbers based on the possibility degree of interval, which can determine the probability value of the comparison of the size of two interval numbers through certain calculation and describe a region quantitatively. The number of intervals is greater (or better) than the other.

Nakahara *et al.* first introduced the concept of probability into the construction of interval probability [25]. They

divided the positional relations of two interval numbers into six cases, which can be expressed as follows:

$$(i)\ a^L \le a^R \le b^L \le b^R \quad (ii)\ a^L \le b^L \le a^R \le b^R$$
$$(iii)\ a^L \le b^L \le b^R \le a^R \quad (iv)\ b^L \le a^L \le a^R \le b^R$$
$$(v)\ b^L \le a^L \le b^R \le a^R \quad (vi)\ b^L \le b^R \le a^L \le a^R$$

On the basis of the above probability method, C. Jiang put forward a commonly used improved interval number possibility construction model [26], [27], which is as follows:

$$P(A \le B) = \begin{cases} 1 & a^R \le b^L \\ \frac{b^L - a^R}{a^R - a^L} + \frac{(a^R - b^L)(b^R - a^R)}{(a^R - a^L)(b^R - b^L)} & \\ \quad + 0.5\frac{(a^R - b^L)(a^R - b^L)}{(a^R - a^L)(b^R - b^L)} & a^L \le b^L < a^R \le b^R \\ \frac{b^L - a^L}{a^R - a^L} + 0.5\frac{b^R - b^L}{a^R - a^L} & a^L < b^L < b^R \le a^R \\ \frac{b^R - a^R}{b^R - b^L} + 0.5\frac{a^R - a^L}{b^R - b^L} & b^L \le a^L < a^R < b^R \\ 0.5\frac{(b^R - a^L)}{(b^R - b^L)}\frac{(b^R - a^L)}{(a^R - a^L)} & b^L < a^L \le b^R < a^R \\ 0 & b^R < a^L \end{cases} \tag{16}$$

1) TRANSFORMATION OF THE OBJECTIVE FUNCTION

$$Z_{\min} = M_Z + \sum_{j=1}^{m} \rho_j^L G_j^L$$
$$Z_{\max} = M_Z + \sum_{j=1}^{m} \rho_j^R G_j^R \tag{17}$$

Here, the objective function $Z = [Z_{\min}, Z_{max}]$.

To solve the objective function more clearly, we introduce the risk factor ε to express that the actual value is not less than the risk of the optimal solution λ due to the existence of uncertain parameters. For any value in Z, we define the risk factor as $\varepsilon = \frac{\nu - Z_{\min}}{Z_{max} - Z_{\min}}$, $\varepsilon \in [0, 1]$.

It can be seen from the above formula that the risk value ε increases with the increase in ν. In the minimization problem, when $\nu = Z_{\min}$, the risk factor $\varepsilon = 0$, this means that the objective function value larger than $Z_{\min}$ can be obtained; when $\nu = Z_{\max}$, the risk factor $\varepsilon = 1$, this means that it is the most risky to obtain the objective function value larger than $Z_{\max}$. By transforming the formula, the follow is obtained:

$$\nu = \varepsilon Z_{\max} + (1 - \varepsilon) Z_{\min} \tag{18}$$

ν is the actual value, so we need to determine the minimum value as follows:

$$\min Z = \varepsilon Z_{\max} + (1 - \varepsilon) Z_{\min} \tag{19}$$

Among them, this risk factor ε represents the risk that the decision-maker can bear. The interval number belongs to the uncertain parameter, so the result will have certain deviation. To make the deviation controllable, we set the maximum deviation to $d_{\max}$ and make $d \le d_{\max}$; among them $d = Z_{\max} - Z_{\min}$.

2) DETERMINACY TRANSFORMATION OF CONSTRAINTS

In this article, by using the possibility degree formula given above, the possibility degree of two interval numbers is limited by giving the confidence level. Then, the interval constraint is transformed into the definite constraint.

For general interval number constraint function, it can be described as $g_j(X, U) \le B_j$ and $g_k(X, U) \ge B_k$. Where X is the n-dimensional decision variable, $U = \{u | u \textit{ is the interval number}\}$, and B_j and B_k are the allowable interval of interval constraint. For the inequality constraint, given the fixed signal level $0 \le \lambda_j \le 1$, the inequality constraint can be transformed into the following:

$$P(g_j(X, U) \le B_j) \ge \lambda_j \tag{20}$$

For the "$\ge$" inequality constraint, such as $g_k(X, U) \ge B_k$, it can be transformed into the "$\le$" inequality constraint: $B_k \le g_k(X, U)$, and then it can be transformed into the following:

$$P(B_k \le g_k(X, U)) \ge \lambda_k \tag{21}$$

Therefore, for equation (10) determining the constraint function, the calculation steps are as follows:

$$p\left(\sum_{i=1}^{N_{dj}} S_{ij} Q_{ij} + \sum_{i=1}^{N_{dj}+N_{tj}} S_{ij} \frac{Q_{Ni}\eta_{ij}}{\eta_{ij}} \le Q_{\max j}\right) \ge \lambda_1 \tag{22}$$

$$p\left(Q_{\min j} \le \sum_{i=1}^{N_{dj}} S_{ij} Q_{ij} + \sum_{i=1}^{N_{dj}+N_{tj}} S_{ij} \frac{Q_{Ni}\eta_{ij}}{\eta_{ij}}\right) \ge \lambda_2 \tag{23}$$

According to the corresponding position of the two interval numbers, the interval probability formula (16) and the confidence interval $\lambda (0 \le \lambda \le 1)$ that the decision maker can accept are used to solve the problem.

IV. SOLUTION OF THE PUMP STATION OPTIMIZATION PROBLEM

A. ANALYSIS OF OPTIMIZATION PROBLEMS

The mathematical description of the problem is as follows: it is required to find an N-element vector and n N-element vectors corresponding to N working conditions in this set of vectors to minimize the objective function $\min \sum_{i=1}^{m} x_i P_i$ when constraints $\sum_{i=1}^{m} x_i S_i \le S$ and $\sum_{i=1}^{m} x_{Ni} Q_i \le Q_N$ are met. The optimal solution of the optimization problem is determined from all the solutions that satisfy the constraints and minimize the objective function. Combined with the optimization design model obtained in Chapter 3, the problem is analyzed to be a nonlinear integer programming problem.

This optimization problem involves the overall selection and number of pumps, the number of pumps selected under

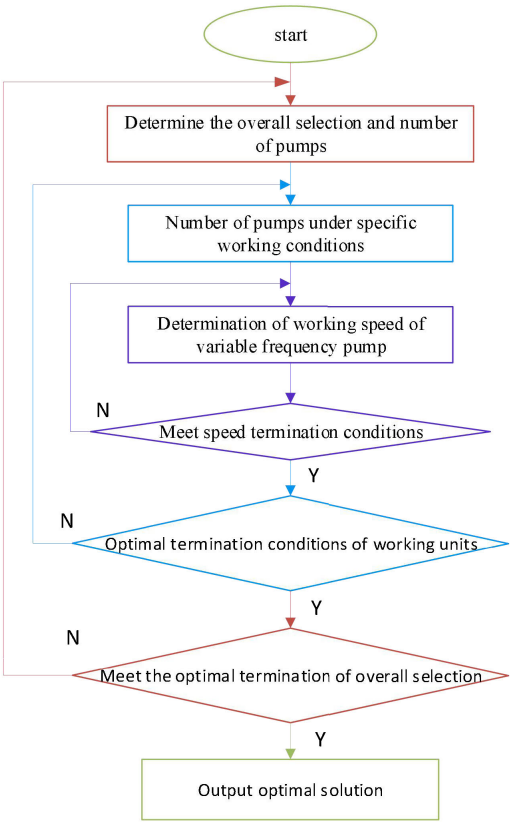

FIGURE 3. Optimization solution flow chart.

each working condition and the working speed of the variable frequency pump under a working condition. It can be seen that the optimization problem has a three-layer optimization solution structure, as shown in Figure 3 below.

B. OPTIMIZATION DESIGN SIMULATION OF PUMP STATION

The ultimate purpose of the optimal design of the pump station is to provide the overall design scheme of the pump station, which includes the overall pump selection of the pump station and the operation and scheduling of the pump under various working conditions. If it is a variable-frequency pump, the speed of the variable-frequency pump under specific working conditions should also be given. The coding method of the overall combination scheme solution of the pump station is determined as follows:

$$[ZD_1, ZD_2, ZD_3, \ldots, ZD_n, ZT_1, ZT_2, ZT_3, \ldots, ZT_m]$$

$D_i(i = 1, 2, \ldots, n)$ represents the specific quantity of fixed speed pump in L pump combination plan. The range of value should be limited to $ZD_i(i = 1, 2, \ldots, n)$. If it is not selected, it will be expressed in 0. $T_i(i = 1, 2, \ldots, m)$ represents the specific quantity of the speed governing pump in the L pump combination scheme. The range of the value should be limited to $ZT_i(i = 1, 2, \ldots, m)$, and if it is not selected, it will be expressed in 0. The coding mode of speed regulating pump is as follows:

TABLE 4. Statistics of water pump information.

Information statistics of constant speed water pump						
Model	rated flow m³/h	head m	Maximum efficiency %	Minimum efficiency %	Area m^2	Price yuan
BL(T)2	2	45	55	43	3	1657
BL(T)4	4	45	57	35	5	1795
BL(T)8	8	48	62	47	6	2671
BL(T)12	12	50	63	55	8	3592
BL(T)16	16	52	66	54	7	4023
BL(T)20	20	47	67	53	6	5371
BL(T)32	32	53	70	58	7	6312
BL(T)45	45	50	74	64	6	8048
BL(T)64	64	51	75	61	8	9423
BL(T)90	90	49	76	60	9	11667
Information Statistics of variable speed water pump						
Model	rated flow m³/h	head m	Maximum efficiency %	Minimum efficiency %	Rated speed r/min	Area	Price
BWE2	2	46	69	64	2780	7	3937
BWE4	4	48	70	65	2750	6	3828
BWE8	8	52	71	64	3000	6	5297
MHI1604	16	50	70	62	3100	7	6200
CDL16	16	52	68	60	3000	6	6399

$[r_{D_1}^1, r_{D_1}^2, \ldots, r_{D_1}^{D_1}; \; r_{D2}^1, r_{D2}^2, \ldots, r_{D2}^{D_2}; \; \ldots, r_{Di}^1, r_{Di}^2, \ldots, r_{Di}^{D_i}]$ $r_{Ti}^1, r_{Ti}^2, \ldots, r_{Ti}^{T_i}$ represents the speed corresponding to the i-th speed regulating pump of T_i number. Since the speed regulation of the water pump is downward, its specific value should be limited to the rated speed of the corresponding speed regulating pump.

To optimize the water supply pump station of the clean circulating water system in the steel plant established in this article, as it is necessary to select the optimal solution. This solution should meet the design requirements of the water supply condition of the pump station from all the pump type warehouses or all the pump type warehouses of the same manufacturer, and the particle swarm optimization algorithm can better solve this kind of combined optimization problem.

C. PUMP TYPE STATISTICS

At present, the five major brands of pumps are available in the Chinese market including Grundfos pumps, Weile pumps, Nanfang pumps, Boshan pumps and new territories pumps. In this article, some pump models with similar range of head parameters and different flow and other performance parameters are counted and stored in an Excel file, as shown in Table 4. In the table, the statistics of a constant speed pump and a variable speed pump are examined separately. The statistical information of a constant speed pump mainly includes the model, rated flow, head, efficiency range of efficient work, floor area and unit price of the water pump. The statistics of a variable speed pump increase the rated speed statistics compared with those of a constant speed

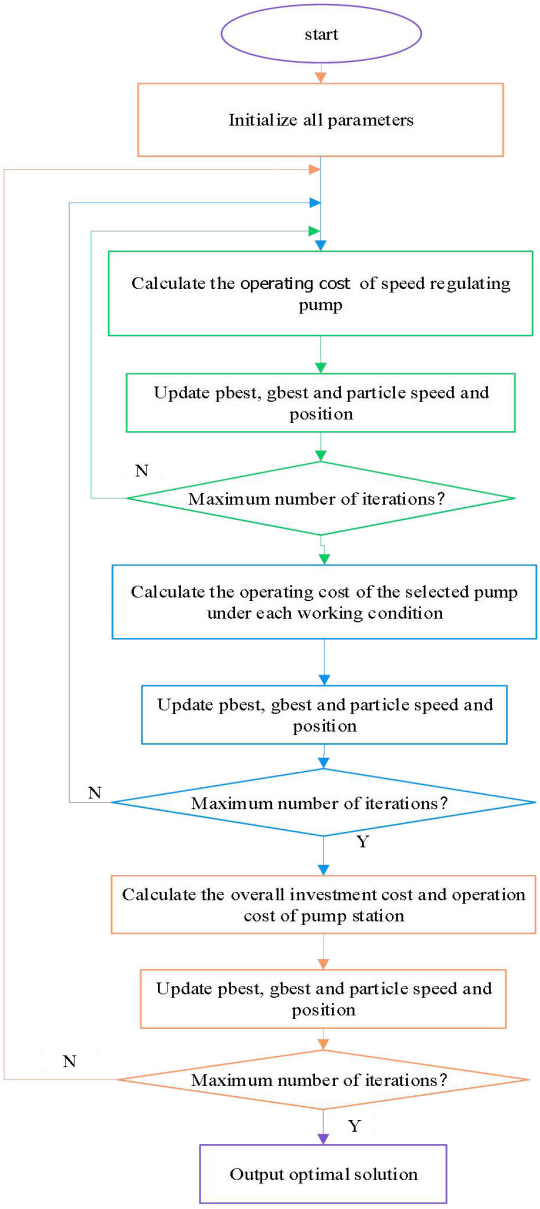

FIGURE 4. Three level particle swarm optimization.

pump, because a variable speed pump changes its speed to change the flow.

D. ALGORITHM INTRODUCTION AND SOLUTION

Particle swarm optimization (PSO) simulates the foraging behavior of birds in flight and optimizes the population through the collective cooperation among birds. This algorithm was proposed by Kennedy and Eberhart [28], [29]. It is simple and easy to implement. It needs fewer parameters to be adjusted and does not need gradient information. PSO is an effective optimization tool for combinatorial optimization problem and integer nonlinear optimization problem [30], [31]. The PSO algorithm first initializes the particle swarm at random, and then the particle finds the global optimal solution through iteration in the solution space. In each

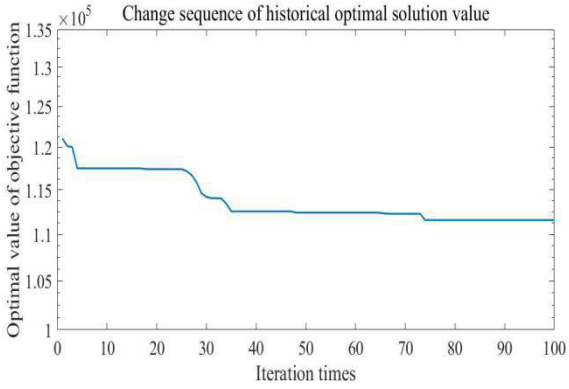

FIGURE 5. Change in the target value.

iteration, particles update their speed and position according to equations (24) and (25):

$$v_{id}^{(k)} = wv_{id}^{(k-1)} + c_1 r_1 (p_{id} - x_{id}^{(k-1)}) + c_2 r_2 (p_{gd} - x_{id}^{(k-1)}) \tag{24}$$

$$x_{id}^{(k)} = x_{id}^{(k-1)} + v_{id}^{(k)} \tag{25}$$

where $d = 1, 2, \ldots, D$; w is the inertia weight; c is the number of iterations; r_1 and r_2 are the random numbers between [0, 1]; c_1 and c_2 are the learning factors. According to equation (24) and (25), the individual fitness value of each particle is calculated, and the individual extreme value and global extreme value are updated by comparing with the previous iteration. When the stop condition is satisfied, the iteration stops and the global optimal solution is found. The problem is solved by three-level particle swarm optimization. Initialize all parameters, enter first-level particle swarm, calculate the operating cost of the speed regulating pump at the current speed, update the corresponding parameters, enter the second-level particle swarm when the maximum number of iterations is satisfied, calculate the running cost of the selected pump under each condition, update the corresponding parameters, enter the third-level particle swarm when the maximum number of iterations is satisfied, calculate the investment cost and operating cost of the pump station and update the corresponding parameters to output the optimal solution. The flow of algorithm is shown in Figure 4.

According to the working conditions in Table 1, the particle swarm optimization algorithm is used to solve the problem, and the annual comprehensive cost is 113853 yuan. The change of the objective function value is shown in Figure 5. The overall model of the pump station is BL(T)32 constant speed pump, BL(T)45 constant speed pump, and BL(T)64 constant speed pump. The overall design scheme of the pump station and the use of specific pumps under each operating condition are shown in Table 5. The water consumption range for each working condition and the flow indication diagram of water pump operation is shown in Figure 6.

According to Table 2, considering the working conditions affected by air temperature, the annual comprehensive cost of the scheme is 87428 yuan when solving with particle swarm

TABLE 5. Optimized design scheme of the pump station without considering the influence of atmospheric temperature.

Overall design scheme of the pump station	Model	BL(T)32	BL(T)45	BL(T)64
	Number	1	4	3
Operation scheme of condition 1	Number	1	4	0
	Speed	constant speed	constant speed	No work
Operation scheme of condition 2	Number	1	4	3
	Speed	constant speed	constant speed	constant speed

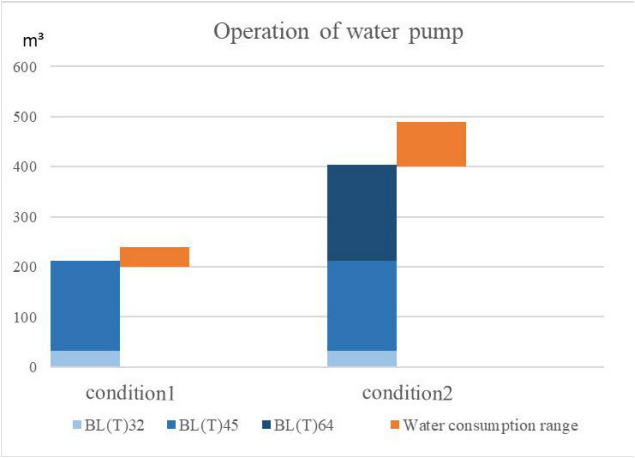

FIGURE 6. Flow indication diagram of water pump operation.

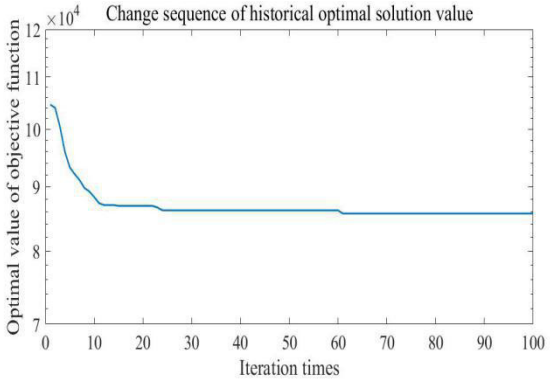

FIGURE 7. Change in the target value considering temperature.

optimization algorithm.The change of the objective function value considering temperature is shown in Figure 7. Three BL(T)45 constant speed pumps, four BL(T)64 constant speed pumps and one CDL16 variable speed pump are selected as the whole pump station. The specific operation of the pump station is shown in Table 6.

The design scheme of pump station selection is mainly used to meet the demand of water volume change in actual

TABLE 6. Optimized design scheme of the pump station considering the influence of atmospheric temperature.

Overall design scheme of the pump station	Model	BL(T)45	BL(T)64	CDL16
	Number	3	4	1
Operation scheme of condition 1	Number	2	0	1
	Speed	constant speed	No work	2897
Operation scheme of condition 2	Number	0	2	0
	Speed	No work	constant speed	No work
Operation scheme of condition 3	Number	3	0	1
	Speed	constant speed	No work	3000
Operation scheme of condition 4	Number	1	3	0
	Speed	constant speed	constant speed	No work
Operation scheme of condition 5	Number	0	3	1
	Speed	No work	constant speed	2434
Operation scheme of condition 6	Number	0	4	0
	Speed	No work	constant speed	No work
Operation scheme of condition 7	Number	1	4	0
	Speed	constant speed	constant speed	No work
Operation scheme of condition 8	Number	3	4	1
	Speed	constant speed	constant speed	2585

working condition by selecting pumps with various performances. Pumps with different flow rates are selected at the same time, and the constant speed of a large pump and the speed regulation of a small pump are generally used to meet the continuous changes of working conditions to solve problems that are difficult to coordinate when only using large pumps. In Table 5, there are few flow types and large range differences under working conditions, and the flow requirements under working conditions can be met through several constant speed pump combinations with different flow sizes. Under working condition 1, one constant speed pump with a flow of 32 m^3 and four constant speed pumps with a flow of 45 m^3 are selected; under working condition 2, one constant speed pump with a flow of 32 m^3, four constant speed pumps with a flow of 45 m^3 and three constant speed pumps with a flow of 64 m^3 are selected. Table 6 considering the influence of air temperature on the working condition flow, the working condition division is more detailed, the range of working condition water consumption is narrowed, and the flow difference between different working conditions is small, so it is difficult to meet the actual demand simply through the combination of different constant speed pumps.

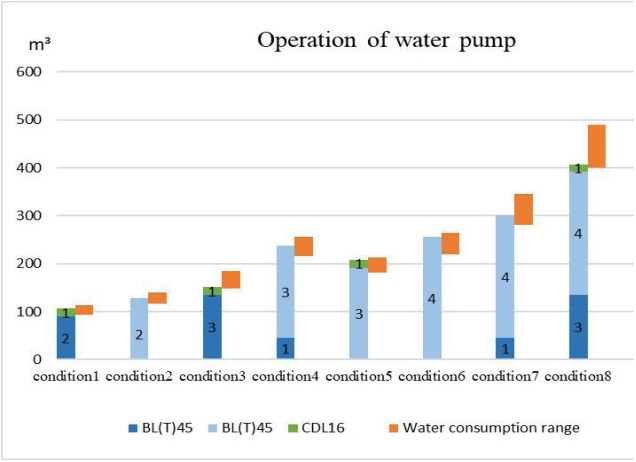

FIGURE 8. Operation of the water pump.

TABLE 7. Comparison of annual costs.

Considerations	Annual investment cost	Annual operating cost	Annual total cost
Temperature not considered	13355	100498	113853
Considering temperature	13610	73818	87428

As shown in Table 6, working condition 1, the actual water consumption interval is 94 to 114 m^3, and the optimal scheme chooses 2 sets of fixed speed pumps with a flow rate of 45 m^3. The residual flow is supplemented by the speed regulating pump with a rated flow of 16 m^3. In the case of conditions 3, 5, and 8, the speed governing pump also plays the same role, and the flow indication diagram of water pump operation is shown in Figure 8.

Through the overall design of the pump station, the annual investment cost can be obtained. A comparison of costs is shown in Table 7 whether the influence of atmospheric temperature is taken into account. In the past, without considering the influence of temperature on the operating flow, the water consumption of a certain operating condition needs to meet the water demand of the system under the worst temperature conditions. In this article, considering the influence of temperature on the operating condition flow, the operating condition flow is more detailed divided by different temperature intervals, and the actual water demand of the system under different temperature intervals is obtained. The overall design scheme of the pump station and the operation scheme of the pump under different working conditions are obtained by the particle swarm optimization algorithm. The water consumption under each working condition is less than that under the worst working condition. Even though the annual investment cost for purchasing water pumps is increased from 13355 yuan to 13610 yuan, the operation cost of the system has been decreased to meet the worst working conditions. The operation cost has been reduced from 100498 yuan to 73818 yuan, and 26680 yuan has been saved. Therefore, the total cost of each year has been reduced from 113853 yuan to 87428 yuan, with remarkable cost savings.

V. CONCLUSION

Given that the influences of temperature are not considered in existing studies, this article makes a statistical analysis on the temperature of city J and finds that the fluctuation range of daily temperature is large, and the temperature has a great impact on the actual flow. To ensure the economic operation of the water supply of the cooling water system, this article takes the minimum annual cost of the investment, repair and operation of the pump station as the objective function, establishes the optimal design model of the pump station, selects the particle swarm optimization algorithm to solve such nonlinear integer programming problems, and finally gives the whole plan of a water supply pump station and operation scheduling under various working conditions. The simulation results show that the particle swarm optimization algorithm can solve this kind of combined optimization problem quickly and effectively. Compared with previous design schemes of water supply pump stations that do not consider the influence of temperature on working conditions, the annual cost is reduced by 23%. Therefore, the research results of this article are verified to achieve optimal design of a pump station and have better practical significance for improving economic benefits.

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