RESEARCH ON AIR-WATER COORDINATED OPERATION OF WATER SIDE FREE COOLING SYSTEM BASED ON IMPROVED PARTICLE SWARM OPTIMIZATION ALGORITHM

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Abstract. Water side free cooling is an important technology for cooling water system to use natural cooling source for energy saving, especially in the field of data center and industrial production. However, the operation regulation of water side free cooling system was lack of scientific basis. This process involves the two-phase circulation of air and cooling water, which requires the coordinated operation of air and water to further optimize the energy consumption. The coordinated operation of air and water includes the coordination of air and water flow in each cooling tower and the matching of the operating numbers of equipment in the system. Firstly, based on the characteristics of the cooling tower, the key equipment in the water side free cooling system, the air-water two-phase heat transfer model in the cooling tower was established. Then, according to the heat transfer model and power model of each equipment in the system, the optimization objectives and constraints are established. An improved particle swarm optimization (PSO) algorithm was proposed to solve the problem of wind water collaborative optimization of water side free cooling system. Finally, this paper takes a small data center cooling water system as an example to analyze the optimization performance of the improved particle swarm optimization algorithm. The simulation results showed that the excellent rate obtained by the improved algorithm can be increased by 36.9%, which is more energy-saving. This method can provide a reference for the energy-saving optimization of water side free cooling system.

1 Introduction

Both data centers and industrial production require the circulating cooling water system to operate continuously throughout the year to provide cooling capacity. The water side free cooling technology can make full use of the outdoor low-temperature air in winter and transition season through the evaporative cooling effect of the cooling tower to reduce the system energy consumption[1]. The water side free cooling system is designed according to the design conditions, but it often operates under partial load conditions. Therefore, the operating parameters of the equipment in the system need to be adjusted according to the actual environmental conditions and load, which is the key to improve the utilization rate of natural cold source and reduce energy consumption[2]. The outlet water temperature of the cooling tower has an important impact on the equipment energy consumption in the water side free cooling system. In the process of operation adjustment, it is necessary to find the working state that minimizes the power consumption of the system.

The existing literature has been involved in the optimization method of cooling tower outlet water temperature. The optimization methods can be divided into variable temperature set point method and constant temperature set point method. In terms of variable temperature setting, Nasrabadi et al. studied two strategies: increasing tower air flow and reducing tower water flow[3]. The results show that the approximation degree of 2°C is basically applicable to all weather conditions. Marques et al. proposed the water temperature split range control strategy and established the PID control loop, which improved the efficiency of the open cooling tower[4]. Chang et al. applied the temperature zone method instead of the set value of the fan to control the outlet water temperature of the cooling tower at 32°C, and the on-line test confirmed the energy saving of this method[5]. In addition, in terms of system optimization, there are also some methods can be used for reference. Mu et al.[6] and Singh[7] control the power output based on the total power feedback model, so as to obtain the energy-saving benefits of the system. Li et al. presents a model-based methodology to optimize cooling water approach temperature in different cooling modes[8]. Liao et al. proposed a simplified method to optimize the approach temperature setting value of cooling water system.[9]. Peesel et al. applied a predictive optimization algorithm to calculate the optimal operating conditions of cooling towers and chillers[10].

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By adjusting the speed of water pump and fan through the temperature setting value, the energy consumption of cooling water system can be reduced to a certain extent. However, the reduction of system energy consumption is based on temperature constraints, which cannot ensure the real-time optimal operation of cooling water system. The existing optimization methods of temperature setting value lack of combination with the operating characteristics under variable conditions, and the optimal rate of the calculated results is not high. In order to solve this problem, this paper established the mathematical model of cooling water system optimization based on the gas-water two-phase heat transfer model of cooling tower, and proposed an improved particle swarm optimization algorithm to solve the wind water collaborative optimization problem of water side free cooling system. Finally, taking a small data center as an example, the energy saving of the proposed method was analyzed.

2 The mathematical model of equipment

2.1 The heat transfer model of cooling tower

2.1.1 Important assumptions

The cooling tower heat exchange model was established based on the following assumptions:

1) The heat exchange direction is only the gas-liquid flow direction;
2) Ignore the heat exchange between the environment and the fluid;
3) The two-phase heat transfer process is independent of time;
4) The enthalpy of saturated wet air is linear with temperature.

2.1.2 The heat transfer model of cooling tower

According to the enthalpy difference theory of cooling tower, the heat exchange of cooling tower can be expressed as:

\[ Q_{c} = r \cdot m_{w}^0 \cdot \Delta h_{w} \cdot AZ \]  

Through the analysis of counterflow two-phase heat transfer in the cooling tower, it can be obtained that:

\[ Q = \frac{pm_{w}}{1 + p \frac{\Delta h_{w}}{m_{w}}} (\hat{h}_{wi} - h_{w}) \]  

\[ t_{wu} = t_{wi} - \frac{p}{c_{w}} \frac{\Delta h_{w}}{m_{w}} (\hat{h}_{wi} - h_{w}) \]  

\[ p = \left( \frac{t_{wi}}{t_{w0}} \right) \left( \frac{t_{ub}}{t_{w0}} \right) \nu \cdot m_{w} \]  

where the parameters \( \nu \) and \( \nu \) are only related to the structural parameters of the cooling tower.

2.2 The power model of fan and water pump

For the open counterflow cooling tower, the head of water pump needs to provide height difference and pipe network resistance. The head of the water pump can be expressed as:

\[ H = SL_{i} + \Delta H \]  

According to the relationship between pump power and flow, head and efficiency, the calculation formula of pump power can be obtained as follows:

\[ P_{p} = \frac{\rho g L}{\eta} \left( SL_{i} + \Delta H \right) \]  

The power model of the fan is similar to that of the water pump. Therefore, the power calculation formula of fan and water pump can be expressed as:

\[ P_{f} = \alpha m_{w}^{0} + \beta m_{w} \]  

\[ P_{t} = \alpha m_{w}^{0} + \beta m_{w} \]  

3 Optimization model and optimization method

The form of water side free cooling system was shown in Figure 1.

3.1 Objective functions and constraints

The optimization goal of water side free cooling is to reduce the total power consumption of the cooling water system as much as possible and meet the requirements of user side load. The expression of the objective function is:

\[ f = \min P_{sys} = \min \left( P_{f} + P_{t} \right) \]  

The equation constraint is that the heat release of the cooling tower is equal to the cooling capacity required on the user side. The expression of equality constraint is:

\[ h = n_{p} \cdot Q_{single \_tower} - \frac{Q}{P_{f} + P_{t}} = 0 \]  

The inequality constraint is the restriction of cooling limit on outlet water temperature. The expression of inequality constraint is:

\[ g = t_{wo \_lim} - \left( t_{wi} - \frac{Q}{n_{p} c_{w} m_{w}} \right) \leq 0 \]  

Using the penalty function method, the optimization model of the problem can be expressed as:

\[ \min F = \min \left[ f + \mu ( \phi h + \phi g ) \right] \]
Where $u$ is the penalty factor, representing the degree of punishment. When $f$ reaches the minimum value, the value of the objective function is also the minimum, indicating that the system energy consumption is the minimum at this time.

3.2 Improved particle swarm optimization algorithm

Particle swarm optimization algorithm has the advantages of fast convergence and high optimization efficiency. It has a good application background in the field of Heating, Ventilating and Air Conditioning (HVAC) \cite{11}. The calculation flow of PSO algorithm was shown in Figure 2.

![Fig. 2. The calculation flow of PSO algorithm.](image)

The selection of penalty factors has a great impact on the calculation results. If the penalty factor is too small, the optimization process will not fully obey the constraints. If the penalty factor is too large, the minimum point will be far away from the optimal solution of the constrained problem. The selection of feasible region will also have a similar impact on the optimization results. Therefore, this paper proposed adaptive penalty factor and feasible region, which were expressed as follows:

$$\mu = e^{10(b-1)}$$

$$h_{\text{boundary}} = Q_x \times 0.05 \times \frac{k_{\max} - k}{k_{\max}} + Q_x \times 0.005$$

4 Results and discussion

In this paper, the water side free cooling system in a small data center was used as a case to simulate and analyze the performance of the improved particle swarm optimization algorithm. The parameters of the power equipment were shown in Table 1.

|                         | Cooling water pump | Cooling tower fan |
|-------------------------|--------------------|-------------------|
| $\alpha$                | 0.00009364         | 0.00004265        |
| $\beta$                 | 0.7107             | 0.0911            |
| $m_{\text{wmin}}$       | 14.31 kg/s         | 9.912 kg/s        |
| $m_{\text{wmax}}$       | 47.70 kg/s         | 33.04 kg/s        |
| $n_{\text{pmin}}$       | 1                  | $n_{\text{min}}$  |
| $n_{\text{pmax}}$       | 3                  | $n_{\text{max}}$  |

The relationship between the improved penalty factor and the proportion of feasible solutions was shown in Figure 3. This showed that the algorithm has a greater penalty for particles in the early stage of iteration, but a smaller penalty for particles in the late stage of iteration. The improvement of adaptive penalty factor can make the optimization process take into account both optimization speed and optimization accuracy.

![Fig. 3. Caption of the Figure 1. Below the figure.](image)

In order to verify the improvement effect of penalty factor and feasible region, the optimization results of fixed penalty factor and feasible region were compared with those of adaptive penalty factor and feasible region. Considering the influence of penalty factor and feasible region comprehensively, the value of fixed penalty factor was set as fixed value 10, and the feasible region was fixed threshold $[-5~5]$. The particle swarm optimization algorithm of fixed penalty factor, adaptive penalty factor and feasible region was calculated for many times, and the distribution of total energy consumption after optimization was shown in Figure 4.

![Fig. 4. The distribution of total energy consumption after optimization.](image)

It can be seen from Figure 4 that the excellent rate obtained by the improved algorithm was increased by 36.9%. Therefore, the optimization results of adaptive
penalty factor and feasible region are better than those of fixed penalty factor and feasible region.

The optimization results of fixed penalty factor and feasible region under different outdoor wet bulb temperatures were compared with those of adaptive penalty factor and feasible region. The results were shown in Figure 5.

![Figure 5](image)

**Fig. 5.** The relationship between total energy consumption after optimization and wet bulb temperature.

The optimal energy consumption value obtained by using the adaptive penalty factor was less than the fixed penalty factor. The maximum difference between the optimized results of the fixed penalty factor and the adaptive factor was up to 40.22%. The energy-saving benefit of the method proposed in this paper becomes more significant with the increase of wet bulb temperature.

## 5 Conclusions

Based on the heat transfer model and power model of water side free cooling system, this paper establishes the mathematical model of energy-saving optimization of water side free cooling system. In order to solve this optimization problem, an improved particle swarm optimization algorithm was proposed in this paper. The simulation results show that this method can give consideration to the optimization accuracy and speed, and the improved particle swarm optimization algorithm can save up to 40.22% energy. The energy-saving performance of the optimization algorithm proposed in this paper is more significant with the increase of wet bulb temperature.

### Nomenclatures

| Symbol | Description |
|--------|-------------|
| A      | cross area (m²) |
| c      | heat capacity (kJ/(kg °C)) |
| H      | pump head (m) |
| h      | enthalpy of air (kJ/kg) |
| h_s    | saturated enthalpy of air (kJ/kg) |
| L      | water volume flow rate (m³/s) |
| m      | mass flow rate (kg/s) |
| n      | number of devices |
| P      | power (kW) |
| Q_c    | heat transmission (kW) |
| Q_e    | cooling load (kW) |
| Q_single_tower | heat transmission of single tower (kW) |
| S      | pipe network impedance (s²/m⁵) |
| t      | temperature (°C) |
| Z      | height of the fills (m) |

**Subscripts**

- a: air
- f: fan
- i: inlet of cooling tower
- o: outlet of cooling tower
- p: pump
- sys: system
- w: water
- wb: wet bulb

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