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Analysis of Influencing Factors on Water Use of Mechanical Draft Cooling Towers in China

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Abstract

Mechanical draft cooling towers are among the most critical water-consuming equipment in industries such as thermal power and petrochemicals. Strengthening their water usage performance is therefore crucial for alleviating China's water resource pressure. To this end, this study employs the makeup water rate indicator to analyze the core factors influencing water-use efficiency in mechanical draft cooling towers, utilizing Spearman's rank correlation coefficient analysis and partial least squares regression (PLSR) methods. The results reveal that ambient temperature and inlet pressure exhibit significant negative correlations with the makeup water rate, while blowdown pressure and concentration multiple show significant positive correlations. Gray correlation analysis indicates that blowdown pressure (correlation degree: 0.923) and concentration multiple (correlation degree: 0.897) are the key driving factors. The PLSR-based prediction model for the makeup water rate demonstrates a strong goodness of fit, with explanatory power exceeding 80%. This research provides a modeling foundation for optimizing the operational control of mechanical draft cooling towers, thereby promoting sustainable management of industrial water use.



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1. Introduction

Water is an indispensable natural resource for socioeconomic development [1]. The per capita water resource possession in China is only 35% of the world average, and nearly two-thirds of cities are facing water shortages to varying degrees. Water scarcity has become a bottleneck restricting the sustainable development of the economy and society [2]. In the industrial sector, cooling towers are the most important water-using equipment. Their core function is to transfer waste heat from production to environmental water areas or dissipate it into the atmosphere through water as a medium, thereby achieving a cooling effect. Among them, mechanical draft cooling towers, compared with other types of cooling towers—including air-cooled and natural draft cooling towers—have higher efficiency, making them the main technology choice in industries such as thermal power and petrochemicals [3]. The relevant water use accounts for 70% to 80% of China's total industrial water use [4]. However, due to differences in the operating conditions, environmental conditions, and design of cooling towers, as well as the lack of efficient management and

control methods, the operating efficiency of cooling towers has decreased, resulting in huge resource waste [5]. Therefore, strengthening the management of water resources used in mechanical draft cooling towers is of great significance, not only for improving industrial water use efficiency and alleviating China's water resource pressure, but also for advancing national water security strategies, supporting achievement of Sustainable Development Goal 6. Enhanced water efficiency not only directly reduces enterprises' operating costs by lowering water consumption per unit of output, thereby boosting industrial economic resilience, but also frees up valuable water resources for other sectors such as agriculture and domestic use. This, in turn, fosters a virtuous cycle where economic growth and the sustainable utilization of water resources mutually reinforce each other.

Existing research on cooling towers primarily focuses on two areas. The first is modeling studies on the performance evaluation of cooling towers. The Merkel model, proposed by Merkel in 1925, links the heat transferred from air to the boundary layer through convection with the heat transferred from the contact interface to the ambient air through evaporation [6]. This model serves as the foundation for many modern cooling tower models and analytical studies [7–9]. However, considering that this method has high computational intensity and slow solving speed [10], some scholars have used polynomial fitting to characterize cooling tower performance [11,12]. For example, Ma et al. [13] calculated the heat transfer capacity using the mass flow rate of air, the inlet water temperature of the cooling tower, and the wet-bulb temperature of the air through the least square method (with a 95% confidence level). In addition, artificial intelligence methods have also been applied to modeling studies on cooling tower capacity. Hosoz et al. [14] developed a three-layer artificial neural network model to predict the performance of counter-flow cooling towers. The model takes the temperature of cooling water entering the tower, the dry-bulb and wet-bulb temperatures of air entering the tower, the mass flow rate of cooling water, and the velocity of gas entering the tower as inputs, and can predict five variables including the temperature of water leaving the tower, the dry-bulb temperature and relative humidity of air leaving the tower. In a recent study, Bueso et al. [15] applied a Multilayer Perceptron (MLP) to estimate the evaporation water volume of desalination cooling tower systems, with as many as 12,000 sets of data used for model training.

The other area of research focuses on analyzing the factors influencing the performance of cooling towers, aiming to optimize their operation modes through external adjustment. In actual production processes, the operating conditions of cooling towers often deviate from the designed ones. Many design parameters, such as ambient temperature, air humidity, and atmospheric pressure, change in real-time, all of which can lead to variations in the operating efficiency of cooling towers [16–18]. By conducting a study on a thermal power plant using a once-through cooling tower, Handayani et al. [19] found that under the impact of climate change, the projected future increase in seawater temperature will cause a rise in the outlet water temperature of cooling towers, thereby reducing the energy efficiency of condensers. Specifically, for every 1 °C increase in cooling water temperature, the efficiency of the power plant decreases by 0.32%. In addition to environmental factors, other aspects such as filler choice [20], water quality control and treatment methods [21] also significantly affect the operating efficiency of cooling towers. Building on this, some studies have begun to focus on how to implement real-time adjustment of cooling tower operations based on changes in the external environment to improve operating efficiency and reduce energy and water consumption [22–24]. For example, Kumari Agarwal et al. [25] designed a model predictive control system that adjusts the speed of cooling tower fans and the flow rate of cooling water circulation pumps according to climatic conditions, aiming to optimize the energy-saving effect of the cooling water system. Nedjah et al. [26] developed a multi-objective particle swarm optimization algorithm and a multi-objective TRIBES

algorithm to find the optimal operating setpoints for the studied industrial cooling system. This approach achieved a 9.5% reduction in electricity consumption while only decreasing the cooling tower efficiency by 5.3%.

In general, existing studies tend to use heat transfer capacity to characterize the performance of cooling towers, with relatively few discussions from the perspective of water use. Meanwhile, they often overlook the impact of external conditions [27]. Research on the influence of external environmental factors on cooling tower capacity has mainly focused on once-through cooling towers, and there remains a lack of studies on the influencing factors specific to mechanical draft cooling towers. Furthermore, to our knowledge, the current management of makeup water for cooling water systems in enterprises is entirely experience-based. It fails to achieve precise water replenishment according to real-time makeup water demand, which consequently leads to water resource wastage. Against this backdrop, this study selects mechanical draft cooling towers as the research object and, for the first time, explores the influencing factors of water resource utilization efficiency of mechanical draft cooling towers from multiple dimensions. Its main innovations are as follows: (1) It constructs the index of makeup water rate to explore water usage of cooling towers, where multiple influencing factors including cooling tower design parameters, external environment, and fan conditions, are involved; (2) based on the identification of key influencing factors, it establishes a predictive model for the makeup water rate of mechanical draft cooling towers. This model enables rapid and accurate prediction of the system's makeup water demand, thereby providing support for the refined management of the makeup water system. This can help enterprises tap into water-saving potential and achieve the sustainable management of water resources.

2. Materials and Methods

This study was divided into two parts. The first part involved conducting a questionnaire survey to collect basic data and evaluate the water use conditions of the surveyed samples. On this basis, the second part aimed to identify the influencing factors through statistical tools, which comprised three steps. In the first step, the relationships among the factors under investigation were qualitatively assessed. In the second step, the most influential factors were identified. Finally, a predictive model was constructed to estimate the makeup water rate in the third step. The research framework is illustrated in Figure 1.

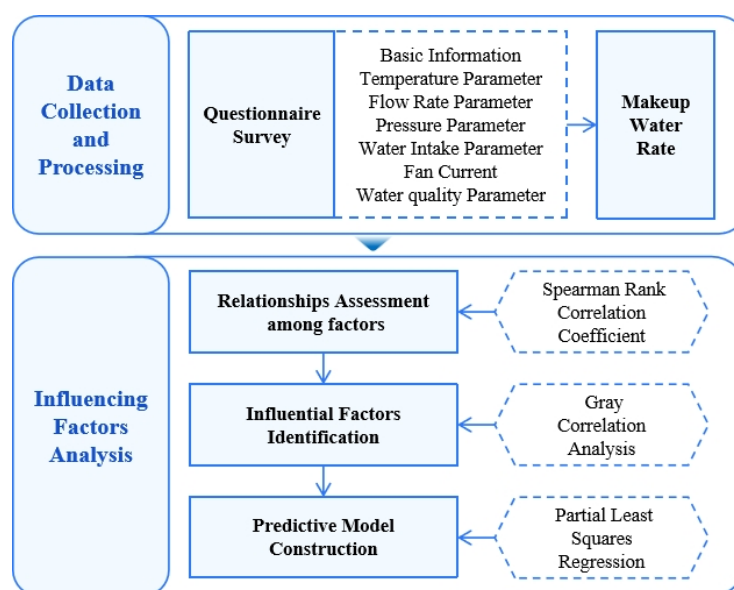


Figure 1. Research framework.

2.1. Data Collection and Processing

The data used in this paper is derived from a questionnaire-based survey. Specifically, the selection of indicators in the questionnaire is based on two aspects: on the one hand, it refers to existing literature [6,24]; on the other hand, it draws on the insights of several personnel engaged in the operation and management of enterprise cooling towers. The questionnaire mainly included geographical location, design parameters of cooling tower, temperature, flow rate, pressure, concentration multiple, and water intake and use. Then, the questionnaire was distributed to enterprises, and the person in charge of operation and maintenance of the cooling water system in each enterprise filled it out according to the actual situation. We initially collected 101 questionnaires. However, due to missing information in some of the completed questionnaires, 73 valid questionnaires were obtained after screening. The statistical analysis results of the data collected for each influencing factor are presented in Table 1. These 73 valid questionnaires were collected from different industries, covering North, Northeast, East, Central-South, Southwest, and Northwest China were collected, which can ensure broad representativeness. And the full structure and core content, as well as the key indicators of the surveyed samples are shown in Appendix A.

Table 1. Statistical Analysis Results of Various Influencing Factors of Mechanical draft Cooling Towers.

Indicator	Range	Mean Values	Standard Deviations
Makeup water rate	0.3–12.75	0.15	0.021
Ambient temperature	−24–38	20.32	13.99
Outlet water temperature	10–39	27.62	5.25
Inlet water temperature	18–43.8	34.15	5.12
Outlet water flow	406–94,000	21,064.55	19,377
Inlet water flow	406–94,000	21,926.11	19,112
Blowdown flow	40–6780	217	760
Inlet pressure	0.1–0.57	0.27	0.086
Outlet pressure	0.1–0.67	0.47	0.121
Blowdown pressure	0.1–0.36	0.28	0.043
Atmospheric pressure	85.4–102.5	99.11	3.94
Fan current	12–390	77.63	97
Concentration multiple	1.3–7.6	4.39	1.24

2.2. Calculation Method for the Indicator Characterizing Cooling Towers Water Use

Water loss in mechanical draft cooling towers originates primarily from evaporation [28], blowdown [29], and windage losses [30]. Therefore, this paper uses the makeup water rate as an indicator to represent the water use efficiency of cooling towers. This indicator directly reflects the proportion of fresh water that must be replenished due to evaporation, blowdown, and leakage in mechanical draft cooling towers, and its calculation is as follows:

$$R = \frac{V_i}{V_i + V_c} \times 100\% \quad (1)$$

where

R = makeup water rate of mechanical draft cooling tower during the statistical period (%);

V_i = makeup water volume of mechanical draft cooling tower during the statistical period (m^3);

V_c = circulating water volume of mechanical draft cooling tower during the statistical period (m^3).

A lower makeup water rate indicates less freshwater consumption under the same circulating water volume, which directly reflects the water-saving effect and operational cost of the system.

2.3. Methods for Influencing Factors Analysis

To clarify the scope of variables for correlation analysis, 12 candidate operational parameters were selected based on the survey content in Table 1, including ambient temperature, outlet water temperature, inlet water temperature, inlet pressure, outlet pressure, blowdown pressure, atmospheric pressure, inlet water flow, outlet water flow, blowdown flow, fan current, and concentration multiple. The dependent variable in the correlation analysis is the makeup water rate, calculated via Equation (1).

2.3.1. Spearman's Rank Correlation Coefficient

Spearman's rank correlation coefficient is a nonparametric form of the Pearson correlation coefficient that makes no assumptions about variable distributions and is suitable for ordinal variables or non-normally distributed data [31]. To initially identify which operational parameters are associated with the makeup water rate, Spearman's rank correlation coefficient was calculated using SPSS software (<https://www.spsspro.com/>) to identify the correlation between the makeup water rate of the mechanical draft cooling towers and various factors, serves as a preliminary screening to exclude parameters with no statistical relevance, laying a foundation for subsequent in-depth analyses such as Gray Correlation Analysis.

2.3.2. Gray Correlation Analysis

Gray correlation analysis is a method for quantitatively describing and comparing the development trends of a system. The basic idea is to determine the closeness of a relationship by assessing the geometric similarity between a reference data series and several comparative data series, reflecting the degree of correlation between the curves. As an important statistical method, the gray correlation analysis method can establish connections in complex systems with limited data [32], providing a quantitative basis for the development trends of the system and further determining the degree of impact of independent variables on the research factor. Multiple studies have applied this method to identify and analyze influencing factors [33,34]. In this study, the gray correlation analysis model was used to analyze the influencing factors of the makeup water rate through steps including the construction of reference and comparative sequences, dimensionless processing, calculation of correlation coefficients, and acquisition of gray correlation degrees. Finally, the significance of the various influencing factors was quantified by ranking their correlation degrees to study the multifactor influences on the makeup water rate of mechanically ventilated cooling towers. This subsequent analysis will quantify the relative influence intensity of these variables, avoiding over-reliance on linear correlation results and better reflecting the consistency of trends between variables in practical operating scenarios.

2.3.3. Partial Least Squares Regression (PLSR)

PLSR is a regression modeling method for multiple dependent and independent variables. It establishes models by extracting latent components from independent and dependent variable sets, which can maximize the explanation of the covariance structure between the independent and dependent variables. This method solves the problem of multicollinearity among independent variables and enables effective prediction when complex relationships exist between independent and dependent variables [35]. In this study, PLSR was used to construct a corresponding simulation prediction model, and all statistical analyses were performed using SPSS statistical software.

3. Results and Discussion

3.1. The Quantitative Correlations Among Influencing Factors

Spearman's correlation coefficient was used to analyze the correlation between the makeup water rate of the mechanical draft cooling towers and factors such as temperature, flow rate, and pressure. Spearman's correlation coefficient results are shown in Figure 2 and Table 2. Through the analysis of the circulating water system in mechanical draft cooling towers, it was observed that the makeup water rate exhibits a strong significant negative correlation with ambient temperature (-0.61 , $p < 0.01$), outlet water temperature (-0.517 , $p < 0.01$), and inlet pressure (-0.551 , $p < 0.01$), and significantly positively correlated with blowdown pressure (0.487 , $p < 0.01$) and concentration multiple (0.494 , $p < 0.01$). The negative correlation likely arises because higher ambient or outlet water temperature, as well as increased inlet pressure, could lead to the system operating at a lower load. This reduces both leakage risk and the need for blowdown, thereby lowering the demand for makeup water. A positive correlation arises because an increased blowdown pressure leads to a higher blowdown volume, requiring makeup water to maintain the water level, and a higher concentration multiple requires makeup water to dilute the salts in the circulating water for water quality control. Variables such as outlet and inlet water flow showed no significant correlation with the makeup water rate, possibly because the core drivers of makeup water are evaporation and blowdown losses, rather than merely flow magnitude.

	Makeup water rate	Ambient temperature	Water outlet temperature	Inlet water temperature	Outlet water flow	Inlet water flow	Blowdown flow	Inlet pressure	Outlet pressure	Blowdown pressure	Atmospheric pressure	Fan current	Concentration multiple
Makeup water rate	1	-0.61	-0.517	-0.434	0.156	0.156	0.112	-0.551	0.114	0.487	-0.054	0.004	0.494
Ambient temperature	-0.61	1	0.708	0.704	-0.127	-0.127	-0.213	0.439	0.017	-0.402	-0.123	0.054	-0.384
Water outlet temperature	-0.517	0.708	1	0.73	-0.173	-0.173	-0.191	0.226	-0.071	-0.246	-0.135	-0.106	-0.298
Inlet water temperature	-0.434	0.704	0.73	1	0.125	0.125	0.029	0.286	-0.11	-0.283	0.227	-0.254	-0.209
Outlet water flow	0.156	-0.127	-0.173	0.125	1	1	0.817	-0.271	0.466	0.217	0.345	-0.462	0.101
Inlet water flow	0.156	-0.127	-0.173	0.125	1	1	0.817	-0.271	0.466	0.217	0.345	-0.462	0.101
Blowdown flow	0.112	-0.213	-0.191	0.029	0.817	0.817	1	-0.233	0.32	0.081	0.178	-0.375	-0.081
Inlet pressure	-0.551	0.439	0.226	0.286	-0.271	-0.271	-0.233	1	-0.07	-0.413	0.147	0.023	-0.309
Outlet pressure	0.114	0.017	-0.071	-0.11	0.466	0.466	0.32	-0.07	1	0.464	-0.072	-0.36	0.3
Blowdown pressure	0.487	-0.402	-0.246	-0.283	0.217	0.217	0.081	-0.413	0.464	1	-0.229	-0.138	0.703
Atmospheric pressure	-0.054	-0.123	-0.135	0.227	0.345	0.345	0.178	0.147	-0.072	-0.229	1	-0.173	-0.025
Fan current	0.004	0.054	-0.106	-0.254	-0.462	-0.462	-0.375	0.023	-0.36	-0.138	-0.173	1	-0.087
Concentration multiple	0.494	-0.384	-0.298	-0.209	0.101	0.101	-0.081	-0.309	0.3	0.703	-0.025	-0.087	1

Figure 2. Heatmap of correlation coefficients for single-factor influencing factors on makeup water rate of mechanical draft cooling towers.

Table 2. Correlation coefficients for single-factor influencing factors on makeup water rate of mechanical draft cooling towers.

Indicator	Makeup Water Rate	Ambient Temperature	Outlet Water Temperature	Inlet Water Temperature	Outlet Water Flow	Inlet Water Flow	Blowdown Flow	Inlet Pressure	Outlet Pressure	Blowdown Pressure	Atmospheric Pressure	Fan Current	Concentration Multiple
Makeup water rate	1 *** (0.000)	−0.61 *** (0.000)	−0.517 *** (0.002)	−0.434 ** (0.010)	0.156 (0.378)	0.156 (0.378)	0.112 (0.528)	−0.551 (0.001 ***)	0.114 (0.520)	0.487 *** (0.003)	−0.054 (0.762)	0.004 (0.981)	0.494 *** (0.003)
Ambient temperature	−0.61 *** (0.000)	1 *** (0.000)	0.708 *** (0.000)	0.704 *** (0.000)	−0.127 (0.475)	−0.127 (0.475)	−0.213 (0.226)	0.439 *** (0.009)	0.017 (0.925)	−0.402 ** (0.018)	−0.123 (0.489)	0.054 (0.763)	−0.384 ** (0.025)
Water outlet temperature	−0.517 *** (0.002)	0.708 *** (0.000)	1 *** (0.000)	0.73 *** (0.000)	−0.173 (0.327)	−0.173 (0.327)	−0.191 (0.280)	0.226 (0.200)	−0.071 (0.689)	−0.246 (0.162)	−0.135 (0.447)	−0.106 (0.552)	−0.298 (0.087 *)
Inlet water temperature	−0.434 ** (0.010)	0.704 *** (0.000)	0.73 *** (0.000)	1 *** (0.000)	0.125 (0.482)	0.125 (0.482)	0.029 (0.872)	0.286 (0.102)	−0.11 (0.534)	−0.283 (0.105)	0.227 (0.196)	−0.254 (0.147)	−0.209 (0.235)
Outlet water flow	0.156 (0.378)	−0.127 (0.475)	−0.173 (0.327)	0.125 (0.482)	1 *** (0.000)	1 *** (0.000)	0.817 *** (0.000)	−0.271 (0.121)	0.466 *** (0.005)	0.217 (0.218)	0.345 ** (0.046)	−0.462 *** (0.006)	0.101 (0.570)
Inlet water flow	0.156 (0.378)	−0.127 (0.475)	−0.173 (0.327)	0.125 (0.482)	1 *** (0.000)	1 *** (0.000)	0.817 *** (0.000)	−0.271 (0.121)	0.466 *** (0.005)	0.217 (0.218)	0.345 ** (0.046)	−0.462 *** (0.006)	0.101 (0.570)
Blowdown flow	0.112 (0.528)	−0.213 (0.226)	−0.191 (0.280)	0.029 (0.872)	0.817 *** (0.000)	0.817 *** (0.000)	1 *** (0.000)	−0.233 (0.185)	0.32 (0.065 *)	0.081 (0.649)	0.178 (0.314)	−0.375 ** (0.029)	−0.081 (0.647)
Inlet pressure	−0.551 *** (0.001)	0.439 *** (0.009)	0.226 (0.200)	0.286 (0.102)	−0.271 (0.121)	−0.271 (0.121)	−0.233 (0.185)	1 *** (0.000)	−0.07 (0.695)	−0.413 ** (0.015)	0.147 (0.405)	0.023 (0.897)	−0.309 (0.076 *)
Outlet pressure	0.114 (0.520)	0.017 (0.925)	−0.071 (0.689)	−0.11 (0.534)	0.466 *** (0.005)	0.466 *** (0.005)	0.32 * (0.065)	−0.07 (0.695)	1 *** (0.000)	0.464 *** (0.006)	−0.072 (0.684)	−0.36 ** (0.037)	0.3 * (0.085)
Blowdown pressure	0.487 *** (0.003)	−0.402 ** (0.018)	−0.246 (0.162)	−0.283 (0.105)	0.217 (0.218)	0.217 (0.218)	0.081 (0.649)	−0.413 ** (0.015)	0.464 *** (0.006)	1 *** (0.000)	−0.229 (0.193)	−0.138 (0.436)	0.703 *** (0.000)
Atmospheric pressure	−0.054 (0.762)	−0.123 (0.489)	−0.135 (0.447)	0.227 (0.196)	0.345 ** (0.046)	0.345 ** (0.046)	0.178 (0.314)	0.147 (0.405)	−0.072 (0.684)	−0.229 (0.193)	1 *** (0.000)	−0.173 (0.328)	−0.025 (0.890)
Fan current	0.004 (0.981)	0.054 (0.763)	−0.106 (0.552)	−0.254 (0.147)	−0.462 *** (0.006)	−0.462 *** (0.006)	−0.375 ** (0.029)	0.023 (0.897)	−0.36 ** (0.037)	−0.138 (0.436)	−0.173 (0.328)	1 *** (0.000)	−0.087 (0.627)
Concentration multiple	0.494 *** (0.003)	−0.384 ** (0.025)	−0.298 * (0.087)	−0.209 (0.235)	0.101 (0.570)	0.101 (0.570)	−0.081 (0.647)	−0.309 * (0.076)	0.3 * (0.085)	0.703 *** (0.000)	−0.025 (0.890)	−0.087 (0.627)	1 *** (0.000)

Note: () is the p value, * indicates significance at 10% level, ** indicates significance at 5% level, *** indicates significance at 1% level.

3.2. The Importance of Various Influencing Factors on Water Use of Cooling Towers

To clarify the influence intensity of various operating parameters on the makeup water rate of mechanical draft cooling towers, after excluding influencing factors with no significant correlation with the makeup water rate of the mechanical draft cooling towers, this study takes the makeup water rate as the parent sequence and selects 6 core operating parameters, ambient temperature, outlet water temperature, inlet water temperature, inlet pressure, blowdown pressure, and concentration multiple as the characteristic sequences. The gray correlation analysis method is used to quantify the correlation degree between each parameter and the makeup water rate. The gray correlation analysis results (resolution coefficient $\rho = 0.5$, data normalized) are shown in Table 3. The closer the correlation coefficient is to 1, the stronger the trend consistency between the characteristic variable and the makeup water rate.

Table 3. Significance of Gray Correlation Degrees of Influencing Factors on Mechanical Draft Cooling Towers.

Evaluation Item	Correlation Degree	Rank
Blowdown Pressure	0.923	1
Concentration Multiple	0.897	2
Inlet Water Temperature	0.897	3
Outlet Water Temperature	0.896	4
Inlet Pressure	0.895	5
Ambient Temperature	0.860	6

The degrees of correlation of all evaluation items with the reference sequence were >0.85 , indicating significant correlations between all the investigated factors and the system behavior. The seven variables influencing the makeup water rate were ranked by importance as follows: blowdown pressure $>$ concentration multiple $=$ inlet water temperature $>$ outlet water temperature $>$ inlet pressure $>$ ambient temperature. The overall data exhibited a gradient distribution of correlation degrees, with a maximum difference of only 0.028 among the top five parameters, indicating a close coupling relationship between the major operational parameters, whereas environmental temperature, as the only external parameter, showed relative independence. The blowdown pressure ranks first with a correlation degree of 0.923, making it the most critical factor affecting the makeup water rate, which may be because blowdown pressure directly affects system blowdown efficiency, and increased pressure may exacerbate water loss, forcing the system to increase makeup water to maintain water balance. Ambient temperature ranks last with a correlation degree of 0.860, and its influence is weaker than that of other parameters, which only affects the makeup water rate by influencing evaporation loss, and is regulated by interfering factors such as system thermal insulation performance and external wind speed, diluting the correlation. The correlation degrees of other parameters with slight differences in their rankings, suggesting that they may share a synergistic mechanism. Among them, the concentration multiple indirectly affects the makeup water rate by adjusting the blowdown frequency, which illustrate reasonably increasing the concentration multiple could reduce blowdown, while water temperature and inlet pressure might change evaporation loss and makeup demand by affecting the heat exchange efficiency in the cooling tower.

These results reflect the operational characteristics of cooling towers and can also provide guidance for the renovation of existing cooling towers and the design of new cooling towers. In particular, for cooling towers located in areas with relatively high ambient temperatures, or in industries with relatively low concentration ratios (such as thermal power generation), and with high inlet and outlet water temperatures, are

typically correspond to relatively high water use. Therefore, for such towers, implementing measures—such as installing louver and optimizing its inclination angle [36], conducting water-saving retrofits [37]—to reduce their water usage is of great significance for the sustainable management of water resources.

In addition, these results provide a key direction for optimizing the makeup water rate control strategies, that is, monitoring and adjusting the blowdown pressure parameters should be prioritized for greater regulatory benefits than other parameters.

3.3. The Validation of the Prediction Model

To further account for the interactions among the influencing factors and improve the accuracy of the simulation prediction model, influencing factors with correlation degrees > 0.85 were selected, and PLSR was used to construct a simulation prediction model for the makeup water rate of mechanical draft cooling towers.

The PLSR model results shown in Table 4 provide quantitative insights into the magnitude and direction of each operational parameter's influence on the makeup water rate of mechanical draft cooling towers, with the model demonstrating good explanatory power, with R^2 of the model being 0.806, which indicates that the model can explain approximately 80.6% of the total variation in the makeup water rate, confirming its reliability for identifying key driving factors.

Table 4. The PLSR Model Coefficient of Makeup Water Rate.

Indicator	Makeup Water Rate
Constant term	1.919
Blowdown Pressure	3.056
Concentration Multiple	−0.026
Outlet Water Temperature	0.163
Inlet Water Temperature	−0.089
Inlet Pressure	−0.251
Ambient Temperature	−0.529
R^2	0.806

Among the explanatory variables, the constant term was 1.919, representing the baseline makeup water rate when all independent variables were zero, which reflects the inherent minimum makeup water demand of the cooling tower system, accounting for unavoidable residual losses, such as minimal drift loss from fan operation, that are not directly regulated by the monitored operational parameters. The coefficient for ambient temperature was -0.529 , indicating that a $1\text{ }^{\circ}\text{C}$ increase in environmental temperature is associated with an average 0.5% decrease in the makeup water rate, possibly due to changes in environmental element that reduce evaporation. In contrast, the positive coefficient for blowdown pressure is significantly higher than that for other variables. A 1 MPa increase in blowdown pressure is associated with an average 3.056% point rise in the makeup water rate, which is six times the magnitude of ambient temperature's influence. The results confirm that it is the key driver of the makeup water rate, and the increased pressure significantly raises the makeup water demand, likely due to water loss during blowdown.

The prediction regression equation for the makeup water rate of mechanical draft cooling towers is given by Equation (2).

$$y = 1.919 + 3.056p_2 - 0.026K + 0.163t_1 - 0.089t_2 - 0.251p_1 - 0.547t_e \quad (2)$$

where

y = makeup water rate of mechanical draft cooling tower (%);

t_1 , t_2 , and t_e = outlet, inlet water temperatures and ambient temperatures ($^{\circ}\text{C}$), respectively;
 p_1 , and p_2 = blowdown and inlet pressures (MPa), respectively;
 K = concentration multiple.

To validate the established prediction model, randomly selected samples were employed to forecast the makeup water rate of mechanical draft cooling towers. Subsequently, a comparative analysis was conducted between the predicted values and the actual observed values (see Figure 3). Results demonstrate that the predicted values and observed values exhibit a consistent variation trend, with negligible discrepancies between them. This finding indicates that the model achieves a satisfactory fitting effect, thereby verifying its reliability in predicting the makeup water rate of mechanical draft cooling towers.

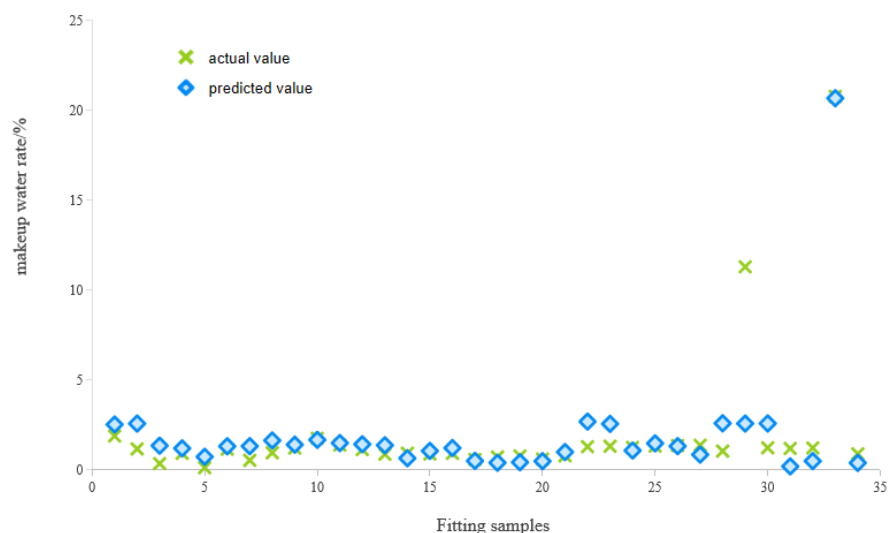


Figure 3. Comparison between predicted and observed values of makeup water rate for mechanical draft cooling towers.

This study constructed a makeup water rate prediction model using PLSR, with the blowdown pressure identified as the core influencing factor. The model demonstrated a cumulative explanatory power exceeding 80%, and the small discrepancies between the predicted and observed values provided data support for optimizing the makeup water system of mechanically ventilated cooling towers.

In practical applications, the methods of using regression or machine learning to examine the quantitative relationships between cooling tower performance and influencing factors can be integrated with the intelligent and digital transformation of cooling towers. By installing temperature sensors, pressure sensors, and other monitoring devices to conduct online detection of relevant data, the enterprises can achieve real-time dynamic calculation of makeup water. This enables precise water replenishment and reduces water waste caused by the current experience-based water replenishment management.

4. Conclusions

Given the substantial water use of mechanical draft cooling towers, improving their performance regarding water usage is crucial for China's sustainable water resource management. To this end, this paper developed the indicator of makeup water rate to analyze the core influencing factors of the water use efficiency in mechanical draft cooling towers. It revealed the importance of each influencing factor and constructed a prediction model for the makeup water rate. This study found significant differences in the correlation and impact of various factors on the makeup water rate, and the main conclusions are as follows:

1. Key influencing factors were identified through Spearman's correlation analysis, confirming that ambient temperature, outlet water temperature, and inlet pressure were significantly negatively correlated with the makeup water rate, whereas blowdown pressure and concentration multiples were significantly positively correlated. Variables such as the inlet water flow showed no significant correlation with the makeup water rate;
2. Gray correlation analysis was used to quantify the importance of the influencing factors, revealing that blowdown pressure, concentration multiple, and inlet water temperature are the core drivers of the makeup water rate, with correlation degrees of 0.923, 0.897, and 0.897, respectively, which were significantly higher than those of external parameters, such as ambient temperature. Therefore, by directly regulating blowdown volume, the blowdown pressure is the primary target for water-saving optimization;
3. The PLSR-based prediction model for the makeup water rate of mechanical draft cooling towers had a cumulative explanatory power of 80.6%, verifying the effectiveness of the multifactor synergistic effects. The consistent trend between the predicted and observed values validates the reliability of the model. Notably, the positive coefficient of blowdown pressure was significantly higher than those of the other variables, further highlighting its critical role.
4. Reducing the blowdown pressure and reasonably controlling the concentration multiple are the key strategies for lowering the makeup water rate, which can be synergistically managed using water temperature parameters.

The findings provide a basis for enhancing water usage efficiency and optimizing operational costs in mechanical draft cooling tower systems, while supporting detailed management of system parameters through intelligent monitoring and dynamic regulation. Future research could further enhance the model's generalization capability by integrating machine learning techniques and exploring the nonlinear mechanisms of multifactor interactions on makeup water rate, thus offering more comprehensive technical pathways for upgrading industrial circulating water systems and advancing water-saving retrofit technologies.

5. Limitation

Industrial cooling water systems present considerable potential for energy conservation and water saving. In this study, by identifying the influencing factors affecting water use of cooling towers and constructing a prediction model, enterprises are able to promptly grasp the demand for makeup water and strengthen the refined management of water resources. Nevertheless, there are still some limitations. First, this study does not account for differences across industries—variations in the design scale of cooling towers among different industries exert a certain impact on the divergence of makeup water rates. In future research, broader investigations can be conducted, with targeted studies focusing on specific industries such as thermal power generation and petrochemical engineering. Second, regarding research methods, this study only considers the direct water use of cooling towers. Leveraging concepts such as Life Cycle Assessment (LCA) or water footprint to incorporate indirect water use constitutes a promising direction for future studies. Furthermore, based on the water use prediction model, future research should further develop an optimization model to minimize circulating water volume, while ensuring the cooling demand of production equipment in response to changes in the external environment.

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Appendix A

Appendix A.1 Structure and Core Content of the Questionnaire

The full structure and core content of the questionnaire used in this study are as follows:

(1) Basic information

This section focuses on the fundamental attributes and operational conditions of the cooling towers, providing context for subsequent analysis of water use efficiency. Key items include:

- Enterprise details: Name, unified social credit code, address, contact person, and telephone number.
- Cooling tower specifications: Number of installed towers, number of daily operating towers, brand/model, processing capacity, and filler type.
- Metering configuration: Whether separate water and energy metering instruments are equipped.
- Operational parameters: Daily operation duration (hours/day) and annual operation days (days/year).

Temperature indicators: Ambient temperature ($^{\circ}\text{C}$), water supply temperature ($^{\circ}\text{C}$), outlet water temperature ($^{\circ}\text{C}$), and return water temperature ($^{\circ}\text{C}$).

Flow rates: Water supply flow (L/min), return water flow (L/min), and blowdown flow (L/min).

Pressure indicators: Inlet pressure (Pa), outlet pressure (Pa), blowdown pressure (Pa), and atmospheric pressure (Pa).

Other parameters: Fan current (A), concentration multiple, and windage loss rate.

(2) Water use information

This section quantifies water intake, circulation, and loss, directly supporting the calculation of the makeup water rate (Equation (1) in the main text). Key items include:

- Statistical period: Start and end dates for water use data recording.
- Makeup water volume: Broken down by water source (conventional water, reclaimed water, rainwater, purchased water, and others), with units in m^3 .
- Circulating water volume (m^3), leakage volume (m^3), reuse volume (m^3), and blow-down volume (m^3).
- Other water losses: Evaporation volume and drift loss volume (to be filled based on on-site records or calculations).

(3) Remarks

A supplementary section for additional notes, with a specific instruction: “For multiple cooling towers, basic information and water use information must be filled out separately for each tower” to ensure data accuracy for multi-tower enterprises.

Appendix A.2 Survey Implementation Notes

The questionnaire was distributed to cooling tower operation engineers and enterprise energy management personnel to ensure professional accuracy of the data.

A total of 101 questionnaires were collected, covering major geographic regions and key industries such as thermal power and petrochemicals, ensuring broad representativeness. Part of representative indicators of the survey sample are shown in Table A1.

Table A1. Representative indicators of the survey sample.

No.	Geographic Regions	Circulating Water Volume (m ³)	Makeup Water Volume (m ³)
1	Central South China	4,079,232	47,232
2	East China	17,280,000	332,400
3	East China	82,080,000	970,040
4	North China	30,908,304	318,888
5	East China	190,080,000	674,125
6	East China	176,462,873	1,536,882
7	East China	166,449,254	1,341,594
8	East China	119,935,862	889,375
9	Central South China	8000	1020
10	East China	9,760,000	91,000
11	Southwestern China	21,084,307	90,390
12	Southwestern China	126,853,760	1,102,536
13	Central South China	3,183,665	284,395
14	Northwestern China	251,813,539	2,539,461
15	Central South China	88,704,000	674,866
16	East China	7,118,496	58,599
17	East China	5,581,224	48,083
18	East China	25,200,000	298,735
19	East China	7,200,000	21,440
20	East China	13,180,240	107,701.2
21	East China	108,000,000	1,294,230
22	East China	60,480,000	707,200
23	East China	125,280,000	674,125
24	East China	82,080,000	674,125
25	East China	59,616,000	814,120
26	East China	38,880,000	489,650
27	East China	73,440,000	879,000
28	East China	34,560,000	437,200
29	East China	60,480,000	584,125
30	East China	54,780,000	674,125
31	East China	38,880,000	695,346
32	East China	34,560,000	484,841
33	East China	26,352,000	386,640
34	East China	64,080,000	734,984
35	East China	82,080,000	721,033
36	East China	111,600,000	1,048,000
37	East China	33,984,000	303,000
38	East China	98,496,000	920,160
39	East China	3,860,000	22,600
40	East China	1,560,000	11,300
41	East China	420,000	3295
42	East China	640,000	3900
43	East China	350,000	2800
44	East China	20,427,747	267,747
45	East China	20,442,847	272,847
46	East China	53,964,785	684,785.8
47	East China	34,664,473	464,473
48	East China	35,042,304	482,304
49	East China	37,238,479	518,479.2
50	East China	34,201,695	361,695

Table A1. Cont.

No.	Geographic Regions	Circulating Water Volume (m ³)	Makeup Water Volume (m ³)
51	North China	7,300,373	100,373
52	North China	11,362,211	142,211
53	North China	946,524	10,524
54	East China	8,208,000	137,930
55	North China	5,616,567	72,567
56	North China	947,880	120,650
57	North China	15,310,838	190,838
58	North China	5,834,302	74,302
59	North China	14,589,276	189,726
60	North China	16,092,000	149,760
61	East China	34,482,643	284,395
62	Central South China	141,000,612	1,463,845
63	East China	203,040,000	3,014,425
64	East China	97,200,000	1,037,940
65	East China	99,360,000	1,154,125
66	Northeastern China	45,360,000	547,842
67	East China	60,480,000	750,000
68	North China	15,312,780	193,887
69	Southwestern China	54,927,835	526,883
70	East China	70,000	815
71	East China	34,560,000	220,000
72	East China	44,640,000	405,000
73	East China	316,000,000	3,190,000

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