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Energy efficiency evaluation of cooling water system based on fuzzy comprehensive evaluation method

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Abstract. In the energy efficiency analysis of cooling water system, the fuzzy comprehensive evaluation method is used to establish the energy efficiency analysis factor system. Firstly, it divides the factors into different levels, quantifies the evaluation indexes of factor sets, establishes the weights of each factor and the membership function by using the analytic hierarchy process (AHP), and constructs a complete fuzzy evaluation system. Then through the description and calculation of a specific example, combined with fuzzy theory, the energy efficiency state of the whole cooling water system and each link is obtained. The feasibility and rationality of the application of fuzzy comprehensive evaluation method to the energy efficiency evaluation of cooling water system are explained by analysis, which provides a new way to solve the problem of energy efficiency evaluation of cooling water system.

1. Introduction

Cooling water system is common in chemical, electric, metallurgical and other enterprises, but its energy consumption is very large, and the reuse efficiency of cooling water is also low. Zhang Xueli [1] et al. put forward the water temperature comparison method to evaluate the performance of cooling tower, Zhu Jing [2] et al. used fuzzy comprehensive method to evaluate the energy efficiency of heat exchanger. However, due to the interaction of the components of the cooling water system, the energy efficiency evaluation of a single part cannot effectively explain the energy efficiency of the whole system, so this aspect needs to be studied.

In this paper, the fuzzy evaluation method is used to put forward the energy efficiency evaluation system of the whole system, and the energy efficiency index of the components of the cooling water system is evaluated from different angles. On this basis, improvement measures are proposed to improve the utilization efficiency of circulating water, save energy, and save costs for enterprises.

2. Overview of fuzzy evaluation methods

Fuzzy comprehensive evaluation method is a kind of evaluation method based on fuzzy mathematics. The core of this method is to quantify the mathematical relationship between two or more variables by using fuzzy sets and membership functions. It breaks through the absolute relationship of the traditional classical set theory [3-4], and approximates the accuracy to the fuzziness. Research or solve some vagueness. Because it is impossible to define energy consumption or energy saving



quantitatively, the energy efficiency evaluation of cooling water circulation system studied in this paper has strong fuzziness, hierarchy and correlation. Fuzzy comprehensive evaluation method can integrate complex energy efficiency indicators and make effective evaluation by using fuzzy mathematics theory [5].

3. Analysis of factors affecting cooling water system

3.1. Energy efficiency index of cooling tower

- (1) Fan efficiency
- (2) Cooling efficiency of cooling towers
- (3) Water loss of cooling tower

There are four main forms of loss in cooling tower: evaporation loss, wind blowing loss, entrainment loss and water withdrawal loss. The loss of water withdrawal is negligible.

$$q_s = q_z + q_c + q_j \quad (1)$$

3.2. Energy efficiency evaluation index of heat exchanger

- (1) Heat flux intensity of heat exchanger surface

This index combines the influence of heat transfer coefficient and temperature difference, and is a relatively comprehensive index. The cladding layer should be thicker than the upper cladding layer.

$$\Upsilon = \frac{Q}{F} = K \cdot \Delta T_m \text{ (kw/m}^2\text{)} \quad (2)$$

- (2) End temperature difference

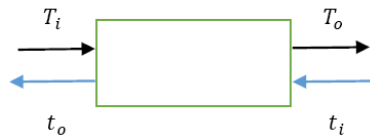


Figure 1. Heat exchange of heat exchanger.

we redefine the performance index of a heat exchanger by using two temperature differences, which is also an indicator of energy efficiency of a direct reaction heat exchanger.

$$\delta = \frac{t_o - t_i}{T_i - T_o} \times C_w \text{ (J/(kg} \times ^\circ\text{C))} \quad (3)$$

3.3. Evaluation index of water pump energy efficiency

- (1) Pump efficiency. (2) Pump head loss. (3) Pump operational efficiency.

3.4. Energy efficiency evaluation index of pipe

- (1) Pipeline surplus coefficient

There are different pressure losses in each pipeline. These pipes are longer and the pressure loss can not be ignored. Therefore, the pipeline surplus coefficient is introduced to calculate the pressure values at both ends of the pipeline.

$$\eta_{gi} = \frac{p_1 v_1 - p_2 v_2}{p_1 v_1}, \eta_g = \Sigma \eta_{gi} / \eta_g \quad (4-5)$$

- (2) Heat loss coefficient of pipeline

Heat loss is directly manifested in the internal temperature of the pipeline, and the external environment temperature also directly affects the heat loss of the pipeline. It can be calculated

according to the following formula:

$$\eta_{ri} = \frac{t_q - t_h}{t_q - t_w}, \eta_r = \Sigma \eta_{ri} / n_g \quad (6-7)$$

3.5. Energy efficiency evaluation index of valves

Surplus coefficient of valve

When the fluid flows through the valve port, pressure loss will occur due to the change of shape. Also select two nodes before and after the valve to calculate the pressure savings coefficient.

$$\eta_{fi} = \frac{p_{f1}v_{f1} - p_{f2}v_{f2}}{p_{f1}v_{f1}}, \eta_f = \Sigma \eta_{fi} / n_f \quad (8-9)$$

3.6. Notation

q_z : Evaporation loss q_c : Wind loss q_j : Entrainment loss q_t : Water withdrawal loss F: Heat exchanger surface area, m^2 t_o : Refrigerant outlet temperature t_i : Refrigerant inlet temperature T_i : Heat medium inlet temperature T_o : Heat medium outlet temperature

q_p : Second flow of pump, m^3/s H_{st} : Lift of pump, m n_g : Number of pipeline segments

4. Energy efficiency evaluation system of cooling water system

4.1. Energy efficiency evaluation factor set

First, determine the set of factors, which is a set of all factors that affect the object to be evaluated [6]. The energy consumption of cooling water system is mainly embodied in the energy consumption of cooling tower, heat exchanger, water pump, pipeline and valve. These five components have different influence weights on the cooling water circulation system, and each component includes different energy efficiency indicators. Therefore, the factors of energy efficiency evaluation are divided into different levels, and the cooling water circulation system has different influence weights. The energy efficiency evaluation index system is shown in Figure.2.

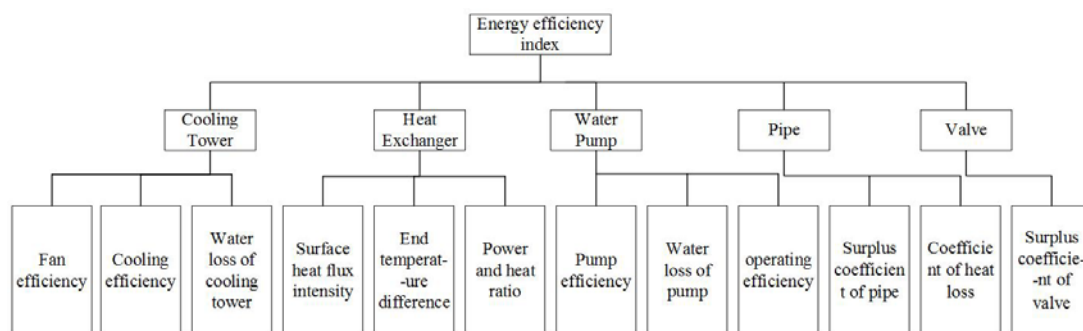


Figure 2. Energy efficiency evaluation factors.

Expressed by matrix: $U = \{U_1, U_2, U_3, U_4, U_5\}$, $U_1 = \{U_{11}, U_{12}, U_{13}, U_{14}\}$, $U_2 = \{U_{21}, U_{22}, U_{23}\}$, $U_3 = \{U_{31}, U_{32}, U_{33}\}$, $U_4 = \{U_{41}, U_{42}\}$, $U_5 = \{U_{51}\}$.

4.2. Evaluation of energy efficiency

Secondly, the energy efficiency of the cooling water system is divided into four states: poor, medium, good and excellent, and the fuzzy set for evaluating each energy efficiency index is determined. Expressed as: $V = \{V_1, V_2, V_3, V_4\}$, There are many ways to determine membership functions[7]. According to the characteristics of energy efficiency evaluation of cooling water system, the linear membership function is adopted in this paper, as shown in Figure.3.

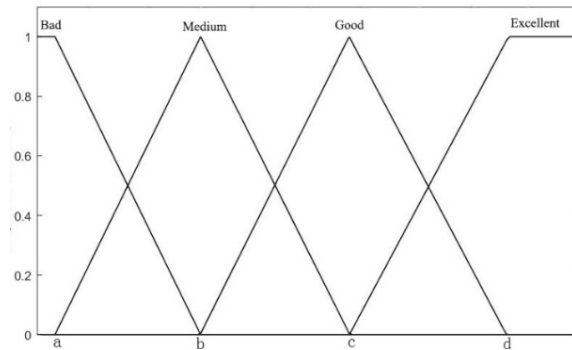


Figure 3. Membership function.

The membership functions of each fuzzy set are as follows:

(1) The membership function of "Bad" and "Excellent" of fuzzy sets is:

$$R_1(x) = \begin{cases} 1, & 0 < x \leq a \\ \frac{x-1}{a-b}, & a < x < b \\ 0, & b < x < 1 \end{cases}, R_4(x) = \begin{cases} 0, & 0 < x \leq c \\ 1 - \frac{x-d}{c-d}, & c < x < d \\ 1, & d < x < 1 \end{cases} \quad (10-11)$$

(2) The membership function of "Medium" and "Good" of fuzzy sets is:

$$R_2(x) = \begin{cases} 0, & 0 < x \leq a \\ 1 - \frac{x-b}{a-b}, & a < x < b \\ 1, & x = b \\ \frac{x-c}{b-c}, & b < x < c \\ 0, & b \leq x < 1 \end{cases}, R_3(x) = \begin{cases} 0, & 0 < x \leq b \\ 1 - \frac{x-c}{b-c}, & b < x < c \\ 1, & x = c \\ \frac{x-d}{c-d}, & c < x < d \\ 0, & d \leq x < 1 \end{cases} \quad (12-13)$$

4.3. Establishment of fuzzy evaluation matrix

After determining the energy efficiency evaluation factor set and comment set, the evaluator needs to evaluate each single factor according to the calculation of its estimated value and expert experience, and get the comment table. This paper mainly determines the comment form by calculating and searching experts. In addition, some evaluation factors are the larger the better type, and some are the smaller the better type [8]. In order to facilitate calculation, the smaller the better type of evaluation factors are taken as the opposite number, such as table.1.

The fuzzy evaluation matrix of every single factor can be obtained by calculating the data and factor sets in the table.

$$V = \begin{bmatrix} 0, 0.195, 0.805, 0 \\ 0, 0.216, 0.784, 0 \\ 0, 0.559, 0.441, 0 \\ 0, 0.427, 0.573, 0 \\ 0, 0.333, 0.667, 0 \\ 0, 0, 0.706, 0.294 \\ 0, 0, 0.803, 0.197 \\ 0, 0.716, 0.284, 0 \\ 0, 0.350, 0.650, 0 \\ 0, 0.262, 0.738, 0 \\ 0, 0, 0.353, 0.647 \\ 0, 0.838, 0.162, 0 \end{bmatrix} \quad (14)$$

Table 1. Ranking of evaluation factors.

First level index	Second level index	Comment Grade				Measured value
		Bad	Medium	Good	Excellent	
Cooling Tower	Fan efficiency	0.55	0.65	0.75	0.85	0.7305
	Cooling efficiency	0.55	0.65	0.75	0.85	0.7284
	Water loss	-50	-35	-15	-8	-26.183
	Surface heat flux	40	60	80	100	71.4680
Heat Exchanger	intensity					
	End temperature difference	0.5	0.6	0.7	0.8	0.6667
	Power and heat ratio	0.5	0.35	0.2	0.1	0.1706
Water pump	Pump efficiency	0.6	0.7	0.8	0.9	0.8197
	Water loss of pump	-80	-55	-30	-15	-47.91
	operating efficiency	0.5	0.6	0.7	0.8	0.6650
Pipe	Surplus coefficient	0.55	0.65	0.75	0.85	0.7238
	Coefficient of heat loss	0.6	0.7	0.8	0.9	0.8647
Valve	Surplus coefficient	0.6	0.7	0.8	0.9	0.7162

4.4. Comprehensive evaluation index weight vector

The weight is the status and importance of the evaluation index. For the factors that need to be evaluated, the proportion is different in the total evaluation index of each level. Therefore, it is necessary to add a proportion to each factor of each level. The sum of the weights of all the evaluation indexes of the first level is 1, and the weight is expressed as:

$$\alpha_i (i = 1, 2, 3, 4, 5), \sum_{i=1}^5 (\alpha_i) = 1$$

The sum of the weights of all the next evaluation index in the first level is 1. The weights of the factors U_{ij} are expressed as: β_{ij} ($i = 1, 2, 3, 4, 5; j = 1, 2, 3, 4$)

Among them: $\beta_{11} + \beta_{12} + \beta_{13} = 1, \beta_{21} + \beta_{22} + \beta_{23} = 1, \beta_{31} + \beta_{32} + \beta_{33} = 1, \beta_{41} + \beta_{42} = 1, \beta_{51} = 1$

The methods to determine the weights of the first-class indicators include: expert estimation, frequency statistics, coefficient of variation, correlation coefficient, angle cosine weighting, entropy method, subjective and objective comprehensive weighting, AHP, etc. In this paper, the analytic hierarchy process (AHP) [9] is used to determine the judgment matrix [10] and calculate the weight by utilizing 9 numbers of 1, 3, 5, 7, 9 and their reciprocal as the scale.

The first level of energy efficiency indicators is divided into cooling towers, heat exchangers, pumps, pipes and valves, according to their energy consumption and scale values, to determine the judgment matrix. Among them, the energy consumption of each part is shown in Table.2, and the index U_i represents the scale value of the relative importance of U_j , as shown in Table.3.

Then the judgment matrix, such as table.4, is solved, that is, the relative weight values of the elements being compared under a single objective.

Add the judgement matrix to the line: $\omega_i = \sum_{j=1}^n \frac{b_{ij}}{n}$

Get vectors: $\omega_i^T = [29, 10.2, 5.476, 6.143, 1.978]$

Table 2. Actual measured values of energy consumption.

02031.des	Actual energy consumption (KJ)
Energy consumption of water pump	27165.16
Energy consumption of cooling tower	6975.648
Energy consumption of heat exchanger	3421.10
energy consumption of pipe	3974.48
energy consumption of Valve	1754.26

Table 3. meaning of measures.

b _{ij} value	definition
1	The i factor is as important as the j factor
3	The i factor is slightly more important than the j factor
5	The i factor is significantly more important than the j factor
7	The i factor is more important than the j factor
9	The i factor is absolutely important than the j factor
reciprocal	b _{ji} = 1/b _{ij}

Table 4. judgement matrix.

A	B1	B2	B3	B4	B5
B1	1	5	7	7	9
B2	1/5	1	3	1	5
B3	1/7	1/3	1	1	3
B4	1/7	1	1	1	3
B5	1/9	1/5	1/3	1/3	1

The obtained vectors are normalized. The weight of each factor U_i is:

$$\alpha_i = \frac{\omega_i}{\sum_{i=1}^n \omega_i} \quad (i = 1, 2, 3, \dots, n)$$

Get normalization vector: $\alpha_i = [0.550, 0.193, 0.104, 0.116, 0.037]$

The consistency of the matrix is detected, and the maximum eigenvalue of the judgement matrix is obtained by MATLAB, which is 5.2029.

$$CI = \frac{\lambda_{max} - 1}{n - 1} = 0.051 < 0.1, \quad CR = CI/RI = 0.051/1.11 = 0.046 < 0.1$$

Among them, $n=5$, and RI is obtained from query random consistency table.

Therefore, the judgement matrix has satisfactory consistency. If we do not meet the requirement of consistency, we need to modify the judgement matrix. For the second level indicators, the weights are determined according to experience and calculation as follows:

$$[\beta_{11}, \beta_{12}, \beta_{13}] = [0.35, 0.4, 0.25]$$

$$[\beta_{21}, \beta_{22}, \beta_{23}] = [0.25, 0.5, 0.25]$$

$$[\beta_{31}, \beta_{32}, \beta_{33}] = [0.4, 0.3, 0.3]$$

$$[\beta_{41}, \beta_{42}] = [0.35, 0.4, 0.25]$$

$$[\beta_{51}] = [1]$$

$$\text{Then: } B = [\alpha_1 \beta_{11} \alpha_1 \beta_{12} \alpha_1 \beta_{13} \alpha_1 \beta_{14} \alpha_2 \beta_{21} \alpha_2 \beta_{22} \alpha_2 \beta_{23}$$

$$\alpha_3 \beta_{31} \alpha_3 \beta_{32} \alpha_3 \beta_{33} \alpha_4 \beta_{41} \alpha_4 \beta_{42} \alpha_5 \beta_{51}]$$

$$= [0.1925 \ 0.22 \ 0.1375 \ 0.04825 \ 0.096 \ 0.04825 \\ 0.0416 \ 0.0312 \ 0.0312 \ 0.0348 \ 0.0812 \ 0.037]$$

4.5. Fuzzy comprehensive evaluation results

The evaluation matrix is:

$$R = B \cdot V = [0, 0.2879, 0.6367, 0.0754]$$

The maximum membership degree principle was adopted in the analysis of the evaluation results. It can be concluded that the energy efficiency of the cooling water system is in a "good" state.

5. Conclusions

(1) The process of applying fuzzy comprehensive evaluation method to cooling water system is described in detail through an example, and the factors affecting the energy efficiency of cooling water system are evaluated effectively.

(2) Through the energy consumption situation of each link of the system, the low energy utilization index can be technically reformed to improve the overall energy efficiency level and save cost.

(3) Through analysis, it can be concluded that the fuzzy comprehensive evaluation method has high rationality and applicability for the energy efficiency evaluation of cooling water system.

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