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Energy Efficiency Evaluation of Industrial Heat Exchangers Based on Fuzzy Matter Element Method

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1. Introduction

As one of the important equipments in industrial production, industrial heat exchangers are widely used in all industrial applications, including food and chemical processing, oil and gas industry, power generation industrial industries and also one of the high energy-consuming equipments, which consume 13%-15% of industrial energy in industrial production [1]. Therefore, the need for energy efficient and compact heat exchangers is now clear in the market, At the same time, the energy efficient heat exchangers conforms to the national policy of energy saving and emission reduction, the actual situation of the industry and the urgent need at present.

Some scholars have researched the energy efficiency evaluation of industrial heat exchangers. Zhang Yanfeng et al [2-3] theoretically analyzed the heat transfer characteristics of heat exchangers and the non-phase-change flow of water and water, and proposed an energy efficiency index based on EEI, which reflects the inherent energy efficiency attributes of heat exchangers and provides a basis for dividing the energy efficiency level of plate heat exchangers. However, the method only considers the inherent properties of the heat exchanger itself, and lacks the control of energy efficiency throughout the whole life cycle of the heat exchanger; Zhu Jing et al [4] put forward the energy efficiency evaluation of heat exchanger based on the fuzzy comprehensive evaluation model. By establishing the energy efficiency evaluation index system and the fuzzy comprehensive evaluation model of heat exchanger, the fuzzy comprehensive evaluation of a heat pipe air preheated is carried out. However, all the energy efficiency evaluation indexes of heat exchanger established in this paper are qualitative indicators, and the evaluation results are subjective. This method is only used to evaluate the energy efficiency of heat exchanger, lacking guidance for energy-saving design and manufacture of heat exchangers; Vytautas Martinaitis et al [5] developed the application of energy analysis for assessing the performance of building mechanical systems. Using the derivative status parameter from enthalpy and entropy, the methodology for calculating the energy efficiency for HVAC equipment is proposed. This study could be useful for creating energy optimized design and developing efficient control of HVAC systems operating at variable reference temperatures; Webb [6] proposed a flow heat transfer energy efficiency evaluation method for single-phase fluid in the tube, which aims to save energy, reduce temperature difference, increase heat transfer and reduce pump power consumption to achieve heat exchanger energy saving. However, no specific energy efficiency evaluation methods and evaluation indicators are proposed for the above four purposes. I1ja Belov [7] proposed a methodology for evaluation of transient performance of, and comparison between plate heat exchanger and plate-fin-and-tube heat exchanger, Through transient behaviour of the studied heat exchangers, which should be of interest for micro-grid applications, but also for thermal management in electronic cabinets and data censers.

Based on the above literature review, the existing energy efficiency evaluation of industrial heat exchangers only evaluate one aspect of the heat exchanger and lack systematic full-life cycle-based evaluation. So this article will start from the life cycle of heat exchange, taking a tube-and-plate heat exchanger is as an example to establish an energy efficiency evaluation index system based on qualitative and quantitative. The fuzzy matter element model [7-9] is applied to the energy efficiency evaluation of tube-and-tube heat exchangers. The evaluation results understand the advantages and disadvantages of energy efficiency in the design of tube-and-tube heat exchangers, so that they can be improved purposefully; On the other hand, users can compare the comprehensive performance of different heat exchangers and select the products that suit them.

2. Industrial heat exchanger energy efficiency evaluation index system

According to the energy consumption status of industrial heat exchanger in the whole "life cycle" and the requirement of energy efficiency test of industrial heat exchanger in DB31/T628-2017 " Industrial Heat Exchanger Energy Efficiency Test and Comprehensive Evaluation Method", the paper establishes an energy efficiency evaluation index system for industrial heat exchangers from two aspects: design and manufacturing factors and operational maintenance factors. The design and manufacturing factors mainly consider whether the structure, form and material of the heat exchanger in the design of the industrial heat exchanger are new and efficient, whether the manufacturing process is carried out according to the manufacturing standards and manufacturing process documents, and the quality of the products in the manufacturing process is controlled; The running and maintenance factors mainly test the heat transfer coefficient, the heat exchange amount and the fluid power consumption ratio, the enthalpy efficiency of the industrial heat exchanger during operation, the duty ratio of the industrial heat exchanger maintenance plan, and the industrial heat in the maintenance process. The age of the exchanger, the newness factor. The established evaluation index system is shown in Table 1.

Table 1

Energy efficiency evaluation index system of industrial heat exchangers

Target layer	Factor layer	Indicator layer
Energy efficiency Evaluation of industrial heat exchangers	Design and manufacturing factors	The weight of the equipment itself is light
		Greening in equipment manufacturing and processing
	Operational maintenance factors	Heat transfer coefficient
		heat exchange capacity and fluid power consumption ratio
		enthalpy efficiency
		Maintenance duty rate
		newness factor

3. Industrial heat exchanger energy efficiency evaluation model

3.1. Determination of fuzzy matter element matrix

The fuzzy matter element combines the evaluation object *M*, the evaluation target's index *C*, and the evaluation target's index value *X* to form a unit for describing the thing $R=(M, C, X)$. If there are $m=(M_1, M_2,\ldots,M_m)$ evaluation targets, the industrial heat exchangers that require energy efficiency evaluation are the top *k*, and the latter *m-k* evaluation targets that are the number of industrial heat exchanger evaluation index grades. The meta matrix X_{ij} is represented as follows:

$$X_{ij}=\left(x_{ij}\right)_{m\times n}=\begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ C_1 & x_{11} & x_{21} & \cdots & x_{m1} \\ C_2 & x_{12} & x_{22} & \cdots & x_{m2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & x_{1n} & x_{2n} & \cdots & x_{mn} \end{bmatrix}. \quad (1)$$

3.2. Determination of fuzzy matter elements with superior membership degree

In the industrial heat exchanger energy efficiency evaluation index system, the dimension and dimension units between each energy efficiency evaluation index are often different. Before the evaluation, each energy efficiency evaluation index should be standardized, so that the absolute quantity of energy efficiency evaluation index become relative quantity, that is, the dimensionless treatment of energy efficiency index. In the evaluation of energy efficiency, the larger the index value, the better the benefit index. The smaller the index value, the better the cost index. The energy efficiency evaluation index of industrial heat exchanger belongs to the benefit index, that is, the larger the index value, the better. The dimensionless processing formula is:

$$r_{ij}=\frac{x_{ij}-min(x_{ij})}{max(x_{ij})-min(x_{ij})},(i=1,2,\cdots,m;\ j=1,2,\cdots,n). \quad (2)$$

In the formula， r_{ij} is the value after dimensionless processing;
$max\,x_{ij}=max(x_{1j},x_{2j},\cdots,x_{mj}),(j=1,2,\cdots,n)$ is the maximum index value of the j^{th} indicator;
$min\,x_{ij}=min(x_{1j},x_{2j},\cdots,x_{mj}),(j=1,2,\cdots,n)$ is the minimum index value of the j^{th} indicator. Using the above formula to process the fuzzy matter element matrix X_{ij}, we can obtain the fuzzy member matrix R_{ij} of the preferred membership as shown below:

$$R_{ij}=\left(r_{ij}\right)_{m\times n}=\begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ C_1 & r_{11} & r_{21} & \cdots & r_{m1} \\ C_2 & r_{12} & r_{22} & \cdots & r_{m2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & r_{1n} & r_{2n} & \cdots & r_{mn} \end{bmatrix}. \quad (3)$$

3.3. Determination of standard fuzzy matter element and differential power complex fuzzy matter element

The determination of the standard fuzzy matter element is generally selected by the superior membership element R_{ij}, and the maximum or minimum value (the minimum value in this paper) of each index is selected from each evaluation object, which is the value of the standard fuzzy matter element. Standard fuzzy matter element formula R_{0j}:

$$R_{0j}=\begin{bmatrix} & M_0 \\ C_1 & r_{01} \\ C_2 & r_{02} \\ \vdots & \vdots \\ C_n & r_{0n} \end{bmatrix}. \quad (4)$$

Calculating the power difference between the standard fuzzy matter element R_{0j} and each of the subordinate fuzzy matter elements R_{ij}, the difference power complex fuzzy matter element is obtained:

$$D_{ij}=\left(d_{ij}\right)_{m\times n}=\begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ C_1 & d_{11} & d_{21} & \cdots & d_{m1} \\ C_2 & d_{12} & d_{22} & \cdots & d_{m2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & d_{1n} & d_{2n} & \cdots & d_{mn} \end{bmatrix}, \quad (5)$$

where: *q* is the power of the difference between the standard fuzzy matter element and the favoured membership element, $d_{ij}=\left|r_{0j}-x_{ij}\right|^q\ (i=1,2,\cdots,m;\ j=1,2,\cdots,n)$ is the difference between the standard fuzzy matter element and the favoured member fuzzy matter element.

3.4. Determination of the weight of energy efficiency evaluation index for industrial heat exchangers

The common methods to determine the weights of evaluation indexes are analytic hierarchy process based on subjective factors [10], etc., and entropy method [11], rough set theory [12-14] etc., based on objective data to determine the weights. There are qualitative indicators and quantitative indicators in the energy efficiency evaluation index system of industrial heat exchangers, and in the evaluation process, one of the indicators exceeds the standard value, and the energy consumption of the industrial heat exchanger will change. Therefore, this paper uses the over- weighted weighting method to determine the weight of energy efficiency evaluation index of industrial heat exchangers, which can solve the above problems and achieve the unity of subjective factors and objective factors. The excess weighting method determines the weight formula as follows:

$$w_{ij} = \frac{\frac{x_{ij}}{\overline{x}_j}}{\sum_{i=1}^{m} \frac{x_{ij}}{\overline{x}_j}}, (i = 1,2,\cdots,m;\ j = 1,2,\cdots,n), \quad (6)$$

$$\overline{x}_j = \sum_{i=k+1}^{m} x_{ij}, (j = 1,2,\cdots,n), \quad (7)$$

where: w_{ij} is the weight of the j^{th} energy efficiency evaluation index of the j^{th} industrial heat exchanger, and $\overline{x}_j$ is the average value of the energy efficiency rating of the j^{th} energy efficiency evaluation index. In addition, weights generally need to satisfy both normal and non-negative, which is:

$$\sum_{j=1}^{n} w_{ij} = 1, w_{ij} > 0, (i = 1,2,\cdots,m). \quad (8)$$

3.5. Determination of progress of compound fuzzy matter element stickers

In fuzzy mathematics, the progress of the paste indicates how close the two fuzzy subsets are. In this paper, the progress of the paste indicates the degree to which the energy efficiency (evaluation sample) of the industrial heat exchanger to be evaluated is close to the corresponding energy efficiency (standard sample) in the energy efficiency standard grade of the industrial heat exchanger. The greater the progress of the post, the closer the sample to be evaluated is to the standard sample, conversely, the opposite. Calculate the paste progress formula as:

$$p_i = 1 - \left(\sum_{j=1}^{n} w_{ij} d_{ij} \right)^{\frac{1}{q}}, (i = 1,2,\cdots,m), \quad (9)$$

where: w_{ij} is the weight of the j^{th} energy efficiency evaluation index of the i^{th} industrial heat exchanger. If q=1, the progress of the post is the progress of Hamming stickers; q=2 is the progress of the European sticker.

According to formula (9), the comprehensive fuzzy matter labelling progress of each industrial heat exchanger can be obtained:

$$P_i = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ p_i & p_1 & p_2 & \cdots & p_m \end{bmatrix}. \quad (10)$$

4. Case analysis

4.1. Shell-and-tube heat exchanger energy efficiency evaluation

In a refinery processing plant, five water-water exchanged shell-and-tube heat exchangers with different designs and different materials were selected, and the energy efficiency data were obtained through on-site inspection, drawing review and historical data of five shell-and-tube heat exchangers. Among them, the source of the indicator value:

Light weight of the equipment itself and greening in the process of equipment manufacturing and processing: The above indicators are qualitative indicators, based on industrial heat exchanger design drawings, on-site manufacturing and processing records, etc., with a score of 100 points.

Heat transfer coefficient, heat exchange capacity and fluid power consumption ratio, enthalpy efficiency: On-site inspection personnel separately tested the selected five shell-and-tube heat exchangers: 1. volume flow and mass flow of cold and hot fluids; 2. The inlet and outlet temperatures of cold and hot fluids; 3. the inlet and outlet pressures and pressure differences of cold and hot fluids; 4. the ambient temperature. According to the standard DB31/T628-2017 "Industrial Heat Exchanger Energy Efficiency Test and Comprehensive Evaluation Method", the heat transfer coefficient, heat exchange amount and fluid power consumption ratio and helium efficiency are calculated.

Maintenance plan duty rate, newness factor: determined according to the field use status, service life and historical operational data related to the user of the shell and tube heat exchanger. The specific statistics are shown in-Table 2.

Table 2

Data statistics of 5 shell-and-tube heat exchangers

Number	Light weight of the device itself C1	Greening in equipment manufacturing and processing C2	Heat transfer coefficient C3, W/m2*K	Heat exchange capacity and fluid power consumption ratio C4, Δ/N	Enthalpy efficiency C5, %	Maintenance duty rate C6, %	Newness factor **C**7
1	95	95	2300	950	95	80	1
2	78	88	2100	850	85	70	1
3	85	80	1850	800	80	60	0.8
4	65	75	1650	650	75	50	0.6
5	55	55	1350	450	60	50	0.4

According to DB31/T628-2017 "Industrial Heat Exchanger Energy Efficiency Test and Comprehensive Evaluation Method", the energy efficiency evaluation index of industrial heat exchanger is divided into five levels, and the classification is shown in Table 3.

According to formula (1) and Table 2, Table 3 shows the energy efficiency evaluation matter matrix of the shell-and-tube heat exchanger:

$$X_{ij}=(x_{ij})_{10\times 7}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 & LevelI & LevelII & LevelIII & LevelIV & LevelV \\ C_1 & 95 & 78 & 85 & 65 & 55 & 95 & 90 & 80 & 70 & 60 \\ C_2 & 95 & 88 & 80 & 75 & 55 & 95 & 90 & 80 & 70 & 60 \\ C_3 & 2300 & 2100 & 1850 & 1650 & 1350 & 2380 & 2000 & 1800 & 1500 & 1300 \\ C_4 & 950 & 850 & 800 & 650 & 450 & 950 & 900 & 800 & 700 & 600 \\ C_5 & 95 & 85 & 80 & 75 & 60 & 95 & 90 & 80 & 70 & 60 \\ C_6 & 80 & 70 & 60 & 50 & 50 & 95 & 90 & 80 & 70 & 60 \\ C_7 & 1 & 1 & 0.8 & 0.6 & 0.4 & 1 & 0.8 & 0.7 & 0.6 & 0.5 \end{bmatrix}.$$

Table 3

The grade 5 shell-and-tube heat exchanger energy efficiency evaluation index

Indicator number	Level I (excellent)	Level II (better)	Level III (medium)	Level IV (poor)	Level V (very poor)
C1	95	90	80	70	60
C2	95	90	80	70	60
C3	2380	2000	1800	1500	1300
C4	950	900	800	700	600
C5	95	90	80	70	60
C6	95	90	80	70	60
C7	1	0.8	0.7	0.6	0.5

According to formulas (2) and (3), the energy efficiency of shell-and-tube heat exchangers is evaluated:

$$R_{ij}=(r_{ij})_{10\times 7}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 & LevelI & LevelII & LevelIII & LevelIV & LevelV \\ C_1 & 1 & 0.575 & 0.75 & 0.25 & 0 & 1 & 0.875 & 0.625 & 0.375 & 0.125 \\ C_2 & 1 & 0.825 & 0.625 & 0.50 & 0 & 1 & 0.875 & 0.625 & 0.375 & 0.125 \\ C_3 & 0.926 & 0.741 & 0.509 & 0.324 & 0.044 & 1 & 0.648 & 0.463 & 0.185 & 0 \\ C_4 & 1 & 0.80 & 0.70 & 0.40 & 0 & 1 & 0.90 & 0.70 & 0.50 & 0.30 \\ C_5 & 1 & 0.714 & 0.577 & 0.429 & 0 & 1 & 0.857 & 0.571 & 0.286 & 0 \\ C_6 & 0.667 & 0.444 & 0.222 & 0 & 0 & 1 & 0.889 & 0.667 & 0.444 & 0.222 \\ C_7 & 1 & 1 & 0.667 & 0.333 & 0 & 1 & 0.667 & 0.50 & 0.333 & 0.167 \end{bmatrix}.$$

From the formulas (4) and (5), the differential power compound fuzzy matter element for the energy efficiency evaluation of the shell-and-tube heat exchanger can be obtained:

$$D_{ij}=(d_{ij})_{10\times 7}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 & LevelI & LevelII & LevelIII & LevelIV & LevelV \\ C_1 & 0 & 0.425 & 0.25 & 0.75 & 1 & 0 & 0.125 & 0.375 & 0.625 & 0.875 \\ C_2 & 0 & 0.175 & 0.375 & 0.50 & 1 & 0 & 0.125 & 0.375 & 0.625 & 0.875 \\ C_3 & 0.074 & 0.259 & 0.491 & 0.676 & 0.956 & 0 & 0.352 & 0.537 & 0.815 & 1 \\ C_4 & 0 & 0.20 & 0.30 & 0.60 & 1 & 0 & 0.10 & 0.30 & 0.50 & 0.70 \\ C_5 & 0 & 0.286 & 0.423 & 0.571 & 1 & 0 & 0.143 & 0.429 & 0.714 & 1 \\ C_6 & 0.333 & 0.556 & 0.778 & 1 & 1 & 0 & 0.111 & 0.333 & 0.556 & 0.778 \\ C_7 & 0 & 0 & 0.333 & 0.667 & 1 & 0 & 0.333 & 0.50 & 0.667 & 0.833 \end{bmatrix}.$$

According to formulas (6) – (8), the weight of the energy efficiency evaluation index of shell-and-tube heat exchanger can be obtained:

$$W_{ij}=(w_{ij})_{10\times 7}=\begin{bmatrix} & M_1 & M_2 & M_3 & M_4 & M_5 & LevelI & LevelII & LevelIII & LevelIV & LevelV \\ C_1 & 0.143 & 0.130 & 0.155 & 0.140 & 0.150 & 0.139 & 0.145 & 0.145 & 0.146 & 0.147 \\ C_2 & 0.143 & 0.146 & 0.145 & 0.162 & 0.150 & 0.139 & 0.145 & 0.145 & 0.146 & 0.147 \\ C_3 & 0.147 & 0.148 & 0.142 & 0.152 & 0.157 & 0.148 & 0.138 & 0.139 & 0.133 & 0.134 \\ C_4 & 0.145 & 0.143 & 0.148 & 0.142 & 0.125 & 0.140 & 0.148 & 0.148 & 0.150 & 0.147 \\ C_5 & 0.143 & 0.143 & 0.145 & 0.162 & 0.165 & 0.139 & 0.145 & 0.145 & 0.146 & 0.147 \\ C_6 & 0.121 & 0.116 & 0.110 & 0.108 & 0.138 & 0.139 & 0.145 & 0.145 & 0.146 & 0.147 \\ C_7 & 0.158 & 0.174 & 0.153 & 0.135 & 0.114 & 0.153 & 0.135 & 0.134 & 0.132 & 0.129 \end{bmatrix}.$$

From the formulas (9) and (10), we can see that the Hamming paste progress compound fuzzy matter element:

$$P_i = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 & M_5 & LevelI & LevelII & LevelIII & LevelIV & LevelV \\ 0.949 & 0.747 & 0.595 & 0.336 & 0.081 & 1 & 0.818 & 0.594 & 0.361 & 0.137 \end{bmatrix}.$$

4.2. Analysis of energy efficiency evaluation results of shell and tube heat exchangers

According to the above calculation results, the energy efficiency of the shell-and-tube heat exchanger No. 1 reaches the level I energy efficiency rating, and the energy efficiency is optimally attributed to the following reasons:

1. Lightweight design of the tube sheet: The tube sheet is one of the main components of the shell-and-tube heat exchanger, and its weight accounts for 15% of the total weight of the equipment. The heat exchanger tube plate is designed in accordance with the latest ASMVIII-II-2015 standard, and the design result is reduced by 4% compared with the original weight. Under the premise of ensuring rigidity and strength, the weight of the tube plate is reduced, and the energy consumption is reduced.

2. Greening in the manufacturing process: By consulting the manufacturing production records and supervising the manufacturing records, the shell-and-tube heat exchanger reduces production costs, shortens the production cycle, improves product quality, and improves the level of technical production without affecting the ecological environment and meet the standards of green manufacturing. For example, in the process of tube sheet processing, the dry cutting technology is used to replace the cutting liquid; during the welding process, several exhaust fans are installed to make the gas discharged into the atmosphere cleanest.

3. Optimizing the flow path of heat transfer fluid: By controlling the deformed surface and changing the flow path of fluid in the plate cavity, low pressure drop and high heat transfer fluid flow can be realized, and the highest efficiency of rake efficiency, heat transfer coefficient, heat transfer capacity and fluid power consumption ratio can be achieved.

4. Other aspects: The tube sheet heat exchanger enhances maintenance operation management, timely decaling, cleaning and corrosion protection.

Therefore, the number 1 tube-and-tube heat exchanger should be actively promoted and applied. Compared with the tube-and-plate heat exchangers No. 2 and No. 3, the main factors affecting the energy consumption of the two are the tube-type heat exchanger newness coefficient and maintenance plan duty rate, indicating whether the tube-plate heat exchanger is maintained in time affect its energy consumption. The tube-and-tube heat exchanger No. 5 has the worst energy efficiency and is a limited-elimination product.

5. Conclusion

In this paper, the energy efficiency evaluation of industrial heat exchanger based on fuzzy matter element is studied, and the fuzzy matter element model is established. Through Case Analysis the energy efficiency optimal design of tube-and-tube heat exchanger is analyzed, and the energy consumption of each tube-and-tube heat exchanger is compared. The main factors affecting its energy consumption provide reference for the design and manufacture of heat exchangers.

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ENERGY EFFICIENCY EVALUATION OF INDUSTRIAL HEAT EXCHANGERS BASED ON FUZZY MATTER -ELEMENT METHOD

S u m m a r y

According to the energy consumption status of industrial heat exchanger in the whole life cycle, the energy efficiency evaluation index system of industrial heat exchanger is put forward firstly. Secondly, aiming at the complexity and fuzziness of energy consumption of industrial heat exchanger, the energy efficiency evaluation model of industrial heat exchanger based on fuzzy matter-element method is established by using fuzzy matter-element theory and combining the concept of Hemingway schedule. Finally, taking the shell-and-tube heat exchanger as an example, five shell-and-tube heat exchangers with different designs and materials were selected to analyze their energy consumption advantages and disadvantages. Via calculation and analysis, the optimal energy efficiency design of the shell-and-tube heat exchanger was obtained. At the same time, reference opinions were provided for the design and manufacture of the shell-and-tube heat exchanger.

Keywords: industrial heat exchanger, index system, fuzzy matter element method, energy efficiency evaluation.

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