A Review of Industrial Heat Exchange Optimization

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Abstract. Heat exchanger is an energy exchange equipment, it transfers the heat from a working medium to another working medium, which has been wildly used in petrochemical industry, HVAC refrigeration, aerospace and so many other fields. The optimal design and efficient operation of the heat exchanger and heat transfer network are of great significance to the process industry to realize energy conservation, production cost reduction and energy consumption reduction. In this paper, the optimization of heat exchanger, optimal algorithm and heat exchanger optimization with different objective functions are discussed. Then, optimization of the heat exchanger and the heat exchanger network considering different conditions are compared and analysed. Finally, all the problems discussed are summarized and foresights are proposed.

1. Introduction

The process industry, represented by raw material production, is one of the main types of modern industrial production, which faces the problems of large energy consumption, low resource utilization and high pollution discharge. Improve efficiency, reduce energy consumption as well as the emissions are the top priority of process industry, and efficient process of industrial production is the key to achieving the above objectives. That means, under the premise of meeting product quality conditions, to reduce costs and consumption, and to achieve green and efficient production. The discrete industry, which is represented by the mechanical manufacturing industry, can achieve efficient green production through intelligent manufacturing technology. Unlike the discrete industry, the process industry is a continuous process of multiphase coexistence involving multiple physical and chemical reactions. It is difficult to optimize and upgrade with intelligent manufacturing technology, optimizing the production process and technology is one of the important ways to achieve transformation and upgrading of the process industry [1].

Heat exchanger transfers the heat from one working medium to another. In order to improve production efficiency of process industry, it is necessary to efficiently produce, transfer and utilize the energy, but also needs to efficiently recover the energy, reduce the total energy consumption, which are generally completed by the heat exchanger and heat transfer network. Therefore, the optimal design and efficient operation of the heat exchanger and heat exchanger network play a very crucial role in reducing the energy consumption of the process industry. As the heat exchanger network system is mainly composed of heat exchangers, compared with other complex systems optimization, its type of equipment

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is relatively simple, the engineering is less difficult, hence the optimization of heat exchanger and its network has caught great attention from more and more scholars at home and abroad [2].

2. Optimal design of heat exchanger

2.1. Overview of heat exchanger

Heat exchanger can be classified according to its heat exchange methods and its structures. There are fixed tube plate heat exchanger, plate heat exchanger, floating head heat exchanger, and plate fin heat exchanger according to the heat exchanger structures can be divided into fixed tube plate heat exchanger, plate heat exchanger, floating head heat exchanger, plate fin heat exchanger.

Plate fin heat exchanger has the characteristics of high heat transfer efficiency, compact structure, light weight and so on. Plate fin heat exchanger between the hot and cold working fluid is generally separated by a layer of aluminum, which has high thermal conductivity, low heat transfer resistance, as well as high heat transfer efficiency. Compared with other types of heat exchangers, in the same volume case, plate fin heat exchanger heat transfer area is relatively larger, the structure is more compact, and the size is smaller.

2.2. Optimization of heat exchanger

In general, the optimization is composed of parameter variable design, objective function and constraint condition. Under the premise of satisfying the constraint condition, the maximum or minimum value of the objective function is realized by adjusting the value of the design parameter, which is the accomplishment of optimization.

The design parameters of the heat exchanger are generally composed of structural variables. The commonly used design parameters of the plate-fin heat exchanger are partition and fin spacing, core length and width, and the number of channel layers [3]. Constraints include structural dimension constraints and performance constraints, and performance constraints impose restrictions on heat transfer efficiency and pressure drop. The optimization is achieved by finding the maximum (minimum) value of the objective function. The objective function provides the purpose of optimization, so as to get the desired design parameters.

The single target optimization can be expressed as:

$$\begin{aligned} &\min f\left(\boldsymbol{x}\right) \\ &g_i\left(x\right) \geq 0, j = 1,2,...,J \\ &h_k\left(x\right) = 0, k = 1,2,...,K \end{aligned} \tag{1}$$

Where the *f(x)* is the objective function, $g_i(x)\geq 0$is the inequality constraint, while $h_k(x)=0$ is the equality constraint.

Multi-objective combination optimization can be indicated as:

$$\begin{aligned} &\min \boldsymbol{f}\left(\boldsymbol{x}\right)=\left(f_1\left(\boldsymbol{x}\right), f_2\left(\boldsymbol{x}\right),..., f_{\mathrm{m}}\left(\boldsymbol{x}\right)\right) \\ &g_i\left(x\right) \geq 0, j = 1,2,...,J \\ &h_k\left(x\right) = 0, k = 1,2,...,K \end{aligned} \tag{2}$$

Where the *f(x)* is the objective function, $g_i(x)\geq 0$ is the inequality constraint, while $h_k(x)=0$ is the equality constraint.

2.3. Overview of optimization algorithm

Through the data modeling of the heat exchanger, the optimization of the heat exchanger can be transformed into a constrained optimization problem, and then solved by a modern optimization algorithm: Genetic Algorithm (GA) [4], Particle Swarm Optimization (PSO) [5], Ant Colony Optimization (ACO) [6], Artificial Bee Colony (ABC) [7], Differential Evolution (DE) [8] and Harmony Search (HS) [9]. At present, GA is the most commonly used optimization method. The PSO also faces the same problem, such as inertia weight, social and cognitive parameters. Similarly, ABC requires the optimal control parameters for different groups of colony. Therefore, it is necessary to introduce a new optimization algorithm which does not need the relevant algorithm parameters.

In order to reduce the burden of manual adjustment, Rao [10] proposed an optimization algorithm based on teaching-learning, which enhances the learning results of students by simulating the teaching process and the learning process among the trainees. In Ref. [11], an improved TLBO algorithm is introduced to optimize the plate-fin heat exchanger and shell-tube heat exchanger in the multi-objective optimization problem of heat exchangers, where the maximization of heat exchanger efficiency and the minimization of total cost are the objective functions.

2.4. Entropy production as the objective function

In Ref.[3], the optimization model of plate fin type heat exchanger is put forward, and the entropy production is used as the evaluation index of heat exchanger performance. The higher the entropy yield, the greater the irreversible loss of the heat exchanger, the lower the energy utilization efficiency. The entropy production of plate fin heat exchanger can be expressed as

$$s'_{gen} = \frac{ds_{gen}}{dL} = \frac{q\Delta t}{t^2\left(1+\tau\right)} + \frac{G}{\rho t}\left(-\frac{dP}{dL}\right) \tag{3}$$

Where L represents the runner length, Δt represents the temperature difference, while G stands for the mass flow rate, $\tau=t/\Delta t$

For counter current plate fin heat exchangers, the sum of the entropy produced by heat transfer and resistance can be expressed as

$$s_{gen} = \left(Gc_p\right)_1 \ln\left(\frac{t''_1}{t'_1}\right) + \left(Gc_p\right)_2 \ln\left(\frac{t''_2}{t'_2}\right) - \left(GR\right)_1 \ln\left(\frac{P''_1}{P'_1}\right) - \left(GR\right)_2 \ln\left(\frac{P''_2}{P'_2}\right) \tag{4}$$

Where c_p is the constant specific heat, R is the gas constant, 1 and 2 are the heat and cold flow.

In the plate fin type heat exchanger, the heat transfer entropy production and the resistance entropy production are contradictory, and the sum of heat transfer entropy and resistance entropy production is optimized as the objective optimization function, and it can not always obtain better heat transfer efficiency. In Ref. [3], the heat transfer entropy and the resistance entropy production are used as the objective function respectively, which can be expressed as:

$$\begin{cases} S_1 = \dfrac{t'_1}{\Phi}\ln\left(1-\dfrac{W_{\min}\left(t'_1-t'_2\right)\eta}{W_1 t'_1}\right) + \dfrac{t'_1 G_2 Cp_2}{\Phi G_1 Cp_1}\ln\left(\dfrac{W_{\min}\left(t'_1-t'_2\right)\eta}{W_2 t'_2}-1\right) \\ S_2 = -\dfrac{R_1 t'_1}{Cp_1}\ln\left(1-\dfrac{\Delta P_1}{P'_1}\right) - \dfrac{G_2 R_2 t'_1}{G_1 Cp_2}\left(1-\dfrac{\Delta P_2}{P'_2}\right) \end{cases} \tag{5}$$

2.5. Weight as an optimization objective function

In the Ref. [11], the core structure parameters of the plate-fin heat exchanger are taken as the design parameters, such as the length and width of the core, the fin type, the fin distance and the fin height, which impose constraints on the lowest efficiency of the heat exchanger, the maximum pressure drop of the hot/cold side fluid and so on, while at the same time, the weight is selected as the objective function to minimize the weight of the heat exchanger.

The mathematic model of the plate-fin heat exchanger optimization with the lightest weight as the objective function is:

$$\begin{aligned} &\min f(\boldsymbol{x}) \\ &\boldsymbol{x} = \begin{bmatrix} L_1 & L_2 & L_3 & ID_h & ID_c & S_h & S_c & H_h & H_c \end{bmatrix} \\ &s.t. \begin{cases} \varepsilon \geq \varepsilon_{\min} \\ \Delta P_h \leq P_{h\max} \\ \Delta P_c \leq P_{c\max} \\ x_{i\min} \leq x_i \leq x_{i\max} \end{cases} \end{aligned} \tag{6}$$

Where L_1, L_2, L_3 are the length and width of the core structure, ID and S stand for the fin type and fin distance respectively, H is the fin height, subscript c and h represent the cold and hot fluid on both sides of the heat exchanger separator. While $\varepsilon_{\min}$ is the lower limit of efficiency, and $P_{h\max}$ and $P_{c\max}$ are the maximum allowable pressure drop for the hot and cold side fluids, respectively.

3. Optimization of Heat Exchanger Network

3.1. Overview

Over the years, many experts and scholars have carried out in-depth and detailed analysis and research on the optimization design of the heat exchange network, and have put forward the optimized design scheme of many kinds of heat exchange networks, many of them have been successfully used in industrial production and gained significant economic benefits [2] [12].

The optimization of the heat transfer network mainly includes: redistribution of the heat load of the existing heat transfer unit; when the original heat exchanger does not meet the requirements, make use of other heat exchangers or new heat transfer equipment; calculate the new heat exchanger unit area and the heat transfer area which is needed to add on the original heat exchanger; when the heat exchanger connection and other heat exchanger network structure parameters change, re-match the cost of the original equipment; when optimized heat transfer network pressure drop is beyond the allowable range, improve the original pump, compressor and other power equipment or new power equipment [13].

Heat exchanger network select heat exchanger as the basic unit, and can form different heat transfer network state through different types, quantity, connection, flow distribution combination. In order to design the optimized heat exchange network, we need to establish the mathematical model of heat exchange network. However, the structure of the heat transfer network is determined according to the actual demand (such as temperature, pressure, heat transfer), the existing technical conditions, the production environment and so on. Therefore, it is difficult to give a general model of the heat exchange network. For some heat transfer network system whose parameters have been identified, its mathematical model can be established [12].

3.2. Main measures

Heat exchanger network optimization measures include increasing the heat transfer area and adjusting the heat transfer network structure. When the temperature difference of the heat transfer network is

relatively large and the heat transfer load is low, the heat transfer area of the existing heat exchange equipment should be considered first. When the heat transfer network structure limits the heat transfer capacity, people generally to adjust the existing heat transfer connection, adjust / add the existing heat transfer equipment, etc. Compared with the increase of heat transfer area, this kind of transformation measures can greatly reduce the consumption of public works, yet the investment cost of transformation is often higher [2].

3.3. Optimization of heat transfer network under different circumstances

In the optimization of the heat exchanger, the optimized objective function and the constraint condition are determined according to the actual situation and the demand. Generally, the comprehensive control of fluid pressure drop, heat transfer efficiency and heat transfer efficiency and pressure drop are mainly considered [12].

3.1.1 Control pressure drop. Pressure drop is an important technical index in heat exchanger network optimization. Heat exchanger network optimization generally needs to re-combine existing heat transfer equipment, adjusts the heat exchanger connection between the heat distributions and to improve the heat load to meet the relevant requirements. When the heat transfer area is insufficient, the heat exchanger area can be increased by improving the existing heat exchanger, or the new heat exchanger can be added to meet the requirements of the heat transfer area. Increasing the heat transfer area and the addition of new heat transfer equipment will generally increase the fluid resistance, thereby increasing the pressure drop. When the pressure drop is too large to exceed the allowable range, it is necessary to increase the existing pump or compressor power to ensure that the fluid flow rate, flow and other technical indicators within a reasonable range, and even need to add related equipment. This may result in additional equipment acquisition costs beyond the cost of heat exchange network optimization.

3.1.2 Enhanced heat transfer. In the practical industrial production, the heat exchange network optimization often sets the total cost per unit of time as the objective function; the optimization program will adjust the heat transfer network structure, including adding heat transfer equipment, re-allocation of the existing heat transfer equipment, etc. However, although excessive adjustment of the heat transfer network can meet the theoretical requirements of the relevant optimization, the construction work is large, the adjustment complexity is high, the downtime is long, and it is limited by the layout of the original heat transfer network. The use of enhanced heat transfer technology in the same heat transfer conditions can reduce the required heat transfer area, and minimize the new heat transfer area or reduce the number of new heat transfer equipment and heat transfer capacity, thereby to effectively reduce the difficulty of heat transfer network optimization.

3.1.3 Heat transfer and pressure drop control. As mentioned above, enhanced heat transfer is an important way to optimize the heat transfer network, which can reduce the heat transfer area or increase the heat load of the heat transfer equipment, and increase the heat transfer area. Compared to increasing the heat transfer area, the cost of strengthening the heat transfer measures is relatively low, which can effectively reduce the investment cost of transformation. However, the heat transfer measures will generally cause a large pressure drop. If the pressure drop is not taken into account, the optimized heat exchange network will be different from the theoretical value. Therefore, it is necessary to control the pressure drop while strengthening the heat transfer.

4. Conclusion

Through the above analysis we can see that the current optimization of industrial heat transfer process mainly includes the optimization design of single heat exchanger and the optimization of heat transfer network.

The optimization technology of the heat exchanger has been developed more maturely and has been applied in industrial production. The design variables of the optimization problem of single heat

exchanger are simple, and the relationship between the design variables and the objective function can be obtained by mathematical modeling, which is transformed into constrained optimization problem and solved by modern optimization algorithm.

The optimization problem of heat exchange network is more complicated, and it is affected by many factors such as the number of heat exchangers, heat transfer area, connection method, fluid pressure drop and heat transfer efficiency, and all the variables interact with each other. It is a typical multi-constrained, multi-variable, multi-objective non-linear engineering optimization problem. Therefore, it is necessary to carry out in-depth research on this problem. Through scientific and reasonable modeling and optimization methods, it can improve the credibility of theoretical calculations, to better serve the actual project.

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