Structural Parameter Optimization of Helical Baffles Heat Exchanger Based on MOPSO

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Abstract. Based on improved flow and heat transfer coupling calculation model of helical baffles heat exchanger, the paper adopts multi-objective particle swarm optimization (MOPSO) to optimize its structural parameters. The shell pass nusselt number and shell pass pressure drop are selected as the objective function, and helical angle and amount of lap are selected as decision variables to obtain optimum combinations of structural parameters. This research provides references for design of helical baffles heat exchanger.

1. Introduction

The traditional shell and tube exchanger uses vertical segmental baffle, and its shell pass fluid flows in a zigzag way. The helical baffle heat exchanger changes to use continuous or discontinuous helical baffle, and its shell pass fluid is advanced helically. The ideal helical baffle should have continuous helical camber, yet due to the difficulty in processing, the current practice is to replace camber with several 1/4 sectorial flat panel to lap with each other to form approximate helicoidal surface (called discontinuous baffle). The helical baffle has greatly improved the performance of heat exchanger compared with segmental baffle. Wherein the structural parameters of helical angle and lapping degree are two key factors influencing shell pass fluid flow and heat transfer characteristics of helical baffles heat exchanger, and domestic and foreign scholars have also delved into the influence of the two structural parameters on shell pass fluid flow and heat transfer property of helical baffle heat exchanger [1]. Wang Q W, et al. made an experimental study on the flow and heat transfer property on shell side of staggered-lapped helical baffles heat exchanger, and were focused on the influence of different helical angles on heat transfer and resistance of shell pass, also compared it with the traditional segmental baffle heat exchanger. The result showed that with shell side flow being the same, the shell pass resistance and shell side heat transfer coefficient of helical baffles heat exchanger all decrease with increase of helical angle, and are smaller than corresponding values of segmental baffle heat exchanger in the same condition [2]. Zhang J F, et al. made an experimental study and analysis on the flow and heat exchange characteristics of helical baffles heat exchanger, finding that the shell side heat transfer coefficient of helical baffle heat exchanger is maximized when helical angle is 40° [3]. Cao Xing, et al. made numerical simulation on helical baffles heat exchanger, finding that with increase of amount of lap, the shell side heat transfer coefficient and pressure drop all increase when the flow is the same, while the heat transfer coefficient is lowered when the pressure drop is the same, and the larger the amount of lap is, the stronger the radial nonuniformity of heat exchange amount on surface of heat exchange tube is...
Based on response surface design and multi-objective genetic algorithm, Wang S optimized the helical angle and lap degree of helical baffle heat exchanger and derived three optimized structures [5]. The actual design process of helical baffle heat exchanger needs to weigh multiple objectives such as heat transfer property and pressure drop, etc., while existing commercial software such as HTRI is all single-objective optimization. These objectives tend to be not very coordinated or even mutually contradictory. The methods of solving multi-objective optimization mainly include linear weighting method, stratified sequencing method and analytic hierarchy process. With significant raising of data processing velocity of computer, recent years have witnessed successful application of evolution algorithm as a heuristic search algorithm to the domain of multi-objective optimization, and it has developed into a relatively hot research direction—evolutionary multi-objective optimization (EMO). Particle swarm optimization (PSO) algorithm is an intelligent swarm optimization algorithm suggested by Kennedy and Ebehtar’t in 1995. It regards each individual in the swarm as a particle without volume or mass in search space. In search space, these particles fly at certain speeds which are dynamically adjusted according to individuals’ flying experience and the whole swarm's flying experience. PSO is featured with the advantages of simple flow which is easy to be realized, concise algorithm parameters, and no need for complicated adjustment, which have made it rapidly applied to some original application domains of genetic algorithm since being suggested. The evolutionary multi-objective algorithm based on PSO is also a research hot spot in recent years. Coello et al. proposed the multi-objective particle swarm optimization (MOPSO) based on crowding distance and B-dominating mechanism [6], which introduces external swarm of adaptive mesh mechanism to not only mutate the swarm particles, but also to mutate span of particle, and the mutation scale is proportional to generation number of swarm evolution. The paper takes shell pass nusselt number and shell pass pressure drop as constraints to optimize helical angle and amount of lap of helical baffle heat exchanger, and uses MOPSO to calculate two mutually contradictory objective functions—nusselt number and pressure drop, lastly searches large solution domain for the optimal design result span to constitute pareto front.

2. Selection of mathematical model
For lapped helical baffles heat exchanger, the helical angle $\beta$ is the included angle between normal of baffle and shell axis, as shown in Fig.1. For staggered lapping, the ratio of the distance from lap point to shell to side length is called lap degree $e$, i.e. $e=l/L\times100\%$.

![Figure 1. The structural representation of helical baffles heat exchanger](image)

At present, the calculation of shell-path design of spiral baffles heat exchanger is carried out by experiment and simulation to obtain its semi-empirical formula. Tinker proposed five groups of flow path of shell and tube exchanger. Based on Tinker model, Xiao X M [7] proposed the coupling
calculation model of flow and heat transfer with means of flow path weighting and local flow pattern weighting based on flow field:

Flow path A—leakage flow path between baffle tube pore and tube
Flow path B—Main flow path of helical flow
Flow path C—leakage flow path between periphery of tube bundle and inner wall of shell
Flow path E—leakage flow path between baffle pore and inner wall of shell
Flow path F—leakage flow path for center of heat exchanger shell pass

2.1. Thermodynamic model

Correlation of Nusselt number with different Reynolds numbers:

\[
Nu = 0.0797\theta_{loc}^{0.4141}Re_{chl}^{(3\times10^{-5}\theta_{loc}+0.4964)^{1/3}}, \quad 100 < Re_{chl} < 1900
\]

\[
Nu = (7.0 \times 10^{-6}\theta_{loc}^{3} - 0.0004\theta_{loc}^{2} + 0.0103\theta_{loc} + 0.0416) \times Re_{chl}^{(-3.9\times10^{-6}\theta_{loc}+0.0002\theta_{loc}2-0.0058\theta_{loc}+0.7016)} P_{r^{-1/3}} \quad 1900 < Re_{chl} < 2 \times 10^{5}
\]

The correlation for flow path proportion with different Reynolds numbers \( \gamma_i = f(\beta, Re) \) is as follows:

\[
\gamma_A = (0.0007\beta^{2} - 0.0098\beta + 0.0188) \times Re^{0.0005\beta^{2}-0.0431\beta+0.0488}
\]

\[
\gamma_B = (0.0055\beta^{2} - 0.2095\beta + 81.0591) \times Re^{-2.7\times10^{-5}\beta^{2}+0.0018\beta-0.0308}
\]

\[
\gamma_E = (0.0026\beta^{2} - 0.2707\beta + 26.3673) \times Re^{-6.0\times10^{-6}\beta^{3}+0.0004\beta^{2}-0.0085\beta+0.0051}
\]

\[
\gamma_F = (0.0351\beta^{2} - 2.4251\beta + 49.7912) \times Re^{4.5\times10^{-5}\beta^{2}-0.0014\beta-0.0492}
\]

The application scope of above formula is \( 5^\circ < \beta < 50^\circ, 3000 < Re < 20000 \);

Total nusselt number of shell pass:

\[
Nu_{total} = \gamma_A Nu_A + \gamma_B Nu_B + \gamma_F Nu_F
\]

Wherein, the calculation of heat transfer does not involve E flow path as it does not contact the heat exchange tube.

2.2. Hydraulic model

The coefficient of local resistance of each flow path is calculated according to table 1. The pressure drop for each flow path is obtained by summing according to equation (11) and (12), lastly the total pressure drop of shell pass is obtained via different weights of \( \gamma_i \).

\[
\Delta P_{total} = \gamma_A (\Delta P_r + \Delta P_j)_A + \gamma_B (\Delta P_r + \Delta P_j)_B + \gamma_E (\Delta P_r + \Delta P_j)_E + \gamma_F (\Delta P_r + \Delta P_j)_F
\]

\[
\Delta P = \Delta P_r + \Delta P_j
\]

\[
\Delta P_j = \kappa \frac{L_{chl}}{d_{chl}} \frac{u_{chl}^2}{2}
\]

Where \( \kappa \) —— coefficient of friction resistance;

\( L_{chl} \) —— length of flow passage, m;

\( d_{chl} \) —— character scale of passage, m;

\( u_{chl} \) —— average flow velocity of fluid in flow passage, m/s.

\[
\Delta P_{j} = \sum \xi \rho \frac{u_{chl}^2}{2}
\]

Where \( \xi \) —— Coefficient of local resistance.
The coupling calculation model of flow and heat transfer is established via numerical simulation to obtain the value of \( \zeta \) when monotube is swept over at different incidence included angles under different \( \text{Res} \):

### Table 1. \( \zeta \) value of monotube with different \( \text{Res} \)

| \( \theta_{\text{loc}} \) | 5\(^{\circ}\) | 15\(^{\circ}\) | 25\(^{\circ}\) | 35\(^{\circ}\) | 45\(^{\circ}\) | 55\(^{\circ}\) | 65\(^{\circ}\) | 75\(^{\circ}\) | 85\(^{\circ}\) | 90\(^{\circ}\) |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1900          | 1.2178 | 1.3530 | 1.4202 | 1.4659 | 1.5018 | 1.5311 | 1.5553 | 1.5772 | 1.5961 | 1.6043 |
| 3800          | 0.6126 | 0.6711 | 0.7012 | 0.7209 | 0.7357 | 0.7483 | 0.7592 | 0.7676 | 0.7758 | 0.7804 |
| 9500          | 0.2210 | 0.2381 | 0.2473 | 0.2526 | 0.2570 | 0.2608 | 0.2640 | 0.2670 | 0.2689 | 0.2703 |
| \( \text{Re}_{\text{chl}} \) | 19000  | 0.1008 | 0.1102 | 0.1139 | 0.1170 | 0.1207 | 0.1217 | 0.1237 | 0.1252 | 0.1249 |
| 38000         | 0.0487 | 0.0599 | 0.0647 | 0.0688 | 0.0717 | 0.0736 | 0.0763 | 0.0777 | 0.0799 | 0.0809 |
| 95000         | 0.0354 | 0.0413 | 0.0440 | 0.0459 | 0.0480 | 0.0501 | 0.0508 | 0.0519 | 0.0531 | 0.0529 |
| 190000        | 0.0167 | 0.0253 | 0.0293 | 0.0333 | 0.0362 | 0.0383 | 0.0412 | 0.0429 | 0.0439 | 0.0447 |

Multi-element nonlinear regression is made via 1stOpt to derive that:

\[
\zeta = \frac{p_1 + p_2x + p_3x^2 + p_4y^2 + p_5y^2}{1 + p_6x + p_7x^2 + p_8y + p_9y^2}
\]  
(12)

Where \( x = \theta_{\text{loc}}, \text{rad}; y = \text{Re}_{\text{chl}}; p_1=-1.9977, p_2=2.6088, p_3=-0.9291, p_4=0.0014, p_5=1.8351 \times 10^{-8}, p_6=1.4965, p_7=-0.5735, p_8=-0.0017, p_9=7.8564 \times 10^{-7}.\)

### 2.3. Relevant parameters

- **Prandtl number of shell pass fluid:** \( P_r = \frac{c_p \mu}{\lambda} \)  
(13)
- **Reynolds number of shell pass fluid:** \( \text{Re} = \frac{d_e G}{\mu} \)  
(14)
- **Mass velocity of shell pass fluid:** \( G = \frac{W}{S} \)  
(15)
- **Equivalent diameter of shell pass:** \( d_e = \frac{4(p_1 \frac{\pi}{4} d_0^2)}{\pi d_0} \)  
(16)
- **Flow area of shell pass:** \( S = \frac{1}{2} B_0 (1 + \frac{d_0}{l}) \)  
(17)

Where \( \theta \) is helical angle, \( e \) is amount of lap, \( W \) is mass flow rate of shell pass fluid in unit of kg/s, and \( n \) is baffles number for one pitch. The new cold drawn seamless steel tube with square arrangement is used in the heat exchanger.

The flow parameters and process parameters set in this calculation example are as shown in table 2. The selection of process parameters conforms to GB/T 151-2014.

### Table 2. Design parameters of shell pass fluid

| Parameter | Water (shell pass) |
|-----------|-------------------|
| Inlet temperature \( t_1 \)\(^{\circ}\)C | 54.1 |
Outlet temperature $t_2/\degree C$ 40.5
Thermal conductivity /W·m$^{-1}$·K$^{-1}$ 0.648
Specific heat at constant pressure c/J·kg$^{-1}$·K$^{-1}$ 676
Kinetic viscosity $\mu$/W·m$^{-1}$·K$^{-1}$ 5.542×10$^{-4}$
Density $\rho$/kg·m$^{-3}$ 988.3
Tube pitch $P_t$/mm 25
Pipe diameter $d_0$/mm 19
Internal diameter of shell $\phi$/mm 250
Pipe length/m 2
Flow rate/m$^3$·h$^{-1}$ $b$

baffles number for one pitch 4

3. Multi-objective optimization
Each particle in the swarm has three properties of position, velocity and fitness. The position information contains the feasible value of to-be-optimized parameter, the velocity information characterizes the change trend of particle position, the fitness characterizes the superiority or inferiority of particle at different positions. The core of particle swarm optimization is optimization and updating of velocity and position, the updating process is iterative to simulate predatory process of biotic population. The formula can be expressed as:

$$v_{i+1} = w \times v_i + c_1 \times r_1 \times (p_{best_i} - p_i) + c_2 \times r_2 \times (g_{best} - p_i)$$  \hspace{1cm} (18)

$$p_{i+1} = p_i + v_{i+1}$$  \hspace{1cm} (19)

Where: $w$ is inertia weight which influences the flying inertia of particles; $c_1$ and $c_2$ are acceleration constants and respectively influence the magnitude of local and global acceleration; $r_1$ and $r_2$ are random numbers between 0-1, which produce fusion effect of local acceleration and global acceleration; $p_{best_i}$ is position information of local optimal fitness, being the optimal position of single particle in history; $p_i$ is the position information of current particle; $g_{best}$ is the position information of global optimal fitness, being the optimal position in current particle swarm. The position of iterated particle can be obtained after the flying velocity $v_{i+1}$ of particle is solved.

Coelle et al. proposed multi-objective particle swarm optimization (MOPSO), which is popularization of particle swarm optimization to solve the problem of parameter optimization in the condition of multiple objective functions. In the multi-objective particle swarm, the fitness ceases to be single value, but is array containing multiple objective function values, which leads to inability to clearly define the superiority or inferiority of different particles. For global optimal particles, MOPSO adopts grid method to define the global leader of multiple non-inferior particles to lead the flying direction of particle swarm. The grid method divides the span of objective function value into uniform grids and determines the leader according to the density of particles in single grid. The more the particles in grid are, the smaller the probability of particles being selected is. Thus, in the sparse grid, the particles are more probable to be selected. For the local optimal particles, a random particle is selected as the local optima when there exist multiple non-inferior particles [8].

3.1. Define objective function, decision variable and constraints condition
Mathematical description of multi-objective optimization can be expressed as follows:

Max $y=f(x)=[f_1(x), f_2(x), \ldots, f_m(x)]$  \hspace{1cm} (20)

s.t. $g_i(x)\leq 0, i=1,2,\ldots,N$  \hspace{1cm} (21)

$h_j(x)=0, j=1,2,\ldots,k$  \hspace{1cm} (22)

Where, $y$ is objective function; $x$ is design variable; $g_i(x), h_j(x)$ are inequality constraints and equality constraints; $M$, $N$ and $k$ are number of state variable.
The objective functions herein are Max Nu, Min ΔP, decision variable is β and e, the constraints of decision variable are determined as follows according to GB151 – 2014: 5° ≤ β ≤ 50°, 0 ≤ e ≤ 1.

3.2. Optimization via Matlab
The Matlab is run to edit code for MOPSO operation. Set the learning factor c1 = c2 = 1.4995, set iteration times as 100, swarm quantity as 100, the proportion of swarm quantity of nondominated solutions as 70%, initial weight as 0.5, weight decay factor as 0.99, expansion factor for nondominated solution set as 0.1, selectivity factor of nondominated solution as 2, elimination factor of nondominated solution as 2.

4. Result and Discussion
The pareto front chart as shown in Fig.2 is obtained via calculation. These solution sets constitute a change curve of shell pass nusselt number and shell pass pressure drop. The pareto optimum solution set of this algorithm covers a wide range and has uniform distribution, being very close to the optimal front, which speak volumes for high applicability of MOPSO to structural optimization of helical baffles heat exchanger. some sets of results is selected from the Pareto optimal frontier, which is listed in Table 3.

![Figure 2: Pareto front chart of MOPSO](image)

| θ/°   | e   | Nu       | Δp/pa    |
|-------|-----|----------|----------|
| 40.1363 | 0.2221 | 23.3648 | 136.3023 |
| 40.4773 | 0.1133 | 22.4379 | 101.0693 |
| 40.3323 | 0.426  | 27.0067 | 238.6152 |

original structure: 18°, 0.1

| θ/°   | e   | Nu      | Δp/pa    |
|-------|-----|---------|----------|
| 18    | 0.1 | 4.2554  | 3.6923×10³ |

Compared with the original structure with a spiral angle of 18° and a lap of 0.1, the optimized structure makes the heat transfer coefficient of the shell side of the spiral baffle heat exchanger significantly increase and the pressure drop of the shell side decreases obviously.
5. Conclusion
Based on the coupled calculation model of flow and heat transfer in a helical baffles heat exchanger, the MOPSO algorithm is used to optimize the structure parameters of the helical baffles heat exchanger, and the Pareto optimal solution set is obtained, in which the heat transfer performance is greatly improved and the pressure drop is significantly reduced. The results show that the MOPSO algorithm has high applicability in the optimal design of the helical baffles heat exchanger.

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