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Heat Exchanger Network Synthesis Considering the Equipment Size of Heat Transfer Enhancement

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The size of heat transfer enhancement equipment has an important effect on the efficiency of heat exchangers and Heat exchanger network (HEN) structure. A novel mixed integer nonlinear programming (MINLP) model of HEN synthesis considering the types and size of enhancement equipment is proposed, solved by hybrid genetic algorithm/simulated annealing algorithm (GA/SA). In this model, the type and size of the enhancement equipment are set as the integers and continuous variables, respectively, and the enhanced equipment costs and operating costs associated with pressure drop are added in the total annual cost (TAC). The MINLP mathematical model of simultaneous synthesis is established by the combining of heat transfer coefficient and pressure drop models of heat exchangers for enhancement equipment and the HEN synthesis model based on the stage-wise superstructure. The new method has distinctive advantages over existing design methods, as the new MINLP model can effectively achieve simultaneous optimization of the types and size of enhancement equipment and HEN. Finally, the feasibility and effectiveness of the proposed model are proved through concrete case analysis.

1. Introduction

In recent years, implementation of enhanced heat transfer technologies can greatly improve heat transfer coefficient of heat exchangers, thereby optimizing the HEN to maximize the use of heat energy and heat recovery (Liu et al., 2016). The main enhanced heat transfer equipment is divided into tube side enhanced heat transfer equipment, such as internal finned tube (Wang et al., 2001), tube twisted-tape (Bhuiya et al., 2013), tube coiled-wire (San et al., 2015), etc., and shell-side heat transfer enhancement technology, such as external finned tube, shell-side helical baffles, etc. And changes in heat transfer enhancement equipment size also affect heat transfer performance and fluid flow properties (Lim et al., 2017).
The heat transfer enhancement technologies have a practical advantage in the retrofit and design of HEN, because it can avoid the structural retrofit of the heat exchanger itself, and has the potential to save energy and reduce investment (Shekarian et al., 2016). The implementations of enhanced heat transfer technologies are relatively simple, which can be easily completed in the normal maintenance period, reducing production losses and the corresponding civil engineering (Pan et al., 2014). Wang et al. (2012) used heat transfer enhancement technology to improve heat transfer without structural modification in the HEN, with pinch method screening suitable heat exchanger to strengthen, and proposed four heuristic rules to eliminate the bottleneck of HEN retrofit. Pan et al. (2012) proposed a simple MILP model to solve the problem of network retrofit considering the heat transfer enhancement technologies, and two step iteration solving strategy and optimization steps were put forward to achieve the maximized profits. Odejobi et al. (2015) considered the heat transfer enhancement technologies in the HEN design to save energy and reduce investment. Based on the stage-wise superstructure, a MINLP model considering the heat transfer enhancement technology of HEN synthesis was established. However, this design method ignores the influence of the pressure drop.
The use of heat transfer enhancement technologies can reduce the difficulty in topology retrofit, and increase the heat transfer coefficient of HEN, but the adverse effects increase on shell side resistance and fouling (Pan et al., 2016). Professor Robin Smith’s research group at the University of Manchester, aimed at the HEN retrofit

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considering the heat transfer enhancement technologies (Jiang et al., 2014), and carries out comprehensive research on HEN after heat transfer enhancement, heat transfer coefficient changes, pressure drop increase and scaling changes (Akpomiemie and Smith, 2017). However, the heat transfer enhancement equipment size was set to be fixed value in the existing research, to simplify the model, reduce the calculation difficulty in the HEN synthesis.
In this study, a MINLP model was established with the changes of types and size on heat transfer enhancement equipment, considering the changes of pressure drop and heat transfer coefficient caused by heat transfer enhancement and the lowest TAC of the HEN was achieved by using hybrid GA / SA algorithm, thereby the corresponding optimal type and size of heat transfer enhancement equipment are obtained.

2. Model formulation

2.1 Problem statement

It is assumed that shell-and-tube heat exchangers are only used in this study. The heat-transfer coefficient and pressure drop of each individual heat exchanger in the network are calculated and added in TAC. The aim with the optimization approach is to determine the type and size of heat transfer enhancement equipment in which the minimum total annual cost is achieved.
To derive the proposed approach for optimization process, it is assumed that the following information is given: inlet and outlet temperatures of streams, physical properties (i.e., viscosity, density, thermal conductivity, specific heat capacity, etc.) of streams. And then the tube-side geometry of heat exchangers (i.e., tube length, tube inner diameter, tube layout angle, tube pitch, number of tube passes, etc.), and shell-side geometry (i.e., shell inner diameter, shell-bundle diametric clearance, etc.) of heat exchangers are known.

2.2 Objective function

The objective function of the expanded optimization model is that the TAC of the HEN, and the TAC includes the utility costs ($C_{utility}$), heat exchanger equipment costs (C_{area}), extra power consumption cost caused by pressure drop and power equipment costs (C_{pump}) and enhanced equipment costs (C_E):

$$
\begin{aligned}
&M\text{in}\cos t = C_{utility} + C_{area} + C_{pump} + C_E \\
&= \sum_i c_{cu}\cdot q_{cui} + \sum_j c_{hu}\cdot q_{huj} + \sum_i\sum_j\sum_k z_{ijk}(a + bA_{ijk}^c) + \sum_i z_{cui}(a + bA_{cui}^c) + \sum_j z_{huj}(a + bA_{huj}^c) + \sum_{j=1}\sum_{k=1}\alpha\frac{m_{j,k}}{\rho_{j,k}}\Delta P_{j,k} \\
&+ \sum_{i=1}\sum_{k=1}\alpha\cdot\frac{m_{i,k}}{\rho_{i,k}}\cdot\Delta P_{i,k} + \sum_i\sum_j\sum_k\sum_{t_E} Bt_E\left(\frac{q_{ijk}}{U_{ij}LMTD_{ij}}\right)^{EP} + \sum_i\sum_j\sum_k\sum_{s_E} Bs_E Bt_E\left(\frac{q_{ijk}}{U_{ij}LMTD_{ij}}\right)^{EP} + \sum_i\sum_j\sum_k a_E z_{ijk}
\end{aligned}
\tag{1}
$$

2.3 Heat transfer calculation

The overall heat transfer coefficient U of the shell and tube heat exchanger is calculated according to the heat transfer coefficient of tube side h_t and the heat transfer coefficient of the shell side h_s, and taking the fouling resistance into account.

$$
U = \left[\frac{D_0}{h_t D_t} + \frac{D_0 \ln(D_0/D_t)}{2\kappa_t} + \frac{1}{h_s} + \frac{R_{in}D_0}{D_t} + R_{D0}\right]^{-1} \tag{2}
$$

The heat transfer coefficient of the tube side h_t and the heat transfer coefficient of the shell side h_s change due to the differences of heat transfer enhancement equipment type, as shown in Eqs (3)-(8).
(1) Heat transfer coefficient of the tube side h_t.
Without heat transfer enhancement equipment in shell and tube heat exchangers, tube side heat transfer coefficient formulation was defined as

$$
h_t = \left(\frac{k_t}{D_t}\right)\cdot Nu_t \tag{3}
$$

The Nusselt number (Nu) is a key parameter affecting the heat transfer coefficient, so when calculating the heat transfer coefficient of the heat exchanger considering the enhanced heat transfer device, only the Nu in heat transfer coefficient calculation formula of the heat exchanger without the enhanced heat transfer device is needed to corrected. With heat transfer enhancement using in tube side, the calculation of h_t only needs to correct Nu_t.

When inserting internal tube fins in the tube side, it's necessary to correct Nu_t (Jensen and Vlakancic, 1999)

$$\frac{Nu_{t,f}}{Nu_t} = (\frac{l_{csw}}{D_t})^{-1/2} (\frac{0.25\pi D_t^2}{0.25\pi D_t^2 - N_f e\delta})^{0.8} f(geometry) \tag{4}$$

When inserting twisted-tape in the tube side, it's necessary to correct Nu_t (Manglik and Bergles, 1993)

$$Nu_{t,T} = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \left(\frac{\pi}{\pi - 4\delta/D_t} \right)^{0.8} \left(\frac{\pi + 2 - 2\delta/D_t}{\pi - 4\delta/D_t} \right)^{0.2} \left(1 + \frac{0.769}{y} \right) \varphi, \ \mathrm{Re}_t \geq 10^4 \tag{5}$$

When inserting coiled-wire in the tube side, it's necessary to correct Nu_t (Garcia et al., 2005)

$$Nu_{t,c} = 0.132 \left(p/D_t \right)^{-0.372} \mathrm{Re}^{0.72} \mathrm{Pr}^{0.37}, \ 1000 \leq \mathrm{Re}_t \leq 8 \times 10^4 \tag{6}$$

(2) Heat transfer coefficient of the shell side h_s
When using external tube fins in shell-side, h_s is corrected by (Serth and Lestina, 2014)

$$h_{s,f} = jH \mathrm{Pr}^{1/3} \left(\kappa_s / D_{es} \right) \tag{7}$$

When using helical baffles in shell-side, h_s is corrected by (Zhang et al., 2009)

$$h_{s,hb} = \left(\kappa_s / D_0 \right) Nu_s \tag{8}$$

2.4 Pressure drop calculation

The friction coefficient (f) is a key parameter affecting the pressure drop, so when calculating the pressure drop of the heat exchanger considering the enhanced heat transfer device, only the parameter f in pressure drop calculation formula of the heat exchanger without the enhanced heat transfer device is needed to corrected.
(1) Pressure drop calculation in tube side:
Without heat transfer enhancement equipment in shell and tube heat exchangers, tube side pressure drop formulation was defined as

$$\Delta P_t = \Delta P_{fi} + \Delta P_r + \Delta P_{ni} \tag{9}$$

Where, ΔP_{fi} is the tube-side pressure drop due to friction loss; ΔP_r is the tube-side pressure drop due to the tube entrance; ΔP_{ni} is the pressure drop in tube-side nozzles.
When internal tube fins using in tube side, the calculation of the pressure drop is different (Jensen and Vlakancic, 1999). And the friction coefficient associated with ΔP_{fi} is needed to correct.

$$\frac{f_{t,f}}{f_t} = \left(\frac{l_{csw}}{D_t} \right)^{-1.25} \left(\frac{0.25\pi D_t^2}{0.25\pi D_t^2 - N_f et} \right)^{1.75} \tag{10}$$

Also with twisted-tape inserting in tube side, the f_t is necessary to correct (Manglik and Bergles, 1993)

$$f_{t,T} = \frac{0.0791}{\mathrm{Re}^{0.25}} \left(\frac{\pi}{\pi - 4\delta/D_t} \right)^{1.75} \left(\frac{\pi + 2 - 2\delta/D_t}{\pi - 4\delta/D_t} \right)^{1.25} \left(1 + \frac{2.752}{y^{1.29}} \right), \ \mathrm{Re}_t \geq 1 \times 10^4 \tag{11}$$

And with coiled-wire inserting in tube side, it's necessary to correct f_t (Garcia et al., 2005)

$$f_{t,c} = 9.35 \left(\frac{H}{\mathrm{t}} \right)^{-1.16} \mathrm{Re}^{-0.217}, \ 2000 \leq \mathrm{Re}_t \leq 3 \times 10^4 \tag{12}$$

(2) Pressure drop calculation in shell side:
External tube fins using in shell-side, the calculation of shell-side pressure drop only needs to correct the friction coefficient (Serth and Lestina, 2014).

$$f_{s,f} = 144\left[f_1 - 1.25\left(1 - {}^{B_c}\!/\!{}_{D_s}\right)(f_1 - f_2)\right] \tag{13}$$

And with helical baffles using in shell side, the friction coefficient f_s is needed to correct (Zhang et al., 2009).

$$f_{s,hb} = C_{fs} \mathrm{Re}_s^{D_{fs}} \tag{14}$$

2.5 Design variables and dimensional constraints

Based on the above research, the usage and size of heat transfer enhancement equipment will be optimized. The main design variables and the related constraints are as follows:
(1) Whether to use heat transfer enhancement equipment: E_{ijk}=0/1.
(2) Heat transfer enhancement equipment in tube side (t_E): internal tube fins; twisted-tape inserts; coiled-wire inserts.
(3) Heat transfer enhancement equipment in shell side (s_E): external tube fins; helical baffles.
(4) Fin height (e) is shown as: $e_{min} \le e \le e_{max}$.
(5) Fin thickness (δ) is shown as: $\delta_{min} \le \delta \le \delta_{max}$.
(6) Fin inclination angle (fr) is shown as: $fr_{min} \le fr \le fr_{max}$.
(7) Twist pitch of twisted-tape inserts (H) is shown as: $H_{min} \le H \le H_{max}$.
(8) Thickness of twisted-tape inserts（t）is shown as: $t_{min} \le t \le t_{max}$.

3. Solution strategy

A new MINLP model is established by combining the HEN synthesis model based on the stage-wise superstructure and heat transfer coefficient and pressure drop calculation model of individual exchanger. The new model combines the heat load and heat capacity of each heat exchange with the main geometric optimization of the heat transfer enhancement technology of the heat exchanger, which can achieve the overall trade-off and the local optimum integration, and based on GA / SA algorithm to get the lowest TAC of HEN. The MINLP model is complex and nonlinear. There are many influencing factors, such as model variables and constraints, which are difficult to solve. The proposed GA / SA algorithm is a feasible strategy to solve this problem. The solution flowsheet of the model in this paper is shown in Figure 1a.

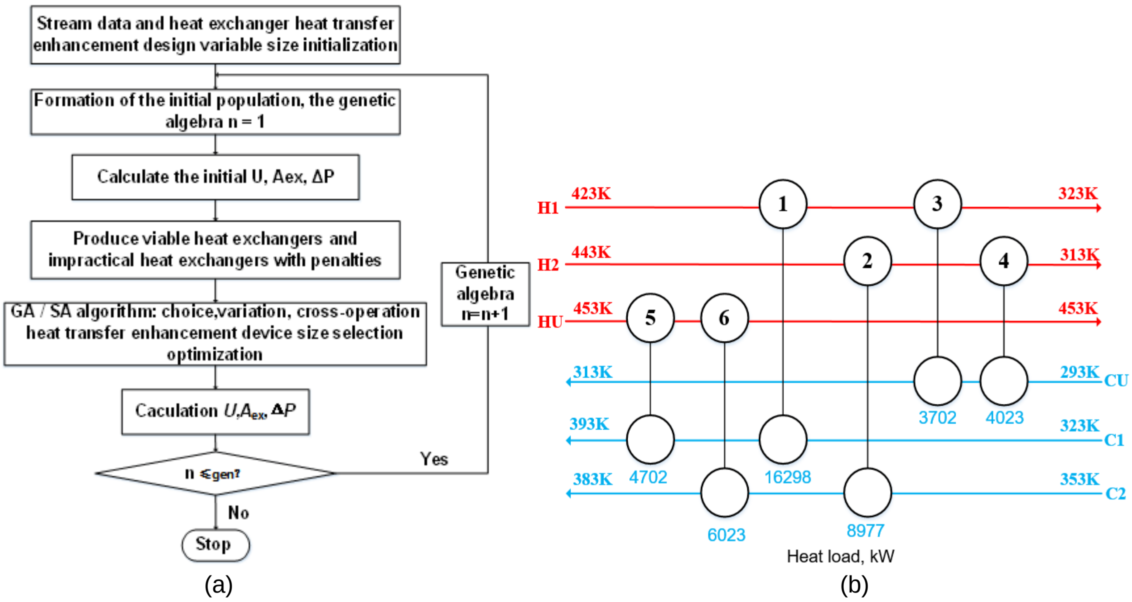

Figure 1: (a) Optimization flow chart. (b) Topological structure for example

4. Example

Example HEN consists of two hot streams and two cold streams. And detailed data about flow streams and heat exchangers are shown in reference (Odejobi et al., 2015).

Table 1: Parameters of heat exchangers 1 and 2 incorporating enhanced heat transfer techniques for example

EXs	$U_{(ex)}$ (kW/m^{2}K)	*e* (mm)	*δ* (mm)	*fr* (°)	*H* (m)	*t* (mm)	Enhancement type	
							Tube side	Shell side
1	0.19	0.56	0.65	25.8	0.10	--	Twisted-tape	External tube fins
2	0.18	0.48	0.61	28.9	--	1.6	Coiled-wire	External tube fins

Table 2: Results comparison for example

Item	Number of EXs	$C_{utility}$ ($)	C_{area}($)	C_{pump}($)	C_E ($)	Total cost ($)
Reference (Odejobi et al., 2015)	7	1,341,127	1,840,780	--- ---	330,694	3,512,601
This paper	6	1,257,045	1,002,263	16,029	956,348	3,231,685

After HEN simultaneous optimization considering the types and size of heat transfer enhancement equipment based on GA/SA algorithm, the optimized HEN is showed in Figure 1b, with a heat exchanger removed and the HEN structure simplified comparing with reference. And the parameters of Ex1 and EX2 incorporating enhanced heat transfer techniques for example are shown in Table 1. In this study, twisted-tape and coiled-wire inserts are used in tube side of the EX1 and EX2, respectively, comparing with fins are both used inside and outside tube in the reference (Odejobi et al., 2015). The specific values of the optimized heat transfer enhancement equipment size can be obtained from the Table 1, while the values in the literature are fixed values. The cost comparison before and after retrofit of the HEN is shown in Table 2. Using the approach to solve example, the utility consumption and capital investment (C_{area}+C_E) savings are 6.27 % and 9.80 %, respectively, while with 7.13 % reduction of the TAC of HEN is achieved.

5. Conclusions

A new MINLP model was proposed for HEN simultaneous optimization considering the types and size of heat transfer enhancement equipment, such that the most suitable exchanger heat transfer techniques and size are identified. And the effective solution strategy was presented based on GA/SA algorithm. With using of simultaneous synthesis model, the heat transfer enhancement equipment types and size were optimized, and the enhanced equipment costs, operating costs, as well as utility costs, heat exchanger equipment costs were traded off by GA/SA algorithm, thus a relatively low TAC was achieved. Using the approach to solve example, the utility consumption and capital investment savings are 6.27 % and 9.80 %, respectively, while with 7.13 % reduction of the TAC of HEN is achieved.

Nomenclature

A	Heat exchanger heat transfer area (m^2)	y	δ/D_t, Dimensionless rate
a、b、c	Related index of heat exchange equipment area costs	Bt_E、Bs_E	Application of tube, shell-side heat transfer enhancement area cost factor
a_E	Heat exchanger installation fixed costs ($·yr^{-1})		
i、j	Hot, cold stream number	l_{csw}	Feature length due to swirling correction
q_{cui}、q_{huj}	Heat load between Cold, heat utilities and flow(kW)	*f(geometry)*	Calculation of Nusselt's inner fin geometric function
c_{cu}、c_{hu}	Unit cost of cold and hot utilities ($·yr^{-1})		
$q_{i,j,k}$	Thermal load between heat flow i and cold flow j in the k-class (kW)	EP	Heat transfer enhancement cost index based on heat exchange area
K	The number of matching between the stream in stage-wise superstructure	Ψ	Correction factor for changes in fluid properties
		z_{huj}	0-1 variable of heater exist or not
z_{ijk}	0-1 variable of heat exchanger exist or not	z_{cui}	0-1 variable of cooler exist or not

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