Applied Mechanics and Materials *Online: 2011-12-22*
ISSN: 1662-7482, Vols. 148-149, pp 1468-1472
doi:10.4028/www.scientific.net/AMM.148-149.1468

Optimal Heat Exchanger Network Synthesis via Particle Swarm Optimization

Ping Wang[1, a], Junliang Xu[1, a] and Tao Lu[2, b*]

[1] School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, China

[2.] School of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, China

[a] wp2006@dlut.edu.cn, [b] likesurge@sina.com

* Corresponding author

Keywords: Heat exchanger network; Superstructure; Particle Swarm Optimization

Abstract. On the basis of superstructure of heat exchanger network (HEN), we established a particle swarm optimization (PSO) model of HEN with no splits, with the target of minimizing investment and operation cost. A typical HEN was solved via a modified particle swarm optimization (PSO). Through comparative of the optimization result, we could know that this method could reach better solution accuracy.

Introduction

Heat exchanger network (HEN) is an important subsystem of petrochemical industry, and the synthesis and optimization of HEN is one of the most important embranchment of process system integration. Currently, there are mainly two types of methods for heat exchanger network synthesis. The first is the pinch technology, which is proposed by Linnhoff [1], for HEN synthesis. There is intuitive physical meaning of this method, however it could not take the investment and operation cost into account at the same time, so usually could not get the optimal solution. The second is mathematical programming, which is represented by superstructure model of mixed integer nonlinear programming (MINLP) proposed by Yee [2], for HEN synthesis. The mathematical programming could be used for solving problems with a large number of variables and various feedbacks, is suitable for designing of HEN and could obtain some optimal networks which could not be obtained by empirical rules.

With the development of computers and the convergence of intelligent algorithms, the mathematical programming for HEN synthesis developed significantly too. For example, Dolan et al. [3] proposed the Simulated Annealing (SA) algorithm, which take multiple objective of cost into account at the same time; Lewin et al. [4] proposed the thought of optimize the HEN via Genetic Algorithm (GA). The potential characteristics of parallel and distributed of the swarm intelligence provide technical assurance to the solution of large account of data.

Introduction of Particle Swarm Optimization

The particle swarm optimization (PSO) is a global optimization evolutionary algorithm developed by Kennedy and Elberhart [5], based on the study of social influence and social learning of a social psychological model. In the adjustable parameters of PSO, the inertia weight (w) is one of the most important. The larger w is help to improve the global search capabilities, and the minor w is help to enhance the local search capabilities. The ways of selection methods of inertia weight are random inertia weight value strategy (RIW), linearly decreasing inertia weight value strategy (LDIW), non-linearly decreasing inertia weight value strategy (NLDIW), Fuzzy adaptive inertia weight value strategy (FIW).

In this paper, we adopt the non-linearly decreasing inertia weight value strategy (NLDIW) of PSO, take w as follows,

$$w = w_{\max} + \left(w_{\max} - w_{\min}\right)\cdot\left(\frac{iter}{iter_{\max}}\right)^2 + \left(w_{\min} - w_{\max}\right)\cdot\left(\frac{2\times iter}{iter_{\max}}\right) \tag{1}$$

By using this strategy, better solution efficiency and improved convergence accuracy could be obtained by accelerate the inertia weight at the early stage to let the algorithm reach local search earlier.

Particle Swarm Optimization Model of HEN

Objective Function. The structure of HEN used in this paper is superstructure. Take the minimum annual cost of HEN as the objective function, which takes cost balance and simultaneous optimization of heat exchanger area, numbers of units and utilities consumption into account at the same time.

$$\begin{aligned} Cost = &\sum_{i=1}^{NH}\sum_{j=1}^{NC}\sum_{k=1}^{NK}\left[C_{ij}^{F}\cdot z_{ijk} + C_{ij}^{A}\cdot\left(A_{i,j,k}\right)^{H_{ij}}\right] + \sum_{i=1}^{NH}\left[C_{c,i}^{F}\cdot z_{c,i} + C_{c,i}^{A}\cdot\left(A_{cu,i}\right)^{H_{cu,i}}\right] \\ &+ \sum_{j=1}^{NC}\left[C_{h,j}^{F}\cdot z_{h,j} + C_{h,j}^{A}\cdot\left(A_{hu,j}\right)^{H_{hu,j}}\right] + \sum_{i=1}^{NH}\left(C_{cu}\cdot q_{cu,i}\right) + \sum_{j=1}^{NC}\left(C_{hu}\cdot q_{hu,j}\right) \end{aligned} \tag{2}$$

Where:

$$q_{cu,i} = \left(T_{i,in}^{h} - T_{i,out}^{h}\right)\cdot F_i^h - \sum_{j=1}^{NC}\sum_{k=1}^{NK} q_{i,j,k} \tag{3}$$

$$q_{hu,j} = \left(T_{j,out}^{c} - T_{j,in}^{c}\right)\cdot F_j^c - \sum_{i=1}^{NH}\sum_{k=1}^{NK} q_{i,j,k} \tag{4}$$

$$A_{i,j,k} = \frac{q_{i,j,k}}{K_{ij}\cdot LMTD_{ijk}} \qquad A_{cu,i} = \frac{q_{cu,i}}{K_{cu,i}\cdot LMTD_{cu,i}} \qquad A_{hu,j} = \frac{q_{hu,j}}{K_{hu,j}\cdot LMTD_{hu,j}} \tag{5}$$

$$\frac{1}{K_{ij}} = \frac{1}{K_i} + \frac{1}{K_j} \qquad \frac{1}{K_{cu,i}} = \frac{1}{K_{cu}} + \frac{1}{K_i} \qquad \frac{1}{K_{hu,j}} = \frac{1}{K_{hu}} + \frac{1}{K_j} \tag{6}$$

In this paper we calculate LMTD adopt the approximate formula proposed by Chen et al [6].

Constraint Conditions. Taking the heat transfer and thermodynamic theories into account, we know that the heat transfer conditions should obey the following constraint conditions. The equality constraints, integer variable constraint, constraints of minimum heat transfer temperature difference, constraints of possible temperature, constraint of non-negative heat transfer and constrains of pinch.

Solve the PSO Model of HEN

Initialize of the particle swarm. Initialize of the heat load of heaters on cold streams;

$$q_{hu,j} = rand()\times F_j^c\cdot\left(T_{j,out}^{c} - T_{j,in}^{c}\right) \tag{7}$$

Calculate the outlet temperature of heaters;

$$t_{1,j,1}^{c} = T_{j,out}^{c} - q_{hu,j} / F_{j}^{c} \tag{8}$$

Calculate heat load of each heat exchanger and temperature of each point;

$$q_{hu,j} = rand() \times q_{i,j,k}^{m} \tag{9}$$

Where: $q_{i,j,k}^{m}$ could be calculated like literature [7].

Update the velocity and location of each particle. Update the heat load of each heat exchanger as follows, and recalculate temperature of each point.

$$\begin{aligned} q_{n,i,j,k}^{v}(iter+1) = w \cdot q_{n,i,j,k}^{v}(iter) + c_1 \cdot rand() \cdot \left(q_{n,i,j,k}^{b} - q_{n,i,j,k}(iter)\right) \\ + c_2 \cdot rand() \cdot \left(q_{n,i,j,k}^{g} - q_{n,i,j,k}(iter)\right) \end{aligned} \tag{10}$$

$$q_{n,i,j,k}(iter+1) = q_{n,i,j,k}(iter) + q_{n,i,j,k}^{v}(iter+1) \tag{11}$$

Case Study

The problem has two hot and two cold streams and a hot and a cold utility are available. Streams and utilities, area and cost data are shown on Table 1. Take $\Delta t_{\min} = 0.1$, $w_{\max} = 0.9$, $w_{\min} = 0.4$, $c_1 = c_2 = 2.05$ and particle number 200, 800 cycles and trace 10 times. The optimal network configuration obtained is presented in Fig. 1. The value of the HEN global annual cost is \$11817. Table 2 shows the comparison with literatures.

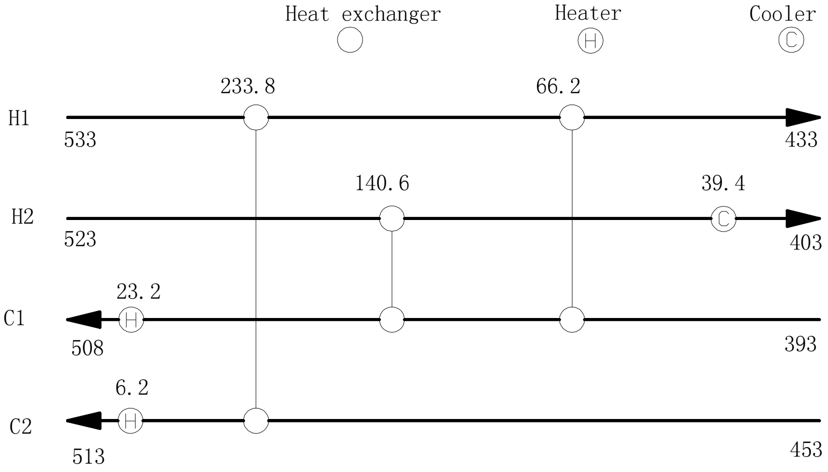

Fig. 1. Optimal HEN.

Table 1. Streams and utilities, area and cost data

Stream	T_{in} [K]	T_{out} [K]	F [kW· K^{-1}]
H1	533	433	3.0
H2	523	403	1.5
C1	393	508	2.0
C2	453	513	4.0
Hu	550	550	--
Cu	293	313	--
Area cost=$300A^{0.5}$, A in m^2		K= 0.2 kW· m^{-2}· K^{-1}	
C_{hu}=110 \$/kW· a^{-1}		C_{cu}=12.2 \$/kW· a^{-1}	

Table 2. Comparison with literature

	Ahmad [8]	Nielsen [9]	This paper
No. of unit	7	8	6
Hot utility (kW)	50	36	29.4
Cold utility (kW)	60	45	39.4
Total annual cost (\$· a^{-1})	12870	12306	11817

The comparison in table II shows us comparing with literature [8] the optimal result of this paper reduced 1 unit and 41.2 kW heat utility and cold utility, and could reduce \$ 1053 per year; and comparing with literature [9] the optimal result of this paper reduced 2 units and 12.2 kW heat utility and cold utility, and could reduce \$ 499 per year;

Summary

In this paper, on the basis of superstructure of heat exchanger network (HEN), we established a particle swarm optimization (PSO) model of HEN with no splits, with the target of minimizing investment and operation cost. A typical HEN was solved via a modified particle swarm optimization (PSO). Through comparative of the optimization result, we could know that this method could more rational allocation of the heat exchanger and could reach better solution accuracy.

Nomenclature

Main symbols:

A	Heat exchanger area [m^2]
C_{cu}	Unit cost of cold utilities [\$/kW·a^{-1}]
C_{hu}	Unit cost of hot utilities [\$/kW·a^{-1}]
C	Cost factor of heat exchanger area
C^F	Fixed fee of heat exchanger [\$]
F	Heat capacity flow rate of streams [kW/K]
K	Overall heat transfer coefficient [W/(m^2·K)]
$LMTD$	Logarithmic mean temperature difference [K]
q	Heat transfer of heat exchanger, heater or cooler [kW]
q^m	The maximum heat transfer [kW]
T	Inlet/Outlet temperature of streams [K]

t^h	Temperature of hot stream [K]
t^c	Temperature of cold stream [K]
z	0/1 integer variables of whether transfer heat or not
$\Delta t_{\min}$	Minimum temperature difference [K]

Subscript :

cu	Cold utilities
hu	Hot utilities
i	Hot streams (i=1,2,…, NH, the total number of hot streams is NH)
j	Cold streams (j=1,2,…, NC, the total number of cold streams is NC)
k	Heat exchanger sub-networks (k=1,2,…, NK)
NC	The total number of cold streams
NH	The total number of hot streams
NK	The total number of heat exchanger sub-networks *NK*=max(*NH*,*NC*)

Acknowledgments

The authors would thank to be supported by “Liaoning Provincial Science and Technology Program project (No.2010224001)”

References

[1] Linnhoff B, Hindmarsh E. The pinch design method for heat exchange networks. Chemical Engineering Science, 1983,38(5):745-763.

[2] Yee T F, Grossmann I E. Simultaneous optimization models for heat integration-II: Heat exchange network synthesis. Computers and Chemical Engineering, 1990, 14:1165-1184.

[3] Dolan W B, Cummings P T, Levan M D. Process optimization via simulated annealing Application to network design [J]. AIChE J., 1989, 35(5):725-736.

[4] Lewin D R. A generalized method for HEN synthesis using stochastic optimization II: The synthesis of cost optimal network. Computers and Chemical Engineering, 1998,22(10):1387-1405.

[5] Chen Guimin, Jia Jianyuan, Han Qi. Study on the strategy of Decreasing Inertia Weight in Particle Swarm Optimization Algorithm. JOURNAL OF XI’AN JIAO TONG UNIVERSITY. 2006,40(1):53-61

[6] Yee T F, Grossmann I E. Simultaneous optimization models for heat integration—I. Area and energy targeting and modeling of multi-stream exchanges [J]. Computers and Chemical Engineering，1990，14(10)：1151-1164.

[7] XIA Tao, JIA Tao, CHENG Jie. A novel approach for simultaneous synthesis of a heat exchanger network via swarm intelligent optimization. Journal of Beijing University of Chemical Technology (Natural Science), 2009, 36(1):97-101.

[8] Ahmad S. Heat exchanger networks: Cost trade-offs in energy and capital [D]. Manchester:UMIDT. (1985)

[9] Nielsen J S, Hansen M W, Joergensen S B. Heat exchanger network modeling framework for optimal design and retrofitting [J]. Computers & Chemical Engineering. 1986,20:s249-s254