Chinese J. Chem. Eng., **14**(5) 574—583 (2006)

Synthesis of Large-scale Multistream Heat Exchanger Networks Based on Stream Pseudo Temperature*

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Abstract Effective temperature level of stream, namely stream pseudo temperature, is determined by its actual temperature and heat transfer temperature difference contribution value. Heat transfer temperature difference contribution value of a stream depends on its heat transfer film coefficient, cost per unit heat transfer area, actual temperature, and so on. In the determination of the suitable heat transfer temperature difference contribution values of the stream, the total annual cost of multistream heat exchanger network (MSHEN) is regarded as an objective function, and genetic/simulated annealing algorithm (GA/SA) is adopted for optimizing the heat transfer temperature difference contribution values of the stream. The stream pseudo temperatures are subsequently obtained. On the basis of stream pseudo temperature, optimized MSHEN can be attained by the temperature-enthalpy (*T-H*) diagram method. This approach is characterized with fewer decision variables and higher feasibility of solutions. The calculation efficiency of GA/SA can be remarkably enhanced by this approach and more probability is shown in searching the global optimum solution. Hence this approach is presented for solving industrial-sized MSHEN which is difficult to deal by traditional algorithm. Moreover, in the optimization of stream heat transfer temperature difference contribution values, the effects of the stream temperature, the heat transfer film coefficient, and the construction material of heat exchangers are considered, therefore this approach can be used to optimize and design heat exchanger network (HEN) with unequal heat transfer film coefficients and different of construction materials. The performance of the proposed approach has been demonstrated with three examples and the obtained solutions are compared with those available in literatures. The results show that the large-scale MSHEN synthesis problems can be solved to obtain good solutions with the modest computational effort.

Keywords multistream heat exchanger network, pseudo temperature, stream heat transfer temperature difference contribution value, genetic algorithm, simulated annealing algorithm

1 INTRODUCTION

The heat exchanger network (HEN) synthesis problem is one of the most studied problems in the field of chemical process engineering and the development of cost-efficient HENs has been proven to be a challenging task[1]. Considerable research has been done in the last few decades, but most of them focused on conventional two-stream (single hot/single cold) heat exchangers. Although multistream heat exchangers are widely used in process industries such as gas processing and ethylene plant to exchange heat energy among more than two streams with different supply temperatures because of their higher efficiency, more compact structure and lower cost than conventional two-stream heat exchangers[2]. However, the investigation on the synthesis of HEN including multistream heat exchangers is limited.

The HEN synthesis problem is formulated as a mixed integer nonlinear programming (MINLP) model for achieving the trade-off and simultaneous optimization between investment cost and operating cost. One of the first simultaneous formulations was presented by Yuan *et al*.[3]. It does not allow splitting of streams and required a heat recovery approach temperature (HRAT) value. A simultaneous method not dependent on the assumption of fixed temperature approaches (HRAT or EMAT) and allowing split streams was proposed by Yee *et al*.[4]. On the basis of the stage-wise superstructure model proposed by Yee *et al*[4]., Yin *et al*.[5] and Wei *et al*.[6] developed the MINLP model and eliminated the assumption on isothermal mixing for stream splits. Although the simultaneous models were rigorous and seemed promising, the major problem was that the number of streams and complexity of the models that could be handled were often restricted because of the large computational work[1].

As for the computational time, Furman and Sahinidis[7] proved that HENs problems are NP-hard. Our experience is that the problems constructed with most rigorous models (like the stage-wise model of Yee *et al*.[4]) are not only the solutions that will have gradual convergence but also, in general, the solution time increases exponentially when more streams are added to the problem. Therefore, for solving large-scale problems, many simplifications have to be

Received 2005-09-01, accepted 2006-03-30.

* Supported by the Deutsche Forschungsgemeinschaft (DFG No.RO 294/9).

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made to assure the mathematical models manageable. Recently, Pettersson[1] solved the problem of large-scale HEN with 39 streams using a sequential match reduction approach. However, the design task is decomposed into three different sequential targets, so this approach cannot guarantee a globally best solution.

The model of MSHEN synthesis problem is a MINLP problem of nondifferentiable, nonconvex, and the dimension of the search space is extremely large. Although traditional optimization methods operate reasonably well on most differential and convex objective functions, they either fail to converge or are easily trapped into a poor local optimum for these complicated problems[6]. Thus the HEN synthesis problem has not been satisfactorily solved and there exists a critical need to explore alternative approaches for them. In this article, a new NLP model is proposed for the synthesis of large-scale industrial MSHEN and a hybrid algorithm named GA/SA is adopted. Moreover, the *T-H* diagram method was used for attaining the utility usages and structure of HEN, which was on the basis of the stream pseudo temperature and optimization of the stream heat transfer temperature difference contribution values. The approach eliminates the integer variables and nonlinear constraints in MINLP model[4—6] and ensures feasibility of solutions. Hence the calculation efficiency of GA/SA can be remarkably enhanced by this approach and more probability is shown in the search of global optimum solution. So this approach is presented for solving industrial-sized MSHEN, which is difficult to solve by traditional algorithm. Moreover, in the optimization of the stream heat transfer temperature difference contribution values, the effects of temperature, the heat transfer film coefficient, and the material of construction on HEN are considered, therefore, this approach can be used to optimize and design HEN with unequal heat transfer film coefficients and different materials of construction. Starting from a group of random initialization solutions and then followed by GA/SA, the automated procedure can find the optimal heat transfer temperature difference contribution value of every stream and the optimal utility usages, exchanger areas, number of units, stream matches and stream split fractions can be attained by the *T-H* diagram method simultaneously. Three examples are presented to demonstrate the performance and effectiveness of this new model and new approach.

2 STATEMENT OF MSHEN SYNTHESIS PROBLEM

The MSHEN synthesis problem can be defined as follows: a set of hot process streams, N_H, to be cooled and a set of cold process streams, N_C, to be heated from known initial temperatures to given target temperatures are given. The heat capacity flow rates and heat transfer film coefficients for the hot and cold streams are also specified. A set of hot utilities, a set of cold utilities, and their corresponding temperatures as well as their relevant cost data are also given. Cost data are also given for possible heat transfer equipment, including fixed and area-dependent cost factors that may also include piping and installation costs. Then the objective is to determine the MSHEN configuration that minimizes the annual cost. The solution defines the network by providing the following items: (1) utilities required; (2) stream matches and the number of units; (3) heat loads and operating temperatures of each exchanger; (4) MSHEN configuration and flows for all branches; (5) area of each exchanger. The heat exchangers are assumed to be of the counter current type.

3 THE *T-H* DIAGRAM METHOD BASED ON THE STREAM PSEUDO TEMPERATURE

3.1 The stream effective temperature level-pseudo temperature

(1) Stream heat transfer temperature difference contribution value.

Stream temperature is an important parameter in heat transfer problem. To further study the problem of heat transfer, stream factual temperature should be transformed into the temperature for representing heat transfer energy level, that is, stream pseudo temperature. In a sense, stream pseudo temperature is determined in terms of its factual temperature and corresponding heat transfer temperature difference contribution value. If the suitable stream heat transfer temperature difference contribution value is calculated, reasonable heat energy distribution can be obtained along the temperature level in the heat exchanger process. So we proposed the concept-stream pseudo temperature to represent its effective temperature level.

The stream pseudo temperature is defined as follows.

For hot stream i

$$T_i^{\mathrm{P}} = T_i - \Delta T_{\mathrm{C}}^i \tag{1}$$

For cold stream j

$$T_j^{\mathrm{P}} = T_j + \Delta T_{\mathrm{C}}^j \tag{2}$$

The calculation formulation of stream heat transfer temperature difference contribution value[8] is presented as follows:

$$\Delta T_{\mathrm{C}}^i = \sqrt{\frac{a_i h_r}{a_r h_i}} \cdot \Delta T_{\mathrm{C}}^r = C \cdot a_i^{\frac{1}{2}} \cdot h_i^{\frac{1}{2}} \tag{3}$$

ΔT_{C}^r, a_r and h_r of reference stream can be determined by the statistical method or by experience, a_i and h_i can be also accurately calculated or be estimated by experience.

Eq.(3) is deduced in terms of maximum principle and minimum heat transfer area of per unit heat load of HEN, however, in Eq.(3) only the economic influence is considered and the thermodynamic influence is not. In the heat exchange process system, the exergy loss of heat transfer is different. The exergy loss at a high temperature level is smaller when compared to that at a low temperature level for the same temperature difference. It also means that to the equivalent exergy loss, the temperature drop at a high temperature level is larger than that at a low temperature level. Therefore, the principle of equal exergy loss distribution was introduced into the equation of the stream heat transfer temperature difference contribution value to make the distribution of exergy flow more reasonable[9].

The exergy equation is defined as,

$$E = Q\left(1 - \frac{T_0}{T}\right) \tag{4}$$

The environment temperature T_0 is assumed as 293K.

In the process of heat transfer between T and $T - \Delta T$, the exergy loss is

$$\Delta E = Q\left(\frac{T_0}{T - \Delta T} - \frac{T_0}{T}\right) \tag{5}$$

Where, ΔE is exergy loss, in general, $T{\cdot}\Delta T \ll T^2$, we can conclude from Eq.(5),

$$\Delta T = \frac{LW}{Q \cdot T_0}(T^2 - T \cdot \Delta T) \approx \frac{LW}{Q \cdot T_0} T^2 \tag{6}$$

From Eq.(6), the following conclusions are obtained. For a given rate of heat transfer (Q) and a given rate of exergy loss (ΔE), heat transfer temperature difference (ΔT) is direct ratio to the square of thermodynamic mean temperature (T^2). In other words, as the temperature levels move lower, to maintain the same rate of exergy loss, the heat transfer temperature difference ΔT must decrease approximately as the square of the temperature. This explains the need to use very small heat transfer temperature difference, on the order of 1K, in the cold boxes of cryogenic process. For example, for the equivalent heat transfer rate and exergy loss, the heat transfer temperature difference of hot exchanger at 500K is perhaps 100 times to heat transfer temperature difference of cold exchanger at 50K.

Eq.(3) only considers economic influence, while the equal exergy loss distribution is considered in the new equation and the suitable stream heat transfer temperature difference values are determined by thermodynamic analysis approach. And the following Eq.(7) is obtained.

$$\Delta T_{\rm C}^{i} = \sqrt{\frac{a_i h_r}{a_r h_i}} \cdot \frac{T_i^2}{T_r^2} \cdot \Delta T_{\rm C}^{r} = C \cdot a_i^{\frac{1}{2}} \cdot h_i^{-\frac{1}{2}} \cdot T_i^2 \tag{7}$$

Eq.(7) introduces the equal exergy loss distribution into the calculation of heat transfer temperature difference contribution value and the thermodynamic and the economic influence are considered simultaneously.

(2) Indefinite interval of heat transfer temperature difference contribution value of stream i ($\Delta T_{{\rm C},i}$).

Since Eq.(7) is not rigorous and error of reference streams data is not avoidable, $\Delta T_{{\rm C},i}$ should span an indefinite feasible interval, for example, $\pm 30\%$ of its initial value perhaps. $\Delta T_{{\rm C},i}$ is a decision variable and when the optimal $\Delta T_{{\rm C},i}$ is achieved, the optimal MSHEN structure is also attained simultaneously.

3.2 The *T-H* diagram method

Reasonable match for heat transfer between the streams can be achieved through the *T-H* diagram which can effectively use temperature levels and reasonably distribute heat transfer temperature difference and heat load. Furthermore, counter current heat transfer in heat exchangers can be achieved by the *T-H* diagram in principle. That is to say, thermodynamic minimum area network can be attained under the given heat load[9]. The synthesis approach includes the following steps.

(1) The mass flow rates, start and target temperatures, thermal capacity, and heat transfer film coefficients for the stream are provided.

(2) The heat transfer temperature difference contribution value for each process stream is evaluated and the stream pseudo temperatures are determined. The hot and cold composite curves are then constructed on the basis of the stream pseudo temperatures; the start and target temperatures for every stream are replaced by their pseudo temperatures, and their heat loads are unchanged. The multiple line segments on the *T-H* diagram represent these streams. One can draw the horizontal lines according to the start and target temperatures of the streams to obtain the temperature intervals on the *T-H* diagram. The hot or cold composite curve is constructed by summing the heat loads at each temperature interval.

(3) The hot and cold composite curves are drawn based on the pseudo temperature. The hot composite curve is placed on the left of the *T-H* diagram and the cold composite curve is placed on the right, and then both of them close up horizontally until they touch each other. The touch point is referred to as the pinch (Fig.1). As in Fig.1, the pinch has the same pseudo temperature for hot and cold streams, but the heat transfer temperature difference is not zero, it is just equal to the summation of the hot and cold stream heat transfer temperature difference contribution values. Once the pinch is located, the hot and cold utility usages and the system heat recovery are determined simultaneously.

(4) The hot and cold composite curves are decomposed into the enthalpy blocks on the *T-H* diagram (Fig.1). Enthalpy blocks are divided by drawing

vertical lines at kink points of composite curves and end points of streams on the *T-H* diagram, and then for the conditions of more times of splitting and mixing of streams and existence of small heat load heat exchangers, the originally vertically cut small blocks should be merged properly to reduce the number of heat exchangers, decrease capital cost, and improve operation. Firstly, all the adjacent small blocks on the *T-H* diagram are merged (for example, block 8 and block 9 are merged a new block Ⅱ) until the small blocks are all separated. Secondly, if the small blocks have only a neighbor block (block 2 in Fig.1), then they should be merged with the neighbor block (for example, block 2 and block 3 are merged as a new block Ⅰ). Finally, if the small blocks have two neighbor blocks (for example block 4), the increase in cost is calculated when block 3 is merged into block 4 and block 4 is merged into block 5, respectively. If the increase in cost of block 3 is higher than that of block 5, block 4 is merged into block 5, otherwise block 4 is merged into block 3. According to the reverse operation of the procedure of making composite curves, the hot and cold stream matches in the enthalpy intervals are determined, that is, HEN is obtained. Heat exchangers including the same hot stream (cold stream) in each block are merged as a multistream heat exchanger, namely, a HEN including multistream heat exchangers is obtained.

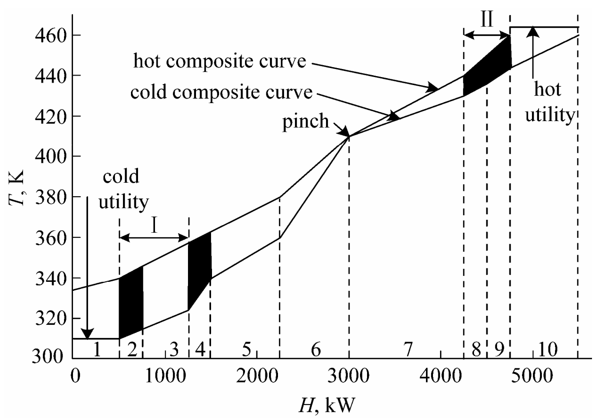

Figure 1 *T-H* diagram based on pseudo temperature

4 GENETIC/SIMULATED ANNEALING ALGORITHM

Genetic algorithm (GA) and simulated annealing algorithm (SA) are, in principle, random methods that are generally used to solve large-scale combination optimization problems. Traditional GA has the disadvantage of premature convergence, but it has better capacity of searching in the global solution. While SA accepts a bad solution according to the Metropolis rule and can break off from local optimum, however, SA knows less to the status of the global searching space and cannot put the searching process into the best promising space, so the calculation efficiency of SA is low. Thus, a combination of the two algorithms is expected to have a good performance to find the global optimum solution. Under this consideration, a hybrid algorithm named GA/SA was developed in the literature [6] and demonstrated successfully in their study. Moreover, in order to improve the accuracy and the convergence speed of GA/SA, float coding was used instead of the traditional binary system coding. Furthermore, OCX (orthogonal crossover) and EC (effective crowding) operators for improving the performance of GA were introduced in GA/SA in addition to the basic crossover and mutation operators. GA/SA shows that fast convergence and good results can be achieved as in the literatures [6,10,11]. In this article, our study also follows the proposed algorithm.

5 METHODOLOGY

5.1 Model formulation

For optimizing HEN simultaneously, the objective function is written as total annual cost, where the contribution to the objective function is composed of the utility cost, the heat exchanger area cost, and the heat exchanger fixed capital cost. Cost equation of heat transfer equipments(including heat exchangers, heaters, and coolers) is $Cf+C\cdot A^B$, where the first item is the fixed cost for heat exchanger, the second one is area cost of heat exchanger, C, A, and B are area cost coefficient, heat transfer area, and exponent for area cost, respectively. The nonlinear cost items are included in the objective function. NLP model formulations in this article are shown in Eqs. (8) and (9).

Minimize:

$$C_{\text{global}} = \sum_i C_{\text{cu}i} \cdot q_{\text{cu}i} + \sum_j C_{\text{hu}j} \cdot q_{\text{hu}j} + \sum_i Cf_{\text{cu}i} + \sum_j Cf_{\text{hu}j} + \sum_k \sum_l Cf_{kl} + \sum_i C_{\text{cu}i} \cdot A_{\text{cu}i}^{B_{\text{cu}i}} + \sum_j C_{\text{hu}j} \cdot A_{\text{hu}j}^{B_{\text{hu}j}} + \sum_k \sum_l C_{kl} \cdot A_{kl}^{B_{kl}} \tag{8}$$

Subject to:

$$\begin{cases} (Th_{\text{in}})_f - (Tc_{\text{out}})_f \geqslant \Delta T_{\min} \\ (Th_{\text{out}})_f - (Tc_{\text{in}})_f \geqslant \Delta T_{\min} \end{cases}$$

$f=1, 2, \cdots$, number of heat transfer equipments (9)

Where, C_{cu} and C_{hu} are per unit cost for cold utility and hot utility, q_{cu} and q_{hu} are cold utility load and hot utility load, A_{cu} and A_{hu} are area of cooler and heater, respectively. Heat transfer area of every match (ij) (including heaters and coolers) is $A_{ij}=q_{ij}/(U_{ij}\cdot LMTD_{ij})$, where U_{ij} and $LMTD_{ij}$ are the total heat transfer coefficient between hot stream i and cold stream j and logarithmic mean approach temperature of match (ij), where $U_{ij}=h_i\cdot h_j/(h_i+h_j)$. A_{kl} is heat transfer area of two-stream or multistream heat exchanger l in enthalpy interval k. $T_{h_{in}}$ and $T_{h_{out}}$ are inlet and outlet temperatures of hot stream in the equipment, $T_{c_{in}}$ and $T_{c_{out}}$ are inlet and outlet temperature of cold stream in the equipment; ΔT_{min} is the allowable minimum approach temperature in the equipment.

5.2 MSHEN synthesis using GA/SA

5.2.1 *Data structure of individual*

GA/SA starts with and manipulates several groups which consist of individuals represented solutions of MSHEN synthesis problem. Each individual in the population is a string coding consisting of a set of heat transfer temperature difference contribution values of process stream, for example, a stream i is a gene representation which can be denoted as ($\Delta T_{C,i}$), specifically. Hence total length of an individual is (N_H+N_C) genes. All the genes are real-value encoded.

5.2.2 *Randomly automated generation of feasible MSHEN*

GA starts with a set of different entities encoded by genes-each representing a solution to the problem, and searches global solution space by selection, crossover and mutation operations, besides searches mostly in the best promising space. So for searching and sampling randomly, a good initial feasible solution generation strategy is expected. If the method of initial solution generation is not suitable, population generation and genetic evolution are maybe plunged in a local solution space and quality of last solution is impacted unavoidably. Heat transfer temperature difference contribution value of every process stream ($\Delta T_{C,i}$) is selected as optimal decision variables of MSHEN synthesis problem. A random generation of a MSHEN involves the following two steps.

Step 1: Generation of the stream heat transfer temperature difference contribution values.

Heat transfer temperature difference contribution value of every stream is generated randomly in a given indefinite interval of its original heat transfer temperature difference contribution value. For example, the original heat transfer temperature difference contribution value of stream i $\Delta T^0_{C,i}$ can be calculated by Eq.(7), and the assumed indefinite interval of temperature difference contribution value of stream i is maybe $[0.7\Delta T^0_{C,i},\ 1.3\Delta T^0_{C,i}]$, then the equation of generated stream heat transfer temperature difference contribution value is $\Delta T'_{C,i} = \text{random}(0.7,1.3) \times \Delta T^0_{C,i}$.

Step 2: MSHEN structure can be attained by the *T-H* diagram method.

Streams pseudo temperatures are calculated by Eqs.(1) and (2) on the basis of a set of random stream heat transfer temperature difference contribution values, and a MSHEN can be obtained by the *T-H* diagram method as described in section 3.2. The total annual cost of MSHEN can be obtained by Eq.(8) as an initial solution of GA.

6 SOLUTION FEASIBILITY OF THE MODEL

At first, the solutions in the initial population of GA/SA started from a set of random stream heat transfer temperature difference contribution values in a feasible internal of its initial value. The HEN structure is obtained by the *T-H* diagram method. The number of decision variables of the model in this article equals to the number of stream heat transfer temperature difference contribution values, that is, the number of process streams. It is assumed that there is a HEN problem of N_H hot streams and N_C cold streams. According to the NLP model, the number of decision variables is N_H+N_C. While in the MINLP model proposed by Yee *et al.*[4], the number of decision variables is $3\times N_H\times N_C\times N_K$ [N_K is the number of stages, N_K=max (N_H, N_C)]. For example, when both N_H and N_C are equal to 10, the number of decision variables in the MINLP model is 150 times of that in the NLP model.

During the generation of initial populations and the evolution of GA/SA, a set of the stream heat transfer temperature difference contribution values corresponds to a feasible solution, that is, a feasible MSHEN structure obtained by the *T-H* diagram method. Hence GA/SA will search in the feasible space of solution, which not only improves the calculation effectiveness but also reduces the repair work of infeasible solutions in GA/SA.

7 CASE STUDY

In this section, the preliminary two examples were solved to give an illustration of the method. The two examples were not very big, but were used in order to compare these results with the results published in the literatures. Yet, the last example is a large-scale MSHEN synthesis problem including 20 streams, and the performance of the NLP model is demonstrated by the results of the example.

For representing detailed network structure data in the graphical representation of HENs of the following three examples, their synthesis results are still represented using a two-stream HEN. Process exchangers are represented by vertical lines and circles on the streams matched with the numbers signed in those circles, the heat loads are underlined (kW), and the temperatures are displayed in regular print (K). All the data units are the same as described in their original literatures, respectively. In addition, in this article the cost equation of the two-stream heat exchangers was used to calculate the cost of multistream heat exchangers.

Example 1

The example is taken from Yee *et al.*[4], which consists of five hot streams, one cold stream and one hot and one cold available utility. Stream data are shown in Table 1. The right column in Table 1 represents the stream heat transfer temperature difference contribution values of optimal network.

Table 1 Stream data and optimal heat transfer temperature difference contribution value for Example 1

Stream	T_{in}, K	T_{out}, K	F_{cp}, $kW\cdot K^{-1}$	Cost, $\$\cdot kW^{-1}\cdot a^{-1}$	Optimized ΔT_C, K
H1	500	320	6	—	2.8
H2	480	380	4	—	3.7
H3	460	360	6	—	1.8
H4	380	360	20	—	3.7
H5	380	320	12	—	3.7
C1	290	660	18	—	1.9
S1	700	700	—	140	—
W1	300	320	—	10	—

Heat transfer coefficient U=1.0kW·m^{-2}·K^{-1} for all matches and the equation of the exchanger cost is cost=1200×[area(m^2)]$^{0.6}$, \$·a^{-1}. The synthesis results are shown in Fig.2 and Table 2. As shown in Fig.2, heat exchangers 1 and 2, heat exchangers 3, 4, and 5, heat exchangers 6, 7, 8, and 9 are merged into a multistream heat exchanger, respectively. According to Table 2, the application of multistream heat exchangers can decrease capital cost remarkably. Under the condition of nearly even utility, the number of heat exchangers reduces to 3 and the capital cost of network reduces to 21% compared with the optimal results shown in literature to date. So, the capital cost of multistream heat exchangers in industries are less than that of conventional two-stream heat exchangers.

Example 2

The example is taken from Yee *et al.*[4], which consists of three hot streams, four cold streams and one hot and one cold available utility. Stream data and optimal heat transfer temperature difference contribution values are shown in Table 3. This is a network of unequal heat transfer film coefficients. The right column in Table 3 represents the stream heat transfer temperature difference contribution values of optimal network. The synthesis results are shown in Fig.3 and Table 4. As shown in Fig.3, heat exchangers 1, 2, and 3, heat exchangers 4, 5, and 6, heat exchangers 7 and 8 are merged into a multistream heat exchanger, respectively. The second row in Table 4 is the cost parameter of optimal MSHEN. Since only the fixed cost was given in Ref.[12], for the purpose of comparison, the cost of hot utility of 130\$·kW^{-1}·a^{-1} and the cost of

Table 2 Comparison of the results in this article with those in the literatures for Example 1

Model	Total area, m^2	Number of units	Fixed charge, $\$\cdot a^{-1}$	Equipment cost, $\$\cdot a^{-1}$	Utility cost, $\$\cdot a^{-1}$	Total annual cost, $\$\cdot a^{-1}$
Ref.[12]	200.9	7	0	59780	516860	576640
Ref.[13]	295.5	9	0	80695	494900	575595
this article①	300.0	6(3②)	0	63176	494120	557296

① refers to multistream heat exchanger network.
② refers to the number of multistream heat exchangers in MSHEN.

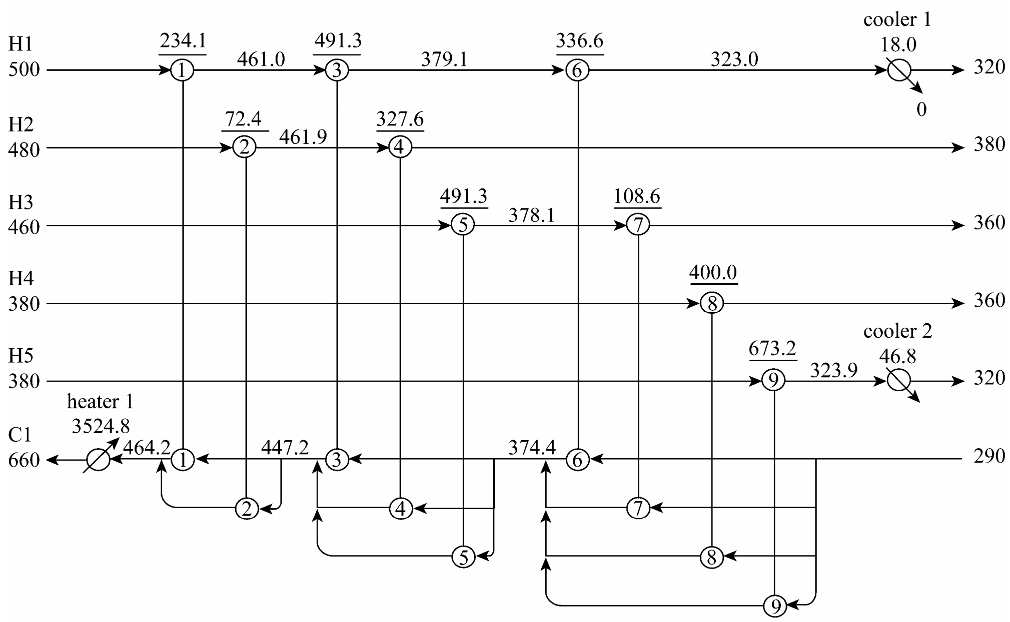

Figure 2 Optimal network for Example 1

Table 3 Stream data and optimal heat transfer temperature difference contribution values for Example 2

Stream	T_{in}, K	T_{out}, K	F_{cp}, $kW\cdot K^{-1}$	h, $kW\cdot m^{-2}\cdot K^{-1}$	Cost, $\$\cdot kW^{-1}\cdot a^{-1}$	Optimized ΔT_C, K
H1	626	586	9.802	1.25	—	15.0
H2	620	519	2.931	0.05	—	62.3
H3	528	353	6.161	3.20	—	3.7
C1	497	613	7.179	0.65	—	13.3
C2	389	576	0.641	0.25	—	15.9
C3	326	386	7.627	0.33	—	7.7
C4	313	566	1.690	3.20	—	7.1
S1	650	650	—	3.50	130	—
W1	293	308	—	3.50	20	—

Table 4 Comparison of the results in this article with those in the literature for Example 2

Model	Total area, m^2	Number of units	Fixed charge, $\$\cdot a^{-1}$	Equipment cost, $\$\cdot a^{-1}$	Utility cost, $\$\cdot a^{-1}$	Total annual cost, $\$\cdot a^{-1}$
Ref.[12]	217.9	9	77400	73598	35185	186183
this study①	147.4	6(3②)	51600	51579	54618	157797

① refers to multistream heat exchanger network.
② refers to the number of multistream heat exchanger in MSHEN.

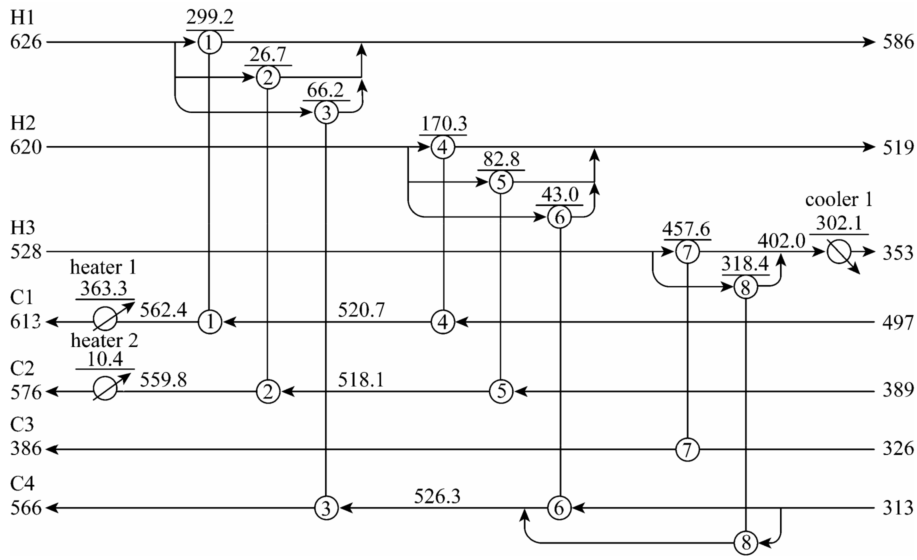

Figure 3 Optimal network for Example 2

cold utility of 20 $\$\cdot kW^{-1}\cdot a^{-1}$ were used. The total annual cost of the network was 186183$\$\cdot a^{-1}$. Although the utility cost of this study is higher than that of the literature, the total annual cost of MSHEN reduces 15% than that in literature.

Heat transfer coefficient $U=1/(1/h_h+1/h_c)$ $kW\cdot m^{-2}\cdot K^{-1}$, for all matches, the equation exchanger cost is cost=8600+670×[area(m^2)]$^{0.83}$, $\$\cdot a^{-1}$.

Example 3

To illustrate the capability of the NLP model for solving the large-scale MSHEN synthesis problem using the *T-H* diagram method on the basis of optimal stream heat transfer temperature contribution value with GA/SA, an example including 10 hot streams and 10 cold streams and one hot and one cold available utility is designed. Stream data and optimal heat transfer temperature difference contribution values are given in Table 5. This is also a network of unequal heat transfer film coefficients. And the problem is equivalent to a two-stream HEN synthesis problem including 100 hot streams and 100 cold streams because of stream splits, which cannot be solved using the MINLP model of Yee *et al*.[4]. The synthesis results are shown in Fig.4 and Table 6. According to Fig.4, heat exchangers 2 and 3, 4 and 5, 6 and 7, 8 and 9, 10 and 11, 12 and 13, 14 and 15, 17 and 18, 19 and 20, 21, 22 and 23, 24 and 25, 26 and 27, 28, 29 and 30, 31 and 32 are merged into a multistream heat

Table 5 Stream data and optimal heat transfer temperature difference contribution values for Example 3

Stream	T_{in}, K	T_{out}, K	F_{cp}, kW·℃$^{-1}$	h, kW·m^{-2}·℃$^{-1}$	Optimized ΔT_C, K
H1	453.2	348.2	30	2.0	6.7
H2	553.2	393.2	15	0.6	13.2
H3	453.2	348.2	30	0.3	22.9
H4	413.2	318.2	30	2.0	9.8
H5	493.2	393.2	25	0.08	46.4
H6	453.2	328.2	10	0.02	89.0
H7	443.2	318.2	30	2.0	10.6
H8	453.2	323.2	30	1.5	12.7
H9	553.2	363.2	15	1.0	13.2
H10	453.2	333.2	30	2.0	5.7
C1	313.2	503.2	20	1.5	15.1
C2	393.2	533.2	35	2.0	16.3
C3	313.2	463.2	35	1.5	4.2
C4	323.2	463.2	30	2.0	13.5
C5	323.2	523.2	20	2.0	15.4
C6	313.2	423.2	10	0.06	68.7
C7	313.2	423.2	20	0.4	21.0
C8	393.2	483.2	35	1.5	16.2
C9	313.2	403.2	35	1.0	4.5
C10	333.2	393.2	15	0.7	5.6
S1	598.2	598.2	—	1.0	—
CW	298.2	313.2	—	2.0	—

Table 6 The synthesis results for Example 3

Model	Total area, m^2	Number of units	Fixed cost, \$·a^{-1}	Equipment cost, \$·a^{-1}	Utility cost, \$·a^{-1}	Total annual cost, \$·a^{-1}
this article①	3229	29(14②)	232000	915869	679903	1827772

① refers to multistream heat exchanger network.
② refers to the number of multistream heat exchangers in MSHEN.

exchanger, respectively. This example in the defined interval of $[0.5\,\Delta T^0_{C,i},\ 1.5\,\Delta T^0_{C,i}]$ is solved using a PC with a 2.8GHz Celeron processor, when the global optimum solution is achieved, the computation time is 2786s.

Heat transfer coefficient $U=1/(1/h_h+1/h_c)$ kW·m^{-2}·℃$^{-1}$, for all matches, the equation of exchanger cost is 8000+800×[area(m^2)]$^{0.8}$, \$·a^{-1}. Cost of hot utility=70\$·kW^{-1}·a^{-1}, cost of cold utility=10\$·kW^{-1}·a^{-1}.

8 CONCLUSIONS

In this study, a new equation for evaluating the stream heat transfer temperature difference contribution value on the basis of the principle of equal exergy loss distribution is proposed. The influence of thermodynamic and economic factors is simultaneously considered in this equation. Besides, a new mathematical model of the synthesis of large-scale MSHEN is presented; a novel automatic generation strategy of MSHEN of stream splits is proposed to provide initial feasible populations for the GA/SA. Moreover, the objective function is the annual cost of MSHEN, which assures optimal MSHEN can be obtained directly. The feasibility of solutions in GA/SA procedure are assured because of the *T-H* diagram method, hence the number of decision variables are remarkably reduced and the calculation efficiency of GA is advanced. In addition, the temperature levels, heat transfer film coefficients, and structure materials of heat exchangers are considered in the optimization of stream heat transfer temperature difference contribution values, so this method can also design and optimize networks with different structure materials and unequal heat transfer film coefficients. The results of the examples show that for the MSHEN synthesis problem the new NLP model is an effective one with

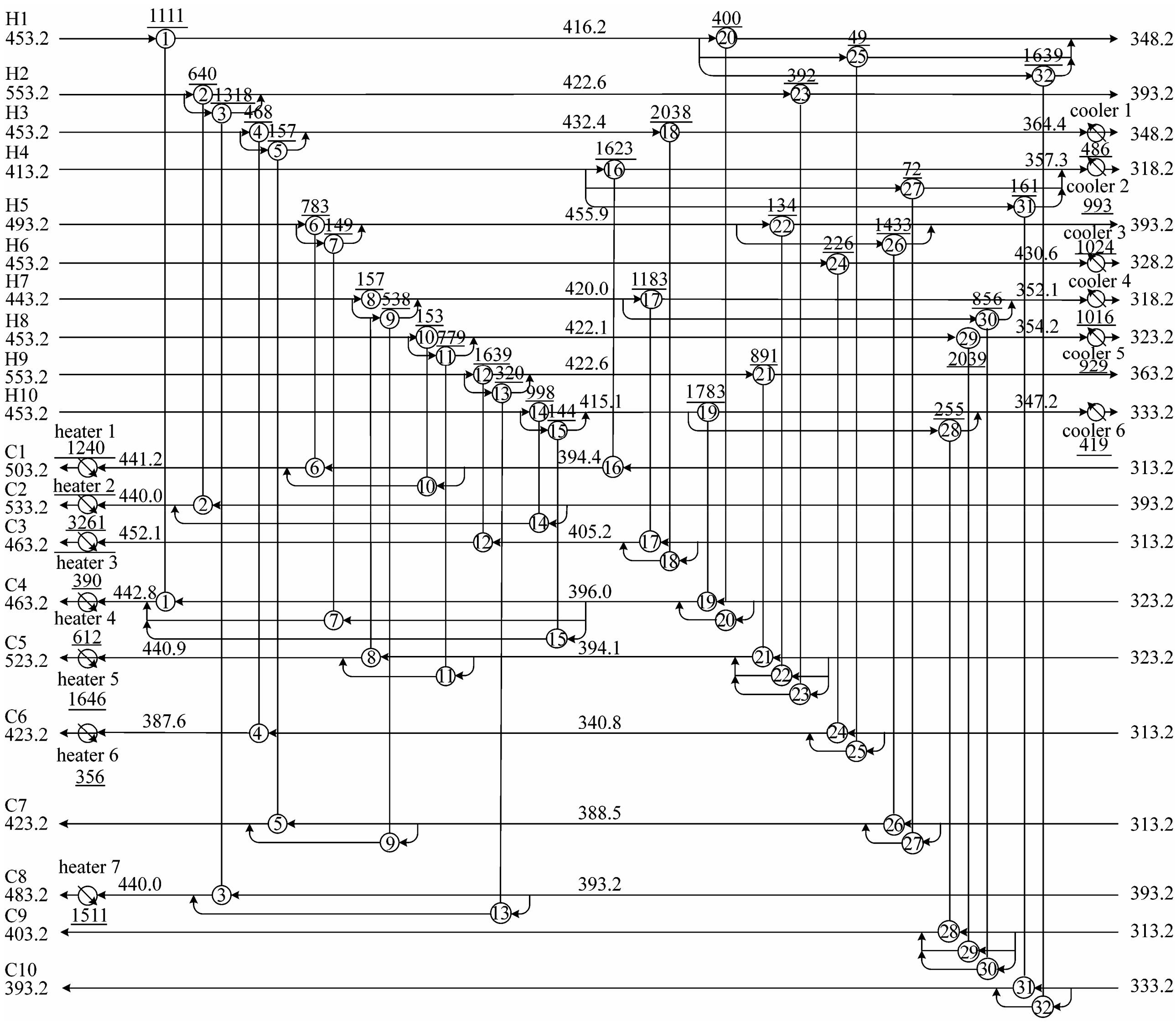

Figure 4 Optimal MSHEN structure for Example 3

less computational effort and more possibility is shown to obtained the optimum solution compared with other MINLP models on the basis of the superstructure.

ACKNOWLEDGEMENT

The authors acknowledge the contribution of Dr. Wei Guanfeng to GA/SA procedure.

NOMENCLATURE

a_i	cost per unit heat transfer area for stream *i*, $\$\cdot m^{-2}$
a_r	cost per unit heat transfer area for reference stream *r*, $\$\cdot m^{-2}$
E	exergy, kW
F_{cp}	heat capacity flow rate of cold stream, $kW\cdot K^{-1}$
h	heat transfer film coefficient, $kW\cdot m^{-2}\cdot K^{-1}$
h_i	heat transfer film coefficient of stream *i* side (including the fouling factor), $kW\cdot m^{-2}\cdot K^{-1}$
h_r	heat transfer film coefficient of reference stream *r* side (including the fouling factor), $kW\cdot m^{-2}\cdot K^{-1}$
Q	heat quantity from the heat source, kW
T	temperature of heat resource, K
T_i, T_j	actual temperatures for stream *i* and *j*, K
T_i^p, T_j^p	pseudo temperatures for stream *i* and *j*, K
T_r	thermodynamic mean temperature for reference stream *r*, K
T_0	environment temperature, K
$\Delta T_C^i, \Delta T_C^j, \Delta T_C^r$	Heat transfer temperature difference contribution values for stream *i* and *j*, and reference stream *r*, K

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