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Improving MSHE Design Procedure Using Genetic Algorithm and Reduced Number of Sections

Joda, F.[1*], Polley, G .T. [2], Tahouni, N. [1] and Panjeshahi, M. H.[1]

[1] School of Chemical Engineering, University of Tehran, P.O. Box: 11365-4563, Tehran, Iran

[2] Institute for Scientific Research, University of Guanajuato, Mexico

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ABSTRACT: Pinch Technology is one of the best methods for designing a multi stream heat exchanger (MSHE) through a network; current pinch-based methods, however, lead to a larger and more complicated design problems. The major drawback of the current methods is they result in designs having more individual MSHE sections than essential, correspond to the enthalpy intervals on temperature vs. enthalpy diagrams or composite curves. In this paper, a new conceptual procedure for optimizing the entrance and exit points of each stream of a MSHE is proposed minimizing the number of sections required for a given duty. Moreover, Genetic algorithm (GA) is used to find the suitable fin type for making the heat exchanger dimensions consistent with manufacturing needs and the fully utilization of allowable pressure drops. Having applied the new design procedure in two industrial case studies, the results showed 11% and 7% cost reductions compared to the current method, respectively.

Keywords: Multi-stream heat exchanger, Optimization, Total annual cost, Composite curves

INTRODUCTION

Cost of energy and investment of heat exchanger networks (HENs) are the most important items of total annual cost (TAC) for any chemical industry (Nejadkooeki and Baroutian, 2012; Afandizadeh *et al.*, 2012; Ashrafi *et al.*, 2012; Ataei *et al.*, 2012, Rashidi *et al.*, 2012; Zeinolabedin *et al.*, 2011; Wang *et al.*, 2011). The most effective way to decrease this cost is to apply heat integration of waste heat streams (Ravagnani *et al.*, 2005). MSHE networks are an alternative to two-stream heat exchangers, especially in cryogenic processes and high energy-consuming, which result in considerable energy and area saving (Wang & Sunden, 2001). In some processes such as cryogenic, there are waste heat streams with small temperature difference where it is impossible to use two-stream heat exchangers in order to recover heat. In such cases, MSHE can be effectively implemented since there is possibility of heat transfer between streams with low temperature difference in an MSHE unit (Faruque *et al.,* 2009).

The first step of optimization of a large process is to offer an exact and efficient model to predict and optimize MSHE efficiency (Faruque *et al.,* 2009). Important parameters to be determined from MSHE design are heat exchanger dimension (length, height and width), number of stream passages and stacking pattern. Complexity of heat transfer paths, which result from differences in physical properties as well as entering and exit temperatures of different streams, makes the MSHE design as one of the most difficult problems in heat transfer engineering. Hence, in a MSHE design, many researchers have used some simplified assumptions. Heseler (1966) presented constant wall temperature assumption, thereafter Prasad & Gurukul (1992), Picon-Nunez (2009) and Wang & Sunden (2001) employed this assumption to design a heat exchanger. Using this assumption, the optimum results of temperature driving force can be achieved because it is possible to prevent many adverse heat streams formation and temperature fields distortion across the heat exchanger.

Heat transfer values in an MSHE depend strongly on stacking pattern, so that only one or at least some optimum stacking patterns lead to an MSHE with a minimum volume satisfying required heat load.

*Corresponding author E-mail:sjoda@ut.ac.ir

Importance of stacking pattern in these heat exchangers was detected by Suesman and Mansour (1979) and Prasad (1996). In the method presented by Prasad, due to constant wall temperature, the temperature driving force per each plate is independent of stacking pattern; therefore different stacking pattern will not have a significant action on MSHE design. Accordingly, it is not possible to investigate the effect of different stacking pattern using the MSHE design methods presented by Picon-Nunez et al. (2002) and Wang and Sunden (2001) because of employing this assumption. Fan (1966) ,according to quantified observation, claimed that minimum volume can be obtained using the segregated method. Ghosh et al. (2011) recently have presented a new method to determine the optimum stacking pattern in multi-stream plate fin heat exchangers (MSPFHE) using genetic algorithms. In addition to optimization of MSHEs, HEN optimization has a major contribution to the cost of industrial processes. Pinch Technology (PT) is a conceptual tool for optimization of a HEN. Network synthesis using conventional heat exchangers has been investigated by many researchers and considerable energy and capital cost savings can be achieved by heat integration in chemical processes. The MSHEN is a complex subject which has not received a lot of academic attention. Picon- Nunez and Polley (1999) extended this technique for MSHEs using the temperature vs. enthalpy diagrams or composite curves. Wang and Sunden (2001) presented a new methodology for design of MSHEs through optimization of HENs. Yee et al. (1990) showed (using mathematical programming) that applying MSHE instead of two-stream heat exchangers in an HEN is more cost-effective. They did not consider the effect of MSHE dimension and stream pressure drops in their model. Other authors such as Kamath et al. (2009), Faruque et al. (2009) have extended the approach proposed by Yee et al. Prasad (1996) and Picon-Nunez et al. (2002) observed the design of MSHENs in a manner that considered the importance of surface selection. Since individual streams enter (and leave) the MSHE at different temperatures, the thermal matching of the streams appears to be a complex problem. However, Picon et al. (2002) like Yee and Grossman (1990) still applied pinch technology to the MSHEN in a way that developed component parts for sections of the exchanger that corresponded to heat load intervals given by the composite curves. Therefore, in each section all the hot streams enter and leave the section at the same temperature. The same rule, of course, is applied to the cold streams.

MSHE design with some sections is a difficult problem. Although it will be easier when the same type of streams have the same temperatures determined according to vertical heat transfer method, this condition leads to design of an MSHE which its number of sections is more than necessary. Therefore, a large volume MSHE will be achieved that lead to increased TAC. If the streams are arranged in vertical heat transfer, either a lot of space is wasted or extra header is required. The problem becomes serious when the number of streams increases. These headers are only used for distributing the streams. Therefore, they occupy relatively large volume without increasing the heat transfer efficiency. Pua (2001) presented a mathematical model to determine optimum entrance and exit points of streams in a MSHE. Nevertheless, their method is time consuming and difficult to program. In this paper, a conceptual method which is easy to use, based on thermodynamics concepts, is presented that enables the designer to find optimum entrance points in a MSHE. This approach yields a situation in which the individual heat exchange matches do not cover the same temperature spans for the streams which enter and leave the sections at different temperatures. It should be noted that design method based on log mean temperature difference (LMTD) method is valid only for MSHE with the same temperature for the same streams (say hot streams) in each section. Prasad (1996) presented a method for MSHE design which can be used even if the entering and exist temperatures of the streams passing through the exchanger are not equal. In this paper, consequently, the Prasad's method is used after reducing the number of sections. Finally, a GA optimizer is used to find optimum type of secondary surfaces along with unifying the flow length of all streams per individual section and obtaining a unified height per all MSHEs in different sections.

MATERIALS & METHODS

The scope of heat recovery can be determined by plotting all process streams on temperature enthalpy axes. Within each temperature range, the hot streams are combined to produce a composite hot stream. Similarly, the composite curve of the cold streams for the problem can be produced. In any temperature range, the enthalpy change of the composite stream is the sum of the enthalpy changes of the individual streams. Specifying the hot utility or cold utility heat duty or ΔT_{min} fixes the relative position of the two curves. Process composite curves can be drawn given flowing heat capacity, supply and target temperatures of hot and cold streams and minimum temperature approach. When heat capacity is assumed to remain constant during heating or cooling, composite curves are formed from straight lines (hot composite curves and cold composite curves) where each change in slope is related to the entry and exit of a stream or more.

Investigation of Heat transfer and flow phenomenon in an MSHE is one of the most complex problems in heat engineering because different streams enter and exit in different temperatures. If the whole heat exchanger is considered as a series of block units which are defined by the enthalpy intervals given by the process composite curves, an MSHE can be used to transfer heat between different cold and hot streams flowing in each enthalpy interval (section). An enthalpy interval is created by drawing vertical lines coming out from two adjacent kink points (points at which the slopes of composite curves through the stream entrance and exit change) whether on hot composite curves or cold composite curves and characterized by a temperature field (inlet and outlet temperatures), a heat load and a stream population. Therefore, a multi-stream plate-fin heat exchanger is composed of several block sections with intermediate entry and exit stream points along the unit length, specified by the composite curves. Once every block has been sized independently from others, they are put together to become the multi-stream heat exchanger in view of manufactures constraints. A typical process composite curve is shown in Fig. 1. This problem would require eight individual sections according to vertical heat transfer and it is necessary to design 8 MSHEs.

Kays and London (1984) showed that in a PFHE, heat transfer coefficient (h) and fanning factor (f) of a large number of fins can be correlated versus Reynolds number according to the following equations.

$$j = a\mathrm{Re}^{-b} \tag{1}$$

$$f = c\,\mathrm{Re}^{-d} \tag{2}$$

where a, b, c, d are coefficients whose value dependent on fin type.

$$\mathrm{Re} = \frac{4Gr_h}{\mu} \tag{3}$$

The only open-literature experimental data for obtaining the above constants has been presented by Kays and London for different types of plate fins. The main geometrical parameters of a plate and fin exchanger are: ratio of total surface area of one side of the exchanger to volume between plates (β), plate spacing (δ), ratio of secondary surface area to total surface area (f_s), hydraulic diameter (d_h), fin thickness (τ) and fin thermal conductivity (κ). Once the surface type is specified, all these parameters are automatically known.

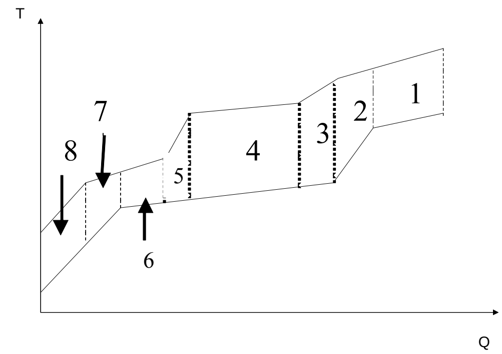

Fig. 1. Typical composite curves

Colburn factor and Pressure drops (ΔP) of PFHE are defined as:

$$\Delta P = \frac{G^2 fL}{2\rho r_h} \tag{4}$$

$$j = \frac{h}{C_P G}\mathrm{Pr}^{2/3} \tag{5}$$

r_h is hydraulic radius and G is mass velocity of fluid moving through free flow area (A_C).

$$j = \frac{\dot{m}}{nWA_c} \tag{6}$$

If P_f (fin density (fin/m)) is large relative to 1, then

$$\frac{A_c}{A} = \frac{1}{r_h} \tag{7}$$

The value of Heat load (Q) per each layer is equal to:

$$Q = \dot{m}\,(\Delta H) = h(nW)LA\eta(T - T_s) \tag{8}$$

where, T and T_s are fluid bulk density and wall temperature, respectively. η is overall surface efficiency and will be obtained from the following equation for rectangular fins (Picon-Nunez and Polley, 2002).

$$\eta = 1 + f_s\left\{\frac{\tanh\left[\left(\frac{2h}{\kappa\tau}\right)^{1/2}\left(\frac{\delta}{2}\right)\right]}{\left[\left(\frac{2h}{k_f\,\tau}\right)^{1/2}\left(\frac{\delta}{2}\right)\right]} - 1\right\} \tag{9}$$

Thus far, two different methods to design of an MSHE in each section have been employed.

First, Picon and Polley (2002) presented a fully developed thermal design procedure for multi-stream plate-fin exchangers and its connection with process heat integration. MSHE design based on Picon-Nunez method (PN method) proceeds by selecting two streams (critical and reference stream) whose allowable pressure drops are lower than others per each section. The main part of MSHE design in their method is based on pressure drop and heat value transferring between them. Hence, MSHE length is equal to length of a two-stream PFHE (containing critical and reference stream) to fully utilize critical stream allowable pressure drop. Therefore, by developing a design method based on LMTD for two-stream PFHEs and uniform passage heat load assumption, one can design MSHEs based on the Number of passages for these two streams. They assumed constant wall temperature and vertical heat transfer assumption to be valid. Their method is limited to design a MSHE with the same type streams that enter and exit heat exchanger at the same temperature. The constant wall temperature is used for selecting fin type of streams. They concluded that same type streams have the same value of $h * A$ (h is heat transfer coefficient and A is heat transfer area). They mentioned that in multi-stream exchangers, full utilization of available pressure drop is seldom achieved in spite of initial design objective. Panjeshahi et al. (2010) developed a new method based on the method proposed by Picon_Nonez *et al.,* 2002. This approach is capable of utilizing the maximum allowable stream pressure drops, and this approach can result in minimum surface area requirements.

Second, Prasad (1996) presented a method to design a counter current MSHE with consideration of extended surface selection which can be utilized for any section, even if the same streams have different entry and exit temperatures because only the constant wall temperature assumption has been applied to derive this method. Fully utilization of allowable pressure drop and application of MSHE design method per each section has further shown the superiority of this method over the old method. Since we have used this method to design an MSHE in each section produced based on proposed method here, all equations and relations of MSHE design related to this method will be explained.

From the above equations (heat transfer, pressure drop and equations related to extended surfaces), the number of layers of each stream (nW) can be calculated from the following equation (Prasad 1996).

$$(nW)^{(2+d-b)} = \frac{c\,\Delta H \dot{m}^{(2+d-b)} \mu^{(b-d)} (pr)^{2/3}}{a A_c^{(2+d-b)} 2^{2(b-d)} C_p r_h^{(b-d)} \eta \Delta T \,\Delta P \rho} \tag{10}$$

Where, ΔT is weighted by means of entry and exit temperature of streams.

$$\Delta T_{he} = \frac{\sum_{i=1}^{i=nh} \dot{m}_i C_{pi} T_{i,in}}{\sum_{i=1}^{i=nh} \dot{m}_i C_{pi}} + \frac{\sum_{i=1}^{i=nc} \dot{m}_i C_{pi} T_{i,out}}{\sum_{i=1}^{i=nc} \dot{m}_i C_{pi}} \tag{11}$$

$$\Delta T_{ce} = \frac{\sum_{i=1}^{i=nh} \dot{m}_i C_{pi} T_{i,out}}{\sum_{i=1}^{i=nh} \dot{m}_i C_{pi}} + \frac{\sum_{i=1}^{i=nc} \dot{m}_i C_{pi} T_{i,in}}{\sum_{i=1}^{i=nc} \dot{m}_i C_{pi}} \tag{12}$$

$$\Delta T = \frac{\Delta T_{he} + \Delta T_{ce}}{2} \tag{13}$$

From Eqs. 1, 3, and 5, heat transfer coefficient can be obtained.

$$h = \frac{2^{2b} a C_p \dot{m}^{(b+1)} r_h^{\,b}}{(nWA_c)^{(b+1)} \mu^b (\Pr)^{2/3}} \tag{14}$$

According to constant temperature assumption and knowing the number of layers and heat transfer coefficients, the flow length can be obtained.

$$L = \frac{\dot{m}\Delta H}{h(nW)A\eta(T - T_s)} \tag{15}$$

where wall temperature (T_s) is easily calculated according to Eq. 16:

$$T_s = \frac{\sum (nW) h_h A_h T_h}{\sum (nW) h_h A_h} + \frac{\sum (nW) h_c A_c T_c}{\sum (nW) h_c A_c} \tag{16}$$

In both methods, MSHE height is determined through comparing the design results of MSHE in different sections. A section with the biggest height is defined as Reference section and height of this section is considered as MSHE height and then the type of fin and Reynolds number of some streams of sections except reference section changed to achieve uniform height in all sections. Thus, a more complex design problem is divided to some easier and smaller ones.

Although, MSHE can be designed by using an easy method based on LMTD method because of validity of vertical heat transfer assumption and temperature equality for the same type of streams in each section, design leads to an MSHE whose geometry dimensions are larger than reality. Therefore, it is necessary to find the optimum inlet and outlet temperature per each section. More cost and space saving can be obtained through merging a section which has small heat load with its previous section. Also, we can reduce complexities of a section which include a stream with a low heat load by transferring it to the neighboring section in which a part of heat transfer of this stream occurs. In the next section we will explain how to find optimum point of entrance and exit of stream and minimum number of necessary sections.

After having specified fin type and allowable pressure of streams per each section, maximum flow length can be calculated according to Eq. 15. As seen from the following equation, allowable pressure drop is distributed to different sections base on heat load of enthalpy interval.

$$\Delta P_{k,j} = \Delta P_{k,total}\left(\frac{\Delta H_{k,j}}{\Delta H_{k,total}}\right) \tag{17}$$

Different streams have different maximum flow length, due to different allowable pressure drop. Therefore, the smallest length is selected as a length of MSHE and Reynolds number of the other streams must be changed to achieve the given duty. In current methods, either free flow area has been calculated based on only rectangular fins, or it has not mentioned to any formula for calculating it. Here, free flow area is calculated with consideration of fin parameters of all kind of fins. If fin is of the type louvered fin or triangular plain fin, free flow area can be obtained as (Shah *et al.*, 2003):

$$A_c = \frac{\delta}{P_f} - \tau\sqrt{\left(\delta^2 - \frac{1}{P_f}\right)} \tag{18}$$

For other types of fin, this area is assumed to be rectangular in shape; therefore, the free flow area is defined as:

$$A_c = \left(P_f - 1\right)\left(F_P - \tau\right)\left(\delta - \tau\right) \tag{19}$$

MSHE width is set to constant value; therefore, height of MSHE can be determined based on the number of layers.

$$H = \sum_{k=1}^{m}\left(N_p\delta\right)_k + \left[1 + \sum_{i=1}^{m}\left(N_p\right)_k\right]\varepsilon \tag{20}$$

When a MSHE have some different sections, each section is designed individually in such a way that uniform length is achieved. Despite achieving the uniform length per section, height of MSHE in different sections must be unified because of manufacturing requirement and easy flow distribution. Hence, the section whose height is larger than others is selected as reference section and design of MSHE in the other sections is repeated until the MSHE height achieves to reference height. It seems that height and length unification depend on each other and their calculation must be done simultaneously for considering interactions between them.

Design of an MSHE in a way that flowing streams in each section must have equal flow length and height of heat exchanger in different sections must be same, depends on fin parameters and Reynolds number of streams. Here, Optimum fin types used per stream flow passages for all sections are selected by GA to minimize the heat exchanger network TAC which is accompanied with satisfying two mentioned constraints and pressure drop maximization of a stream through determining Reynolds numbers to solve a nonlinear set of equations.

In many papers, geometry parameters of fins (fin pitch, fin length and fin density) are usually selected as decision variables of optimization. In this paper, the necessary data to identify 57 fins specified by Kays and London, have been collected and arranged based on their numbers. Therefore, if fin number according to their number in the data base is selected as GA decision variable, the number of optimization variables will become less than those when decision variables are fin geometry parameters.

In GA, a population of chromosomes, which is usually generated randomly, is selected as an initial solution instead of selection a point in the traditional optimization methods. Therefore, possibility of convergence will be increased due to extension of search space. Three operators used for generation of next population are reproduction, crossover, and mutation respectively. Most proper chromosomes of current generation (parent chromosomes) to produce chromosomes of next generation (offspring) are selected by reproduction operator based on their fitness function value. The one point crossover operator, which is usually used in GA, selects randomly a bit from parent chromosomes and split them from this point. Two new chromosomes are created through exchanging tails. If the value of a bit in a chromosome of new generation is randomly changed which is done by mutation operator, then the opportunity of escaping from falling into local optimum is increased due to searching in vicinity of the chromosome (Boozarjomehry and Masoori, 2007).

Here, a new methodology is proposed to reduce individual sections defined by the alignment of the hot and cold composite curves for MSHE design. Consolidation of individual sections will be continued before violation of heat transfer and thermodynamic laws and prohibiting inverse heat transfer throughout the heat exchanger. Optimum stream entrance and exit points will be achieved by applying the golden rule presented here, so that older methods' complexities will be decreased considerably.
Golden rule: Entry ports must be positioned so that there is a finite temperature difference between the incoming stream and the opposing streams.
Here we explain how this rule can be employed for input cold and hot streams.
a: For a hot stream entering at a position lower than the hot composite curve the options can be identified by drawing a horizontal line moving right.
b: The cold streams entering the exchanger also require to be matched against hot streams at a finite temperature difference. We can adopt the same approach to check feasibility. This time we have horizontal lines that go to the left.

As illustrated, the example in Fig. 1 needs eight sections. In this example we observe (Fig. 2) the hot stream entering at the second entry temperature on the hot composite is hot enough to be matched against the cold streams leaving the exchanger. However, this is not the case for the third entry point (Fig. 3). This stream cannot be matched with those cold streams. Therefore, it must be used in a separate section.

The second item of the golden rule is used to check reducing sections from the viewpoint of input cold streams. For example, a horizontal line going to the left should be drawn from the input port of cold streams of section 1 to check feasibility of combining the section 1 and 2. If this line has a finite difference from the port of output hot streams of section 2, unification of sections 1 and 2 will not have any problems. In order to check the feasibility of integration of section 3 to the last unified section, this trend should be able to continue. It means that the distance between incoming hot stream to section 3 and the opposing cold stream from unified section must be checked (Fig. 4). From the information displayed in Figs 2, 3 and 4, we observe that a first section of the exchanger could involve the streams shown in the box highlighted in Fig. 5.

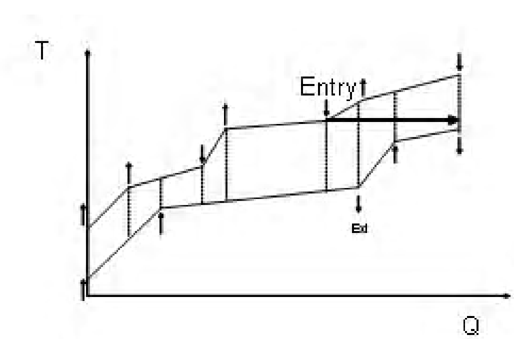

Fig. 2. Locating the first entry point of hot stream

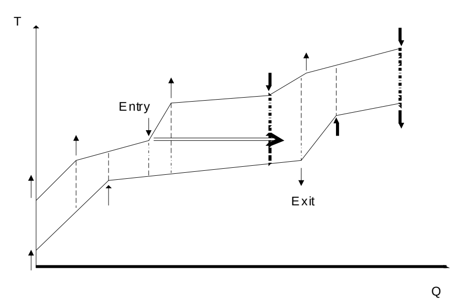

Fig. 3. Locating the second entry point of a hot stream

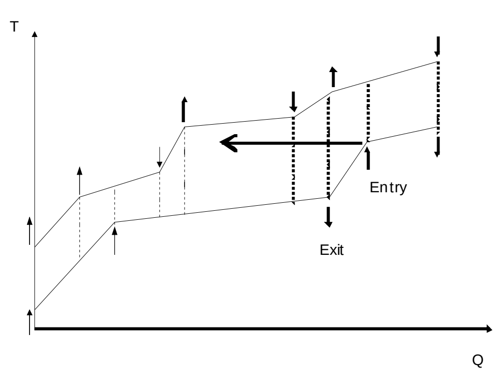

Fig. 4. Locating the first entry point of cold stream

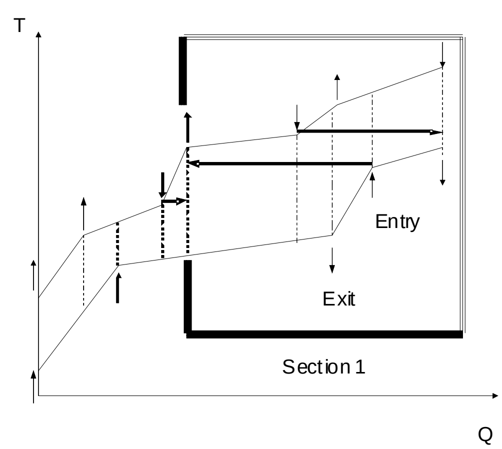

Fig. 5. Definition of Section 1

Moving to the next section we observed that it is the entry of a cold stream that is the limiting factor (Fig. 6). This leads directly to the definition of the second section (Fig. 7). The third section simply completes the duties (Fig. 8).

Thus heat recovery of network in this example is changed to three sections using the developed method. A computer program has been written to implement this method for any case In this paper, GA is the outer layer of optimization problem. It is used to determine the type of fins, such that flow length (L) of all streams in each section must be equaled and MSHE in different sections have the same height (H). These constrains are formulated as shown in equations 19 and 20, and satisfied by penalty method (Yeniay and Ankara, 2005).

$$L_{1,j} = L_{2,j} = \cdots = L_{m,j} \qquad j = 1 \cdots N \tag{21}$$

$$H_1 = H_2 = \cdots = H_N \tag{22}$$

wherem is the summation of available streams per each section. Pressure drop of all streams should be lower or equal to their allowable pressure drop.

$$\sum_{j=1}^{N} dP_{i,j} \le \Delta P \left(\Delta P_{allowable}\right)_i \qquad k = 1 \cdots m \tag{23}$$

The objective is to minimize TAC, which is expressed by the following equation: The capital costs and operating and maintenance costs are determined from Peng and Ling (2008):

$$\text{Total Annual Cost(TAC)} = \text{Capital Cost} + \text{Operating and Maintenece Cost} = IC + OMC \tag{24}$$

$$IC = \left(f_c + A \times u_c\right) \times C_1 \tag{25}$$

$$C_1 = \frac{(1+i)^{t_P}}{t_P} \tag{26}$$

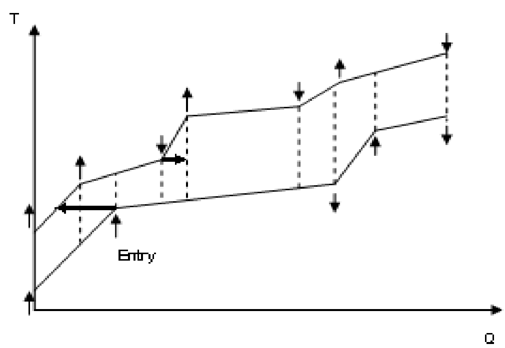

Fig. 6. Thermodynamics controlling second section definition

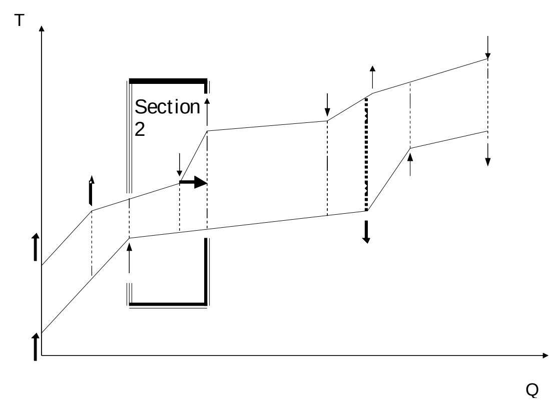

Fig.7. Definition of Section 2

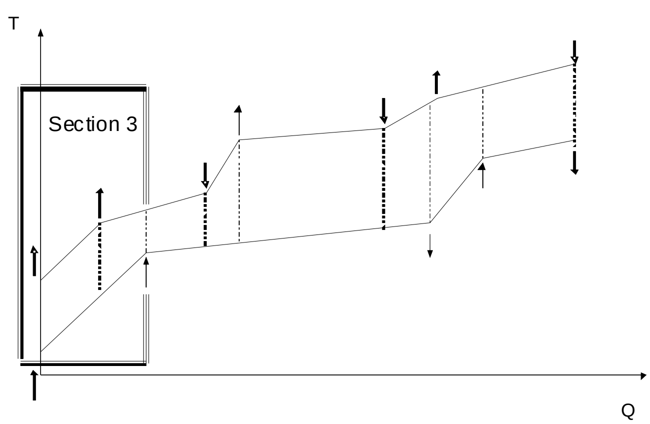

Fig. 8. Definition of Section 3

$$OMC = \frac{(E_c + E_h) \times AH \times fe}{1000} \quad (27)$$

where E is pumping power and can be determined from the following equation:

$$E_n = \frac{\Delta P_n \dot{m}_n}{\rho_n \eta_P} \quad (28)$$

The method proposed here simultaneously determines the MSHE geometric dimensions, the thermal-hydraulic parameters in all heat recovery sections per generation. Full pressure drop utilization of one stream (say critical stream) is a design objective which is obtained during the design steps. A modified Newton-Raphson method is used to solve the nonlinear set of equations shown in the following equation.

$$\begin{aligned} &dP_{c,1} + dP_{c,2} + \cdots + dP_{c,N} = dP_c\,(allowable) \\ &nW\,(Total)_1 = nW\,(Total)_2 \\ &nW\,(Total)_2 = nW\,(Total)_3 \\ &\vdots \\ &nW\,(Total)_{N-1} = nW\,(Total)_N \end{aligned} \quad (29)$$

where N is equal to the number of sections. Total number of layers ($nW(Total)_j$) and pressure drop of critical stream ($dP_{C,j}$) per j[th] section are selected as independent variables obtained by knowing the Reynolds number of critical stream for given fin type and heat duty. The passage number of other streams can be calculated after knowing the number of layers of critical streams owing to the same passage-wise heat transfer rate per section.

RESULTS & DISCUSSION

Here, two case studies are investigated to show the effect of section reduction on TAC. TAC is calculated based on parameter values given in Table 1. Minimum temperature approach at pinch point is an important factor for minimizing the utility demand of the process and the capital cost of the plant heat exchanger equipment, that it is determined during the targeting. Here, only one minimum temperature approach is considered for both examples. Because the reason is that the main aim of this work is to compare the results of MSHE design when vertical heat transfer is used to obtain the necessary blocks with section reduction method has been applied. (fig.9).

Case study I: In the first example as shown in Table 2, there are three hot streams and five cold streams. Heat recovery for this example is divided to four sections, if the composite curves are constructed at $\Delta T_{min} = 6\ ^\circ C$ and vertical heat transfer is assumed (Wang and Sunden, 2001). Fig. 10 shows the number of constant enthalpy interval (section) on the composite curves. It is assumed that allowable pressure drops are linearly distributed through the entire heat recovery network.

Some needed parameter values to design like plate thermal conductivity and plate thickness, have not been presented by Wang and Sunden (2001). Therefore, in this paper in addition to design of MSHE based on new method, MSHE design has been also accomplished based on current method to increase accuracy of comparing of the results of MSHE design between dividing of heat recovery based on vertical heat transfer and new presented method, . Heat recovery is divided to three sections after implementation of the new method presented in this study. Second and third sections are combined to make a new section as shown in Fig. 10. It is impossible to reduce more, because of thermodynamics constraints. The optimization variables must be regulated to achieve unified flow length of streams and MSHE height. In this example, the fin type of hot and cold streams flowing into the layers are optimization variables of GA. Stream C1 can utilize its full allowable pressure drop along the length of MSHE. Here, MSHE width is set to one meter. Pressure drop and necessary heat transfer area of each stream through the heat recovery networks are shown in Table 4. After calculating stream heat load and cross sectional area using given fin parameters, the necessary number of layers per each stream can be determined. Heat transfer coefficient and MSHE length and height will be calculated according to Eq. 15 and 20. If fin number belongs to rectangular plain or strip fin group, cross sectional area is calculated based on Eq. 19; otherwise the cross sectional area will be calculated using Eq. 18 which is useful for louvered fin or triangular plain fin type. This process must be applied for all streams per all sections. Therefore, Geometric dimensions of MSHE (length and height) given in Table 3 can be calculated. If vertical heat transfer is assumed, then there will be 17 optimization variables which are equal to the number of fins employed in flow passage of hot and cold streams flowing in four sections, but this number is reduced to 13 when the new proposed method of section reduction is used. Before applying the new proposed method to define the necessary sections, as shown in the Fig. 10, Streams H_1 and C_1 exist in the first

Table 1. Values of economic parameters in equations 23 and 24

parameter	uc($/m^2)	fc ($)	AH (hr/year)	fe ($/kWh)	i (%)	tp (years)
values	1900	30000	8000	0.065	15	10

fe: electric cost ($/kWh), fc : fixed cost ($), uc: unit cost of PFHE per unit area ($\$/m^2$), i :Interest rate (%), t_p: operating period (year)

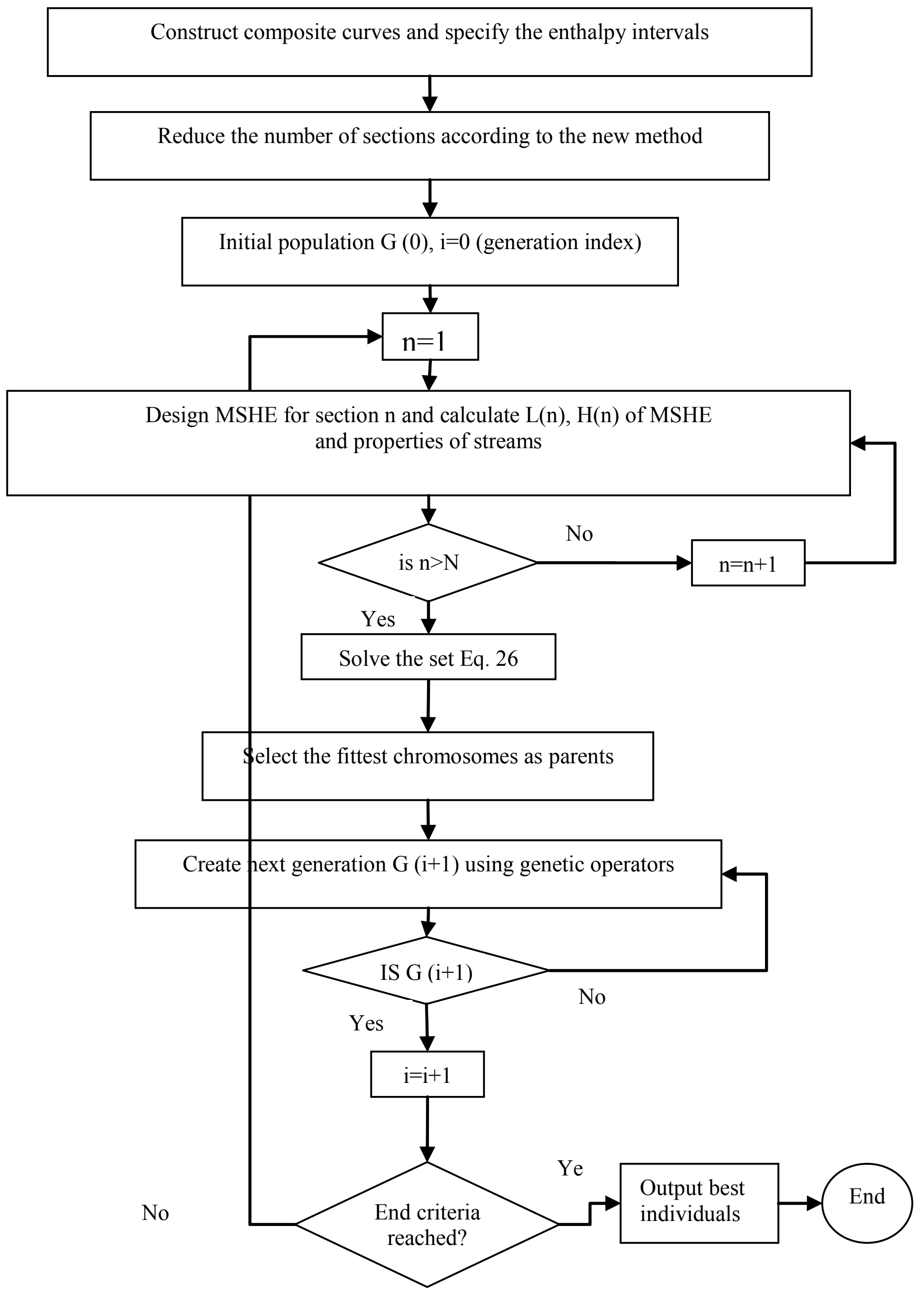

Fig. 9. MSHE Design Algorithm based on reduced sectionsusing GA

Table 2.Stream data and physical properties, Example I (Wang & Sunden, 2001)

Stream	Ts	Tt	$\dot{m}$	Pr	Cp	ρ	μ	ΔP
H1	88	38	29.17	4	3800	1050	0.0004	25000
H2	76	40	96.25	3	4180	990	0.0005	70000
H3	76	40	137.58	3	4180	990	0.0005	80000
C1	0	45	43.73	7	4180	990	0.001	40000
C2	45	70	60.23	3	4180	990	0.0005	50000
C3	0	60	62.15	5	4180	990	0.0008	60000
C4	60	70	76.45	3	4180	990	0.00004	6000
C5	70	90	38.5	2	4180	990	0.00004	30000

Ts: supply temperature (°C), Tt: target temperature (°C), $\dot{m}$: mass flow rate of a stream (kg/s), Pr: Prandtl number, Cp: specific heat of stream (J/ kg K), μ: dynamic viscosity (kg/m s), ρ: density (kg/m^3), ΔP: pressure drop (Pa)

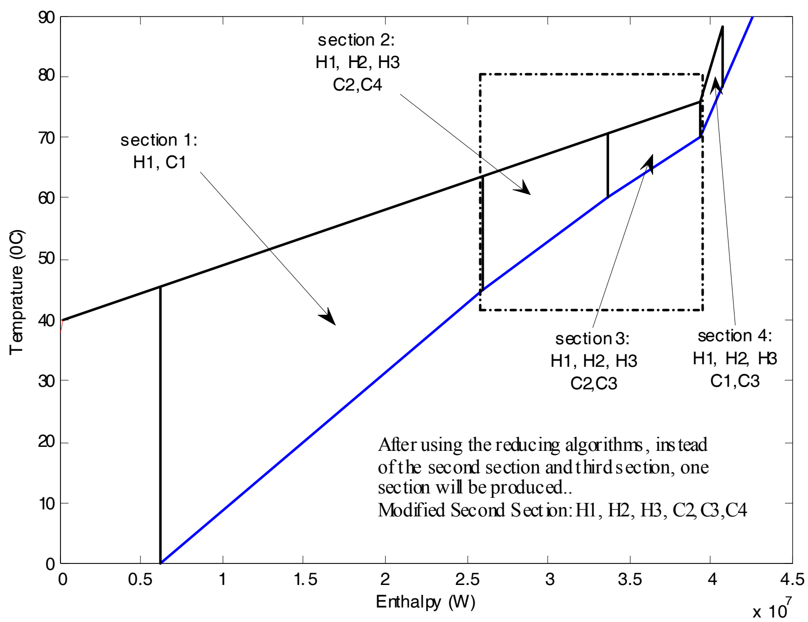

Fig.10. minimum number of sections, Example I

Table 3. Comparing between MSHE dimension from Current methods and New method, Example I

Section	Current Method		New Method	
	H (m)	L (m)	H(m)	L (m)
1	0.87	0.27	0.74	0.26
2	0.87	0.58	0.74	0.98
3	0.87	0.66	0.76	0.421
4	0.87	0.6	-----	-----

H: effective exchanger Height, L: effective exchanger Length

Table 4. Pressure drop and Heat transfer area calculated by current and New Method, Example I

Stream	Current Method		New Method	
	ΔP (Pa)	A(m^2)	ΔP (Pa)	A(m^2)
H1	21020.19	352.13	21021.67	128.7872
H2	17912.28	279.25	11539.87	286.1093
H3	15737.52	521.21	10109.33	387.5414
C1	2547.77	149.93	2758.064	175.2457
C2	4886.81	202.37	22192.31	286.5414
C3	5036.19	385.4	12228.73	278.8826
C4	2820.00	120.97	14241.68	192.5887
C5	188.03	104.82	73.99668	142.1171

A: Heat transfer area

section so that add 2 optimization variables to the list of total variables. H_1, H_2, H_3, C_2 and C_4 (five variables) are the streams flowing in the second section. Section 3 includes H_1, H_2, H_3, C_2 and C_3 (five variables) and in the section 4, there are H_1, H_2, H_3, C_1 and C_3 (five variables). Since, after using the new method, section 2 and 3 create a unit section, 4 variables will be subtracted from the total variables. It means that, we have 13 variables to design an MSHE based on new method. Hence, the computation become simpler and the required time for MSHE design will be reduced.

To achieve an optimum solution using GAs, it is necessary to select GA parameters such as population size and crossover and mutation probabilities correctly. First, an iterative process was used to determine the population number, and then the mutation rate and crossover rate were checked. The value of crossover and mutation are set to 0.7 and 0.08, respectively after applying this iteration process. Initial population which is an important parameter to get convergence, is set to 125 chromosomes per each generation.

Case study II: The second case is a crude oil preheats train which includes 6 hot streams and one cold stream. The flow sheet of process and the relevant data for the process are shown in Fig. 11 and ýTable 5, respectively (Picon and Polley, 1999). The composite curves in Fig. 12 are set to have a minimum temperature difference (ΔT_{min}) of 30æ%C. The exchanger is divided to seven sections, if vertical heat transfer is valid. The number of variables of GA which represents the total number of available hot and cold streams at all individual sections is equal to 27. After using the new method to determine the optimum entrance and exist of streams along the exchanger, the number of sections will be reduced to three and the number of variables will be equal to 15 as shown in Fig. 13. Subsequently, it leads to decreased number of iterations to solve the nonlinear set of equations and the optimum fitness will be obtained in less time. The necessary CPU-time to get the optimum results for MSHE design based on current method using a PC, Pentium four (830 MHz/ 4MB RAM) takes two hours, while MSHE design based on the new method is accomplished during half an hour.

The presented results of MSHE design by Picon and Polley are not suitable to show the effect of applying the proposed method on TAC, Because they designed an MSHE based on LMTD method which we cannot use this method to design after using the new method. Therefore, in this example, the design results of current method have been reproduced.

For this case, MSHE design is also performed based on 1.0 m width. The hot stream H4 which flows through heat recovery is selected as critical stream. Final dimensions of MSHE obtained from current and proposed method are compared in Table 6. Total pressure drop and heat transfer surfaces of the individual streams are presented in Table 7. The details of each section of MSHE calculated by the proposed method are given in Tables 8 to 10. Proper fin types used in the fluid flow passages are specified by GA to minimize the difference between MSHE height in each individual section. In this case, also like the first case study, an iteration process is used to determine GA parameters. The value of crossover, mutation and Initial Population are set to 0.7, 0.05 and 125 chromosomes, respectively. Table 11 presents a comparison between MSHEN TAC obtained from new and current methods for both examples. The results show a considerable improvement of TAC, 11.11% for the first example and 7.1% for the second one, due to using a new method to reduce the number of sections and locate the optimum entry and exit points of streams. When optimizing entrance points, overall area for a network is minimized. The effect of area reduction on the volume and then cost completely differs from the results reported in Table 11.

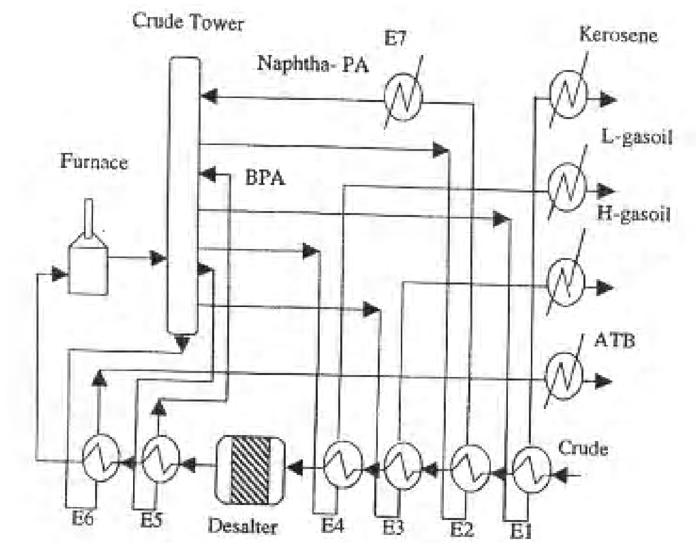

Fig.11. Process flow sheet, Example II

Table 5. stream data and physical properties of streams, Example II (Picon_Nunez&Polley, 2000)

Stream	Ts	Tt	$\dot{m}$	ΔP	ρ	Cp	μ	K	R
Kerosene (H1)	180	30	23	45630	700	2600	0.3	0.12	0.00144
LGO (H2)	270	40	44	59880	700	2600	0.4	0.12	0.00142
HGO (H3)	350	30	13	29470	750	2600	0.5	0.12	0.00140
ATB (H4)	380	50	56	85960	750	2600	0.5	0.12	0.00142
Naphtha (H5)	150	100	253	65360	630	2600	0.2	0.12	0.00137
BPA (H6)	290	190	148	74760	750	2600	0.4	0.12	0.00157
Crude (C1)	20	390	200	172440	800	2600	1.0	0.12	0.00147

κ: plate thermal conductivity (W/m°C), R: Fouling (m2ÚC/W)
ATB: atmospheric tower bottoms, BPA: Bisphenol A, HGO: heavy gas oil, LGO: light gas oil

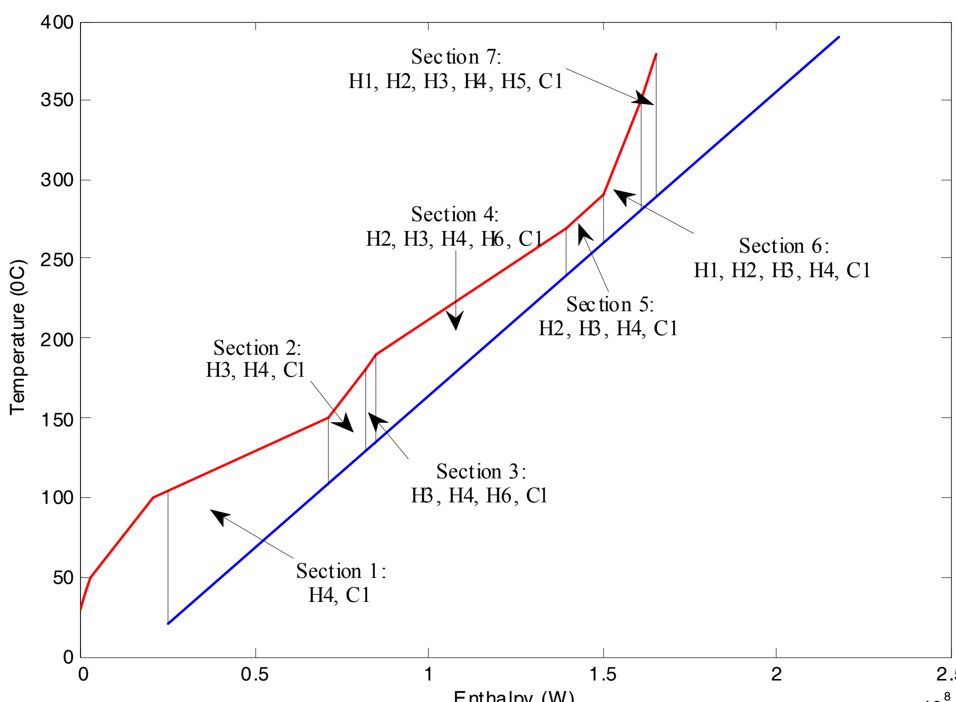

Fig.12. process composite curves and conventional number of sections, Example II

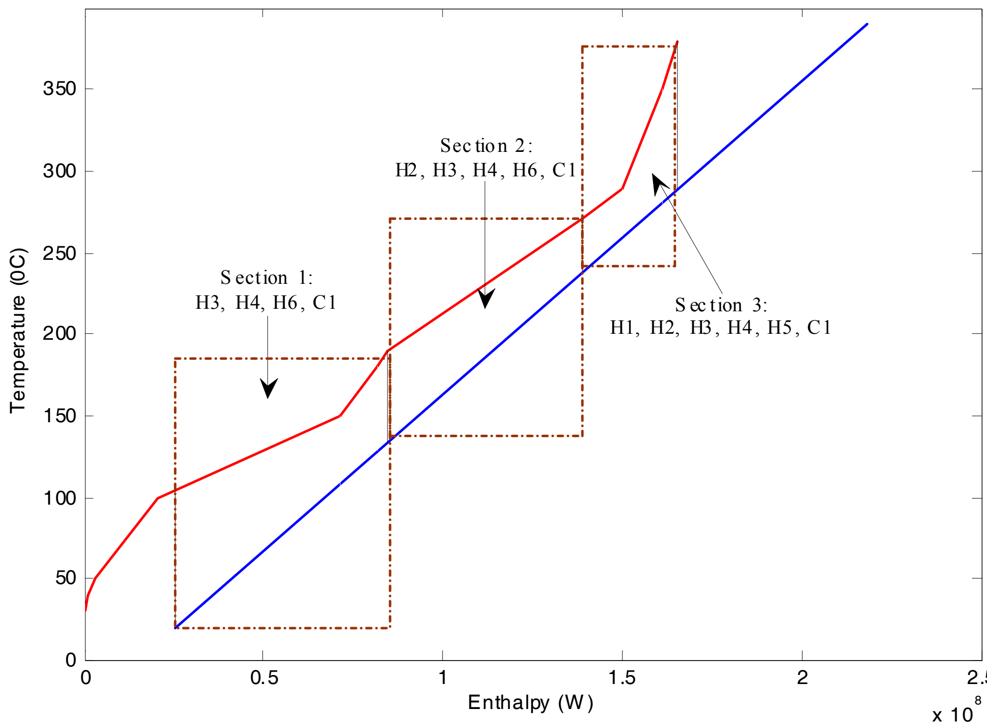

Fig.13. minimum number of sections, Example II

Table 6. Comparing between MSHE dimension from Current method and New method, Example II

Section	Current Method			New Method		
	H (m)	L (m)	V(m^3)	H (m)	L (m)	V (m^3)
1	2.0	0.15	0.3	1.95	1.2	2.34
2	2.0	0.2	0.4	1.95	0.95	1.85
3	2.0	0.55	1.1	1.95	0.9	1.76
4	2.0	1.6	3.2	-----	-----	-----
5	2.0	0.13	0.26	-----	-----	-----
6	2.0	0.35	0.7	-----	-----	-----
7	2.0	0.5	1	-----	-----	-----

V: Heat exchanger volume

Table 7. Pressure drop and Heat transfer area calculated by current and New Method, Example II

Stream	Current Method		New Method	
	A(m^2)	ΔP (Pa)	A(m^2)	ΔP (Pa)
H1	101.5803	7422.444	49.78	7970.57
H2	585.6436	14903.94	359.95	13551.59
H3	302.6148	16217.14	220.54	16685.76
H4	1336.748	70099.09	1489.77	70012.42
H5	533.9726	5562.36	312.68	13077.75
H6	1673.656	8916.974	1349.94	12089.97
C1	5279.347	25126.1	5367.32	56524.01

Table 8. Final results for Section 1, Example II

Stream	nW	Re	$h(W/m^2K)$	η	ΔP (Pa)	$A(m^2)$	Fin Type
H3	12.58	1522.39	919.81	0.91	2745.83	86.02	LF: 3/8-6.06
H4	74.49	442.89	282.32	0.9	395.56	1203.44	PF: 11.11(a)
H6	35.8	3155.45	3023.91	0.58	7800.64	593.06	LF: 1/7-15.75(D)
C1	515.58	122.87	1763.71	0.89	32929.03	1889.23	PF: 46.45T

LF: louvered fin, PF, plain fin

Table 9. Final results for Section 2, Example II

Stream	nW	Re	$h(W/m^2K)$	η	ΔP (Pa)	$A(m^2)$	Fin Type
H2	22.10	1666.80	2500.72	0.71	5682.84	251.3021	SF: 1/8-13.5
H3	6.53	1012.98	2130.43	0.63	7784.9	97.94043	SF: 1/9-22.68
H4	28.13	3351.35	4813.47	0.91	63461.82	128.7817	SF: 1/10-19.35
H6	66.09	1881.48	1904.19	0.76	4289.33	756.876	WF: 11.5—3/8 W
C1	413.41	122.87	2442.75	0.68	13480.27	1858.022	SF: 1/10-27.3

SF: strip fin, WF: wavy fin

Table 10. Final results for Section 3, Example II

Stream	nW	Re	$h(W/m^2K)$	η	ΔP (Pa)	$A(m^2)$	Fin Type
H1	9.80	5758.04	2245.36	0.83	7970.57	49.78	LF: 3/8(a)-6.06
H2	18.75	3587.68	1970.51	0.83	7868.75	108.65	LF: 3/8(a)-8.7
H3	5.54	2506.55	1719.39	0.83	6155.03	36.57	SF: 1/4(s)-11.1
H4	23.86	2506.55	1719.39	0.83	6155.03	157.55	SF: 1/4(s)-11.1
H5	64.79	14373.79	3699.4	0.76	13077.75	312.68	LF: 3/8(a)-6.06
C1	413.82	122.74	2443.96	0.68	10114.71	1720.07	SF: 1/10-27.3

Table 11.Comparison between Total area and TAC obtained from new and current methods

	Example I				Example II			
Method	A (m2)	V (m3)	Number of Variables	TAC ($/Year)	A(m2)	V (m3)	Number of Variables	TAC ($/Year)
Current Method	2116.07	1.84	17	1642229.34	9846.512	6.96	27	7580717
New Method	1877.813	1.3034	13	1459724	9149.983	5.95	15	7045326

CONCLUSION

In this paper a new conceptual method is proposed to reduce the MSHE sections correspond to the enthalpy intervals on composite curves. The main feature of this method is merging the unnecessary MSHE sections which are obtained based on vertical heat transfer through the composite curves. Having found the optimum entrance and exit points of each stream along the heat exchanger length, the final MSHE presented less number of sections and less complexity in design. A computer program is written to find the optimum entrance/exit stream points according to the new proposed approach. This source is then linked with a GA code to identify the suitable fin types in order to achieve heat exchanger dimensions consistent with a real design. The methodology has been applied to the design of a MSHE for two industrial cases. The results indicated the high potential space and cost savings.

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