Cost Effective Heat Exchanger Network Design with Mixed Materials of Construction

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ABSTRACT: *This paper presents a simple methodology for cost estimation of a near optimal heat exchanger network, which comprises mixed materials of construction. In traditional pinch technology and mathematical programming it is usually assumed that all heat exchangers in a network obey a single cost model. This implies that all heat exchangers in a network are of the same type and use the same materials of construction (an assumption that is unwarranted). The method introduced in this article enables the designer to decomposes the total cost of a heat exchanger into two elements, namely cost of the tubes and cost of the shell, thereby predict a more reliable cost for the network. By subsequent use of the binary variables and evaluation of the physical conditions of the streams, one can assign the streams to pass either through shell or tubes. Whereby, shell and tubes can be of different materials and therefore different cost models can be applied. Another advantage of the approach is that the pressure drop in each side of the exchanger (shell or tubes) can be assessed leading to more accurate evaluation of corresponding heat transfer coefficient for each individual stream. Finally an objective function (total cost) can be defined based on mixed materials of construction and different values of heat transfer coefficients. The proposed model has been utilized in three different case studies and the results are compared with those of a commercially available software (SUPERTARGET). The comparison shows reductions of more than 17% and 14% in total annual costs in the two cases, and 2.5% reduction in third, confirming the fact that more accurate evaluation of heat transfer coefficient for each individual stream can lead to better network design.*

KEY WORDS: *Heat exchanger network, Mathematical programming, MINLP model, Optimization, Mixed materials of construction*

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INTRODUCTION

In the last two decades, important achievements have occurred in the area of synthesis, design and optimization of heat exchanger networks (HEN): e.g. see reviews by Gundersen and Naess [1], Gundersen [2], Linnhoff [3], Jezowski [4], Grossmann and Kravanja [5]. Some of the major achievements are as follows:

Hall and Ahmad introduced a method based on a weighting factor which can account for non-uniform costs due to different materials of construction [6].

Colberg and Morari presented two transshipment Non Linear Programming (NLP) formulations to calculate the area target and capital cost target for HEN problems. Given any specified number or set of matches and different heat transfer coefficients and cost laws, this method is designed to predict the trade off between area or cost and the number of matches and the effect of forbidden matches upon the minimum area or cost. The solution provides the area or cost target, temperature profiles for each stream and the distribution of heat loads and areas among specific matches [7].

Jegede and Polley proposed a modification of the pinch design targeting methods to allow for non-uniform exchanger specifications which can have a major impact on the capital cost of a HEN.The use of an exchanger classification table is suggested as a tool to aid in the design of a HEN in this manner [8].

Yee and Grossmann assumed linear area cost functions, arithmetic mean driving force temperature differences, and no stream splitting on the Mixed Integer Non Linear Programming (MINLP) model [9].

In this paper, a simple methodology for the cost estimation of a near optimal heat exchanger network, which comprises mixed materials of construction is suggested. In traditional pinch technology and also in mathematical programming, it is usually assumed that all heat exchangers in a network, obey a single cost model. This implies that all heat exchangers in a network are of the same type and use the same materials of construction. However, this assumption in many cases can cause a significant error in estimation of the actual cost of the network and ultimately affects the reliable estimation of minimum approach temperature prior to design. The method introduced in this article, enables the designer to predict a more reliable cost of the network. The idea is to decompose the total cost of a single heat exchanger into two elements, namely cost of the tubes and cost of the shell. Then with the use of binary variables and evaluation of the physical conditions of the streams, one can assign the streams to pass either through shell or through tubes. In this case, shell and tubes can be of different materials of construction and therefore different cost models can be applied. Finally an objective function (total cost) will be defined based on mixed materials of construction.

COST MODEL FOR SHELL AND TUBES

The starting point is an expression for the capital cost (CC) of a single heat exchanger. If "A" is the surface area, then a simple cost law typically has the form:

$$CC = a + bA^{c} \tag{1}$$

Where **a**, **b** and **c** are the cost law coefficients which depend on heat exchanger specifications such as materials of construction, pressure rating, and type of the exchanger. Therefore, these coefficients will vary from exchanger to exchanger. This means that the assumption of identical **a**, **b**, and **c** for all exchangers, will lead to an nonrealistic cost target. The exchanger specifications (i.e., materials of construction, pressure rating, and type) are dictated by the chemical nature and operating conditions of the process streams. An example of cost data for different materials of construction is given in table 1. "A" is exchanger area in m^2 [6].

A (CS-SS) exchanger, means the shell is made from carbon steel and tubes from stainless steel, and cost of such exchanger can be determined using the appropriate cost model. For example suppose the area of exchanger is

Table1: Cost data of an exchanger with various materials of construction

Exchanger Materials	Capital Cost($)
Shell & Tube (CS-CS)	$30800 + 750\ A^{0.81}$
Shell & Tube (SS-SS)	$30800 + 1644\ A^{0.81}$
Shell & Tube (CS-SS)	$30800 + 1339A^{0.81}$
Shell & Tube (Ti-Ti)	$30800 + 4407A^{0.81}$
Shell & Tube (CS-Ti)	$30800 + 3349\ A^{0.81}$
Shell & Tube (SS-Ti)	$30800 + 3749\ A^{0.81}$

10 m^2, and the actual cost of the exchanger is \$39445. In this case, if both shell and tubes were assumed to be from carbon steel, then the cost of the exchanger from CS-CS cost model in table 1 may be found as \$35642 (lower than actual cost). However, if SS-SS cost model was chosen, the cost would be found as \$41414 (higher than actual cost). Now let us consider the following equation:

***Cost of Exchanger* (CS-SS), (\$) =**

$$35642X + 41414Y = 39445 \tag{2}$$

Where X and Y are the cost contributions of carbon steel shell and stainless steel tubes. The same can be done for A= 20 m^2.

***Cost of Exchanger* (CS-SS), (\$) =**

$$39289X + 49409Y = 45957 \tag{3}$$

The solution to equations (2) and (3) gives X= 0.341058 and Y= 0.658932. These values can be considered as cost contribution factors for carbon steel (X) and stainless steel (Y) in a mixed material exchanger. Therefore, (CS-SS) cost model can be rewritten as:

***Cost of Exchanger (*CS-SS),(\$) =**

$$10507.9128 + 255.8745A^{0.81} + 20292.0872 + 1083.123A^{0.81} \tag{4}$$

Where the cost of shell and tubes are now decomposed. This procedure is repeated for other materials and the corresponding cost models are summarized in Table 2.

The proposed models have also been used to calculate the cost of exchangers with larger area (50 ***m***^{2} & 500 ***m***^{2}). The results are represented in table 3 and compared with those of the old cost models (Table 1).Values in parentheses show the results of the old model (Table 1).

To illustrate the area of one match, two streams are considered as in Fig. 1.

Cost of Exchanger,(\$)=

$$(10507.9128 + 255.8745A^{0.81})_{\text{shell}} + (20292.0872 + 1083.123A^{0.81})_{\text{tube}} \tag{5}$$

The superstructure of a heat exchanger containing all possible configurations is shown in Fig. 2. As can be seen, each stream splits into two streams and passes through tubes or shell.

In a heat exchanger, if the hot stream is corrosive and the cold stream non-corrosive, then the hot stream should be introduced into tubes which are made from a resistant material such as stainless steel, while the shell can still be made from less expensive material like carbon steel. However, sending hot stream through shell will force the exchanger to be made entirely from stainless steel and therefore would be more expensive. Table 4 shows all possible configurations for such a heat exchanger.

Zero values indicate the configurations, which are not possible or economically not feasible.

To account for these configurations, two binary variables (one for shell and one for tubes) must be assigned in the objective function. Now the corresponding cost model can be selected based on the appropriate configuration. Table 5 can be used as cost models reference for any configuration.

All configurations of superstructure are shown in Table 6. The possible arrangements are shown using binary variable 0,1. The non economical and impossible arrangements are shown using the binary variable 0.

Thus, there are four feasible exchangers for each case. This problem is shown with two types of binary variables. Binary variable $z_{t,ij}$ is equal to 1 if the cold stream passes through tubes and equal to 0 if otherwise. The other binary variable $z_{s,ij}$ is 1 if the cold stream passes through the shell and 0 if otherwise. This arrangement is shown in Table 7 and 8.

Finally, the general cost model can be defined as the capital cost for each exchanger. Obviously, this can be expanded to the capital cost for the heat exchanger network. The capital cost of an exchanger consists of cost of tubes and cost of shell.

The general cost model for a heat exchanger is shown below:

General Cost Model for a Heat Exchanger =

$$(a_{t,i} + a_{s,j})z_{s,ij} + (a_{t,j} + a_{s,i})z_{t,ij} + ((b_{t,i} + b_{s,j})z_{s,ij} + (b_{t,j} + b_{s,i})z_{t,ij})A^{0.81} \tag{6}$$

For match H2 - C2 we have i=2 , j=2

Table 2: Cost models for different materials of construction (tube cost & shell cost)

Exchanger Specification	Capital Cost ($)
Shell (CS)	$10508 + 255.874\ A^{0.81}$
Tube(CS)	$20292 + 494.125\ A^{0.81}$
Shell(SS)	$10508 + 560.877\ A^{0.81}$
Tube(SS)	$20292 + 1083.123\ A^{0.81}$
Shell(Ti)	$10508 + 1389.7\ A^{0.81}$
Tube(Ti)	$20292 + 3017.31\ A^{0.81}$

Table 3: Comparison of the two models

Material	A=50 m^2	A=500 m^2
(CS-CS)	48633(48633)	45940(45940)
(SS-SS)	69890 (69890)	283188(283188)
(CS-SS)	62638 (62638)	236364(236364)
(Ti-Ti)	135587(135587)	707364(707364)
(Cs-Ti)	108628(110430)	533300(544939)
(SS-Ti)	115880 (119941)	580124(606347)

Table 4: Possible configuration for the heat exchanger

Stream	Hot (Tube)	Hot (Shell)
Cold (Tube)	0	0
Cold (Shell)	1	0

Table 5: Cost models for any configuration

St.	Spe	a_t	a_s	b_t	b_s
H1	SS	20292	10508	183.12	560.877
H2	CS	20292	10508	494.125	255.874
C1	CS	20292	10508	494.125	255.874
C2	Ti	20292	10508	3017.31	1389.7

Table 6: All configurations of two streams and two cold streams in each stage

Streams	$(H1)_t$	$(H1)_s$	$(H2)_t$	$(H2)_s$
Cold 1 (Tube)	0	0	0	0
Cold 1 (Shell)	1	0	1	0
Cold 2 (Tube)	0	1	0	1
Cold 2 (Shell)	0	0	0	0

$$\mathrm{Cost} = \$(20292\times 0+10508\times 1+20292\times 1+10508\times 0)+$$
$$(255.874\times 1+1389.7\times 0+3017.31\times 1+1389.7\times 0)A$$

Finally the cost model can be defined as:

$$\mathrm{Cost} = \$(10508 +20292) +(255.874*1 +3017.31)*A^{0.81} \tag{7}$$

PROBLEM STATEMENT

Fig. 3 shows a two stages superstructure for a two hot – two cold stream synthesis problem. At each stage, each hot stream splits into twice the number of cold streams and each cold stream splits into twice the number of hot streams.

Each stream can pass through tubes or shell based on configuration. The heat exchanger network synthesis (HENs) problem addressed in this paper can be stated as follows: Given are a set of hot process streams (HP) to be cooled and a set of cold process streams (CP) to be heated up.The available data are:

1- Heat capacity flow rates,
2- The initial and target temperatures for each stream ,
3- The temperature of hot and cold utility,
4- Material of construction for each stream,
5- Binary variables corresponding to the best configuration.

Solution to the objective function, subject to constraints will reveal the minimum hot and cold utility loads, selection of appropriate matches and their heat loads, the number of units, optimum flows for possible stream splits, and the area of each exchanger for mixed materials of construction. However, in this study, the following basic assumptions are made:

1- Constant heat capacity flow rates
2-Constant heat transfer coefficients
3- Counter current heat exchangers
4- No phase change
5- No by pass

SUPERSTRUCTURE AND FORMULATION

In this section, an MINLP formulation for the synthesis of an optimal heat exchanger network is presented. The formulation is based on a network superstructure (Fig. 3) and consists of a number of stages. It allows for every potential match within each stage by splitting the streams.

Table 7 : Binary variables for cold streams passing through tubes ($z_{t,ij}$)

Streams	Hot 1 (Shell)	Hot 2 (Shell)
Cold 1 (Tube)	0	0
Cold 2 (Tube)	1	1

Table 8: Binary variables for cold streams passing through shells ($Z_{s,ij}$).

Streams	Hot 1 (tube)	Hot 2 (tube)
Cold 1 (Shell)	1	1
Cold 2 (Shell)	0	0

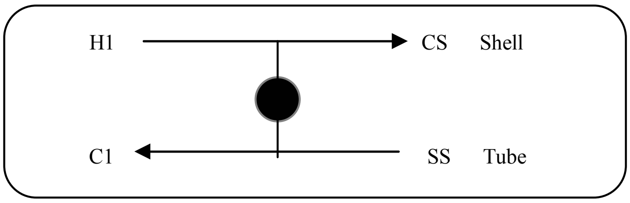

Fig. 1: Heat exchange between two streams

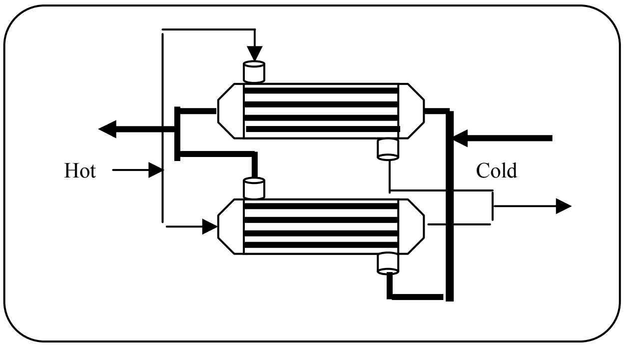

Fig. 2: *The superstructure of a heat exchanger*

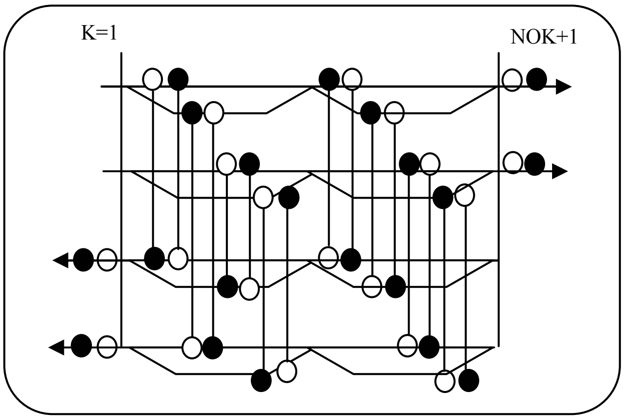

Fig. 3: Superstructure of HEN

The superstructure is simple enough to keep the large nonlinear combinatorial heat exchanger network synthesis problem tractable with available solution techniques.

The superstructure is conceptually similar to a spaghetti design. However, it differs in two important ways:

1) The number of stages is two, smaller than the number of enthalpy intervals and less than the number of stages recommended by Yee and Grossmann [9].

2) There is an opportunity for crisscross heat transfer when beneficial (streams have quite different heat transfer coefficients). The outlet temperatures of every stage are considered as variables for optimization.

In a two-stage superstructure for a problem involving two hot and two cold streams, a matching scheme may be developed within each stage as follows:

Each hot stream splits into as many branches as the number of cold streams.

Each cold stream splits into as many branches as the number of hot streams within the interval and Every hot stream is then matched with every cold stream once.

In this method, binary variables ($z_{t,ij}$ and $z_{s,ij}$) define the best configuration of matches between hot streams and cold streams so as to minimize the total annual cost.

Filled circles show streams passing through tubes and hollow circles show streams passing through shells. However, there are certain restrictions which should be considered. An isothermal mixing junction is assumed at the outlets of the stages. This simplification allows elimination of the mixing junction equations and the nonlinear heat balances for the individual stream splits.

Binary variables ($z_{t,ij}$ and $z_{s,ij}$) account for the existence of matches. These binary variables are also used to define forbidden matches or other restrictions in heat exchanger network synthesis.

Indices

i = hot process or utility stream.
j =cold process,
k = stage number

sets

HP = $\{ i \mid i$ is a hot process stream$\}$,

HU =Hot utility,
CP = { j | j is a cold process stream},
CU= Cold utility,
ST = Stage number in the superstructure,
NOK= Total number of stages.

Data

TIN = inlet temperature of stream,
TOUT = outlet temperature of stream,
F = heat capacity flow rate,
U= overall heat transfer coefficient,
b_{ti} = area cost coefficients for hot streams passing through tubes,
b_{tj} = area cost coefficients for cold streams passing through tubes,
b_{si} = area cost coefficients for hot streams passing through shell,
b_{sj} = area cost coefficients for cold streams passing through shell,
a_{ti} = fixed charge of exchanger for hot streams passing through tubes,
a_{tj} = fixed charge of exchanger for cold streams passing through tubes,
a_{si} = fixed charge of exchanger for hot streams passing through shell,
a_{sj} = fixed charge of exchanger for cold streams passing through shell,

Parameters

CHU= Cost of hot utility,
B= Exponent of area cost,
QHU= Total hot utility usage,
Ω= An upper bound of heat load of exchanger,
Γ= An upper bound of temperature difference,

Binary Variable

z_{ij} = Binary variable to denote existence of match (i,j),
zhu_j = Binary variablesto denote that cold stream j, exchanges heat with hot utility,
zcu_i = Binary variable to denote that hot stream i exchanges heat with cold utility,
z_{ijk}= Binary variable to denote existence of match(i,j) in stage k,
z_s= Binary variable to denote cold stream passing through shell,
z_t= Binary variable to denote cold stream passing through tubes,
$z_{t,cu}$= Binary variable to denote cold utility passing through tubes,
$z_{s,cu}$= Binary variable to denote cold utility passing through shell,
$z_{t,HU}$= Binary variable to denote hot utility passing through tubes,
$z_{s,HU}$= Binary variable to denote hot utility passing through shell,

Positive Variables

$dt_{i,k}$ =Approach temperature for match (i,j) at temperature location k,
$dtcu_i$ = Approach temperature for the match of hot stream i and cold utility,
$dthu_j$ =Approach temperature for the match of cold stream j and hot utility,
q_{ijk} = Heat exchanged between hot process stream i and cold process stream j in stage k,
qhu_j =Heat exchanged between hot utility and cold stream j,
qcu_i =Heat exchanged between cold utility and hot stream i,

With above definitions, the formulation can now be presented. In the superstructure, utility streams can in general be treated as process streams with unknown flow rates. However, for simplicity in the presentation, utility streams are matched only at the outlet of the superstructure.

Overall heat balance for each stream

An overall heat balance for each stream is needed to ensure sufficient heating or cooling of each process stream. The overall energy balances for the hot and cold streams are given below:

$$(TIN_i - TOUT_i)MCp_i = \sum_{k\in ST}\sum_{j\in CP} q_{ijk} + qcu_i \qquad (7)$$

$$(TOUT_j - TIN_j)MCp_j = \sum_{k\in ST}\sum_{i\in HP} q_{ijk} + qhu_j$$

Heat balance at each stage

An energy balance is also needed at superstructure to determine the temperature.

Energy balances for hot and cold streams in each stage are given as:

$$(t_{i,k} - t_{i,k+1})MCp_i = \sum_{j \in CP} q_{ijk} \qquad (8)$$

$$(t_{j,k} - t_{j,k+1})MCp_j = \sum_{i \in HP} q_{ijk}$$

Assignment of superstructure inlet temperature

Fixed inlet temperature of the hot process streams (TIN) are assumed and assigned as the inlet temperatures to the superstructure. For hot streams, the superstructure inlet corresponds to temperature location k =1, while for cold streams, the inlet corresponds to location NOK+1

$$TIN_i = t_{i,1} \qquad (9)$$

$$TIN_j = t_{j,NOK+1}$$

Feasibility of temperature

Constraints are also needed to specify a monotonic decrease of temperature at each successive stage k. In addition, a bound is set for the outlet temperature of the superstructure. Note that the outlet temperature of each stream at stage does not necessarily correspond to the cold stream’s target temperature since the hot utility load for each cold stream is determined based on its target temperature, as given by these equations:

$$t_{i,k} \geq t_{i,k+1} \qquad (10)$$

$$t_{j,k} \geq t_{j,k+1}$$

$$TOUT_i \leq t_{i,NOK+1}$$

$$TOUT_j \geq t_{j,1}$$

Hot utility load

Hot utility (qhu_j) and cold utility (qcu_i) are assumed to be placed outside the superstructure. Hence the utility load for each stream is determined based on its temperature at the outlet of the superstructure and its target temperature.

$$(t_{i,NOK+1} - TOUT_i)MCp_i = qcu_i \qquad (11)$$

$$(TOUT_j - t_{j,1})MCp_j = qhu_j$$

Logical Constraints

Logical constraints and binary variables are needed to determine the existence of the process match. The 0-1 binary variables are represented by z_{ij} for process stream matches and zhu_j for matches involving hot utilities and zcu_i for matches involving cold utilities.

$$q_{ijk} - \Omega z_{ijk} \leq 01 \qquad (12)$$

$$qcu_i - \Omega zcu_i \leq 0$$

$$qhu_j - \Omega zhu_j \leq 0$$

$$z_{ijk}, zcu_i, zhu_j = 0,$$

Calculation of approach temperature

Since the superstructure assumes isothermal mixing at the stage outlets, the area calculation can be done using the temperature differences at the stage boundaries. When the heat load on a match is zero (i.e., it does not exist), the area requirement of the match is zero irrespective of the temperature differences. However, it is possible to get negative temperature differences for a match of zero load when the hot stream temperature is less than the cold stream temperature. To avoid numerical errors, the calculation of temperature differences is done with the binary variables for match existence. The following equations appropriately set the temperature differences when the match exists.

Objective Function

$$dt_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma(1 - z_{ijk}) \qquad (13)$$

$$dt_{ijk+1} \leq t_{i,k+1} - t_{j,k+1} + \Gamma(1 - z_{ijk})$$

$$dtcu_i \leq t_{i,NOK+1} - TOUT_{CU} + \Gamma(1 - zcu_i)$$

$$dthu_j \leq TOUT_{HU} - t_{j,1} + \Gamma(1 - zhu_j)$$

For the simultaneous optimization of energy and area targets, the objective function involves cost terms for hot utility and area. The objective function to be minimized is the total annual cost target for the network. The Paterson approximation is used for log means temperature difference (LMTD). In this formulation for simultaneous energy and area targeting, the objective function involves cost terms for energy, units and area.

$$TAC = \min CHU \sum_{j \in CP} qhu_j + CCU \sum_{i \in HP} qcu_i + \qquad (14)$$

$$\sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} CF_{ij} Z_{ij} + \sum_{j \in CP} CF_{HU,j} zhu_j +$$

$$\sum_{i \in HP} CF_{i,HU} zcu_i +$$

$$\sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST}\left[\frac{q_{ijk}\times((b_{t,i}+b_{s,j})z_{s,ij}+(b_{t,j}+b_{s,i})z_{t,ij})^{\frac{1}{B}}}{\dfrac{(h_{t,i}\times h_{s,j})z_{s,ij}+(h_{s,i}\times h_{t,j})z_{t,ij}}{(h_{t,i}+h_{s,j})z_{s,ij}+(h_{s,i}+h_{t,j})z_{t,ij}}\mathrm{LMTD}_{ij}}\right]^{B}+$$

$$\sum_{i\in HP}\left[\frac{qcu_{i}\times((b_{t,i}+b_{s,cu})z_{s,cu}+(b_{t,cu}+b_{s,i})z_{t,cu})^{\frac{1}{B}}}{\dfrac{(h_{t,i}\times h_{s,cu})z_{s,cu}+(h_{t,cu}\times h_{s,i})z_{t,cu}}{(h_{t,i}+h_{s,cu})z_{s,cu}+(h_{t,cu}+h_{s,i})z_{t,cu}}\mathrm{LMTD}_{i,cu}}\right]^{B}+$$

$$\sum_{i\in HP}\left[\frac{qhu_{j}\times((b_{t,j}+b_{s,HU})z_{s,HU}+(b_{t,HU}+b_{s,j})z_{t,HU})^{\frac{1}{B}}}{\dfrac{(h_{t,j}\times h_{s,HU})z_{s,HU}+(h_{t,HU}\times h_{s,j})z_{t,HU}}{(h_{t,j}+h_{s,HU})z_{s,HU}+(h_{t,HU}+h_{s,j})z_{t,HU}}\mathrm{LMTD}_{i,HU}}\right]$$

The advantage of this approach is that the pressure drop in each side of the exchanger (shell or tubes) can be assessed. This leads to a more accurate evaluation of corresponding heat transfer coefficient for each individual stream.

CASE STUDIES

Case Study 1

This example is taken from Shenoy [10] involving two hot and two cold streams, 1 cold utility and 1 hot utility stream. The overall heat transfer coefficients for all matches are the same. The specification for all streams is shown in Table 9.

The corresponding MINLP model, involves 66 single equations, 53 single variables and 12 discrete variables. The example was solved by MINLP model to minimize Total Annual Cost (TAC). The final optimum network is shown in Fig. 4.

The annual cost of hot utility and cold utility is \$/yr51200. The area requirement is 1590m^2 and the total capital cost is \$851602. The solution obtained by the proposed method is 17.8% lower than the solution produced by commercialy available software, Supertarget 6.

Case Study 2(Threshold Problem)

This example is taken from Gundersen & Grossmann [11] and again involves two hot and two cold streams, 1 cold utility and 1 hot utility stream. The overall heat transfer coefficients for all matches are the same. The specification for all streams is shown in Table 13.

Table 9: Problem data for case study 1

Stream	Tin (°C)	Tout (°C)	MCp	h	Spec
H1	175	45	10	0.2	SS
H2	125	65	40	0.2	CS
C3	20	155	20	0.2	SS
C4	40	112	15	0.2	CS
HU	180	179	__	0.2	CS
CU	15	25	__	0.2	CS
Cost Hot utility =120			Cost Cold utility = 10		

$A_f = (1+i)^n/n$

A_f= Annualization Factor

i = Rate of Return of Capital Interest =0.1

n =Expected Plant Life=5 year

Table 10: Results of HEN in this work

HX	Q (kW)	Area (m^2)	Materials of Construction
1	460.735	171.534	SS/SS
2	519.265	202.273	CS/SS
3	1839.265	712.340	CS/SS
4	560.735	305.547	CS/CS
5	400	119.009	CS/SS
6	320	80.004	CS/SS
Total	4100	1590	

Table 11: The results of HEN using Supertarget

HX	Q (kW)	Area (m^2)	Materials of Construction
1	460.2	183	SS/SS
2	639.8	377	CS/SS
3	1839.265	972	CS/SS
4	440.2	305.547	CS/CS
5	400	119.009	CS/SS
6	200	59	CS/SS
7	120	26	CS/CS
Total	4100	2041	

The corresponding MINLP model, involves 66 single equations, 53 single variables and 12 discrete variables. The example was solved by MINLP model to minimize TAC. The final optimum network is shown in Fig. 6.

The annual cost of hot utility is \$/yr 81000 and no cold utility is needed. The area requirement is 3954.25m^2 and the total capital cost is \$2594554. If the Supertarget 6 was used, the TAC would have been 1052173\$/yr this is about 14.7% higher than the solution obtained by the proposed method of this paper.

Case Study 3

This example is taken from Hall [6] and involves five hot and four cold streams, 1 cold utility and 1 hot utility stream. The specification for all streams is shown in Table 17, and the resultant network is shown in Fig. 8. The comparison of results is presented in Table 18, showing 2.5 % reduction in capital cost.

CONCLUSIONS

Design of heat exchanger networks involves two tasks: synthesis of the HEN structure and determination of exchanger heat loads in order to meet the specified requirements.

Conceptually speaking, two methods are presented based on the pinch technology, the first method is present by Hall et al. [6], which accounts for non-uniform exchanger specification but assumes equal area distribution and the second method is presented by Jegede and Polley [8], which is than first method, because it accounts for specifications in terms of matches rather than in terms of stream but these targeting approaches don't apply to design heat exchanger network.

This paper has presented an automatic approach and a simple methodology for the cost estimation of a near optimal heat exchanger network, which comprises mixed materials of construction However, the approach may be extended, with reduced accuracy to networks comprising different exchanger type (Plate and Frame – Spiral) by use the same exponent of shell and tube heat exchanger and design heat exchanger network by mathematical programming.

The proposed model was utilized and examined in three different case studies and the results were compared with those of a commercially available software (SUPERTARGET). The comparison shows reduction of

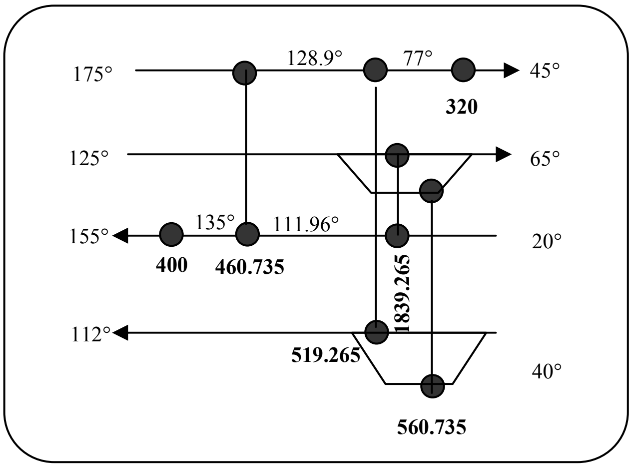

Fig. 4: Optimum design for HEN by Model

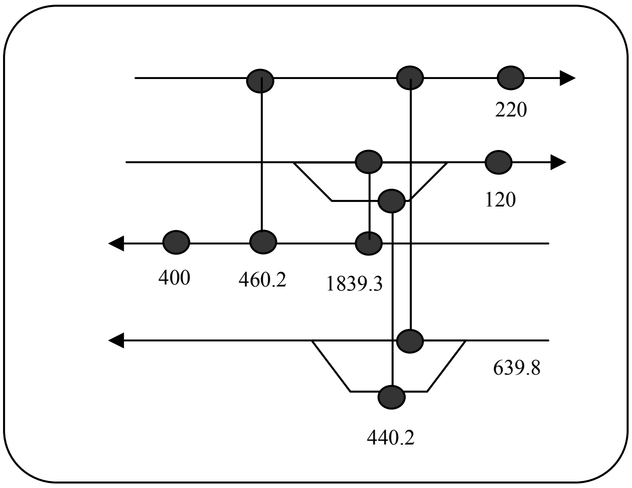

Fig. 5: Optimum design for HEN by Supertarget

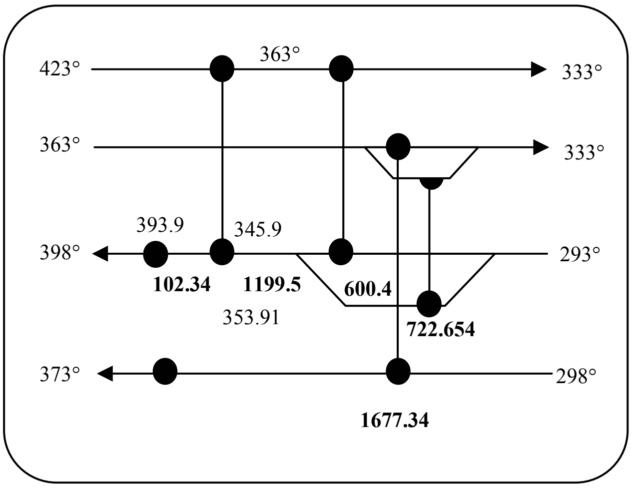

Fig. 6: Optimum design for HEN

Table 12: Comparison of results of HEN

Specification	This work	Supertarget
Hot Utility (kW)	400	400
Cold Utility (kW)	320	320
Number of Units	6	7
Area	1590	2041
Operating cost ($/yr)	51200	51200
Capital Cost ($)	851602	1031584
Total annual Cost ($/yr)	325502	383475.2

Table 13: Problem data for case study 2

Stream	Tin (°k)	Tout (°k)	MCp kW/°K	h	Spec
H1	423	333	20	0.1	Ti
H2	363	333	80	0.1	SS
C3	293	398	25	0.1	CS
C4	298	373	30	0.1	SS
HU	453	452		0.1	CS
CU	288	293		0.1	Ti
Cost Hot utility =120			Cost Cold utility = 10		

$A_f = (1+i)^n/n$

A_f= *Annualization Factor*

i = *Rate of Return of Capital Interest* =0.1

n =*Expected Plant Life*=5 *year*

Table 14: Results of HEN

HX	Q (kW)	Area (m^2)	Materials of Construction
1	1199.547	1063.058	CS/Ti
2	600.453	445.586	CS/Ti
3	722.654	536.574	CS/SS
4	1677.346	1743.762	SS/SS
5	102.346	36.208	CS/CS
6	572.654	129.067	CS/SS

Table 15: Rresults of HEN using Supertarget

HX	Q (kW)	Area (m^2)	Materials of Construction
1	390.9	160	CS/Ti
2	40	20	CS/Ti
3	1519.1	1422	CS/SS
4	880.9	730	SS/SS
5	675	201	CS/CS
6	1369.1	1919	SS/Ti
Total	4875	4452	

Table 16: Comparison of results of HEN

Specification	This work	Supertarget
Hot Utility (kW)	675	675
Cold Utility (kW)	0	0
Number of Units	6	5
Area	3954.25	4203.2
Operating cost ($/yr)	81000	81000
Capital Cost ($)	2594554	3015110
Total annual Cost ($/yr)	916711	1052173

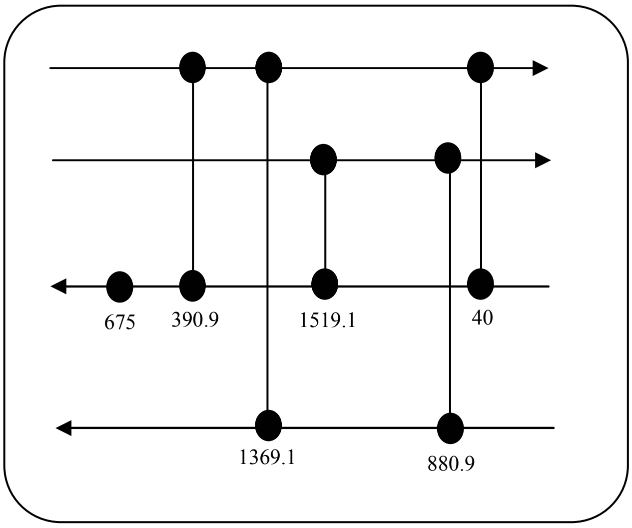

Fig. 7: Optimum design for HEN by supertarget

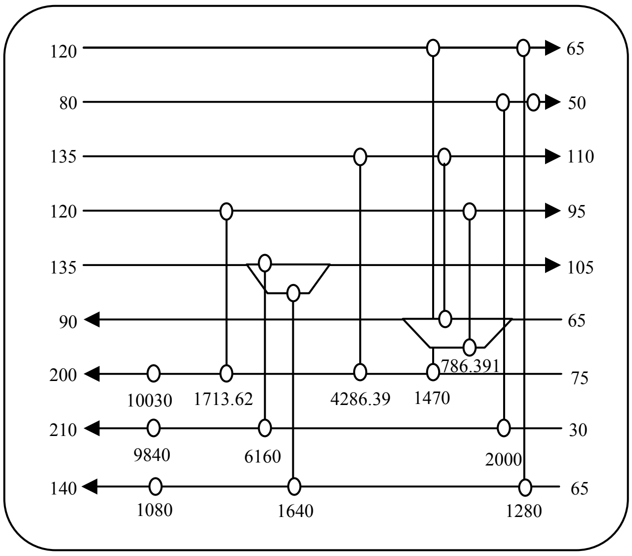

Fig. 8: Optimum design for HEN (ΔTmin=20 °C)

Table 17: Problem data for case study 2

Stream	Tin (°C)	Tout (°C)	MCp (kW/°C)	h (kW/m^{2}C)	Specification
H1	120	65	50	0.5	CS
H2	80	50	300	0.25	CS
H3	135	110	290	0.3	SS
H4	220	95	20	0.18	SS
H5	135	105	260	0.25	CS
C6	65	90	150	0.27	SS
C7	75	200	140	0.25	CS
C8	30	210	100	0.15	CS
C9	60	140	50	0.45	SS
HU	250	249		0.3	CS
CU	15	25		0.2	CS
Cost Hot utility =120			Cost Cold utility = 10		

$A_f = (1+i)^n/n$

A_f= *Annualized Factor*

i = *Rate of Return of Capital Interest =0.1*

n =*Expected Plant Life=5 year*

Table 18: The comparison of results of HEN

	Hall [6]	Jegede [8]	This Work
Energy Consumption (MW)	20.95	20.95	20.95
Area (m^2)	9739	9659	9724
No of Units	13	13	13
Capital Cost ($)	2971438	2986560	2895651

more than 17% and 14% in total annual costs in the two cases, and 2.5% in third, confirming the fact that more accurate evaluation of heat transfer coefficient for each individual stream can lead to better network design.

Nomenclature

A	Heat exchanger area
MCp	Heat capacity flow rate
h	Film heat transfer coefficient
q	Heat load for an exchanger
T	Temperature
U	Overall heat transfer coefficient
z	Binary variable
LMTD	Log Mean Temperature Difference
Ω	An upper bound for heat exchange
Γ	An upper bound for temperature, Difference,
	Subscripts
HEN	Heat exchanger network
MINLP	Mixed Integer Non Linear Programming
NLP	Non Iinear Programming
TIN	Inlet Temperature
TAC	Total Annula Cost
TOUT	Outlet Temperature
NOK	Total Number of Stages
i	Hot stream
j	Cold stream
k	Temperature location

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