Retrofit of Heat Exchanger Networks Considering Existing Structure: A New Targeting Procedure

Panjeh Shahi, Mohammad Hassan*
Department of Chemical Engineering, Faculty of Engineering, University of Tehran, Tehran, I.R. Iran

Nouzari, Mohammad Mahdi
Department of Energy Engineering, Faculty of Engineering, Science and Research Branch, Islamic Azad University, Tehran, I. R. Iran

ABSTRACT: *A new retrofit targeting procedure, based on pinch technology has been developed. The new procedure considers existing structure of a given network and finds the most compatible configuration with the network. To achieve this aim, the procedure uses a linear programming technique that maximizes the compatibility. Good compatibility between old and new networks helps to make the best use of capital in retrofit projects.*

The procedure has been tested by doing two case studies, in which the results compared to other established methods, and realized significant improvement.

KEY WORDS: Pinch technology, Retrofit, Heat exchanger networks, Targeting, Network Structure, Area matrix

INTRODUCTION

Retrofit of heat exchanger networks using pinch technology, is the main part of process integration technology. During retrofit, energy consumption of processs is reduced by improving energy efficiency of heat exchanger network. To achieve this purpose, new area in the network is installed. The cost of additional area against energy saving defines project economics. The project scope will be set according payback period and / or investment limit.

During the past two decades, many retrofit procedures have been developed and applied to different process industries. *Tjoe* and *Linnhoff* [1] proposed the first Pinch retrofit method and introduced the concept of Area Efficiency of HEN's. *Shokoya* and *Kotjabasakis* [2] proposed a technique based on area distribution matrix that overcomes the limitations introduced by Tjoe's method. *Polley* and *Panjeh Shahi* [3] extended the targeting and design procedures of Tjoe and Linnhoff by considering stream allowable pressure drops.

In recent years, *Nie* and *Zhu* [4] proposed a decomposition strategy in which the unit-based model is used to indicate which units require additional area, then special attention is paid to these units, in terms of pressure drop constraints. Thus, units with and without additional area requirements are treated differently during optimization. *Zhu* and *Asante* [5] also proposed a diagnosis and optimization approach for retrofitting. This approach searches for topology changes in diagnosis stage, followed by an evaluation and cost optimization stages. Promising modifications are selected from the diagnosis stage and assessed in terms of the impacts on implementation cost, operability and safety.

* *To whom correspondence should be addressed.*
1021-9986/2001/1/44 9/$/2.90

Urbaniec et al. [6] also proposed and applied another version of decomposition approach to retrofit design of energy systems in the sugar industry. In this approach, the energy system is decomposed, that is, conceptually separating the evaporator (in which vapors and condensates are generated) from the process heating subsystem (in which these heat carriers can be regarded as utilities).

It is quite obvious that each of these methods have their own advantages and disadvantages. So, in order to develop a better and more efficient retrofit approach two or three methods might be modified and combined to build a new one. In this paper, we first try to modify the Area Matrix approach proposed by *Shokoya* and *Kotjabasakis* [2] to overcome its problems and low accuracy, and then, in the second stage (which will be presented in another article) combine the modified method with fixed pressure drop approach proposed by *Polley* and *Panjeh Shahi* [3]. Therefore, this article represents the first part of a research for simultaneous consideration of both existing network structure and stream allowable pressure drops.

Energy and area targeting

The concept of targeting prior to design define how a process can be operated in best order to achieve a desired result. Minimum energy and area of process are two important targets.

For energy targeting at each minimum temperature approach (ΔT_{min}), it is necessary to construct the 'composite curves'[7]. According to Fig. 1, minimum energy consumption of process is the right overshoot of the composite curves.

For calculating minimum heat exchange area, we should apply vertical heat transfer model by dividing composite curves into enthalpy interval regions. According to this model, *Townsend* and *Linnhoff [8]* presented a simple equation called "Bath Formula" :

$$A_{min} = \sum^{intervals,i} \left(\frac{1}{\Delta T_{LM,i}} \right) \sum^{streams,j} \left(\frac{q_{ij}}{h_j} \right) \qquad (1)$$

where :

$\Delta T_{LM,i}$ is logarithmic mean temperature difference of enthalpy interval i of the composite cureves

q_{ij} is the heat change of stream j in enthalpy interval i

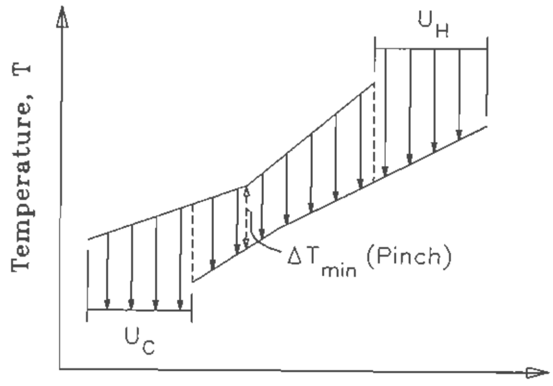

Fig. 1: Composite curves and vertical heat transfer model

h_j is the heat transfer coefficient of stream j (including film, wall and fouling resistance)

The equation can be written in a revised form :

$$A_{min} = \sum^{streams,j} A_j = \sum^{streams,j} \sum^{intervals,i} \left(\frac{1}{\Delta T_{LM,i}} \right) \left(\frac{q_{ij}}{h_j} \right) \qquad (2)$$

where A_j is termed the 'area contribution of stream j'.

We can write minimum area equation in stream wise form (based on area contributions) or match wise form (based on contact area). The relation between area contribution and contact area has been shown in the Fig. 2.

The two above equations are both in stream wise formulation. It is possible to rewrite minimum area equation in match wise form. According to spaghetti model we will have :

$$A_{min} = \sum^{streams,j} A_{cj} = \sum^{streams,j} \sum^{intervals,i} \left(\frac{q_{ij}}{\Delta T_{LM,i}} \right) \left(\frac{1}{h_j} + \sum^{opposing\,streams,k} \frac{CP_k}{\sum CP_k} \frac{1}{h_k} \right) \qquad (3)$$

It is clear that both minimum energy and area requirement are functions of the selected minimum temperature difference approach. Thus, by varying the temperature approach, we can develop a relationship between the minimum energy and area needs. Fig. 3 shows the relationship on "area-energy plot" as an ideal curve.

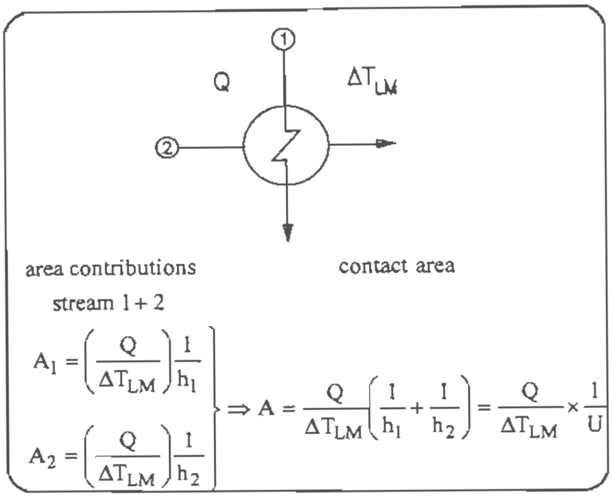

Fig. 2: Relationship between area contributions and contact area

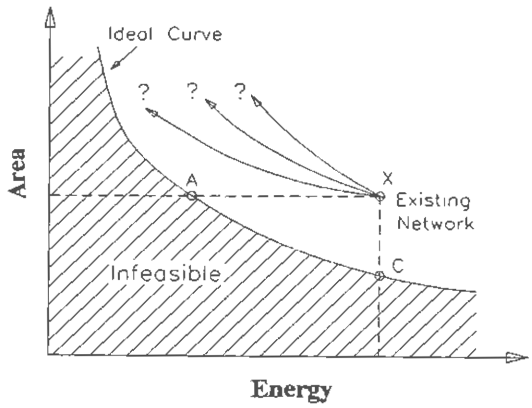

Fig. 3: Area-energy plot, ideal curve and retrofit strategy

In retrofit problem, the first step is to compare the performance of existing plant (point X in Fig. 3) with the ideal curve (point C in Fig. 3). *Tjoe* and *Linnhoff* [1] defined area efficiency (α) for the comparison :

$$\alpha = \frac{A_{ideal}(\text{point C})}{A_{existing}(\text{point X})} \qquad (4)$$

It is obvious that better retrofits are those which make good use of the existing area.' The ideal retrofit would move from existing inefficient point (X) to the most efficient that could have been achieved with the same area (point A). However, given that any modifications are going to require investment, it is expected to follow a path similar to those shown in Fig. 3. The optimum retrofit path cannot be determined simply.

Established retrofit targeting- α based procedures

Tjoe and *Linnhoff* suggested a way in which a bound could be placed . They argued that a retrofit which used area less efficiently than the existing plant was unlikely to be cost effective. They then assumed that all retrofits at least maintain area efficiency and suggested a constant efficiency line on the plot (Fig. 4). The method is called "Constant α". s

According to Fig. 4, all points on targeting curve have the same area efficiency. It means that:

$$\alpha = \frac{A_{tx}}{A_x} = \frac{A_{ty}}{A_y} \qquad (5)$$

The constant α method provides a reasonable bound on the location of good retrofits. However, for the targeting of project scope, the curve can be too conservative. *Silangawa* [9] recommends that if the efficiency of existing network is 0.9 or less, a curve parallel to the ideal curve should be used. We know how area should be used in network. We know how area should be used in network. We can, therefore expect the area efficiency of the network to improve as new area added. Silangawa 's method assumes that all of the new area is added in an ideal manner. According to Fig. 4, it means that :

$$A_x - A_{tx} = A_y - A_{ty} \qquad (6)$$

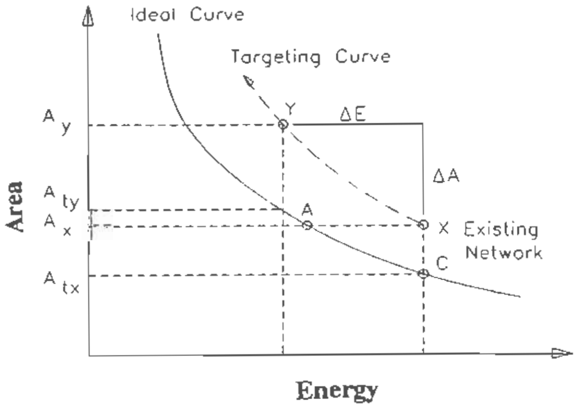

Fig. 4: Area-energy plot, ideal and retrofit targeting curve

Established retrofit targeting-area matrix procedure

Shokoya and *Kotjabasakis* [2] presented a combined method based on pinch technology and mathematical programming. The method considers existing structure of network during retrofit. They argued a new idea that vertical heat transfer model is flexible and is not limited by spaghetti model. Therefore, different forms of vertical heat transfer model can result in minimum area.

The method is called Area Matrix and has a match wise orm. Area Matrix method is based on four matrices: existing area matrix, target area matrix, retrofit area matrix and deviation matrix. Basis of the procedure is to find a form of vertical model that is most compatible with the existing network structure. Linear programming model is used to achieve the above aim. The compatibility between retrofit area matrix and existing area matrix makes that retrofit be performed with minimum modification and less additional area.

The area distribution of the existing network, when represented in matrix format, gives the "Existing Area Matrix". The existing area for each existing match ($A_{e,ij}$) is entered in the cell corresponding to that match. By summing up all the entries in the matrix, we arrive at the total existing area (A_x):

$$A_x = \sum_i \sum_j A_{e,ij} \tag{7}$$

For calculating the minimum area, the spaghetti model is used (vertical heat transfer model). According to the model, the total area of each match ($A_{v,ij}$) is sum of the area of the match, over all enthalpy intervals. If we write the area distribution of all matches in matrix format, we will get the "Target Area Matrix". The sum of all entries in this target area, gives the same minimum heat transfer area requirement :

$$A_{min} = \sum_i \sum_j A_{v,ij} \tag{8}$$

where :

$$A_{v,ij} = \sum_n \frac{Q_{ij,n}}{\Delta T_{LM,n}} \left(\frac{1}{h_i} + \frac{1}{h_j} \right) \tag{9}$$

The "Retrofit Area Matrix" is the optimized form of target area matrix subjected to existing area matrix.

The difference between the retrofit area matrix and the existing area matrix is termed the "Deviation Matrix". Entries in deviation matrix are determined by subtracting the existing matrix from that of retrofit area matrix.

It may be foreseen that some matches have positive deviations, some have negative deviations, whilst others, have zero deviations. The zero deviation implies that the exchanger(s) on the match has(have) been vertically placed in the existing network and no changes to the area is necessary. The positive deviation signify a potential additional area. So the match has a need to install some new area. The negative deviation implies that more area has been installed on the match than is requited for vertical heat transfer. The amount of existing area on the match is composed of a vertical element and a criss-cross element. If we reuse a criss-cross element in retrofit design, criss-crossing iss necessary and we must pay the corresponding penalty. To determine the total criss-cross area, is enough that to calculate sum of the criss-cross elements of all matches in the network. It is equal to the sum of negative entries of the deviation matrix $\left(\sum \text{neg.dev.}\right)$.

For calculating the penalty caused by reusing of criss-cross elements, the method introduced the Penalty Accountability Factor (Y) [10] :

$$Y = \frac{\text{area penalty}}{\sum \text{negative deviations}} \tag{10}$$

It is assumed that Y is a linear function of energy reduction (ΔE). Minimum value of penalty accountability facstor (Y_{min}) is occurred at the existing condition and suppose that the maximum value is 1 and related to zero temperature approach (ΔE_0) . Therefore :

$$Y_{min} = \left. \frac{\text{area penalty}}{\sum \text{negative deviations}} \right|_{\text{existing}} \tag{11}$$

$$Y = Y_{min} + \frac{\Delta E(1 - Y_{min})}{(\Delta E)_0} \tag{12}$$

The additional area equation is then calculated as :

$$\Delta A = (\sum \text{negative deviations}).Y + A_{min} - A_X \tag{13}$$

Although the area matrix procedure is more scientific than α-based methods (i.e. constant α and incremental α) and the targeting result of area matrix is more accurate than α-based methods, but area matrix have two drawbacks.

The first drawback is when sum of negative deviations becomes zero. In such condition, according to Eq. (13), penalty term goes to zero and area efficiency becomes equal to one. However, in retrofit problem, it is rare that all of the network area align vertically and area efficiency of network becomes equal to one.

The second and essential drawback relates to the penalty accountability factor (Y) and its Eq. (12). Penalty accountability factor is not a linear function of energy reduction. Also, its maximum value can be greater than one. These two problems cause that area matrix results at some points have low accuracy (especially when sum of negative deviations is near to zero).

New retrofit targeting procedure: Functional α

For correcting the drawbacks of Linear Y procedure, at first stage, the "Hybrid Targeting Method" is introduced. The method is a combination of area matrix method and constant α method. In this method, we define criss-cross ratio as below :

$$\text{criss-cross ratio} = \frac{\sum \text{neg.dev.}}{A_{min}} \tag{14}$$

When criss-cross ratio is greater than or equal to 0.05, the method uses the area matrix equation. But, when criss-cross ratio is less than 0.05, the method follows the constant α formula and assumes that area efficiency of network is equal to a fixed value (α_{max}). According to the method, we have :

$$\begin{cases} \dfrac{\sum \text{neg.dev.}}{A_{min}} \geq 0.05 \Rightarrow \\ \quad \Delta A = (\sum \text{negative deviations}).Y + A_{min} - A_x \\ \dfrac{\sum \text{neg.dev.}}{A_{min}} < 0.05 \Rightarrow \Delta A = \dfrac{A_{min}}{\alpha_{max}} - A_x \end{cases} \tag{15}$$

Although the hybrid method resolves some disadvantages of area matrix, but the problem related to the penalty accountability factor (Y) still exists.

For solving this problem, we introduce a direct relationship between criss-cross ratio and area efficiency. This work results in the "Functional α" method.

In the new method, we again use the LP optimization to determine the retrofit area matrix :

$$\begin{bmatrix} \text{target} \\ \text{area} \\ \text{matrix} \end{bmatrix} \Leftarrow \text{LP optimization} \Rightarrow \begin{bmatrix} \text{existing} \\ \text{area} \\ \text{matrix} \end{bmatrix}$$

$$\Downarrow$$

$$\begin{bmatrix} \text{retrofit} \\ \text{area} \\ \text{matrix} \end{bmatrix}$$

Fig. 5: LP optimization of target area matrix yields the corresponding retrofit area matrix

then, the deviation matrix is calculated as :

$$\begin{bmatrix} \text{deviation} \\ \text{matrix} \end{bmatrix} = \begin{bmatrix} \text{retrofit} \\ \text{are a matrix} \end{bmatrix} - \begin{bmatrix} \text{existing} \\ \text{are a matrix} \end{bmatrix}$$

Fig. 6: The deviation matrix shows the difference between retrofit and existing area matrices

Now, we can calculate the sum of negative deviations ($\sum$neg.dev.) from the deviation matrix. In this stage we introduce a linear relationship between criss-cross ratio and area efficiency :

$$\alpha = \alpha_{max} - \frac{(\alpha_{max} - \alpha_{existing})}{\left(\dfrac{\sum \text{neg.dev.}}{A_{min}}\right)_{existing}} \times \left(\frac{\sum \text{neg.dev.}}{A_{min}}\right) \tag{16}$$

According to the above equation, we assume that the area efficiency of network is a function of criss-cross ratio, and the area efficiency varies linearly between the existing value and the maximum value. Experience shows that this maximum value is almost the same (0.96) in problems which use assumed-h area algorithm.

The additional area equation is :

$$\Delta A = \frac{A_{min}}{\alpha} - A_{existing} \tag{17}$$

Comparison between functional α procedure and the established retrofit targeting procedures

The main drawback of the α-based procedures (constant α and incremental α) is that they can not incorporate the structure of existing network during targeting. Therefore, their targeting results aren't accurate. Though, the area matrix procedure considers the existing network structure during targeting, and its results is more accurate than the α-based results, but having used the penalty accountability factor (Y) and its wrong equation, some error in targeting results will occur.

The new method not only considers the existing network structure, but also defines the criss-cross ratio parameter and introduces a new relationship that gives more accurate results than all the previous methods.

In Figs. 7 and 8, we show the targeting curves of the method. In Fig. 7, it is shown that targeting curves of constant α method goes far as energy reduction increases, and targeting curves of incremental α method is a curve parallel to ideal curve.

Table 1: Stream data for case study 1

Stream	TS (°C)	TT (°C)	CP $\left(kW/K\right)$	h $\left(kW/m^2K\right)$
H1	165.0	95.0	148.0	0.45
H2	240.0	65.0	86.0	0.35
C1	125.0	220.0	139.0	0.55
C2	61.0	192.0	54.6	0.40
C3	70.0	185.0	62.0	0.64

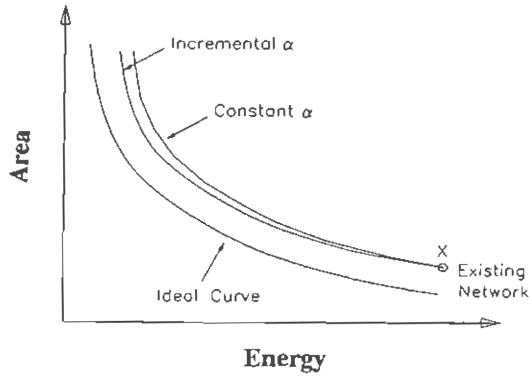

Fig. 7: Targeting curves of α-based methods

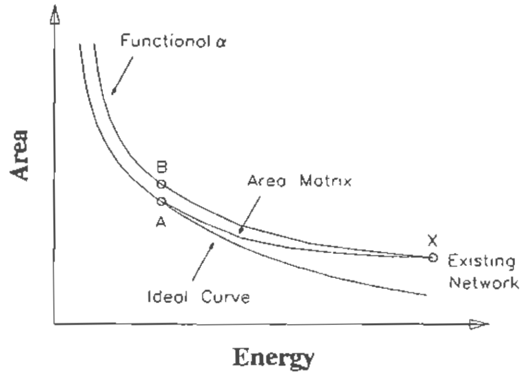

Fig. 8: Targeting curves of area matrix and functional α methods

It can see in Fig. 8 that targeting curve of area matrix gets close to ideal curve as sum of negative deviations reaches to zero (point A), and after the point, targeting curve of area matrix and ideal curve are the same. Also, from Fig. 8, we can see that targeting curve of functional α approaches ideal curve as sum of negative deviations reaches to zero (point B), and after the point, targeting curve of functional α is parallel to ideal curve.

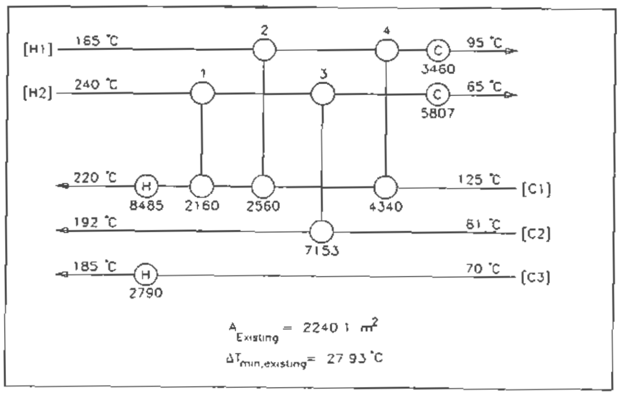

Fig. 9: Heat exchanger network of case study 1

Case study 1-retrofit for energy saving

We want to evaluate accuracy of the new method (functional α)in comparison with the established methods during range targeting. The heat exchanger network and stream data have been shown in Fig. 9 and Table 1, respectively.

The minimum temperature approach for the existing network is 27.93 °C and existing heat exchange area is 2240.1 m^2 that distributed on four exchangers.

Range targeting are performed between 27.93 °C and 5 °C, and then compared additional area of each targeting smethod with the final design. Since the existing area efficiency is less than 0.9, we use incremental α method. The discrepancy of the different targeting methods from design point has been graphically shown in Fig. 10. The absolute values of maximum and minimum error and average of absolute errors have been given in Table 2. It

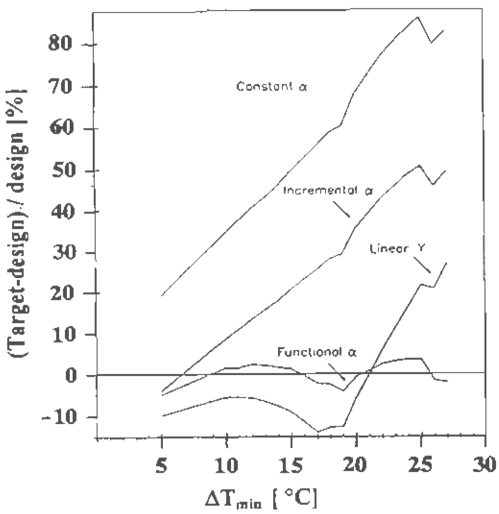

Fig. 10: Discrepancy of targets from design points for case study 1

can be seen that functional α method is more accurate and reliable than other methods.

The targeting curve of functional α method is shown in Fig.11. The comparison between target and design shows area efficiency is a linear function of criss-cross ratio.

Fig.12 demonstrates the targeting curve of area matrix procedure (linear Y method). The comparison between target and design shows penalty accounability factor (Y) is not a linear function of energy reduction ratio ($\Delta E/\Delta E_0$). Also, it shows the design values of Y are greater than one in some points. Though, in linear Y method the maximum value of Y is one.

Case study 2-retrofit for energy saving

We want to evaluate accuracy of the new method (functional α) in comparison with the established methods during range targeting. The heat exchanger network and stream data are shown in Fig. 13 and Table 3, respectively.

The minimum temperature approach for the existing network is 41.9 °C and existing heat exchange area is 2310.1 m^2, that distributed on four exchangers.

We performed range targeting between 41.9 °C and 5 °C, and then compared additional area of each targeting method with the final design values. Since the existing area efficiency is greater than 0.9, we use constant α

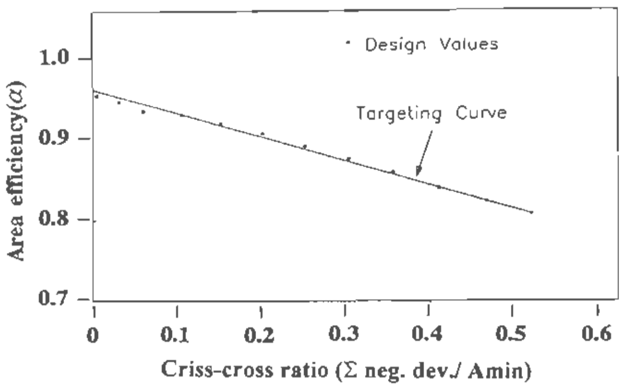

Fig. 11: Variation of area efficiency versus criss-cross ratio for case study 1

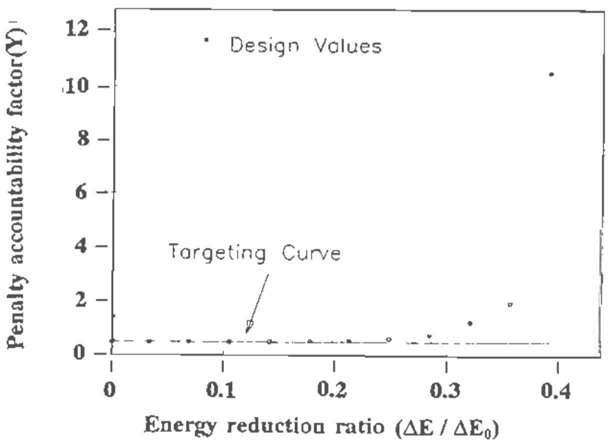

Fig. 12: Variation of penalty accountability factor versus energy reduction ratio for case study 1

Table 2 : Relative error of different methods for case study 1

|Error|, (%)	Constant α	Incremental α	Linear Y	Functional α
Minimum	18.9	4.0	0.2	0.5
Maximum	85.6	50.3	26.7	4.9
Average	58.9	28.9	10.9	2.2

Table 3 : Stream data for case study 2.

Stream	TS (°C)	TT (°C)	CP (kW/K)	h (kW/m^2K)
H1	159.0	77.0	228.5	0.40
H2	267.0	80.0	20.4	0.30
H3	343.0	90.0	53.8	0.25
C1	26.0	127.0	93.3	0.15
C2	118.0	265.0	196.1	0.50

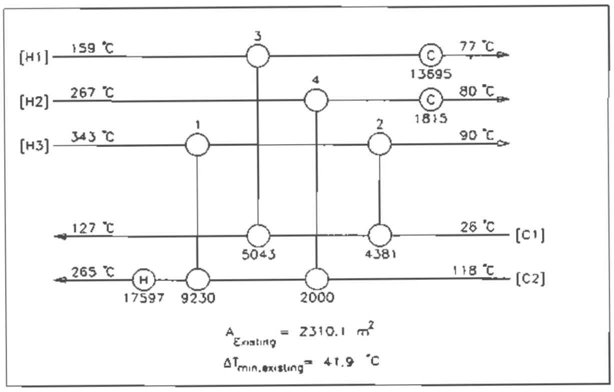

Fig. 13: Heat exchanger network of case study 2

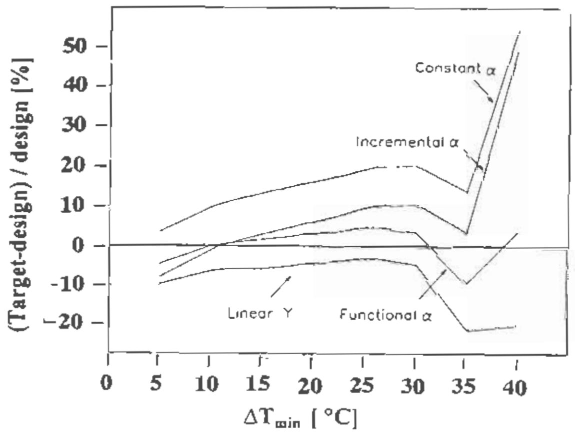

Fig. 14: Discrepancy of targets from design points for case study 2

method. The discrepancy of the targeting methods from design has been shown graphically in Fig. 14. It can be seen that error bound of functional α method is narrow and acceptable. The absolute values of maximum and minimum error and average of absolute errors have been given in Table 4. It is agaim seen that functional α method is more accurate and reliable than other methods.

Fig. 15. demonstrates the targeting curve of functional α method. The comparison between target and design shows that area efficiency is a linear function of criss-cross ratio (approximately). Also, it shows the behavior of targeting curve is not linear in criss-cross ratio less than 0.1.

Fig. 16 shows the targeting curve of area matrix procedure (linear Y method). The comparison between

Table 4 : Relative error of different methods for case study 2.

|Error| , (%)	Constant α	Incremental α	Linear Y	Functional α
Minimum	3.5	0.1	3.2	0.1
Maximum	54.4	39.4	21.4	9.5
Average	16.4	5.9	6.7	3.0

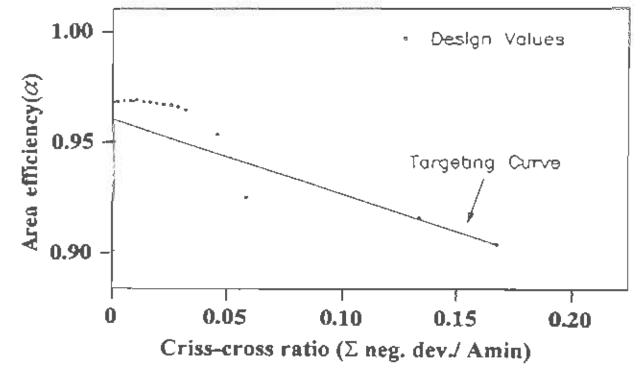

Fig. 15: Variation of area efficiency versus criss-cross ratio for case study 2

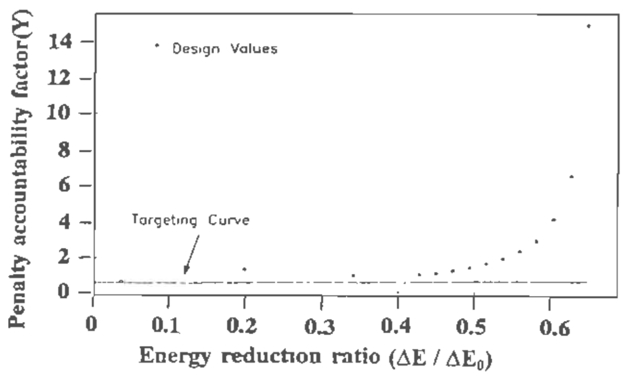

Fig. 16: Variation of penalty accountability factor versus energy reduction ratio for case study 2

target and design shows penalty accounability factor (Y) is not a linear function of energy reduction ratio ($\Delta E/\Delta E_0$). Also, it shows the design values of Y are greater than one in some points. Though, in linear Y method the maximum value of Y is one.

CONCLUSION

The criss-cross ratio, defined in this paper, is an important parameter when performing range targeting in retrofit. According to this parameter, a new method (functional α) has been established which considers the existing structure of the network and uses linear programming technique to find the most compatible structure with the existing structure. By performing two case studies, It is shown that the method is more accurate and reliable than other methods.

Received: 2nd, February 2000; Accepted: 15th, January 2001

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