Heat Exchanger Network Retrofit Considering Pressure Drop and Heat-Transfer Enhancement

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For the heat-exchanger-network (HEN) retrofit project to be successful it should satisfy not only a specified heat-recovery target but also pressure-drop constraints. The problem of dealing with the pressure-drop aspects is very complex, since there are many options that affect pressure drop. To integrate these options more systematically and solve this problem more effectively, a decomposition strategy is proposed. At the first stage, the unit-based model is used to indicate which units require additional area. In the second stage, special attention is paid to these units, where area distribution, shell arrangements, the use of heat-transfer enhancement, and other options are optimized for these units. At the same time, the units without additional area requirement are modeled using simple models. Thus units with and without additional area requirements are treated differently during optimization. By doing this, the pressure drop can be calculated accurately while the overall model remains simple and easy to solve. Heat-transfer enhancement is a very attractive option for HEN retrofit, since it can effectively eliminate or reduce the additional surface area space. This will eliminate additional piping, new shells or units, and their required space, which lead to much lower modification costs and less implementation time.

Introduction and Review

Considerable research effort has been put into deriving methods for the design of heat-exchanger networks (HENs), and an excellent review of these methods has been provided by Gundersen and Naess (1988). Most of the research carried out to date, however, is relevant primarily for grassroots HEN design. The presence of an existing HEN in the retrofit scenario greatly complicates the design task, as the retrofit design procedure must take the existing infrastructure into account. Generally there are three cases where an existing HEN needs retrofit. These three cases include an increase in the process throughput, a drive to achieve improved energy efficiency, and changes to processes. In all these cases, the retrofit objective is to produce a cost-effective HEN design, subject to any design and operation constraints.

Current methods for HEN retrofit design use either thermodynamically based methods (such as pinch analysis), or mathematical programming methods, or methods with a combination of these two approaches.

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Tjoe and Linnhoff (1986) proposed the first pinch retrofit method and introduced the concept of area efficiency of HENs. This concept is used to set targets for additional area and utility reduction. Similar to the grassroots design, in the design phase of the method the whole network is divided into two parts: above and below the process pinch. Heuristic rules are then used to correct cross-pinch matches.

The main limitation of the targeting approach based on the area-efficiency concept is that the area target produced does not reflect the area distribution within the HEN. Shokoya and Kotjabasakis (1991) proposed a technique that overcomes this limitation by incorporating the area distribution of the existing HEN into the targeting mechanism. This technique also provides additional guidance for the design task, and enables the generation of retrofit HEN designs that are simpler than those obtained using the method of Tjoe and Linnhoff (1986).

Carlsson et al. (1993) introduced the cost matrix for HEN retrofit, which includes the costs of exchange area, piping and auxiliary equipment, pumping, and maintenance associated with each potential match. This cost matrix is used together with a set of rules to perform designs for two subsystems below and above the process pinch. As no targeting is performed in this method, the capital-energy trade-off is evaluated by producing several designs at varying heat-recovery levels.

Polley et al. (1990) extended the targeting procedure of Tjoe and Linnhoff (1986) by considering pressure drops. This was achieved by using the relationship between the pressure drop (ΔP), heat-transfer coefficient (h), and the heat-transfer area (A), which is in the form of $\Delta P = KAh^m$. Instead of specifying the heat-transfer coefficients for the streams, the allowable pressure drop is specified for each stream. The heat-transfer coefficients for streams are calculated iteratively to minimize the total area. Thus the target-area procedure is modified based on the fixed pressure drops rather than fixed film coefficients. The design phase is similar to the method of Tjoe and Linnhoff (1986).

On the other hand, mathematical programming methods convert the HEN retrofit problem into an optimization task, by formulating the retrofit problem as a mathematical model. Early mathematical programming methods for HEN retrofit were based on a grassroots scenario. More dedicated retrofit methods that were developed later contain explicit expressions for the cost of topology modifications.

Ciric and Floudas (1989) proposed a two-stage approach consisting of a match selection stage and an optimization stage. The match selection stage used a mixed-integer linear (MILP) transshipment model to select process-stream matches and match assignments, while the optimization stage used a nonlinear (NLP) formulation to optimize the match order and flow configuration of matches in terms of capital cost. The heat-recovery level is fixed in optimization. These two stages were later combined into a single stage by Ciric and Floudas (1990), using an MINLP formulation to simultaneously optimize all HEN retrofit aspects.

Yee and Grossmann (1991) also produced a two-stage approach to address the retrofit problem, which consists of a prescreen stage and an optimization stage. The prescreen stage is used to determine the optimal heat-recovery level and assess the economic feasibility of a retrofit design. Only the number of new units required to achieve the optimum investment are carried forward to the optimization stage. During the optimization stage, the heat-recovery level is allowed to vary and an MINLP model is used to simultaneously optimize all the aspects for a HEN retrofit.

The strength of pinch analysis is that it provides a high degree of user control and interaction. More importantly, it provides physical insights to the HEN retrofit problem. However, it leaves designers with too many choices to select on the basis of their experience. In addition, the design process is very time-consuming due to the nature of heuristic rules used.

On the other hand, by formulating it as an optimization task, the mathematical programming methods allow the HEN design procedure to be automated. However, the weaknesses of mathematical programming as a tool for retrofit HEN design is the lack of user interaction, it is sensitive to initialization, and it requires expensive computation time.

In order to combine the advantages of pinch analysis and mathematical programming, Asante and Zhu (1997) developed a new method for HEN retrofit and introduced the concept of network pinch. The network pinch provides new physical insights into the nature of the retrofit problem: an existing network structure presents a bottleneck (network pinch) that limits the increase in heat recovery. Structural modifications must be made to overcome the network pinch. The difference between the network pinch and process pinch is that the network pinch is a characteristic of both the process streams and the network topology, while the process pinch is a characteristic of the process streams alone. The network pinch retrofit procedure consists of two stages: a diagnosis stage and an optimization stage. The diagnosis stage is designed to identify promising topology changes. The topology changes identified in the diagnosis stage are passed on to the optimization stage, which optimizes the trade-off between heat recovery and modification costs.

Importance of Considering Pressure Drop for HEN Retrofit

Currently, most design methods for HEN retrofit do not consider the pressure-drop aspects. Although these methods can determine the allocation of additional area, they cannot tell how the additional area should be implemented. The major reason behind this is that current methods use an exchanger unit as the basis for retrofit design and they do not address the effects of shell configuration and area distribution in shells within one unit. In reality, however, additional area can be implemented by inserting tubes into an existing unit, by putting new shells in series or in parallel, by changing the design of exchanger internal structure, and by enhancing heat transfer using enhancement techniques. Different implementation has a significant impact on pressure drops and film coefficients.

Let us use an example to illustrate this point. Figure 1a shows a serial arrangement of a two-shell unit with pressure drop $\Delta P = 1$ bar, and heat transfer coefficient $h_t = 1000$ W/m^2 °C (for the tube side). When two shells are rearranged in a parallel structure (Figure 1b), the pressure drop is reduced to $\Delta P = 0.25$ bar, while the h-value is reduced to 574 W/m^2 °C. Therefore, shell arrangement has a significant impact on pressure drop and heat-transfer coefficients. In conjunction with shell arrangement, area distribution on the basis of shells instead of units could have a significant effect on pressure drop as well.

Therefore, if current design methods are used, there is no guarantee that the allowable pressure drop can be satisfied in

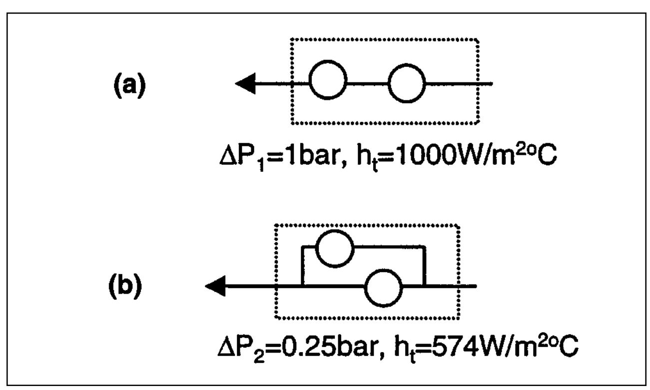

Figure 1. Different shell arrangements for one unit.

a retrofitted network. It could be a very extensive trial-and-error process to obtain an economical design that also satisfies the pressure-drop constraints. In many cases, a retrofit design could exceed the capacity of existing dominant pumps or compressors. Usually, it is not justifiable to purchase an expensive pump or compressor for a HEN retrofit project, since it is usually more expensive than new heat exchanger area.

Therefore, the pressure aspects need to be taken into consideration in the conceptual design stage. To provide a more complete retrofit design, one should consider the following aspects simultaneously:

1. Make the best use of the existing area.
2. Minimize additional area.
3. Minimize structural modifications.
4. Determine the implementation of additional area.
5. Meet the pressure-drop constraint.

All five of these problems are interconnected with each other, and form a very complex problem. Previous methods have addressed the first three issues quite extensively. In particular, the network pinch approach (Asante and Zhu, 1997) can effectively tackle the problem (issue 3). However, the problem with the implementation of additional area and pressure drop (issues 4 and 5) has yet to be addressed systematically.

The discussion so far shows the necessity and importance of considering pressure drop in the conceptual design stage. It also indicates that additional area should be determined simultaneously with its implementation.

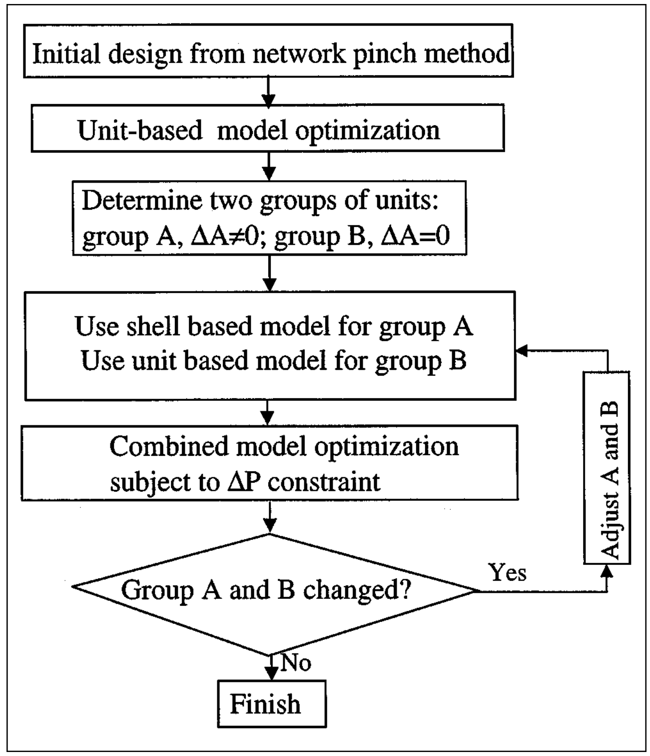

Figure 2. Procedure for optimization.

Strategy of Considering Pressure Drop for HEN Retrofit

What has been recognized previously for a given HEN structure, additional area, and shell arrangement needs to be optimized under the pressure-drop consideration. One possible way to tackle this optimization problem is to build a general superstructure, in which all the possibilities are considered; that is, every existing exchanger may require additional area with all possible shell arrangements and other pressure-drop-related options. Clearly, this will result in an unmanageable optimization problem.

In this work, it is assumed that for a practical and economical retrofit design, additional area should be concentrated on a small number of units in order to minimize the piping and civil work. It would then follow that the optimization can be decomposed into two stages:

First stage: Screening for a small number of units requiring additional area.

Second stage: Considering serial/parallel shell arrangements for these units.

The screening purpose can be achieved by using unit-based optimization (see the subsection titled "Mathematical model for unit-based model") without considering the actual shell arrangement. The unit-based optimization will indicate which units require additional area (group A) and which units do not (group B). In the second stage of optimization, a combined model is formulated and optimized. This combined model consists of two models, namely a shell-based model (the subsection titled "Superstructure for shell arrangement") and a unit-based model. The shell-based model is used for optimizing the shell arrangement for the units belonging to group A, while the unit-based model is used for the units belonging to group B. In this way, we use the shell-based model to calculate additional area and pressure drops more accurately for those units in group A (the subsection titled "Pressure-drop calculations"), while the unit-based model is good enough for those units that do not need additional area. Due to interactions between different groups during the combined optimization, the units belonging to group B may prove to require additional area and vice versa. Then groups A and B need to be updated accordingly. This iteration is repeated until convergence is reached so that the units belonging to groups A and B maintain their characteristics (that is, $\Delta A \neq 0$) for group A and $\Delta A = 0$ for group B).

The overall procedure is shown in Figure 2. The topology change options are first determined by applying the network pinch method (Asante and Zhu, 1997). Then the proposed two-stage optimization is used to determine area distribution and shell arrangement under pressure-drop constraint.

Apart from area allocation and shell arrangement, there are also other options for tackling the pressure-drop problem, such as exploiting spare pressure drops in existing streams, modifying existing pumps/compressors, exploiting utility streams, and the application of enhancement techniques. These options are problem specific. Once some of the options are identified, they can be modeled and included in the combined model. In this way, all possible options can be optimized simultaneously to tackle the pressure problem. Detailed discussions for these options are given in the sec-

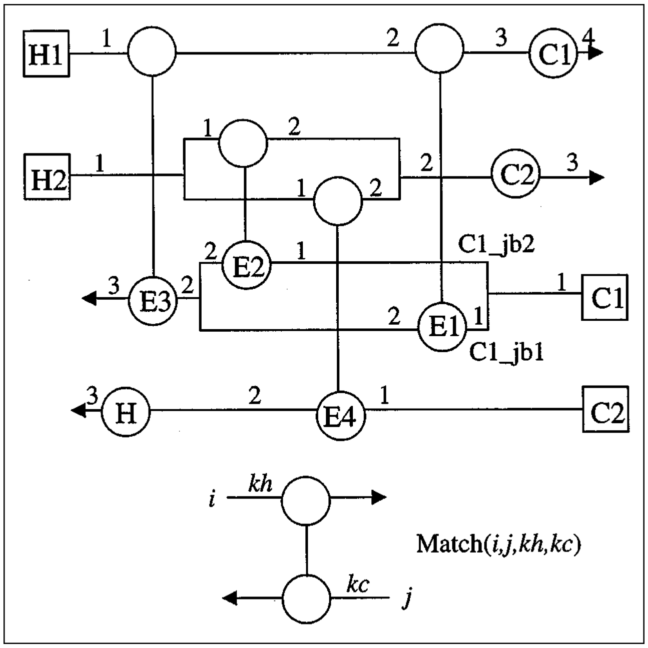

Figure 3. Component locations represented by nodes.

tions titled "Other opportunities for pressure-drop consideration" and "Consideration of heat-transfer enhancement."

Mathematical Formulation

Mathematical model for the unit-based model

Node Representation for Network Structure. For optimization of an existing HEN, the first question is how to represent the HEN structure in the mathematical model. There are three components in a HEN with different features: matches, splitters, and mixers. The relative locations of these three components on the streams define the network structure. The "node representation" is used here to represent the relative location of matches, splitters, and mixers presented in the network (Figure 3).

Nodes are numbers put before and after each component from the inlet temperature side to the outlet temperature side. All components are uniquely defined by the nodes and their related streams. For example, the location for E3 can be defined as (H1,C1,1,2). The third and fourth elements in parenthesis denote the nodes on the hot stream and the cold stream, respectively.

Similarly, the location for E1 can be defined as (H1,C1_jb1,2,1), where C1_jb1 is the branch from C1. For a splitter, its location node, branches, and the main stream to which it is affiliated should be defined. For example, the location for the splitter on C1 is denoted as csplit (C1,1,C1_jb1) and csplit (C1,1,C1_jb2). The location for a mixer is defined as being next to its corresponding splitter. For example, since the splitter on C1 has the node number of 1, the node number, 2, is assigned to the mixer that is next to the splitter. Note that nodes are defined in consecutive numbers for each main stream and each branch separately. In this way, the network connections are defined precisely.

Mathematical Model. To formulate mathematical programming models, sets and indices are defined first (see Notation section). The purpose of defining three sets, *KH*, *IB*, and *NIB* is to distinguish a main stream, a branch associated with and without a local split superstructure (Asante et al., 1996). For example, if there are no splits for hot stream *i*, this stream is assigned to set *KH* only. Thus, no variables associated with splits will be defined for this stream during optimization.

Furthermore, for streams involving splits, some of them may need a local superstructure to optimize the split structure, while others may only require optimization of branch flow rates without needing to use the local superstructure. The difference between these two kinds of splits is handled by using sets, *IB* and *NIB*. For those needing a superstructure, splits are put into both *IB* and *NIB*. For those not needing a superstructure, splits are put into *IB* but not into *NIB*. The preceding discussion also applies to sets *KC*, *JB*, and *NJB*. In this manner, we therefore do not need to embed the local superstructure for every split, and so can reduce the size of the overall superstructure. This is particularly useful for the case where there are many splits that require different treatment. We use Figure 4 to illustrate this point further.

In the network shown in Figure 4, there are three splitters. When considering operability, layout, and so forth, two matches on branches on splitter 2 must be implemented in parallel. However, the matches on splitter 1 and splitter 3 need to be optimized to find the best serial/parallel configuration using the local superstructures. To achieve this, the branches on splitter 1 and splitter 3 are put into both set *JB* and set *NJB*, while branches on splitter 2 are only defined in set *JB* and are excluded from set *NJB*. In this way, a user can have control over split configurations, which also helps reduce the size of the overall superstructure.

Note that this local superstructure is similar to that proposed by Floudas et al. (1986). The difference is that in Floudas et al.'s work, the superstructure is applied to all matches, while the local superstructure is only applied to

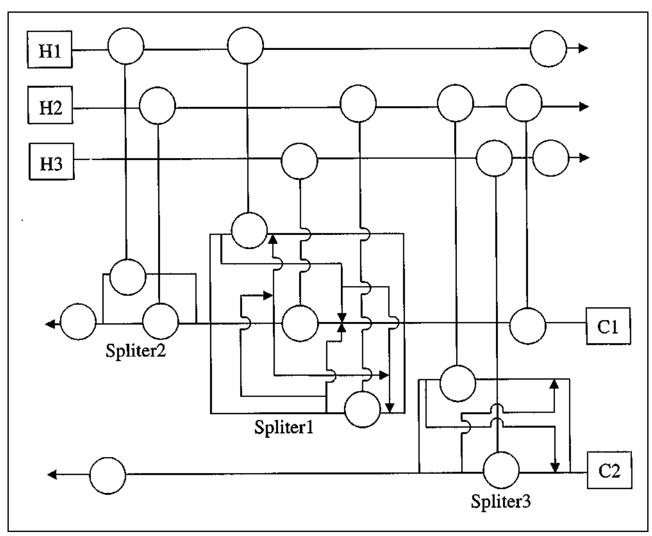

Figure 4. Different kinds of branches considered in the model.

matches located on branches. Therefore, the complexity of the overall superstructure is very much reduced.

There are four CP definitions for hot branches ($hvcp_{ib}$, $hmcp_{nib}$, $hecp_{nib}$, and $hbcp_{nib,anib}$) and for cold branches ($cvcp_{jb}$, $cmcp_{njb}$, $cecp_{njb}$, and $cbcp_{njb,anjb}$), respectively. They are explained graphically using Figure 5, and the cold branches are used as examples for illustration.

According to Figure 5a, the branch under consideration is denoted as *njb*, while other branches are denoted as *anjb*; $cvcp_{njb}$ is the CP for *njb* from the main stream splitter; $cmcp_{njb}$ is the CP for *njb* between branch mixer and branch splitter and is used to calculate the heat loads for the matches located on *njb*; $cecp_{njb}$ is the CP for *njb* between the branch splitter and the main stream mixer; $cbcp_{njb,anjb}$ is the CP from another branch *anjb* merging with *njb*. Similarly, $cbcp_{anjb,njb}$ is the CP for the branch separating from *njb*. When the local stream superstructure is not considered, the problem becomes much simpler (Figure 5b).

Using the preceding definitions, we can formulate the unit-based model, which includes mass balance and energy balance for matches, splitters, and mixers.

Energy Balance for Match xp. A match can be located either on a main stream or on a branch. When a match is on a main stream, the stream is not assigned for set *IB* (or *JB*). On the other hand, if a match is on a branch, and this branch belongs to *nib* (or *njb*), the local stream superstructure will be embedded automatically during optimization. In contrast, if a branch is $ib \notin NIB$ (or $jb \notin NJB$), the local stream superstructure is not considered for this branch:

$$\left(HCP_i|_{i\notin IB} + hvcp_{ib}|_{ib\notin NIB} + hmcp_{nib}\right) \times \left(HT_{i,kh} - HT_{i,kh+1}\right)|_{m(xp,i,j,kh,kc)} = \left(CCP_j|_{j\notin JB} + cvcp_{jb}|_{jb\notin NJB} + cmcp_{njb}\right)\left(CT_{j,kc+1} - CT_{j,kc}\right)|_{m(xp,i,j,kh,kc)}. \quad (1)$$

Temperature Handling for Splitters. When branch *ib* (or *jb*) is not in set *NIB* (or *NJB*) (Figure 5b), the temperature of first node for the branch is equal to the temperature of its splitter node:

$$HT_{ib,1}|_{ib\notin NIB} = HT_{i,kh}|_{hsplit(i,kh,ib)} \quad (2)$$

$$CT_{jb,1}|_{jb\notin NJB} = CT_{j,kc}|_{csplit(j,kc,jb)}. \quad (3)$$

For branch $nib \in NIB$ (or $njb \in NJB$), the energy balance needs to be taken to determine the temperature for its first node:

$$HT_{nib,1}hmcp_{nib} = HT_{i,kh}hvcp_{nib}|_{hsplit(i,kh,nib)} + \sum_{anib} HT_{anib,LAST_{anib}}hbcp_{nib,anib}|_{hsplit(i,kh,anib)}. \quad (4)$$

$$CT_{njb,1}cmcp_{njb} = CT_{j,kc}cvcp_{njb}|_{csplit(j,kc,njb)} + \sum_{anjb} CT_{anjb,LAST_{anjb}}cbcp_{njb,anjb}|_{csplit(j,kc,anjb)}. \quad (5)$$

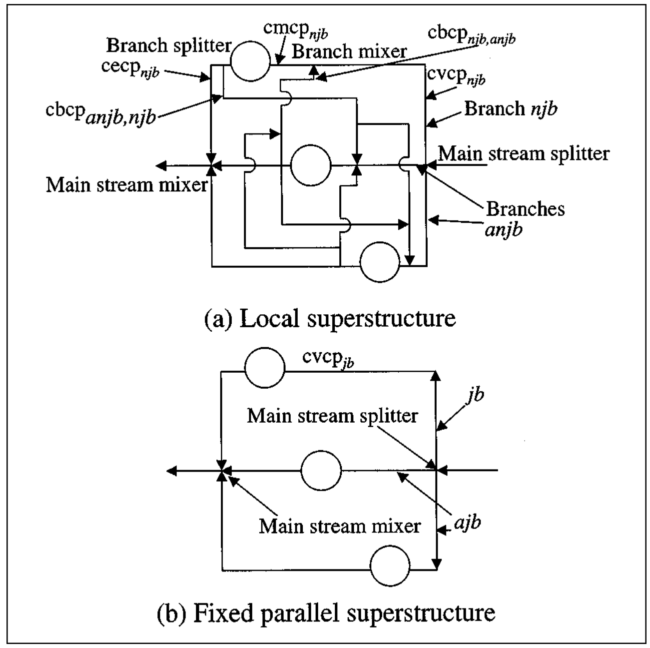

Figure 5. CP definitions for cold branches.

Temperature Handling for Main-Stream Mixer.

$$HT_{i,kh+1}HCP_i|_{i\notin IB} = \sum_{ib} hvcp_{ib}HT_{ib,LAST_{ib}|ib\notin NIB \text{ and } hsplit(i,kh,ib)} + \sum_{nib} hecp_{nib}HT_{nib,LAST_{nib}}|_{hsplit(i,kh,nib)} \quad (6)$$

$$CT_{j,kc+1}CCP_j|_{j\notin JB} = \sum_{jb} cvcp_{jb}CT_{jb,LAST_{jb}}|_{jb\notin NJB \text{ and } csplit(j,kc,jb)} + \sum_{njb} cecp_{njb}CT_{njb,LAST_{njb}}|_{csplit(j,kc,njb)}. \quad (7)$$

Mass Balance for Main-Stream Splitter.

$$HCP_i|_{i\notin IB} = \sum_{ib} hvcp_{ib}|_{hsplit(i,kh,ib)} \quad (8)$$

$$CCP_j|_{j\notin JB} = \sum_{jb} cvcp_{jb}|_{csplit(j,kc,jb)}. \quad (9)$$

Mass Balance for Branch Mixer.

$$hmcp_{nib}|_{hsplit(i,kh,nib)} = hvcp_{nib} + \sum_{anib} hbcp_{nib,anib}|_{hsplit(i,kh,anib)} \quad (10)$$

$$cmcp_{njb}|_{csplit(j,kc,njb)} = cvcp_{njb} + \sum_{anjb} cbcp_{njb,anjb}|_{csplit(j,kc,anjb)}. \quad (11)$$

Mass Balance for Branch Splitter.

$$hmcp_{nib}|_{hsplit(i,kh,nib)} = hecp_{nib} + \sum_{anib} hbcp_{anib,nib}|_{hsplit(i,kh,anib)} \quad (12)$$

$$cmcp_{njb}|_{csplit(j,kc,njb)} = cecp_{njb} + \sum_{anjb} cbcp_{anjb,njb}|_{csplit(j,kc,anjb)}. \quad (13)$$

Heat-Load Calculation for Matches.

$$q_{xp} = (HCP_i|_{i \notin IB} + hvcp_{ib}|_{ib \notin NIB} + hmcp_{nib}) \times (HT_{i,kh} - HT_{i,kh+1})|_{m(xp,i,j,kh,kc)} \quad (14)$$

$$q_{xh} = (CCP_j|_{j \notin JB} + cvcp_{jb}|_{jb \notin NJB} + cmcp_{njb}) \times (CT_{j,kc+1} - CT_{j,kc})|_{m(xh,hu,j,kh,kc)} \quad (15)$$

$$q_{xc} = (HCP_i|_{i \notin IB} + hvcp_{ib}|_{ib \notin NIB} + hmcp_{nib}) \times (HT_{i,kh} - HT_{i,kh+1}|_{m(xc,i,cu,kh,kc)}). \quad (16)$$

Driving-Force Definition.

$$DT1_{xa} = (HT_{i,kh+1} - CT_{j,kc})|_{m(xa,i,j,kh,kc)} \quad (17)$$

$$DT2_{xa} = (HT_{i,kh} - CT_{j,kc+1})|_{m(xa,i,j,kh,kc)}. \quad (18)$$

Here Paterson's (1984) approximation for logarithmic mean temperature difference is used:

$$DTLM_{xa} = \frac{2}{3}\sqrt{DT1_{xa}DT2_{xa}} + \frac{1}{3} \times \frac{1}{2}(DT1_{xa} + DT2_{xa}). \quad (19)$$

Heat Transfer Area Calculation for Match xa.

$$q_{xa} = A_{xa}U_{xa}DTLM_{xa}. \quad (20)$$

Temperature Approach Constraint. The temperature approaches for a match at two ends should be greater than a given value [exchanger minimum approach temperature (EMAT)]:

$$DT1_{xa} \geq EMAT \quad (21)$$

$$DT2_{xa} \geq EMAT. \quad (22)$$

Additional Area.

$$AD_{xa} \geq A_{xa} - Ae_{xa}. \quad (23)$$

Equation 23 can ensure that the existing area (Ae_{xa}) will be used first before requiring additional area.

Utility Consumption Calculation. Total hot-utility consumption and total cold-utility consumption are summations of the heat loads for heaters and coolers, respectively:

$$THC = \sum_{xh} q_{xh} \quad (24)$$

$$TCC = \sum_{xc} q_{xc}. \quad (25)$$

Supply and Target Temperature Assignment. The temperature for the first node of the main stream is equal to the supply temperature of the main stream. The temperature for the last node of the main stream is equal to the target temperature of the main stream.

$$HT_{i,1}|_{i \notin IB} = TIN_i \quad (26)$$

$$CT_{j,1}|_{j \notin JB} = TIN_j \quad (27)$$

$$HT_{i,LAST_i}|_{i \notin IB} = TOUT_i \quad (28)$$

$$CT_{j,LAST_j}|_{j \notin JB} = TOUT_j. \quad (29)$$

Objective Function. The objective function is to minimize the total cost, which is the summation of the investment for additional area and the gain in the utility consumption reduction.

$$\text{Minimize } TCOST = DCF\sum_{xa}(b \times AD_{xa}^c) - HC(HUEX - THC) - CC(CUEX - TCC). \quad (30a)$$

In the case of a fixed heat-recovery level, Eq. 30a is simplified to:

$$\text{Minimize } TCOST = DCF\sum_{xa}(b \times AD_{xa}^c). \quad (30b)$$

Equations 1–30 form the model for the unit-based optimization. It is a nonlinear model (NLP). This model can be used to optimize the trade-off between the additional area cost and the utility cost reduction, or to minimize the additional area cost or a fixed energy-recovery level.

Linear model for initialization

To solve the nonlinear model just discussed more effectively, the following linear model is formulated that can provide a feasible initial point.

Energy Balance for Process Match xp. In this linear model, the local split superstructure for branches is not considered and CP values for branches are fixed:

$$HCP_i(HT_{i,kh} - HT_{i,kh+1}) = CCP_j(CT_{j,kc+1} - CT_{j,kc})|_{m(xp,i,j,kh,kc)}. \quad (31)$$

Heat Loads for Heaters and Coolers.

$$q_{xh} = CCP_j\big(CT_{j,kc+1} - CT_{j,kc}\big)|_{m(xh,hu,j,kh,kc)} \quad (32)$$

$$q_{xc} = HCP_i\big(HT_{i,kh} - HT_{i,kh+1}\big)|_{m(xc,i,cu,kh,kc)}. \quad (33)$$

Temperature Handling for Splitters and Mixers. The temperature for the first node for a branch is equal to that of the node where the splitter is made:

$$HT_{ib,1} = HT_{i,kh}|_{hsplit(i,kh,ib)} \quad (34)$$

$$CT_{jb,1} = CT_{j,kc}|_{csplit(j,kc,jb)}. \quad (35)$$

The temperature for a mixer is determined by the energy balance around the mixer:

$$HT_{i,kh+1}HCP_i = \sum_{ib} HT_{ib,LAST_{ib}}HCP_{ib}|_{hsplit(i,kh,ib)} \quad (36)$$

$$CT_{j,kc+1}CCP_j = \sum_{jb} CT_{jb,LAST_{jb}}CCP_{jb}|_{csplit(j,kc,jb)}. \quad (37)$$

Objective Function.

$$\text{Minimize } THC = \sum_{xh} q_{xh}. \quad (38)$$

Equations 31–38 plus the temperature assignment equations (Eqs. 26–29) form the linear model for initialization. The variables in the linear model are the intermediate temperatures and the heat loads for the utility matches.

Superstructure for shell arrangement

After solving the unit-based model, a number of units may require additional area. For these units, shell arrangements must be considered in order to address the pressure-drop problem properly.

Let us consider the case of an exchanger unit with one shell requiring additional area (Figure 6). In this case, it is assumed that new area is placed into a single new shell. For this unit, the additional area could be installed in series (Figure 6a) or in parallel (Figure 6b). Both arrangements are covered by the small superstructure shown in Figure 6c. Although Figure 6c covers bypass possibilities, this kind of structure is usually not implemented within one exchanger unit, as only pure serial or pure parallel arrangements are considered. Thus, the bypass ratio takes either a value of 1 (corresponding to the serial arrangement in Figure 6a) or 0 (corresponding to the parallel arrangement in Figure 6b).

Similarly, for an existing unit with two shells, the existing shells can be in series (Figure 7b) or in parallel (Figure 7c). If the two existing shells will not be rearranged, then Figure 7b will lead to the arrangements of b1 or b2, which can be covered by the superstructure b3. Figure 7c will lead to the arrangements of c1 or c2, which can be embedded in the superstructure c3. If considering rearrangement of existing shells, however, either Figure 7b or Figure 7c will lead to the four possible arrangements, b1, b2, c1 and c2. These four

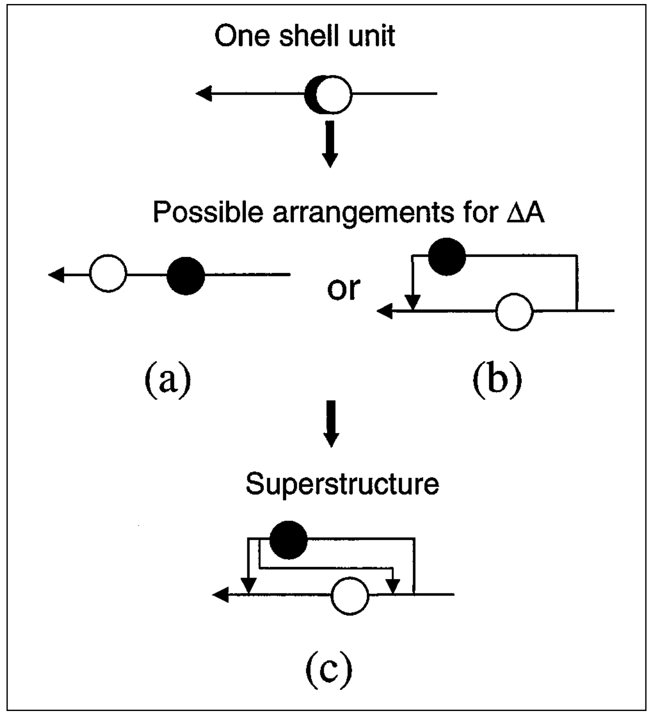

Figure 6. Superstructure for one-shell existing unit requiring additional area.

arrangements can be embedded in the superstructure Figure 7d through different combination of branch and bypass ratios (0 or 1).

For exiting units with more than two shells, corresponding supersturctures can be derived in a similar way. For the grassroots design, shells in one unit usually are of the same sizes. But in the retrofit scenario, it is possible to design shells with different sizes from existing ones to achieve an economical design.

In some cases, the unit-based optimization gives negative values of additional area for some units. This indicates that the effective area (UA) and the pressure drop for these units should be reduced in order to shift the reduced pressure drop to other units for better use. This can be achieved using the superstructure in Figure 8. To compensate for the reduction in the heat-transfer load in the existing exchanger due to splitting, a new shell is embedded in the structure.

Pressure-drop calculations

Calculations for Different Shell Arrangements. An existing shell may be allocated in a serial position or a parallel position, which requires using different equations to calculate both the pressure drops and heat-transfer coefficients. Assume the existing shell E1 with pressure drop, ΔP_0, and heat-transfer coefficient, h_0. When E1 is placed in series (Figure 9a), we can assign

$$\Delta P_1 = \Delta P_0 \quad \text{and} \quad h_1 = h_0. \quad (39)$$

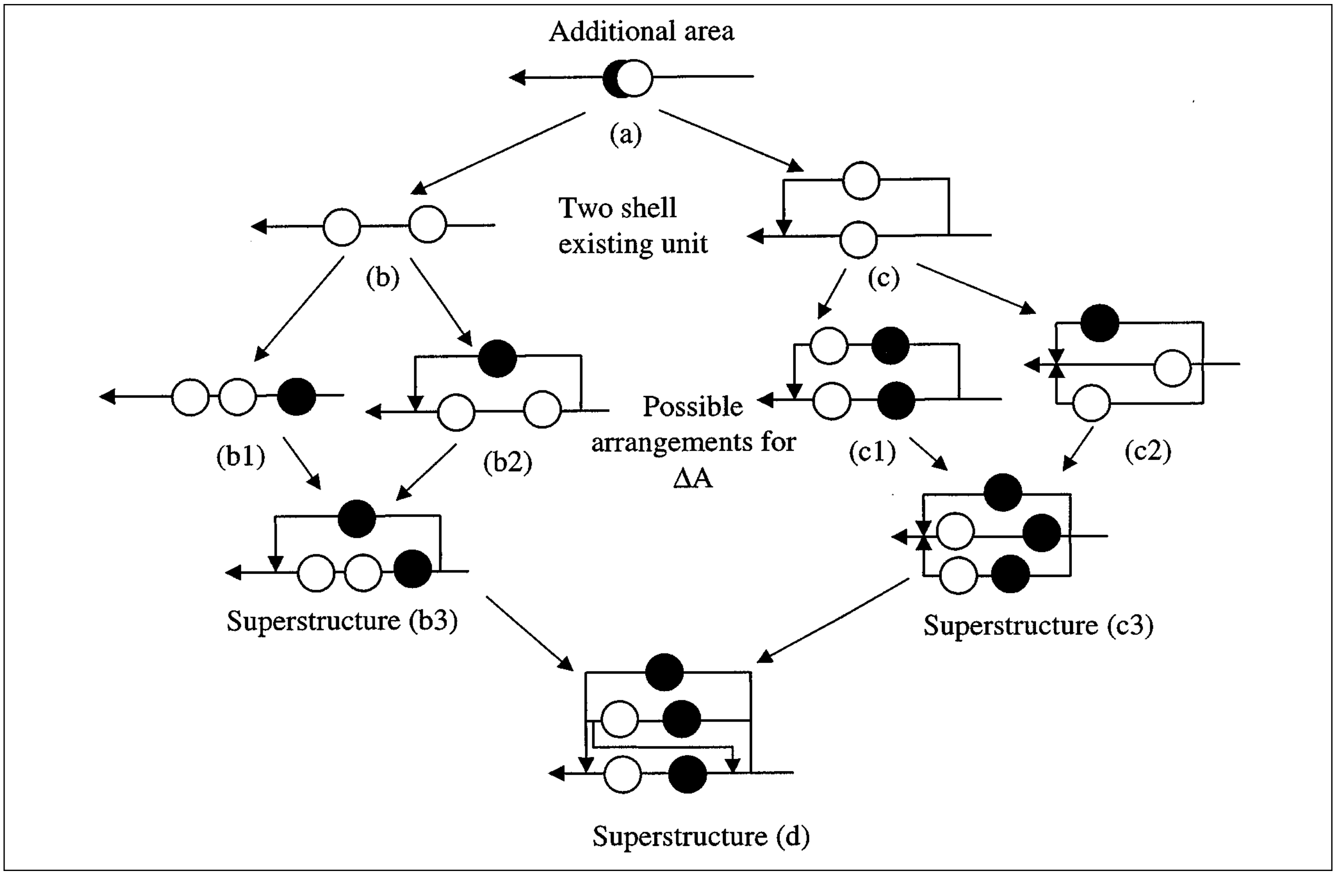

Figure 7. Superstructure for two-shell existing unit requiring additional area.

On the other hand, if E1 is placed in parallel (Figure 9b), the pressure drop, ΔP_1 for this existing shell is calculated to be

$$\frac{\Delta P_1}{\Delta P_0} = \left(\frac{r_1}{r_0}\right)^2, \tag{40}$$

where r_0 and r_1 are the split ratios for the branch on which E1 is allocated before and during optimization.

Meantime, the heat-transfer coefficient can be calculated for E1 in the parallel configuration. If the stream is allocated at the tube side of E1, then

$$\frac{h_1}{h_0} = \left(\frac{r_1}{r_0}\right)^{0.8} \tag{41}$$

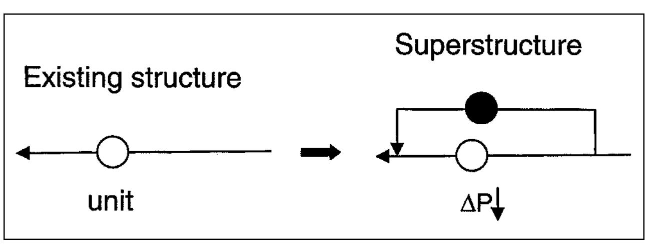

Figure 8. Superstructure for reduced effective area.

otherwise, if the stream is allocated at the shell side, then

$$\frac{h_1}{h_0} = \left(\frac{r_1}{r_0}\right)^{0.6}. \tag{42}$$

Calculations for New Shells. The specifications, which include the heat load, pressure drop, and the inlet and outlet temperatures, should be determined for new shells. New cor-

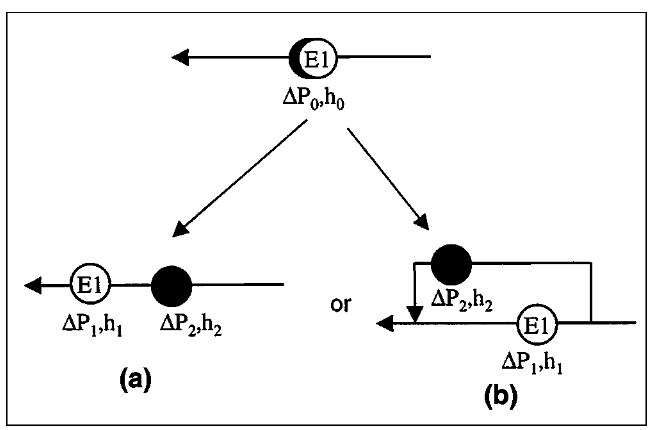

Figure 9. Pressure-drop calculation for serial/parallel arrangement.

relations for pressure drop and heat-transfer coefficients are developed from this work as follows:

For the Tube Side:.

$$\begin{cases} \Delta P = K_{1t} A v^{2.8} + K_{2t} v^2 \\ h = K_{ht} v^{0.8}. \end{cases} \tag{43}$$

For the Shell Side:.

$$\begin{cases} \Delta P = K_{1s} v^{1.83} + K_{2s} A v^{2.83} + K_{3s} A v^3 \\ h = K_{hs} v^{0.52}, \end{cases} \tag{44}$$

where v is velocity and A is surface area in an exchanger shell. The K constants in the correlations are estimated as functions of the physical stream properties, volumetric flow rates. A detailed derivation of the preceding correlations can be found in Nie (1998).

Note that high velocity will give a high heat-transfer coefficient, but also a high pressure drop. From practical considerations, there should be lower and upper bounds for the velocity used. For liquids, the velocity should be within $1 \le v \le 3$ m/s for tube side and $0.3 \le v \le 1$ m/s for the shell side. For vapors, the velocity depends on the operating pressure and is much higher than that used for liquids (Coulson et al., 1983).

Calculations for overall pressure drop. After calculating pressure drops for the individual exchanger shells that are allocated on a stream, we need to calculate the overall stream pressure drop. It should be pointed out that pressure drop is an intensive property. We can add pressure drops only when units or shells are allocated in series. For a parallel structure, a pressure drop is equal to the maximum of the pressure drops in the branches. Mathematically, we have for the serial configuration in Figure 9a,

$$\Delta P = \Delta P_1 + \Delta P_2, \tag{45}$$

and for the parallel structure in Figure 9b,

$$\Delta P = \max(\Delta P_1, \Delta P_2). \tag{46}$$

The max operator will cause discontinuity. To avoid this problem, we replace Eq. 46 with Eq. 47, as

$$\begin{aligned} \Delta P &\ge \Delta P_1 \\ \Delta P &\ge \Delta P_2. \end{aligned} \tag{47}$$

The overall pressure drop for a stream is then calculated as the summation of the individual pressure drops by taking serial/parallel configurations into account. Obviously, the pressure drop for the whole stream satisfy the allowable pressure-drop constraint:

$$\Delta P \le \Delta P_{\text{allowable}}. \tag{48}$$

Remarks.

- Equations 1–30 and 39–48 form the combined unit- and shell-based model. Equations 1–29 provide the mass and heat balances for the network structure. Equations 39–48 deal with pressure-drop calculations. The objective for the combined model is the same as that defined in Eq. 30.
- It should be noted that a good quality design could be achieved by using the proposed models, since the unit-based model provides a very good initial point for the combined model optimization. This is because in the unit-based model, effects of heat loads, locations of exchanger units, and additional area are taken into account properly, which provides a good basis for the combined model optimization when these effects are fine-tuned simultaneously with shell arrangement, film coefficients, and pressure drops. Due to its strong nonlinearity with high nonconvexity, however, the global optimum could not be guaranteed with this method.
- Although a heat-exchanger network may involve many streams, not every stream will exhibit the pressure-drop problem. To reduce the problem dimension, it is necessary to identify the streams, which are constrained by the pressure drop, and involve them during optimization. Thus the number of constraints can be reduced.
- It must be noted that there are significant differences between Polley et al.'s pressure-drop correlation (1990) and the ones in Eqs. 43 and 44. The major difference is that the correlation in Eqs. 43 and 44 is used for individual exchangers, while Polley et al.'s correlation was specific for the whole stream and was derived based on the assumption of an identical film coefficient for all exchangers located on one stream. In fact, exchangers located on one stream may have much different film coefficients. This is particularly true for the retrofit scenario where existing exchangers may have different geometrical arrangements (that is, tube size, baffle spacing, tube length, etc.), which results in very different film coefficients.

Other Opportunities for Pressure-Drop Consideration

Broadly speaking, there are other opportunities that can be available in practice to tackle the pressure drop problems. These are explained in detail as follows.

Opportunity 1—Exploiting the streams with spare ΔP capacity

In HEN retrofit, not every stream will exhibit the pressure drop problem. Some streams may have an actual pressure drop of much less than the allowable one. This provides an opportunity for shifting pressure drop from more constrained streams to these streams. Consider the example in Figure 10. Currently, stream C1 is constrained by the pressure drop, while stream H1 has the additional capacity of consuming more pressure drop. If we increase the pressure drop for H1 by modifying either the tube side or the shell side of the existing exchanger, the heat-transfer coefficient will be increased. Thus the existing unit can carry more heat load for the same existing area. As a consequence, the heat load for the new exchanger can be reduced and the new exchanger can be designed in a smaller size. Therefore, the pressure-drop constraint for stream C1 can be satisfied.

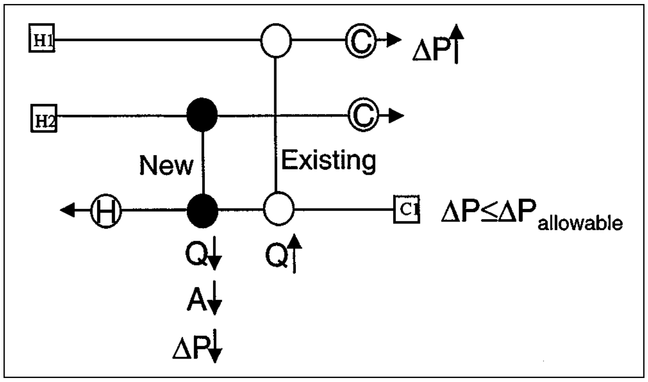

Figure 10. HEN with one stream constrained by pressure drop.

Opportunity 2 — Releasing pressure drop from existing units

Figure 11 shows a heat-exchanger network with three units: unit A with two shells in series, unit B with four shells in series, and one new unit. Their performances are displayed under each unit.

The allowable pressure drop for the stream is 1.7 bar. After deduction of the pressure drops from the two existing units, the allowable pressure drop for the new unit is 0.1 bar, which is very tight for the design of the new unit. To overcome this problem, we could release the pressure drop by changing the shell arrangement for units A or B. We can use this arrangement to increase the allowable pressure drop for the new unit.

However, the impacts on pressure drop and area from modifying unit A or B are different. If unit A is modified, the area for the new unit is reduced to 470 m^2. On the other hand, a change in the shell arrangement for unit B results in 435 m^2 of area for the new unit, which is a better option. For both modifications, the heat load (Q) and pressure drop (ΔP) for units A and B are reduced. The reduced heat load and pressure drop are shifted to the new unit. To distinguish the different modifications, the criterion of using the ratio $\Delta Q/\Delta(\Delta P)$ is proposed. ΔQ and $\Delta(\Delta P)$ are the reductions in heat load and pressure drop resulting from changing the existing shell arrangement. This ratio indicates the sensitivity of heat load change toward pressure-drop shifting. Different modifications may give different values of $\Delta Q/\Delta(\Delta P)$. For example, $\Delta Q/\Delta(\Delta P)|_A = 12$ for modifying unit A, and $\Delta Q/\Delta(\Delta P)|_B = 8$ for modifying unit B, which implies that a small heat load reduction in unit B causes large reduction in pressure drop. Thus, $\Delta Q/\Delta(\Delta P)$ can be used as a criterion for identifying which unit has a greater potential for pressure-drop shifting. These units are then put into the overall superstructure with possible modifications for shell arrangement, to be optimized simultaneously with other options.

Opportunity 3 — Modifying the existing pumps to increase the allowable $\boldsymbol{\Delta P}$

In some cases, we can modify the existing pumps (such as increase its impeller size or increase rotating speed, etc.) to increase its discharge pressure. As a result, the pump capacity is improved and the allowable pressure drop for the HEN can be increased.

Opportunity 4 — Exploiting utility conditions

Consider the example in Figure 12. After an increase in the flow rate for C1, the target temperature of C1 falls from 120°C to 108°C for the existing area. Assume that this target temperature is crucial and that we need to restore it to 120°C. We could add more area to the existing process exchangers, but this may raise the pressure drop beyond the limit of the existing pump. Alternatively, if we can replace the existing utility of 200°C with a higher temperature utility of 260°C, more heat can be transferred in the heater due to an increased temperature driving force. Then the crucial temperature can be restored without needing to modify the process exchangers.

The second way of retaining the original target temperature of C1 is to replace the existing utility with another utility with a higher heat-transfer coefficient, say, $h = 1200$ W/m^2

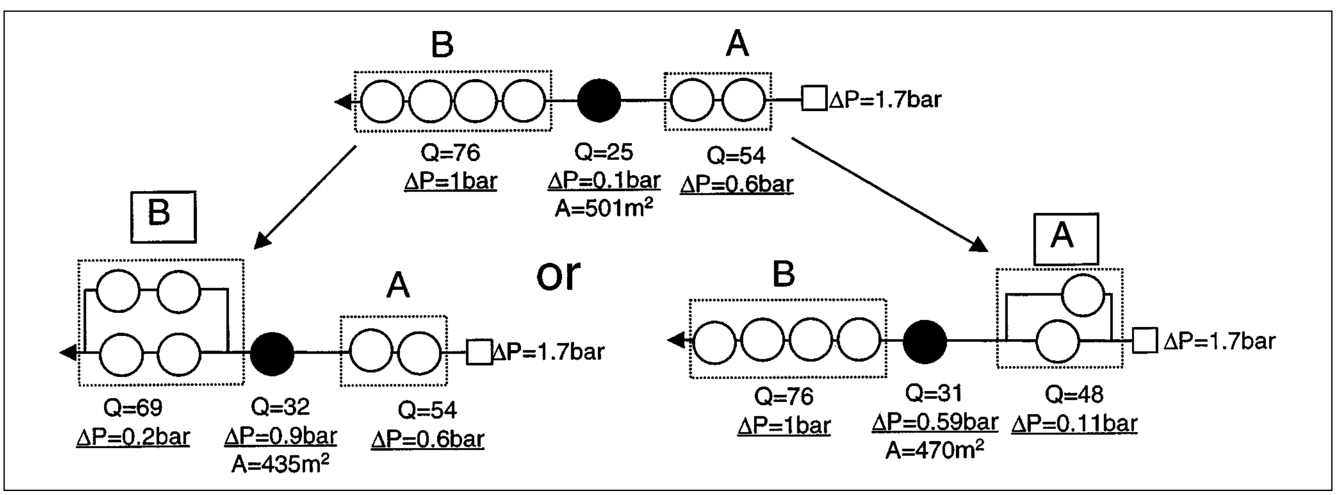

Figure 11. Stream in a HEN with pressure-drop constraint.

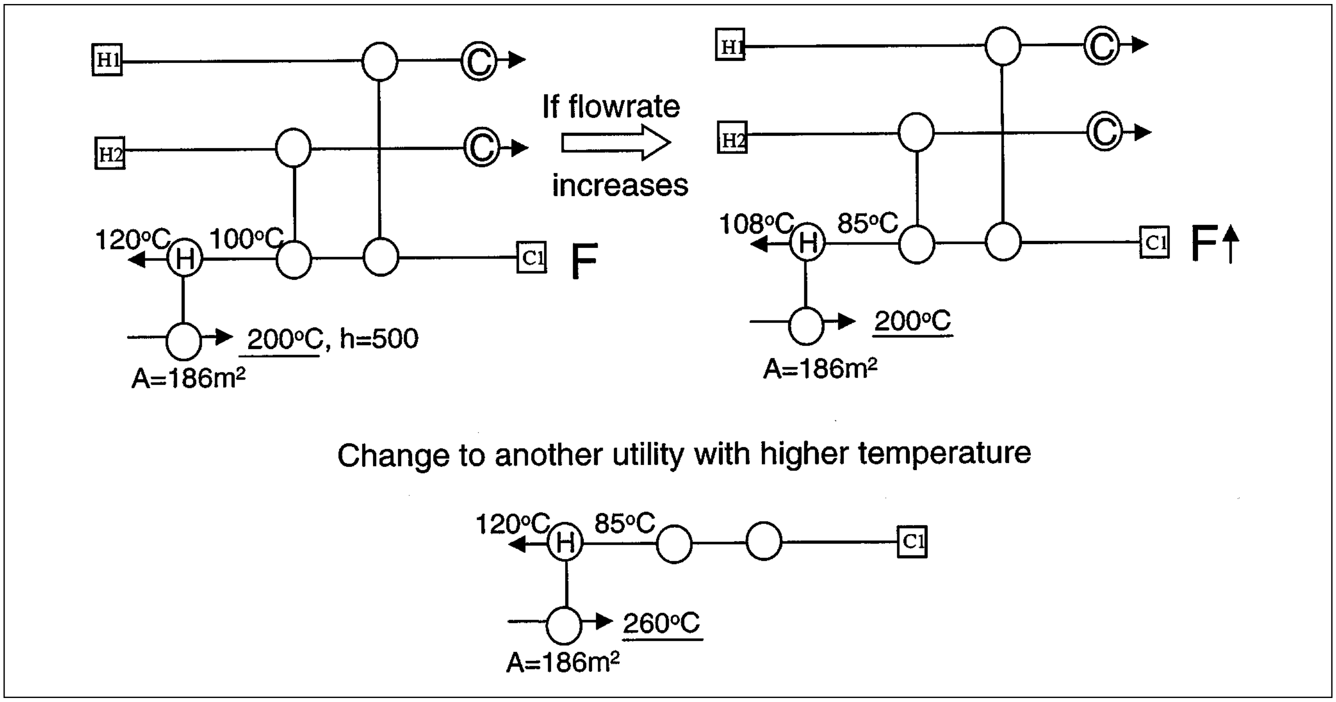

Figure 12. Impacts from utilities with different temperatures.

°C. As a result, the crucial temperature can be maintained without the need of additional area. In both cases, there will be no pressure-drop problem for C1.

Remarks.

• The opportunities cited earlier can be used to optimize the distribution of the pressure drop and additional area. These options together with their costs can be modeled and included in the combined model. Optimization then gives the most economic options.

• In contrast to the opportunities, there may be some practical situations that may impose constraints on optimization. For example, in some cases, it is not possible to install new shells on some units due to limited space or the fact that foundations are not strong enough to support more shells. On the other hand, it is preferable to install additional area on some units where space is available. These situations can be handled as forbidden changes or as compulsory changes.

Consideration of Heat-Transfer Enhancement

Heat-transfer enhancement is a very attractive option for HEN retrofit, since it can eliminate or reduce the requirement of additional area, which results in significant reduction in piping and civil engineering work (Zhu et al., 1999). Thus application of enhancement techniques is considered in this work.

As explained previously, additional area can be implemented using new shells in series or parallel to existing shells. Alternatively, it can also be implemented using enhancement techniques without the necessity of adding new shells. This is because heat transfer in an existing unit can be enhanced and more heat load can be transferred with the same area. In some case, the combination of enhancement and adding new shells can be adopted when a large amount of additional area is required. These options can be included in the superstructure shown in Figure 13.

In Figure 13, h_t represents the tube-side heat-transfer coefficient for plain tubes, and h_{te} represents the heat-transfer coefficient for enhancement tubes. The ratio of h_{te}/h_t is called the enhancement ratio, which indicates the augmentation of heat transfer or enhancement level. When applying enhancement, we need to consider as many enhancement techniques as possible, each with its enhancement level and cost.

The cost for enhancement material is correlated with area as

$$\mathrm{Cost}_{en} = c_1 + c_2 A. \tag{49}$$

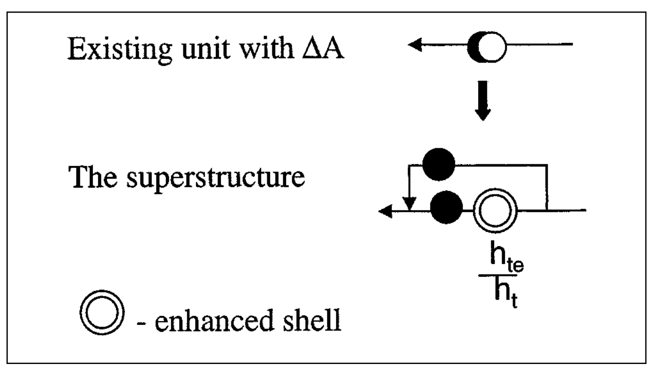

Figure 13. Superstructure for new shell and enhancement.

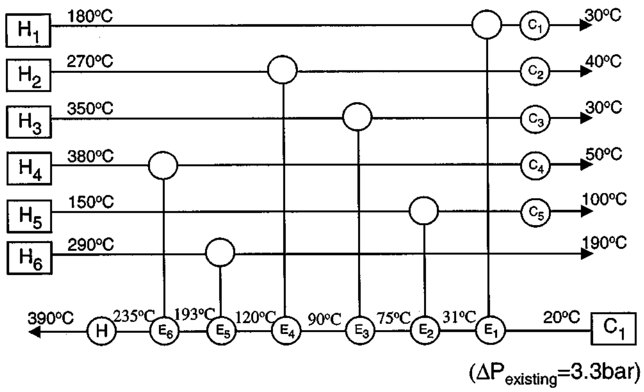

Figure 14. Existing preheat train.

The pressure drop for an enhancement technique is correlated in the following form, which is proposed by Polley et al. (1992):

$$\frac{\Delta P_{en}}{\Delta P_t} = a_1 \left(\frac{h_{te}}{h_t} \right)^{a_2}. \tag{50}$$

In order to calculate the pressure drop in the optimization more conveniently, the pressure-drop relation in Eq. 50 is recorrelated in the following form:

$$\frac{\Delta P_{en}}{\Delta P_t} = 1 + c_3 \left(\frac{h_{te}}{h_t} - 1 \right)^{c_4}. \tag{51}$$

For every enhancement technique, there is an enhancement limit defined by the technique, and this limit can be expressed in Eq. 52:

$$\frac{h_{te}}{h_t} \le \left(\frac{h_{te}}{h_t} \right)_{\max}. \tag{52}$$

The objective function in Eq. 30a is modified by including the enhancement cost and the costs for other options mentioned earlier:

$$\text{Minimize } TCOST = DCF \sum_{xa} \left(b \times AD_{xa}^{c} + Cost_{en} \right) - HC(HUEX - THC) - CC(CUEX - TCC). \tag{53}$$

Table 1. Specifications for Exchange Units

	E1	E2	E3	E4	E5	E6
Tube side	Cold	Cold	Cold	Cold	Cold	Cold
Shell side	Hot	Hot	Hot	Hot	Hot	Hot
Area (m^2)	280	1480	280	800	2760	1360
Serial × parallel	1×1	1×1	1×1	2×1	3×2	4×1
Baffle spacing	255	1246	197	420	605	510
Tube count	1075	2827	1075	1590	1810	1590
Tube pass	2	2	2	2	2	2
Tube size (mm)	19×2	19×2	19×2	19×2	19×2	19×2
Tube pitch (mm)	25.4	25.4	25.4	25.4	25.4	25.4
Tube pattern	90°	90°	90°	90°	90°	90°

Table 2. Physical Properties

Stream	Density (kg/m^3)	Spec. Heat Capacity (J/kg·°C)	Viscosity μ (Pa·s)	Thermal Cond. k (W/m·°C)
H1	700	2,600	0.3×10^{-3}	0.12
H2	700	2,600	0.4×10^{-3}	0.12
H3	750	2,600	0.5×10^{-3}	0.12
H4	750	2,600	0.5×10^{-3}	0.12
H5	630	2,600	0.2×10^{-3}	0.12
H6	750	2,600	0.4×10^{-3}	0.12
C1	800	2,600	1.0×10^{-3}	0.12

The network structure defined by Eqs. 1–29, the pressure drop equations for plain tubes (Eqs. 39–48), and the pressure-drop equations for enhancement (Eqs. 49–52), together with the objective function (Eq. 53), form the extended combined unit and shell-based model. The result from the optimization will give optimal area and pressure-drop distribution, shell arrangement, and the optimal use of enhancement and other economical options. In the meantime, it also gives the specification of new exchangers.

Case Study

Figure 14 shows a preheat train for a crude unit. The crude feed C1 is heated by a number of hot products in the heat-exchanger network, then heated further in the fired furnace before it is fed to the crude column. Table 1 shows the specifications for each exchange unit. The convention of the HEXTRAN software (version 7, 1994) is used. For example, series × parallel = 1 × 1 denotes that the unit has one shell, while series × parallel = 3 × 2 indicates that the unit has three shells in series in each of two branches. Tables 2 and 3 show the physical properties and the stream data, respectively. The network is simulated using HEXTRAN software, and its performance is listed in Table 4. The crude feed flows through the tube side in every unit, and the total pressure drop for the crude feed incurred in the HEN network is 3.3 bar. It should be noted that the total pressure drop incurred in the feed discharge line is much larger than 3.3 bar, and is typically on the order of 30 bar.

The existing feed temperature prior to the furnace is 235°C (which corresponds to the fuel consumption of 80.6 MW). To reduce the fuel consumption in the furnace, it is planned to increase the feed temperature to 260°C (which corresponds to the fuel consumption of 67.6 MW), which is equivalent to 16% fuel reduction. To achieve this, we need to recover more heat from the existing HEN by installing additional area. However, the current crude pump is already op-

Table 3. Stream Data

Stream	Supply Temp. (°C)	Target Temp. (°C)	FCp (kW/°C)	Flow Rate (kg/s)
H1	180	30	59.8	23
H2	270	40	114.4	44
H3	350	30	33.8	13
H4	380	50	145.6	56
H5	150	100	657.8	253
H6	290	190	384.8	148
C1	20	390	520	200

Exchanger area installation cost (\$) = 57,050 + 864 area (m^2).

Table 4. Rating of the Existing Network

	E1	E2	E3	E4	E5	E6
h (Tube) W/m$^2\cdot$°C	1,946	898	1,946	1,423	713	1,423
h (Shell) W/m$^2\cdot$°C	1,282	2,066	895	1,115	1,217	1,076
r_f (Tube) m$^2\cdot$°C/W	0.00147	0.00147	0.00147	0.00147	0.00147	0.00147
r_f (Shell) m$^2\cdot$°C/W	0.00117	0.00112	0.00104	0.00109	0.00143	0.00127
U, W/m$^2\cdot$°C	253	238	241	240	195	228
ΔP_t, bar	0.54	0.22	0.54	0.60	0.29	1.06
ΔP_s, bar	0.07	0.25	0.06	0.13	0.26	0.34

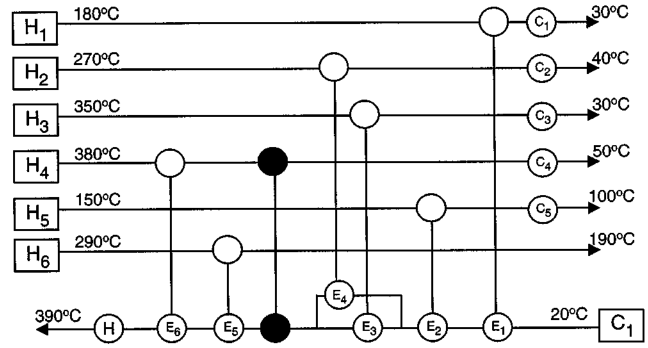

Figure 15. Modified network suggested by network pinch method.

erated at its maximum capacity. Therefore, the problem is to find the most economic retrofit design to achieve the planned energy savings under the pressure-drop constraint of 3.3 bar.

First step: Select the structural modifications

The modifications suggested by the network pinch method (Asante and Zhu, 1997) include one stream split and one new unit, as shown in Figure 15. The heat loads, area, and shell arrangement need to be determined to satisfy the heat-recovery level and the pressure-drop constraint.

Second step: Unit-based optimization

The unit-based optimization is carried out to determine the area distribution, and the model is solved using software GAMS (Brooke et al., 1992). Figure 16 shows the optimization results (to save space, only the cold side of the network is shown). The results show that additional areas are concentrated on two units: E5 and the new unit.

Conventional methods would take the result in Figure 16 as the solution. After we put this result into HEXTRAN, however, it is found that the pressure drop for the new network is 3.5 bar, which is beyond the allowable pressure drop. To remedy this solution, we may consider purchasing a new crude pump, which would cost about $815,000 to install.

What this example has shown us is that conventional methods determine additional area first and calculate the pressure-drop afterwards. Thus there is no guarantee that the pressure-drop constraint can be satisfied with retrofitted network.

In contrast, the new method takes the solution from the unit-based optimization as an initial solution. Based on this result, we are going to optimize the implementations of the additional area in the next step while ensuring that the pressure-drop constraint is satisfied.

Third step: Combined unit- and shell-based optimization

The second-stage optimization indicates that a retrofit design requires the addition of a new exchanger and that exchanger E5 requires additional area. At this stage of optimization, we need to determine the specifications for the design of the new exchanger and the location of the new shells for E5. These new shells could be installed in series or in parallel with the existing shells. The superstructure in Figure 17 is adopted to consider these two possibilities.

Then the shell-based model is applied to E5, while the unit-based model is still employed for other units. After running the combined model, a modified retrofit design is obtained that satisfies the pressure-drop constraint (Figure 18).

Note that the area distribution is modified and the total additional area is increased, due to consideration of the pressure-drop constraint. Also note that exchanger E1 requires negative additional area. This implies that for better use the effective area for E1 needs to be reduced in order to shift the pressure drop from E1 to E5 and the new unit. This aspect will be used in the next optimization stage.

Fourth step: Repeat the combined optimization

After running the combined model in the third step, group A now includes units E1 and E5, and group B includes units E2, E3, E4, and E6, which is different from the second step optimization. Thus, we need to run the combined model again. At this stage, the shell arrangements for both E1 and

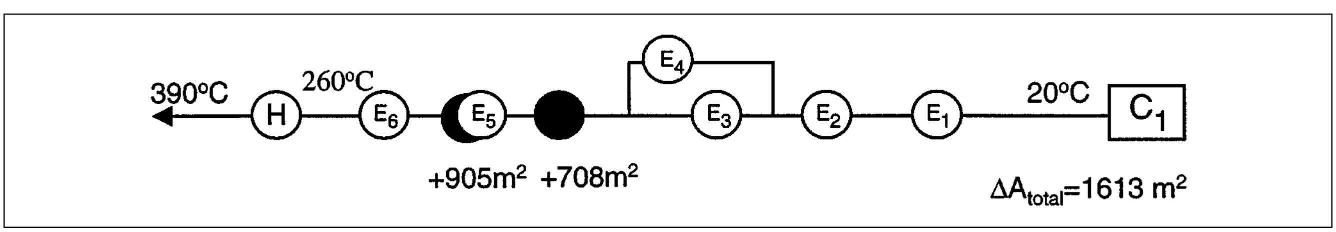

Figure 16. Area distribution from the unit-based optimization.

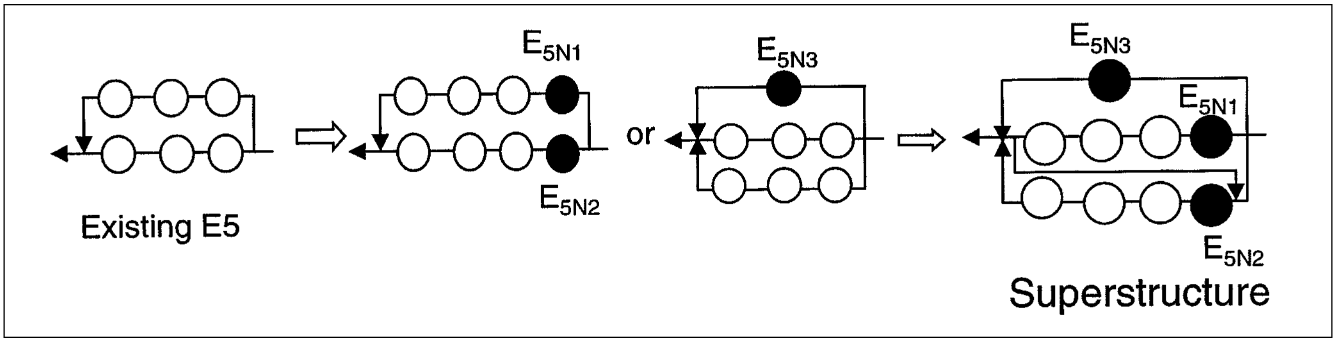

Figure 17. Superstructure of shell arrangements for E5.

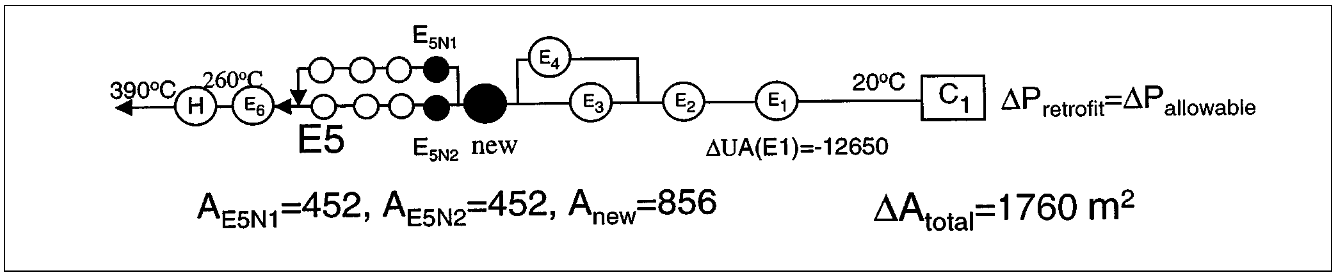

Figure 18. Area distribution and shell arrangement after running the combined model.

E5 need to be considered. The superstructure for E5 is the same as that shown in Figure 17. The superstructure of Figure 8 is adopted for E1.

After running the combined model for a second time, the items in groups A and B remained unchanged. Thus, the optimization procedure converges with the optimal area distribution and the shell arrangements determined simultaneously under the pressure-drop constraint. The results are given in Figure 19. Note that the unit-based model requires 11 CPU seconds and each run of the combined model requires 33 CPU seconds on a 100-MHz Pentium PC connected in a network.

Table 5 shows a comparison of the solutions obtained by the new method and the conventional method. It can be observed that by considering a better area distribution and shell arrangement, the new method can eliminate the problem with pressure-drop constraint. The penalty of doing so is an increase in total additional area. However, there is no need to purchase a new pump. This results in a much cheaper design than the conventional design.

Use of other opportunities for the case study

Increase the Pressure Drop for Stream H4. By examining the performance of the pump installed on hot stream H4, we found that it is possible to increase the pressure drop on this stream. This can be achieved by modifying the shell side of E6, such as increasing the number of baffles, or using baffles with smaller cut. As a result, the pressure drop is quadrupled and the velocity is doubled to 0.78 m/s compared with the existing velocity on the shell side. This new velocity is within the acceptable region. Then the overall heat-transfer coefficient for E6 is increased from 228 W/m^2 °C to 247 W/m^2 °C. As a result, E6 can transfer more heat load, which means that less heat load is required for new shells to transfer. As an overall consequence, the total additional area is reduced to 1,500 m^2.

Increase the Discharge Pressure for the Pump on C1. If we assume that the existing pump for C1 is modified and that it can provide the allowable pressure drop of 3.8 bar, two effects can be observed. The first effect is that total additional

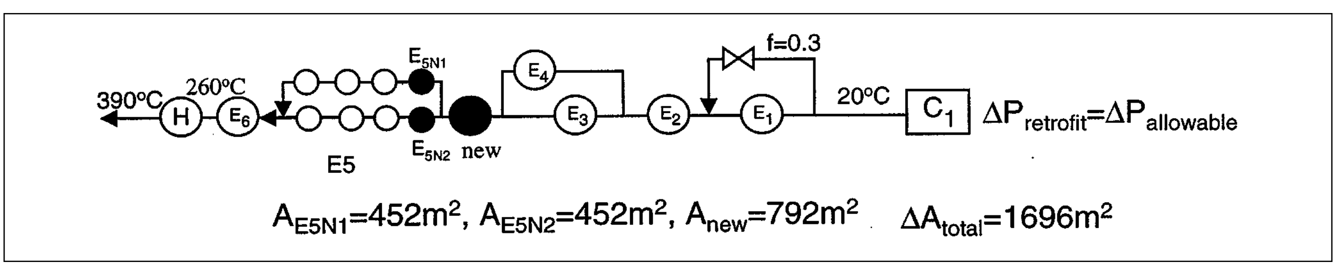

Figure 19. Optimal retrofit design using new shells.

Table 5. New Method vs. Conventional Method

	Conventional Method	New Method
Additional area	1,613 m^2	1,696 m^2
No. of modifications	2	3
Area cost	$1,565,000	$1,636,500
Pump cost	$815,000	0
Total cost	$2,380,000	$1,636,500

area is reduced from 1696 m^2 to 1640 m^2 (compare the design of Figure 19), and the second effect is that a bypass for E1 is not required.

Consider Heat-Transfer-Enhancement Techniques. In this case, the possibility of using enhancement techniques is considered for E5. The heat-transfer coefficient ratio for E5 is $h_s/h_t = 1.7$ which is bigger than 1. This implies that the tube side is the controlling side for heat transfer and that E5 is suitable for tube-side enhancement. To eliminate the additional area for E5, an enhancement ratio of $h_{te}/h_t = 1.6$ is required.

According to the required enhancement ratio and Reynolds number of the tube side ($Re = 10{,}000$), the enhancement material, coiled wire 5.5 (Polley et al., 1992; Zhu et al., 1999), is recommended.

The pressure-drop for coiled wire 5.5 is calculated as

$$\frac{\Delta P_{en}}{\Delta P_t} = 1 + 1.383\left(\frac{h_{te}}{h_t} - 1\right)^{0.66}.$$

The cost of this enhancement material is estimated to be

$$\text{Cost}_{en} = 40\,A.$$

The superstructure for unit E5 (Figure 20) is employed. After running the combined model, the refined retrofit design using the enhancement is obtained (Figure 21).

Table 6 lists the costs of different designs: the conventional method, plain tube design, and enhancement design. It can be observed that the enhancement cost is much less than purchasing new shells. Thus enhancement is preferred for implementing additional area in unit E5. The total cost, including the new unit and enhancement material, is about $1m compared with the cost of $1.64m for the plain tube design.

Conclusion and Discussion

Most HEN retrofit designs are moderated by pressure-drop constraints imposed by the existing pump/compressors. To tackle the pressure-drop problem, a two-stage approach is proposed. The first stage is the unit-based optimization from which the existing units are classified into two groups, the first group including units requiring additional area, and the second group including units that do not need additional area. In the second stage of the combined model optimization, the units in the first group are given special attention. These units are modeled and optimized by considering the shell arrangement, enhancement, and other options simultaneously. At the same time, the units in the second group are treated as black boxes and a unit-based model is used for these units. By doing so, the pressure drops can be calculated accurately for different units, while the model can be maintained in a simple format that is easy to be solved.

It has been observed that two common options—area distribution and shell arrangement—usually have major effects on pressure drop. But other options can play important roles in solving the problems as well. These options include (a) exploiting the streams with spare pressure-drop capacity; (b) releasing pressure drop from the existing units; (c) modifying the existing pumps; (d) taking advantage of the utility conditions; and (e) using heat-transfer enhancement. These options are problem-specific. If some of these options are identified, for a retrofit project, they can be modeled and linked

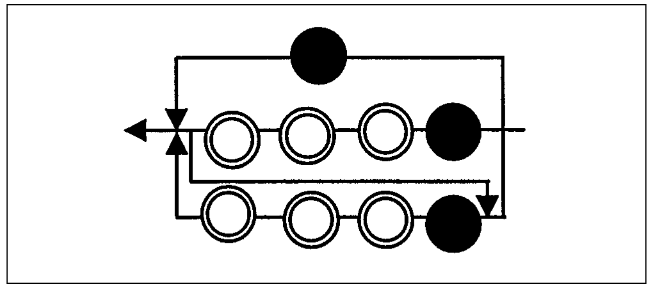

Figure 20. Superstructure for E5.

Table 6. Cost Comparison Between Different Methods

	Conventional Method	New Method with Plain Tube	New Method with Enhancement
Additional area, m^2	1,613	1,696	890
Units modified	2	3	3
Area cost, $	1,565,000	1,636,500	824,800
Pump cost, $	815,000	0	0
Enhancement cost, $	0	0	179,300
Total cost, $	2,380,000	1,636,500	1,004,100

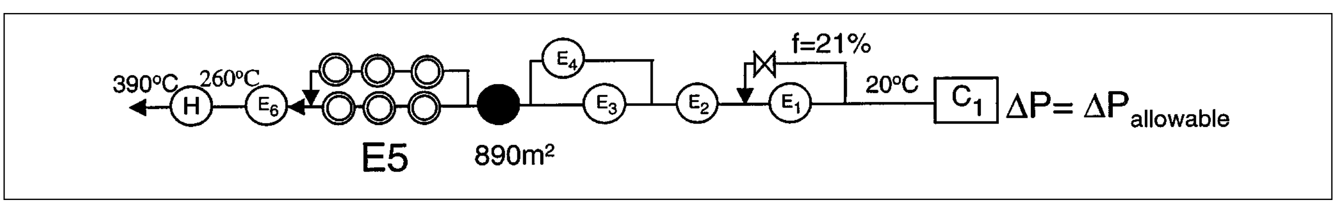

Figure 21. Optimal retrofit design using enhancement.

with the overall model. In this way, all the options are optimized simultaneously, to tackle the pressure-drop problem with minimum capital cost.

We need to emphasize that heat-transfer enhancement is a very attractive option for HEN retrofit. It not only can eliminate or significantly reduce additional area, but is also a much less expensive option for comparing new shells using plain tubes. More importantly, the application of enhancement results in less space, less piping and civil engineering work, and thus much less expensive modification costs and less implementation time.

Acknowledgment

The authors thank Dr. Nii Asante for his variable input to this work.

Notation

Set and Indices

$I = \{i | i$ is a hot stream or a hot branch$\}$
$J = \{j | j$ is a cold stream or a cold branch$\}$
$KH = \{kh | kh$ is a node on a hot stream or a hot branch$\}$
$KC = \{kc | kc$ is a node on a cold stream or a cold branch$\}$
$IB = \{ib | ib$ is a hot branch$\}$, $IB \subset I$
$JB = \{jb | jb$ is a cold branch$\}$, $JB \subset J$
$NJB = \{njb | njb$ is a cold branch on which local superstructures are considered$\}$, $NJB \subset JB$
$XA = \{xa | xa$ is a match$\}$
$XP = \{xp | xp$ is a process−process match$\}$, $XP \subset XA$
$XH = \{xh | xh$ is a heater$\}$, $XH \subset XA$
$XC = \{xc | xc$ is a cooler$\}$, $XC \subset XA$
$HSPLIT = \{hsplit_{i,kh,ib} |$ location and affilitation for hot branches$\}$
$CSPLIT = \{csplit_{j,kc,jb} |$ location and affilitation for cold branches$\}$
$M = \{m_{xa,i,j,kh,kc} |$ location for matches$\}$

Parameters

CCP_j = heat capacity flow rate for cold stream or cold branch j
HCP_i = heat capacity flow rate for hot stream or hot branch i
U_{xa} = overall heat-transfer coefficient for match xa
TIN = inlet temperature for a stream
$TOUT$ = outlet temperature for a stream
$HUEX$ = existing hot-utility consumption
$CUEX$ = existing cold-utility consumption
HC = unit cost for hot utility
CC = unit cost for cold utility
a,b,c = coefficients in the area-cost equation
DCF = discounting factor

Variables

$hvcp_{ib}$ = heat capacity flow rate for hot branch ib from main stream splitter
$hmcp_{nib}$ = heat capacity flow rate for hot branch nib between branch mixer and branch splitter
$hecp_{nib}$ = heat capacity flow rate from hot branch nib between branch splitter and main stream mixer
$hbcp_{nib,anib}$ = heat capacity flow rate from hot branch $anib$ to hot branch nib
A_{xa} = optimal area required for match xa
AD = additional area

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Manuscript received May 7, 1998, and revision received Feb. 3, 1999.