Pergamon

0098-1354(95)00167-0

*Computers chem. Engng* Vol. 19, Suppl., pp. S149–S154, 1995
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0098-1354/95 $9.50 + 0.00

# OPTIMAL DESIGN OF CONTROLLABLE HEAT-EXCHANGER NETWORKS UNDER MULTI-DIRECTIONAL RESILIENCY-TARGET CONSTRAINTS

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## ABSTRACT

Controllable design of heat exchanger networks is formulated as constrained nonlinear optimization problem. The objective of this new method is to find the individual exchanger areas and bypass fractions which minimize the total annualized cost (or the total area) of the given heat exchanger network structure and, at the same time, to satisfy all the target temperature constraints (hard or soft) for a set of disturbances predefined in all possible directions. This is achieved by solving only one constrained optimization problem which considers the exchanger model equations (heat transfer and mixing) and constraints (resiliency index, heat load and the minimum approach temperature) simultaneously for all possible predefined disturbance directions. With the proposed method, a retrofit design satisfying given set of resiliency-target constraints of a heat exchanger network at minimum cost is accomplished.

## KEYWORDS

Heat exchanger networks; flexibility; resiliency; controllable retrofit design; optimization

## INTRODUCTION

Heat Exchanger Networks (HENs) are among the major components of chemical processing systems; they determine to a large extent the energy efficiency of a process. In a HEN, the hot and cold streams are matched in order to reduce the amount of utility consumption and/or the total cost. Many heuristic, evolutionary and algorithmic steady-state (static) synthesis methods are available to generate HENs for fixed (nominal) values of stream supply temperatures, flow rates and target temperatures. In practice, however, stream supply temperatures and flowrates can vary. Thus, a HEN must cope with desired or undesired variations in operating conditions.

Grossmann and Morari (1983) define the ability to tolerate the undesired changes in external (supply temperatures and flowrates) and internal (heat transfer coefficients) variables (uncertainties) as "resiliency", and the ability to tolerate the desired changes in operating conditions as "flexibility". They introduce some procedures to test feasibility of HENs. Saboo *et al.* (1985) and Swaney and Grossmann (1985) introduced two different measures to indicate the largest deviations of uncertain variables from nominal values for which a HEN structure remains feasible. These flexibility/resiliency indexes identify the worst case values of the uncertain variables which limit flexibility/resiliency for the proposed HEN structure.

Controllability issues of HENs have been looked at by few authors. Mathisen *et al.* (1991) reviewed different controllability measures and showed how these measures might be used to select bypasses and appropriate pairings among controlled and manipulated variables. They concluded that structural designs and bypass selections where all critical targets are controlled by either utility streams or bypasses with a

direct effect should be preferred. Mathisen *et al.* (1992a), Mathisen and Skogestad (1992b), Mathisen (1994) suggested several optimization problems and proposed to take controllability into account by adding control-related constraints to the problem formulation. Huang and Fan (1992) applied a knowledge-engineering (fuzzy logic) approach to incorporate controllability issues into synthesis of HEN structures by expressing the effect of disturbance propagation on structural controllability in a controllability-assessment table that reveals fuzzy relations between the disturbance sources and control variables. Konukman *et al.* (1994) have investigated the effects of bypass streams on disturbance propagation paths via formulating the problem as constrained nonlinear optimization (minimization of target temperature deviations subject to target temperature constraints) for a typical predesigned HEN. Different range constraints on the hot and the cold targets have been imposed in order to demonstrate the possibility of creating alternate disturbance propagation paths via bypass stream manipulations.

In this work, a new method for the retrofit design at minimum cost of a HEN satisfying a given set of resiliency-target constraints is presented. The problem is formulated as a single constrained nonlinear optimization problem and the individual exchanger areas and bypass fractions which minimize the total annualized cost (or the total area) of the given HEN structure are obtained. The resulting retrofit design (with updated exchanger areas and optimally located bypass streams) also satisfies all the target temperature constraints (hard or soft) for a set of disturbances predefined in all possible directions.

## MATHEMATICAL FORMULATION

The major problem in control of HENs is the lack of enough degrees of freedom, i.e., there may not be enough number of variables to manipulate in order to achieve control objectives. Static HEN synthesis methods never consider bypass of one or multiple exchangers and generally yield structures which do not contain any or enough number of stream splits, and do not necessarily accommodate utility exchangers for each of the target streams. Therefore, the manipulatable variables (heater or cooler loads, stream-split ratios) that may be present in a HEN structure obtained from static design methods may not be sufficient to achieve the desired control performance, especially if the target temperatures are to be controlled precisely (hard targets). Hence, inclusion of one or more bypass streams is necessary to broaden the controllable range of a HEN. However, the addition of bypasses requires updating the individual exchanger areas and/or utility exchanger loads. Therefore, it is necessary to re-evaluate the cost of the retrofit HEN possessing bypass stream(s).

In order to make a controllable design, the range of the disturbances must be predefined. In this work, we define a general *design resiliency index (DRI)*. For a designed network, DRI is the maximum permissible simultaneous deviation of identical magnitude for all combinations of the + or – directions (multidirectional) in all disturbances (deviations from nominal values of the stream supply temperatures or flowrates). For a given structure, the proposed formulation enables, through solution of only one optimization problem, the determination of design parameters (exchanger areas, nominal values of bypass flows, utility requirements) which yield minimum cost HEN for the specified DRI. The objective of the formulation is to minimize the total annualized cost (investment and operating costs) of the HEN. The resulting retrofit design may not necessarily be a maximum energy recovery (MER) structure (even if the original design is a MER). For cases where it is not desired to change utility consumption levels (i.e., if the original design is a MER design and if the retrofit design is to be a MER design as well), the formulation of the problem can be reduced to minimization of the total area of the network. For such purely total area minimization problems, the temperatures of the streams entering the utility exchangers should be kept constant (as hard targets) for zero-disturbance conditions. However, compared to the total annualized cost minimization, this formulation limits the number of possible bypass configurations; thus decreasing the degrees of freedom.

For a given HEN structure consisting of countercurrent exchanger the problem is formulated as follows:

objective function:
$$\text{Min}\left[\gamma\sum_{j=1}^{NE}\left(C_E+\alpha A_j^{\beta}\right)+\sum_{k=1}^{NC}C_C Q_{c,k}^{0}+\sum_{l=1}^{NH}C_H Q_{h,l}^{0}\right] \qquad (1)$$

For every disturbance direction (i) in all the source streams and for every exchanger (j) in the network the following equality and inequality constraint can be written:

$i = 0, \ldots, 2^{NS}$ and $j = 1, \ldots, NE$ ($0^{th}$ direction indicates zero disturbance (nominal design values))

energy equations:
$$w^i_{h,j}\left(1-u^i_{h,j}\right)\left(T^i_{hi,j}-T^i_{he,j}\right)+w^i_{c,j}\left(1-u^i_{c,j}\right)\left(T^i_{ci,j}-T^i_{ce,j}\right)=0 \quad (2)$$

$$w^i_{h,j}\left(1-u^i_{h,j}\right)\left(T^i_{hi,j}-T^i_{he,j}\right)-U_jA_j\Delta T^i_{lm,j}=0 \quad (3)$$

where:
$$\Delta T^i_{lm,j}=\frac{\left(T^i_{hi,j}-T^i_{ce,j}\right)-\left(T^i_{he,j}-T^i_{ci,j}\right)}{\ln\left[\left(T^i_{hi,j}-T^i_{ce,j}\right)/\left(T^i_{he,j}-T^i_{ci,j}\right)\right]} \quad \text{and} \quad U_j=\frac{1}{\left(1/h_{h,j}\right)+\left(1/h_{c,j}\right)} \quad (4)$$

For every mixing point after an exchanger (only the bypass of single exchanger is considered, and only if bypass is present):

energy equations:
$$u^i_{h,j}T^i_{hi,j}+\left(1-u^i_{h,j}\right)T^i_{he,j}-T^i_{hf,j}=0 \quad (5)$$

$$u^i_{c,j}T^i_{ci,j}+\left(1-u^i_{c,j}\right)T^i_{ce,j}-T^i_{cf,j}=0 \quad (6)$$

Inequality constraints for every disturbance direction (i) and for every exchanger (j) in the network:

load constraints:
$$T^i_{he,j}-T^i_{hi,j}\le 0 \quad , \quad T^i_{ci,j}-T^i_{ce,j}\le 0 \quad (7)$$

minimum approach temperature constraints:
$$T^i_{ce,j}-T^i_{hi,j}\le \Delta T_{min} \quad , \quad T^i_{ci,j}-T^i_{he,j}\le \Delta T_{min} \quad (8)$$

bypass ratio constraints (only if bypass is present):
$$0\le u^i_{h,j}\le 1 \quad , \quad 0\le u^i_{c,j}\le 1 \quad (9)$$

The heat load of the heaters and coolers for the zero-disturbance case should be given:
$$Q^0_{c,k}=w^i_{h,j}\left(T^0_{hf,j}-T^t_{h,k}\right) \quad , \quad Q^0_{h,l}=w^i_{c,j}\left(T^t_{c,l}-T^0_{cf,j}\right) \quad (10)$$

In order to complete the general formulation given above:

1- the connections between exchangers should be represented as equality constraints,
2- the target temperatures of the network should be defined as hard (equality) or soft (inequality/range) constraints,
3- the temperatures of all the source streams entering the exchangers should be defined as equality constraints (desired resiliency constraint) for every disturbance direction (i).

## EXAMPLES

***Example 1:*** Definition of the HEN problem is as given in Table 1. For this HEN problem, two different solutions (initial designs) were obtained using two standard synthesis algorithms. One of the solutions (Figure 1.a) was obtained from the algorithm suggested by Yee and Grossmann (1990) which begins with a superstructure and searches for the minimum annual cost via a MINLP based algorithm. The values of the economic parameters used are given in Table 2 (annual rate of return on investment cost, $\gamma$, was taken as unity). The second solution (Figure 1.b) was obtained via the pinch method of Linnhoff *et al.* (1982) after eliminating the exchanger with minimum load by breaking the loop present in the original pinch-design structure. Both solutions contain three heat exchangers and one cooler, both of them are MER structures, and the temperature-based flexibility indexes (Saboo *et al.*, 1985; Swaney and Grossmann 1985) of the both structures are found to be 2 K. The difference in matches of the hot and cold streams should be noticed.

Disturbances are considered only in the source stream temperatures. The bypass-stream locations (shown by the dashed lines) were decided upon such that the critical targets are controlled by either utility streams or bypasses with a direct effect, which is in accordance with the suggestions (considering the ease of control) of Calandranis and Stephanopoulos (1988) and Mathisen (1994).

The proposed method was tested for the two different base-case structures. In both problems, the temperatures of the hot and cold streams leaving the HEN without matching with the cold utility were considered as hard targets (no deviation from their nominal values were allowed). Whereas, for both structures, the temperatures entering the utility exchangers were left free. The increases in the areas of the individual exchangers and the total areas of the HENs, relative to those of the initial designs (zero-disturbance with no bypass streams), as a function of DRI are shown in Figure 2.a and Figure 2.b. Generation of such figures requires considerable computation time since the optimization problem defined above should be solved repeatedly for each DRI value until the maximum DRI is reached. Beyond the maximum DRI, one or more inequality constraints become active; structure limits. The optimizations were done using GAMS/MINOS5.

As the retrofit design versus DRI curves indicate, there is a trade-off between flexibility and investment cost for both structures over the whole range of DRI. It should be noted that MER characteristics of both structures are not violated by the increase in the DRI values. There is a significant difference between the maximum DRI values of the structures; 15.8 K for the first structure and 3.2 K for the second. The maximum DRI is the value of DRI for which a HEN structure furnished with bypass stream(s) can stay feasible. For example, the first retrofit design, with the bypass locations as shown in Figure 1.a, can tolerate all combinations of the + or – directed disturbances of at most 15.8 K in magnitude in all the source-stream temperatures.

Table 1. Definition of example problem 1

| Flow | HCF (kW/K) | $T_{in}$ (K) | $T_{out}$ (K) | $h_{ind}$ (kW/m$^2$K) |
|---|---|---|---|---|
| Hot 1 | 10 | 620 | 385 | 1 |
| Hot 2 | 15 | 720 | 400 | 1 |
| Cold 1 | 20 | 300 | 560 | 1 |
| Cold 2 | 30 | 280 | 340 | 1 |

Table 2. Economic parameters used for the evaluation of the examples

| | |
|---|---|
| $C_E$ | 5500 $ |
| $\alpha$ | 150 $/m$^2$ |
| $\beta$ | 1 |
| $C_C$ | 15 $/kW-year |
| $C_H$ | 80 $/kW-year |
| $\Delta T_{min}$ | 10 K |




Fig. 1. Two different solutions of the HEN problem given in Table 1.

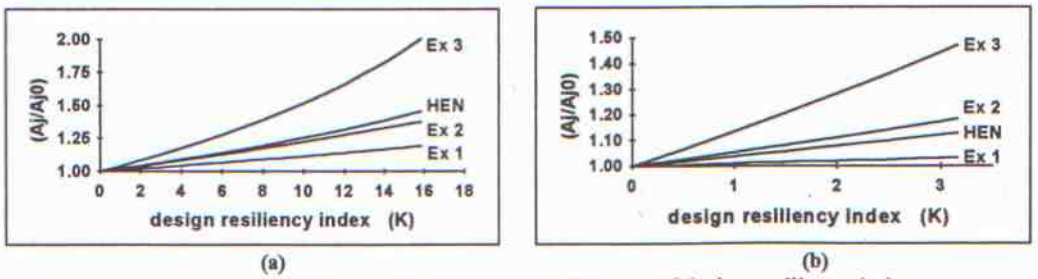



Fig. 2. Retrofit designs of the two different solutions as a function of design resiliency index.

***Example 2:*** This example is known as the 4SP1 problem in the literature and is defined in Table 3. The economic parameters of this problem are identical to those given in Table 2 (except the minimum approach temperature which was taken as zero). In this example, the annual rate of return on investment cost, $\gamma$, was taken as 0.15. The structure (Figure 3) has been obtained via the pinch method by breaking a loop. In this structure, we decided to locate a bypass (shown by the dashed line) on the cold side of exchanger 2, in accordance with the heuristics outlined in Mathisen (1994). Disturbances are considered

only in the source stream temperatures. Figure 4 shows the changes in the investment (total area), operating (utility consumption) and total costs as a function of DRI. For this structure the maximum DRI value is 15 K. In this structure, the split ratio is considered as a manipulated variable as well. Even though the structures with final splits are difficult to control (they may give inverse responses) (Mathisen, 1994), they introduce extra degrees of freedom to the problem and hence affect the trade-off between cost and flexibility in a favorable way.

Table 3. Definition of example problem 2

| Flow | HCF (kW/K) | $T_{in}$ (K) | $T_{out}$ (K) | $h_{ind}$ (kW/m$^2$K) |
|---|---|---|---|---|
| Hot 1 | 8.79 | 620 | 385 | 1 |
| Hot 2 | 10.55 | 720 | 400 | 1 |
| Cold 1 | 7.62 | 300 | 560 | 1 |
| Cold 2 | 6.08 | 280 | 340 | 1 |

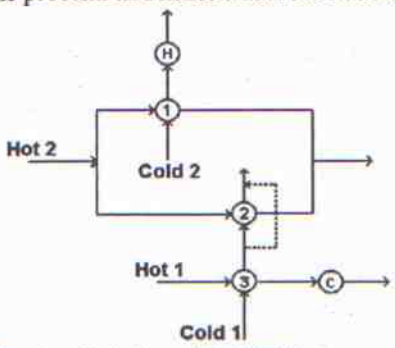



Fig. 3. Solution of the HEN problem given in Table 3.

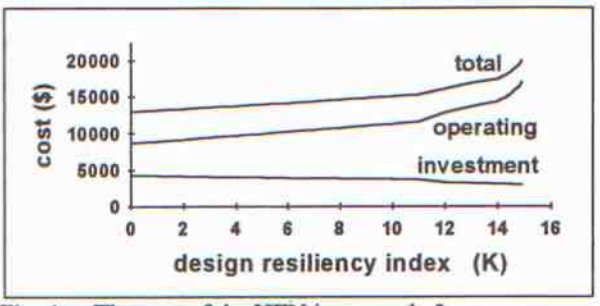



Fig. 4. The cost of the HEN in example 2 as a function of design resiliency index.

## CONCLUSION

In this work, a method was introduced for the design of controllable HENs with given structure. With the proposed method, flexible and controllable retrofit designs may be obtained for the alternative network structures and possible bypass configurations that may emerge during synthesis of a HEN problem. The proposed method enables assessment of trade-offs between operability, flexibility, controllability and controllable design once the location of bypass streams (e.g., utilizing the operability, flexibility and controllability related heuristics available in the literature (Mathisen, 1994)) are decided upon.

In the examples, the targets are considered to be hard targets and the results show that the cost of increasing flexibility/resiliency to obtain a controllable design is the increase in investment and/or operating costs. However, in cases where some of the targets are considered as soft targets, or, for some HEN structures with stream splits, it was found that controllable designs could be obtained by judiciously locating only the bypass stream(s) without any increase in the total cost.

## NOMENCLATURE

$A_j$ area of $j^{th}$ exchanger
$A_{j0}$ area of $j^{th}$ exchanger for zero-disturbance design case
$A_{tot}$ total heat transfer area of the exchangers
$C_C, C_H$ cost coefficients for cooling and heating
HCF heat capacity flowrate
$h_{c,j}$ individual heat transfer coefficients for cold stream entering exchanger j
$h_{h,j}$ individual heat transfer coefficients for hot stream entering exchanger j
$h_{ind}$ individual heat transfer coefficients for streams
NE number of exchangers in the network
NC number of coolers in the network
NH number of heaters in the network
NS number of source streams (cold and hot) entering the network
$Q^0_{c,k}$ heat load of $k^{th}$ cooler for zero-disturbance case
$Q^0_{h,l}$ heat load of $l^{th}$ heater for zero-disturbance case

$T^i_{ce,j}$ temperature of cold output of $j^{th}$ exchanger for $i^{th}$ disturbance direction
$T^i_{ci,j}$ temperature of cold input of $j^{th}$ exchanger for $i^{th}$ disturbance direction
$T^i_{cf,j}$ temperature of cold stream leaving $j^{th}$ exchanger after mixing point for $i^{th}$ disturbance direction
$T^t_{c,l}$ target temperature of cold stream leaving $l^{th}$ heater
$T^i_{he,j}$ temperature of hot output of $j^{th}$ exchanger for $i^{th}$ disturbance direction
$T^i_{hi,j}$ temperature of hot input of $j^{th}$ exchanger for $i^{th}$ disturbance direction
$T^i_{hf,j}$ temperature of hot stream leaving $j^{th}$ exchanger after mixing point for $i^{th}$ disturbance direction
$T^t_{h,k}$ target temperature of hot stream leaving $k^{th}$ cooler
$u^i_{c,j}$ cold side bypass fraction for $j^{th}$ exchanger for $i^{th}$ disturbance direction
$u^i_{h,j}$ hot side bypass fraction for $j^{th}$ exchanger for $i^{th}$ disturbance direction
$w^i_{c,j}$ heat capacity flowrate of cold stream entering $j^{th}$ exchanger for $i^{th}$ disturbance direction
$w^i_{h,j}$ heat capacity flowrate of hot stream entering $j^{th}$ exchanger for $i^{th}$ disturbance direction
$T_{in}$ stream inlet temperature to network
$T_{out}$ stream outlet temperature from network
$\Delta T_{min}$ minimum approach temperature
$U_j$ overall heat transfer coefficient for exchanger j
$\alpha,\beta,C_E$ investment cost coefficients for exchangers
$\gamma$ annual rate of return on investment cost

## ACKNOWLEDGMENT

Financial support provided by the Boğaziçi University Research Fund (Project No.94A0525) is greatly acknowledged. We are also thankful to Mr. Derya Uztürk for his help.

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