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A Simple Method for Grouping Streams in Heat Exchanger Networks Including Match Constraints

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Abstract

Problem decomposition in process integration, which was first described in 1997, was a new method aimed at making pinch technology capable of solving problems that included constraints. However, this method directly depends on human decisions, and as a result, it is not possible to automate it with a computer program. Therefore, the possibility of making errors is very high for complicated problems. In this study, a new methodology for grouping streams is presented that eliminates the above-mentioned problems. The method considers each hot stream and all of the cold streams, which have no constraints concerning group membership. Contrary to the previous method, in which each stream only belongs to one group, in our improved method, each cold stream may appear in more than one group: therefore a factor called the "Belonging Fraction" is defined for each stream to demonstrate how much of a cold stream belongs to a given group. The final groups are determined by calculation of these belonging fractions. In addition, a heat exchanger network is obtained by solving the problem. The network can be used as a basic design by heat exchanger network designers.

Keywords: Pinch technology; Heat recovery; Process integration; Problem decomposition; Heat exchanger network

Introduction

The heat exchanger network synthesis problem is one of the most studied problems in process synthesis and the development of cost-efficient heat exchanger networks has proven to be a challenging task. In the synthesis process, decisions about level of heat recovery as well as network structure, size and type of heat exchangers are made. A network resulting in the overall most economical solution when considering both utility costs and investment costs for all units of the energy recovery network is targeted. During the last three decades, a considerable number of methods have been proposed for the design task. These methods are thoroughly presented in the review articles by Gundersen and Naess [1], and Furman and Sahinidis [2].

In general terms, the objective of heat exchange network synthesis is to find out the structure of a heat exchanger network, which facilitates the task of the cooling of a given set of hot streams and the heating of a given set of cold streams to the desired levels with a minimum of investment and operating costs. Basically, there are two types of approach for solving the heat exchange network synthesis problem: (1) sequential methods and (2) simultaneous methods. The sequential methods attempt to reduce the computational complexity of the problem by decomposing the main problem into sub problems, which are then solved sequentially. The simultaneous methods solve the problem without any decomposition. The sequential methods seldom lead to globally optimal solutions.

Optimization methods form the backbone of the heat exchange network synthesis models. For a specified number of hot and cold streams, there are a large number of possibilities of network structure. Heat exchange network synthesis attempts to find the optimum among all the network configurations from the standpoint of minimum utility consumption, minimum number of units and minimum cost, etc.

Although heat exchange network synthesis has been one of the most-studied problems in process synthesis, even small heat exchange network synthesis problems have not been solved to global optimality to date. In fact, even finding feasible solutions using simultaneous synthesis methods has been troublesome. The complexity of the heat exchange network synthesis problem provides, therefore, enough scope for the development of specialized optimization algorithms [2].

One of the best known heat exchange network design methods is the pinch analysis method [3,4]. In pinch analysis subproblems are solved successively with different targets in a heuristic order of decreasing significance. The subproblems are solved with the aim of obtaining: the minimum utility cost, the minimum number of exchanger units and the minimum capital cost of the network.

Pinch Analysis

These techniques were first developed in the late 1970s by teams led by Bodo Linnhoff, whilst he did his Ph.D. under the supervision of Dr. Flower [5].

Pinch analysis is a methodology for minimizing the energy consumptions of chemical processes, by calculating thermodynamically feasible energy targets (or minimum energy consumption), and achieving them by optimizing heat recovery systems, energy supply methods, and process operating conditions. It is also known as process integration, heat integration, energy integration, or pinch technology.

Pinch analysis can increase the energy efficiencies of individual chemical processes. It has established itself as a highly versatile tool for process design. Originally pioneered as a technique for reducing the energy costs of new plants, it was later adapted for retrofits [5].

Pinch analysis quickly proposes good ideas for heat integration during complex processes, e.g. by using a grand-composite curve. Thermodynamic analysis does not guarantee a global optimum solution

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because it cannot be used simultaneously with the material balance, but it quickly proposes good ideas for heat and power integration during complex processes. Combined heat and power design adds degrees of freedom to the optimization method [6].

Pinch techniques are used in the chemical industry for improving heat integration regarding utility systems. Ahmad and Hui [7] extended the concept for direct and indirect integration.

Using the site-source and site-sink profiles, the targets for steam generation and utilization between processes were set by Dhole and Linnhoff [8]. Hui and Ahmad [9] developed a procedure for the cost optimum integrations of different processes using exergetic steam costing.

Over the last four decades, the problem of designing and synthesizing optimal heat exchanger networks has been the focus of an extensive number of studies [1,3,10-16]. In regard to this problem, a set of hot streams at a set of initial (stream) temperatures need to be cooled to a corresponding set of target temperatures, and a set of cold streams at a set of initial (stream) temperatures need to be heated to another corresponding set of target temperatures. The objective is to determine the structure of the heat exchange network and associated heat exchanger (HEX) heat load/duty, together with additional heaters and coolers (utilities), if required. This brings all streams to their target temperatures provided that the heat exchange network's HEXs input and output temperature differences are greater than or equal to the heat exchange network minimum approach temperature (ΔT min).

A heat exchanger network's design may depend on the heat-pinch targeting stage, as an approach whereby the hot and cold composite curves (CCs) are used to determine the heat energy targets (heat recovery, cold utility, and hot utility) at a specified minimum approach temperature ΔT min [1,17]. The targeting stage will allow the designer of HENs to determine the best performance achievable prior to actual synthesis. Energy targets may be set using CCs, where the minimum hot and cold utility requirements are determined.

Over past decades, pinch analysis techniques have been used for the systematic design of heat recovery [18] and material conservation systems [18-20], in the process plants. In particular, pinch analysis is widely used in the area of resource conservation such as the recovery of solvent [18-20], water [21-27], utility gas [28-31], and property-based integration [32,33]. This family of techniques is complementary to mathematical optimization techniques, since they offer advantages with respect to problem analysis and visualization. In addition, they also provide useful insights and performance targets for facilitating the subsequent detailed design stage.

Pinch analysis is a very useful method for estimating the maximum possible internal integration, by using a graphical technique. Pinch analysis techniques have been used when including those additional sources which also approach the fraction of the maximum possible internal integration to the value 1.

Despite all of its advantages, it has not been possible to use pinch technology to solve problems involving match constraints. Because, in practice, forbidden matches usually exist in most problems, there was a need to overcome this significant drawback.

Amidpour completed his PhD dissertation on a decomposition method and later Amidpour and Polley applied problem decomposition in process integration to address this drawback [34,35].

The proposed procedure involves four steps.

Step 1 involves developing a stream cascade table for the overall problem.

Step 2 is to decompose the overall problem. The streams are segregated into a number of groups. The first group called the "free group" consists of those streams that are not subject to any match constraint and can later be transferred to any other group. The other groups are made up of the streams that can be freely matched with the other streams in the same group, but they can only be matched with the streams in the other groups under specific circumstances. The stream cascade tables are developed for each of these groups using the individual cascades, which are already developed for the overall problem in step 1.

Step 3 includes the evolution of matches. In this stage, the streams from the "free group" are distributed among the various "constrained groups". Examination of the stream cascade tables from the "constrained groups" shows the temperature levels at which heat is needed or available.

Step 4 consists of a refinement of solution. The final stage involves an examination of the possibilities of sharing the free streams among the "constrained groups", and an evaluation of the possible benefits of making the previously identified matches between these groups.

Although decomposition of the overall problem is the most challenging part of the procedure, no reliable method has been developed for grouping streams, and designers have to choose from the available options manually. As a consequence, the results directly depend on human decisions, and because the possibility of making errors is so high, in very complex problems, errors are virtually certain. This weak point motivated us to establish a new methodology for grouping streams that eliminates the problems mentioned above.

Description of Method

The example implemented by Ahmad and Linnhoff to make the claim that "supertargeting" is necessary for identification of the best network structures is again used to describe our grouping method [36]. In addition, this example was employed by Linnhoff and O'Young [37] and later by Amidpour and Polley in order to describe their decomposition methods. The definition of the problem is presented in Table 1.

Stream	Cp(MW/C)	Supply Temperature (°C)	Target Temperature (°C)
H1	0.1	327	30
H2	0.25	220	160
H3	0.02	220	60
H4	0.34	160	45
C1	0.2	100	300
C2	0.07	35	164
C3	0.175	80	125
C4	0.06	60	170
C5	0.2	140	300
C6	0.3	10	60

Table 1: Problem Definition.

Hot Stream	Forbidden Matches
H1	C1, C5, C6
H2	C2, C5, C6
H3	--------
H4	C1, C6

Table 2: Forbidden Matches.

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Forbidden matches for the problem are shown in Table 2.

The method considers each hot stream and all of the cold streams, which have no constraints concerning group membership. Contrary to Amidpour and Polley's method, in which each stream belongs to just one group, in the improved method, each cold stream may appear in more than one group; therefore, a factor called the "Belonging Fraction" is defined for each stream to demonstrate how much of a given cold stream belongs to a given group. The initial groups are illustrated in Figure 1. For instance, as shown in Figure 1, cold stream 1 is in both group 2 and group 3 simultaneously, and cold stream 4 appears in all groups.

Although the method is based on hot streams, it would not make a difference in the maximum heat recovery if cold streams were considered as a basis.

The Q_{Hi} represents the maximum heat available for recovery of the i^{th} hot stream in group i, which is calculated using pinch technology. It is evident that there is no match constraint in the individual groups, so the cascade table can be freely used.

The method follows the same strategy to calculate the maximum heat available for recovery from each cold stream. This means that all hot streams that have no match constraint with a specific cold stream are found. The cascade table is then employed to determine the amount of heat that can be transferred to that cold stream under ideal conditions. This amount of heat is called for stream Q_{cj} for stream j.

a_{ij} shows the belonging fraction of cold stream j in group i.

Now, the objective function and the constraints should be defined. The target is to maximize the amount of heat recovery. Therefore, the objective function can be expressed as follows:

$$R = Max\left(\sum_{i\in I}\sum_{j\in C_i} a_{ij} Q_{Hi}\right)$$

Defining the constraints requires the following points to be considered:

1. The sum of heat that is given to the cold streams in a group must not be more than the maximum heat available for recovery from the hot stream (Q_{Hi}) in that group. To make sure that this condition is observed, the following constraints have been defined:

$$\sum_{j\in C_i} a_{ij} \le 1 (i \in I)$$

If the sum of heat required by the cold streams in a group is less than the maximum heat available for recovery from the hot stream in that group, then the correlated constraint could be omitted.

2. The sum of heat received by each cold stream must not be more than the maximum absorbable heat, which is calculated before

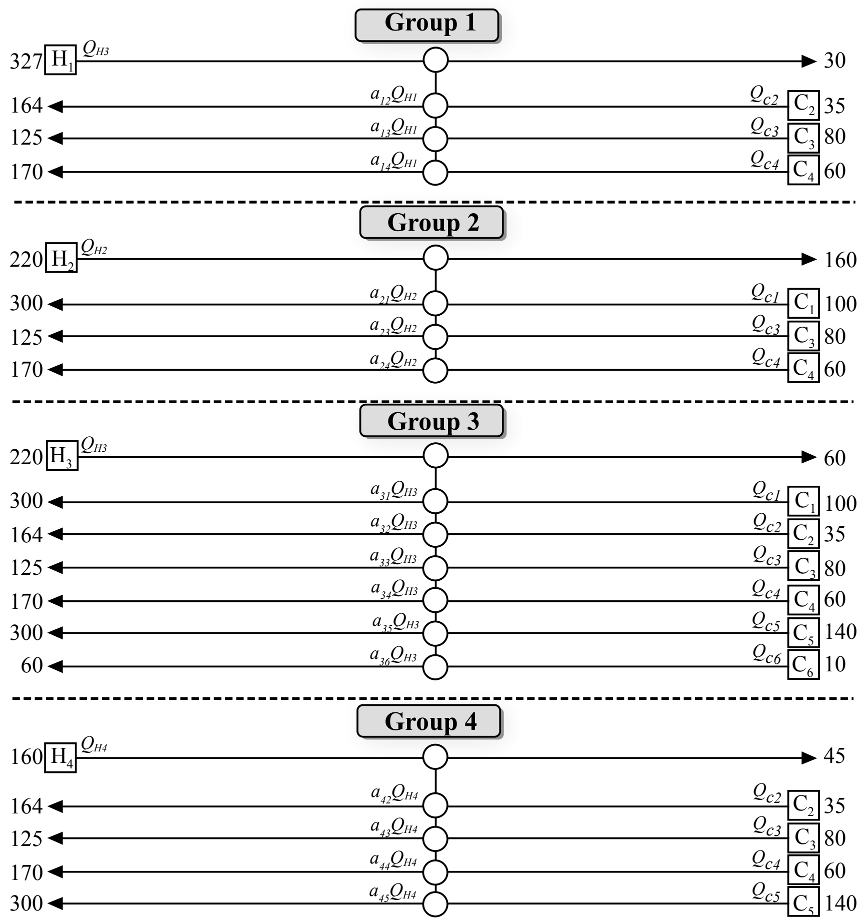

Figure 1: Initial groups.

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Name	Value
a_{12}	0.3842
a13	0.3350
a14	0.2808
a21	1
a23	0
a24	0
a31	0.6875
a32	0
a33	0
a34	0
a35	0.3125
a36	0
a42	0
a43	0
a44	0
a45	0.0857

Table 3: Belonging Fractions.

Name	Load(MW)
$H_1\vert C_2$	9.03
$H_1\vert C_3$	7.875
$H_1\vert C_4$	6.6
$H_2\vert C_1$	15
$H_2\vert C_3$	0
$H_2\vert C_4$	0
$H_3\vert C_1$	2.2
$H_3\vert C_2$	0
$H_3\vert C_3$	0
$H_3\vert C_4$	0
$H_3\vert C_5$	1
$H_3\vert C_6$	0
$H_4\vert C_2$	0
$H_4\vert C_3$	0
$H_4\vert C_4$	0
$H_4\vert C_5$	2

Table 4: Heat Exchangers Load.

(Q_{Cj}). To satisfy this condition, the following constraints have been defined:

$$\sum_{i \in H_j} a_{ij} Q_{Hi} \le Q_{cj} \, (j \in J)$$

3. To guarantee that the temperature difference of any match is not less than the minimum approach temperature (ΔT min), some other additional constraints should be developed.

   Each cold stream in a group is individually considered with the hot stream in the same group and pinch technology is applied to them. Thus, the maximum heat available for recovery between these two streams is obtained. This amount of heat is called Q_{ij}, which shows the maximum heat available for recovery between hot stream *i* and cold stream *j*. Now, constraints may be defined as follows:

   If $(Q_{ij} < Q_{Hi}) and (Q_{ij} < Q_{cj})$ then $a_{ij} Q_{Hi} \le Q_{ij}$ end

4. All belonging fractions are between 0 and 1. Therefore, the following constraints should be considered: $0 \le a_{ij} \le 1$

5. The belonging fractions are gained through solving the problem. These belonging fractions determine the final groups. In addition, a heat exchanger network is suggested to designers.

Results

The obtained belonging fractions a_{12} to a_{45} are presented in Table 3.

The results shown in Table 3 lead to grouping the streams as follows:

Because the belonging fractions of cold streams 2, 3 and 4 in group 1 are 0.384, 0.335 and 0.281, respectively, and they are 0 in other groups, these streams assigned to group 1. As can be seen, the belonging fraction of cold stream 1 in group 2 is 1, so it is put into group 2. Cold stream 5 is just allowed to match with hot streams 3 and

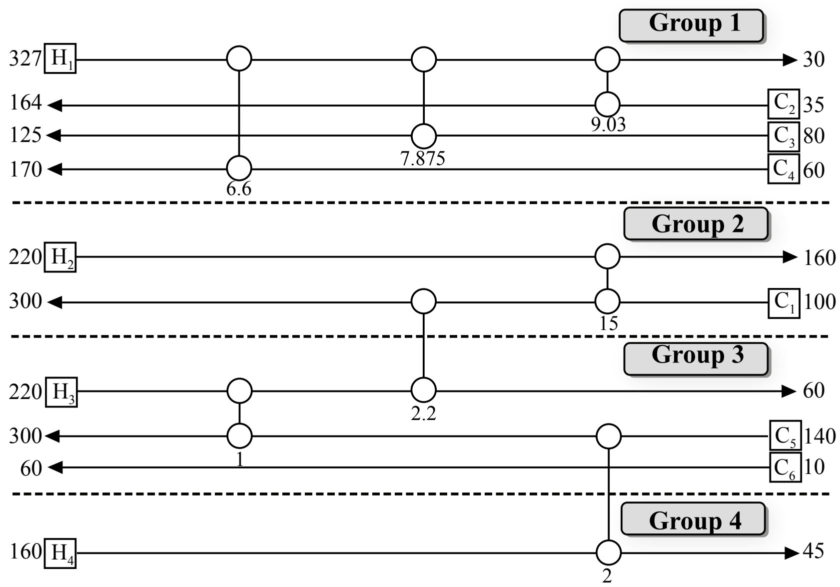

Figure 2: Final Groups and Suggested Network.

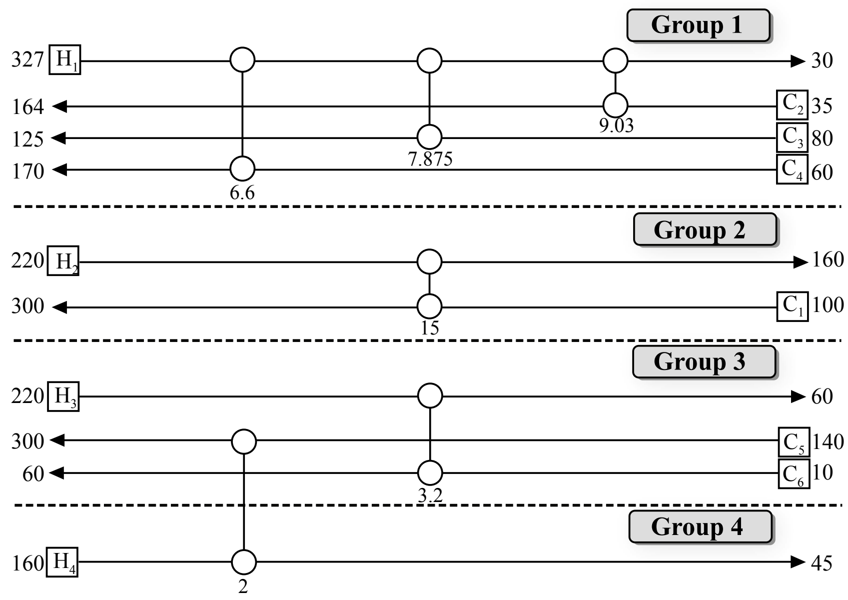

Figure 3: New Network.

4. The belonging fraction of cold stream 5 in group 3 is 0.312, which is greater than its amount (0.086) in group 4, so cold stream 5 should go into group 3. In addition, because of the constraints of the problem, cold stream 6 can only be matched with hot stream 3. Therefore, hot stream 3 and cold streams 5 and 6 forms the group 3. Finally, group 4 contains only hot stream 4. The heat load of the heat exchangers can now be calculated using the obtained belonging fractions.

Table 4 demonstrates the amount of heat load transferred between two streams that are gained from the belonging fractions.

The final groups are illustrated in Figure 2. Additionally, the suggested network produced by our method can be seen in this figure. Because each group involves no match constraints, the network can be improved simply by implementing pinch technology at the discretion of the designers.

For example, if changes are applied to the third group of the produced network, a new network will be created. From this point on, the first network is called “network 1”, and the second network is called “network 2”. The new network is shown in Figure 3.

As is evident from Figure 3, there is one less heat exchanger in network 2 than in network 1.

Moreover, cold stream 1 is satisfied in network 1, whereas in network 2, stream 6 has the same condition. According to the site needs, these two options are available for designers to choose from.

Network 2 is the same as the network designed by Amidpour and Polley [35].

The results show 43.705 MW of total heat recovery, which is 2 MW more than the heat recovery calculated by Linnhoff and O’Young [37], who attempted to solve this problem before.

Conclusions

In this paper, a new methodology for grouping streams has been developed to overcome the drawbacks of Amidpour and Polley’s decomposition method. The presented method considered any cold stream as having no constraint with each hot stream in a group, so each cold stream may appear in more than one group. The belonging fraction was defined for each stream to demonstrate how much of a cold stream belongs to a group. Based on the obtained belonging fractions, the final groups were formed. Two different heat exchanger networks were produced from our grouping method that both resulted in 43.705 MW of total heat recovery, which is 2 MW more than the heat recovery reported by Linnhoff and O’Young [37].

Nomenclature

a_{ij} Belonging fraction of cold stream *j* in group *i*

C_i Set of the cold streams which have no match constraints with hot stream *i*

C_p Heat capacity

H_j Set of the hot streams which have no match constraints with cold stream *j*

I Set of hot streams

J Set of cold streams

Q_{cj} Maximum heat available for recovery of j^{th} cold stream

Q_{Hi} Maximum heat available for recovery of i^{th} hot stream

Q_{ij} Maximum heat available to transfer from i^{th} hot stream to j^{th} cold stream

R Total heat recovery

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