A NEW ALGORITHMIC HEURISTICS FOR THE SYNTHESIS OF OPTIMAL HEAT EXCHANGER NETWORK

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Abstract. This paper proposes a new method for the discovery and design of an optimal heat exchanger network. The method is based upon the concept of pinch, a problem reduction technique and the heuristics developed in this work. It generates subproblems in a logical way and solves the subproblems by the heuristics to synthesize an optimal network structure. It is thought that the heuristics can preserve the minimum utility consumption, the minimum number of heat exchanger units, and the minimum number of stream splittings needed for a given problem. The minimum heat exchanger area for the optimal network can then be obtained by adjusting the temperatures associate with the heat exchanger in the optimal network structure. The method is applied to the problems appeared in the literatures. The results show the reductions in the number of heat exchanger units for some problems.

Keywords. Heat exchanger network symthesis ; heuristic programming

INTRODUCTION

Heat exchanger network synthesis (HENS), a major problem in process synthesis, has attracted lots of attention in the literature in the past two decades. From the viewpoint of energy recovery and conservation, the study of HENS is a problem of considerable practical importance. The problem represents a real-life situation and basic insigts gleamed by such analyes have led to 30-50% energy savings in many process industries (Linnhoff and Vredeveld,1984).

The synthesis problem was first formulated by Masso and Rudd(1969)and many researchers (Hohmann,1971;Nishida,Liu and Lapidus,1977;Linnhoff and Flower, 1978;Linnhoff and Hindmarsh, 1983;Su and Motard,1984;Floudas, Ciric and Grossman,1986) have since proposed a variety of different design algorithms for HENS. In their work, the major targets to be achieved for HENS are the minimum utility consumption, the minimum number of units and the minimum area. Among these targets, the concept of the minimum utility was introduced first by Hohmann (1971)and refined by Linnhoff and Flower(1978) by developing the concept of pinch. To incoporate the minimum number of units with the minimum tility, Flower and Linnhoff(1980) proposed a thermodynamic combinatorial algorithm, Cerda and Westerberg(1983)Suggested an algorithm which uses the LP transportation model together with a mixed integer programming, and Popoulias and Grossman(1983)used the LP transshipment model followed by a mixed integer linear programming. Most recently Floudas, Ciric and Grossman(1986)added a nonlinear programming to achieve the minimum heat exchanger area for a given network structure. However, the extra capital and operating costs for stream splittings have often been ignored in their studies. Trivedi,O'Neill and Roach (1989)have pointed out that the additional piping and maintenence costs associated with stream splittings should be included in cost equation.

Different cost equations (Masso and Rudd,1969; Linnhoff and Flower,1978;Trivedi, O'Neill and Roach,1989) have been proposed for estimating the annual cost of a given network. Still it is uncertain that which formula should be used for the best estimation. In gualitative termes, however, it is commonly accepted that the relative emphasis should be given to

1) the minimum utility consumption
2) the minimum number of heat exchanger units
3) the minimum number of stream splittings
4) the minimum heat exchanger area for a given network structure.

In this work, the first three items in the above targets are considered first to generate an optimal network structure. The minimum area, the remaining target, is then achieved by adjusting the temperatures associated with the heat exchanger units by a nonlinear programming technique.

The method begins with calculating the pinch temperature to identify independent networking zones. The actual network procedure then takes place in one of the divided zone. The networking procedure here consists of two parts. In the first part, the streams related to the pinch temperature are considered to satifsy the pinch conditions. The remaining streams, which are not associated with the pinch temperature, are then treated to generate a complete optimal network structure in the zone. The optimality of the network structure is thought to be obtained by formulating subproblems and applying the heuristics developed in this work to the subproblem. The method finally generate an optimal network by a nonlinear programming technique.

A detaild descriptions for finding the pinch temperature and for adjusting the temperatures in the optimal network structure are omitted in this paper. It is suggested for interested readers to refer Linnhoff and Flower(1978)for the pinch temperature calulation, and Floudas, Ciric and Grossman(1986)for the nonlinear optimization.

FEASIBILITY OF A MATCH AND AND TYPES OF MATCHES

The principal target of HENS is to meet the minimum utility consumption. In other words, coolers cannot be used in the zone above the pinch and no heaters are allowed in the zone below the pinch to satisfy the minimum utility consumption. To achieve this, the networking procedure in this work begins at the pinch and continues toward the end of the zone. It is noted that the procedure can be identically applied to the different zone. And it is assumed that the zone for networking dealt in the following discussion is the zone above the pinch (the zone having higher temperatures than the pinch temperature) unless there is a specific mentioning.

To design a heat exchanger network for a given problem, it is necessary to find a match repeatedly among the hot streams having heating availability and the cold streams having cooling availabilty until all the hot streams lose their heating availability. Now, let's define a feasible match as a match that can preserve the minimum utility consumption. Then, there must be two requirements for a match to be feasible. These are the location of the minimum temperature approach at the pinch and the cooling availability left after a match. The second requirement in practical term is that no cooler should be necessary to extinguish the heating availability after the match. Thus to be a feasible match the following two conditions must be satisfied at the pinch.
1) The heat capacity flow of the cold stream to be matched must be larger than (or at least the same as) that of the hot stream to be matched.
2) The pinch temperature must be identical to the lowest temperature of the streams having heating or cooling availabilities after a match.

Since the first condition in the above is removed in the zone besides the pinch, it is convenient to have two types of matches based upon the location where a match occurs. In this work, a match at the pinch is called an essential match and a match in the zone besides the pinch is called a residual match.

SUBPROBLEMS AND HEURISTICS

It is desirable to search all the possible networks for a given HENS problem to obtain the best solution. As pointed out by Ponton and Donaldson(1974), however, it seems impossible to find all the possible networks for a problem of a resonable size from the viewpoint of time consumption and complexity that arises from considering the stream splitting and merging. Thus it is necessary to logically reduce the size of a problem without losing the optimality in the final network structure, so as that all the possible networks for the reduced subproblem can be found. A detailed procedure to generate the subproblems and the heuristics to find an optimal match are given in the following discussion.

<u>For Essential Match</u>

To meet the reguirement of the minimum utility consumption, no coolers should be allowed in the zone above the pinch. And two conditions already mentioned in the previous section should be satisfied at the pinch to be a feasible match. Between these conditions, the first condition can generate candidates for feasible matches among a hot stream and cold streams. The second condition then be tested for the feasibility of the matches.

Judging from the implication of the first condition, it is natural to consider the hot stream with the largest heat capacity flow among hot streams first. Thus it is necessary to rearrange the streams as in the following order.

$$C_{CP1} > C_{CP2} \cdots C_{CPK} \cdots C_{CPNC-1} > C_{CPNC} \quad (1)$$
$$H_{CP1} > H_{CP2} \cdots H_{CPK} \cdots H_{CPNH-1} > H_{CPNH} \quad (2)$$

where, C_{CPK} is the kth largest cold stream heat capacity flow and H_{CPK} denotes the kth largest hot stream heat capacity flow. NC and NH are the number of cold streams and hot streams respectively.

Now to satisfy the first condition for the feasibility of matches, it is required to examine if

$$C_{CPK} > H_{CPK} \quad \text{for } k = 1,2, \ldots NH \quad (3)$$

If Eq. (3) is violated for the jth largest heat capacity flow, the situation can be represented as

$$C_{CPK} > H_{CPK} \text{ for } k = 1,2, \ldots j-1$$
$$C_{CPj} < H_{CPj} \text{ for } j < NH \quad (4)$$

For the sake of simplicity, let the situation in Eq. (3) be case 1 and the situation in Eq. (4) be case 2. Then it can be said that the stream splitting may not be needed for case 1. For case 2, however, the stream splitting should be required at least once to remove the difficulty. In any case, it is thought that the original problem can be reduced without affecting the optimality in the final network structure.

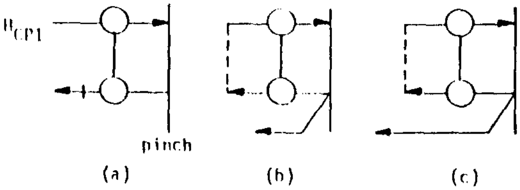
<u>Subproblem formulation for case 1.</u> It is easily seen in this case that there is at least one cold stream for each hot stream at the pinch for the feasible matches. Since the main objective here is to make the target temperatures of the hot streams become higher than the pinch temperature through the feasible matches, it is necessary to select the streams associated with the pinch temperature. The selected streams are then rearranged as in Eq. (1) and Eq. (2) to give a HENS problem for the essential matches. In this reorganized HENS problem, it can be easily thought that the best strategy of networking is to consider the hot streams one by one. And the choice of the hot stream to be considered first should be the hot stream with H_{cp1}. Because all the cold streams having their heat capacity flows larger than (or the same as) H_{cp1} are the candidates for the feasible matches to this hot stream. Choosing an other hot stream, for example the hot stream with H_{cpk} for k>1, it is difficult to select the canidates among the cold streams for the feasible matches due to considerations on the hot streams hvaing their heat capacity flows larger than H_{cpk}. For this reason the subproblem to the reorganized HENS problem simply becomes as follows ;

$$\text{SP1} : H(H_{cp1}),\ C(C_{cp1}),\ C(C_{cp2}),\ \ldots\ C(C_{cpk})$$
$$C_{cpk} > H_{cp1} \quad (5)$$

where, $H(H_{cp1})$ denotes the hot stream with H_{cp1} and $C(C_{cpk})$denotes the cold stream with C_{cpk}.

It is noted here that $H(H_{cp1})$ and a cold stream among the candidates in Eq. (5) can be eleminated from the reorganized HENS problem after finding the optimal feasible match as a solution to SP1. Then the reduced problem can again be rearranged as in Eq. (1) and Eq. (2) to give a new HENS problem. This process can be repeated until no hot streams left to be considered.

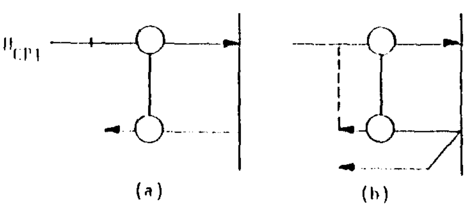
<u>Heuristics for case 1.</u> The solution to SP1 should be optimal feasible. Thus it is important to test the optimality and the feasibility of possible matches. Here, the optimality can be established by finding the configuration which yields the minimum number of units and the minimum number of stream splittings for the extinction of the heating availability in SP1 . The feasibility is then obtained by examining if the configuration satisfies the second feasibility condition described in the previous section. Fig. 1 shows the possible configurations to remove the heating availability in SP1 using one heat exchanger and a heater. To distinguish the configurations for this case from configurations for other cases, the identifier, HE1-1 is used.



Fiq.1. Three possible confiquations for HE1-1

The hierarchy of the heuristics in Fig. 1 is denoted by (a), (b) and (c). In configuration HE1-1-(a), there are no stream splittings. Thus this configuration must be sought first for the optimality. The configurations HE1-1-(b) and HE1-1-(c) can occur if configuration HE1-1-(a) violates the feasibility condition. Between these two configrutations, configuration HE1-1-(b) should be prefered since the cooling availability of the splitted cold stream in HE1-1-(b) is greater than that in HE1-1-(c).

However, if there are no such configurations as in HE1-1-(a) for SP1, the configurations shown in Fig. 2 should be sought. As easily can be seen in Fig. 2, these configurations need more than one heat exchanger to extinguish the heating availability. Hence the hierachy of Heuristics HE1-2 is lower than that of Heuristics HE1-1.



Fiq.2. Two possible confiquration for HE1-2

Since configurations shown in Fig.1 and Fig.2 actually represent all the possible configurations for SP1, the solution to SP1 can simply be obtained by finfinding the match whose configuration is in the highest hierechy.

<u>Subproblem and heuristics for case 2.</u> The main target in solving this case is to remove the difficulty of $C_{cp1} < H_{cp1}$, and to make the case become case 1. There are basically two remedies to overcome this difficulty. One is seperating a cold stream to generate two new cold streams. The other is seperating a hot stream to split the heating availability. However, the former technique must be considered first since the latter technique will generate one more hot stream which require at least one extra heat exchanger for the extinction of heating availability. Thus to continue the discussion on formulation of subproblems for case 2, it is necessary to distinguish the techniques to be used. Let the technique of a cold stream splitting be case 2-1 and the technique of a hot stream splitting be case 2-2.

For case 2-1, the splitted cold stream should be able to make two hot streams, including the hot stream with H_{cpj}, have their target temperature higher than the pinch temperature through the heat exchange. Thus the subproblems in this case can be formulated as follows.

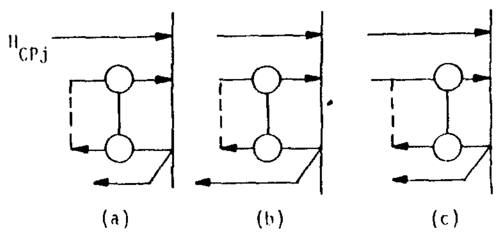
SP2 :

SSP1 : $H(H_{cp1})$, $H(H_{cpj})$, $C(C_{cp1})$, ..., $C(C_{cpk1})$
where $C_{cpk1} > H_{cp1} + H_{cpj}$

SSP2 : if C_{cp2} H_{cp1}, then
$H(H_{cp2})$, $H(H_{cpj})$, $C(C_{cp1})$, ..., $C(C_{cpk2})$
otherwise
$H(H_{cp2})$, $H(H_{cpj})$, $C(C_{cp2})$, ..., $C(C_{cpk2})$
where $C_{cpk2} > H_{cp2} + H_{cpj}$

SSPi : if $C_{cpk} > H_{cpk-1}$, then
$H(H_{cpi})$, $H(H_{cpj})$, $C(C_{cpk-1})$, $C(C_{cpk})$
for k=2,3, ... ki
where $C_{cpki} > H_{cpi} + H_{cpj}$
for i=3,4, ... , j-1 (6)

The subsubproblems formulated above represent the subproblem for case 2-1. It is seen that the all the feasible matches can be sought from the subproblem without losing the optimality in the final network structure. The solutions of the subproblem in this case actually guarantee the feasibility. And the optimality for the best solution can be obtained by considering all the possible configurations for the case. Fig. 3 shows the hierachy of the heuristics obtained by examing all the possible configurations for the solutions to the subproblem.



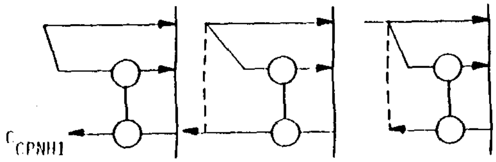
Fiq.3. Three possible configuration for HE2-1

In Fig. 3,configurations HE2-1-(a) and HE2-1-(b) are prefered to configuration HE2-1-(c) since less heat exchangers are needed for the extinction of the heating availability of the hot stream with H_{cpj}. For the reason mentioned in the previous section it is thought in this case that configuration HE2-1-(a) is superior to configuration HE2-1-(b). It is mentioned here that the match between the hot stream with H_{cpj} and the unmatched splitted cold stream in Fig. 3 is not considered at this stage since the reorganized problem, after deleting the streams which are shown in Fig. 3 as a matched pair, can have a better solution.

If there are no feasible solution to the subproblem obtained by splitting a cold stream a hot stream splitting (case 2-2) is considered next. In this case a hot stream having its heat capacity flow larger than H_{cpj}, must be splitted to give feasible matches with $C(C_{CPNH,1})$, $C(C_{CPNH,2})$. The subproblem for this case can be represented as follows.

$$SP3: H(H_{cp1}),\ H(H_{cp,i+1}),\ \ldots\ H(H_{cp,j}),\ C(C_{CPNH,1}),\ C(C_{CPNH,2}) \quad \text{where } H_{cp1} < C_{CPNH,1} + C_{CPNH,2} \tag{7}$$

Fig.4 shows three possible configurations for the case. Since the solutions to SP3 cannot gurantee the feasibility, the configurations in Fig. 4 are constructed by considering both the feasibility and the optimality. The hierachy of heuristics HE2-2 are also represented by (a), (b) and (c)



(a) (b) (c)

Fig.4. Three possible configuration of HE2-2

For Residual Match

After performing essential matches, there are stream which are not associated with the pinch temperature left to be considered in the zone. As seen in the previous section, the heat capacity flows of streams were important to satisfy the first feasibility condition for the essential match. However in the residual match, the temperatures associated with streams are important as a part of the second feasibility condition mentioned in the earlier section. In other words, to have possibly a feasible match the source temperture of the cold stream to be matched must be lower than (at least the same as) the target temperature of the hot stream to be matched. Thus it is necessary to rearrange the streams in ascending order of temperatures as in Eq. (8) and Eq. (9), and to examine if Eq. (10) is satisfied.

$$C_{s,1} < C_{s,2} < \ldots < C_{s,k} \ldots < C_{s,NC} \tag{8}$$
$$H_{t,1} < H_{t,2} < \ldots < H_{t,k} \ldots < H_{t,NH} \tag{9}$$

$$C_{s,k} < H_{t,k} \text{ and } C_{p,k} > H_{p,k} \text{ when } C_{s,k} = H_{t,k} \quad \text{for } k = 1,2,\ldots NH \tag{10}$$

where, $C_{s,k}$ is the kth lowest cold stream source temperature while $H_{t,k}$ denotes the kth lowest hot stream target temperature.

The situation where Eq. (10) is violated can also be written in a mathmatical form as follows

$$\begin{aligned} &C_{s,k} < H_{t,k} \text{ and } C_{p,k}\ H_{p,k} \text{ when } C_{s,k} = H_{t,k} \\ &C_{s,j} > H_{t,j} \text{ or } C_{p,j} < H_{p,j} \text{ when } C_{s,j} = H_{t,j} \\ &\text{for } k = 1,2 \ldots j-1,\quad j < NH \end{aligned} \tag{11}$$

For simplicity let the situation in Eq. (10) be case 1 and the situation in Eq. (11) be case 2, and consider the subproblems and the heuristics for each case.

Subproblem formulation for case 1. In this case, it is natural to reduce the heating availability of the hot streams from the lowest hot stream target temperature. Thus it is necessary to confine our attention to the hot stream having $H_{t,1}$. The best match then can be found by considering all the possible configurations that can occur among this hot stream and all the cold strams for the extinction of the heating availability of this hot stream. The following subproblem for the case is formulated based upon the above observation.

$$SP3: H(H_{t,1}),\ C(C_{s,1}),\ C(C_{s,2}),\ \ldots\ C(C_{s,NC}) \tag{12}$$

Heuristics for case 1. Fig. 5 shows the possible configurations to completely eleminate the heating availability of the hot stream with $H_{t,1}$ by using two or less heat exchangers and a heater without splitting streams.

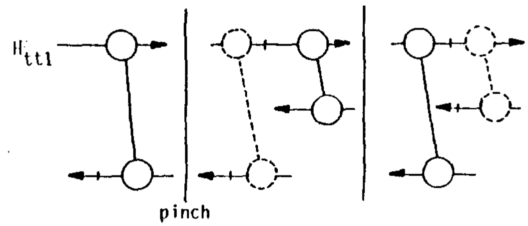
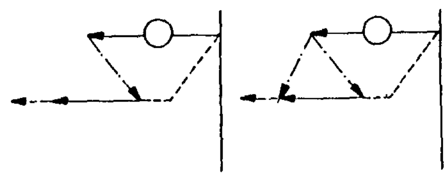


Fig.5. Three possible configurations in HR1-1

The trick employeed in this case is also to make just one unavoidable match (the match depicted by a solid line). The remaining hot stream for the configurations of HR1-1-(b) and HR1-1-(c) is treated as a new hot stream to form a new problem. It is worth mentioning here that the possibility of merging the splitted cold stream to form a new cold stream and then participated in the subproblem as shown in Fig. 6 should be considered.

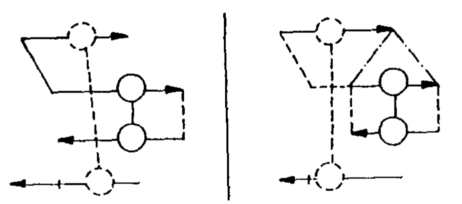


(a) (b)

Fig.6. Stream merging methods

In Fig. 6, it is noted that the stream merging can be considered only if the availability of the merged stream (the solid line without circle in Fig. 6) is larger than that of the original splitted stream (the broken line in Fig. 6). Case (a) in Fig. 6 indicates a total merge while case (b) in Fig. 6 shows a partial merge.

More possible configurations of using two heat exchangers for the case can be found in Fig. 7 and Fig. 8. It should be easy to deduce the hierachy from the configurations. Thus a detailed explanation is omitted here.



(a) (b)

Fig.7. Two possible configurations in HR1-2

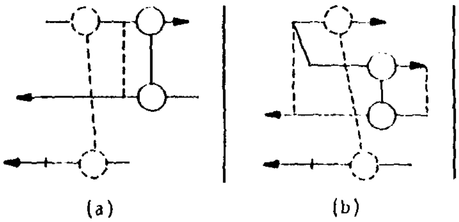


Fig.8. Two possible configurations in HR1-3

<u>Subproblem formulation for case2.</u> This case is similar to case 2 in essential match from the stand point of the necessity to generate a new cold stream, which can remove the difficulty of $C_{nt1} > H_{tt1}$. The subproblems in this regard can be formulated as follows.

SP4 ;

SSP1 : $H(H_{tt1})$, $H(H_{ttj})$, $C(C_{nt1})$, $C(C_{nt2})$, ... $C(C_{tk1})$
where $C_{ntk1} < H_{tt1}$ and $C_{cpk} > H_{cp1}$
for $C_{ntk1} = H_{tt1}$

SSP2 : if $C_{nt2} < H_{tt1}$ or $C_{cp2} > H_{cp1}$
for $C_{nt2} = H_{tt1}$
$H(H_{tt2})$, $H(H_{ttj})$, $C(C_{nt1})$, $C(C_{nt2})$, ...
$C(C_{ntk2})$
otherwise
$H(H_{tt2})$, $H(H_{ttj})$, $C(C_{nt2})$, ... $C(C_{ntk2})$
where $C_{ntk2} < H_{tt2}$ and $C_{cpk2} > H_{cp2}$
for $C_{ntk2} = H_{tt2}$

SSpi : if $C_{cpk} < H_{ttk-1}$ or $C_{cpk} > H_{cpk-1}$
for $C_{cpk} = H_{ttk-1}$, then
$H(H_{tti})$, $H(H_{ttj})$, $C(C_{ntk-1})$, $C(C_{ntk})$
for k=2,3, ... ki
where $C_{ntki} < H_{tti}$ or $C_{cpki} > H_{cpi}$
for $C_{ntki} = H_{tti}$
for i = 3,4, ... j-1 (13)

<u>Heuristics for case 2.</u> Fig. 9 shows the possible configurations for the solution to subproblem SP4. As can be seen in Fig. 9, the hierachy is determined by considering the number of cold stream splittings and the availability of the unmatched splitted cold stream. Finally for the case of reguiring more than two heat exchangers to extinguish heating availability of the hot stream, a similar heuristcs can be developed as discussed in this section.

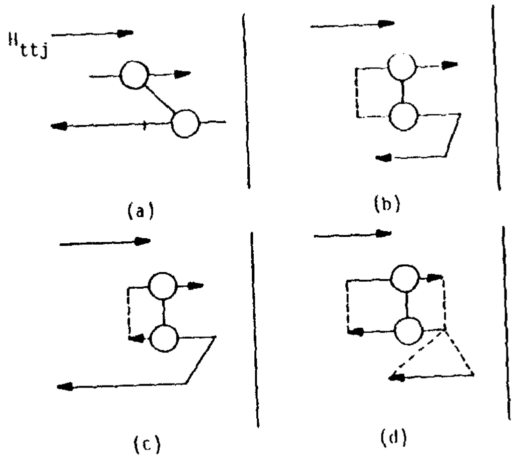


Fig.9. Four possible configurations for HR2

EXAMPLE

The second example in Floudas, Ciric and Grossman(1986) was selected to demonstrate the superiority of the networking prodecure developed in this work. The original data for the example are given in table 1. To adjust the minimum approach temperature of 10 K, data are provided by subtracting 10K from the temperatures of the hot streams in table 1.

<u>Table 1 Problem Data for Example</u>

Stream	FC_p, KW/K	T_{in}, K	Tout, K
H1	111.844	492.65	337.41
H2	367.577	337.41	310.00
H3	29.7341	395.48	300.00
C1	9.236	320.00	670.00
C2	112.994	368.72	450.00
C3	107.698	320.00	402.76

The result of the pinch analysis (by T1 method) shows a pinch temperature of 492.65 K. Thus the original problem can be depicted as shown in Fig. 10. Since there is no hot streams in the zone above the pinch, a heater must be installed to make cold stream C1 to reach its target temperature. In the zone below the pinch in Fig. 10, hot stream H1 and cold stream C1 have to be considered for an essential match. Although hot stream H1 can extinguish the cooling availability of cold stream C1. The match without splitting H1 is infeasible since the new pinch temperature will differ from the lowest hot stream temperature after the match. Thus hot stream H1 must be splitted (by HE1-1-(b)) to give the configuration shown in Fig. 11.

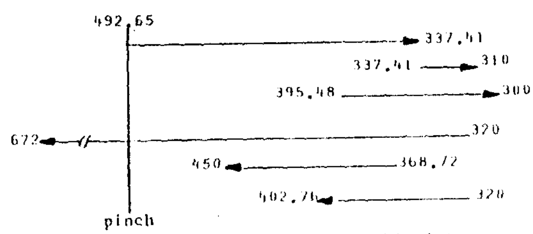


Fig.10. Example problem in a graphical form

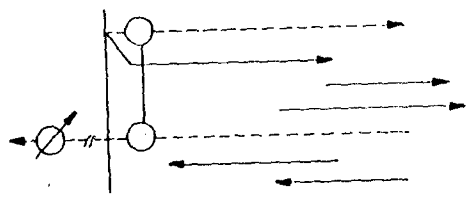


Fig.11. Essential match by HE1-1-(b)

In Fig.11, since there are no cold stream related to the pinch the residual match can begin. Cold stream C2 and the remaining splitted hot stream are selected first because of their low temperatures. For the same reason stated for the essential match, the cold stream has to be splitted again (by HR2-(b)). The result of this match is shown in Fig. 12.

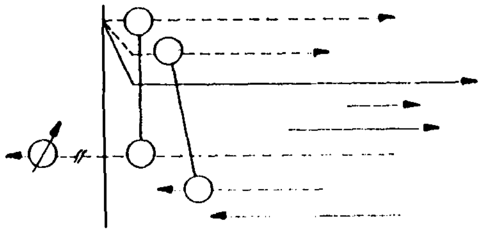


Fig.12. First residual match by HR2-(b)

Although there is only one cold stream left to be considered in Fig. 12, it is difficult to find a best match. However applying the heuristics in turn, it can be found that the best configuration in this case must be the match as shown in Fig. 13.

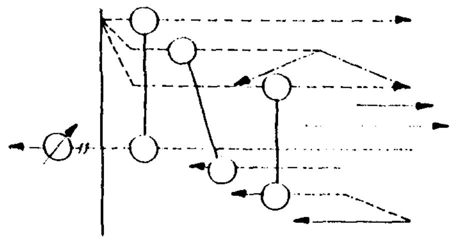


Fig.13. Second residual match by HR1-1-(b)

The remaining matches have been already thought when the match shown in Fig. 13 was found. The resulting optimal network structure now can be tested to give the minimum heat exchanger area. Fig. 14 shows the optimal network for the example problem.

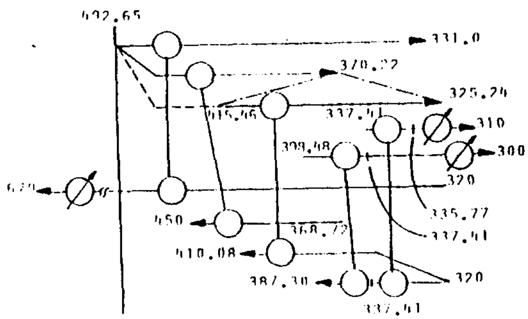


Fig.14. Final network for the example

In Fig. 14 the network is constructed by using five heat exchangers, two coolers and a heater. The reduction in the number of heat exchanger units is two compared with the result obtained by Floudas, Ciric and Grossman (1986), where seven heat exchangers, two coolers and a heater was used.

CONCLUSION

Although the networking procedure developed here is relatively simple in nature, it can generate an optimal heat exchanger network even for camplex problems such as the problem shown in the previous section. The method can also be easily programmed to automate heat exchanger network synthesis. The method was applied to typical HENS problems appeared in the literature. The results show reductions in the number of heat exchanger units, reductions in number of stream splittings or reductions in total heat exchanger area for some problems compared to the results obtained by earlier researchers.

The method can cover the HENS problems with phase changes as well as the HENS problems with large dimensionality. It is believed that the method can be modified to solve the HENS problems with forbidden matches for some streams.

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