Synthesis of Heat Exchanger Networks:

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I. Systematic Generation of Energy Optimal Networks

A thermodynamically orientated method is presented for the synthesis of heat exchanger networks. With this method, the problem is solved in two stages. In the first stage, preliminary networks are generated which give maximum heat recovery. In the second stage, the most satisfactory final networks are evolved using the preliminary networks as starting points. In this paper, emphasis is given to the synthesis of the preliminary networks. Two four-stream examples are solved. In Part II, emphasis will be given to the synthesis of final networks.

SCOPE

The problem of automatically synthesizing chemical process networks has recently attracted some attention in the chemical engineering literature. Relevant work has been reviewed by Hendry et al. (1973) and Hlavacek (1975). As an easily formulated and comparatively simple subproblem, the automatic synthesis of heat recovery networks has received a great share of this attention. For a survey covering this special field, see, for example, Siirola (1974).

Essentially, the synthesis task consists of finding a feasible sequence of heat exchangers in which pairs of streams are matched, such that the network is optimal as judged from overall cost viewpoint. The difficulties arise from the extremely large number of possible stream combinations. Even for small problems, all possible networks cannot normally be enumerated, due to the inordinate demand for computer store and time. Techniques like branch-and-bound (for example, Lee et al., 1970) and tree searching (for example, Pho and Lapidus, 1973) have helped to reduce the number of combinatorial possibilities to be enumerated, but the largest problem solved so far in the literature by means of such techniques involved no more than ten streams (Pho and Lapidus, 1973). Also, optimality could not be strictly guaranteed with these techniques, and cyclic network structures (that is, structures in which two streams are matched against each other more than once) could not be obtained unless the combinatorial problem was allowed to increase in size quite significantly (Rathore and Powers, 1975).

An alternative synthesis method, presented by Ponton and Donaldson (1974), is mainly based on the heuristic of always matching the hot stream of highest supply temperature with the cold stream of highest target temperature. This method can yield cyclic network structures without additional computational effort, and it has been applied to problems of realistic size (see Donaldson et al., 1976). Unfortunately, the method is somewhat unreliable in the sense that it may produce results which are quite far from optimum so that it tends to generate demand for additional heuristics in unexpected situations.

Rathore and Powers (1975), among others, pointed out that costs for steam and cooling water will normally be more important than the costs for plant to the extent where several quite dissimilar network topologies will all feature near optimal costs insofar as they feature near maximum energy recovery. Based on this observation, they recommended a procedure to identify the upper bound on energy recovery for a given problem, and to carry out a depth first tree search in order to rapidly identify some, but not all, networks with maximum or near maximum energy recovery. These networks, they argued, will feature similar and near optimal costs. They can then be compared on grounds of safety, control, starting-up procedures, etc. A strategy of this sort appears even more justified by reports about poor control behavior and other difficulties found with automatically synthesized networks (see, for example, Hlaváček, 1975).

Nishida et al. (1977) presented an algorithmic evolutionary synthesis method which appears to be suitable for the solution of realistic size problems. It employs three basic criteria: trying to ensure maximum energy recovery, trying to minimize total heat transfer area, and trying to minimize the total cost of the network. The total heat transfer area is minimized by a minimum area algorithm, while the total cost is minimized using evolutionary rules. Maximum energy recovery is sought by a theorem and corollaries using a heat content diagram adopted from previous work (see Siirola, 1974). Hohmann (1971) presents a method for synthesis of minimum area networks which also includes a technique for assessing the feasibility of a system of streams assuming a suitable approach temperature and given utility supplies. Hohmann and Lockhart (1976) describe developments which are aimed at assessing the feasibility of a network of exchangers by examination of the minimum approach temperature found in the network. Both techniques indirectly provide correct estimates

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of resource requirements by confirming the feasibility of a network for assumed utility supplies.

A new synthesis method (called temperature interval, or TI method) is proposed which also makes use of the fact that desirable network structures will normally feature high degrees of energy recovery. The method deals with the problem in two stages. In the first stage, preliminary networks are generated which exhibit the highest possible degree of energy recovery. In the second stage, these preliminary networks are used as convenient starting points when searching for the most satisfactory network from other points of view. Apart from costs, criteria like safety constraints, controllability, etc., are easily observed.

In this paper, the main emphasis is laid on the first stage (that is, generation of preliminary networks). The original synthesis problem is split into subproblems, each of which extends over a limited temperature interval only. Synthesis of subnetworks which solve these subproblems is trivial, even when carried out in a way which ensures maximum overall energy recovery. The approach is based on thermodynamic theory and is thoroughly systematic. Combinatorial problems are considerably reduced, since suitable networks can be methodically assembled from smaller units so that there is no need to carry out searches through the complete solution space. In cases where maximum energy recovery would require too complex or too expensive a network, this will be recognized during the synthesis, and the introduction of parallel stream splitting may be considered.

The second stage (that is, search for the most satisfactory final networks) is discussed in detail in Part II.

CONCLUSIONS AND SIGNIFICANCE

The temperature interval method as presented allows the user to identify the upper bound on energy recovery for a given heat exchanger network synthesis problem. This method is based on enthalpy balances which also form the basis of the methods of Hohmann (1971) and Nishida et al. (1977). It also allows the user to systematically generate a variety of networks which perform at this upper bound. The networks are produced by the TI method with very small computational effort. This has been made possible by interpreting the problem on thermodynamic rather than on combinatorial grounds; the physical constraints which govern the feasibility of heat transfer are kept as relaxed as possible by an entirely systematic procedure.

Since synthesis problems are normally based on cost optimization, the fact that optimality is sought with respect to heat recovery rather than costs might appear to be a disadvantage of the TI method. However, as noted previously (Siirola, 1974), the overall costs are heavily dominated by the cost of energy. So different networks which solve the same problem and feature maximum heat recovery are all suitable starting points when evolving the most satisfactory final networks. This has been demonstrated by means of two examples; the TI method was shown to identify with great ease a variety of energy optimal networks so that a choice of different solutions with, for example, different control characteristics (but similar and near optimum costs) could rapidly be identified.

PROBLEM STATEMENT

The way in which the synthesis task was defined has varied in the literature, but most of the recent work has concentrated on the solution of identical types of problems (for example, Masso and Rudd, 1969; Lee et al., 1970; Hohmann, 1971; McGalliard and Westerberg, 1972; Pho and Lapidus, 1973; Ponton and Donaldson, 1974; Rathore and Powers, 1975; Hohmann and Lockhart, 1976; Nishida et al., 1977). The following is a brief outline of this type of problem:

A set of z streams, of known mass flow rates and constant specific heat capacities, are to be brought from given supply temperatures T_S to given target temperatures T_T. For $T_S > T_T$, the stream in question is called a hot one and for $T_T > T_S$, a cold one. Apart from heat exchange between the streams, cooling with cooling water and heating with steam may be considered. The heat exchangers, heaters, and coolers are countercurrent, single-pass units operating with a given minimum approach temperature ΔT_{min}. The use of multistream exchangers and/or parallel stream splitting is not considered. The streams are all single phase. Change of phase can be accommodated using known ways of reformulating the problem (Donaldson et al., 1976). Given these constraints, that network is to be found which is optimal with respect to the annual cost of steam, cooling water, and plant. For a more detailed problem description as well as design data, see, for example, Nishida et al. (1977). Hohmann (1971), Hohmann and Lockart (1976), and Nishida et al. (1977) solved the same type of problem except for the fact that they included parallel stream splitting. While stream splitting will be discussed in detail in Part II, its implications will be briefly summarized at appropriate points in this paper.

THE TEMPERATURE INTERVAL METHOD

The temperature interval method will be illustrated by solving a four-stream example, called test case No. 1. The data for the problem are given in Figure 1.

Any network which will solve the problem may be thought of as an array of n subnetworks, see Figure 2. Each of these subnetworks includes all streams (or parts of streams) which fall within a defined temperature interval. The temperatures T_1, T_2, ... T_{n+1} are deduced from the problem data in the following way. Each stream's supply and target temperatures are listed after the temperatures of the hot streams have been reduced by the minimum temperature difference ΔT_{min}. The highest temperature in the list is called T_1, the second highest T_2, and so on. Generally, the following expression holds

$$n \leq 2z - 1 \tag{1}$$

with the equality applying in cases where no two temperatures coincide.

Each subnetwork represents a separate synthesis task. However, since all streams in a subnetwork run through the same temperature interval, the synthesis task is very easy. Consider, for example, $SN(1)$ in Figure 2. There is

Stream No. and Type	Heat Capacity Flowrate "Cp" [kW/°C]	T_S [°C]	T_T [°C]	Heat Load $Cp(T_S - T_T)$ [kW]
(1) COLD	3.0	60	180	−360
(2) HOT	2.0	180	40	280
(3) COLD	2.6	30	105	−195
(4) HOT	4.0	150	40	440
				Σ = 165

Fig. 1. Data for test case No. 1.

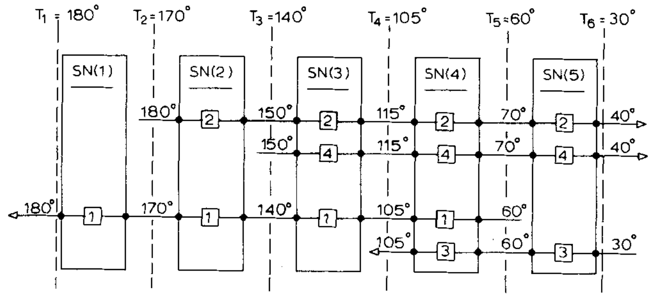


Fig. 2. Subnetworks defined through temperature intervals (for test case No. 1).

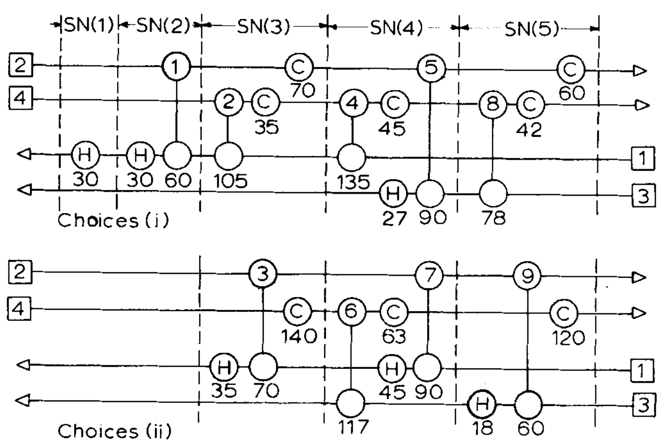


Fig. 3. Subnetwork designs for test case No. 1.

only one cold stream so that there is no alternative but to introduce a heater, see Figure 3*. In the case of $SN(2)$, there is only one hot and one cold stream to be matched, and a heater is required to deal with the residual of the cold stream (which has the higher heat capacity flow rate). Evidently, this heater must be placed on the hot side of the exchanger, since otherwise the $\Delta T_{\min}$ constraint would be violated.

For $SN(3)$, $SN(4)$, and $SN(5)$, two alternative designs can be identified in each case which require different amounts of heat to be supplied by the heaters.

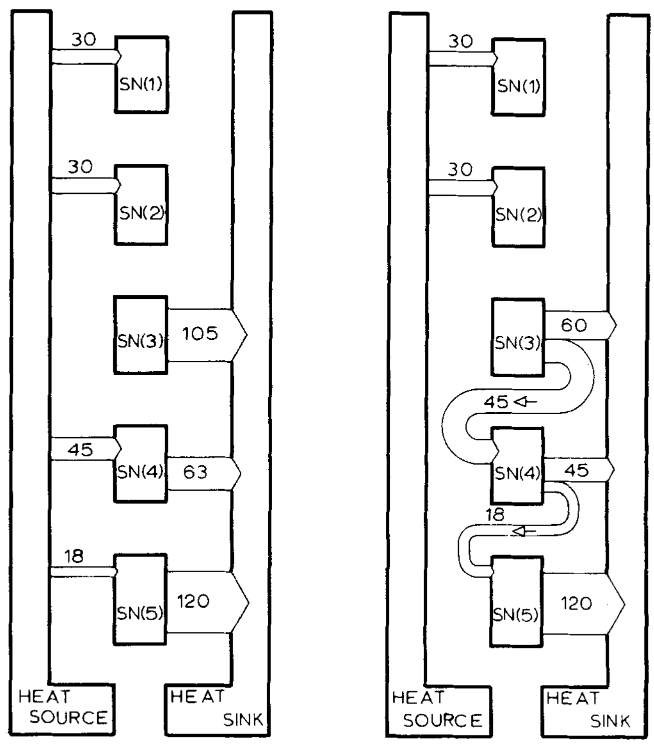
These designs can be proposed by simple inspection, but in more complex cases, a systematic method will be required:

1. Rank the hot and cold streams in order of decreasing heat capacity flow rates.
2. Specify matches between the first hot and first cold, second hot and second cold, etc., streams until the only original streams left are either all hot or all cold.
3. Match the largest remaining stream with the largest residual of the primary matches, the second largest remaining stream with the second largest residual, etc. (at this stage, temperature constraints must be considered).
4. Whatever remains after these steps, that is, original streams, primary residual, or secondary residuals, etc., the final step is to match these against utility heat and cold.

This method will produce a single design which may not be more convenient than others at a later stage in the synthesis but which will always produce a subnetwork structure in which the heater and cooler loads are not greater than those obtained by different rules. Even smaller heater and cooler loads may be found by either using parallel stream splitting within the subnetwork or by creating cyclic subnetwork structures using a structure such as one developed by the above method as a starting point. These possibilities will be discussed in detail when we deal with the second example, test case No. 2.

If the aim of the synthesis task were to design each subnetwork on its own to use the minimum process utility heat, choices (i) in Figure 3 would be adopted throughout when assembling the final network. It is, however, the overall requirement for process utility heat which is to be minimized, and the following considerations will show that choices (ii) for $SN(4)$ and $SN(5)$ should not necessarily be discarded.

In Figure 4a, a heat flow diagram is given showing all five subnetworks as well as a heat source (representing process utility heat) and a heat sink (that is, cooling water). Choice (i) has been adopted for $SN(3)$. This uses the lowest possible intake of process utility heat for $SN(3)$. For $SN(4)$ and $SN(5)$, however, choices (ii)



(a) (b)

Fig. 4. Introducing matches between subnetworks.

* The particular way of representing a heat exchanger network graphically which has been adopted in Figure 3 is used throughout this work. Hot streams run to the right at the top of the diagram, and cold streams run to the left at the bottom. Beneath each symbol for heaters (H), coolers (C), and exchangers , heat loads are noted in appropriate units (kilowatts throughout this work). The exchangers are numbered in their upper node.

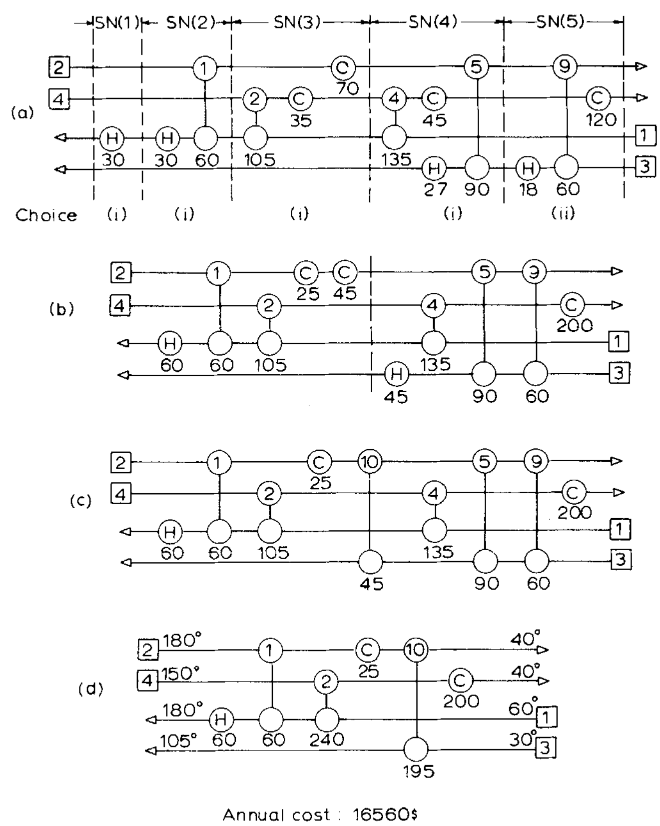


Fig. 5. Final synthesis for test case No. 1. The figures beneath the symbols for heaters, coolers, and exchangers represent heat loads in kW. The figures shown on the streams (in structure (d)) represent temperatures in °C.

have been adopted. This leads, in each case, to higher process heat intakes than would have been required if choices (i) had been adopted. These increases are seen to be irrelevant, however, if the arrangement shown in Figure 4*b* is realized. The coolers and heaters in Figure 4*a* have partly been converted into exchangers between streams from different subnetworks.

Such a conversion is possible because there is, for example, no hot stream in $SN(3)$ with a temperature lower than $T_4 + \Delta T_{\min}$ (see Figure 2), and there is no cold stream in $SN(4)$ and $SN(5)$ with a temperature above T_4. The equivalent argument can be repeated for any of the subnetworks. Thus, transformations such as the one from Figure 4*a* to Figure 4*b* can be assumed regardless of the particular values of temperatures or heat capacity flow rates.

Whatever method is used for synthesizing a network, the maximum degree of energy recovery will never be realized if the method creates, at an early stage, a situation which later results in prohibitive constraints. One way of avoiding such a situation is by making sure, during each step of the synthesis, that the freedom of choice of design decisions at later steps is not prejudiced. This freedom of choice can be related to the source temperature of the next unit of heat which is to be exchanged; the higher this temperature is, the more flexibility there is as to where this unit of heat may be placed in the network. Accordingly, the freedom of choice can be maximized, throughout the synthesis, simply by matching a hot stream section to that particular cold stream section which has the highest temperature. This is the main function of the temperature partitions between the original subnetworks of the TI method; heat will be passed on from the K^{th} subnetwork to the next one of lower temperature only after all cold streams within the K^{th} subnetwork have been provided for.

In this way, the maximum variety of subnetwork design is available. The same principle, of course, appears in estimation of minimum resource requirements by the present method or as expressed in alternative forms by Hohmann (1971), Hohmann and Lockhart (1976), and Nishida (1977). In these cases, however, subnetworks are not used, so that freedom of choice is not an explicit consideration.

It should be noted that any arbitrarily selected temperatures would be suitable as partitions between subnetworks. The particular choice of temperatures recommended here is just very convenient from the point of view of minimizing the number and complexity of the subnetwork designs and the labor of assembly into a total network for the whole system.

Returning to Figure 3, it is now evident that choices (ii) may be considered for $SN(4)$ and $SN(5)$, even though they are not optimum solutions for these subnetworks in isolation. Their adoption would not prejudice an overall optimum, since the extra amount of heat is available from hot streams at higher temperatures, and no extra process utility heat is needed. For $SN(3)$, however, choice (ii) cannot be adopted without introducing extra process utility heat; there is no excess heat available from $SN(1)$ or $SN(2)$. Consequently, choice (ii) for $SN(3)$ need no longer be considered. Figure 5 shows the subsequent development of a network for the whole system. In Figure 5*a*, a set of selected subnetwork designs is presented. Choice (i) has adopted for $SN(4)$, since this produces a first match which is identical to the last match in $SN(3)$ (both matches connect streams 4 and 1). This might make it possible later to merge neighboring exchangers into single larger units. For $SN(5)$, choice (ii) has been adopted, since this produces a first match which is identical to the last one in $SN(4)$. As it stands, the whole network would require an input from process utility heat of 105 kW and an output (through coolers) of 270 kW. However, since all subnetworks designs are consistent with a minimum overall requirement for process utility heat, it is possible to replace pairs of coolers and heaters with equal loads by new exchangers until a network is obtained which shows the highest possible degree of energy recovery.

The only heaters that can be replaced by new exchangers are the two on stream 3 for which suitable coolers (that is, coolers operating at higher temperatures) can be identified. Coolers to match against the two heaters on stream 1 do not exist. In Figure 5*b*, coolers and heaters have been rearranged accordingly; the two heaters on stream 1 and the three coolers on stream 4 have been merged. It was necessary to shift one of the original coolers through exchanger No. 4. This can, evidently, be done without hesitation, since it must increase the temperature difference within the exchanger. Similarly, the two heaters on stream 3 were merged after one of them had been shifted through exchanger No. 5. This shift also increases the temperature difference within the exchanger. Finally, the cooler on stream 2 has been split into two parts. This has been done to provide a heater and a cooler with corresponding equal loads on the cold and the hot sides of the dividing line between the original subnetworks $SN(3)$ and $SN(4)$. According to the arguments put forward above, a new exchanger can be formed from such an arrangement without any need for checking temperature levels. This new exchanger is shown, as match No. 10, in Figure 5*c*. Evidently, parts of the coolers on stream 4 might have been used as well to form new exchangers, but this would have prejudiced the feasibility of the next, and last, step in the synthesis. Matches No. 2 and No. 4 can be merged, likewise matches No. 10, No. 5, and No. 9. A network results which consists of six units (that is, three exchangers, one heater, and two coolers), see Figure 5*d*. The annual cost is \$16 560/yr, using the data of Table 1.

It is easy to see that the network finally arrived at does indeed achieve the best possible degree of energy recovery. Although hot stream No. 2 would, potentially, be capable of heating cold streams up to 170°C, it cannot do so in the particular case of cold stream No. 1 because the heat capacity flow rate of stream No. 1 is too large. Therefore, stream No. 4 has to heat up stream No. 1 to as high a temperature as possible (that is, 140°C), and from this temperature upwards, stream No. 1 may absorb whatever heat is available from stream No. 2. The remainder of the heat which is required to bring stream No. 1 to its target temperature must be supplied through a heater from the process utility. Both matches, No. 1 and No. 2, operate at the minimum temperature difference at the adjacent ends of the exchangers. Any increase in the temperature differences of these exchangers would adversely affect the degree of energy recovery achieved by the whole network. This tight constraint on the energy recovery situation is reflected in the fact that there is no choice open in Figure 3 as to the design for $SN(1)$, $SN(2)$, and $SN(3)$.

It is worth noting at this point that the juxtaposition of the cooler and exchanger 10 on stream 2 suggests that some improvement would result if these units were rearranged. If the positions are reversed, the temperature difference in exchanger 10 will be infeasible. If, however, steam 2 is split and the cooler and exchanger 10 placed on parallel branches, a network identical to that obtained by the method of Nishida et al. (1977) is obtained.* The cost will be \$16 481/yr. The relationship between networks not involving split streams and their splitting equivalents will be discussed in Part II.

A different initial combination of subnetwork designs to that selected in Figure 5*a* would have led to a different final network. Also, different choices of heaters and coolers for the formation of new exchangers would have led to different final networks. Figure 6*a* shows maximum heat recovery at a marginally lower overall cost than Figure 5*d* or its split stream modification. Figure 6*b* also shows maximum heat recovery, again, but at higher cost because it incorporates an additional exchanger. Note, however, that this structure allows the designer to choose the size of one match (other than match No. 1). Structure 6*b* may thus be called a more flexible design than the others. Also, its cost could still be improved by making use of this flexibility. Structure 6*c*, finally, consists of only five units (one heater, three exchangers, and one cooler) but does not feature maximum heat recovery so that the overall cost is higher.

All three networks in Figure 6 were obtained by means of a consistent variation of the initial designs chosen for $SN(4)$ and $SN(5)$ as well as of the way in which coolers and heaters were transformed into exchangers. In the context of this latter task (manipulation of heaters and coolers), however, more complicated changes had to be considered than the simple shifts through exchangers discussed above. The rules governing such changes will be given in the second paper, and the following remarks must suffice at this time. Each of the four final networks shown in Figure 5*d* and Figure 6, as well as any other topology which solves the problem, can be obtained from any initial

* The authors acknowledge the assistance of a reviewer in providing this example.

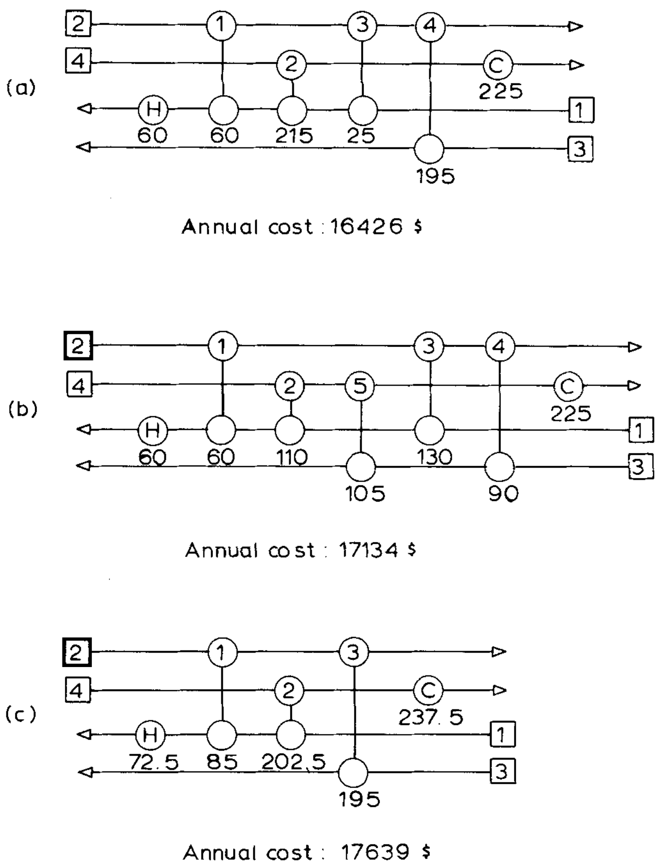


Fig. 6. Three more solutions for test case No. 1.

TABLE 1. DESIGN DATA

Steam Pressure	45 bars
Temperature	258°C
Latent heat	1 676 kJ/kg
Cooling water temperatures	$T_{in} = 30°C$; $30°C \leq T_{out} \leq 80°C$
ΔT_{min}	10°C
Overall heat transfer coefficient	1 000 W/m^{2}K (heaters) 750 W/m^{2}K (exchangers and coolers)
Cost of steam	0.006 \$/kg
Cost of cooling water	0.00015 \$/kg
Equipment availability	8 500 hr/yr
Cost of heat transfer area a	3 000 ($a^{0.5}$) \$ (a in m^2)
Annual rate of return	0.1

SN	COLUMNS: Streams and Temperatures — Hot Streams (2) (4)	T [°C]		Cold Streams (1) (3)	1 Deficit	2 Accumulated input	3 Accumulated output	4 Maximum permissible input	5 Maximum permissible output
			180		[kW]				
SN(1)		180	170		+30	0	-30	+60	+30
SN(2)		150	140		+30	-30	-60	+30	0
SN(3)		115	105		-105	-60	+45	0	+105
SN(4)		70	60		-18	+45	+63	+105	+123
SN(5)		40	30		-102	+63	+165	+123	+225

Fig. 7. Problem table for test case No. 1.

Stream No. and Type	Heat Capacity Flowrate "Cp" [kW/°C]	T_S [°C]	T_T [°C]	Heat Load Cp (T_S - T_T) [kW]
(1) COLD	3.0	60	180	-360
(2) HOT	2.0	180	40	280
(3) COLD	2.6	30	130	-260
(4) HOT	4.0	150	40	440
				Σ = 100

Fig. 8. Data for test case No. 2.

SN	Streams and Temperatures: Hot Streams (2) (4)	T [°C]		Cold Streams (1) (3)	Deficit [kW]	Accumulated input [kW]	Accumulated output [kW]	Maximum permissible input [kW]	Maximum permissible output [kW]
			180						
SN(1)		180	170		+30	0	-30	+60	+30
SN(2)		150	140		+30	-30	-60	+30	0
SN(3)		140	130		-30	-60	-30	0	+30
SN(4)		70	60		-28	-30	-2	+30	+58
SN(5)		40	30		-102	- 2	+100	+58	+160

Fig. 9. Problem table for test case No. 2.

combination of subnetwork designs. Equally well, the networks shown in Figure 6 can be deduced from the one shown in Figure 5*d* and vice versa. It is, thus, sufficient to identify only one suitable design for each subnetwork, even if a variety of final structures is to be investigated.

The Problem Table

For more complicated problems, it would be a lengthy procedure to evaluate possible designs for each subnetwork and discuss their suitability by means of sketches like Figure 4. Fortunately, a far more rapid procedure can be adopted.

In Figure 7, the search for the upper limits to the loads of heaters and coolers in the subnetworks is carried out in a systematic way. The data used refer to test case No. 1, and Figure 7 represents what will be referred to as a problem table. In column 1, the values are given of the net heat requirement for each subnetwork. This deficit D_K is the difference between the heat input I_K, which corresponds to the heat supplied by the heater(s), and the heat output O_K, that is, the heat removed by the cooler(s). For the K^{th} subnetwork, the term D_K may be calculated by means of Equation (2):

$$D_K = I_K - O_K = (T_K - T_{K+1})(\Sigma Cp_{\text{cold}} - \Sigma Cp_{\text{hot}}) \quad (2)$$

The summations only include the streams present in $SN(K)$. Since Equation (2) is just an enthalpy balance, the results will be independent of any subnetwork design subsequently adopted. D_K will be positive or negative, depending on whether the heat capacity flow rates of the hot streams are less or greater than those of the cold streams. If D_K is positive, more heating than cooling is required.

Consider, now, the principle shown in Figure 4 in which the output from $SN(K)$ is passed to $SN(K + 1)$ to satisfy any requirements for heat in $SN(K + 1)$. If there is no separate connection to a process utility heat source in $SN(K + 1)$, Equation (3) can be used to calculate the maximum amount of heat made available to $SN(K + 1)$:

$$I_{K+1} = O_K \quad (3)$$

Equation (4) may be used to calculate the heat output from $SN(K + 1)$:

$$O_{K+1} = O_K - D_{K+1} \quad (4)$$

Thus, assuming no heat supply to $SN(1)$, the figures for the inputs and outputs for each subnetwork are found in columns 2 and 3.

The physical significance of these figures is as follows. If no process utility heat is supplied to any of the subnetworks, and all surplus heat from the matches between the streams in one subnetwork is passed to the next, the heat inputs to each subnetwork would be given as the values in column 2 and the heat outputs in column 3. If any of the values in column 3 are negative, as is the case here for $SN(1)$ and $SN(2)$, process utility heat must be introduced to these subnetworks to increase these outputs to zero. It follows that if one must use process utility heat anywhere in the system, it may as well be introduced at its highest available temperature, that is, into $SN(1)$ and then passed through the sequence of subnetworks. In this way, the amount of heat available in the intervening subnetworks is increased to maximize the choice of subnetwork designs. Accordingly, columns 4 and 5 in Figure 7 have been drawn up. They are based on exactly the same sequence of calculations as columns 2 and 3, with the single difference that the minimum heat requirement for the whole network (the most negative figure in column 3) is introduced as the input to $SN(1)$ from process utility heat sources. As a result, the figures in columns 4 and 5 represent the heat flows into and out of the subnetworks for the case where the necessary minimum process utility heat is received at the highest possible temperature.

The transfer of this heat from one subnetwork to the next creates the maximum degree of choice for subnetwork design without any adverse effect on consumption of resources. Any further increase of a subnetwork's heat input must be provided by additional heat from process utilities. Thus, the figures in columns 4 and 5 represent the upper limits for the heater and cooler loads in the subnetworks which must not be exceeded if subnetworks are to be designed which do not prevent maximum energy recovery. In this sense, they are maximum permissible values (see Figure 7). Comparing the limits obtained in Figure 7 for $SN(3)$, $SN(4)$, and $SN(5)$ with the alternative designs shown for these subnetworks in Figure 3, it is clear that choices (ii) could be adopted for $SN(4)$ and $SN(5)$, but not for $SN(3)$.

Owing to the logic on which the problem table is based, three values in columns 3, 4, and 5 will have a significance not just for the subnetwork to which they belong, but also for the whole problem. In Figure 7, these figures are shown boxed:

1. The bottom figure in column 3 denotes the net cooling requirement for the whole problem as found by an overall enthalpy balance (see Figure 1).

2. The top figure in column 4 is the minimum process utility heat requirement for the whole problem (see networks shown in Figure 5*d* and Figure 6).

3. The bottom figure in column 5 is the corresponding cooling requirement for the whole problem (see, again, networks shown in Figure 5*d* and Figure 6).

In summary, the following procedure is used:

1. The temperature $T_1, T_2 \ldots T_{n+1}$ are identified.

2. An enthalpy balance, that is, Equation (2), must be solved for each subnetwork, giving figures for net heat requirements, column 1.

3. Columns 2 and 3 are calculated by means of Equations (3) and (4), assuming $I_1 = 0$.

4. Columns 4 and 5 are produced by adding the value of the most negative entry in column 3 to each entry in

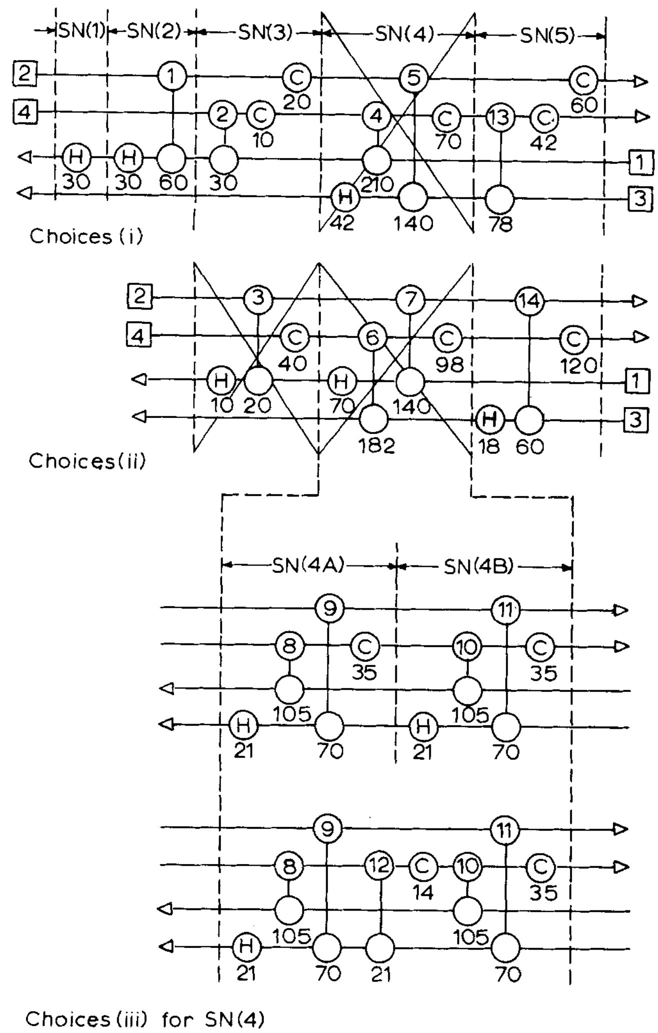


Fig. 10. Subnetwork designs for test case No. 2.

columns 2 and 3. If there is no negative entry in column 3, columns 4 and 5 are identical to columns 2 and 3.

The problem table will then show:

1. Values for the total process heat and cooling loads which will be required if maximum energy recovery is achieved.

2. Maximum permissible figures for the heater and cooler loads of each subnetwork which must not be exceeded if the final network is to be optimum from an energy recovery point of view.

These figures do not depend upon the particular way in which the subnetwork in question, or any other subnetwork, is constructed. Thus, it is possible to design individual subnetworks without reference to the others.

Energy Recovery vs. Network Complexity

In Figure 8, data are given for a second example, test case No. 2. The example is identical to test case No. 1 except that the target temperature of stream No. 3 has been raised to 130°C. The problem table is given in Figure 9. The minimum requirement for process utility heat is unchanged compared to Figure 7 (that is, 60 kW), but the figures for net cooling requirement (that is, 100 kW) and for actual cooling load (that is, 160 kW) are different owing to the change in heat load of stream No. 3. Also, the maximum permissible limits for input and output of $SN(3)$, $SN(4)$, and $SN(5)$ allow less variation in choice of subnetwork design than those in Figure 7. This latter fact indicates that topologies which would ensure maximum energy recovery might have to be more complex for test case No. 2 than they are for test case No. 1.

In Figure 10, subnetwork designs are shown for test case No. 2. Just as in Figure 3, choices (i) and (ii) include, for each subnetwork, all possible solutions with not more than one match per stream. A comparison, however, of these designs with the problem table in Figure 9 shows that choice (ii) for $SN(3)$ and also both possibilities for $SN(4)$ do not conform to the appropriate limits for input and output. Choice (i) for $SN(4)$ exceeds the limit by 12 kW and choice (ii) by 40 kW. So, a different design has to be sought for $SN(4)$ such that lower values for input and output will result.

As noted previously, it is possible to use parallel steam splitting within the subnetwork, and indeed it is always possible to design split stream subnetworks which require only one service, that is, either heaters or coolers, not both. In this case, if steams 3 and 4 are split into 3a (0.6), 3b (2.0), 4a (0.4), 4b (0.6), and 4c (3.0) (where the figures in brackets show the heat capacity flow rates), it is possible to specify three exchangers between the following pairs of streams, 1 and 4c, 2 and 3b, 3a and 4b, leaving a single cooler situated on stream 4a with a load of only 28 kW.

However, when the designer comes to merge the subnetworks to produce a final network for the whole problem, any shifting of heaters or coolers will be impeded by the splitting and merging of streams within subnetworks

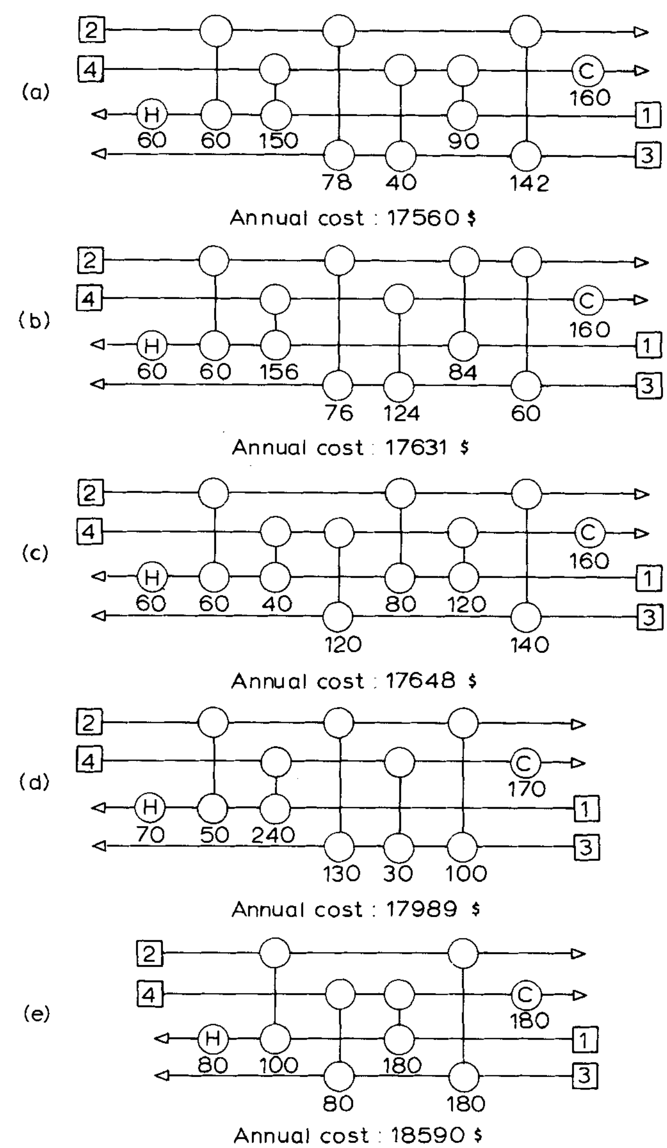


Fig. 11. Solutions for test case No. 2.

unless the same stream is split in exactly the same proportions in a number of adjoining subnetworks.

Thus, while parallel stream splitting within the subnetworks is often an easy solution to the problem of not prejudicing maximum heat recovery, the disadvantages in merging such subnetwork designs later often outweigh these benefits. This is not to say that stream splitting has not a place in design of the final optimal network, merely that steam splitting is not a convenient technique in the design of subnetwork structures.

If parallel stream splitting is not used, then a cyclic design with heater and cooler loads reduced to sufficiently low values can always be found to give maximum energy recovery.

In Figure 10, such a design has been found in a systematic way. Firstly, $SN(4)$ has been split into $SN(4A)$ and $SN(4B)$, and for both these subnetworks the same topology has been chosen as featured by choice (i) for $SN(4)$. (This choice results from matching the largest streams first as suggested earlier.) Secondly, the cooler in $SN(4A)$ has, according to the principle illustrated in Figure 4, been matched against the heater in $SN(4B)$ to form a new exchanger (match No. 12 in Figure 10). Consequently, the total heater load in $SN(4)$ is half that in choice (i), which brings it below the maximum permissible limit shown in Figure 9.

This method of finding a subnetwork design with sufficiently low figures for input and output will sometimes produce solutions with more exchangers than strictly necessary. [For $SN(4)$ in Figure 10, for example, a cyclic solution exists with an input of 30 kW and only four exchangers.] This method is, however, simple compared with evolutionary or exhaustive search methods, and experience has shown that it is very easy to eliminate superfluous exchangers during the final synthesis (as shown in Figure 5). If splitting a subnetwork into two parts does not sufficiently reduce the figures for input and output, the same procedure might be adopted after division into three parts, four parts, and so on. If choice (ii) had been used, division into three parts would be necessary. If the exchangers introduced in this way begin to seem unrealistically small, the increase in equipment cost can, based on the different designs for the subnetwork in question, be compared to the corresponding savings owing to the steam and cooling water economies for that subnetwork. It can be shown that this will give a fair indication of whether maximum energy recovery would be economical for the whole problem, even allowing for any subsequent merging of exchangers to give the final network. If exchanger costs turn out to be prohibitively large, it will be worthwhile to revert to the introduction of parallel stream splitting despite the known inconveniences for future merging of exchangers and shifting of heaters and coolers.

For test case No. 2, however, the annual cost of choice (iii) for $SN(4)$ is clearly below the one for choice (i), and, accordingly, choice (iii) has adopted for final synthesis. Together with choices (i) for $SN(1)$, $SN(2)$, $SN(3)$ and choice (ii) for $SN(5)$ (to obtain the neighboring matches No. 11 and No. 14), this guarantees that topologies can be found, after manipulation of heaters, coolers, and exchangers, which feature maximum energy recovery. In Figure 11, three such topologies are shown (structures *a*, *b*, and *c*). They are the only three which exist with eight pieces of equipment which do not use split streams. The cost of structure *a* could be further improved by surface optimization. Structures *d* and *e* in Figure 11 represent alternative solutions with simpler network structures, made possible by progressive movement away from maximum heat recovery. With pricing parameters given in Table 1, the solutions with maximum energy recovery are cheapest, but different relative weights of equipment vs. utility costs might make the other solutions more economic. This point, as well as the fact that questions concerning control, safety, starting-up procedure, reliability, maintenance,, etc., must, ultimately, be considered in synthesis work makes it evident that the identification of a great variety of near optimum cost structures is rather more desirable than the identification of a single optimum structure. In this context it is worth emphasizing that structures like *d* and *e*, as well as any other near optimum cost structure, are rapidly obtained from structures like *a*, *b*, or *c*, by means of the manipulation of heaters and coolers, the rules of which will be given in Part II (see Linnhoff and Flower, 1978). The design engineer remains in positive control over the balance he is prepared to strike between maximum energy recovery and simplicity or cheapness of network design. Stream splitting can be introduced at this final stage with fewer disadvantages than at the stage of subnetwork design.

CONCLUDING REMARKS

Comparison with Other Synthesis Methods

Nishida et al.'s method is based on a systematic ordering of all heat loads occurring in a problem according to their temperature. Thus, the basic strategy is thermodynamically orientated and based on similar enthalpy balances to those of the TI method. The ways in which matches between streams are introduced, however, are rather different in the two methods. Nishida et al. introduce matches in such a way that parallel stream splitting may appear necessary at an early stage in the synthesis. The TI method, by contrast, introduces matches in such a way that maximum energy recovery can always be obtained by alternative cyclic subnetwork structures. This by no means prevents the introduction of stream splitting at any stage but delays such a step until the definite need for doing so has been confirmed. (A detailed discussion of this will be given in Part II.) A further difference lies in the contrast between the evolutionary rules, cited by Nishida et al., and the thermodynamically based concepts developed in Part II of this paper to implement desirable design strategies. Lastly, minimum utility requirements cannot be predicted using Nishida's method unless explicit consideration is made of feasible networks (see below).

Ponton and Donaldson's method is based on the main heuristic of always matching the hottest hot stream with the cold stream of highest target temperature. This heuristic is thermodynamically sensible and will, in many cases, lead to thermally efficient networks. A systematic safeguard, however, against individual matches which would prejudice an overall optimum for the whole network is not provided. The TI method, by contrast, may introduce similar matches (the second subnetwork will normally consist of an exchanger between the hottest hot stream and the highest target cold stream, etc.), but by introducing coolers and heaters for the various residuals, different matches must result if these should be essential to ensure maximum heat recovery.

When compared to combinatorial methods such as suggested by Rathore and Powers (1975), the TI method exhibits the following advantages: maximum energy recovery and low computational effort in finding multiple solutions (including split stream structures, see Part II).

The Upper Bound on Energy Recovery

Rathore and Powers (1975) have recommended a simple rule to find the upper bound on energy recovery, but the feasibility of heat transfer is checked merely from a temperature point of view. If, as in the two test cases, the heat capacity flow rates are such that they adversely affect the extent to which heat transfer is feasible, this cannot be detected by their rule. When applied to the test cases, steam requirements of only 30 kW are wrongly predicted.

Nishida et al. (1977) determine the maximum amount of heat exchange among process streams in their corollary 2 using the same rule as suggested by Rathore and Powers with the consequent shortcomings. However, situations such as in the two test cases could be identified using their synthesis method if step 2 of their design procedure (p. 82 of their text) were repeatedly applied during the synthesis. (This has not been demonstrated by Nishida et al.) Consequently, networks utilizing minimum utilities may be found, but an algorithm to compute minimum utilities independently of the design of explicit network structures does not follow.

Hohmann (1971) used the conventional enthalpy/temperature diagram for synthesis but suggested a feasibility table for estimation of minimum resource requirements. This is based on an analogous type of enthalpy balance as the problem table, yielding identical results for utility requirements of an overall problem. However, it does not predict limits to inputs and outputs within temperature intervals and cannot therefore be used for the task of synthesizing networks which achieve maximum energy recovery.

The problem table and the TI method allow first identification of minimum utility requirements independent of network design and then synthesis of networks which necessarily achieve minimum requirements.

The Role of ΔT_{min}

Although part of the network specifications rather than the problem data, ΔT_{min} influences the results shown in the problem table. In this context it should be noted that allowances for minimum approach temperatures need not be introduced in as simple a way as used in this paper. Each stream may be assumed to contribute part of the overall value ΔT_{min} which thus becomes a function of the two streams being matched in an exchanger. Depending upon, for example, whether the fluid in question is corrosive or the flow rate is subject to excessive variations, values for the contributions could be chosen which differ among the various streams, etc. This would lead to different values for the maximum permissible limits as well as for the upper bound on energy recovery. A technique for carrying out sensitivity analysis which would establish the influence of assumptions regarding ΔT_{min} on the upper bound on energy recovery (and thus on utility costs) follows automatically (Linnhoff, 1978). The theoretical limit for the upper bound on energy recovery, which can only be approximated in practice, can be found by setting up a problem table based on the assumption $\Delta T_{min} = 0$ throughout.

Solution of More Complex Problems

The two examples chosen to illustrate the TI method are not chosen to be typical of many larger real problems, since their purpose is to aid explanation of the thermodynamic principles. The complexities of real problems necessitate further developments not discussed in this paper but which do not alter the basic method. One frequent criticism of the test examples used in the literature is the assumption of constant specific heat capacity. It is convenient to distinguish between minor nonlinearity of the enthalpy-temperature relation, for example, as in most liquid streams and the major effects of change of phase. In the calculation of the problem table, the net heat requirements are found from an enthalpy balance on the subnetworks; consequently, explicit calculation of specific heat capacities is not strictly necessary.

The variations in specific heat capacities are only important in the design of subnetwork structures. Minor variations in specific heat capacity may create situations where the smallest approach temperature is found in the interior of an exchanger, but it is thought unlikely that this would remain undetected in the final stages of a synthesis. In any case, allowance for this can be made in assigning the ΔT_{min} values for exchangers. Major variations such as those due to change in phase do not introduce radically different problems. Often, different phases and the transitions may be represented as separate streams. Indeed, for the final stages of the synthesis, the practical necessity of separating single phase units from vaporizers or condensers tends to prevent accidental specifications of internal crossovers.

An important aspect of the design of larger systems is that of specifying the choice of different sources of process heat and cold. From a thermodynamic point of view, sources of process heat or cold are only distinguished by their capacity and temperature. The procedure for setting up the problem table yields the total quantity of process utility heat and, by virtue of the overall enthalpy balance, the total quantity of process cold.

With reference to Figure 4*b*, it is important to recognize that the procedure adopted in the solution of test case No. 1 of introducing the total process heat requirement in $SN(1)$ has the advantage of maximizing the choice of subnetwork designs for $SN(1)$. However, in a hypothetical case, where for reasons of availability or cost the heat input was split between $SN(1)$ and $SN(2)$ as shown, the only change in the design procedure is to limit the available designs of $SN(1)$. The choice of subnetwork structures available for $SN(2)$ to $SN(5)$ is unaltered. The final network would be as shown in Figure 5*d*, except for the provision of two heaters on stream 1 each served by a separate process utility source. In the same way, if it is assumed that there is an additional source of process cold only capable of absorbing heat at temperatures above 60°C, it is clear that the single cooler on stream 4 in Figure 5*d* could be replaced by two coolers of loads 80 and 120 kW, respectively, each served by a different utility source.

While these examples of multiple resources are trivial in themselves, there is no doubt that very complicated systems can be analyzed and successful networks designed using subnetworks based on the problem table (Linnhoff, 1978).

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NOTATION

C_p = heat capacity flow rate, kW/°C
D_K = deficit in enthalpy balance [Equation (2)], kW
I_K = heat input into K^{th} subnetwork, kW
n = number of subnetworks in a problem
O_K = heat output from K^{th} subnetwork, kW
$SN(K)$ = K^{th} subnetwork
T_S = supply temperatures, °C
T_T = target temperatures, °C
$T_1, T_2, \ldots T_{n+1}$ = temperatures of cold streams between subnetworks, °C

z = number of streams in a problem
ΔT_{min} = minimum temperature difference within heat exchangers

LITERATURE CITED

Donaldson, R. A. B., W. R. Paterson, and J. W. Ponton, "Design of Complex Heat Recovery Networks: Synthesis, Simulation and Uncertainty," paper presented at Design Congress 76, organized by IChemE/EFCE, Birmingham, U.K. (Sept. 9-10, 1976).

Hendry, J. E., D. F. Rudd, and J. D. Seader, "Synthesis in the Design of Chemical Processes," *AIChE J.*, 19, 1 (1973).

Hlavácek, V., "Report by the Rapporteur" to Session II of "Computers in the Design and Erection of Chemical Plants," 8th European Symposium of the Working Party on "Routine Calculation and the Use of Computers in Chemical Engg," Karlovy Vary, Czechoslovakia (31/8-4/9, 1975).

Hohmann, E. C., "Optimum Networks for Heat Exchange," Ph.D. thesis, Univ. S. Calif. (1971).

———, and F. J. Lockhart, "Optimum Heat Exchanger Network Synthesis," paper No. 22a, AIChE National Meeting, Atlantic City, N.J. (1976).

Lee, K. F., A. H. Masso, and D. F. Rudd, "Branch and Bound Synthesis of Integrated Process Design," *Ind. Eng. Chem. Fundamentals*, 9, 48 (1970).

Linnhoff, B., Ph.D. thesis, Univ. Leeds, U.K. (1978).

———, and J. R. Flower, "Synthesis of Heat Exchanger Networks. II: Evolutionary Generation of Networks with various Criteria of Optimality," *AIChE J.* (1978).

Masso, A. H., and D. F. Rudd, "The Synthesis of System Designs: II. Heuristic Structuring," *ibid.*, 15, 10 (1969).

McGalliard, R. L., and A. W. Westerberg, "Structural Sensitivity Analysis in Design Synthesis," *Chem. Eng. J.*, 4, 127 (1972).

Nishida, N., Y. A. Liu, and L. Lapidus, "Studies in Chemical Process Design and Synthesis: III. A Simple and Practical Approach to the Optimal Synthesis of Heat Exchanger Networks," *AIChE J.*, 23, 77 (1977).

Pho, T. K., and L. Lapidus, "Synthesis of Optimal Heat Exchanger Networks by Tree Searching Algorithms," *ibid.*, 19, 1182 (1973).

Ponton, J. W., and R. A. B. Donaldson, "A Fast method for the synthesis of optimal heat exchanger networks," *Chem. Eng. Sci.*, 29, 2375 (1974).

Rathore, R. N. S., and G. J. Powers, "A Forward Branching Scheme for the Synthesis of Energy Recovery Systems," *Ind. Eng. Chem. Process Design Develop.*, 14, 175 (1975).

Siirola, J. J., "Status of Heat Exchanger Network Synthesis," paper No. 42a, submitted to AIChE national meeting, Tulsa, Okla. (Mar. 10-13, 1974).

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II. Evolutionary Generation of Networks with Various Criteria of Optimality

An evolutionary method is presented for the synthesis of heat exchanger networks. Starting from feasible solutions which preferably exhibit maximum energy recovery,* the method allows systematic promotion of desired design features such as low overall cost, suitability for starting-up procedures, observation of safety constraints, etc. Seven examples based on standard literature problems are used to illustrate the method.

SCOPE

In Part I, previous work on heat exchanger network synthesis was discussed and a new synthesis method proposed. It allows systematic generation of networks which achieve maximum energy recovery.

However, attempts to obtain useful interaction between the systematic approach of a formalized method and the imaginative, heuristic based intelligence of the experienced designer may not be automatically successful. As with other systematic methods, variations of design constraints such as ΔT_{min} (that is, the minimum temperature difference to be permitted within an exchanger), or of costing parameters, are possible, but whether or not such variations will produce desired differences in the final networks cannot be easily predicted. Once the design constraints are defined and the criteria of optimality approximated in a feasible quantitative manner, an automatic algorithm will base decisions on marginal numerical differences which may not be very relevant from points of view such as safety, control, reliability, etc.

Until recently, the literature dealing with the synthesis of heat exchanger networks offered little advice in this matter. The identification of near optimum cost structures for a given problem was usually chosen as the objective. Rathore and Powers (1975), however, observed that the costs of networks showing a high degree of energy recovery are near optimal as well as quite insensitive to significant changes in network topology. They suggested the following strategy: identification of a number of networks featuring high degrees of energy recovery, and final selection of one of these networks using whatever combination of criteria seems relevant.

Apart from enabling the user to consider aspects other than costs, such an approach has the merit that not all feasible structures have to be enumerated. This helps to overcome the problem of dimensionality which is usually very large in the synthesis of heat exchanger networks.

There are, however, two basic disadvantages in the approach. Firstly, the computational effort required per final candidate structure identified may not be significantly reduced. Secondly, some suitable candidates might not be found because they narrowly fail to meet design constraints (such as ΔT_{min}) or the problem specifications (such as a target temperature for a stream).

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* The synthesis of such solutions has been discussed in Part I (see Linnhoff and Flower, 1978).

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