Synthesis of Multipass Heat Exchanger Networks

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The recent advancements in heat exchanger network synthesis provide efficient thermodynamic methods and programming methods for generating optimum heat exchanger networks (HENs). The articles by Gundersen and Naess (1988) and Linnhoff (1993) provide a comprehensive review of the earlier references on this topic. Most of these methods consider the use of single pass exchangers. In industrial practice, the use of a single pass exchanger is limited and the use of multipass exchangers is common. In spite of the common use, little work has been reported (Parkinson, 1982; Liu et al., 1985) on the synthesis of multipass heat exchanger networks. The approach of Liu et al. (1985) starts the design of multipass networks from the optimum singlepass networks; as shown later in this article, this may lead to nonoptimal designs for multipass networks with a greater number of shells. In this article, a systematic procedure is presented for the synthesis of multipass HENs with the objective of a minimum number of shells without violating either the minimum utility requirement or the minimum approach specifically; this procedure does not start the design of multipass networks from optimum singlepass networks. Further, for multipass exchangers, the cost function (Liu et al., 1985) includes a number of shells and the logarithmic mean temperature difference (LMTD) (°C) correction factor, which is

$$C = aN\left(\frac{Q}{U\,(\mathrm{LMTD})\,F\,N}\right)^{b} \qquad (1)$$

In the present work the values of a and b are taken as 1,456 and 0.6, respectively, except for problem TC1 for which the same are taken as 3,000 and 0.5, respectively. The cost of a multipass exchanger appears to depend mainly on the number of shells rather than the heat-transfer area, because the cost exponent b is usually less than one. Based on such a cost function, a network with a less number of shells is likely to require less capital investment than the one with a greater number of shells. Therefore, there is an attempt to develop a procedure which leads to networks with a smaller number of shells. In this article, such a procedure is outlined as a set of seven rules, and the application of the rules is illustrated with two example problems.

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Basic Multipass Exchanger

Most industrial heat exchangers are multipass in nature for reasons of size limitation fouling, improved heat-transfer coefficients, mechanical expansion, cleaning, and so on. In multipass heat exchangers, the flow is partly countercurrent and partly cocurrent. The design equation for multipass heat exchanger is

$$Q = U\,A\,F\,(\mathrm{LMTD}) \qquad (2)$$

The correction factor F is applied to the logarithmic mean temperature difference (LMTD) to obtain the true temperature difference. The work of Bowmen et al. (1940) provides the value of F for different shell and tube pass combinations. Although any exchanger with F above zero should operate theoretically, it is not so practically due to the assumptions involved in the derivation of expressions for F. Hence, it is not advisable to use values of F less than 0.8 (Liu et al., 1985). In a design problem, if F is found to be less than 0.8, then the number of shells has to be raised until the value of F is at least 0.8. The number of shells for any match is evaluated (Liu et al., 1985) using the temperature data by

$$N = \frac{\ln\left[\dfrac{1-P}{1-RP}\right]}{\ln R} \qquad (3)$$

where

$$R = (T_{hi} - T_{ho})/(T_{co} - T_{ci})$$

$$P = (T_{co} - T_{ci})/(T_{hi} - T_{ci})$$

Although many types of multipass exchangers do exist, the most commonly used in process plants is the 1-2 shell and tube exchanger. Arrangements like 2-4, 3-6, 4-8, and so on can be represented as 1-2 shells in series; temperature relationship for the 1-2 exchanger is well known (Kern, 1950). If the outlet temperature of the cold stream (T_{co}) is greater than the outlet temperature of the hot stream (T_{ho}), then ($T_{co} - T_{ho}$) is called the temperature cross (Figure 1). Any 1-2 exchanger with a temperature cross, that is, $T_{co} > T_{ho}$, becomes infeasible, as its F value is less than 0.8. Also, for the 1-2

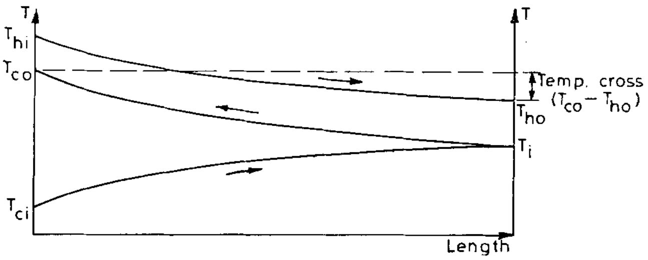


Figure 1. Temperature cross in 1-2 exchanger.

heat exchanger, a zero temperature cross, that is, $T_{co} = T_{ho}$, closely corresponds to $F = 0.8$ for any combination of R and P. Using the zero temperature cross as the basis, a set of rules are proposed for the synthesis of multipass HENs.

Rules for Matching

Rule I. Matching should always be performed to exchange the heat to the maximum possible extent which means a zero temperature cross for the match (equating the outlet temperatures of hot and cold fluids).

Rule II. For nonpinch problems, matching should always begin from the hot end side with the hottest/highest heuristic, that is, matching first the hottest hot stream with the highest cold stream, the second hottest hot stream with the second highest cold stream, and so on.

Rule III. Matches which can exchange more heat irrespective of hottest/highest heuristic are always preferable, if feasible matches are guaranteed for the remaining streams, as it results in the reduction of number of shells.

Rule IV. Coolers on hot streams need not necessarily be placed towards the end. They can be placed in between if it results in the reduction of number of shells.

Rule V. For pinch problems, matching should always start from the pinch with the following criteria: (1) for pinch matches above pinch, $CP_h \le CP_c$; (2) for pinch matches below pinch, $CP_h \ge CP_c$.

Rule VI. For above pinch design, $NH \le NC$, for below pinch design, $NH \ge NC$. If any of the conditions mentioned in rule V or rule VI are not satisfied, splitting of streams becomes necessary to avoid minimum approach temperature violation.

Rule VII. The hottest/highest heuristic still holds true for nonpinch matches in pinch problems.

Many of the above said rules have been proposed and used (Ponton and Donaldson, 1974; Linnhoff and Hindmarsh, 1983) in different contexts. These rules have traditionally been applied for the synthesis of singlepass networks with the objective of reducing the number of units. The rules are suitably modified in the present article to synthesize multipass networks where the objective is to reduce the number of shells rather than number of units. Judicious application of these rules to reduce the number of shells for the synthesis of multipass HENs is illustrated with two example problems to indicate the possibility of arriving at lower cost designs which seem to have been discarded by earlier procedures.

Example 1 (4SP2)

The optimum network solution obtained by Liu et al. (1985) for 4SP2 is shown in Figure 2a. For heaters, only a singlepass exchanger was assumed with steam (isothermal) as the heating medium. The total number of shells required was found to be 18; total heat-transfer area and capital cost were estimated as 326.1 m^2 and \$147,995, respectively. This is a nonpinch problem; using the proposed set of rules, matching should start from the hot end with the hottest/highest heuristic. Using the stream data, the minimum hot utility required is calculated as 336.8 kW and is placed as a heater on stream 4. Applying Rule II by exchanging heat until the hot stream outlet temperature equals the cold stream outlet temperature, the first match will be between stream 1 and stream 4 with a heat load of 564 kW. This procedure is repeated until all the streams reach their target temperatures. The network thus obtained is shown in Figure 2b. In this network, match 4 and match 6 are obtained by applying Rule III. All other matches are obtained by applying Rule II. The number of shells, the heat-transfer area and capital cost are estimated to be 10, 303.6 m^2 and \$110,811, respectively. Using the procedure of Trivedi et al. (1987), the target number of shells for this problem is 14. The number of shells obtained by Liu et al. (1985) is four more than the target, whereas the same is four less than the target using the present approach. Reduction in heat-transfer area and capital cost are 6.9% and 25%, respectively, than those estimated by Liu et al. (1985); the reduction in area is not high but the reduction in capital cost is substantial which should be attributed to the significant reduction in the number of shells.

Example 2 (7SP4)

The optimum multipass network obtained using Liu et al.'s approach for 7SP4 is shown in Figure 3a, and the network synthesized by the suggested approach is given in Figure 3b. The number of shells calculated by Liu et al.'s (1985) approach (25) is one less than the target number of shells (26), whereas it is five less than the target by the suggested approach. Even though this is a pinch problem, it is possible to

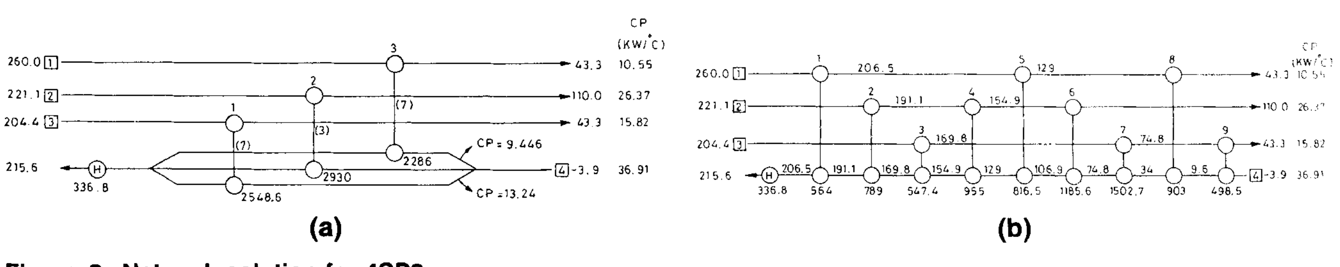
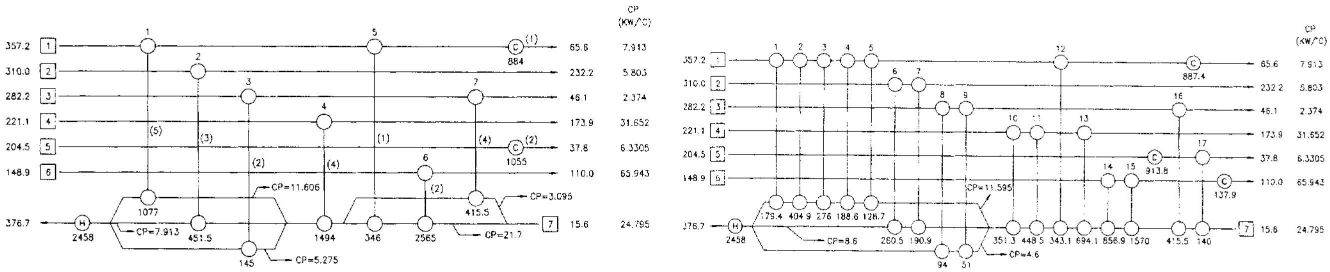


Figure 2. Network solution for 4SP2.

(a) Using the procedure of Liu et al. (1985) (the number in brackets on each match indicates the number of shells); (b) proposed solution.



(a) (b)

Figure 3. Network solution for 7SP4.

(a) Using the procedure of Liu et al. (1985) (the number in brackets on each match indicates the number of shells); (b) proposed solution.

reduce the number of shells below the target. This is due to the typical nature of the problem with only one cold stream whose inlet temperature is less than all the hot streams' target temperatures, thus giving ample choice for matching of streams below pinch. Interestingly, in the proposed solution the cooler on stream 5 is not placed at the end as is usually done, because its current location helps in reducing the number of shells. The heat-transfer area computed by the suggested approach is more (376.8 m^2) than that of Liu et al. (364.2 m^2), but the capital cost for the network is lower ($159,144) than that of Liu et al. ($168,255). This is again attributed to the lower number of shells in the suggested solution.

Discussion

Various literature problems were studied using the present approach. The details of the study are given elsewhere (Reddy, 1989). A comparison of the results is shown in Table 1, along with the solutions obtained by Liu et al.'s (1985) approach and the number of shells targeted by Trivedi et al. (1987). In all the problems studied except 7SP1, the design obtained by the present approach is found to require lower capital costs than those estimated by Liu et al.'s (1985) approach. In some cases like 4SP2, 4SP4, and 6SP4, the reduction in cost is quite significant. Moreover, in all the cases, the number of shells by the present approach is either equal to or less than the number by Liu et al.'s (1985) approach. Interestingly, in some cases (4SP2 and 7SP4), the number of shells by the present approach is even less than the target number of shells. An increase in area by the proposed design should be expected because of uneven distribution of approach temperatures and lower values of LMTD correction factors. The increase in area, however, does not seem to affect the final cost much, since the cost function seems to depend more on the number of shells than on the heat-transfer area.

The methodology presented in this article for the systematic synthesis of multipass HENs leads mostly to networks with lower cost. Moreover, it avoids splitting of streams unless it is necessary, thus reducing the complications in controlling the network structure. However, the designs obtained from the suggested approach may prove costly due to the complex piping arrangements than the modified countercurrent designs, unless the reduction in cost is significant enough to offset the added cost of complex piping. However, there is a possibility to reduce this cost by adding the adjacent shells wherever possible in the new designs. The rules presented for the matching of streams are not new but their systematic application for synthesis of multipass HENs is new. Some of the rules (Rule III and Rule V) have limitations in that their application needs beforehand knowledge of the matches to be performed later and involve trial and error matching. The systematic and sequential application of these rules depend on the nature of the problem and the problem data. Even though the application of the suggested rules is not straight-

Table 1. Comparison of Multipass Network Solutions

			Liu et al. Approach			Suggested Approach		
Problem	Shells Target	Reference of Optimum Singlepass Solution Reported	N	Heat-Transfer Area (m^2)**	Capital Cost ($)	N	Heat-Transfer Area (m^2)**	Capital Cost ($)
4SP1	9	Linnhoff and Flower (1978)	9	72.1	45,097	9	72.3	44,372
4SP2	14	Linnhoff and Flower (1978)	18	326.1	147,995	10	303.6	110,811
4SP4	8	Wood et al. (1985)	11	24.1	24,718	10	21.8	20,996
TC1	*	Linnhoff and Flower (1978)	18	71.2	104,372	17	72.7	101,080
5SP1	12	Linnhoff and Flower (1978)	12	185.4	89,640	11	182.4	85,533
6SP1	14	Linnhoff and Flower (1978)	14	259.7	113,993	13	253.9	111,894
6SP4	14	Floudas et al. (1986)	24	1736.8	408,980	17	1771.6	363,638
7SP1	16	Linnhoff and Flower (1978)	17	269.8	129,131	17	289.4	132,272
7SP2	10	Linnhoff and Flower (1978)	12	119.8	64,454	11	114.3	61,858
7SP4	26	Papoulias and Grossmann (1983)	25	364.2	168,255	21	376.8	159,144
10SP1	17	Linnhoff and Flower (1978)	21	263.3	134,931	18	281.3	133,798

*Not possible to estimate the number of shells due to typical problem data.

**U value for area estimation is taken as 0.8517 kW/m^2 °C for exchangers and coolers, and 1.1356 kW/m^2 °C for heaters.

forward, the analysis of different example problems reveals that the suggested approach usually leads to networks which are better in aspects like capital cost and control. The findings in this article should serve as a warning to the researchers working in this area not to ignore the number of shells objective for the design, even though such designs lead to a greater number of matches and require several nonadjacent matches, but ultimately may prove to be cost-optimal designs.

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Notation

A = heat-transfer area, m^2
C = capital cost
CP_c = heat capacity flow rate of cold stream, kW/°C
CP_h = heat capacity flow rate of hot stream, kW/°C
N = number of shells rounded to integer
NC = number of cold streams
NH = number of hot streams
P = thermal efficiency $=(T_{co}-T_{ci})/(T_{hi}-T_{ci})$
Q = heat load, kW
R = heat capacity flow rate ratio $=CP_c/CP_h=(T_{hi}-T_{ho})/(T_{co}-T_{ci})$
T = temperature, °C
T_{ci} = inlet temperature of cold stream, °C
T_{hi} = inlet temperature of hot stream, °C
T_i = temperature at the end of first pass, °C
U = overall heat-transfer coefficient, kW/m^2 °C

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