Shell Targeting in Heat Exchanger Networks

K. K. Trivedi, J. R. Roach,
B. K. O'Neill
Department of Chemical Engineering
University of Adelaide
Adelaide, South Australia 5000

A problem in the design of heat exchanger networks (HEN) is the of prediction the total minimum number of shells required in a network. (It is assumed that shell-and-tube type heat exchangers are used. A unit is a composite assembly of TEMA shells. "Shell" in this paper refers to a TEMA shell.) In the established network-synthesis procedures (Linnhoff et al., 1982), each exchanger unit is assumed, without verification, to be a single shell. However, the estimated capital cost of the final design changes drastically on relaxing this assumption. This becomes a necessity when the design is considered in greater detail and actual shells are determined. Cost estimation based on the individual shell areas in an actual design leads to a proposal for an optimum design which is different from that obtained when assuming single-shell units. However, final design with a minimum number of *shells* and *units* is likely to be closer to the global optimum. Hence, a target for the minimum number of shells should be set so that the design engineer has some guidelines to identify better designs.

Shell Targeting

Targets can be set for minimum number of units, minimum utility consumption, and minimum area. Methods for finding these targets are well established (Linnhoff et al., 1982; Townsend and Linnhoff, 1984). However, methods for setting targets for the minimum number of shells have not been reported in the literature to date. A systematic procedure for shell targeting is developed.

Consider a four-stream problem, the networks for which are illustrated in Figure 1. For this problem, the minimum number of units $U_{min} = 2$, as a subset equality exits. Two different designs with *two* units are possible. Network (a) requires only two shells, whereas network (b) requires four shells; as a consequence, the latter will have a greater capital cost. The difference in the number of shells between both the designs results from the different levels of temperature at which the exchangers are placed. Hence, the minimum number of units can be predicted independently of the actual matches, but the number of shells required in the network is dependent upon the stream matches.

In Table 1, target values are reported for the number of units, number of shells (predicted using the method described below), and the minimum-area requirements for a variety of literature problems. The reported solution values for the problems are included. The total annual costs of the solutions based on the area per unit and area per shell are reported. A minimum logarithmic mean temperature difference (LMTD) correction factor of 0.8 was assumed for calculating the number of shells required by an exchanger. The solution is not sensitive to the assumed value of F_t.

Two designs have been reported in the literature for the well-documented problem 4sp1. Design 1 utilizes five units and ten shells. Design 2 has five units and nine shells. Both these designs have a minimum number of units and are maximum energy-recovery designs. The total area required by design 2 is less than design 1 and the cost based on both shells and units is less than design 1. Thus, a design that contains minimum number of units and features maximum energy recovery may not necessarily be the optimum design. A similar situation exists for the problems 4sp2, 7sp2, and 10sp1. Problem 5sp1 provides an interesting example. The design based on the criterion of number of units favors the solution of Nishida et al. (1977). However, for a shell-based design, Masso and Rudd's (1969) network is shown to be optimal. From the above examples, it can be concluded that a design featuring *minimum number of units, minimum number of shells, and whose total area is close to the minimum targeted area* is likely to be the optimum. It therefore seems apparent that a target for the minimum number of shells is required to

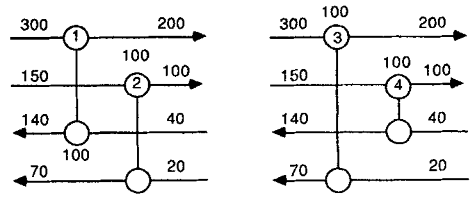

Figure 1. Networks for example 1.
Left. Network (a): 2 units, 2 shells; MER design
Right. Network (b): 2 units, 4 shells; MER design

Table 1. Target Values for Units, Shells, and Area and Actual Design Values for Literature Problems

	Targets					Solutions			Costs $\times 10^2$	
Problem	Units	Shells	Area*	Design	Reference	Units	Shells	Area	Shell	Unit
4sp1	5	9	54	1	Lee et al. (1970)	5	10	79	290	273
				2	Hohmann (1971)	5	9	66	282	268
4sp2	4	14	21	1	Linnhoff & Flower (1978)	7	14	30	259	217
				2	Nishida et al. (1977)	6	16	27	260	204
				3	Linnhoff & Flower (1978)	4	15	36	273	199
				4	Linnhoff & Flower (1978)	4	18	28	270	195
5sp1	5	12	130	1	Masso & Rudd (1969)	5	12	174	421	388
				2	Nishida et al. (1977)	5	13	186	423	386
7sp1	7	16	217	1	Masso & Rudd (1969)	8	18	290	1,074	1,021
				2	Linnhoff & Flower (1978)	7	16	277	996	946
7sp2	7	10	92	1	Linnhoff & Flower (1978)	7	10	109	297	282
				2	Masso & Rudd (1969)	7	14	134	317	291
7sp4	8	26	28	1	Papoulias & Grossmann (1983)	10	25	36	7,679	7,582
10sp1	10	17	212	1	Nishida et al. (1977)	10	19	276	1,512	1,419
				2	Linnhoff & Flower (1979)	10	19	255	1,445	1,406
				3	Linnhoff & Flower (1979)	10	21	271	1,569	1,522
				4	Su & Mortard (1983)	10	18	254	1,486	1,449
				5	Papoulias & Grossmann (1983)	10	23	296	1,513	1,456

Cost Data

Δt_{min}, K = 11.1 for all problems
Steam temp., K = 555 for 4spl, = 508 all other problems
Latent heat, kJ · kg^{-1} = 1,527.25 for 4spl, = 1,785.205 all other problems
Cooling water temp., K = 311–322
Heat transfer coefficient, kW · m^{-2} · K^{-1}
  Exchangers and coolers = 0.8517
  Heaters = 1.1356
Cooling water cost, \$ · kg^{-1} = 1.1×10^{-4}
Steam cost, \$ · kg^{-1} = 2.2×10^{-3}
Cost coefficient = 1,456
Cost exponent = 0.6
Rate of return = 0.1 for calculations in above problems
Operating time, h/yr = 8,500

*Minimum area calculated by a modification of Townsend and Linnhoff (1984) formula that includes F_t factors

readily identify the final optimum design. In the following section, a simple technique is developed for estimating the quasi-minimum number of shells required in a HEN.

Estimation of Number of Shells in a Heat Exchanger Network

The balanced composite curves can be considered to be the "operating lines" for a network and may be used for shell targeting.

Estimation of total number of shells required by cold streams

• Commencing with a cold stream target temperature, a horizontal line is drawn until it intercepts the hot composite curve, Figure 2. From that point a vertical line is dropped to the cold composite curve. This section, defined by the horizontal line, represents a single exchanger shell in which the cold stream under consideration gets heated without the possibility of a temperature cross. In this section, the cold stream will have at least one match with a hot stream. Thus, this section implies that the cold stream will require at least one shell. This procedure ensures an adequate logarithmic mean temperature correction factor as explained in the Appendix.

• Repeat the procedure until a vertical line intercepts the cold composite curve at or below the starting temperature of that particular stream.

• The number of horizontal lines will be the number of shells the cold stream is likely to require to reach its target temperature.

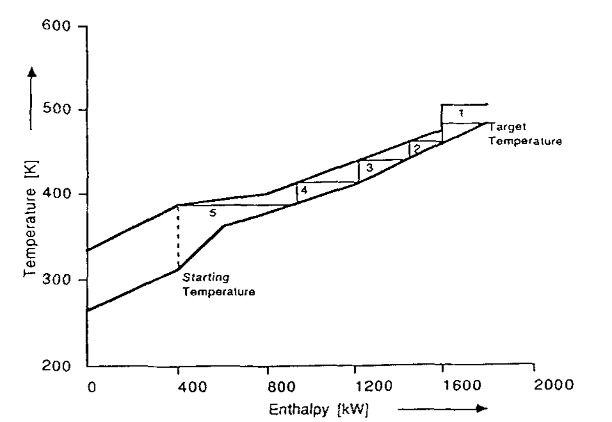

Figure 2. Shell target for a cold stream; five shells required.

• Repeat the procedure for all the cold streams.

• The sum of the number of shells for all the cold streams is the total number of shells required by the cold streams to reach their respective target temperatures.

Figure 2 shows the procedure for a cold stream for the given set of composite curves, which requires five shells. An analogous procedure can be utilized for the hot stream as follows.

Estimation of total number of shells required by hot streams

• Starting from the hot stream initial temperature, drop a vertical line on the balanced composite curve until it intercepts the cold composite curve. From this point construct the steps in the form of horizontal and vertical lines until a horizontal line intercepts the hot composite curve at or below the hot stream target temperature.

• The number of horizontal lines will be the number of shells required by the hot stream for heat exchange in the network.

• Repeat the procedure for all the hot streams.

• The sum of the number of shells required by the hot streams will be the total number of shells required by the hot streams to reach their respective target temperatures.

The **quasi-minimum** number of shells required in the network would be the **maximum** of either the total number of shells required by the hot streams or the total number of shells required by the cold streams. Bell (1981) has reported a similar procedure for estimating the number of shells required in a single mulitpass heat exchanger.

This procedure, for large values of Δt_{min} may predict the *quasi-minimum number of shells* to be less than the *minimum number of units for maximum energy recovery.* Hence, the target of minimum number of units should be used as a lower bound for the quasi-minimum number of shells. Application of this method to a variety of problems has resulted in prediction of the minimum number of shells to an accuracy of plus/minus one shell.

Setting targets for shells can be useful in locating the optimum value of Δt_{min} prior to design (Trivedi and Roach, 1986). Current research is directed toward estimating this value.

Acknowledgment

This research was supported by the University of Adelaide. The authors thank J. Willmore for assistance in development of the necessary software.

Notation

F_t = LMTD correction factor
P = thermal effectiveness
R = heat capacity ratio
U_{min} = minimum number of units

Appendix: Number of Shells Required by an Exchanger Unit

A shell-and-tube exchanger may possess a number shells in series to meet the required performance. The number of shells required is dependent on the LMTD correction factor F_t. This factor is defined as the ratio of the actual mean driving force ΔT_m for any flow system to the best possible value for countercurrent flow ΔT_{LM}. If the exchanger is operated at too low a value of F_t, it falls in the region where a large decrease in F_t occurs for a small difference in capacity ratio. This results in

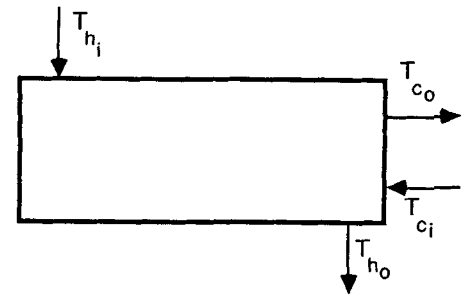

Figure 3. Multipass heat exchanger unit.

poor operability of the exchanger. To overcome this situation, often multiple shells are used for the same duty.

The value of F_t is fixed by the designer, who determines the tradeoff between ΔT_m and the exchanger cost. Normal design practice recommends a minimum value of F_t of about 0.8. "This criterion provides a reasonable value for a TEMA *E* and *J* shells, but is too restrictive for units in series and multitube-pass cross flow ($F_{t_{min}} = 0.95$), where larger F_t penalties can be tolerated and are economically justified. However, the best generalized recommendation that can be given is to use $F_{t_{min}} = 0.8$," (Taborek, 1984).

Consider an exchanger unit shown in Figure 3. The relationship for F_t can be formulated by defining two parameters, R (heat capacity ratio) and P (thermal effectiveness):

$$R = \frac{T_{h_i} - T_{h_o}}{T_{c_o} - T_{c_i}} \tag{A1}$$

$$P = \frac{T_{c_o} - T_{c_i}}{T_{h_i} - T_{c_i}} \tag{A2}$$

Equation A3, although only strictly correct for a 1–2 exchanger, is a reasonable approximation for all types of TEMA shells and flow arrangements (Taborek, 1984):

$$F_t = \frac{\eta}{\delta \ln \{[2 - P(1 + R - \eta)]/[2 - P(1 + R + \eta)]\}} \tag{A3}$$

where

$$\eta = \sqrt{R^2 + 1} \tag{A4}$$

$$\delta = \left. \frac{R - 1}{\ln (1 - P)/(1 - PR)} \right|_{R \neq 1} \tag{A5}$$

$$\delta = \left. \frac{1 - P}{P} \right|_{R \to 1} \tag{A6}$$

Now, if $T_{h_o} = T_{c_o}$ then from equation (A2)

$$T_{h_i} = (R + 1) \times T_{c_o} - R \times T_{c_i} \tag{A7}$$

Substituting this in Eq A3 we get,

$$P = \frac{1}{R + 1} \tag{A8}$$

Hence, $F_t = f(R)$.

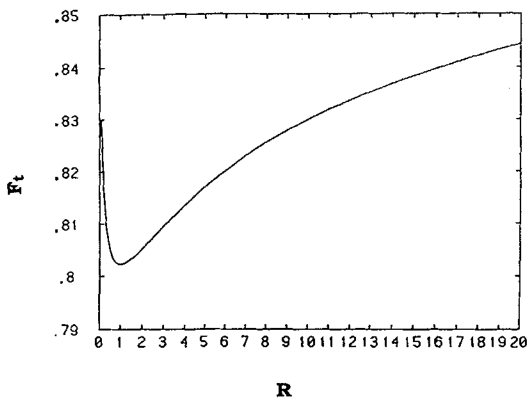

Figure 4. Plot of F_t vs. capacity ratio R.

Figure 4 is a plot of F_t values for different values of R for the condition stated above. It can be seen that the value of F_t is always greater than 0.8, for any value of R. This condition implies that no temperature cross occurs and only a single shell will be required for the unit. However, if the above condition was not satisfied then multiple shells would be required, for the reasons discussed above, with no temperature cross occurring in each shell. Thus, a single shell can be represented by the horizontal line on the composite curves in Figure 2. This simple graphical representation of the condition ensures that there will be no temperature cross.

Literature Cited

Bell, K. J., in *Heat Exchangers: Thermal-Hydraulic Fundamentals and Design,* S. Kakac, A. E. Bergles, F. Mayinger, eds., Hemisphere, New York (1981).

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

Linnhoff, B., and J. R. Flower, "Synthesis of Heat Exchanger Networks I and II," *AIChE J.,* **24,** 633 (1978).

Linnhoff, B., *et al.,* "User's Guide on Process Integration for the Efficient Use of Energy," Inst. Chem. Eng., Rugby (1982).

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

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

Papoulias, S. A., and I. E. Grossman, "A Structural Optimization Approach to Process Synthesis. II: Heat Recovery Networks," *Comp. Chem. Eng.,* **7,** 707 (1983).

Su, J., and R. L. Motard, "Evolutionary Synthesis of Heat Exchanger Networks," *Comp. Chem. Eng.,* **8,** 67 (1984).

Taborek, J., in *Heat Exchanger Design Handbook,* v. 1, Hemisphere, New York (1984).

Townsend, D. W., and B. Linnhoff, "Surface Area Targets for Heat Exchanger Networks," Inst. Chem. Eng. Ann. Meet., Bath, UK (April, 1984).

Trivedi, K. K., and J. R. Roach, "Overall Capital-Energy Trade-off in Heat Exchanger Networks," Chemeca '86, Adelaide, Australia (Aug., 1986).

Manuscript received Sept. 22, 1986 and revision received July 20, 1987.