On the Similarity of Area Targets and Shells Targets in Heat Exchanger Networks

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Abstract. The synthesis of heat exchanger networks (HEN) is an important field in process systems engineering, and considerable research efforts have been directed towards this goal in the past four decades. Many methodologies have been proposed to optimize the energy consumption in the process industries, with objectives of minimum utility consumption, minimum heat exchanger area, minimum number of heat exchange equipment, and minimum overall annualized cost. The strength of the Pinch Technology, the heuristics-based design and optimization method for HEN, lies in setting targets before the design. These targets, viz., area targets, units targets, shells targets, and total cost targets, are later used in arriving at optimal HEN. In the present paper, a new methodology has been presented which demonstrates the similarity of area targets and shells targets in an HEN employing multipass heat exchangers. Since area targets are inaccurate and fraught with uncertainties, it is pertinent to replace them with shells targets. Based on this, a design heuristics has been proposed for achieving optimal HEN.

1. Introduction
The heat exchanger network (HEN) design has attracted the attention of research community of chemical engineering, due to its importance in conserving energy. The problem of HEN design may be defined as the determination of a cost-effective network to exchange heat amongst a set of process streams, where any heating and cooling requirements not satisfied by exchange among these streams must be provided by external utilities (e.g., steam, hot oil, cooling water, and refrigerants). A considerable amount of research effort has been directed towards synthesizing and optimizing HEN. Its significance can be attributed to its role in controlling the costs of energy for a process [2].

Heat exchangers comprise an important part in the chemical process industries. They affect the energy efficiency of a process plant [9], hence efficient design of HEN is of paramount importance. The HEN synthesis problem consists of developing a network, which requires least capital investment and also the least amount of utilities.

Significant progress has been witnessed in the research on synthesis and optimization of HEN in the past few decades. Emphasis on energy efficient processes has increased because of continuous rise in the energy costs. The HEN synthesis problem tackled in literature mostly concerned with the use of single pass heat exchanger, while in practice, multi-pass exchangers are more often used, namely to meet the space constraints. In a multipass exchanger, one fluid is in parallel and counter flow with respect to the other fluid half of the time each. Moreover, multipass exchangers often require more than
one shell. Neglecting the number of shells and the additional area required by such exchangers during the synthesis of HEN can lead to errors in capital cost estimations. The most popular approach for the synthesis of multipass HEN is the pinch design method. In this method the HEN problem is decomposed in three sequential steps, targeting, synthesis, and optimization. [11].

The synthesis of a HEN is usually a very complex task that implies a combinatorial problem for matching hot and cold flow streams in order to permit a maximum energy recovery to be achieved.

A classic problem that has occupied the area of process engineering for over four decades is the synthesis of heat exchanger networks (HEN). Several approaches have been employed to address this problem. They can be generally categorized into sequential synthesis or simultaneous synthesis methods and are often based on evolutionary or optimization principles. Neither of these method categories are able to guarantee global optimality; the former because they are based on heuristic rules and the latter because they are based on nonlinear programming techniques that can only guarantee local optimality.

2. Shells Targeting for Heat Exchanger Networks

The shell and tube heat exchanger is the most commonly used type of heat transfer equipment used in chemical and allied industries. In case of the simplest shell and tube exchanger, the 1-2 type, the liquid in one tube pass flows in counter flow while in the other pass flows in parallel relative to shell fluid. Multipass arrangements are also quite widely used. The advantages of this type of exchangers are discussed by many authors [3].

Most of the HEN design methods described in literature make the simplifying assumption of countercurrent exchangers. While in practice, multipass shell and tube exchangers are universally used. Some researchers have attempted to apply procedures developed for countercurrent heat exchange to multipass exchangers.

The difference between number of exchanger units and actual number of shells has a significant effect on capital cost of the HEN [10]. Kardos and Strelow [7] pointed out that an optimal solution of the HEN problem based on purely countercurrent heat exchanger only will remain optimal in practice if each unit can be realized by one exchanger. This is the exception rather than the rule, indicating that one should consider shells rather than units at the synthesis stage. It may also be pointed out that the optimal HRAT (Heat Recovery Approach Temperature) for multipass HEN will always be higher than the optimal HRAT for counter-current HEN.

In the present work, a comparison has been made of area target and shells target. It is demonstrated that both areas target and the shells targets lead of similar conclusions about the optimal HEN. The shortcomings of area target have also been pointed out, and it is proposed that shells target should be used in practice, instead of area target, to achieve optimal heat exchanger networks.

3. Number-of-Shells Targeting: A New Approach

Let us study the heat recovery scenario between the two streams, one hot and one cold, given in figure 1 below:

![Figure 1: A two stream network problem](image)

The difference between the outlet temperature of hot stream, $T_2$, and outlet temperature of cold stream, $t_2$, is called temperature approach. As the amount of heat recovered (thus the exchanger duty)
increases, temperature approach \((T_2 - t_2)\) decreases, and heat transfer area increases. But this variation is not proportional to \((T_2 - t_2)\).

In figure 2, \(Q\) vs. area is plotted, and in figure 3 \((T_2 - t_2)\) vs. area is plotted. It is clear from figure 3 that at smaller temperature approach values, area increases rapidly with heat load. Hence, after certain heat load further heat recovery will no more be economical. This optimum heat load of the exchanger depends, among other factors, on the cost of utilities, the exchanger cost law, the cost of money (interest rate) and payout period.

**Figure 2: Effect of temperature approach on heat recovery, \(Q\)**

**Figure 3: Effect of temperature approach on area and number of shells**

But an analysis based on area targeting is fraught with some uncertainties which affect the determination of the optimum exchanger size. These are discussed below.

- Area targeting methods require a priori knowledge of convection heat transfer coefficients, \(h\). These are very seldom available in practice. They can be calculated where heat exchangers
already exist, or estimated from preliminary sizing calculations. But, in the majority of real plants, the data required is only available in a very inaccurate form or not at all. The situation may be worse when there is a mixture of shell and tube and plate heat exchangers, or some streams have special flow characteristics. Heat exchanger design procedures reveal that the stream heat transfer coefficient \( (h) \) are not constant but match dependent \[6\]. Heat transfer coefficients not only depend on the nature and the type of the other stream to which the match is effected, but also on the material of construction of the exchanger through which the fluid flows, and also on the type of the exchanger used.

- Utility costs are not fixed and vary not only from place to place but also from plant to plant (thus making a widely acceptable design applicable at various sites impossible).
- Pre-design \( U \) values are approximate and based on previous experience or obtained from literature; thus making area estimate quite inaccurate.
- It is common for the cost laws to be accurate about \( \pm 10\% \). The payout period is mostly a qualitative decision and depends more on the management of the plant and other local factors rather than any sound economic criterion. But a change in payout period (say, 3 years vs. 4 years) affects strongly the location of optimum \[8\].
- Finally, the cost of money (interest rates used to annualize the capital cost) varies from place to place and from time to time. Hence the trade-off between energy and capital costs can be grossly misleading.

Now, the question is: how to overcome this problem? For multipass exchangers (containing one or more shell passes), the designer can have a theoretically sound yet simple tool as discussed below.

For multipass exchangers the heat recovery is affected by \( LMTD \) correction factor, \( F_T \). As temperature approach decreases, \( F_T \) decreases rapidly. If \( F_T < 0.8 \) one should increase the number of shells till \( F_T \) becomes greater than 0.8. For a given temperature approach, we can estimate directly the number of shells required using a formulation given by Gulyani \[4\] or by using Ahmad et al.’s formulation \[1\]. The heat recovery vs. number of shells for above stream set is also plotted in figure 2, and temperature approach vs. number of shells in figure 3. The plots show that the two curves, i.e., the variation of area and number of shells with \((T_2 - t_2)\), show similar trend.

Hence it may be concluded that the effect of incremental heat recovery (and temperature approach) is same on both the area and the (real) number of shells.

Above analysis shows that one can replace area by number of shells in assessing practically feasible heat recovery. Further, a range of \((T_2 - t_2)\) can be selected where heat recovery seems to be economically viable without resorting to costing. From the nature of curves in figure 2 and 3, one can see that at about \( Q = 2350 \) or \((T_2 - t_2) = -70\), shells = 4, the slope of the curve is steep and further heat recovery does not seem to be economical. To highlight this, the slope of number-of-shells curve has been plotted in figure 4 below. It is clear that the slope drops drastically after a certain value of \((T_2 - t_2)\), equal to \(-70\).
After evaluating this approach for several case studies, it was found that above results are general and can be extended to HEN containing more than two streams. This is illustrated using stream data of problem given in Table 1 below, using a procedure based on composite curves [12]. Area target and shells target were computed at different HRAT values. These are plotted in figure 5, and sample calculations are tabulated in Table 2.

Table 1: Stream Data

| STREAM | $T_S$ (°C) | $T_T$ (°C) | CP (kW/°C) |
|--------|------------|------------|------------|
| H1     | 180        | 40         | 200        |
| H2     | 150        | 40         | 400        |
| C1     | 60         | 180        | 300        |
| C2     | 30         | 130        | 220        |

Table 2: Calculations for area and shell targets

| Enthalpy interval | No. of streams | $T_1$ (°C) | $T_2$ (°C) | $t_1$ (°C) | $t_2$ (°C) | LMTD (°C) | $\Delta Q$ (kW) | $A/m^2$ | $N_S$ | $N_{SS}$ (streams–1) |
|-------------------|----------------|------------|------------|------------|------------|------------|------------------|--------|------|---------------------|
| 1                 | 2              | 300        | 299        | 160        | 180        | 129.27     | 120              | 0.928  | 0.071| 0.071               |
| 2                 | 2              | 180        | 150        | 140        | 160        | 14.43      | 120              | 8.316  | 1.504| 1.504               |
| 3                 | 3              | 150        | 145        | 130        | 140        | 12.33      | 60               | 4.866  | 0.529| 1.058               |
| 4                 | 4              | 145        | 80         | 60         | 130        | 17.38      | 784              | 45.109 | 3.365| 10.095              |
| 5                 | 3              | 80         | 66.67      | 30         | 60         | 27.50      | 156              | 5.673  | 0.686| 1.372               |
| 6                 | 3              | 66.67      | 40         | 10         | 15         | 39.86      | 320              | 8.028  | 0.348| 0.696               |
| Total             |                |            |            |            |            |            | 1560             | 72.920 | –    | 14.796              |
After establishing the fact the area estimation can be replaced by shells estimation to help identify optimal HEN comprising multipass exchangers, it is pertinent now to device ways to facilitate fast estimation of shells in a network. This has been discussed in detail by Gulyani et al. [5]. An expression for estimating number of shells based on temperature cross have been derived by Gulyani [4] and compared with Ahmad’s expression [1].

4. The Heuristics for Match Selection
Heuristics rule, which exploits the specific characteristic of multipass exchangers has been proposed below. This rule facilitate quick identification of near-optimal networks on the basis of number of shells.

“For a given level of heat recovery (i.e., HRAT) and given number of matches, the network structure featuring minimum number of shells will be optimal.”

5. Conclusions
Despite the spectacular developments in the understanding and design of HEN, certain lacunae still exist and need to be addressed. One such lacunae is in the difficulty and accuracy of area targets, while shells targets can be established with much more accuracy. Since in practice, most HEN feature multiple heat exchangers, it is of immense practical use, if area target can be replaced by shell target. This paper established that this can be done, as both area and shell targets lead to the same optimal network.

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