Retrofitting Heat Exchanger Networks Based on Simple Pinch Analysis

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It has been well-established that the energy and capital costs of a heat exchanger network are both dependent upon the minimum allowable temperature approach ΔT_{min}. As a result of the rapidly growing oil prices in recent years, there appears to be an urgent need to retrofit the existing "optimal" networks so as to reduce the current utility consumption rates with smaller ΔT_{min} values. A simple pinch-based approach is proposed here to accomplish this task while keeping additional capital investment to a reasonable level. In particular, every cross-pinch match is removed, and its heat loads on the hot and cold streams are both divided into two according to the pinch temperatures. At either side of the pinch, the divided heat loads on each stream are combined and then matched according to a systematic procedure derived from simple pinch analysis. Two examples are provided to illustrate this procedure.

1. Introduction

The heat exchanger network (HEN) design method is a matured technology for energy integration in the process industries,[1−4] which has already been applied successfully in numerous grass-root and revamp projects for over two decades. With the rapidly growing energy costs in recent years, there is a renewed interest in retrofitting the existing "optimal" HENs which were designed under the presently outdated cost structure. A number of good reviews on this issue can be found in the work of Yee and Grossmann,[5] Asante and Zhu,[6] and Ponce-Ortega et al.[7] Thus, a full literature survey is omitted here for the sake of brevity.

Generally speaking, the existing HEN retrofit methods can be considered as either pinch- or model-based. The former approach is adopted in this study due to the fact that, in practical applications, it is easier to implement the manual design steps and to exercise engineering judgment. Tjoe and Linnhoff[8] proposed a calculation procedure to determine the appropriate minimum temperature approach ΔT_{min} after retrofit by considering the energy savings, investment cost, and payback period. On the basis of a set of general design guidelines, the existing cross-pinch exchangers were then eliminated, shifted, or rematched strictly above or below the new pinch temperature. Additional exchangers could also be placed if necessary. Finally, the resulting network was evolved manually by shifting loads around the heat-load loops and along the heat-load paths so as to yield a retrofit design which is closely compatible with the existing one.[5] Despite the fact that satisfactory results were reported, there is still a lack of systematic and specific procedure to produce the modified HEN designs.

An improved pinch-based retrofit procedure is developed in this work to lower the utility consumption levels of any given HEN at the cost of minimal capital investment. For illustration clarity, the remainder of this paper is structured as follows: The identification and partition methods of the cross-pinch heat loads are first presented in the next section. The specific steps to modify a given HEN are then listed in section 3. Two examples are provided next in the subsequent sections to demonstrate the effectiveness of the proposed approach. Conclusions are given at the end of this paper.

2. Identification of Cross-Pinch Heat Loads

It is assumed in this work that the updated ΔT_{min} after retrofit can be determined in advance by considering the payback period, investment cost, and energy savings.[8] Consequently, the corresponding pinch temperatures can also be computed. The cross-pinch heat loads in the original design can then be identified by comparing the hot and cold temperature spans of each exchanger with the new pinch points. All possible scenarios can be found in Figure 1. Notice that the dashed line in each case denotes the pinch-point location and it can be associated with different temperatures, i.e., T_p and t_p, for the hot and cold streams respectively. In the exchangers described in Figure 1, the cold-stream temperature rises from t_s to t_t while the hot-stream temperature decreases from T_s to T_t. The hatched area stands for the cross-pinch heat load.

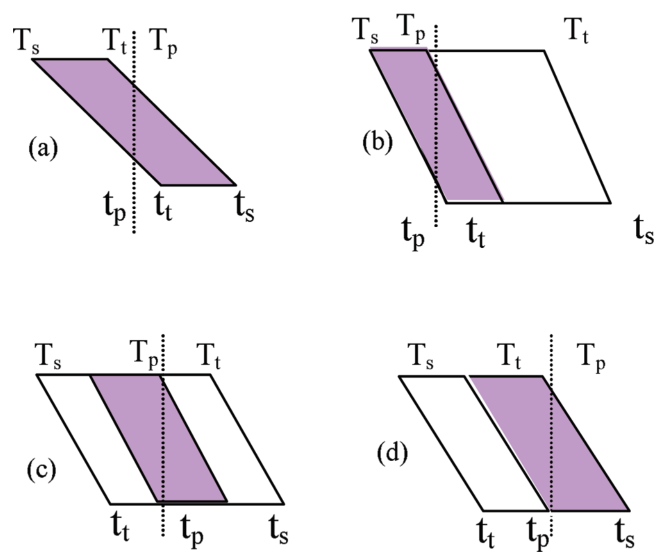

Figure 1. Four types of cross-pinch heat loads.

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It is obvious that the entire heat duty of the exchanger in Figure 1a is the cross-pinch heat load because the lowest hot-stream temperature is above the pinch while the highest cold-stream temperature is below pinch. As for the other three scenarios, only part of the exchanger duty is transferred across the pinch and the exact cross-pinch heat load can be easily determined according to the following formulas:

$$Q_{cr} = FC_{p_H}(T_s - T_p) \quad \text{for case (b)}$$
$$Q_{cr} = FC_{p_H}(T_s - T_p) - FC_{p_C}(t_t - t_p) \quad \text{for case (c)}$$
$$Q_{cr} = FC_{p_C}(t_p - t_s) \quad \text{for case (d)}$$

where Q_{cr} denotes the cross-pinch heat load, and FC_{p_H} and FC_{p_C} represent the heat-capacity flow rates of hot and cold streams, respectively. Notice that the cross-pinch heat load(s) can be considered as specific retrofit target(s), i.e., the heat loads that must be removed so as to achieve the desired utility consumption levels due to ΔT_{min} reduction.

3. Retrofit Procedure

The proposed retrofit method can be applied according to the following steps:

Step 1: Determine the hot and cold pinch temperatures and the corresponding energy targets according to a specified ΔT_{min}.

Step 2: Identify and remove all cross-pinch heat matches. Divide their heat loads on the *process streams* into two parts according to the corresponding pinch temperatures.

Step 3: Combine the unmatched split loads of each stream which are on the same side (i.e., below or above) of the pinch.

Step 4: At both sides of the pinch, match the above combined heat loads according to a modified version of the pinch design method.[9]

(1) **Feasibility check at the pinch point:** The modified feasibility criteria given below must be satisfied for proper match placement.

- Number inequalities for unmatched heat loads

$$N_H \le N_C + n_C \quad \text{above the pinch}$$
$$N_H + n_H \ge N_C \quad \text{below the pinch}$$

where, N_H and N_C denote the numbers of unmatched heat loads at the pinch on hot and cold streams respectively; n_C is the number of cold streams just above the pinch which are without unmatched loads but can be reached by at least one *heat load path* in a general sense;[9] n_H is the number of hot streams just below the pinch which are without unmatched loads but can be reached by one or more generalized heat load path. Notice that the above-mentioned n_C cold streams above the pinch and n_H hot streams below the pinch can be considered as additional unmatched heat loads at our disposal. Such a heat load above the pinch can be viewed as an *imaginary* sink of the generalized heat load path with the regular heating utility as the source, while the source and sink of a generalized heat load path below the pinch should be associated with an aforementioned hot stream and a cooling utility respectively. Finally, it should be noted that *stream splitting* may be necessary if any of the inequality constraints discussed here is violated.

- CP inequalities for individual matches: For each *pinch match*, the temperature approach must not decrease away from the pinch, that is,

$$FC_{p_H} \le FC_{p_C} \quad \text{above the pinch}$$
$$FC_{p_H} \ge FC_{p_C} \quad \text{below the pinch}$$

where FC_{p_H} and FC_{p_C} are the heat capacity flow rates of hot and cold heat loads, respectively. To avoid creating additional matches, splitting process streams is *not* the preferred measure in the present case to enforce the above constraints. Instead, it may be possible to invalidate the violated CP inequality by eliminating the heat load just above the pinch and placing it at a higher temperature on the same hot stream or by moving the heat load on the cold stream just below the pinch to a lower temperature in a similar fashion.

(2) **Match placement:** Match placement should be started at the pinch and then developed by moving away from the pinch sequentially according to temperature. To minimize the number of extra exchanger units, the conventional tick-off rules should be modified as follows:

- The heat duty of every match above the pinch should be assigned (by shifting heat load via heat load path if necessary) so as to exhaust the heat load on hot stream. If this is not possible, then the heat duty should equal the heat load on cold stream.
- The heat duty of every match below the pinch should be assigned (by shifting heat load via a generalized heat load path if necessary) so as to exhaust the heat load on cold stream. If this is not possible, then the heat duty should equal the heat load on hot stream.

Step 5: Break the heat load loops above and below the pinch. Recalculate the heat duties, the inlet and outlet temperatures of the involved matches.

Step 6: Assign the new matches to available exchangers.

Generally speaking, the industrial heat exchangers are almost always over designed by 15−30%. An existing exchanger can

Table 1. Stream Data of Example 1

stream no.	stream type	FC_p (kW/K)	T_s (K)	T_t (K)
1	hot	2	423	333
2	hot	8	363	333
3	cold	2.5	293	398
4	cold	3.0	298	373

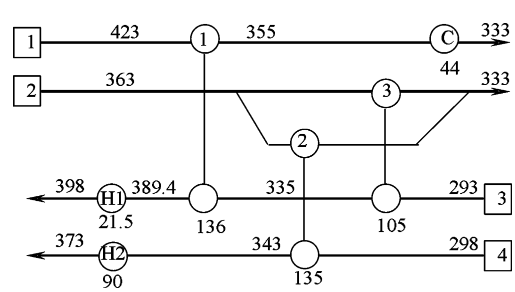

Figure 2. Original HEN design in example 1.

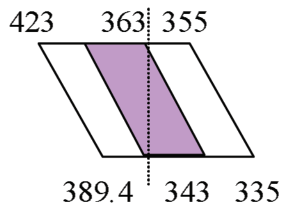

Figure 3. Operating conditions of exchanger 1 in example 1.

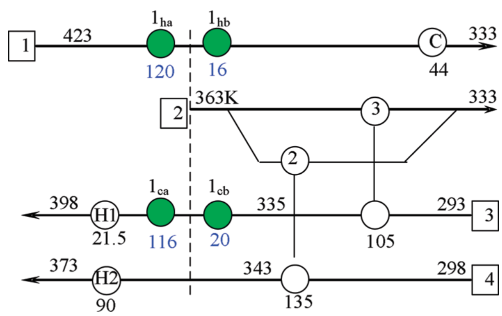

Figure 4. Intermediate network obtained after splitting heat loads of cross-pinch exchanger in example 1.

usually be adopted to realize a new match between the same hot and cold streams if its heat duty is "close" to the original design level (say ±20%). If there are more than one candidate match competing for the same existing exchanger, the one with the largest heat load should be selected.

4. Example 1

This example is taken from the work of Linnhoff and Hindmarsh,[9] and the stream data are given in Table 1. The original network design is shown with standard grid diagram in Figure 2. The inlet and outlet temperatures of each exchanger are shown above the horizontal stream lines in kelvin (K), while its heat duty is given underneath the dumbbell-shaped match symbol in kilowatts (kW). The corresponding minimum cold and hot utility consumption rates are 44 and 111.5 kW, respectively. If the desired minimum temperature approach after retrofit is set to be 20 K, the new energy targets can be determined with the problem table algorithm,[9] i.e., 40 kW of the cold utility and 107.5 kW of the hot utility. The corresponding pinch temperature is 363 K for the hot streams and 343 K for the cold streams. Notice that the utility consumption levels in the original design are both higher than the new energy targets by an amount of 4 kW; that is, a heat flow of 4 kW is crossing the pinch. By inspection, it can be observed that exchanger 1 fits the match pattern described in Figure 1c. To be more specific, the match pattern of exchanger 1 is depicted with actual temperatures in Figure 3.

The cross-pinch heat load can be determined by calculating the heat-load deficit above or below the pinch. In the former case, the split heat load of hot stream is the following: $Q_h = 2(423 - 363) = 120$ kW. The split heat load of the cold stream is the following: $Q_c = 2.5(389.4 - 343) = 116$ kW, and therefore, the heat deficit above the pinch should be $Q_c - Q_h = -4$ kW. In the latter case, the split heat load of hot stream is the following: $Q_h = 2(363 - 355) = 16$ kW. The split heat load of the cold stream is the following: $Q_c = 2.5(343 - 335) = 20$ kW, and thus, the corresponding heat deficit is $Q_c - Q_h = 4$ kW. From the above simple calculations, it can be clearly seen that there is indeed a heat flow of 4 kW crossing the pinch in exchanger 1. The intermediate network obtained after partitioning its heat loads on the hot and cold streams is provided in Figure 4. Notice that the locations of split loads are marked by green color, and their values are specified in blue.

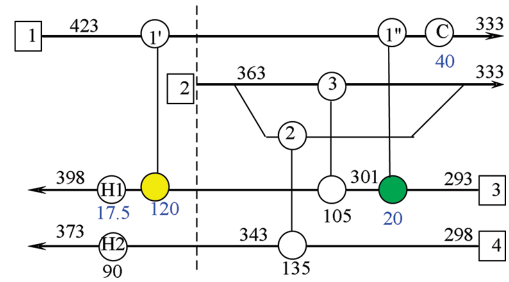

Figure 5. Final retrofit design in example 1.

Table 2. Stream Data of Example 2

stream no.	stream type	FC_p (kW/K)	T_s (K)	T_t (K)
1	hot	228.5	432	350
2	hot	20.4	540	353
3	hot	53.8	616	363
4	cold	93.3	299	400
5	cold	196.1	391	538

Because there is only one exchanger crossing the pinch, step 3 can be bypassed. As for step 4, we find that both feasibility criteria are satisfied above the pinch while the second criterion is violated below the pinch. The match above the pinch can then be placed according to the modified tick-off heuristic. To circumvent the problem below the pinch, load 1_{cb} should be moved to the right of exchanger 3 so as to invalidate the second feasibility criterion. As a result, it is possible to match loads 1_{hb} and 1_{cb}. Finally, the existing exchanger 1 can be assigned to exchanger 1′ (marked by yellow color) and exchanger 1″ (marked by green color) represents an added one according to step 6. The resulting network is presented in Figure 5, in which the affected heat duties are marked by blue numbers. It is not surprising to note that this solution is truly optimal.

5. Example 2

The second retrofit example is adopted from the work of Tjoe and Linnhoff.[8] The modified stream data are given in Table 2 in SI units and the corresponding HEN design in standard grid diagram can be found in Figure 6. It should be noted that minor inconsistencies are present in the original data set. There are two alternatives to fix this problem:

(1) The target temperature of hot stream 2 can be adjusted from 361 to 353 K.

(2) The heat-capacity flow rate of hot stream 2 can be changed from 20.4 to 21.31 kW/K.

The former option is adopted here for illustration purpose, while similar results can also be obtained if the latter is selected.

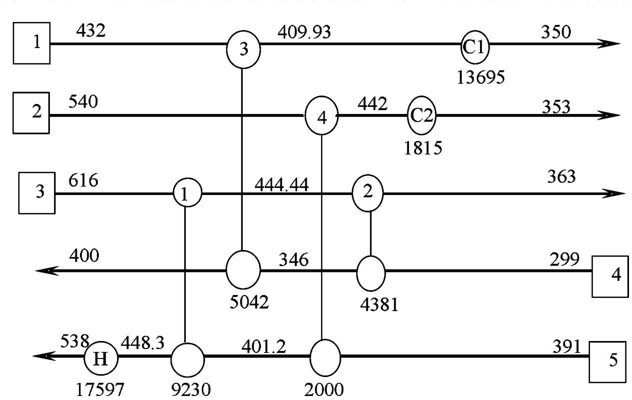

Figure 6. Original HEN design in example 2.

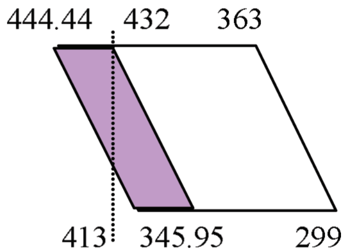

Figure 7. Operating conditions of exchanger 2 in example 2.

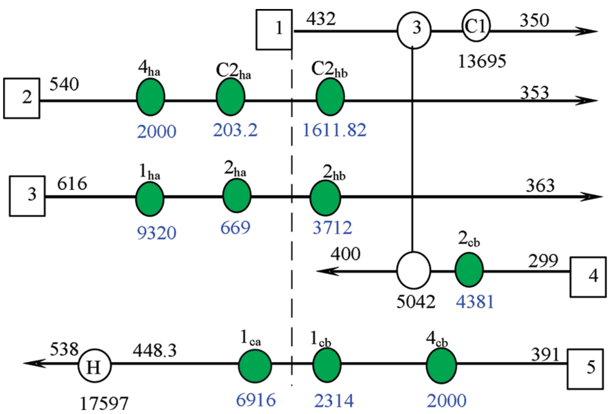

Figure 8. Intermediate network obtained after splitting heat loads of cross-pinch exchangers in example 2.

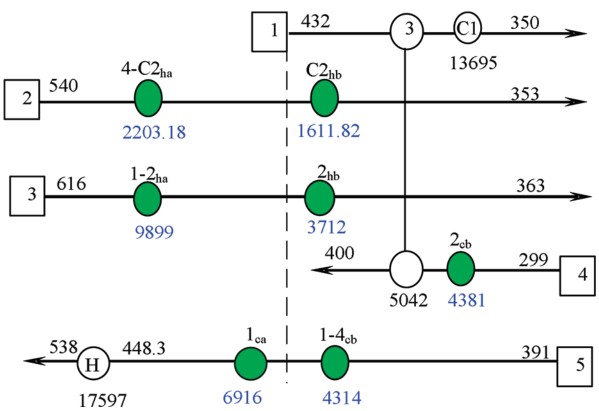

Figure 9. Intermediate network obtained after combining split heat loads of cross-pinch exchangers in example 2.

Let us assume that the chosen minimum approach temperature after retrofit is 19 K.[8] By implementing the problem table algorithm,[9] it can be determined that the corresponding pinch temperature is 432 K for the hot streams and 413 K for the cold streams. The minimum hot and cold utility consumption rates in this case are 12410.1 and 10323.8 kW, respectively, and each is lower than that required in the original design by an amount of 5186.8 kW.

By inspecting Figure 6, it can be found that the temperature spans of exchangers 1, 2, 4, and C2 fit the cross-pinch patterns in Figure 1d, b, a, and b, respectively. Their corresponding cross-pinch heat loads can be found to be 2314.0, 699.3, 2000, and 203.2 kW. The sum of these cross-pinch heat loads is 5186.5 kW. Notice that there is an absolute error of 0.3 if this value is compared with the aforementioned energy saving (5186.8 kW), which can be attributed to the roundoff error in hand calculation.

The next task is to split the heat loads of these cross-pinch exchangers according to the new pinch temperatures. For illustration convenience, let us consider exchanger 2 as an example (see Figure 7). The heat load on the hot stream in this

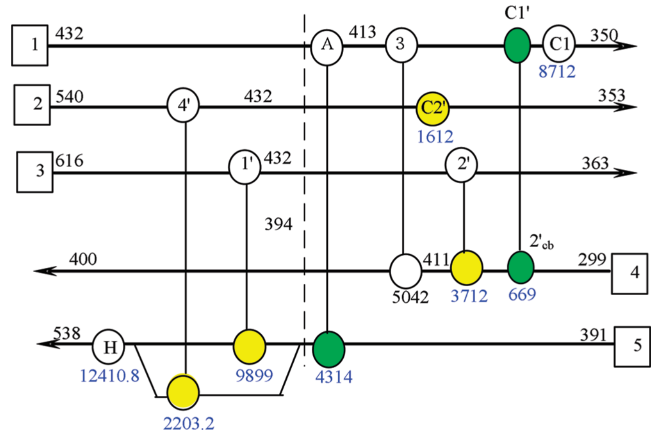

Figure 10. Intermediate network obtained after matching combined heat loads in example 2.

exchanger is split into 2_{ha} (above the pinch) and 2_{hb} (below the pinch), and their values can be computed respectively to be 699 kW and 3712 kW. Since the exit temperature of cold stream is below the pinch, the corresponding heat load below the pinch 2_{cb}, i.e. 4381 kW, in indivisible. The heat loads of other cross-pinch exchangers can also be partitioned according to the proposed method. The resulting network is shown in Figure 8, and all split heat loads are specified in blue numbers.

By combining the split heat loads on each stream at both sides of the pinch, the network in Figure 9 can be obtained. The retrofit designs above and below the pinch can then be produced separately:

- Above the pinch: Notice that $N_H = 2$, $N_C = 1$, and $n_C = 0$ in this case. In order to match cold heat load 1_{ca} with hot heat loads $[4.C2]_{ha}$ and $[1.2]_{ha}$, stream 5 should be split into two to satisfy both feasibility criteria simultaneously. The heat duties of the corresponding matches can be assigned according to the modified tick-off rule and, consequently, the utility consumption rate in the heater H is reduced to the target level as expected.
- Below the pinch: Since $N_H = 2$, $n_H = 1$, and $N_C = 1$, the first feasibility criterion at the pinch is satisfied in this situation. To satisfy the second criterion, the pinch match should be placed between the unmatched heat load $[1.4]_{cb}$ and the imaginary heat source on stream 1 (by shifting heat load from cooler C1). The heat duty of this match can be assigned according to the modified tick-off heuristic, i.e., 4314 kW. The next match should be placed away from the pinch between the unmatched loads 2_{hb} and 2_{cb}, and its heat

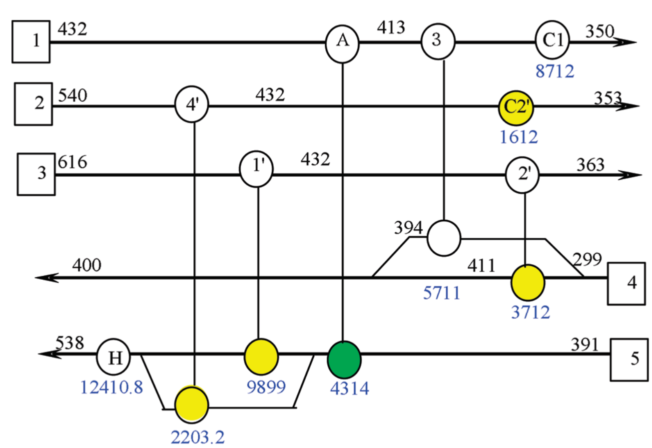

Figure 11. Final retrofit design in example 2.

duty should be 3712 kW. There are two alternative heat sources available for matching the remaining load of 2_{cb}, i.e., the imaginary load on stream 1 or $C2_{hb}$ on stream 2. Since both of them lead to the same final retrofit design, only the first option (see Figure 10) is developed in the sequel. Notice that, in this case, $C2_{hb}$ must be cooled by utility and the two matches between streams 1 and 4 can be merged by breaking the corresponding heat load loop. It should also be noted that the two heat loads on stream 4 should be changed from serial to parallel to restore the temperature constraints on exchanger 3. The resulting network is shown in Figure 11.

Finally, the new matches can be assigned to the available exchangers according to the criteria given in step 6. Matches 1′, 2′, 4′, and C2′ may be realized with the existing exchangers for the original matches 1, 2, 4, and C2, while exchanger A should be added to achieve the desired energy saving.

6. Conclusions

A novel pinch-based retrofit method is developed in this work to reduce the utility consumption rates in any given HEN design. The specific retrofit targets, i.e., the cross-pinch heat loads, are first determined exactly with simple hand calculations. By eliminating these heat loads, the revamped network can then be systematically produced with a revised version of the pinch design method. Since it is only necessary to modify the cross-pinch matches and the existing exchangers can be utilized as much as possible, the required capital investment is kept at a reasonably low level. The effectiveness of the proposed approach is clearly demonstrated in the examples provided in this paper.

Acknowledgment

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