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Recent Development in the Retrofit of Heat Exchanger Networks

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This work presents a methodology for heat exchanger network (HEN) retrofit, which is applicable to complex industrial revamps, considering existing networks and constraining the number of modifications. The network pinch approach (Asante and Zhu, 1996) has been modified and extended to apply to the HEN design with multi-segmented stream data. The modified network pinch approach combines structural modifications and cost optimisation in a single step to avoid missing cost-effective design solutions.

1. Introduction and previous work

Numerous investigations have been carried out to improve the performance of HENs. The HEN design approaches can be grouped into three major categories: pinch analysis methods, mathematical programming methods and stochastic optimisation methods. Linnhoff and Hindmarsh (1983) developed a method to design for the minimum hot and cold utility demand, for a set of hot and cold streams and a selected minimum temperature approach (ΔT_{min}), based on several heuristic rules. Because pinch analysis is difficult to apply to large scale problems, mathematical modelling methods were developed. Optimisation of HEN is generally formulated as a mixed-integer non-linear programming (MINLP). To avoid being trapped into local optimum, simplifications are made to convert the MINLP into Linear Programming (LP) (Papoulias and Grossmann, 1983; Cerda and Westberg, 1983), or Non-linear programming (NLP) as in the work of Yee *et al.* (1990). Other attempts have been made to reduce the size of the problem, using "block" (Zhu *et al.*, 1995) and "stage" (Asante and Zhu, 1996) concepts. Compared to deterministic methods, stochastic methods have more chance to find the global optimum for MINLP problems, due to the random nature of the optimisation methods. Commonly used algorithms in the synthesis of HENs are Genetic Algorithms (Wang *et al.*, 1998; Lewin *et al.*, 1998a, b) and Simulated Annealing (SA) (Dolan *et al.*, 1989).

Not all of the research above is suitable for HEN retrofit. Moreover, there has been no work considered the varying thermal property (e.g. heat capacities) issue of process

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streams. Non-constant thermal properties often arise when multi-component streams are cooled down or heated up, such as in refining preheat trains.

The network pinch method (Asante and Zhu, 1996) combines physical insights into retrofit problems and mathematical programming techniques. The bottleneck of the existing network configuration is first identified by redistributing the heat loads of existing exchangers, which is referred to as pinching the existing network. Then each candidate structural modification that may overcome the bottleneck of the HEN configuration is optimised at a time for maximum heat recovery. A list is generated after all suggested modifications are optimised, showing the corresponding maximum heat recovery for a given modified HEN topology. The difficult MINLP problem is decomposed into MILP problem and NLP problem. Although it is a sequential approach, it explores possible topology modifications in a systematic way and at the same time allows user interactions in the design procedure.

However, the existing network pinch approach assumed constant thermal properties with temperature in the design of HENs and stream split fractions are not considered in pinching existing networks. Moreover, the existing approach only carries out cost-optimisation in the optimisation stage after the diagnosis stage. The design with minimum cost cannot be guaranteed since the selection of the potential modifications is not based on costs but energy demands. In this paper, the network pinch design method (Asante and Zhu, 1996) is modified to overcome these limitations.

2. Problem definition and HEN structure representation

There are some streams for which the thermal properties (e.g. heat capacity) are highly dependent on temperature. For those streams, multi-segment formulations are employed. The whole temperature range is broken into several intervals (the stream in each interval is referred to as a segment).

The representation of the HEN structure in this work employs a node-based representation. The links between every component in the heat exchanger network are represented by nodes. There are four nodes assigned to a heat exchanger unit: hot side inlet node, hot side outlet node, cold side inlet node and cold side outlet node. For unit operations, two nodes are associated with them, namely inlet and outlet nodes. Each node is associated with a unique temperature, which means that a new node is defined only if the temperature varies. The unique one-node-one-temperature data structure removes redundant data, and is able to represent very complex networks using moderate memory. Stream splitting is considered in the HEN simulation and design, utility exchangers can be located at any places in the HEN and the number of exchangers on a given stream or branch is not limited.

The HEN is modelled as an interconnected set of network elements, namely process heat exchangers, utility heat exchangers, stream splitters and mixers and unit operations. Because multi-segmented stream data are employed, the set of equations are not linear with respect to temperature. Therefore, if all the exchangers are specified in terms of heat load, the temperatures for all of the streams are calculated sequentially. The calculation order is from the start of each stream to the end of that stream.

3. Network pinch approach for HEN retrofit

In the first step of the modified network pinch method, the network pinch is identified by redistributing heat transfer loads between the existing matches and in the meantime varying stream split fractions for maximum heat recovery (minimum utility demand). Given a network having N_{HX} heat exchangers and N_{BR} stream branches, the objective of the pinching problem is to minimise utility demand of the network by varying heat loads of existing exchangers and stream split fractions, subjected to minimum temperature approach constraints and stream enthalpy constraints.

The number of variables N_{VARY} in the pinching problem is the sum N_{HX} and N_{BR}. Considering the large number of optimisation variables and the non-linearity of the problem, the pinching problem is very complex. Normally N_{HX} is larger than N_{BR}, since N_{BR} is limited for the reason of controllability. The relative importance of the heat exchangers suggests decomposing the pinching problem into two levels (Figure1). In the outer loop the stream split fractions are optimised, and in the inner loop the heat loads of existing exchangers are redistributed. The minimum utility requirement obtained in the inner loop serves as the objective function value for the outer loop optimisation. The decomposition of the pinching problem reduces the complexity of the problem since the number of optimisation variables in each level is smaller than the total number of optimisation variables.

In the inner loop, the stream split ratios are fixed. The optimisation problem is related purely to heat loads, and subject to minimum temperature approach constraints and stream enthalpy balance constraints. A polynomial correlation is used to represent node temperatures in terms of enthalpy change. The proposed polynomial correlation is implemented to optimise the heat loads in the inner loop. The calculated temperature of a stream ($TT_{ppcalc,j}$) is equivalent to the temperature after process-to-process heat recovery. It is clear that the smaller the difference between $TT_{ppcalc,j}$ and the target temperature TT_j is, the lower the utility demand. The Levenberg-Marquardt algorithm is used to solve the inner loop optimisation where heat loads of existing matches are distributed for maximum heat recovery. The outer loop is to optimise stream split fractions using the sequential quadratic programming (SQP) algorithm.

After the bottleneck of the HEN configuration is diagnosed by pinching the network, different types of modifications are suggested to overcome the pinch. The modifications fall into four groups: re-piping and re-sequencing existing matches, adding new matches and introducing stream splitting. In practice, adding additional heat transfer area to one heat exchanger unit is not only about installing new area. The associated pipe work also requires modifications, which can be more expensive than the installed area. To take into account retrofit costs, in the current study, the network pinch approach of Asante and Zhu (1996) is modified as shown in Figure 2, where the structure searches in the diagnosis stage and the cost-optimisation are combined into one stage. The design problem then becomes a search for the most cost-effective structural changes in only one step, rather than sequential steps of a search for structural changes followed by a capital-energy optimisation. The one-step approach avoids missing potentially cost-effective designs in the diagnosis stage, by ranking the alternative designs based on costs, rather than heat recoveries.

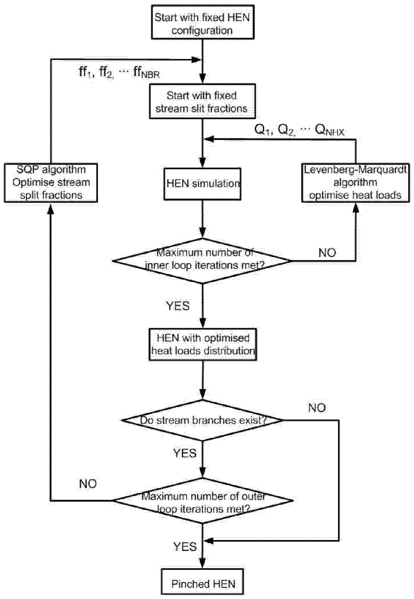

Figure 1 Optimisation approach for pinching a network

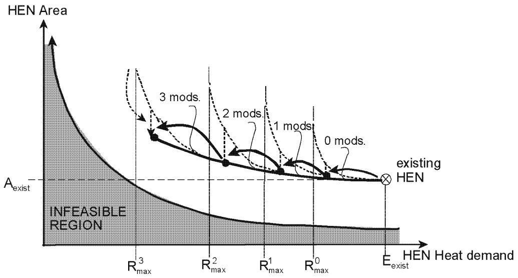

Figure 2 Modified network pinch approach design strategy

(mods: modifications; : maximum heat recovery with i modifications, kW; Eexist: Energy demand of the existing network, kW; Solid black curve represents the current search procedure of structural modifications; Dotted curve stands for the search procedure of original network pinch approach of Asante and Zhu (1996))

In the new network pinch approach, each candidate modification is optimised for minimum total cost directly. The minimum total cost of each modification is used as the criterion for ranking potential modifications. The design problem thus becomes a NLP problem. The simulated annealing algorithm with a feasibility solver (Chen *et al*., 2008) is employed to solve this NLP problem. The advantages of the algorithm are solutions of better quality, capability of dealing with an infeasible initial design and fewer simplifications to the models of HENs to ensure convergence.

4. Case studies

The application of the modified network pinch is illustrated through adding a new exchanger unit in an existing preheat train. The structural bottleneck of the existing crude oil preheat train for a minimum temperature approach of 30 °C is identified using the developed two-level pinching method. The existing crude oil preheat train is also pinched using the SQP algorithm to optimise the heat loads and stream split fractions in a single step. In addition, the network is pinched by using the method of Asante and Zhu (1996), in which only heat loads are redistributed for maximum heat recovery. The minimum utility demands attained using the three methods are compared in Table 1.

Table 2 shows the performance of the optimised design with a new match using the developed approach. The performance of the best design without any topology modifications is also shown in Table 2, and compared with the results of adding a new exchanger.

Table 1 Energy demand of pinched HEN

	Existing HEN	Pinched HEN Approach 1	Approach 2	Approach 3
Coil Inlet Temperature (°C)	231	258	243	261
Hot Utility (MW)	88.95	74.17	82.42	72.97
Cold Utility (MW)	92.33	77.48	85.77	76.29

Approach 1: Network pinch: only heat loads varied; Approach 2: SQP algorithm: heat loads and split fractions varied in a single step; Approach 3: Two-level approach: network pinch varying both heat loads and split fractions

Table 2 Energy and cost reduction after adding a new match

	Existing network	No modification	Adding a new match
Hot Utility (MW)	88.95	72.97 (18%*)	68.59 (23%*)
Cold Utility (MW)	92.33	76.29 (17%*)	71.91 (22%*)
Operating cost (MM$/y)	27.29	22.78 (18%*)	21.42 (23%*)
Additional area (m^2)	-	1334	1655
Capital investment (MM$)	-	2.57	2.94
Payback (year)	-	0.33	0.32

*: percentage of saving with respect to base case

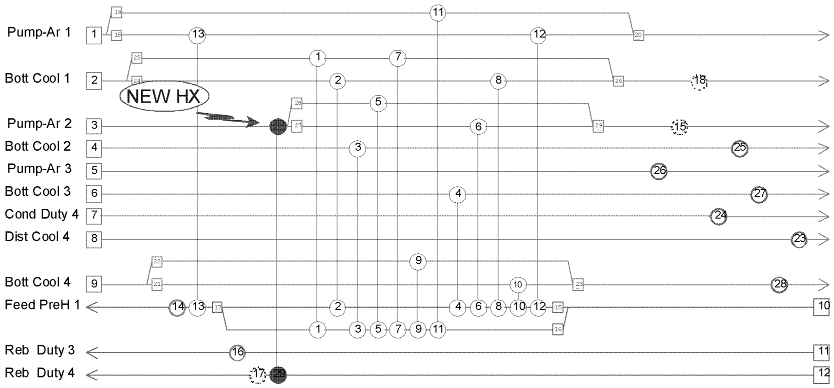

Figure 3 Suggested location of adding a match

Table 1 shows that the developed two-level approach gives pinched HEN with most heat recovery, indicating that it is more capable of exploring the scope for recovering heat with the existing HEN configuration and determining the network topology bottleneck. It can be seen from Table 2 that by adding a new exchanger, the cost-effective retrofit design saves 20 MW hot and cold utilities, around 23% of the base case energy consumption. Table 2 also shows that a further 4 MW hot utility can be saved by adding a new exchanger, compared with no structural changes. These results indicate that in some cases, cost-effective retrofit does not always require topology modifications. Figure 3 presents the most cost-effective design with a new exchanger.

5. Conclusions

A retrofit design methodology is proposed for HENs of process streams with temperature-dependent thermal properties. The two-level pinching approach is developed for the optimisation of continuous variables (heat loads and stream split fractions if there are existing stream splitters in the network) so that the heat recovery of the existing HEN is exploited to make sure that the bottleneck is the network topology rather than heat transfer areas. Moreover, the search for structural changes and capital-energy optimisation are combined into a single step for the first time, in order not to miss cost-effective designs. The new HEN retrofit design approach enables identifying the most critical HEN configuration changes, and provides access to designers, which makes sure the retrofit designs are mathematically optimum and industrially applicable.

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