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Advanced HENs Design for Multi-Period Operation Using P-graph

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This work deals with multiperiod-operation HEN synthesis and explores the use of the Process Graph (P-graph) with its associated algorithms for the problem. Heat exchanger networks (HEN) synthesis has been evolving from a steady state towards design flexibility and resilience. It designs a network for a set of steady states, assigned to operation periods – multiperiod operation. The P-graph enables the systematic automated generation of rigorous superstructures and the derivation of the optimal solution HENs via the combinatorially Accelerated Branch and Bound optimisation algorithm (ABB).

1. Introduction

HEN synthesis has been evolving for several decades starting from considering a fixed steady state. The Pinch Design Method (Linnhoff and Hindmarsh, 1983) defined a simple efficient procedure for obtaining utility targets before design, followed by a design procedure achieving the targets. Further elaborations introduced the capital and total cost targets (Linnhoff and Ahmad, 1990), extensions to total sites (Klemeš et al., 1997), as well as total sites integrating renewables (Perry et al., 2008).
Recognising the inherently varying nature of process operation – due to changing ambient conditions, worker shifts and market supply-demand balances, flexibility requirements have been added to the design problems. From the methodologies for synthesising flexible HENs, the multi-period optimisation paradigm has been introduced by Floudas and Grossmann (1986), using an MILP model. Mathematical Programming (MP) have been also used by Aaltola (2002) and Verheyen and Zhang (2006). Ahmad et al. (2008) used Simulated Annealing. Use of MP for multiperiod HEN synthesis faces major challenges and limitations, which can be efficiently overcome using P-graph. The present work explores the application of an advanced approach to the HEN synthesis by employing the P-graph framework (Friedler et al., 1992, 1993). This approach is superior to the MP approach due to exploiting the combinatorial nature of the problem and the structure of the feasible links between the operating units.

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2. HEN design for flexibility and multiperiod operation

Various definitions of flexibility can be found in the literature (Floudas and Grossmann, 1987; Cerda et al., 1990;). Generally flexibility means ability to retain specific properties under varying conditions. A HEN is termed flexible if, for a given set of steady-state operating points, it is capable of satisfying the heating and cooling demands of the process streams remaining feasible. The set of operating points over which to ensure feasibility can be defined in two ways:

(i) *A list of discrete operating points*. This is usually done if the expected system operating conditions can be predicted with some certainty or approximated (Floudas and Grossmann, 1986). The steady states are assigned to operation periods and the methodology is referred to as multiperiod operation.

(ii) The network nominal conditions and the variation intervals of each of the non-manipulated inputs (Cerda et al., 1990; Swaney and Grossmann, 1985). For HENs, such inputs may be the process stream flow-rates and their inlet temperatures. This defines one or more continuous feasibility regions in the space of the disturbances.

Although representation (ii) brings conceptual understanding of flexibility, representation (i) is more convenient. If the set of steady operating periods are properly defined, this will adequately describe the corresponding continuous feasibility regions.

2.1 Synthesis with uncertainty ranges

The synthesis task under ranges of uncertainty of some network parameters is generally tackled in several stages:

(a) Obtain thermodynamic targets for heat recovery by identifying all pinch locations and utility targets, resulting from the variations in the parameter values.

(b) Decompose the temperature range of the process streams into sub-networks/blocks

(c) Considering each sub-network as an energetically balanced system, obtain a minimum number of units topology. This stage usually uses the approach defining a superstructure with all significant options and further optimising and reducing it.

(d) The resulting heat exchange matches are further assigned to actual exchangers and sized.

A methodology following this approach has been developed by Cerda et al. (1990), Cerda and Galli (1990) and Galli and Cerda (1991). They introduced the concepts of permanent and transient process streams (Figure 1). The areas enclosed in the corresponding rectangles represent the heat duties required by the streams.

The synthesis procedure constructs a superstructure for every sub-network and optimises the combination of these to find a topology with minimum number of units Heat cascades comprising permanent and transient stream components are constructed for the heat recovery problems.

The procedure further defines the sub-networks delimited by dominant pinch points. These are derived from the heat flows in the permanent problem heat cascade. A temperature boundary in the combined heat cascade is a candidate for a dominant pinch point if it features a zero heat flow according in the permanent heat cascade - a necessary condition. The sufficient condition is that each candidate must also cross a new pair of hot and cold process streams and maximum energy recovery.

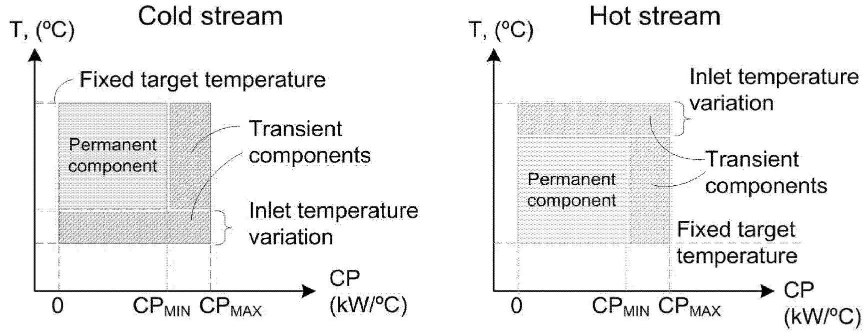

Figure 1. Permanent and transient components of process streams

The matches in each sub-network are sized based on the worst operating conditions within the range of variation of the uncertain parameters.

2.2 HEN Synthesis for multiperiod operation using Mathematical Programming

This approach translates the variability of the process parameters into a list of discrete operating points, which are assigned to different periods throughout an operating cycle of a period - usually one year. These periods can be assigned specific duration weights, ambient conditions and utility costs. The task is then to synthesise a minimum total cost network capable of working feasibly during all the periods with their associated operating points. A clear advantage of this approach is that it allows direct optimisation of the total network cost.

There are two major problems with this approach. The first comes from the fact that the process systems, including HENs, almost never operate at fixed points. It is difficult to predict precisely the operating points in which the process under design will operate. The second is the computational difficulty imposed by the optimisation of the resulting superstructures, since the formulations are generally non-linear (MINLP). Some of the multiperiod methods for HEN synthesis simplify the formulations, aiming for minimum utility cost and allowing only isothermal mixing of split stream branches, arriving at MILP formulations.

3. Need for a rigorous intensification tool

The complexity of process synthesis and that of HENs in particular arises from the simultaneous presence of continuous and combinatorial aspects. The combinatorial complexity increases exponentially with the number of candidate operating units - heat exchangers, splitters and mixers. It is due to the large number of possible permutations. MP has been used with moderate success for reducing superstructures. Very few applications of constructing the superstructures using MP are known. For larger size problems the application of this approach becomes increasingly difficult as:

(i) The size of the algebraic optimisation problem grows, where the solver needs to examine combinations of integer variable values clearly infeasible from topological point of view;

(ii) The huge number of topological options makes it rather difficult to build the necessary problem superstructures without rigorous combinatorial tools. As a result practical problems are too complex/difficult to be solved. If the problem is simplified to be solvable by MP, modified problem may no longer represent adequately the original task.

4. P-graph for HEN Synthesis

The HEN synthesis methodology based on the P-graph framework could be efficiently applied for problems of practical complexity. The framework is superior to MP due to exploiting the combinatorial nature of the problem and the structure of the links feasibility. P-graph is a rigorous mathematical tool for unambiguous mathematical and visual representation of HENs. Its combinatorial instruments are (i) the axioms ensuring representation unambiguity (Friedler et al., 1992); (ii) the algorithms generating the maximal network structure (Friedler et al., 1993) and for generation of all possible solution structures (Friedler et al., 1995); (iii) the overall algorithm for superstructure optimisation and reduction (Friedler et al., 1996). They have several important properties making P-graph superior in solving process synthesis problems:

- Automatic generation of the problem superstructure. The P-graph axioms form the mathematical basis for rigorously describing the process topology. The algorithms gives the candidate operating units and streams/materials, they automatically generate the problem superstructure, following the rules/options specified by the users.
- The optimisation of the generated superstructures avoids the examination of infeasible combinations of binary variable values representing the process units. This is achieved by applying the branch-and-bound paradigm to the strict options defined by the superstructure. The general integer programming solvers need to examine the infeasible combinations and evaluate them against the specified constraints.
- As a result the P-graph framework drastically reduces the combinatorial search space compared to pure MP (Friedler et al., 1995 and 1996).

The P-graph framework defines a set of 5 axioms (Friedler et al., 1992). These are the principles for process network consistency.. A similar principle is the law of mass conservation, also regarded as an axiom in many available dictionaries. These axioms seem trivial. However, from the viewpoint of computational algorithms and graph theory they are absolutely essential. They make the solvers aware of the corresponding system constraints and ensure that only the feasible topologies are considered.

There are three main algorithms in the P-graph framework – MSG - Maximal Structure Generation (Friedler et al., 1993), SSG -Solution Structure Generation (Friedler et al., 1995) and ABB (Friedler et al., 1996). MSG refers to the algorithm for generating the rigorous maximal structure of the network (hyperstructure). SSG generates all the SS contained in the MS by systematically traversing the MS and identifying all feasible and meaningful topology options. Another important issue is that even the number of the solution structures is often overwhelmingly large for realistic engineering problems. This in turn means that the computational time for complete exhaustive evaluation may be significantly long. This is tackled by combining the superstructure traversing capability of the SSG algorithm with the Branch-and-Bound paradigm from optimisation theory. This gives rise to the ABB (Accelerated Branch-and-Bound) algorithm. P-graph has been applied to HEN synthesis as an initial step in this direction (Nagy et al., 2001) and extended into the hP-graph. This includes both production units and HEs. Simplifying assumptions are introduced to facilitate the HEN synthesis problem. It is the partitioning of the process streams into smaller pieces, which are considered to exchange heat completely or not to exchange at all.

5. Extensions being developed

5.1 Interfaces of the P-graph algorithms

The algorithms used by the P-graph framework provide key interfaces whose implementation needs addressing. The most important are the branching rules of the ABB algorithm need specifications of how the heat exchange matches between streams are generated and how the corresponding HE units with their associated heat transfer areas are allocated. The ABB algorithm also requires a bounding procedure which, at each branching point of the decision tree, needs to evaluate the lower bound on the HEN total cost. One possibility is to perform Supertargeting using Pinch Technology, applied to the remaining problem- i.e. the part of the process streams which has not been yet allocated heat exchange matches. The most important challenge is to make the derived lower bounds on total costs as tight as possible without compromising their bounding property.

5.2 Multiperiod formulation specifics

The nature of the multiperiod formulation itself presents specific issues which has been resolved. One particular problem is the identification of the set of operating periods with their associated steady state operating points. For each period, the corresponding representative operating point has to be estimated, including the corresponding process stream flowrates, temperatures and heat capacity flowrates. The period durations need to be determined, alongside the overall operating horizon to be considered. The challenge pertaining to the combination of multiperiod problem formulation and applying the P-graph is how to appropriately bind the same heat exchange matches, operating during different periods, to particular heat exchanger units and to adequately calculate the network capital cost.

6. Conclusions

Solution of these tasks reduces the cost of HENs as a usual overdesign covering the more capacity demanding periods can be minimised. The tests carried so far have been proving that the resulting optimised HENS can be around 20 % more compact. This brings considerable savings in the capital cost covering reduced heat transfer area, constructions, foundations, piping as well as the lower operating cost, reducing the need for overdesigned pumps/compressors.

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