Computers and Chemical Engineering 106 (2017) 243–268

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Optimal retrofit of heat exchanger networks: A stepwise approach

Etienne Ayotte-Sauvé*, Omid Ashrafi, Serge Bédard, Navid Rohani

CanmetENERGY, Natural Ressources Canada, 1615 Lionel-Boulet, P.O. Box 4800, Varennes, Quebec, J3X 1S6, Canada

ARTICLE INFO

Article history:
Received 23 February 2017
Received in revised form 5 June 2017
Accepted 6 June 2017
Available online 10 June 2017

Keywords:
Heat exchanger networks
Optimization
MINLP
Retrofit
Heat path

ABSTRACT

This paper introduces a new stepwise approach for the optimal retrofit of heat exchanger networks. At each iteration, the proposed method involves superstructures which embed retrofit alternatives as well as numerical optimization to minimize the project's total annualized cost. In order to reduce calculation times, new algorithms are proposed to thin out superstructures. These are based on thermodynamic criteria, namely on the concept of heat path, and on new graph theoretical results. To carry out the numerical optimization tasks, novel mixed integer nonlinear models are developed. These models support any combination of constant, polynomial and (continuous) piecewise linear enthalpy functions of temperature. Numerical examples are presented for the retrofit of the preheat train of an atmospheric crude unit and for the retrofit of a fluid catalytic cracking plant. The new method is shown to reduce calculation times and total annualized costs reported in the literature.

1. Introduction

A heat exchanger network (HEN) can be retrofitted in order to take into account modifications of process requirements, such as feed or product specifications, arising from a plant wide modernization. The goal of such modifications ranges from increasing heat recovery to increasing process throughput. In order to maximize heat recovery in a HEN, a wide range of retrofit projects can be examined. The present study focuses on structural modifications, such as adding new heat exchangers, relocating or modifying the area of existing heat exchangers, utility switching and splitting process streams. Other aspects, which are not covered in the present work, include heat transfer enhancement (e.g. via tube inserts), related pressure drop and pump capacity considerations, safety and maintenance, plant geography, flexibility, uncertainty (e.g. uncertain utility prices and production volumes), process control and multiperiod considerations. In the scientific literature, methodologies for HEN retrofit have garnered increasing attention over the years. Papers presented before 1993 are succinctly reviewed by Jezowski (1994) while Sreepathi and Rangaiah (2014) cover the period from 1993 to 2013. The following paragraphs aim to bridge the remaining gap in the timeline.

Literature survey

At their core, solution methods for the HEN retrofit problem tend to exploit either thermodynamic principles and insights or mathematical programming, sometimes combining aspects of both. In some approaches, the problem is partitioned into a set of subproblems which are then solved in sequence; these methods are often termed sequential or stepwise. On the other hand, simultaneous approaches for HEN retrofit solve the whole problem in one step via deterministic or non-deterministic numerical optimization.

From the thermodynamic point of view, the process pinch approach for HEN retrofit (Tjoe and Linnhoff, 1968) remains widely used more than thirty years after its inception. However, novel visualization tools were developed in recent years. Yong et al. (2015) introduce the shifted retrofit thermodynamic grid diagram which enables the assessment of both process pinch and network pinch (Asante, 1996) locations. The authors show how thermodynamic feasibility and varying energy prices can be taken into account using their diagram. To complement this tool, Nemet et al. (2015) propose the retrofit tracing grid diagram, which maps all streams and all heat exchangers distinctly using a single temperature axis. Cross-pinch analysis and non-vertical heat transfer can be evaluated using this tool. Gadalla (2015) introduces a graphical representation where axes correspond to cold and hot process stream temperatures respectively and where a heat exchanger corresponds to a line segment whose length is proportional to its duty (when specific heat capacities are constant with respect to temperature). The author demonstrates how process pinch principles can be applied in the context of this new diagram and how network pinch locations can be identified. Gadalla et al. (2016) apply this tool to a crude oil distillation system. Bonhivers et al. (2014a) introduce the thermodynamic concept of bridge, related diagrams to identify bridges and transportation tables to calculate the associated heat recovery

---

* Corresponding author.
E-mail address: etienne.ayotte-sauve@canada.ca (E. Ayotte-Sauvé).

http://dx.doi.org/10.1016/j.compchemeng.2017.06.008
0098-1354/

benefits. This concept is later applied in the context of a stepwise methodology for HEN retrofit (Bonhivers et al., 2014b). Using visual and conceptual tools, these sequential approaches bring valuable insights by helping to identify bottlenecks, assess thermodynamic feasibility and aid the engineer in devising retrofit options. However, these methods require the experience of the engineer to apply a set of heuristics. Trial and error is often necessary in order to obtain a precise retrofit topology.

From a mathematical programming perspective, the HEN retrofit problem is inherently a mixed-integer nonlinear program (MINLP). Like the HEN synthesis problem, the retrofit problem is NP-hard (Furman and Sahinidis, 2001). In broad terms, this computational complexity result states that the HEN retrofit problem is part of a difficult family of problems for which the existence of an efficient (i.e. polynomial) solution algorithm is unlikely. As a consequence, some authors try to approximate the problem (e.g. via linearizations), to reduce the underlying superstructure, to decompose the problem in a sequence of simpler problems or to solve it using heuristic resolution approaches, e.g. stochastic algorithms such as genetic algorithms or simulated annealing. Bagajewicz et al. (2013) build upon the transportation model of Cerda and Westerburg (1983). They develop a mixed-integer linear (MIP) model for HEN retrofit, which they term the heat integration transportation model. They add new equations to count exchangers and shells as well as to represent splitting and non-isothermal mixing. Their model can handle the retrofit task in a simultaneous manner. For a crude oil case study, they show that their model yields a retrofit project with a higher net present value than the pinch retrofit method. While promising, this approach requires the end-user to choose a temperature interval partition that affects the precision of the area estimations as well as the calculation time. Deciding how many intervals to consider may prove difficult *a priori*, i.e. before numerical optimization, and could therefore require trial and error. In terms of computational efficiency, their full relocation model may require more than one hour of calculation time for a case study with less than ten heat exchangers and less than ten process streams, even with a non-zero optimality gap (Nguyen et al., 2010).

Asante (1996) introduces the stepwise network pinch approach. At each step, a thermodynamic heuristic defines and thins out superstructures for network topology modifications via a MIP model. A subsequent nonlinear model (NLP) is used for economic optimization. This approach enables the user to intervene at any step in order to select or discard retrofit options based on plant specific considerations (e.g. safety, maintenance, piping costs) whose cost is sometimes difficult to accurately model a priori. One topological modification at a time is considered, adding a single new heat exchanger, relocating a single existing heat exchanger or introducing a single stream split at each iteration. Varbanov and Klemes (2000) complement this method with a set of heuristics to help define retrofit options when the network pinch approach fails, namely when no network pinch exists. Bakhtiari and Bédard (2013) propose a modified network pinch method by permitting flexibility in the process source and target temperatures as well as by using the match penalty concept to rank retrofit options at each step. This enables the end-user to favor options which would bring the final design closer to the minimal utility consumption target. Smith et al. (2010) replace the MIP model used to identify pinching matches by a NLP model and a two-level algorithm where split fractions are allowed to vary in order to eliminate artificial pinching matches. They also propose to rank options with respect to their total annualized cost rather than their total utility consumption at each step. The cost optimization is carried out using simulated annealing. While augmenting the scope and result quality of the original network pinch approach, the calculation times depend on simulated annealing algorithmic parameters which the end-user may have difficulty in selecting. Pan et al. (2013a) present a two-step approach involving a network structure optimization step followed by an investment optimization step. The first step involves using the network pinch heuristic to limit the size of network superstructures and gradually increasing the number of stages until maximum retrofit profit is reached. In both steps, they develop a MIP model by using first order Taylor approximations of nonlinear terms and by initializing the value of the logarithmic mean temperature difference (LMTD). Their MIP model is solved using an iterative substitution procedure. This approach shows promise, notably for large scale case studies. For a HEN with roughly 30 heat exchangers, their approach requires 8400 s of computing time. Such calculation times may limit the possibility to carry out multiple runs, namely for sensitivity analysis, solution robustness considerations or to take into account uncertainty.

Ochoa-Estopier et al. (2015) construct a two-level method which uses simulated annealing to define topology modifications in the first stage and assess feasibility in the second stage as a nonlinear least-squares problem. This approach offers the advantage that user-defined constraints can be easily defined. However, simulated annealing parameters that affect algorithmic performance, namely move probabilities, are difficult to define without considerable experience or trial and error. Liu et al. (2014) use a hybrid genetic algorithm to tackle the retrofit task. Unfortunately, the efficacy of their approach is not demonstrated on case studies with more than six process heat exchangers. Sreepathi and Rangaiah (2015) consider both single-objective and multi-objective optimization in the context of HEN retrofit where stream specific heat capacities vary with respect to temperature. They use integrated differential evolution and a genetic algorithm (NSGA-II) for these respective tasks. Pareto curves provide a valuable tool to visualize trade-offs in the retrofit project. However, calculation times to generate such curves can go above seven hours. Čuček and Kravanja (2015) propose a hybrid stepwise approach involving a MIP model, pinch analysis and the use of the TransGen and HENSYN software tools to carry out a HEN retrofit within a total site framework. Čuček et al. (2015) apply this method to an industrial case study. Although promising results are shown, details of the method are scarce and no comparative analysis with existing approaches is made. It is therefore difficult to assess the proposed method. Kang and Liu (2015b) consider the integration of a heat pump to further improve heat recovery in the HEN of a pulp and paper mill as well as reducing the CO_2 emissions of a biomass gasification process. They solve a MINLP model using the GAMS solver DICOPT with CPLEX and CONOPT for MIP and NLP subproblems respectively. The authors acknowledge that their approach should be extended to multiple stage heat pumps involving multiple heat sources and heat sinks.

A considerable amount of new approaches have been introduced in recent years to take into account heat transfer enhancement, fouling and pressure drop considerations in the context of HEN retrofit. Although these topics are outside the scope of the present work, recent developments are reviewed here briefly. Onishi et al. (2015) tackle the problem of pressure recovery for process streams within HEN retrofit via coupling with a turbine, a compressor and a motor. They model the problem using generalized disjunctive programming and treat it numerically as a MINLP problem with GAMS solver SBB. Their approach could in principle be used for cases where stream properties vary with respect to temperature. However, this feature was not demonstrated on a case study. Jiang et al. (2014) consider the problem of adding heat exchanger area and carrying out heat transfer enhancements, taking into account pressure drops, without network topology modifications. Their method is based on a sensitivity analysis and permits end-user interaction during the algorithmic steps. They implicitly exploit heat paths (Linnhoff and Hindmarsh, 1983) to assess thermodynamic infeasibility by identifying negative utility loads when shifting heat from a