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An alternative strategy for global optimization of heat exchanger networks

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ABSTRACT

The HEN synthesis problem is one amongst many engineering problems which can be characterized as highly combinatorial, nonlinear and nonconvex, all contributing to computational difficulties shown either in a form of long computational times and/or in identifying poor locally optimal solutions. In this work, a new strategy for global optimization of heat exchanger networks (HENs) is presented. We first introduce a concept of stage-wise superstructure augmented by an aggregated substructure. On this basis, the HEN synthesis problem is formulated as a mixed integer nonlinear program (MINLP). The strategy for providing globally optimal solutions relies on solving a single convex MINLP which incorporates piecewise linear and nonlinear convex underestimators of the nonconvex linear fractional terms present in the nonconvex MINLP. It is shown that the optimal solution of the convex MINLP can provide a lower bound tight enough that the gap between the upper and lower bound falls below 1%. In addition, an algorithm for identifying good locally optimal solutions is presented. The approach was tested on two examples, showing that currently we are able to solve small HEN synthesis problems to global optimality with reasonable computational effort, while good locally optimal solutions can be identified for larger problems.

1. Introduction

In an era of ever increasing prices of materials and energy, the benefits of global optimization are becoming more and more recognized. Many engineering optimization problems exhibit properties which cause difficulties when trying to identify globally optimal solution(s). Unless specialized global solvers [1], various model reformulations [2], and custom-made algorithms [3] are used, only locally optimal solution can be guaranteed. It is important to note that the relative differences between locally optimal and globally optimal solutions when solving large and complex optimization problems can exceed 30%. Thus, finding globally optimal solutions is in many cases highly desirable, if not a necessity, from practical reasons e.g. when the objective is to find the most cost-efficient solution.

The synthesis of HENs is generally a complex task, for the design needs to be thermodynamically and technologically feasible, and economically viable. The most widely used technology for HEN synthesis is the Pinch Analysis [4]. Its concepts were continuously improved over the past decades with the aim to address many different issues (e.g. HEN retrofit [5], total site integration [6] water and energy minimization [7] etc.) correlated to improving sustainability of chemical processes [8]. It is argued, however, that mathematical programming techniques – capable of dealing with the discrete/continuous nature of HEN synthesis problem – offer the most effective way to efficiently incorporate all the three aspects.

Yee and Grossmann [9] proposed a MINLP formulation based on a stage-wise superstructure (SWS) which became recognized as a quintessential concept for the MINLP-based research work regarding HEN synthesis. Recently, Yee and Grossmann's formulation, although elaborated, can be traced in many works addressing various topics arising in HEN synthesis. Some of these are: synthesis of HENs comprising different types of heat exchangers [10], incorporation of pressure drop effects into the synthesis problem [11], flexibility and static operability of HENs [12], synthesis of HENs with detailed design of heat exchange equipment [13], efficient handling of phase transition phenomena (evaporation, condensation) [14] in HEN synthesis problems, multi-period operation [15] etc.

In the previous approaches, thermodynamic and technological feasibility are the focus. The two are achieved by extending the original formulation [9] with additional constraints, which must be satisfied in any feasible solution. On the other hand, the criterion for selecting the optimal design is usually given by minimal total annualized cost, which brings us to the core of the problem.

The MINLP model presented by Yee and Grossmann [9] is nonconvex. First, because of nonconvex terms for calculating heat

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