Computers and Chemical Engineering 56 (2013) 184–201

Contents lists available at SciVerse ScienceDirect

Computers and Chemical Engineering

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

Supply-based superstructure synthesis of heat and mass exchange networks

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ARTICLE INFO

Article history:
Received 12 March 2010
Received in revised form 26 March 2013
Accepted 17 May 2013
Available online 28 May 2013

Keywords:
Mass exchange networks
Synthesis
Superstructure

ABSTRACT

A new simultaneous mixed integer non-linear programing (MINLP) approach to heat exchange network synthesis (HENS) and mass exchange network synthesis (MENS) is presented. This supply-based superstructure (SBS) approach uses the supply temperatures/compositions of all the streams (including utilities) present in the synthesis problem to define heat/mass exchange superstructure intervals. The intermediate temperatures/compositions are variables used in the optimization of the network total annual cost (TAC). The ability of each stream to exchange heat/mass in any interval in the SBS is subject to thermodynamic/mass transfer feasibility. The paper presents the mathematical formulations for optimizing the TAC for HENS and MENS. The SBS synthesis technique has been applied to nine literature problems involving both HENS and MENS. The solutions obtained are in the same range as those in the literature, with one solution being the lowest of all.

1. Introduction

Energy and mass optimization in process plants have been accomplished using synthesis tools which are either sequential or simultaneous in nature, although most of the simultaneous mathematical optimization techniques do in fact involve more than one solution stage.

Pinch technology as a synthesis tool for heat exchanger networks (HENs) started in the late 1970s (Linnhoff & Flower, 1978). It is based on physical and thermodynamic insight and involves two stages: targeting and design. The first step is to determine the minimum energy consumption so as to obtain the annual operating cost (AOC) target. The network synthesis is then decomposed into sub-networks below and above the pinch, and the problem solved independently for each sub-network, using heuristics to evolve networks with minimum units. This may be compared with the annual capital cost (ACC) target obtained from the pinch curves (Linnhoff & Flower, 1978; Linnhoff & Hindmarsh, 1983). It has been the most dominant sequential method (El-Halwagi, 1997; Smith, 2005).

El-Halwagi and Manousiouthakis (1989) developed a mass exchange network (MEN) analogue of the pinch technology approach to heat exchange networks but their method can only target for the minimum mass separating agents (MSAs) needed for a separation task. Hallale and Fraser (2000a, 2000b) in their quest for capital cost targeting developed the y–y^* tool for targeting the mass exchanger area for both stage-wise and continuous contact columns.

Other developments in pinch based HENS and MENS (including some pinch related mathematical approaches for HENS) are contained in Shenoy (1995), Floudas (1995), El-Halwagi (1997), and Smith (2005).

The general problem with the pinch technique is its sequential nature. The simultaneous approaches on the other hand involve the use of mathematical programing models (Floudas, 1995) to optimize the total annual cost (TAC) in a single step. Costs which contribute to the TAC in heat and mass exchanger networks are annual operating cost (AOC, utility and mass separating agent costs) and annualized capital cost (ACC, heat and mass exchanger costs). Efforts have been made over the years to exploit the dynamic nature of mathematical programing to produce networks where the TAC can be optimized in a single step (Bagajewicz, Pham, & Manousiouthakis, 1998; Chen & Huang, 2005; Comeaux, 2000; Isafiade & Fraser, 2008a, 2008b; Papalexandri, Pistikopoulos, & Floudas, 1994; Szitkai, Farkas, Lelkes, Fonyo, & Kravanja, 2006; Yee & Grossmann, 1990). Note that none of these methods can guarantee globally optimum solutions, due to the inherent convexity of the HENS and MENS problems (Floudas, 1995).

One of the simultaneous approaches adopted by various workers to optimize the TAC in HENS and MENS is the use of superstructures. For instance, Yee and Grossmann (1990) presented a simplified stage wise superstructure (SWS) for HENS, which is an extended version of the superstructure developed by Grossmann and Sargent (1978) where, within each stage, heat exchange can

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http://dx.doi.org/10.1016/j.compchemeng.2013.05.010

occur between hot streams and cold streams. In the SWS, heat exchange can also occur between each hot stream and each cold stream within each stage in the superstructure. The SWS also bears resemblance to the spaghetti design concept of Linnhoff and co-workers (e.g. Linnhoff & Ahmad, 1990; Linnhoff, Mason, & Wardle, 1979) that shows division of the composite curves into sections, which is viewed by Yee and Grossmann (1990) as a series of stages.

Comeaux (2000) presented a reducible superstructure for MENS where the superstructure intervals were defined using the supply and target compositions of the rich streams and the equilibrium equivalent compositions of the lean streams in the rich phase. A stream extension rule (Comeaux, 2000) was adopted for the lean streams to ensure that each lean stream can match at least once with each rich stream in the superstructure. The superstructure made use of the branch flow rates to determine the existence or otherwise of matches between rich and lean streams. The superstructure was then modeled as a non-linear program (NLP) to determine the TAC of the networks.

Szitkai et al. (2006) applied the key idea of Yee and Grossmann (1990) along with the pinch technique and the mixed integer non-linear programing (MINLP) formulation of Papalexandri et al. (1994) to develop a MENS superstructure similar to Yee and Grossmann's HENS model. The authors verified their superstructure using the pinch designs of Hallale and Fraser (2000a, 2000b). The adapted superstructure retains most of the features of Yee and Grossmann's model and is referred to in this paper as 'SWS', although the authors did not call it this.

Emhamed et al. (2007) used a hybrid method for the optimization of mass exchange networks. The main idea of Emhamed et al. involves the use of integer cuts and bounds to the lean stream to exclude non-optimal solutions. The authors use the driving force plot (DFP) supertargeting method of Hallale (1998) to determine the initial flow sheet in the first step, and the flow sheet is then optimized using the MINLP formulation model of Szitkai et al. (2006) in the second step.

Isafiade and Fraser (2008a, 2008b) used a framework similar to the SWS of Yee and Grossmann (1990) and Szitkai et al. (2006) to optimize the design of heat and mass exchange networks. Their interval based MINLP superstructure (IBMS) model is constructed using the supply and target temperatures/compositions of either the hot/rich or cold/lean sets of streams. If the intervals are defined by hot/rich streams then the cold/lean streams are assumed to participate in all the intervals. The reverse is the case for a cold/lean stream based superstructure. The exchange of heat/mass between hot/rich streams and cold/lean streams in an interval is subject to thermodynamic feasibility, both for heat transfer and the equilibria that govern mass transfer.

The SWS technique and its derivatives, as well as the IBMS technique, all have isothermal mixing in common. In addition, the SWS of Yee and Grossmann (1990) is conceptually similar to a spaghetti design. In spaghetti design, however, the number of stages and enthalpy intervals are necessarily equal, but in SWS, the number of stages is typically much smaller than the number of enthalpy intervals. The choice of a larger number of stages is necessary for more combinations of stream matches (Shenoy, 1995).

Other workers have adopted an Evolutionary Algorithm (EA) method for the simultaneous synthesis of HENs. Lewin (1998) presented a generalized simultaneous method for the synthesis of heat exchanger networks based on a Genetic Algorithm (GA), a form of Evolutionary Algorithm (Goldberg, 1989), using NLP. In this formulation both the objective function and the constraints are non-linear. The author proposed a solution based on the observation that an optimal solution usually involves relatively few stream splits. The NLP problem was solved using a cascaded algorithm involving an upper level non-linear optimization of the stream split flows, and a lower level pseudo-linear optimization of the heat exchanger duties.

Krishna and Murty (2007) applied a modified differential evolution method (DEM), another form of EA, to HENS. The DEM is suitable for optimization problems with continuous variables so it needed to be modified to allow for the integer variables in HENS problems. The model considered stream splitting but did away with the simplifying assumption of isothermal mixing of the split streams of Yee and Grossmann (1990). Their model can also handle compulsory and forbidden matches in optimization of HENs. The DEM approach is more likely to find the true optimum than the Genetic Algorithm approach (Price & Storn, 1997).

The state space approach is another technique that has been adopted for the optimization of TAC in HENS and MENS. Bagajewicz et al. (1998) presented the application of the state space approach to HENS and MENS using NLP, demonstrating the flexibility of the approach in HENS and MENS formulation through the use of various operators. They showed that the state space approach contains a network superstructure as a special case but the approach can only guarantee local optimality.

Martin and Manousiouthakis (2001) also synthesized HENs and MENs using the state space approach. Martin and Manousiouthakis' work provides analytical proofs that, under certain assumptions, bypass streams and recycle streams can be set to zero without compromising the global optimality of the HEN/MEN minimum TAC problem. The resulting NLP formulation of the TAC HEN problem is solved to global optimality, using a hybrid algorithm with branch and bound underestimation and interval analysis. The two simple examples solved do not contain sufficient information to check the validity of their claim. A feature of this work is that two different streams, one hot and one cold, can be mixed to achieve the required outlet temperature (the same for both), as shown in their second example. While this may be helpful in certain situations, this is not generally applicable, and has not been implemented by any other workers in this field.

2. Problem statements

2.1. HENS

Given a number of hot and cold process streams (to be cooled and heated respectively), the task is to synthesize a heat exchanger network which can transfer heat from the hot streams to the cold streams in order to achieve a minimum total annual cost network. Given also are the heat capacity flowrates, supply and target temperatures and heat transfer coefficients of each process stream. Available for service are heating and cooling utilities whose costs, supply temperatures, target temperatures and heat transfer coefficients are also given, along with annual operating time, heat exchanger costs and the annual cost of capital.

2.2. MENS

Given a number of rich streams and a number of MSAs (lean streams), the task is to synthesize a network of mass exchangers that can preferentially transfer certain species from the rich streams to the MSAs in order to achieve a minimum total annual cost network. Given also are the flowrate of each rich stream and the supply and target compositions. In addition, the supply and target compositions for each MSA together with the mass transfer equilibrium relations are also given for each MSA. The flowrate of each MSA is unknown and is to be determined as part of the synthesis task. Also given are the annual operating time, mass exchanger sizing and cost information and the annual cost of capital.