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Interval-based MINLP superstructure synthesis of heat exchange networks

*A.J. Isafiade, D.M. Fraser**

Chemical Engineering Department, University of Cape Town, Cape Town 7700, South Africa

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ABSTRACT

An interval-based mixed integer nonlinear program (MINLP) superstructure model for the synthesis of heat exchange networks (HENs) is presented. The intervals of the superstructure are defined by the supply and target temperatures of either the hot or cold set of streams (including utilities). Heat can be exchanged between each hot and cold stream within each interval. This model can simultaneously trade-off energy, heat transfer area and number of units while at the same time generating a close to optimal network structure. Constraints on matches can easily be handled as well as streams with significantly different heat transfer coefficients. This model, unlike other simultaneous HEN synthesis models, avoids the need for the nonlinear mixing equations by mixing streams at equal temperatures. Multiple utilities can also easily be included in the superstructure. The model is applied to five example problems in the literature and it is shown to produce satisfactory results. A special feature of this method is that no particular initialisation procedure is required in order to obtain the optimal solution.

1. Introduction

Heat exchanger network synthesis has been the most studied area of process synthesis. Methods based on physical insights, mathematical programming (MP) and a hybrid of both approaches have been used. Pinch technology (PT) has been the most dominant under the physical insights approach. The hybrid approach embeds the physical insights as provided mainly by pinch technology in mathematical programming models.

2. Established synthesis methods

2.1. *Pinch technology*

The pinch technology synthesis approach involves two major steps, targeting and design. Targets can be set for the minimum hot and cold utilities needed by a network at a specified minimum temperature difference ($\Delta T_{\min}$); such targets correspond to maximum energy recovery. The pinch design method of Linnhoff and Hindmarsh (1983) can be used to meet such energy targets in the network structure generation. An increase in the value of $\Delta T_{\min}$ leads to a reduction in the amount of energy that could be recovered from process streams, hence an increase in the utilities that need to be brought into the network.

Both Townsend and Linnhoff (1984) and Ahmad and Linnhoff (1984) developed techniques for capital cost targeting. Linnhoff and Ahmad (1990) gave a more detailed algorithm for establishing the trade-off among the competing costs in the synthesis of HENs. They set out detailed targeting methods for energy, area and number of units as well as techniques with which to meet such targets in designs. Each of these targets alongside the costings is carried out for a

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Abbreviations: AC, air cooling; CU, cold utility; CW, cooling water; DFP, driving force plot; EMAT, exchanger minimum approach temperature; GAMS, general algebraic modeling system; GCC, grand composite curve; HEN, heat exchanger network; HENS, heat exchanger network synthesis; HPS, high pressure steam; HRAT, heat recovery approach temperature; HU, hot utility; IBMS, interval based MINLP superstructure; LPS, low pressure steam; MINLP, mixed integer nonlinear programming; MP, mathematical programming; MPS, medium pressure steam; NLP, nonlinear programming; OLD, optimum load distribution; RPA, remaining problem analysis; SWS, stage-wise superstructure; TAC, total annual cost.

* *Corresponding author*. Tel.: +27 21 650 2515; fax: +27 21 650 5501.
E-mail address: Duncan.Fraser@uct.ac.za (D.M. Fraser).

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Nomenclature

A	area cost coefficient
C	set of cold process and utility streams
CB	fixed charge for exchangers
CU	cost per unit of cold utility
dt_{ijm}	driving force for match (i, j) in interval m
D	area cost index
F_i	flow rate of hot stream i
F_j	flow rate of cold stream j
H	set of hot process and utility streams
HU	cost per unit of hot utility
i	hot process or utility stream
j	cold process or utility stream
m	index for temperature interval (total number of interval boundaries = $m+1$)
M	set of temperature intervals in superstructure
N	number of exchanger units
q_{ijm}	heat exchanged between hot stream i and cold stream j in temperature interval m
S	number of streams
$t_{i,m}$	temperature of hot stream i at hot end of interval m
$t_{j,m}$	temperature of cold stream j at hot end of interval m
T_i^s	supply temperature of hot stream i
T_i^t	target temperature of hot stream i
T_j^s	supply temperature of cold stream j
T_j^t	target temperature of cold stream j
U	overall heat transfer coefficient
y_{ijm}	binary variable indicating the existence of match i, j in interval m in the optimal network

Greek letters

Ω	upper bound for heat exchanged in match i, j
Φ	upper bound for driving force in match i, j

range of $\Delta T_{\min}$ values in order to obtain the total annual cost (TAC) for each $\Delta T_{\min}$. The lowest TAC target is then chosen as the optimum. This procedure is known as supertargeting. The design technique set out by Linnhoff and Ahmad (1990) involves designing for minimum (or near minimum) number of units while trying to approach vertical heat transfer. The other design methods used are the CP rules for matching at the pinch (Linnhoff et al., 1982), the driving force plot (DFP, Linnhoff and Vredeveld, 1984) and remaining problem analysis (RPA, Ahmad, 1985; Tjoe, 1986). In as much as these approaches might produce good designs, they are fraught with shortcomings.

In order to apply the CP rules, matching needs to start at the pinch and move outwards, so it is by its nature sequential. The DFP is based on how the driving forces of matches approach those of the composite curves (Linnhoff and Ahmad, 1990). It does not take into consideration the consequence of heat loads on heat exchange area. This can result in poor designs for matches which are close to the pinch and at the same time have large heat duties. RPA (like the CP rules) also does not give a specific sequence in which matches need to be evaluated; hence the method can be time consuming.

2.2. *Multiple utilities*

Shenoy et al. (1998) used the cheapest utility principle (CUP) to target for optimum utility selection. The CUP involves favouring the use of the cheapest utility as the total energy usage increases. The $\Delta T_{\min}$ is fixed and the use of each utility is varied so as to determine which utility (or set of utilities) give the least operating and associated capital costs at that $\Delta T_{\min}$. The approach is different from the grand composite curve (GCC) method of Linnhoff et al. (1982) in that it takes the capital cost implications of the additional utilities into consideration during targeting. However, with this approach, there is no simultaneous trade-off between the multiple utilities and capital, as is the case with the pinch technology approach involving single hot and cold utilities. Also, the approach is tedious and time consuming and the designs with which to meet such targets are still those of the conventional pinch approach with the associated shortcomings discussed earlier.

The pinch technology method does not easily allow for constrained matches such as forbidden or preferred matches. Also the concept of vertical heat transfer only strictly predicts the minimum area for situations in which the heat transfer coefficients of the participating streams are all the same, however this is never the case with real industrial heat exchange problems.

2.3. *Mathematical programming*

Papoulias and Grossmann (1983) modelled the pinch minimum utility targeting method in a linear programming (LP) environment using the transhipment model. The authors extended the model to account for the minimum number of matches (and the heat load on each match) using mixed integer linear programming (MILP) alongside the minimum utility solution. The MILP model can give a number of global solutions having the same number of units. Gundersen and Grossmann (1990) extended this MILP transhipment model to account for vertical heat transfer alongside a minimum heat exchange area as a method with which to screen the different solutions. Floudas et al. (1986) set up a nonlinear programming (NLP) model which uses fixed minimum utility targets as well as a fixed number of matches target (both determined from a fixed heat recovery approach temperature, HRAT). The NLP model determines the minimum investment cost network by fixing the exchanger minimum approach temperature (EMAT) as EMAT ≤ HRAT.

The aforementioned MP approaches involve solving the HEN problems as subproblems; hence they are sequential in nature. This introduces an inappropriate trade-off among the energy, number of units and the area requirement. Decisions at each step can affect the optimality of the subsequent steps; hence the methods can result in suboptimal networks (Floudas, 1995).

The shortcomings of the sequential approaches led to the use of simultaneous synthesis techniques. These techniques involve setting up the heat exchange problem as a superstructure (or hyper structure) which embeds all possible networks. Such superstructures are subsequently optimised in order to determine the best network. Floudas and Ciric (1989) combined the minimum number of units target and the minimum cost network generation steps of the sequential approach in a single step using a mixed integer nonlinear programming (MINLP) approach. They then extended the MINLP model to cater for heat transfer across the pinch (Ciric and Floudas,