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Supply and target based superstructure synthesis of heat and mass exchanger networks

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ABSTRACT

This paper presents new methods for the optimisation of superstructures involving heat exchanger networks (HENs) and mass exchanger networks (MENs). The techniques developed in this study explore the use of key variables (namely supply temperatures/compositions and target temperatures/compositions) in HENs and MENs to define the intervals of superstructures. Such superstructures are modeled as mixed integer non linear programmes (MINLP) with the objective of minimisation of the total annual cost (TAC) for each network. The superstructures presented in this paper are derivatives of the interval and supply based superstructures (IBMS and SBS) developed previously. Two different superstructures are developed in this paper: the first uses the supply temperature/composition of hot/rich streams and the target temperature/composition of cold/lean streams (denoted supply and target based superstructure, S&TBS), while the second superstructure uses the target temperature/composition of hot/rich streams and the supply temperature of cold/lean streams (denoted target and supply based superstructure, T&SBS). Five HEN examples and three MEN examples are presented. The results obtained compare well with those in the literature.

Keywords: Heat exchanger networks; Mass exchanger networks; Superstructure; Total annual cost

1. Introduction

The tasks of synthesizing cost effective heat exchanger networks (HENs) and mass exchanger networks (MENs) have become key aspects of process synthesis. Heat exchanger network synthesis (HENS) has received much attention over the years. For example, Lee et al. (1970) formulated HENS problems using the branch and bound technique of Lawler and Wood (1966) with the aim of optimal energy exchange to obtain a network of minimum cost. In their formulation, no stream splitting was considered. The technique of Lee et al., though helped in the reduction of combinatorial difficulty in HENS, but the highest number of streams that has been solved in the literature by this technique is ten (Pho and Lapidus, 1973). Another shortcoming of the method of Lee et al. is the difficulty in obtaining cyclic structures; as such optimality cannot be guaranteed (Rathore and Power, 1975). Nishida et al. (1977) presented an algorithmic evolutionary synthesis method that appears to be more suitable for more sizable HENS problems but the approach is sequential.

Linnhoff and Flower (1978) presented a thermodynamically based temperature interval synthesis method from which the pinch concept for HENS developed. The method is premised on the basis that a cost effective network should exhibit a high degree of energy recovery. They subdivided their approach into two stages: in the first stage, a preliminary network that gives the highest possible energy recovery was generated, in the second stage; the preliminary network generated in the first stage served as the initial point to search for the most satisfactory network from the view points of cost, safety, and control, among other considerations.

In the application of pinch technology to process synthesis, the design requirement is that there should be no heat flow across the pinch. The first step is to determine the minimum energy consumption to obtain the annual operating cost (AOC) target. The network synthesis is then decomposed into subnetworks below and above the pinch, and the problem solved independently for each subnetwork, using heuristics to evolve networks with minimum units. This may be compared with the annual capital cost (ACC) target obtained from the pinch

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Nomenclature

Sets

C	cold process and utility streams
H	hot process and utility streams
R	rich process streams
S	lean streams (process and external MSAs)
K	temperature/composition intervals in the superstructure

Indices

i	hot process or utility stream
j	cold process or utility stream
k	index for temperature/composition boundary ($k = 1, \ldots, NOK + 1$)
l	lean stream (process or external mass separating agent)
r	rich process stream

Parameters

AC_l	annual cost per unit of lean stream l
ACH_{rl}	annual cost per height for continuous contact columns involving rich stream r and lean stream l
ACT_{rl}	annual cost per stage for staged columns involving rich stream r and lean stream l
AFC	area cost coefficient for heat exchangers
b	equilibrium line intercept
$C_{j,k}$	represents the existence of cold stream j in interval K (i.e. between temperature interval boundaries k and $k+1$)
CB_{ij}	fixed charge for heat exchangers
CB_{rl}	fixed charge for mass exchanger columns involving rich stream r and lean stream l
CS	starting location for cold streams in the superstructure
CE	ending location for cold streams in the superstructure
CU	cost per unit of cold utility
D	area cost index for heat/mass exchangers
$H_{i,k}$	represents the existence of hot stream i in interval K (between temperature interval boundaries k and $k+1$)
HS	starting location for hot streams in the superstructure
HE	ending location for hot streams in the superstructure
HU	cost per unit of hot utility
K_w	lumped mass transfer coefficient
m	equilibrium constant for the transfer of component from rich stream r to lean stream l
NOK	number of temperature/composition intervals
$R_{r,K}$	existence of rich stream r in interval K (between composition interval boundaries k and $k+1$)
$RST_{r,k}$	rich stream r start at composition interval boundary k
$RED_{r,k}$	rich stream r end at composition interval boundary k
$S_{l,k}$	existence of lean stream l in interval K (between composition interval boundaries k and $k+1$)
$SST_{l,k}$	lean stream l start at composition interval boundary k
$SED_{l,k}$	lean stream l start at composition interval boundary k
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
$T_{Hi,k}^s$	Supply temperature of hot stream i at interval boundary k
$T_{Cj,k}^s$	Supply temperature of cold stream j at interval boundary k
$T_{Hi,k}^t$	Target temperature of hot stream i at interval boundary k
$T_{Ci,k}^t$	Target temperature of cold stream j at interval boundary k
T_k	temperature of interval boundary k
X_l^s	supply composition of lean stream l
X_l^t	target composition of lean stream l
Y_r^s	supply composition of rich stream r
Y_r^t	target composition of rich stream r
Y_l^{*s}	equilibrium supply composition of lean stream l
Y_l^{*t}	equilibrium target composition of lean stream l
Y_k	composition of interval boundary k
$Y_{Ri,k}^s$	supply composition of rich stream r at interval boundary k
$Y_{Ri,k}^t$	target composition of rich stream r at interval boundary k
$Y_{Si,k}^{s*}$	equilibrium supply composition of lean stream l at interval boundary k
$Y_{Si,k}^{t*}$	equilibrium target composition of lean stream l at interval boundary k
Γ_H	upper bound for driving force in match i, j
Γ_M	upper bound for driving force in match r, l
ε_{min}	minimum composition difference in the lean phase
Ω_H	upper bound for heat exchanged in match i, j
Ω_Z	upper bound for mass exchanged in match r, l
\$	conditional operator

Binary variables

Z_{ijk}	variable showing the existence of match i, j in interval K in the network
Z_{rlk}	variable showing the existence of match r, l in interval K in the network

Positive variables

dt_{ijk}	heat exchanger driving force for match i, j in temperature interval K
dy_{rlk}	mass exchanger driving force for match r, l in composition interval K
F_i	flow rate of hot stream i
F_j	flow rate of cold stream j
G_r	rich stream flowrate
L_l	lean stream flowrate
M_{rlk}	mass exchanged between stream r and stream l in composition interval K
N_{rlk}	number of stages in staged column rlk
q_{ijk}	heat exchanged between stream i and stream j in temperature interval K