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Synthesis of mass exchange networks for single and multiple periods of operations considering detailed cost functions and column performance

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ABSTRACT

Mass exchange network synthesis (MENS) can be used to reduce pollutant emissions into the environment as well as reduce the need for mass separating agents (MSAs). Designing an efficient network using mathematical programming is not a trivial task, due to the fact that the design equations involved are highly non-linear. Chemical plant process parameters also change from time to time due to issues such as changes in environmental conditions, plant start-up/shut-downs, changes in process feed quality, change in product quality demand, and some other disturbance in the system. Such changes in process parameters result in what is known as multi-period operations; hence the synthesised network has to be flexible to handle these changes. In order to circumvent the issues associated with solving non-linear equations in mathematical programming environment, most methods have simplified the cost functions for MENS. Solutions obtained from these methods may not be realistic because the simplified cost functions are based on the assumption that the diameter of a column is 1 m or 2 m and that the capital cost of packed columns are dependent only on the height of the column. The simplified models do not make provision to check whether the resulting designs are prone to flooding, operate at optimal pressure drops or even whether the ratio of column diameter to size of packing materials would enhance efficient operations. Furthermore the models assumed single period operations for mass exchange network systems. This paper presents a new synthesis method for single and multi-period MENS using detailed cost functions and correlations which check whether selected columns are prone to flooding or not and whether they have optimal pressure drops that ensure efficient separations as well as optimal use of MSAs. The solutions obtained are compared with an existing method that used pinch technology.

1. Introduction

The world's attention is gradually shifting towards the need to reduce the emission of pollutants into the environment as well as towards reducing the exploitation of scarce and expensive resources which are used by chemical plants as mass separating agents (MSAs). Mass exchanger network synthesis (MENS) can be used to accomplish the aforementioned reductions in pollutant emissions and use of MSAs. Pinch technology (El-Halwagi and Manousiouthakis, 1989; Hallale and Fraser, 2000a,b) and mathematical programming (Chen and Hung, 2005; Szitkai et al., 2006; Isafiade and Fraser, 2008) are methods which have been used for the synthesis of mass exchange networks (MENs). However, most of these methods have assumed that mass exchange operations are single period processes and are designed for optimal operation for only a single

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Nomenclature

Abbreviations

ACC	annual capital cost
AOC	annual operating cost
HENS	heat exchange network synthesis
IBMS	interval based MINLP superstructure
LMCD	logarithmic mean composition difference
MENS	mass exchange network synthesis
MIBS	multi-period interval based MINLP superstructure
MINLP	mixed integer non-linear programming
MSBS	multi-period supply based superstructure
SBS	supply based superstructure
TAC	total annual cost

Sets

R	rich process streams
S	lean process and external streams
INT	superstructure intervals
P	periods of operation

Indices

r	process rich streams
l	process lean and external lean streams
k	index representing interval, 1, . . ., NOI and composition location, 1, . . ., $NOI + 1$
p	index for operation periods ($p = 1, \ldots, NOP$)

Parameters

AC_l	annual operating cost per unit of lean stream l
$CB_{r,l}$	installation cost for mass exchanger r, l
Vis_r	viscosity of stream l (Pa s)
FP	column packing factor
$G_{r,p}$	flow rate of rich stream in period p (kg s^{-1})
$RHOL_{r,l}$	lean stream density for match r, l (kg m^{-3})
$RHOG_{r,l}$	rich stream density for match r, l (kg m^{-3})
$X^s_{l,p}$	supply composition of lean (process or external) stream for period p
$X^t_{l,p}$	target composition of lean (process or external) stream for period p
$Y^s_{r,p}$	supply composition of rich process stream for period p
$Y^t_{r,p}$	target composition of rich process stream for period p
$Y^{*s}_{l,p}$	equilibrium supply composition of lean (process or external) stream for period p
$Y^{*t}_{l,p}$	equilibrium target composition of lean (process or external) stream for period p
DOP	duration of each period p
NOP	number of periods
Ω_p	exchanged mass upper limit for in match r, l in period p
Φ	driving force upper limit for match r, l in period p
π	mathematical constant = 3.142
$\mu_{r,l,k,p}$	viscosity of the gas (Pa s)
Sc	gas Schmidt number
ω	function of the wetted packed surface
a_G	experimental constant which is a function of packing
β	experimental constants which is functions of the packing
d_e	equivalent packing diameter (m)
$\in$	fractional voidage of the column packing
$G'_{r,l,k,p}$	superficial gas mass velocity (kg m^{-2} s^{-1})
a	packing specific surface area (m^{-2} m^{-3})

Binary variable

$Z_{r,l,k}$	represents the existence of match r, l in interval k in the optimal network

Positive variables

$A_{r,l,k,p}$	cross-sectional area of column r, l, k in period p (m)
$D_{r,l,k}$	maximum diameter of column r, l, k (m)
$FLV_{r,l,k,p}$	flow factor for column r, l, k in period p
$KF_{r,l,k,p}$	flooding parameter for column r, l, k in period p
$Fr_{r,l,k,p}$	rich stream split branch flowrate r, l, k in period p (kg s^{-1})
$Fl_{r,l,k,p}$	lean stream split branch flowrate for column r, l, k in period p (kg s^{-1})
$H_{r,l,k}$	maximum representative height for match r, l, k (m)
$TH_{r,l,k}$	true height of column r, l, k (m)
$ky_{r,k,p}$	overall mass transfer coefficient for the rich phase (kg s^{-1} m^{-3})
$dy_{r,l,k,p}$	mass exchanger driving force
L_p	liquid flowrate at periphery of packing (m^3 s^{-1} m^{-1})
$L_{l,p}$	flowrate of lean stream in period p (kg s^{-1})
$LMCD_{r,l,k,p}$	logarithmic mean composition difference between rich stream r and lean stream l in interval k and period p
$M_{r,l,k,p}$	mass exchanged between rich stream r and lean stream l in interval k and period p (kg s^{-1})
$y_{r,k,p}$	composition of rich process stream in interval boundary k and period p
$x_{l,k,p}$	composition of lean (process or external) stream in interval boundary k and period p
$y^*_{l,k,p}$	equilibrium composition of lean (process or external) stream l in composition interval boundary k and period p.

steady-state case. The methods are also based on the use of simplified capital cost functions developed by Papalexandri et al. (1994) which assumes that the diameter of a column is 1 m and that the cost of a column is based only on the number of stages for staged columns and on the height of the column for packed columns. For packed columns, which is the focus of this paper, the existing synthesis procedures do not make provision for checking whether the resulting columns have optimal pressure drops, proneness to flooding, and suitability of ratios of column diameter to size of packing materials.

One other shortcoming associated with the existing methods is that they are based on single periods of operations, which implies that when process parameters change, the MEN may not be flexible enough to handle the changes.

2. Literature review

Synthesis of mass exchange networks is gradually gaining attention like its heat exchange network synthesis (HENS) counterpart. Some of the methods that have been developed

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