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Comparing three configurations of the externally heat-integrated double distillation columns (EHIDDiCs)

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ABSTRACT

In terms of separation of a binary mixture of ethylene and ethane, three configurations of externally heat-integrated double distillation columns (EHIDDiCs), including a symmetrical EHIDDiC (S-EHIDDiC), an asymmetrical EHIDDiC (A-EHIDDiC), and a simplified asymmetrical EHIDDiC (SA-EHIDDiC), are compared with respect to aspects related to process design and controllability. It has been found that the A-EHIDDiC and SA-EHIDDiC are superior to the S-EHIDDiC in terms of thermodynamic efficiency as well as in terms of process dynamics and controllability. As for the comparison between the A-EHIDDiC and SA-EHIDDiC, the latter shows somewhat comparable behaviors with the former in terms of process design and controllability. These results demonstrate that the asymmetrical configuration should generally be favored over the symmetrical one for the development of the EHIDDiC. It is feasible to approximate external heat integration using three heat exchangers between the high- and low-pressure distillation columns involved.

1. Introduction

Recently, we proposed and studied external heat integration between rectifying section and stripping section of high-pressure (HP) and low-pressure (LP) distillation columns involved in a pressure-swing distillation system separating a binary azerotropic mixture of acetonitrile and water (Huang, Shan, Zhu, & Qian, 2008). It was found that this kind of heat integration could help to improve process design not only in thermodynamic efficiency but also in terms of capital investment. In terms of the separation of an ideal ternary mixture of hypothetical components A, B, and C, we further systematized the idea and termed this kind of processes the externally heat-integrated double distillation columns (EHIDDiCs) (Huang, Liu, Ma, & Wang, 2010). It was demonstrated that under appropriate operating conditions, the EHIDDiC could become even more thermodynamically efficient than a conventional distillation system with the condenser/reboiler type heat integration. To facilitate the design and implementation of the EHIDDiC, we proposed further to employ three heat exchangers to approximate external heat integration between the rectifying section and the stripping section of the HP and LP distillation columns, respectively, and the conducted simulation studies indicated that it could be a reasonable design option in terms of steady state performance (Huang et al., 2009; Wang, Huang, & Wang, 2010). Because of the involvement of the HP and LP distillation columns, the synthesis and design of the EHIDDiC is much more complicated than that of conventional distillation columns and one of the most important issues in process development lies in the determination of process configurations for external heat integration. Several schemes can be recommended including those with heat transfer from the whole rectifying section to the whole stripping section and from the whole/top part of rectifying section to the bottom part of/whole stripping section. The number of alternatives increases further when three heat exchangers were introduced to approximate external heat integration because their locations and sizes become key decision variables for process synthesis and design. In addition to its economical feasibility, process dynamics and controllability should also be considered as an important index in process development because the EHIDDiC involves simultaneously mass-integration and energy-integration between the HP and LP distillation columns. Although process integration is an effective means for enhancing the thermodynamic efficiency of chemical processes, it may cause complications in process dynamics and even operational difficulties might be aroused (Hernández & Jiménez, 1999; Huang et al., 1996; Luyben & Hendershot, 2004; Schmal, Van Der Kooi, De Rijke, Olujić, & Jansens, 2006; Serra, Espuña, & Puigjaner, 2003; Wang & Wong, 2007). This makes it necessary to examine process dynamics and controllability along with the synthesis and design of the EHIDDiC (Kamaruddin, Hamid, Sin, & Gani, 2010).

The primary objective of this work is to study the impacts of the various configurations for external heat integration on the design and operation of the EHIDDiC. Three specific configurations of the EHIDDiC are derived and these include a symmetrical EHIDDiC

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Nomenclature

a_{ij}	interaction parameters for the Peng–Robinson equation of state
A	parameter of a mixture for the Peng–Robinson equation of state
A_{con}	heat transfer area in condenser (m^2)
A_{HI}	heat transfer area for external heat integration (m^2)
A_{reb}	heat transfer area in reboiler (m^2)
b	bottom product flow rate (kmol/h)
B	parameter of a mixture for the Peng–Robinson equation of state
B_0–B_4	coefficients of enthalpy formulation
CI	capital investment ($)
CN	condition number
cost	investment ($)
d	distillate flow rate (kmol/h)
D	diameter of a distillation column (m)
f	fugacity (kPa)
F	feed flow rate (kmol/h)
H	enthalpy (kJ)
H^0	ideal enthalpy (kJ)
H_1–H_6	locations of the heat exchangers in the SA-EHIDDiC
Ht	height of a distillation column (m)
k	vapor–liquid equilibrium constant
K_c	proportional gain
L	liquid flow rate (kmol/h)
M	stage holdup (kmol)
M_W	average molecular weight (kg/kmol)
MRI	minimum singular value
nc	number of components
n	number of stages
OC	operating cost ($)
P	pressure (kPa)
P_H	pressure in the top of the HP distillation column (kPa)
p^s	saturation pressure (kPa)
Q	heat duty (kJ/h)
Q_{HI}	heat transfer load (kJ)
R	ideal gas law constant (kJ/(kmol K))
RR	reflux flow rate (kmol/h)
S	splitting ratio of feed flow
T	temperature (K)
TAC	total annual cost ($)
T_I	integral time (h)
U	overall heat transfer coefficient (kW/(m^2 K))
V	vapor flow rate (kmol/h)
V_m	molar volume (m^3/mol)
x	liquid composition
y	vapor composition
z	compressibility factor
z_F	feed composition

Greek letters

β	payback period (year)
ε	error tolerance
λ	element of RGA
ω	acentric factor
τ	stage hydraulics time constant (s)

Superscripts

F	feed
L	liquid phase
sp	product specification
V	vapor phase
t	times of iteration

Subscripts

b	bottom
c	critical state
con	condenser
d	distillate
HP	high pressure
i	component index
j	stage index
LP	low pressure
reb	reboiler

characterized by external heat integration between the whole rectifying section and the whole stripping section of the HP and LP distillation columns, respectively, an asymmetrical EHIDDiC characterized by external heat integration between the top part of the rectifying section and the whole stripping section of the HP and LP distillation columns, respectively, and a simplified asymmetrical EHIDDiC characterized by employing three heat exchangers to represent external heat integration between the HP and LP distillation columns. In terms of the separation of a binary mixture of ethylene and ethane, the three process schemes are thoroughly investigated in terms of their steady and dynamic state behaviors. The intricate relationship between process synthesis and design and process dynamics and controllability is analyzed and some concluding remarks are summarized in the last section of this article.

2. Principle and configuration of the EHIDDiC

For a conventional distillation column, its rectifying section (or the equivalent one in the case of a multiple feed distillation column) releases heat in operation and is thus reasonable to be considered as a potential heat source. On the contrary, its stripping section (or the equivalent one in the case of a multiple feed distillation column) inhales heat in operation and is thus reasonable to be considered as a potential heat sink. Hence, external heat integration can be arranged between the rectifying section and the stripping section of two individual distillation columns. With regard to the necessary temperature driving forces, they can be satisfied with the adjustments of the operating pressure of each distillation column, thus circumventing the employment of an expensive compressor and throttle valve as in the heat pump assisted or internally heat-integrated distillation columns (Nakaiwa et al., 2003; Schmal et al., 2006).

Fig. 1a shows a schematic diagram of the EHIDDiC separating a common mixture in the HP and LP distillation columns involved. It can be noted that the rectifying section of the HP distillation column is stage-to-stage heat-integrated with the stripping section of the LP distillation column. Because of the external heat integration, the reboiler of the LP distillation column and the condenser of the HP distillation column can be simultaneously omitted through the careful adjustment of feed splitting ratio, thereby introducing mass-integration into the EHIDDiC. This offers a possibility of maximizing the potentials of the reduction in operating cost.

3. Alternative configurations of the EHIDDiC

Since the schematic shown in Fig. 1a features an equal number of stages in the rectifying section of the HP distillation column and the stripping section of the LP distillation column, it can only be applied to the separation of some mixtures with specific thermodynamic