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Design and operation of dividing-wall distillation columns. 2. Process dynamics and operation

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ABSTRACT

In the first paper of this series, it was demonstrated that the black-hole problem of dividing-wall distillation columns (DWDCs) could effectively be diminished through over-design in terms of careful adjustment of the number of stages. Because the over-design serves to coordinate the relationship between the prefractionator and main distillation column involved, it yields frequently favorable effect to process dynamics and controllability and this represents essentially an additional advantage of such process modifications to diminish the black-hole problem. The three example systems studied in the first paper of this series are again employed to ascertain the anticipation. The DWDCs with and without the over-design are strictly compared in terms of open- and closed-loop controllability studies. It is found that the over-design helps to coordinate the interaction between the prefractionator and main distillation column involved and leads consequently to improved process dynamics and capabilities in disturbance rejection and set-point tracking. The outcome confirms again the necessity of diminishing the black-hole problem in the synthesis and design of the DWDCs. Though the interpretation is gained from the three example systems studied, it should be considered to be of general significance to the design and operation of the DWDCs.

1. Introduction

For a dividing-wall distillation column (DWDC) separating a ternary mixture, it is frequently found infeasible to greatly boost the purity of its intermediate product from its nominal steady-state value even under the extreme operating condition of an infinite boil-up rate or an infinite reflux ratio [1–5]. This represents essentially a serious drawback of the DWDC and can confine considerably process applicability and flexibility. The strong coupling between the prefractionator and main distillation column involved is responsible for such an unfavorable behavior despite the fact that it also represents the main thrust for the enhancement of thermodynamic efficiency of the DWDC. Recently, we referred to the issue as the black-hole problem of the DWDC and pointed out that it could be diminished through over-design in terms of careful adjustment of the number of stages in the prefractionator and main distillation column involved [6]. Because the adjustment of the number of stages affects the flow rates and compositions of the interlinking flows between the prefractionator and main distillation column involved, it can function as an effective method to compromise the interaction between these two highly integrated units and serve to diminish the black-hole problem of the DWDC (Fig. 1). Although the over-design philosophy was demonstrated to be effective in enhancing the applicability and flexibility of the DWDC, its impact to process dynamics and controllability has remained yet to be studied so far. Since it is also an important issue that influences the applicability and flexibility of the DWDC, it should be studied in great detail.

Since 1990, considerable effort has been dedicated to the studies of the dynamics and control of the DWDCs [7–10]. In particular, open-loop controllability assessment was frequently used to analyze the mass and thermal coupling between the prefractionator and main distillation column involved [11–13]. Hernández and Jiménez conducted detailed comparison between the DWDC and distillation columns with a side rectifier or stripper [14]. They pointed out that although the DWDC needed the lowest utility requirement it exhibited degraded process dynamics and controllability as compared with the distillation columns with a side rectifier or stripper. Serra et al. employed the Morari resiliency index, condition number, relative gain array, and closed-loop disturbance gain as performance indexes to examine the relationship between process synthesis and design and process dynamics and controllability [15,16]. They indicated that the deliberate addition of stages to the DWDC could improve process

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Nomenclature

Symbols

A	Hypothetical component
A_{vp}	Vapor pressure constant, kPa
B	Hypothetical component, benzene, butanol, or bottom product flow rate, mol/s
B_{vp}	Vapor pressure constant, kPa
C	Hypothetical component
CC	Composition controller
CN	Condition number
d	Input signal
D	Distillate flow rate, mol/s
$DRGA$	Dynamic relative gain array
$DWDC$	Dividing-wall distillation column
E	Ethanol
F	Feed flow rate, mol/s
FC	Flow rate controller
G	Process transfer function
k_{off}	Open-loop gain when the rest of loops are open
k_{on}	Open-loop gain when the rest of loops are in automatic
FPD	Final process design
IPD	Initial process design
LC	Level controller
$MASS$	Maximally achievable steady state
$MIMO$	Multiple-input and multiple-output
MRI	Morari resiliency index
n	Dimensionality
NT	Number of stages
P	Propanol or pressure, Pa
PC	Pressure controller
Q	Reboiler heat duty, KW
R	Reflux flow rate, mol/s
SVD	Singular value decomposition
I	Intermediate product flow rate, mol/s
T	Toluene or temperature, K
U	Matrix of output singular vectors
V	Matrix of input singular vectors
y	Process output signal
X	o-Xylene

Greek Letters

α	Relative volatility
σ_1	Minimum singular value
σ_n	Maximum singular value
Σ	Matrix of singular values
λ	Element of RGA
ω	Frequency

Subscripts

A	Component index
B	Component index or bottom product
C	Component index
D	Distillate product
I	Intermediate product
E	Component index
P	Component index
T	Component index
X	Component index

Superscript

s	Saturation

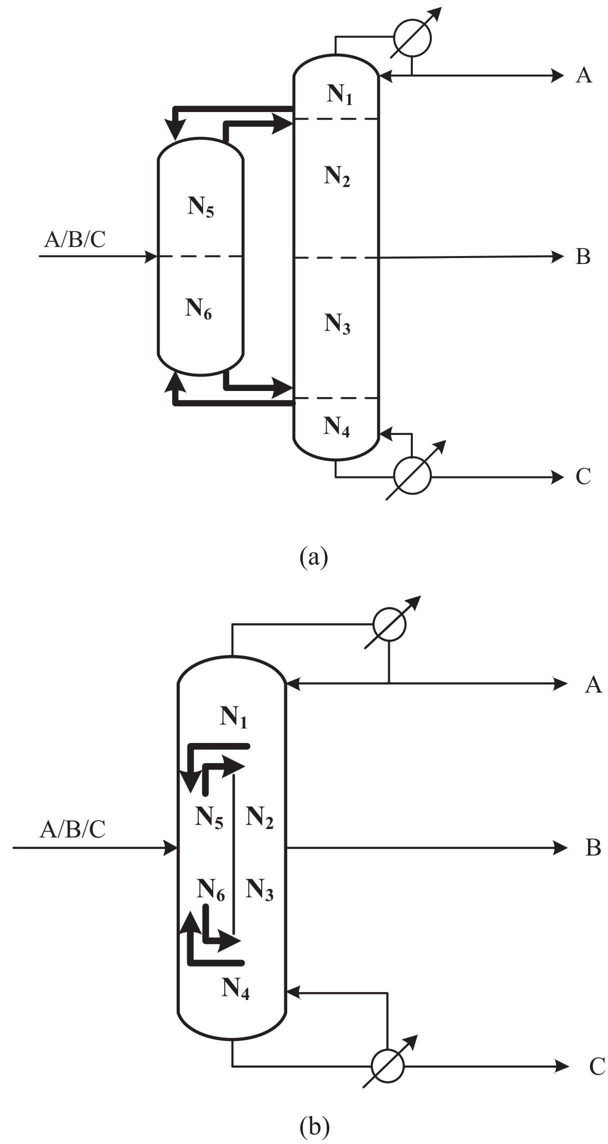

Fig. 1. Sectional stage number and interlinking flows in the Petlyuk distillation column and DWDC (a) Petlyuk distillation column, (b) DWDC.

dynamics and controllability. Regarding the operation of the DWDC, there usually exist two kinds of control configurations, i.e., the three-point and four-point control schemes [1]. In the case of the three-point control scheme, the liquid and vapor split ratios are

Table 1
Physical properties, operating conditions, and product specifications of example I.

Parameter		Value
Condenser pressure (bar)		3.0
Stage pressure drop (bar)		0.0068901
Feed compositions (mol%)	A	33.3
	B	33.3
	C	33.4
Feed flow rate (mol/s)		27.8
Feed thermal condition		1.0
Relative volatility A:B:C		4:2:1
Latent heat of vaporization (kJ/kmol)		29,053.7
Vapor pressure constants	A (A_{vp}/B_{vp})	13.04/3862
	B (A_{vp}/B_{vp})	12.34/3862
	C (A_{vp}/B_{vp})	11.65/3862
Product specifications (mol%)	A	99
	B	99
	C	99