Computers and Chemical Engineering 93 (2016) 372–381

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

# Control structure selection for four-product Kaibel column

Xing Qian[a,b,c,**], Shengkun Jia[a,b], Sigurd Skogestad[c,*], Xigang Yuan[a,b]

[a] School of Chemical Engineering and Technology, Chemical Engineering Research Center, Collaborative Innovation Center of Chemical Science and Engineering, 300350 Tianjin, China
[b] State Key Laboratory of Chemical Engineering, Tianjin University, 300350 Tianjin, China
[c] Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

ARTICLE INFO

*Article history:*
Received 29 March 2016
Received in revised form 5 July 2016
Accepted 18 July 2016
Available online 19 July 2016

*Keywords:*
Dividing wall column
Kaibel column
PID control

ABSTRACT

Dividing wall column configurations have a large savings potential in terms of capital and energy. This paper uses dynamic simulation to investigate three alternative control structures for one of these configurations, namely the Kaibel column. Four components, here selected as methanol, ethanol, *n*-propanol and *n*-butanol, are separated into pure products within a single column shell. Control structure 1 (CS1) uses only temperature controllers and is therefore particularly interesting from an industrial point of view. Since the control objective is to control the four product compositions, the two other control structures use also composition controllers. Surprisingly, for composition control, the simple temperature control scheme (CS1) is almost as good at steady-state and much better from a dynamic point of view than the two other more complex control structures.



## 1. Introduction

Distillation is an important and widely used separation process in the chemical industries. However, distillation is generally an energy- and capital- intensive process. Process intensification technologies are able to reduce both energy and costs (Chu et al., 2011; Dejanovic et al., 2010; Emtir et al., 2001; Hernandez et al., 2003; Kiss, 2014; Staak et al., 2014; Yildirim et al., 2011). Dividing wall columns (DWC), which have been successfully introduced into the process industries, provide a promising trend for process intensifications. It is a single shell, direct material coupling distillation column which needs less energy, capital and space than a conventional column (Triantafyllou and Smith, 1992). Compared with conventional distillation configurations, the energy saving amount of DWCs is up to 30% (Triantafyllou and Smith, 1992). Furthermore, DWCs can be applied to azeotropic, extractive, and reactive distillations, which lead to azeotropic dividing wall columns (ADWC) (Kiss and Suszwalak, 2012; Le et al., 2015; Sun et al., 2011; Wu et al., 2014), extractive dividing wall columns (EDWC) (Kiss and Ignat, 2012; Kiss and Suszwalak, 2012; Tavan et al., 2014; Xia et al., 2012) and reactive dividing wall columns (RDWC) (Delgado-Delgado et al., 2012; Ignat and Kiss, 2013; Kiss et al., 2009; Lee et al., 2012; Qian et al., 2015; Wang et al., 2014).

The main obstruction for DWC industrialization is the fear of operability problems because of its complex structure and interactions among different control loops. Researchers have investigated controllability and operability of Petlyuk column, ADWC, EDWC and RDWC. Mutalib and Smith (Mutalib and Smith, 1998) investigated degrees of freedom in the three-product Petlyuk (dividing wall) column. Halvorsen and Skogestad (Halvorsen and Skogestad, 1999) studied optimal operation and control of the three-product Petlyuk (dividing wall) column. Serra et al. (Serra et al., 2000) studied the influence of design and operating conditions on the dividing wall column by comparing optimal and non-optimal operations. Skogestad et al. (Dwivedi et al., 2013a, 2013b) studied the control of three-product Petlyuk (dividing wall) column and four-product extended Petlyuk (dividing wall) column. Chien et al. (Wu et al., 2013a; Wu et al., 2013b; Wu et al., 2014) investigated the design and control of azeotropic dividing wall columns (ADWC), extractive dividing wall columns (EDWC) and reactive dividing wall columns (RDWC). Xu et al. (Xia et al., 2013; Xia et al., 2012) studied the different control structures for extractive dividing wall columns (EDWC). Yuan et al. (Qian et al., 2015) proposed a reactive dividing wall columns (RDWC) for selective hydrogenation and separation of C3 stream. Buck (Buck et al., 2011) applied model predictive control (MPC) of three-product dividing wall column. Kiss and Rewagad (Kiss and Rewagad, 2011; Rewagad and Kiss, 2012) investigated

* Corresponding author at: Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway.
** Corresponding author at: School of Chemical Engineering and Technology, Tianjin University, Beiyangyuan Campus, Yaguan Road 135, Jinnan District, 300350 Tianjin, China.
*E-mail addresses:* xingqian@tju.edu.cn (X. Qian), skoge@ntnu.no (S. Skogestad).

http://dx.doi.org/10.1016/j.compchemeng.2016.07.019
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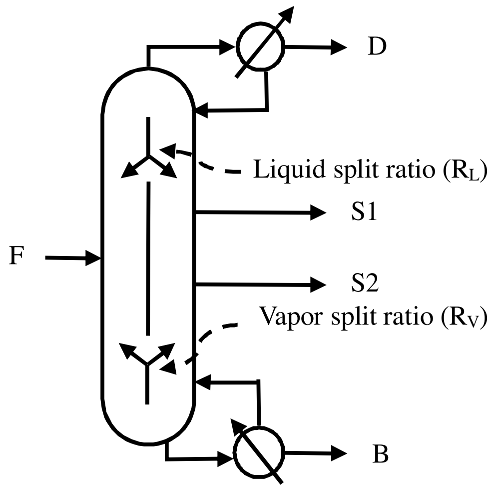


**Fig. 1.** The four-product dividing wall column (Kaibel column).

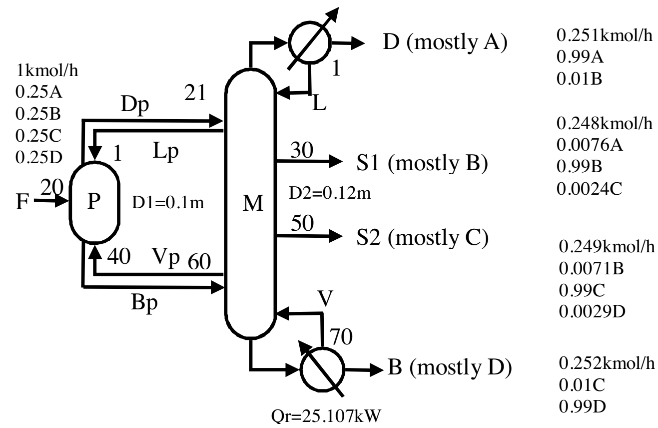


**Fig. 2.** Prefractionator (P) and main section (M) of Kaibel configuration showing theoretical stages in each section (Thermodynamically equivalent to Fig. 1).

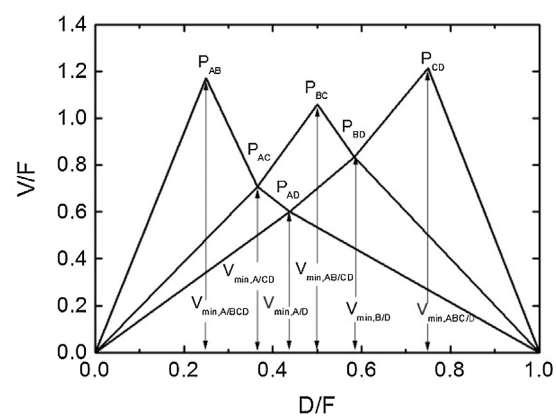


**Fig. 3.** Vmin diagram for sharp separation of equimolar M-E-P-B feed.

traditional PID control and advanced MPC of three-product dividing wall column.

Although researchers have investigated control structures for different DWC configurations, relatively few studies have been done on the four-product Kaibel column in Fig. 1. The four-product Kaibel column is less energy efficient than the four-product extended Petlyuk (dividing wall) column, but it can still save up to 30% energy cost compared to conventional distillation because it performs a sharp split in the prefractionator (Halvorsen and Skogestad, 2003). More importantly, the capital savings can be up to 50% because three conventional distillation columns can be replaced by a single dividing wall column. This paper considers three alternative single-loop PI control structures for a four-product Kaibel column which separates a mixture of methanol, ethanol, *n*-propanol and *n*-butanol. In CS1, only temperature controllers are used. Dwivedi et al. (Dwivedi et al., 2012b) experimentally verified a similar control structure in the lab-scale experiment with good results. Temperature control is faster, more applicable and less expensive than composition control. In CS2, composition controllers are added on top of CS1. The impurity compositions in the outlet streams of distillation columns are controlled in order to retain the main product purity in the product streams. In CS3, the maximum value of light impurity compositions in side product streams and the impurity composition in the bottom stream is controlled by manipulating the reboiler duty. Feedforward controllers are added to accelerate the response and reduce the deviations in the product streams. In addition, control structures CS2 and CS3 use the vapor split as a manipulated variable. The vapor split has so far not been reported as a manipulated variable in industrial scale DWC. However, Dwivedi et al. (Dwivedi et al., 2012a) used the vapor split in the lab-scale experiment with good results, and this may be applied to commercial DWC in the future.

## 2. Process description

The separation of methanol (A), ethanol (B), *n*-propanol (C) and *n*-butanol (D) is used as the case study for the Kaibel column. The feed of 1 kmol/h is equimolar saturated liquid. The approximate relative volatilities for methanol (A), ethanol (B), *n*-propanol (C) and *n*-butanol (D) are 7.1, 4.43, 2.15 and 1, respectively.

The simulations use the two-shell configuration in Fig. 2, which is thermodynamically equivalent to the four-product Kaibel column in Fig. 1. The steady state design was performed with Aspen Plus, and the dynamic simulations were done with Aspen Plus Dynamics. The thermodynamic model uses the NRTL liquid activity equation.

The Vmin diagram in Fig. 3 shows the minimum vapor flows in various sections required for sharp separation of an equimolar A-B-C-D feed. The y-axis shows the minimum boilup (V/F) and the x-axis shows the net product withdrawal (D/F) in a conventional two-product column. The peak $P_{AB}$ gives the minimum vapor flow (V/F) required for separating A and B. Similarly, the point $P_{AD}$ denotes the minimum vapor flow required to separate A and D.

In the two-shell Kaibel configuration in Fig. 2, the prefractionator performs a sharp AB/CD split while the main section completes the A/B and C/D separations. The composition profiles of the prefractionator and the main section are shown in Fig. 4. The specifications for the main component in the four products (D, S1, S2, B) are all 99%. The nominal data for the case study Kaibel column are shown in Table 1.

## 3. Control structures

Before the Aspen Plus steady state simulation results are exported to Aspen Plus Dynamics, the tray sizing feature in Aspen Plus is used to size the column. The reflux drum and the sump of the column are sized to provide 10 min holdup with 50% liquid level space (Luyben, 2013; Luyben and Chien, 2011).

The pressure of the column is controlled with the condenser duty (Qc). The two level controllers use the product streams (D and B) as manipulated variables, which corresponds to a standard "LV-configuration". PI controllers are used in this paper, except P controllers for levels. The gains and integral times of the pressure