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Dynamic Analysis and Controllability of Dividing-Wall Distillation Columns

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This paper reports a dynamic analysis and controllability for the dividing-wall distillation columns (DWCs). In this study the controllability of DWCs using a three-point control structure and reversing loops in the three-point control structure is investigated. To examine the performance of the proposed control system, two illustrative case studies are presented as follows: the separation of ethanol – 1-propanol – 1-butanol mixture and the separation of methanol – ethanol – 1-propanol mixture. Dynamic simulation is performed in the aim to demonstrate that the column handles well the feed flow and feed composition disturbances. The dynamic response of the investigated control strategies shows that DWCs have good controllability properties.

1. Introduction

Distillation is the most common used separation technique in the chemical and petrochemical process industries, but is also the most energy intensive unit operation. To overcome this problem, several heat integrated and fully thermally coupled distillation systems were studied, and it was proved that thermally coupled configurations, such as the dividing-wall distillation columns, are promising energy-alternative solutions. Theoretical studies have shown that DWCs can lead to about 30% energy and capital cost savings compared with conventional distillation systems. Despite the advantages of the DWC, the industry is still reluctant to introduce it on a large scale due to not yet well-established design procedures and fear of control issues (Emtir, et al., 2001). These issues derive from the increased number of DWCs freedom degrees compared to conventional distillation columns. In literature, there are presented just a few studies on the controllability of DWCs (Serra, et al., 2000;Ling and Luyben, 2009; van Diggelen, et al., 2010). In a recent study, Ling and Luyben (2010) studied two types of temperature control structures for the separation of an ideal BTX ternary mixture in a DWC. In another study, Kiss and van Diggelen (2010) investigated more advance control strategies and make a comparison of various control strategies based on PID loops. Commercial simulators, such as HYSYS and Aspen Plus, provide reliable environments for steady-state and dynamic simulation of distillation columns, including conventional PID controllers. A special structure as the DWC can also be implemented using thermodynamic equivalent schemes (Woinaroschy and Isopescu, 2010). This study explores two DWC control strategies based on PID loops. PID controllers have the advantage of a short development time and small development effort.

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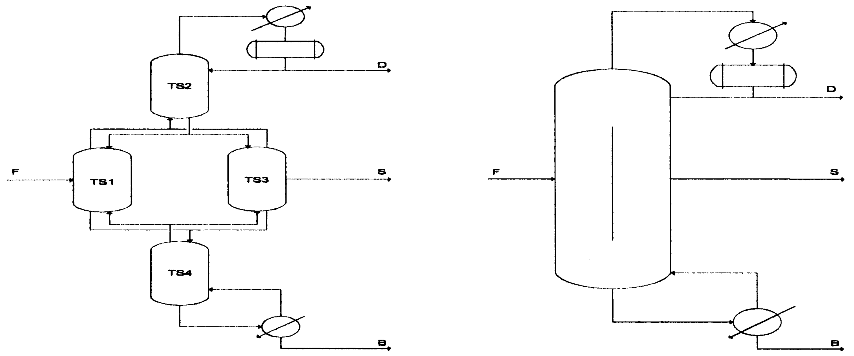

Figure 1. Design structure of the DWC. Four column equivalent scheme (left), DWC structure (right).

2. Dynamic analysis

The key part of the dynamic analysis is the selection of control outputs and manipulated variables for each control loop. For the dynamic simulation and analysis a four column equivalent structure was implemented in HYSYS (Figure 1).

3. Control strategies

The control objective is the purity of all three components (0.99 mole fraction). A DWC has seven degrees of freedom, namely: condenser duty (*Qc*), product rates (distillate *D*, side stream *S*, bottom *B*), reflux rate (*R*), reboiler duty (*Qr*) and the liquid split between the two sections of the column (*LS*). The stability of the column is assured by the levels in the reflux drum, column bottom and top pressure of the column. Typically these are controlled by the distillate (*D*) flow rate or reflux rate (*R*), bottom flow rate (*B*), and condenser duty (*Qc*). The four degrees of freedom left (*S*, *R* (*D*), *Qr* and *LS*) can be used to control four variables. Because composition analyzers are expensive, require high maintenance and introduce deadtime into the control loops, it is desirable to use inferential temperature measurements instead of direct composition measurements.

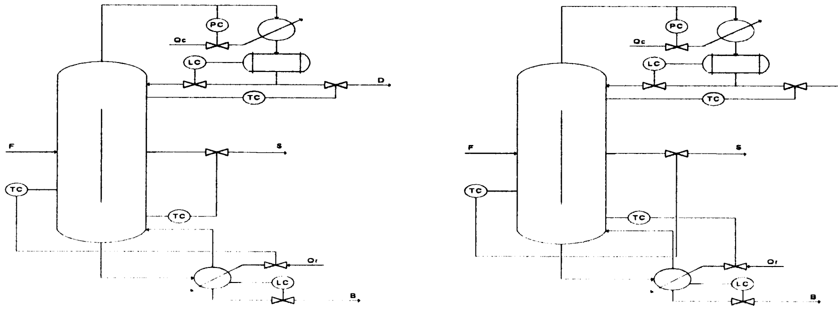

Figure 2. Control structures based on PID loops. Three point control structure (left), Reversing loops in the three point control structure (right).

In this study the controllability of DWCs is investigated using a three point control structure and reversing loops in the three point control structure using temperature measurements (Figure 2).

3.1 Case study 1

In the first case study the separation of the ternary alcohol mixture ethanol (*A*), 1-propanol (*B*) and 1-butanol (*C*) was considered. The design of the DWC was done using HYSYS. General data resulted from the design procedure are presented in Table 1. As controlled variables three temperatures were chosen, as follows: temperature on tray 10 in top section (*10_ (TS2)*), temperature on tray 15 in side draw (*15_(TS3)*) and temperature on tray 9 in bottom section (*9_(TS4)*). For the dynamic simulations performed for this study, disturbances of +10% in the feed flow rate, and +10% in the feed composition (*xA* and *xC*) were used. In the three point control structure the loop pairing is: *10_ (TS2) – D*, *15_ (TS3) – S* and *9_ (TS4) – Qr*. Figures 3 and 4 shows the dynamic results for the three point control structure.

Table 1: General data for Case study 1.

parameters and operating conditions	value
feed flow rate (kmol/h)	100
feed composition (mole fraction)	ethanol, 0.2 1-propanol, 0.6 1-butanol, 0.2
tray number of prefractionator (TS1)	28
tray number of top section (TS2)	18
tray number of side draw (TS3)	28
tray number of bottom section (TS4)	15
feed tray position	14 (TS1)
side draw tray position	6 (TS3)

For the second control structure (reversing loops in the three point control structure) the loop pairing *15_ (TS3) – S* and *9_ (TS4) – Qr* is switched to the alternative pairing *15_ (TS3) – Qr* and *9_ (TS4) – S*. The dynamic results for this control structure are presented in Figures 5 and 6. The results obtained for both control structures are comparable in terms of performance and the system appears controllable.

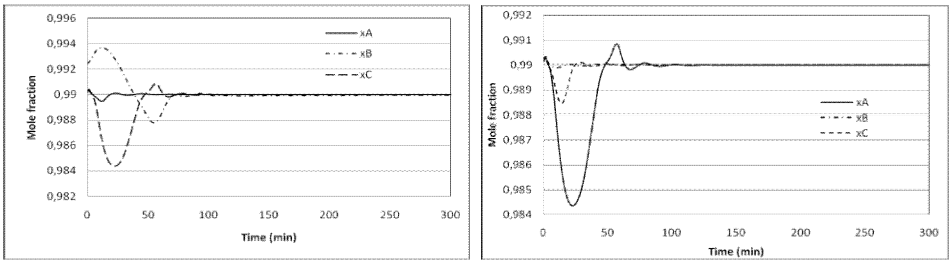

Figure 3. Dynamic response for the three point control structure at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

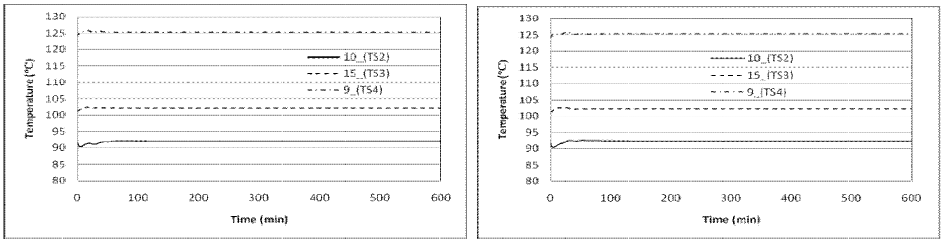

Figure 4. Trends of controlled temperatures at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

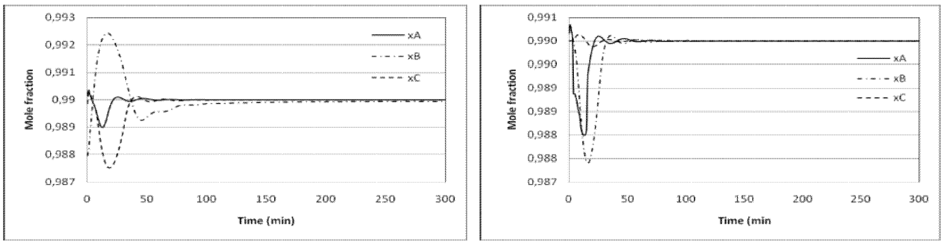

Figure 5. Dynamic response for the reversing loops in three point control structure at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

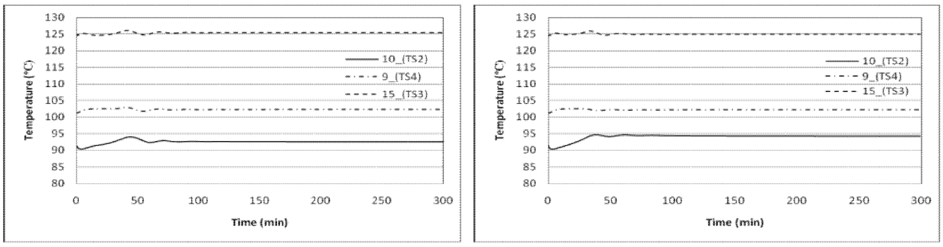

Figure 6. Trends of controlled temperatures at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

3.2 Case study 2

A ternary mixture of methanol (A), ethanol (B) and 1-propanol (C) is separated in a DWC. The design of the DWC and the dynamic simulation for this case study was done in a similar manner as in Case study 1. In Table 2, general data from the design procedure are presented. The selected controlled temperatures are: temperature on tray 8 in top section (8_ *(TS2)*), temperature on tray 21 in side draw section (*21_ (TS3)*) and temperature on tray 6 in bottom section (*6_(TS4)*). The control loops pairing is: *8_ (TS2) – D*, *21_ (TS3) – S*, *6_ (TS4) – Qr* for the three point control structure and *8_ (TS2) – D*, *21_ (TS3) – Qr*, *6_(TS4) – S* for the reversing loops in the three point control structure. As in Case Study 1 the results of the dynamic simulations for both control structures (Figure 7 – 10) shows that the system appears controllable.

Table 2: General data for Case study 2.

parameters and operating conditions	value
feed flow rate (kmol/h)	100
feed composition (mole fraction)	methanol, 0.2 ethanol, 0.6 1-propanol, 0.2
tray number of prefractionator (TS1)	36
tray number of top section (TS2)	15
tray number of side draw (TS3)	36
tray number of bottom section (TS4)	11
feed tray position	18 (TS1)
side draw tray position	18 (TS3)

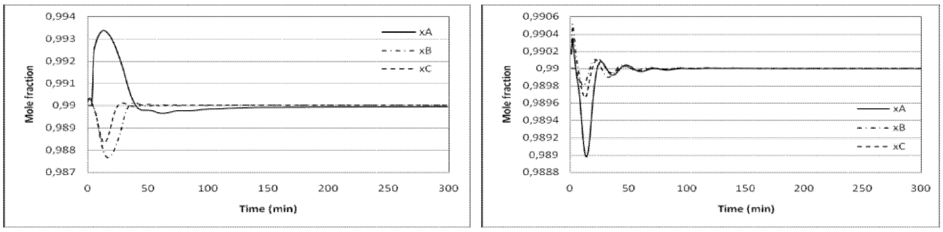

Figure 7. Dynamic response for the three point control structure at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

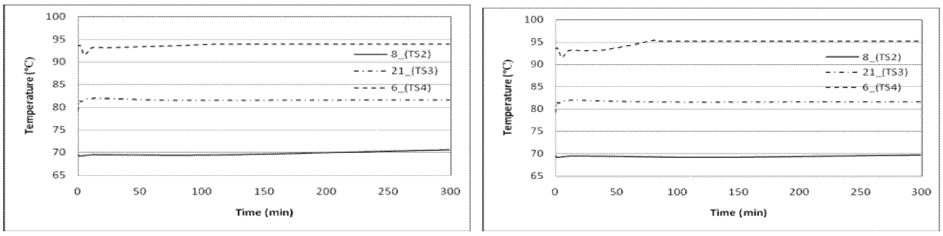

Figure 8. Trends of controlled temperatures at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

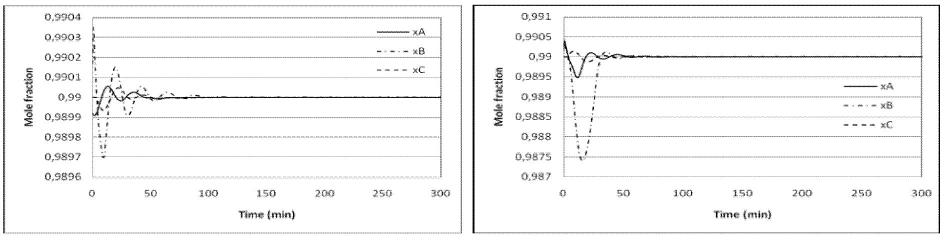

Figure 9. Dynamic response for the reversing loops in three point control structure at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

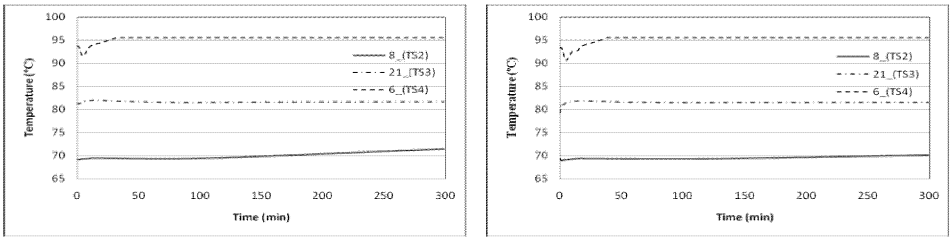

Figure 10. Trends of controlled temperatures at a disturbance of +10% in the feed flow rate (left) and +10% xA, xC in the feed composition (right).

4. Conclusions

In this study, the controllability of DWCs was investigated using two control strategies based on PID loops. The dynamic simulation results for the investigated case studies demonstrate that both control structures can handle well persistent disturbances in feed flow rate and feed composition. Also, the results indicate that simple PID controllers can provide reasonable control. Moreover, it can be concluded that DWCs have good control properties.

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