

## DYNAMIC ANALYSIS AND CONTROLLABILITY OF DIVIDING-WALL DISTILLATION COLUMNS USING A FOUR POINTS CONTROL STRUCTURE

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*Lucrarea prezintă analiza dinamică și de controlabilitate pentru coloanele de rectificare cu perete de divizare (DWC). Controlabilitatea coloanelor de rectificare cu perete de divizare este investigată utilizând o structură de control cu patru puncte. În scopul evaluării performanței structurii de control propuse este abordată separarea unui amestec neideal format din metanol – etanol – 1-propanol. Simularea dinamică este efectuată în scopul demonstrării stabilității sistemului în cazul perturbațiilor debitului de alimentare și ale compoziției acestuia. Rezultatele obținute pentru strategia de control investigată indică eficiența controlului colonelor de rectificare cu perete de divizare.*

*The paper reports a dynamic analysis and controllability for dividing-wall distillation columns (DWCs). The controllability of DWCs is studied using a four points control structure. The performance of the proposed control structures was investigated for the case study of a nonideal methanol – ethanol – 1-propanol mixture separation. Dynamic simulation is performed in order to demonstrate that the column handles well the feed flow and feed composition disturbances. The dynamic response of the investigated control strategy shows that DWCs have good controllability properties.*

**Keywords:** dividing-wall distillation columns, feedback control, dynamic analysis

### 1. Introduction

Distillation systems require substantial amounts of energy and their design must be approached with energy conservation in mind. Therefore many efforts have been focused on the development of energy efficient solutions and several heat integrated and fully thermally coupled distillation systems were studied. 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

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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 [1]. These issues derive from the increased number of DWCs freedom degrees compared to conventional distillation columns. Therefore, the control of DWCs is more difficult compared to the control of a two-column separation sequence. In literature, there are presented few studies on the controllability of DWCs [2 – 7]. 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 [8]. Triantafyllou and Smith [9] developed a design procedure based on a three-column model. In their model, the final structure has to be iteratively adjusted, as the number of trays on both sides of the dividing wall must be the same. This problem also arises when a commercial simulator is used to establish the final column topology. Kim [10] developed a structural design methodology for full thermally coupled distillation columns based on minimum tray structure to give high-energy efficiency. The operational complexity of a DWC derives from the increased number of freedom degrees as compared to a simple column with a side draw. Halvorsen and Skogestad [11] found that the liquid and vapor split ratios, considered as two additional freedom degrees, are important for the thermal efficiency of the DWC. In their work, Wang and Wong [12] found that for a column with finite number of stages the energy efficiency of the design depends on the designed values of the liquid and vapour splits. In a recent study, Ling and Luyben [13] 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 [14] investigated more advance control strategies and made a comparison of various control strategies based on PID loops, within a multi-loop framework (DB/LSV, DV/LSB, LB/DSV, LV/DSB) versus more advanced controllers such as LQG/LQR and high order controllers obtained by  $H_\infty$  controller synthesis and  $\mu$ -synthesis.

In the present work the design of the DWC was made in the frame of HYSYS process simulator and the control properties of DWC were investigated using a four points control structure, based on PID loops with inferential temperature measurements. PID controllers have the advantage of a short development time, and small development effort. Because composition analyzers are expensive, requiring high maintenance and introducing deadtime into the control loops, inferential temperature measurements are used, instead of direct composition measurements.

## 2. Design of DWC using HYSYS

DWC is not available as a standard unit operation in HYSYS. This structure can be implemented using equivalent schemes. To establish the initial configuration of the DWC (number of trays in each section of the DWC, feed tray, side-draw and the position of interlinking vapor and liquid streams), a short-cut design option available in HYSYS process simulator was used. This is based on Fenske-Underwood-Gilliland-Kirkbride equations. This structure is largely used in the design step, as generally mentioned in the literature [9]. To develop the short-cut design method the dividing-wall distillation column is divided into three sections (Fig. 1). Section 1 corresponds to the prefractionator, and section 2 and 3 correspond to the main column [15]. A four column equivalent structure was derived and modified from this initial design by repeated rigorous simulation (Fig. 2), in order to achieve purity requirements (0.98 mole fraction) and minimum energy consumption. The corresponding final design of the DWC structure can be used for dynamic simulations, due to its capabilities of reflecting the internal streams and geometrical characteristics of the tray sections [8].

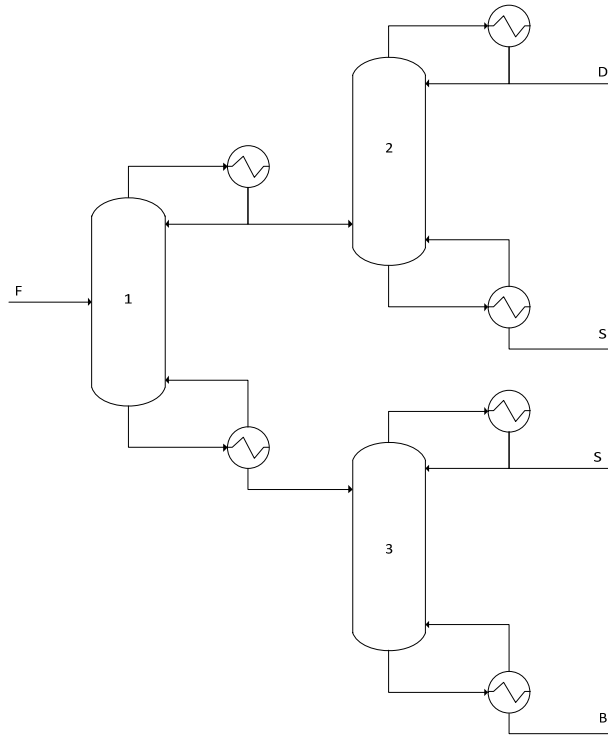


Fig. 1. Three column short-cut model

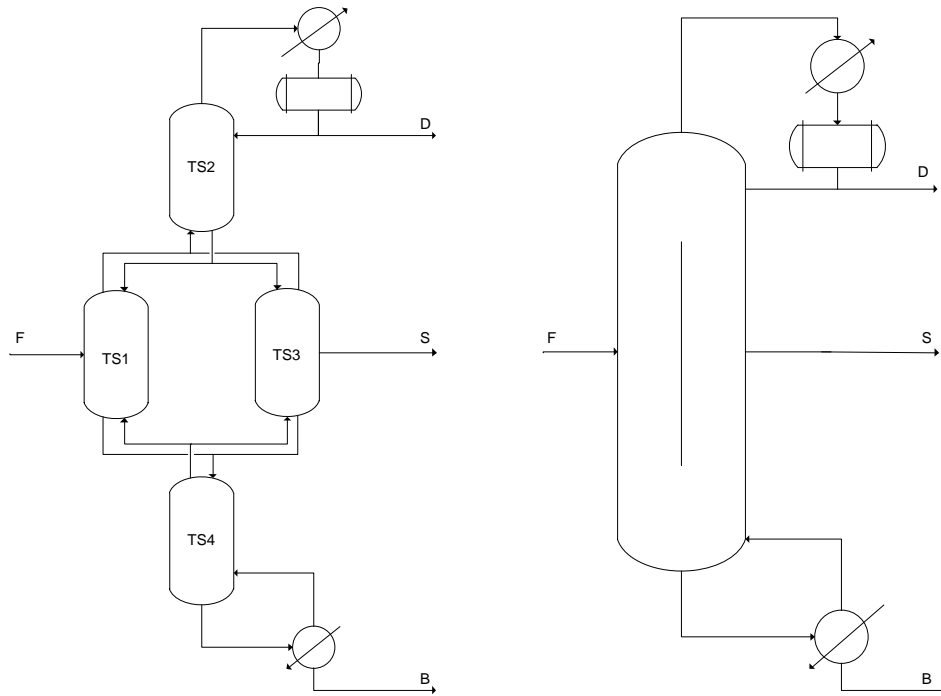


Fig. 2. Design structure of the DWC. Four column equivalent structure (left) and DWC Structure

#### 4. Control strategy

The main objective of the control strategy consists in the column products purity (0.98 mole fraction). The key part of the dynamic analysis is the selection of the control outputs and manipulated variables. In a previous work, Halvorsen and Skogestad [11] identified the following five manipulated variables: condenser duty ( $Q_R$ ), reflux rate ( $R$ ), side rate ( $S$ ), vapor ( $VS$ ) and liquid ( $LS$ ) splits. In their work, Mutalib and Smith [16] have introduced the degrees of freedom analysis, showing that the DWCs have a more complex structure compared with side draw columns. They also investigated the impact of vapour and liquid split on column control. The vapour split ratio is free to adjust by imposing the same pressure drop on both sides of the DWC, therefore the  $VS$  is not considered as a manipulated variable. A DWC has seven degrees of freedom: condenser duty ( $Q_c$ ), product rates (distillate  $D$ , side stream  $S$ , bottom  $B$ ), reflux rate ( $R$ ), reboiler duty ( $Q_r$ ) 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, and by the column bottom and top pressures. Typically, these are controlled by the distillate ( $D$ ) flow rate or

reflux rate ( $R$ ), bottom flow rate ( $B$ ), and condenser duty ( $Q_c$ ). The four degrees of freedom left ( $S$ ,  $R$  ( $D$ ),  $Q_r$  and  $LS$ ) can be used to control four variables. In this study, the controllability of DWCs is investigated using a four points control structure by performing temperature measurements (Fig. 3).

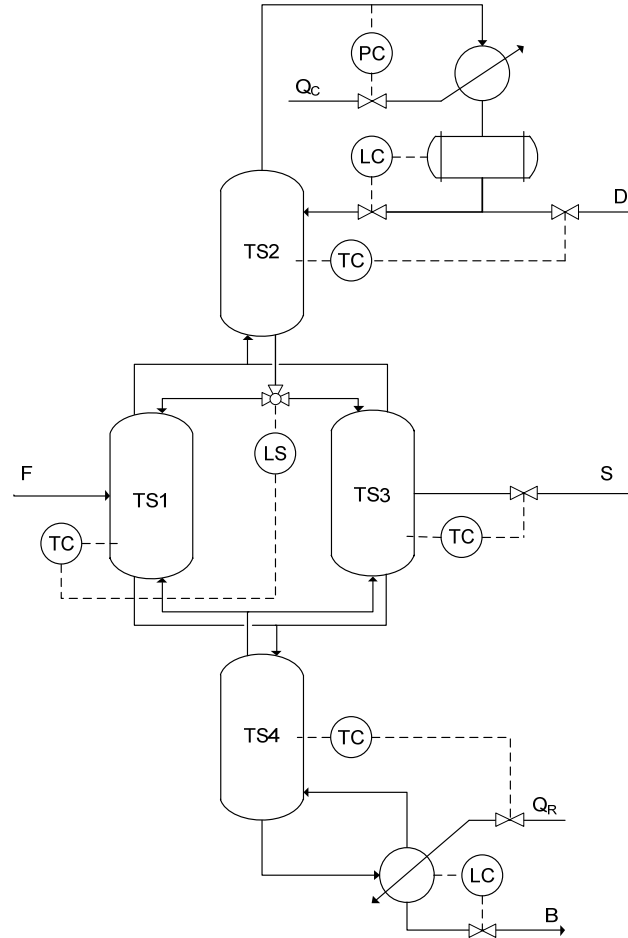


Fig. 3. Four points control structure

## 5. Case study

The separation of a ternary nonideal alcohol mixture, *i.e.*, methanol – ethanol – 1-propanol was considered. The design of the DWC was done using HYSYS as described previously. General data resulted from the design procedure are presented in Table 1. As controlled variables, four temperatures were chosen,

as follows: temperature on tray 11 in prefractionator ( $11_{(TS1)}$ ), temperature on tray 8 in top section ( $8_{(TS2)}$ ), temperature on tray 21 in side draw ( $21_{(TS3)}$ ) and temperature on tray 6 in bottom section ( $6_{(TS4)}$ ). The method used to select the best location for temperature measurements for control is based on the column temperature profile analysis. The best locations are determined by analyzing the response of the temperature profile to changes made in the liquid and vapor flows inside the column. For the dynamic simulations, disturbances of  $\pm 10\%$  in the feed flow rate, and  $\pm 10\%$  in the feed composition ( $x_A$  and  $x_C$ ) were used. In the four points control structure the loop pairing is:  $11_{(TS1)} - LS$ ,  $8_{(TS2)} - D$ ,  $21_{(TS3)} - S$  and  $6_{(TS4)} - Qr$ .

Table 1

General data for case study

Parameters and operating conditions	Value
Feed flow rate (kmol/h)	100
Feed composition	methanol, 0,2 ethanol, 0,6 1-propanol, 0,2
Side draw flow rate (kmol/h)	60
Thermal state of the feed stream	liquid at boiling temperature
Thermal state of the side-draw stream	liquid at boiling temperature
Condenser type	total
Pressure in top of the column and in condenser (bar)	1
Reflux ratio	9
Reboiler type	total
Reboiler heat duty (kWh)	2938
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 (TS1)

Figs. 4 and 6 show the dynamic results of the four points control structure at a disturbance of  $\pm 10\%$  in the feed flow rate. The trends of controlled temperatures at a disturbance of  $\pm 10\%$  in the feed flow rate are presented in Figs. 5 and 7. The dynamic simulation show no control problems for feed flow disturbances and the three product purities return to their desired values after a relatively short settling time. Figs. 8 and 10 show the dynamic response of the control structure for  $\pm 10\%$   $x_A$  and  $x_C$  disturbances in feed composition. In Figs. 9 and 11 the trends of the controlled temperatures at disturbances of  $\pm 10\%$   $x_A$  and  $x_C$  are presented. When feed composition is changed, the response of product purities is quite different. However, product purities are returning to their desired values.

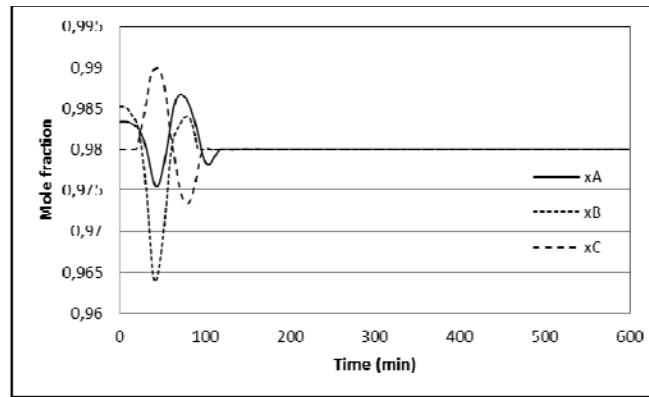


Fig. 4. Dynamic response of the four points control structure at a disturbance of +10% in the feed flow rate

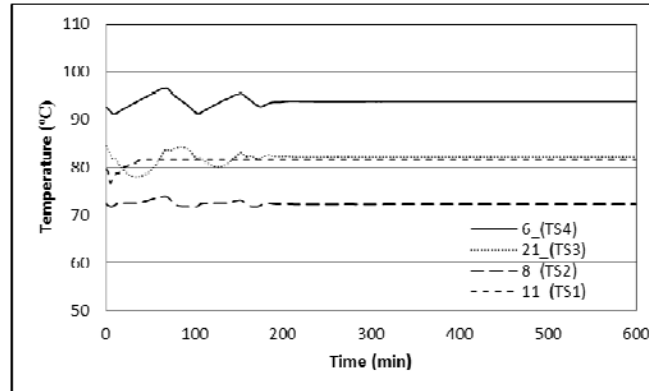


Fig. 5. Trends of controlled temperatures at a disturbance of +10% in the feed flow rate

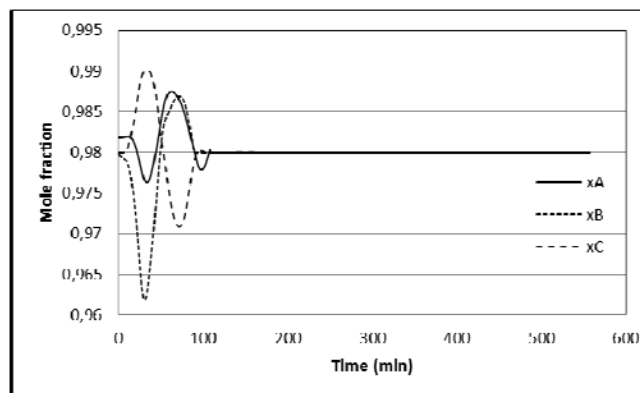


Fig. 6. Dynamic response of the four points control structure at a disturbance of -10% in the feed flow rate

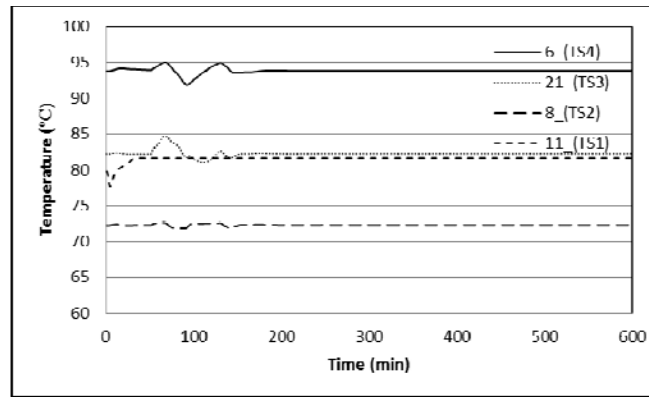


Fig. 7. Trends of controlled temperatures at a disturbance of -10% in the feed flow rate

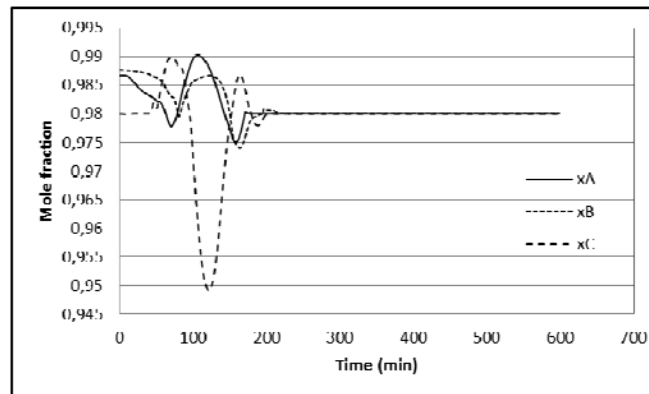


Fig. 8. Dynamic response of the four points control structure at a disturbance of +10% xA and xC in the feed composition

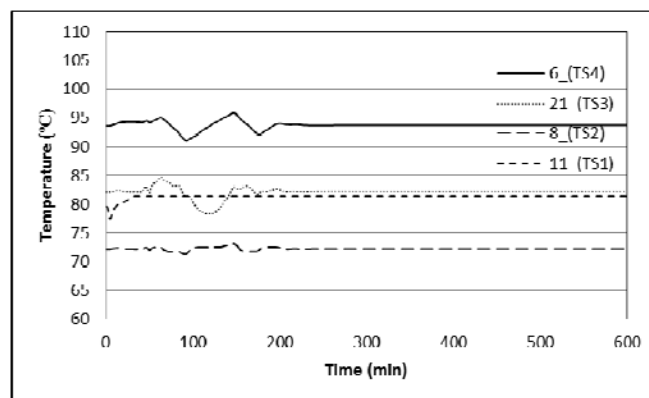


Fig. 9. Trends of controlled temperatures at a disturbance of +10% xA and xC in the feed composition



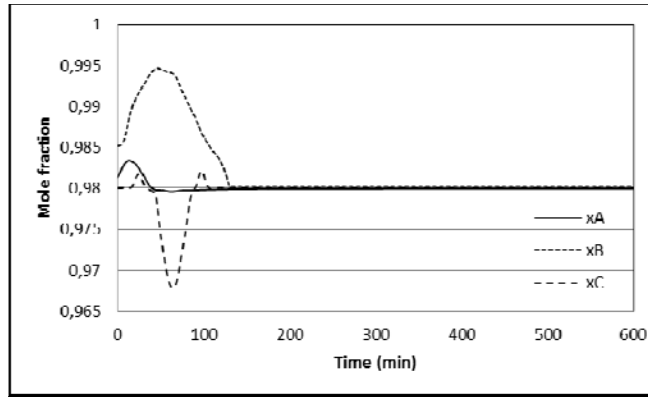


Fig. 10. Dynamic response of the four points control structure at a disturbance of -10%  $x_A$  and  $x_C$  in the feed composition

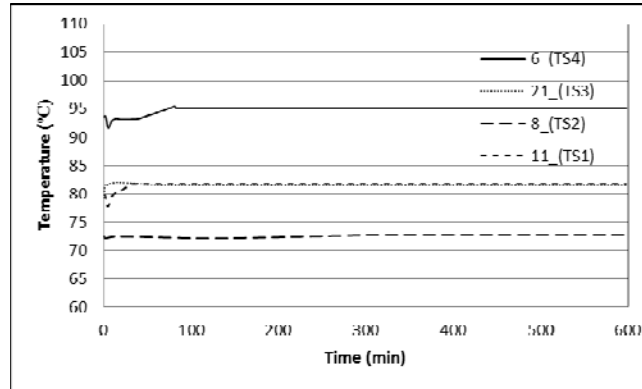


Fig. 11. Trends of controlled temperatures at a disturbance of -10%  $x_A$  and  $x_C$  in the feed composition

## 5. Conclusions

In this work, the controllability of DWCs was investigated using a four points control structure based on PID loops using temperature measurements.

In order to test the performance of the control structure, the case study of separation of a ternary nonideal methanol – ethanol – 1-propanol mixture in a DWC was taken in consideration.

The results of the dynamic simulation for the investigated case study demonstrate that the system appears to be controllable and the proposed control structure can handle well persistent feed flow rate and feed composition disturbances. The control scheme gives a stable dynamic response in product compositions for the assumed feed flow and feed composition disturbances.

In addition, the results indicate that PID controllers provide reasonable control, and may be successfully used. Moreover, one can conclude that DWCs have good control properties.

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