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IMPROVED CONTROL STRATEGIES FOR DIVIDING-WALL COLUMNS

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Abstract
This study investigates the controllability of dividing-wall columns (DWC) and makes an ample comparison of various control strategies based on PID loops, within a multi-loop framework (DB, DV, LB, LV) versus more advanced controllers such as LQG/LQR and high order controllers obtained by H_∞-controller synthesis and μ-synthesis. All these controllers are applied to a DWC used in an industrial case study – the ternary separation of benzene-toluene-xylene. The performance of these control strategies and the dynamic response of the DWC is investigated in terms of products composition and flow rates, for various persistent disturbances in the feed flow rate and feed composition. Significantly shorter settling times can be achieved using the advanced controllers based on LQG/LQR, H_∞ and μ-synthesis.

Keywords: DWC control, multi-loop PID controller, LQG/LQR, H_∞ and μ-synthesis

1. Introduction

Distillation remains among the most important separation technologies in the chemical industry. However, in spite of the flexibility and the widespread use, one important drawback is the considerable energy requirements, as distillation can generate more than 50% of plant operating costs. An innovative way out is using advanced process integration techniques. Conventionally, a ternary mixture can be separated via a direct sequence (most volatile component is separated first), indirect sequence (heaviest component is separated first) or distributed sequence (mid-split) consisting of 2-3 distillation columns. In the last decades, ternary separations progressed via thermally coupled columns such as Petlyuk configuration to a novel design that integrates two columns into one shell – a setup known today as dividing-wall column.[1] DWC offers the following key benefits: high purity for all three or more product streams reached in only one column, high thermodynamic efficiency due to reduced remixing effects, lower capital investment due to the integrated design, lower energy requirements compared to conventional separation sequences, and small footprint due to the reduced number of equipment units. The DWC concept is a major breakthrough in distillation technology, as it brings significant reduction in the capital invested as well as major savings in the operating costs, up to 25–40%.[2-3] Figure 1 illustrates the ternary separation alternatives using Petlyuk and DWC.

This study explores various DWC control strategies based on PID loops, within a multi-loop framework versus more advanced controllers. The controllers are applied to an industrial DWC used for the ternary separation of benzene-toluene-xylene. The performance of these control strategies is investigated in terms of products composition and flow rates, for various persistent disturbances.

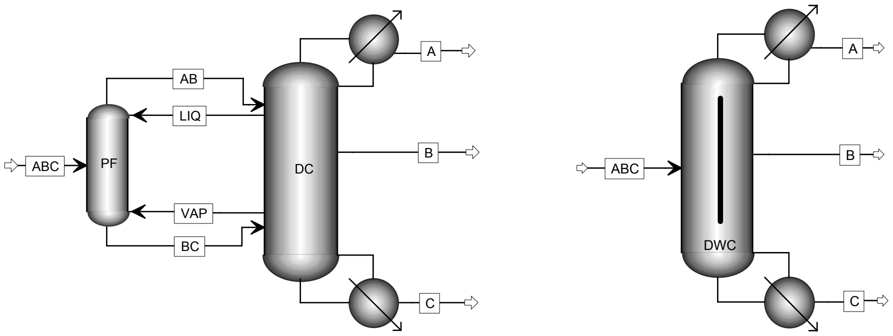

Figure 1. Petlyuk configuration (left). Dividing-wall column (right).

2. Problem statement

The integration of two columns into one shell leads also to changes in the operating mode and ultimately in the controllability of the system. Although much of the literature focuses on the control of binary distillation columns, there are just a few studies on the controllability of DWC.[4-6] The problem is that different DWC separation systems were used hence no fair comparison of controllers is possible. To solve this problem, we explore the issues of DWC control on a single separation system and compare various multi-loop PID control strategies versus more advanced controllers – such as LQG/LQR, GMC, and high order controllers based on the H_∞ norm μ-synthesis[7] – ultimately finding an improved DWC control strategy.

3. Dynamic model

Several reasonable simplifying assumptions were made: 1. constant pressure, 2. no vapor flow dynamics, 3. linearized liquid dynamics and 4. neglected energy balances and enthalpy changes. The dynamic model of the DWC is implemented in Mathworks Matlab combined with Simulink and it is based on the Petlyuk model previously reported in literature by Halvorsen and Skogestad.[8] A rigorous steady-state simulation was also developed in AspenPlus to validate the assumptions of the model. Figure 2 illustrates the simulated dividing-wall column. The column is divided into six sections, each containing 8 trays, with a total of 32 trays in the main column and 16 in the prefractionator side. When disturbances are not present, the feed flowrate is assumed to be F=1, feed condition q=1 (saturated liquid) and equimolar compositions of A, B and C in the feed.

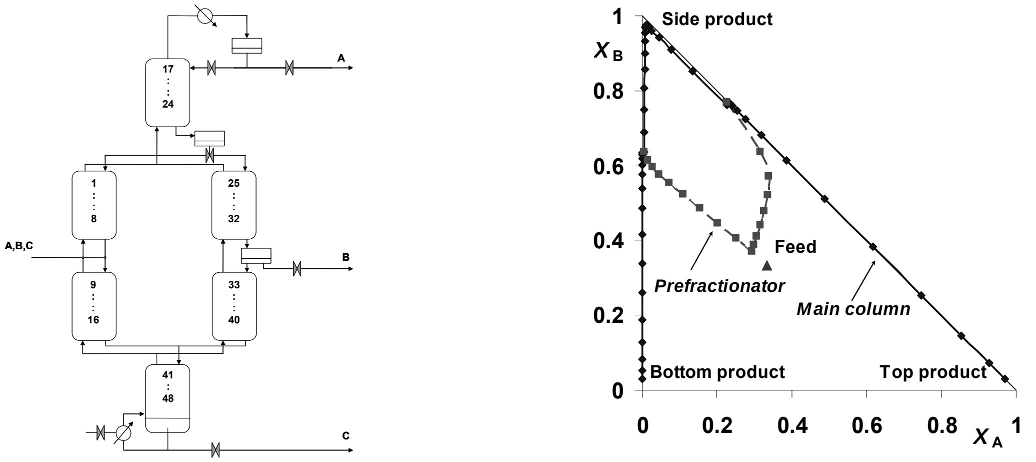

Figure 2. Schematics of the simulated DWC (left). Composition profiles inside the DWC (right).

4. Control strategies

PID loops within a multi-loop framework. The most used controllers in industry are the PID controllers. In case of a DWC, two multi loops are needed to stabilize the column and another three to maintain the setpoints specifying the product purities. As there are six actuators (D S B L_0 V_0 R_L) using PID loops within a multi-loop framework, many combinations are possible. However, there are only a few configurations that make sense from a practical viewpoint. The level of the reflux tank and the reboiler can be controlled by the variables L_0, D, V_0 and B respectively. Hence, there are four inventory control options to stabilize the column, the combinations: D/B, L/V, L/B and V/D to control the level in the reflux tank and the level in the reboiler. Figure 3 illustrates the control structures based on multi-loop framework of PIDs.

Linear Quadratic Gaussian control (LQG) is a combination of an optimal controller LQR and optimal state estimator (Kalman filter) based on a linear state-space model with measurement and process noise. LQG is an extension of the optimal state feedback that is a solution of the *Linear Quadratic Regulation* (LQR) which assumes no process noise and availability of the full state for control. An additional feed-forward controller can be added or LQG can be extended with an integral action.

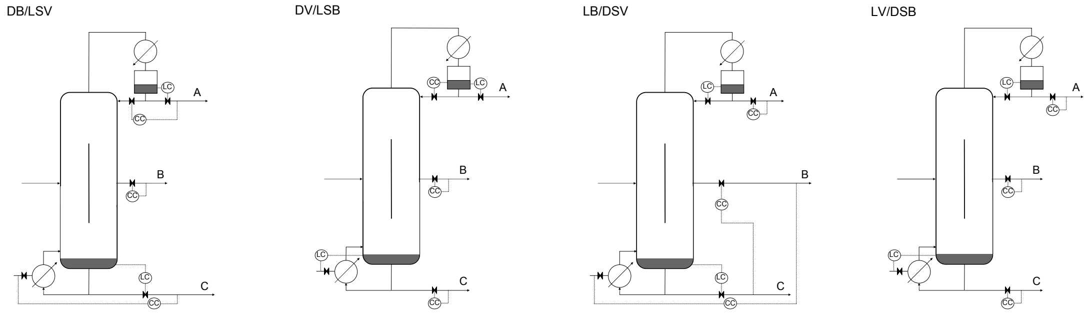

Figure 3. Control structures based on PID loops within a multi-loop framework.

Multivariable controller synthesis. Two advanced controller synthesis methods were used in order to obtain a robust controller: *loop shaping design procedure* (LSDP) and the *μ-synthesis* procedure. In contrast to previous studies, the inventory control and regulatory control problems are solved simultaneously in this work.

5. Results and discussion

In this work, we use the ternary mixture benzene-toluene-xylene (equivalent to A, B, C) and the purity setpoints [0.97 0.97 0.97] for the product specifications. For the dynamic simulations performed in this study, disturbances of +10% in the feed flow rate (F) and +10% in the feed composition (xA) were used, as these are among the most significant ones at industrial scale. Note that persistent disturbances give a better insight of the quality of the controller than zero mean disturbances, as typically after a temporary disturbance the product compositions return to their given setpoints. Moreover, the effect of measurement noise on the control performance was also investigated.

As shown next by the results of the dynamic simulations, all PI control structures cope well with persistent disturbances. The PI control structure LB/DSV controls the DWC in a similar timescale to DB/LSV. The disturbances resulting from the changes in the nominal feed are controlled away; showing only a small overshoot in the product purities; less than 0.02 for both cases. However, the control structure DV/LSB and LV/DSB make the DWC return to steady state only after a long settling time (>1000 min).

Note that the RGA analysis clearly distinguishes between the LV/DSB and DB/LSV control structures, where the DB/LSV option is preferable to LV/DSB. The pairing x_A-V and x_B-V is predicted and also proved to be more effective than x_B-L and x_C-L.

The LQG controller with feed forward control has only good results for disturbances in the feed flowrate. For other disturbances the tuning of the feed forward terms is less straightforward. The controller has no feedback on the error term that is the difference of the setpoints and the measured values. As a result offset in the product purities appears. This problem is solved by combining the LQG controller with an integral term (Figure 4).

A stop criterion is used for all test cases in order to have a fair comparison of the controllers – the simulation is stopped if the condition $||(x_A,x_B,x_C) - (0.97,0.97,0.97)||^2 < 1e^{-10}$ holds at time t_1 and also holds at time $t_2=t_1 + 40$ min, where $t_1<t_2$. The dynamic responses of the DWC at persistent disturbances – smaller settling times meaning better control – are shown in the next figures (5-12).

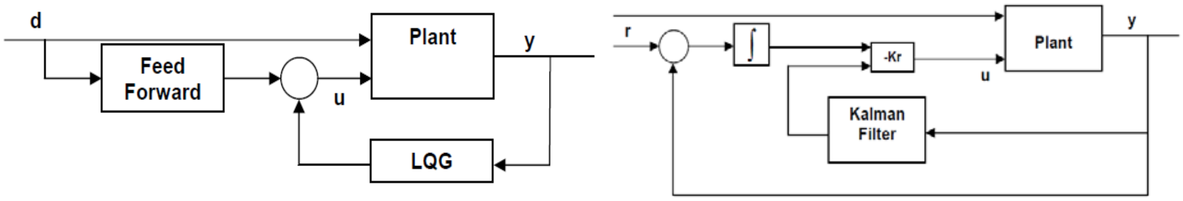

Figure 4. LQG controller with feed-forward (left), or extended with integral action (right).

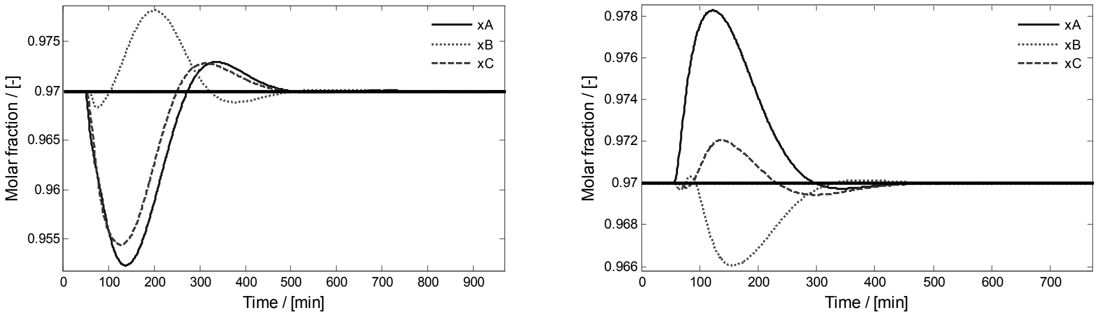

Figure 5. Dynamic response of the DB/LSV control structure, at a persistent disturbance of +10% in the feed flow rate (left) and +10% x_A in the feed composition (right).

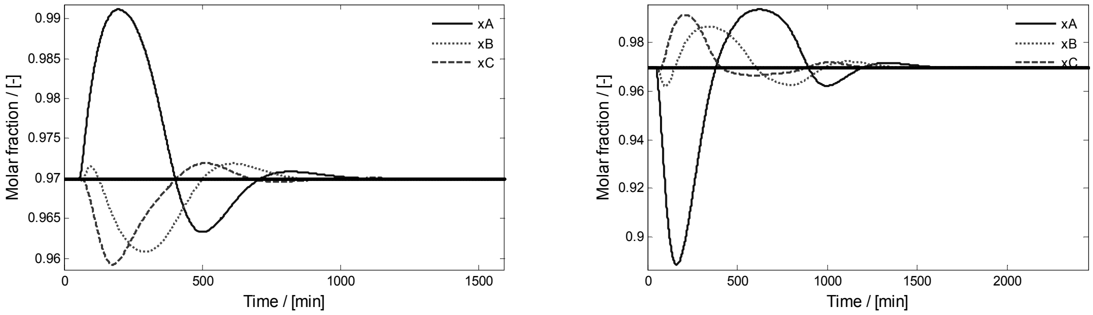

Figure 6. Dynamic response of the DV/LSB control structure, at a persistent disturbance of +10% in the feed flow rate (left) and +10% x_A in the feed composition (right).

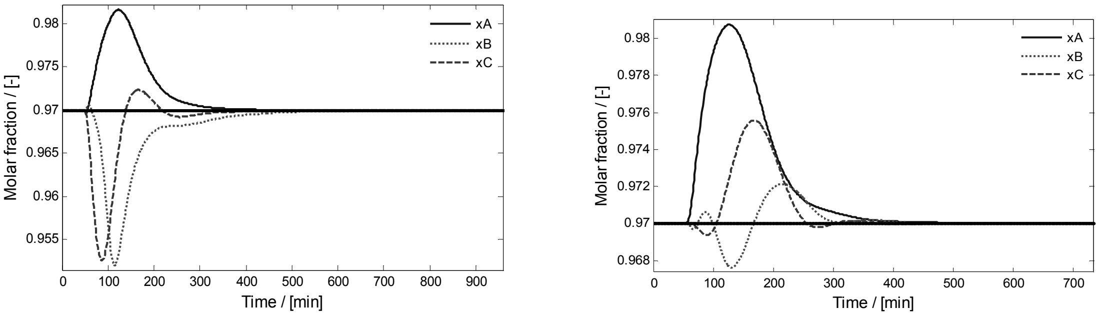

Figure 7. Dynamic response of the LB/DSV control structure, at a persistent disturbance of +10% in the feed flow rate (left) and +10% x_A in the feed composition (right).

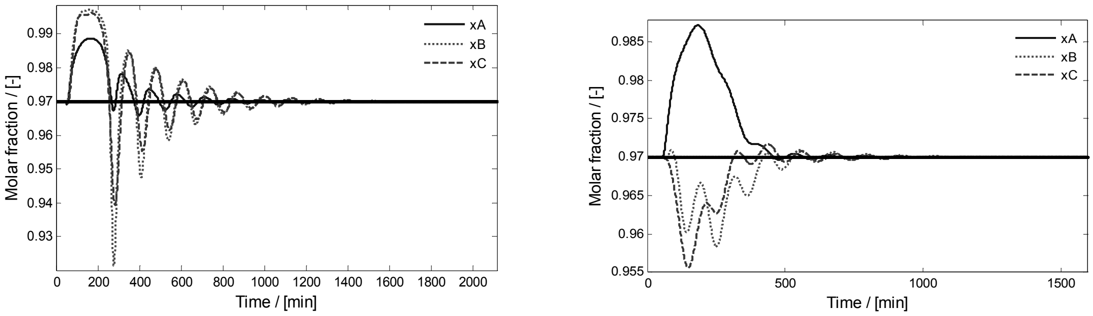

Figure 8. Dynamic response of the LV/DSB control structure, at a persistent disturbance of +10% in the feed flow rate (left) and +10% x_A in the feed composition (right).

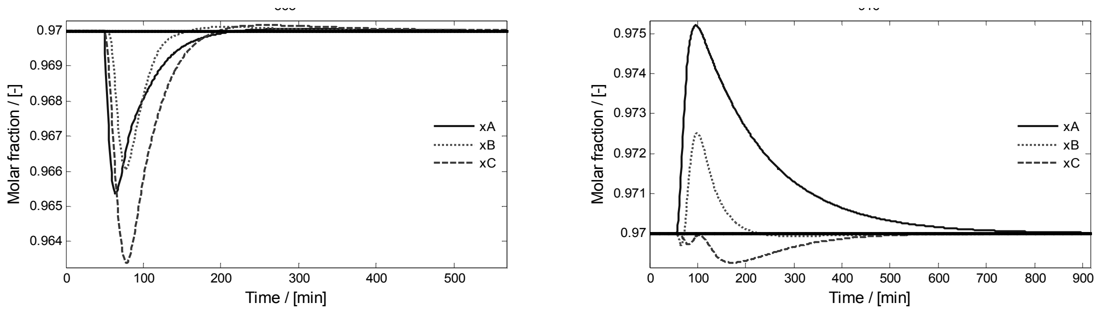

Figure 9. Dynamic response of the LQG controller combined with integral action, at a persistent disturbance of +10% in the feed flow rate (left) and +10% xA in the feed composition (right).

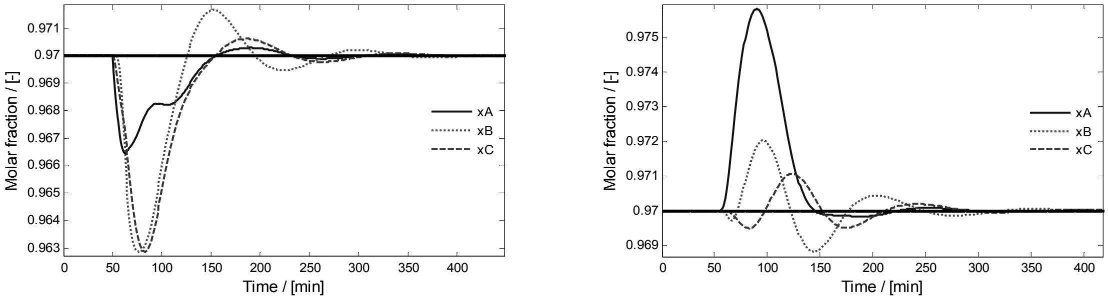

Figure 10. Dynamic response of the LSDP-controller, at a persistent disturbance of +10% in the feed flow rate (left) and +10% xA in the feed composition (right).

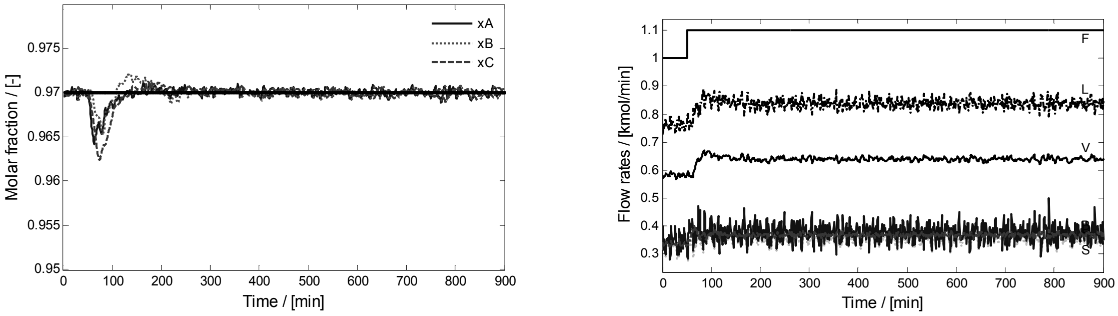

Figure 11. Dynamic response of the μ-controller, at a persistent disturbance of +10% at t=50min in the feed flow rate while there is white measurement noise and a time delay.

The dynamic simulations show no control or stability problems of the closed loop system. Furthermore, there is a trade off between a short settling time in the case of no measurement delay and noise, and a very smooth control action in case of measurement noise. A short settling time results in a more chaotic control if noise is present.

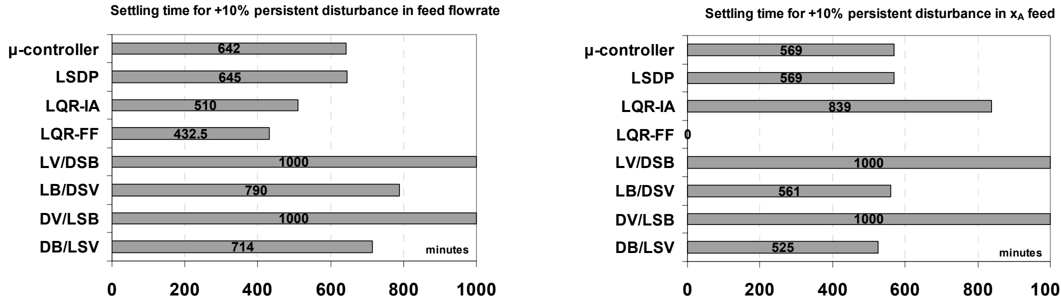

Figure 12. Settling time for +10% disturbance in the feed flow rate and X_A in the feed.

6. Conclusions

The advanced control strategies presented in this work were applied to a DWC separating the ternary mixture benzene-toluene-xylene. The results provide significant insight into the controllability of DWC, and gives important guidelines for selecting the appropriate control structure. The dynamic model of the DWC used in this study is not a reduced one, but a full-size non-linear model that is representative for industrial separations. Due to practical considerations based on the physical flows, there are basically four control strategies possible based on PID loops within a multi-loop framework: DB/LSV, LB/DSV, DV/LBS, LV/DSB. The results of the dynamic simulations show that the first two are the best among the decentralized multivariable PI structured controllers, being able to handle persistent disturbances in short times.

The DWC model is not only non-linear but also a true multi-input multi-output (MIMO) system, hence the applicability of a MIMO control structure starting with a LQG controller was also investigated. Two options were explored: feed forward control and addition of an integral action. The LQG-FF controller has good results for a persistent disturbance in the feed flowrate. However, for changes in the feed composition and condition it is difficult to find a good tuning. Moreover, persistent disturbances other than the ones used for tunning cannot be controlled with LQG. Nevertheless, combining LQG with an integral action and reference input solves the problem. Moreover, robustness against measurement noise results in a more conservative tuning.

The loop-shaping design procedure (LSDP) used in this work leads to a feasible μ-controller that has some additional benefits, while specific model uncertainties can be incorporated in the control structure. However, reduction of the LSDP controller is not possible since the reduced controller is unable to control the column. In contrast, the μ-controller can be reduced while still having a good control performance. In the DWC case described here, the obtained μ-controller is able to minimize the settling time when handling persistent disturbances. While PI control structures are also able to control the DWC, significantly shorter settling times can be achieved using MIMO controllers. Moreover, persistent disturbance are efficiently controlled using a MIMO controller.

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