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On Controllability of Four-Product Dividing Wall Columns

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Although potential for reduction of energy requirement and related carbon dioxide emissions is highly attractive – around 50% compared to conventional three column sequences – process industries are still reluctant to consider implementation of four products fully thermally coupled dividing wall columns, mainly due to concerns related to controllability of two or three vapor splits as encountered in complex DWC arrangements. This paper presents results of a simulation study that could bring some relief in this respect, indicating that a temperature-driven control structure, in conjunction with very tight control of temperature profiles in prefractionation section, as well as in the product draw regions of the column, is capable of restoring the operation to health from typical disturbances in feed quality.

1. Introduction

Carbon dioxide emission reduction requirements exhibit an ever increasing pressure on energy-intensive natural gas, oil refining and bulk chemicals manufacturing process industries, pushing them to consider implementation of advanced distillation technologies. The most promising in this respect is Dividing Wall Column (DWC) technology, which, proven in more than 300 applications worldwide, uses approximately 30% less energy, capital investment and plot area compared with a conventional distillation arrangement. With application of more complex four-product DWCs, these savings could be as much as 50% (Halvorsen et al, 2013). As demonstrated elsewhere (Dejanović et al, 2013, 2014), these configurations are feasible from a design and construction viewpoint, both as new designs and most importantly as energy saving and/or capacity increasing option for existing plants. However, controllability related concerns, primarily those arising from the fact that there are no proven means available yet to reliably control the vapor traffic on either side of a partition wall, may be considered as one of the prime reasons for lack of daring on users' side to make a decisive step toward practical implementation.

There has been a number of papers published on the subject of control of three-product columns, however know-how on the practical control of more complicated, four-product columns is still lacking. Few research papers that exist deal with the simplest, single partition variant, i.e. Kaibel column that trades off simplicity in design and operation for lower energy efficiency compared to fully extended Petlyuk configurations. One of them is by Dwivedi et al. (2012) that show the results for temperature control of a pilot-scale Kaibel column. Furthermore, a feasible control structure for the full 4-product Petlyuk arrangement is presented by Dwivedi et al. (2013). This can be regarded as a full degree-of-freedom approach, where all internal liquid and vapor splits are assumed to be available as manipulated variables. However, by reducing the number of control loops, e.g. fixing vapor splits by design, it is still possible to achieve satisfactory control when actual vapor rates are at or above minimum values required to achieve the specified separation. In distillation control, a key issue is that every simple two-product column needs at least one-point control to avoid drift of the composition profile (Skogestad, 2007). This is also valid for every internal sub-column in a Petlyuk arrangement. A recent paper by Yuan et al. (2017), illustrates that even a simple control structure with four stabilizing temperature controllers is able to successfully handle various disturbances for a 3-product DWC.

Present paper introduces and discusses results of a dynamic simulation study on performance of two control structures developed for control of a four-product DWC with so-called 2-2-4 internal arrangement (Dejanović et al., 2014). Aspen HYSYS V9 was used to simulate and assess performance of developed temperature-

driven control structures. It is anticipated that results will indicate if developed structures are able to control the process in a satisfactory manner – by successfully returning product qualities within required specifications in a reasonable time frame after introduction of disturbances, using only traditional means of control. The key point believed to be crucial for achieving this is very tight control of temperature profiles in both prefractionation section, as well as in the product draw regions of the column. Constant vapor split with desired nominal values are realized by the wall placement and internals design in the industrial solutions of today. However, there is an ongoing effort on using active vapor splits. Strandberg (2011) built a 4 product pilot-scale Kaibel column and did successful experiments with active vapor split control using a simple device on each side of the wall with an electric motor driven internal valve for the vapor and a liquid downcomer. Most recently, industrial scale relevant designs of vapor-split controlling devices have been introduced in patent and general literature (Kang et al., 2017).

2. Simulation and results

2.1 Basic simulation setup

The main reason for choosing 2-2-4 structure is its relative simplicity – it has only one reboiler, one condenser and two partition walls and is most likely to be used in practice. Feed and product specifications are based on real-life industrial plant - reformate re-distillation unit, which is using conventional distillation columns for the required separations. Since real feed has a vast number of different components in relatively small fractions, feed used in simulation was reduced to 15 most abundant components, shown in Table 1.

Table 1: Feed composition

Component	Mole fraction
n-Butane	0.030
i-Pentane	0.082
n-Pentane	0.058
2-Mpentane	0.086
n-Hexane	0.046
Benzene	0.102
3-Mhexane	0.019
Toluene	0.249
E-Benzene	0.031
p-Xylene	0.037
m-Xylene	0.107
o-Xylene	0.048
1,4-EBenzene	0.033
1,3,5-MBenzene	0.060
1M3-EBenzene	0.013

Required product specifications are as follows:
Top product (C_5-C_6 fraction), with max 1.5 mass % benzene
Side product 1 (BRC – benzene rich cut), with 65-70 mass % benzene
Side product 2 (Toluene-rich fraction), with min 98 mass % toluene
Bottom product (E-benzene and heavier), with max 0.1 mass % toluene

Control structures considered in this study were temperature-driven only and based on traditional means of control i.e. PID controllers. Vapor splits were left uncontrolled, depending on the pressure drop in given sections at given process conditions and were changing accordingly with change in liquid splits. Liquid splits were regulated using temperature control. The goal of such setup was to examine the possibility to control this configuration of a fully thermally coupled 4-product DWC in a satisfactory manner without active vapor split control in this first study. Introduced disturbances were step changes in composition of feed stream, specifically, ± 10 % change in fraction of benzene and toluene separately. Internal arrangement of this DWC (see Figure 1a) was modelled using an equivalent sequence of seven columns, as shown in Figure 2 a/b, which is suitable for dynamic simulation, because all vapor and liquid splits are represented by streams connecting independent columns, and therefore very easy to regulate and/or quantify. Column design data is shown in Table 2. Steady state temperature profile used as a basis for control structure selection and performance analysis is shown in Figure 1b.

Table 2: Column design data (Numbers in parentheses indicate stages above and below feed stage)

Column	Number of stages	Feeds	Draws
Col. 1	31	-	C_5/C_6 – stg. 1
Col. 2	8	-	-
Col. 3	35 (16+19)	-	BRC – stg. 16
Col. 4	22 (11+11)	Feed – stg. 11	-
Col. 5	15	-	-
Col. 6	35 (17+18)	-	Toluene – stg. 17
Col. 7	22	-	Heavies – stg. 22

2.2 Control structures

Two temperature-driven control structures were developed and their performance tested against disturbances. Both structures follow several basic rules that allow the column to run without composition drift and to be able to respond to any kind of disturbances:

- pressure is tightly regulated and held constant at the top of the column;
- liquid levels, both in the column sump and top accumulator are regulated;
- reflux is regulated using temperature control;
- prefractionator products' composition must be controlled.

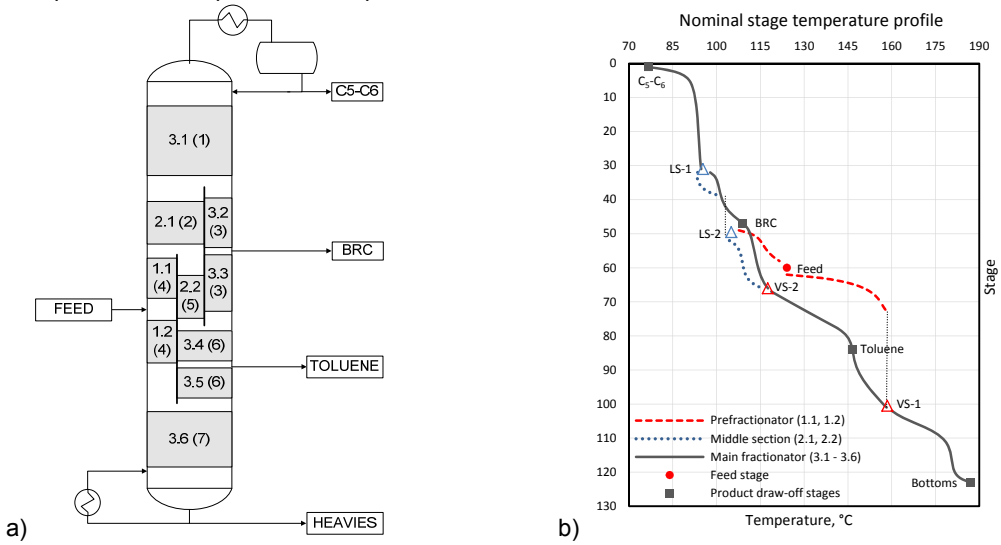


Figure 1: Physical arrangement of sections in 2-2-4 configuration (a) with corresponding temperature profiles (b). Numbers in parentheses in (a) designate the corresponding column number in expanded model (Figure 2)

In both cases, vapor splits were simulated using valves with fixed degree of openness, allowing certain variations caused by changes in the pressure drop across sections due to active liquid split control. Since the key to proper column response to changing feed composition and rate is maintaining prefractionator within optimal operation, active liquid split control is a must. All PID regulators were tuned using a SIMC method, (Skogestad, 2003), assuring very tight regulation and response.

Control structure 1 (CS-1):

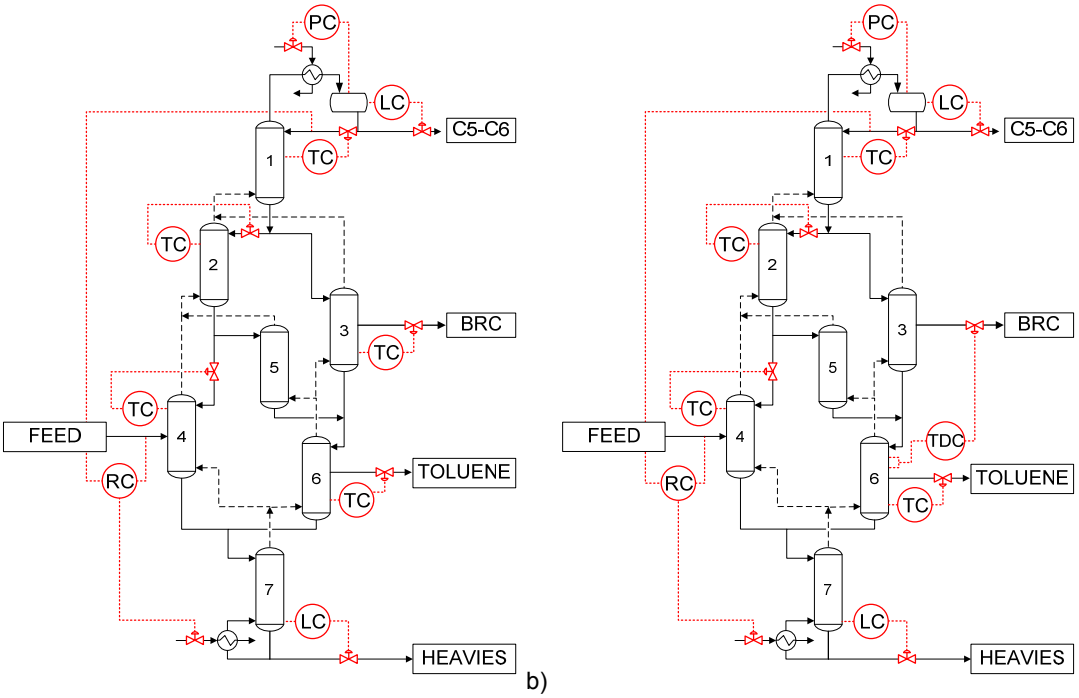
CS-1, shown schematically in Figure 2a, controls the composition by regulating single stage temperatures in sections of the main prefractionator (Columns 1, 3 and 6 in figure 2a). Temperatures are regulated by adjusting the reflux rate and draw rate of side products, BRC and Toluene. For better responsivity, temperature loops are in cascade with flow rate controllers. Prefractionator (column 4) and column 2 are temperature-controlled by adjusting the liquid flow from upper sections. Single stage temperature in column 2 is regulated by changing liquid split 1 (LS-1), while single stage temperature in column 4 is regulated by changing liquid split 2 (LS-2). For selection of controlled stages, a steady-state sensitivity study was carried out, recording stage temperature changes after variations of inlet feed composition. Final selection depended on sensitivity, but also taking practical rules by Skogestad (2007) into consideration. List of controlled stage temperatures is given in Table 3. Fixed reflux-to-feed ratio control is used to control reboiler heat duty.

Control structure 2 (CS-2):

Configuration of CS-2, shown in Figure 2b, is identical to CS-1 in terms of pressure, level, heat duty regulation and prefractionator temperature control. Temperature regulation in section 6 consists of single stage temperature regulation, regulated by toluene product draw rate, and temperature differential controller, regulated by BRC product draw rate.

Table 3: Temperature regulated stages

Manipulated variable	CS-1: Controlled temperature	CS-2: Controlled temperature
Reflux	Stg. 2 @ Col. 1	Stg. 2 @ Col. 1
Liquid split 1	Stg. 4 @ Col. 2	Stg. 4 @ Col. 2
Liquid split 2	Stg. 8 @ Col. 4	Stg. 8 @ Col. 4
BRC draw rate	Stg. 30 @ Col. 3	(Stg. 10 – Stg. 18) @ Col. 6
Toluene draw rate	Stg. 25 @ Col. 6	Stg. 25 @ Col. 6

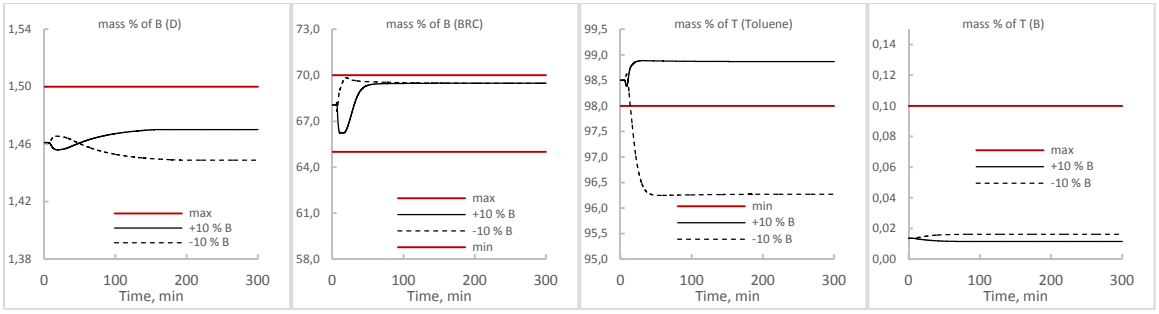


a) b)

Figure 2: Layout of Control structure 1 (a) and Control structure 2 (b)

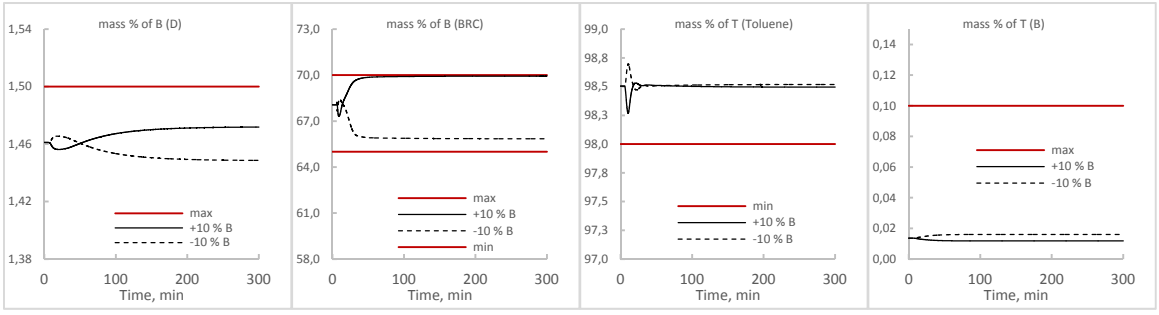
3. Results and discussion

Simulation results are shown graphically in Figures 3 to 6. Step change of inlet composition was introduced after 5 minutes of run-time and the response was recorded continuously during 300 minutes. Dynamic response of two control structures to a ± 10 % change of inlet benzene content and a ± 10 % change of inlet toluene content is shown separately for each product specification expressed in mass percent: (a) benzene content in distillate, B (D), (b) benzene content in Benzene Rich Cut, B (BRC), (c) toluene content in Toluene product stream, T (T), and (d) toluene content in bottoms, T (B).



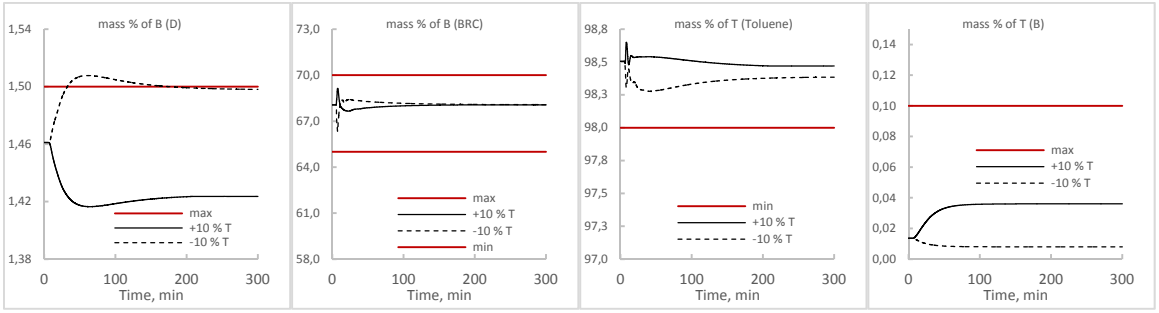
a) b) c) d)

Figure 3: Dynamic response of CS-1 to ± 10 % change of benzene content in the feed.



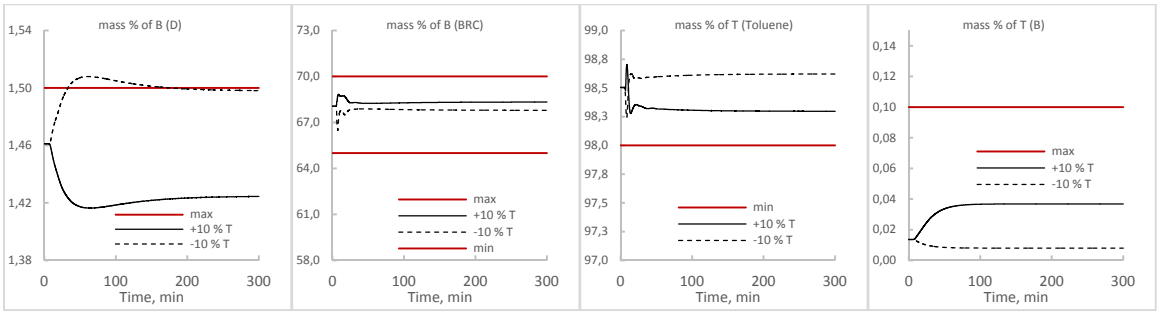
a) b) c) d)

Figure 4: Dynamic response of CS-2 to ± 10 % change of benzene content in the feed.



a) b) c) d)

Figure 5: Dynamic response of CS-1 to ± 10 % change of toluene content in the feed.



a) b) c) d)

Figure 6: Dynamic response of CS-2 to ± 10 % change of toluene content in the feed.

As seen on the dynamic responses on Figures 3 and 5, CS-1 is unable to respond to all disturbances in a satisfactory manner. While the process settles well within 3 hours, required final product purities are not met in every case. Specifically, in case of -10 % benzene feed fraction disturbance, toluene product goes well below required specification. To understand this, it must be noted that side product draw-offs influence not only composition of the product itself, but also that of products below and above – e.g. by decreasing BRC draw-off rate, benzene content in BRC increases, but so do impurities in toluene product too. Decreased draw-off rate of toluene product affects in the same manner toluene product contents and bottom product impurities. In this specific case, toluene product contains too much of lighter impurities, which can be concluded by indicated compositions of BRC and bottom product on the dynamic response graphs. It is therefore clear that product draw-off rates of BRC and toluene product must be adjusted in this case. Since they are regulated by single stage temperature, it is clear that having two fixed-temperature stages in the side product draw-off sections of the main fractionator is not enough because temperature profile between them can vary greatly, leading to off-spec product. Temperature 'plateau' several stages above Toluene product draw stage (see Figure 1b) has been recognized as the most important part of temperature profile in this case. Toluene product purity strongly correlates with this plateau, with purity being better when the plateau is wider, i.e. through more stages. This fact, along with the fact that changes in compositions of every product exhibit different sensitivity to change in specific product draw rate, allows formulating CS-2 as a modification of CS-1. BRC draw rate is adjusted so that temperature differential between stages 10-18 of Column 6 is fixed and therefore toluene content is controlled more tightly, while benzene content is still well within product specifications, which is clearly seen on dynamic responses shown in Figures 4 and 6. Response of toluene content in Toluene product is now significantly different in comparison with CS-1, without even going into off-spec area. CS-2 also exhibits slightly faster settle times for benzene content in BRC and marginally lower energy consumption, as seen in Table 4. The downside of temperature-driven structures in this case is lack of efficient heat duty control and potential for reaching the optimal energy efficiency. Ideally, heat duty should be adjusted to provide the minimum energy required for the separation of the most difficult split, at the same time allowing all easier splits to carry out. In this case, most difficult split is toluene – ethyl benzene, e.g. separation between Toluene and Bottoms product. Thus, key variable to be used for efficient heat duty control is Bottoms product impurity, T (B). However, since its content is minor relative to all other components in the Bottoms and needs to be regulated within very narrow window, its effect on stage temperature is marginal, within measurement noise, which makes temperature-based heat duty regulation difficult. While fixed reflux-to-feed ratio does keep products within specification, it doesn't fully utilize energy efficiency potential.

Table 4: Numerical results after reaching steady-state. Liquid and vapor splits are given as a ratio of mass flow to prefractionator side and total mass flow before split.

	Base case	+10 % B		-10 % B		+10 % T		-10 % T	
Control structure:		CS-1	CS-2	CS-1	CS-2	CS-1	CS-2	CS-1	CS-2
B (D), mass %	1.46	1.47	1.47	1.45	1.45	1.42	1.42	1.50	1.50
B (BRC), mass %	68.06	69.48	69.93	69.48	65.86	68.07	68.31	68.08	67.81
T (Toluene), mass %	98.50	98.87	98.50	96.27	98.52	98.46	98.30	98.38	98.662
T (B), mass %	0.01	0.01	0.01	0.02	0.02	0.04	0.04	0.01	0.01
Reflux ratio	4.206	4.260	4.258	4.152	4.155	4.346	4.342	4.075	4.077
LS_1	0.6157	0.6183	0.6207	0.6100	0.6107	0.6198	0.6203	0.6112	0.6108
LS_2	0.3907	0.3689	0.3714	0.4130	0.4111	0.4012	0.4018	0.3830	0.3826
VS_1	0.5980	0.5953	0.5970	0.5994	0.5989	0.5972	0.5975	0.5987	0.5984
VS_2	0.3367	0.3328	0.3332	0.3386	0.3407	0.3372	0.3370	0.3364	0.3366
Q, MW	4.593	4.580	4.579	4.606	4.606	4.571	4.571	4.614	4.614

4. Conclusion

The goal of this work was to examine the abilities of temperature control structures in regulating complex, four-product, fully thermally coupled (Petlyuk) dividing wall column. The input data and product specifications were based on real industrial case of a reformate fractionation complex. Two control structures were proposed and their performance analyzed in regards to maintaining product specifications and settle times after introduction of disturbances. Results show that Control structure 2 can effectively maintain all four product qualities within their limits in all cases, having relatively quick response and settle times. From performance of Control structure 1 it appears that single–point (stage) temperature control of the main fractionator is insufficient to maintain desired product quality. The temperature differential control, proposed in Control structure 2, appeared to be capable of maintaining proper temperature and composition profile of the main fractionator. Temperature-driven liquid split control proved to be satisfactory, even with non-controlled vapor splits. The structure is straightforward to implement in an industrial DWC with conventional control system. Adding active vapor splits may be an option to extend the range of possible feed compositions that can be separated with full energy savings and specified product purity.

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