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PRACTICAL CONTROL OF DIVIDING-WALL COLUMNS

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Abstract
This paper studies the practical implementation of stabilizing control for a Kaibel dividing-wall column. Control configurations with varying number of temperature loops are tested and compared with special attention to the use of the liquid split ratio as a manipulated variable.

Keywords: Dividing-wall columns, Process control, Optimal operation, Kaibel column

1. Introduction

Dividing wall distillation columns (DWC) have received considerable attention in the last decades. Although the patent of DWC was submitted by Wright[1] in 1949, and the basic theory that outlined potential energy savings by fully thermally coupled columns was presented by Petlyuk[2] in 1965 the industry were reluctant. The breakthrough came with the work of Kaibel[3] in 1987 and several DWCs were realized within BASF through the 1990's. Theoretical expressions for minimum energy for 3-component ideal zeotropic mixtures were presented by Fidkowski[4] in 1987. Extension to any number of components, sharp and non-sharp splits, and the general extended Petlyuk arrangement was presented by Halvorsen[5] (2001). Typical savings are reported in the range from 15% to 30% compared to conventional sequences. However, not many papers have been published on operation. Wolff and Skogestad[6] (1995) showed that it is important to set the liquid and vapour splits at their right values. Triantafyllou and Smith[7] investigated selection of manipulated variables both from simulations and by a pilot plant column (1992).

We will here focus on how to operate the column in practice, where the goal is to achieve acceptable operation using simple control policies. Acceptable operation generally means achieving desired product purities with an energy usage reasonably close to the minimum. However, in this study we assume fixed energy usage and the objective is to achieve as pure products as possible. In particular, we will investigate the importance of properly adjusting the liquid split ratio, R_L, which determines the relative amount of reflux to the two sides of the dividing wall.

2. Method

We start by defining optimal operation for the Kaibel column. In this paper we look at a column with a given number of stages, and we assume that the energy input (boilup V) is fixed. Therefore, instead of minimizing energy input for a given separation, we define a problem where the overall objective (Equation 1) is to minimize the sum of the impurity flows of all product streams.

$$J = D(1 - x_{A,D}) + S_1(1 - x_{B,S_1}) + S_2(1 - x_{C,S_2}) + B(1 - x_{D,B}) \tag{1}$$

The column modeled has 8 stages in each column section except for 12 in each of the two prefractionator sections. The feed components are an equimolar mixture of Methanol (A), Ethanol (B), propanol (C) and Butanol (D). The vapor-liquid equilibrium is modeled using the Wilson equation. We assume a fixed feed rate (F), fixed vapor boilup rate ($V=V_{max}$) and fixed vapor split ratio (R_V). The vapor split ratio is assumed constant because it is difficult to adjust in practice. Assuming that the distillate (D) and bottoms (B) flows are used for level control, the remaining degrees of freedom for control are then the reflux (L), the side stream flows (S_1 and S_2) and the liquid split ratio (R_L).

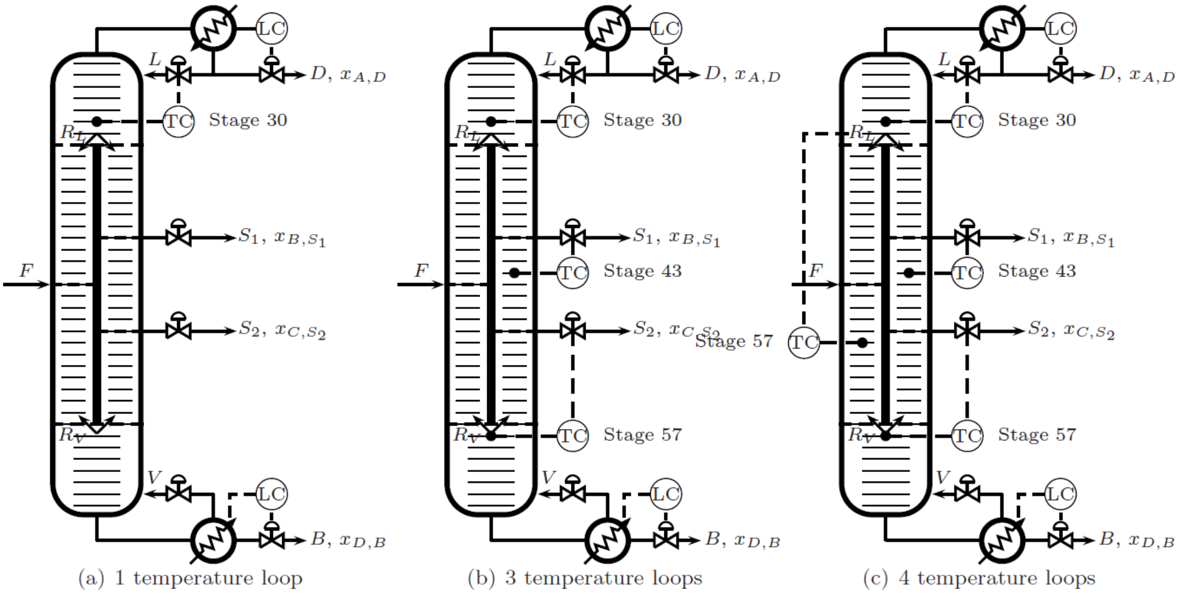

Figure 1. Kaibel column control configurations (In all cases F, V and R_V are fixed).

These remaining four degrees of freedom are sometimes held constant, but preferably they should be adjusted during operation, for example, by keeping selected temperatures constant. Three configurations are studied in the paper:

1. One temperature loop: Reflux, L is used for temperature control (also used for the other cases) (Fig. 1a)
2. Three temperature loops: Adding temperature loops for the two side streams S_1 and S_2 (Fig. 1b)
3. Four temperature loops: Adding a temperature loop for the liquid split, R_L (Fig.1c)

The temperature locations were not chosen with a detailed analysis, but are based on dynamic consideration and common recommendations[8]. In general, the controlled temperatures should be within separate "internal sections" if there are several control loops. These internal sections for this case are: The prefractionator which is to the left of the dividing wall, the sections between D and S1, S2 and B, and finally the total reflux section between S1 and S2. The locations chosen here within a column section are based on steady-state gain and the stage-to-stage temperature difference. The key of controlling a point on a temperature profile is to keep the profile in position and thereby also the product purities when disturbances occur. It is required that heat supply is sufficiently large for the most demanding expected disturbance. Conventional PI-controllers and tuning procedures are used.

2.1 Loss definitions

Throughout this paper we compare for a given disturbance, the resulting objective function value (Steady-state value of the impurity flows) for a given control configuration (J_d) relative to the nominal (optimal) value (J_{nom}):

$$L_{nom} = \frac{J_d - J_{nom}}{J_{nom}} \tag{2}$$

We also define the loss relative to the truly optimal J for the given disturbance, $J_{opt,d}$ (re-optimized with respect to L, S_1, S_2 and R_L):

$$L_{opt} = \frac{J_d - J_{opt,d}}{J_{opt,d}} \tag{3}$$

3. Effect of liquid split ratio

We first investigate how the column behaves for the two configurations where the liquid split ratio is not used for control. The set points for the temperature controllers are kept at their nominal values, while we vary the liquid split ratio R_L away from its optimal value.

Table 1. Kaibel column with one temperature loop closed: Effect of changes in R_L

	$\Delta R_{L,-50}$	$\Delta R_{L,-25}$	Nominal	$\Delta R_{L,+25}$	$\Delta R_{L,+50}$
R_L	0.1286	0.1929	0.2572	0.3215	0.3858
$X_{A,D}$	0.9759	0.9733	0.9703	0.9701	0.9704
$X_{B,S1}$	0.7166	0.8223	0.9361	0.8788	0.8055
$X_{C,S2}$	0.7163	0.8455	0.9589	0.8907	0.8208
$X_{D,B}$	0.9406	0.9855	0.9949	0.9977	0.9918
J	0.1626	0.0932	0.0349	0.0657	0.1027
L_{nom} (%)	366	167	0	88	194

Table 2. Kaibel column with 3 temperature loops closed: Effect of changes in R_L

	$\Delta R_{L,-50}$	$\Delta R_{L,-25}$	Nominal	$\Delta R_{L,+25}$	$\Delta R_{L,+50}$
R_L	0.1286	0.1929	0.2572	0.3215	0.3858
$X_{A,D}$	0.9760	0.9734	0.9703	0.9701	0.9703
$X_{B,S1}$	0.7141	0.8109	0.9361	0.9388	0.9105
$X_{C,S2}$	0.8071	0.9283	0.9589	0.8701	0.7339
$X_{D,B}$	0.9950	0.9949	0.9949	0.9971	0.9985
J	0.1332	0.0769	0.0349	0.0576	0.1113
L_{nom} (%)	282	120	0	65	219

We set R_L to -25% and -50% of its initial (optimal) value which signifies that more (too much) reflux is directed to the main column. Also, we increase R_L by 25 and 50%, which means that more reflux is directed to the prefractionator as compared to the optimal value. The resulting product purities, objective function value and percentage loss for the case with one temperature loop can be seen in Table 1 and Table 2 show the values for the configuration with three temperature loops closed. From the tables we see that changing the liquid split away from its optimal setting has a detrimental effect on the side stream purities. The configuration with three temperature loops performs slightly better than the one-loop configuration, but the differences are relatively small. For the largest positive change in R_L, the three-loop configuration is actually the worst. This is because the controller on sidestream 2 enforces a large flow on the stream with most impurities.

Figure 2 shows the temperature profiles in the column for the configuration with 3 temperature loops. The first (a) is the nominal (optimal) operating point, while the second (b) and third (c) show the profiles when the liquid split is set too low ($0.50R_{L,opt}$) and too high ($1.50R_{L,opt}$) respectively. The three controlled temperatures are all in the main column (as indicated in the figure), so that when more of the reflux is directed to the main column (b), the Prefractionator temperature profile is shifted upwards, while the main column profile has less shift. Conversely, when too much reflux is sent to the prefractionator (c), the section is cooled and the profile is "lowered".

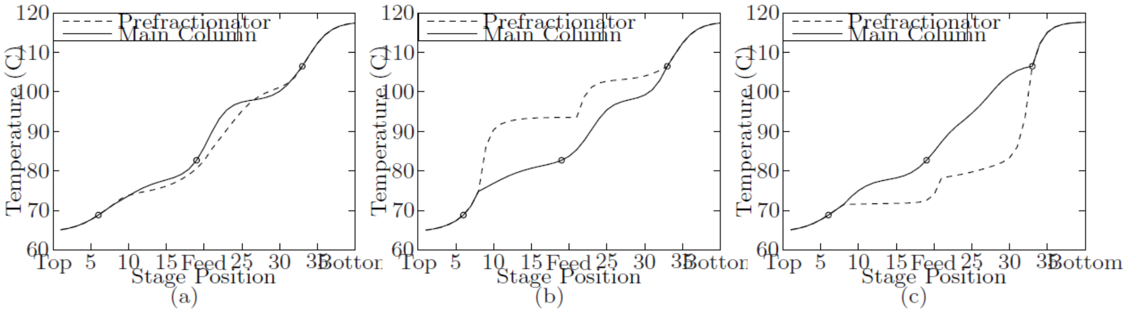

Figure 2. Kaibel column with 3 temperature loops closed: Column temperature profiles.
(a) Nominal profile, (b) $R_L = 0.50R_{L,opt}$, (c) $R_L = 1.50R_{L,opt}$. Controlled temperatures are encircled.

When R_L is too low, there is a breakthrough of component C in from the top of the prefractionator into the main column. This leads in turn to large impurity in the first sidestream. When R_L is set too high, we get breakthrough of component B from the bottom of the prefractionator into the main column. This prevents us from reaching high purity in the second sidestream. In both the cases where the liquid split ratio is implemented incorrectly we observe large reductions in the sidestream product purities. Clearly, it is important to achieve the right split of the reflux for the successful operation of the Kaibel column. Before we look into how to adjust the liquid split ratio, we will see how the single-loop and 3-loop configurations perform under some different disturbances.

3.1 Disturbance rejection

The two control configurations (1 and 2) are subjected to disturbances in feed rate (F), feed composition (z_F) and vapor split (R_V). The disturbance in feed composition is a 20 % increase in $z_{B,F}$ with corresponding reduction in $z_{D,F}$. For the vapor split, both a 10 % and a 50 % increase are simulated. To compare the results of the simulations, we have re-optimized the solution with respect to L, S_1, S_2 and R_L for each disturbance with R_V remaining fixed.

Table 3. Kaibel column with 1 temperature loop closed: Effect of disturbances

	Nominal	ΔF_{+10}	$\Delta z_{B,F+20}$	ΔR_{V+10}	ΔR_{V+50}
F	1.0000	1.1000	1.0000	1.0000	1.0000
$z_{B,F}$	0.2500	0.2500	0.3000	0.2500	0.2500
V	3.0000	3.0000	3.0000	3.0000	3.0000
R_L	0.2572	0.2572	0.2572	0.2572	0.2572
R_V	0.3770	0.3770	0.3770	0.4147	0.5655
$x_{A,D}$	0.9703	0.9692	0.9703	0.9723	0.9813
$x_{B,S1}$	0.9361	0.9586	0.9658	0.8642	0.4993
$x_{C,S2}$	0.9589	0.8896	0.7925	0.8883	0.4963
$x_{D,B}$	0.9949	0.8485	0.7989	0.9875	0.8820
J	0.0349	0.0955	0.1181	0.0718	0.2876
L_{nom} (%)	-	174	238	106	724
L_{opt} (%)	-	137	199	105	675

Table 4. Kaibel column with 3 temperature loops closed: Effect of disturbances

	Nominal	ΔF_{+10}	$\Delta z_{B,F+20}$	ΔR_{V+10}	ΔR_{V+50}
F	1.0000	1.1000	1.0000	1.0000	1.0000
$z_{B,F}$	0.2500	0.2500	0.3000	0.2500	0.2500
V	3.0000	3.0000	3.0000	3.0000	3.0000
R_L	0.2572	0.2572	0.2572	0.2572	0.2572
R_V	0.3770	0.3770	0.3770	0.4147	0.5655
$x_{A,D}$	0.9703	0.9692	0.97044	0.9723	0.9812
$x_{B,S1}$	0.9361	0.9364	0.9363	0.8510	0.4594
$x_{C,S2}$	0.9589	0.9426	0.9362	0.9444	0.4963
$x_{D,B}$	0.9949	0.9952	0.9962	0.9947	0.9951
J	0.0349	0.0430	0.0433	0.0614	0.2696
L_{nom} (%)	-	23.2	24.1	75.9	672
L_{opt} (%)	-	6.7	9.6	75.4	627

Tables 3 and 4 show the relevant inputs, resulting purities and objective function values after the disturbances for the two configurations. Here, the three-loop configuration is clearly better than the case with only one temperature loop as can be expected. However, the large change in vapor split (R_V) cannot be handled by either configuration. The dynamic responses for the case with three temperature loops are shown in Figure 3.

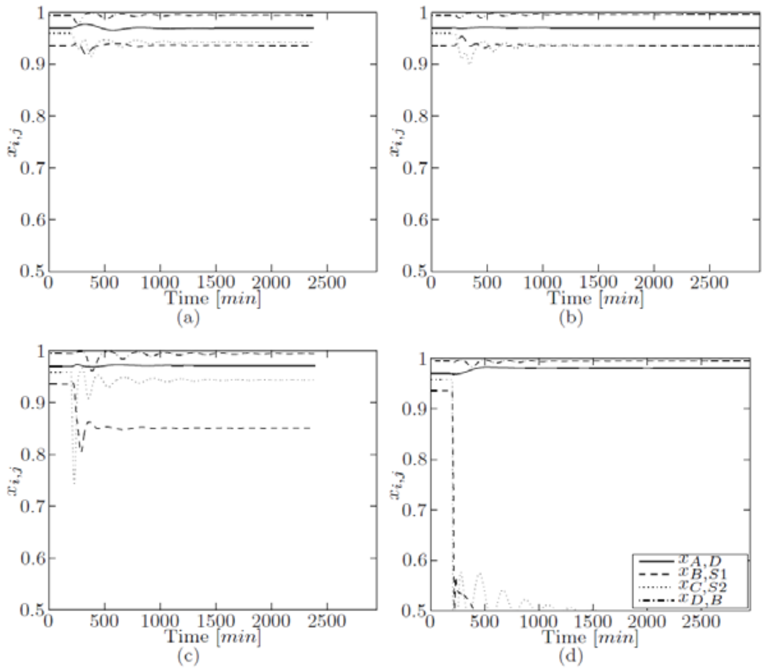

Figure 3. Kaibel column with 3 temperature loops closed: Disturbance responses (a) F + 10%, (b) $z_{B,F}$ +20%, (c) R_V + 10% and (d) R_V + 50%

4. Using liquid split for feedback control

So far we have been treating the liquid split ratio (R_L) as a disturbance, while using the reflux and side stream flows to control selected temperatures. However, the liquid split is also a degree of freedom that can be used for control. We will now add an additional temperature loop using R_L to the Kaibel dividing-wall column, and compare the perfomance to the previous configurations.

4.1 Kaibel column with four temperature loops

The fourth temperature loop is added to stabilize the prefractionator profile using the liquid split as manipulated variable. The temperature selected should be in the prefractionator section of the column, and the particular stage location used here was chosen considering the steady-state gain and the stage-to-stage temperature difference, but no detailed analysis was made.

With four temperature loops now closed, we subject the model to the same disturbances as above. The dynamic responses for the configuration can be seen in Figure 4. Although the response to the changes in vapor split in Figures 4 (c) and 4 (d) show some dynamic variation, the extra temperature loop manages to reduce the loss in purity considerably as compared to the configurations where R_L is not used for control. The resulting purities, inputs, objective function value and percentage loss are given in Table 5 for the four disturbances. The table shows that the control configuration gives very good disturbance rejection, and for the smaller change in R_V, nearly zero loss. The results confirm the findings of Halvorsen et. al.[9], that either R_L or R_V needs to be adjusted online. Even for large disturbances in vapor split, the configuration with four temperature loops closed has very low loss.

5. Conclusions

In this paper, we have studied the practical implementation of stabilizing control for a dividing-wall distillation column. In the study, we assume that the objective is to maximize the purity of all product streams, and we show that setting the correct liquid split ratio is essential in achieving the potential purities. Control configurations with varying number of temperature loops have been tested and compared. We show that the liquid split can be used to control a temperature in the prefractionator section and thereby reduce the sensitivity to disturbances. Adjusting the liquid split is particularly important in reducing the column's sensitivity to the vapor split ratio.

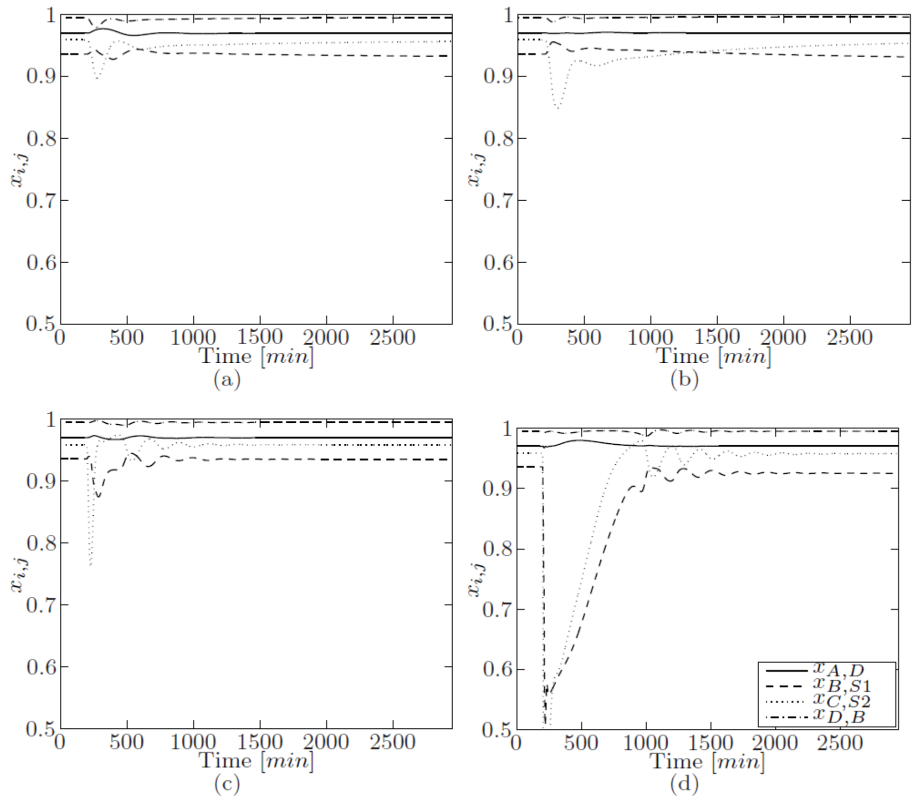

Figure 4. Kaibel column with 4 temperature loops closed: Disturbance responses (a) F + 10%, (b) $z_{B,F}$ +20%, (c) R_V + 10% and (d) R_V + 50%

Table 5. Kaibel column with 4 temperature loops closed: Effect of disturbances

	Nominal	ΔF_{+10}	$\Delta z_{B,F+20}$	ΔR_{V+10}	ΔR_{V+50}
F	1.0000	1.1000	1.0000	1.0000	1.0000
$z_{B,F}$	0.2500	0.2500	0.3000	0.2500	0.2500
V	3.0000	3.0000	3.0000	3.0000	3.0000
R_L	0.2572	0.2572	0.2572	0.2572	0.2572
R_V	0.3770	0.3770	0.3770	0.4147	0.5655
$X_{A,D}$	0.9703	0.9694	0.9706	0.9703	0.9705
$X_{B,S1}$	0.9361	0.9324	0.9315	0.9354	0.9254
$X_{C,S2}$	0.9589	0.9562	0.9535	0.9590	0.9580
$X_{D,B}$	0.9949	0.9945	0.9958	0.9949	0.9950
J	0.0349	0.0406	0.0405	0.0351	0.0380
L_{nom} (%)	-	16	16	0.6	8.9
L_{opt} (%)	-	0.7	2.5	0.3	2.4

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