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Dynamic behaviour and control of extended Petlyuk distillation arrangements

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Abstract

Thermal coupling of heat and mass leads to complex configurations and difficult control problems. We study here the dynamic behavior of a high purity, 4-product extended Petlyuk column with nominal operating point close to the analytic minimum energy for sharp seperation and propose and four different decentralized control structures. We subject the different control structures to wide range of disturbances and propose robust control structures that can handle them while remaining close to the minimum energy for the given purity specification. Another aspect of this work is the use of V-min diagrams which can predict a worst case disturbance and can reason out the failure of a particular control structure. The general control structures shown here can be extended to other prefractionator arrangements as well like Kaibel column.

Keywords: Thermally coupled columns, Petlyuk Column, Decentralized control

1. Introduction

The major inefficiencies in the conventional distillation sequences result from remixing losses. This can be reduced significantly by direct material coupling and by doing the easiest split first. Petlyuk et al. (Petlyuk 1965) proposed such a scheme to separate feed into three products, using an prefractionator that does only the easiest split. This concept can easily be extended to carry out separation of feed into more than three products. There are more than 100 industrial uses (Dejanovic, Matijasevic et al. 2010) of divided wall columns reported in BASF. Further different research groups(Wolff and Skogestad 1995; Mutalib and Smith 1998; Mutalib, Zeglam et al. 1998; Niggemann, Gruetzmann et al. 2006; Olujic, Jödecke et al. 2009; Niggemann, Hiller et al. 2010) have conducted rigorous experimental and simulation studies to conduct dynamic studies related to start up as well as normal operation of such systems. In this work, we will show for the control studies done on a four product extended Petlyuk column.

2. Four-product extended Petlyuk column

Figure 1 shows the schematic of a four product Petlyuk column. We study the separation of four components namely methanol (A), ethanol (B), propanol (C) and n-butanol (D). The total numbers of columns required for this separation are six and are labeled in figure 1. The system is operated so as to do the easiest separation first. In the prefractionator column C1, only A/D components are completely separated, components B and C are allowed to mix from both the ends of the column C1. There are in total 10 valves including the boilup rate. The liquid reflux, condenser duty and the bottom product rate are consumed for the liquid and vapor inventory control. Note that we use four vapor distribution valves as operational degree of freedom. This is unconventional but, can be implemented in real systems (Agrawal and Fidkowski 1998) and a prototype of vapor split valves was also demonstrated experimentally (Dwivedi, Halvorsen et al. 2011).

2.1. Model Details

The process is modeled in Matlab using simplifying assumptions of constant relative volatility and constant internal molar flows. The relative volatiles are assumed closed to that of the components used. The pressure assumed is atmospheric. Large number of stages are assumed (=60) in each column. The nominal operating point uses energy equivalent to analytical minimum as given by solving Underwood equations. The base purities of the four products are greater than 99.4 mol %.

2.2. V-min diagrams

V-min diagram is a tool to visualize the minimum boilup requirement for sharp and non sharp separation in conventional and thermally coupled distillation sequences. It is based on solution of Underwood equations for ideal mixtures. The V-min diagrams in principle can also be extended to non-ideal mixtures too. Another important application of this tool is to calculation internal flow rates of vapor and liquid in thermally coupled arrangements. We will show the use of this tool to evaluate the result of disturbances.

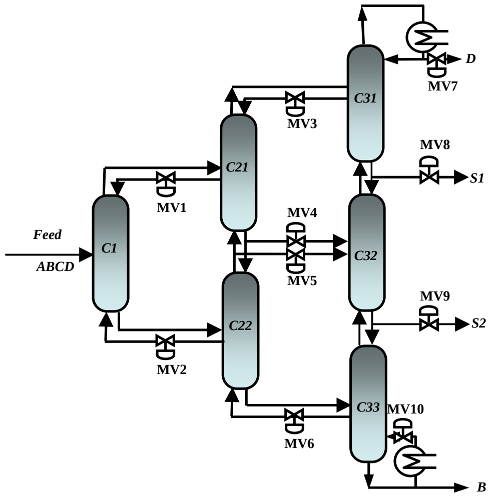

Figure 1: Schematic of four product Petlyuk column

3. Proposed Control Structures

The systematic design procedure for plant wide control structure lays emphasis on economic objective (Skogestad 2000). This work is done for a case where all the products are equally priced and price of energy consumption is high, product purities become the active constraints and these move to the stabilizing layer. In such a case all degrees of freedom are consumed and there are no unconstrained degrees of freedom. We are the left with the composition control problem (Skogestad 2007). In this work, we propose four decentralized control structures which are either composition inferential or temperature inferential and evaluate their control performance on composition in event of disturbances. We have named them as CS1, CS2, CS3 and CS4 for convenience. See table 1 for more details.

3.1. CS1 (Composition based regulatory layer)

This is the simplest and the most intuitive control structure. Here we use the 10 valves to control the key impurity in each stream leaving the columns.

3.2. CS2 (Composition based regulatory layer)

This is exactly same as the CS1, except that the boil up controls the sum of light impurities in three product streams S1, S2 and bottoms

3.3. CS3(temperature inferential regulatory layer)

Here, two sensitive temperatures in columns C1, C21, C22. A sensitive temperature in rectifying sections of C31, C32 and C33 with flow rates of products D, S1 and S2 respectively. The boil up is used to control sum of one temperature in stripping sections of all there columns C31, C32 and C33.

3.4. CS4 (Composition –temperature cascade regulatory layer)

Here the composition measurements are used in master composition controllers in C1, C21 and C22 which update setpoints for slave temperature controllers. The controllers in C31, C32 and C33 are same as in CS3.

Table 1: Comparison of proposed regulatory control structures [1, 2, 3, 4]

Valve	Controlled Variable			
	CS1	CS2	CS3	CS4
MV1	x_D in C1 top [1]	x_D in C1 top	T_{RS} [2] in C1	T_{RS} in C1 [4]
MV2	x_A in C1 bottom	x_A in C1 bottom	T_{SS} [3] in C1	T_{SS} in C1 [4]
MV3	x_B in C21 top	x_B in C21 top	T_{RS} in C21	T_{RS} in C21 [4]
MV4	x_D in C22 top	x_D in C22 top	T_{SS} in C21	T_{SS} in C21 [4]
MV5	x_A in C21 bottom	x_A in C21 bottom	T_{RS} in C22	T_{RS} in C22 [4]
MV6	x_C in C21 bottom	x_C in C21 bottom	T_{SS} in C22	T_{SS} in C22 [4]
MV7	x_B in C31 top	x_B in C31 top	T_{RS} in C31	T_{RS} in C31 [4]
MV8	x_C in C32 top	x_C in C32 top	T_{RS} in C32	T_{RS} in C32 [4]
MV9	x_D in C33 top	x_D in C33 top	T_{RS} in C33	T_{RS} in C33 [4]
MV10	x_C in C33 bottom	x_A in C31 bottom+ x_B in C32 bottom+ x_C in C33 bottom	T_{SS} in C31+ T_{SS} in C32+ T_{SS} in C33	T_{SS} in C31+ T_{SS} in C32+ T_{SS} in C33

[1] x: composition

[2] T_{RS}: one sensitive temperature in rectifying section

[3] T_{SS}: one sensitive temperature in stripping section

[4] temperature setpoints corrected by master composition controller

4. Results

The proposed control structures are subjected to disturbances such as changes in feed rate, feed composition, feed vapor fraction and as well as product composition setpoint changes. The results for the same are summarized in table 2. The tables shows that the effect of disturbances namely feed rate, feed composition (z_F) changes, feed vapor fraction changes and also change in product compositions setpoints.

We see that the CS1 fails for the disturbances of feed composition changes in components propanol (C) and n-butanol (D). This response can be explained using the V-min diagram shown in figure 2. The black line in the figure show the V-min diagram for the nominal feed and the red line show the V-min for the changed feed compostion of z_F = [0.25 0.25 0.20 0.30]. The minimum boil up required (= the boil required for most difficult binary split) for doing the sharp separation for the new composition is now set by the point V_{AB} in the figure instead of V_{CD}. The CS1 fails as the boilup (MV10) can not “see” this changed requirement. This leads to CS2, where boilup now controls sum of light keys in products B, S_1 and S_2. The CS2 also thereby ensures a two point control in C31 and C32 also leading to a more robust control structure. CS2 thus can handle all the disturbances under study.

Table 2: Summary of closed-loop responses using each control structure [1, 2]

Disturbance	Control Structures			
	CS1	CS2	CS3	CS4
Feed +10 %	Handles[1]	Handles	Handles	Handles
z_F = [0.20 0.30 0.25 0.25]	Handles	Handles	Handles	Handles
z_F = [0.25 0.20 0.30 0.25]	Handles	Handles	Handles	Handles
z_F = [0.25 0.25 0.20 0.30]	**Fails**	Handles	Handles	Handles
z_F = [0.20 0.25 0.25 0.30]	Handles	Handles	Handles	Handles
z_F = [0.20 0.25 0.30 0.25]	Handles	Handles	Handles	Handles
z_F = [0.25 0.20 0.25 0.30]	Handles	Handles	Handles	Handles
$q_F = 0.8$	Handles	Handles	Handles	Handles
x_D= -5%	**Fails**	Handles	NA[2]	Handles
x_{S1}= -5%	Handles	Handles	NA	Handles
x_{S2}= -5%	Handles	Handles	NA	Handles

[1] Handles: Implies that the response is stable. In case of CS1, CS2 and CS4, no/little steady state composition offset. In case of CS3, there shall be steady state composition offset.

[2] NA: CS2 is temperature inferential. Product composition setpoint changes can not be given directly.

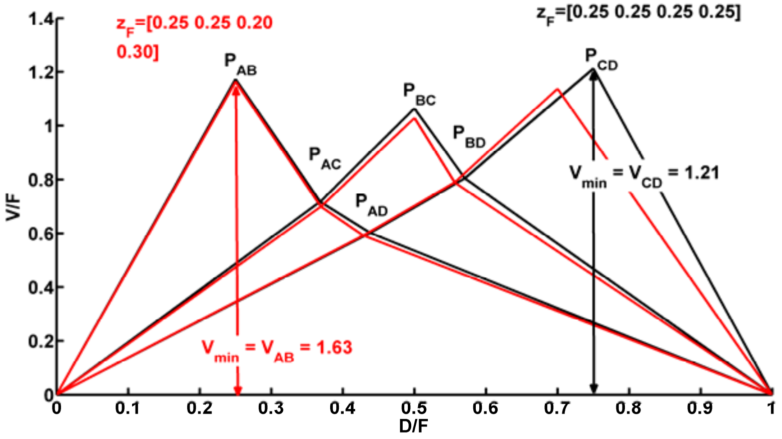

Figure 2: V-min diagrams for given feed.
Black lines: z_F=[0.25 0.25 0.25 0.25]; Red lines: z_F=[0.25 0.25 0.20 0.30].

CS3 is a temperature inferential controller, although all response is stable for all disturbances, there are large product composition offsets for some disturbances. This is because the prefractionator columns C1, C21 and C22 handle separation of multiple components. To get sharp separations, the temperature control alone is not sufficient and temperature setpoints need correction by a supervisory composition controller. This leads to the CS4, where the temperature setpoints are adjusted to get back to the same purity specification in the event of feed composition disturbances.

5. Conclusion

This study proves that thermally coupled columns like 4-product Petyluk arrangement can be operated using simple decentralized regulatory controllers using either composition measurements or temperature measurements. The composition based CS2 and CS4 could handle all the disturbances under study and the product purity of all the products could be restored.

The control problem is multivariable and there are significant interactions. The control performance can be improved using advanced multivariable controllers can be considered for future works. The expensive compositions measurement can be replaced by soft sensors and can be an interesting future work.

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