

Optimal operation of thermally coupled Kaibel distillation columns

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Abstract

The objective of this paper is to study the Kaibel distillation column from operability point of view. Two different objectives, namely minimizing energy consumption at fixed product purities and maximizing product purities with a fixed boilup are considered. We have visualized the objective functions around the optimum. This can be used to get insight in column behavior and as a basis for control structure design.

Keywords: Kaibel column, thermally coupled distillation columns, optimal operation

1. Introduction

The thermally-coupled Petlyuk¹ distillation column separates the feed into three products in a prefractionator-sidestream arrangement with a direct coupling of vapor and liquid streams between prefractionator and main column. The arrangement has only a single reboiler and a single condenser. The divided-wall distillation column (DWC) realizes the fully thermally coupled Petlyuk column in a single shell. This arrangement can be further generalized by adding a second side stream to give the Kaibel² arrangement which is capable of separating four products with a single reboiler and condenser. This tight integration makes it challenging to design and control the column, compared to the conventional sequence of simple columns. The design challenges have been mostly solved, but operation and control remains largely an open issue.

There are two main issues in terms of operation and control. First, the column, and in particular the column profile, needs to be "stabilized" to avoid drift^{3,4}. This dynamic issue is not studied in this paper. Second, the column needs to be operated as close to its optimum as possible in terms of minimum energy. This is mainly a steady-state issue and is the focus of this paper. It is important because a main motivation behind the Kaibel column is to save energy. The problem is to achieve this in practical operation where there may be unknown disturbances and model uncertainty and we mainly need to rely on temperature measurements.

In terms of optimal operation it is usually assumed that the objective is to make products of given purity using the minimum energy. However, in practical operation this is often not the issue, but rather to make the purest possible products with a given energy. In the paper we discuss both these cases.

The issue is to find a good control structure, including selecting which temperatures to control. This is an important issue for practical industrial operation. In this work, we use the approach of self-optimizing control for selecting the appropriate control variables for the divided-wall distillation column. Self-optimizing control is when we can achieve an acceptable loss L (in terms of energy or in terms of purity) with constant setpoint values c , for the controlled variables⁵. We will not consider this procedure here, but rather aim at obtaining insight into the column behavior which may be used for selecting candidate feedback variables.

2. Minimizing the energy consumption

The model under study is shown in Figure 1 and is considered for separation of the first four simple alcohols (Methanol, Ethanol, 1-Propanol, 1-butanol). Since the product purities are fixed in this case, there remain two degrees of freedom (vapor and liquid splits) which are used to minimize energy consumption. Since the products purities are constraints, the splits are inter-related and do not have such a freedom to be changed independently as optimization variables to get to the minimum energy requirement. So, it is difficult to run the optimization program as is done for the other case. Therefore, to get a feeling about where the optimum is, the minimum vapor rates is found from the V_{min} -

diagram⁶. We use these rates together with the pinch point compositions at the ends of the prefractionator from the ideal as an initial guess. Figure 1 shows the structure which is used for this purpose with the Vmin-diagram. The flow rates and compositions of the returning streams (R2 and VB2) to the prefractionator are obtained from the ones which are entered in the prefractionator column (R1 and VB1). The split values from this simulation are used in the original model to find the minimum energy required for the separation.

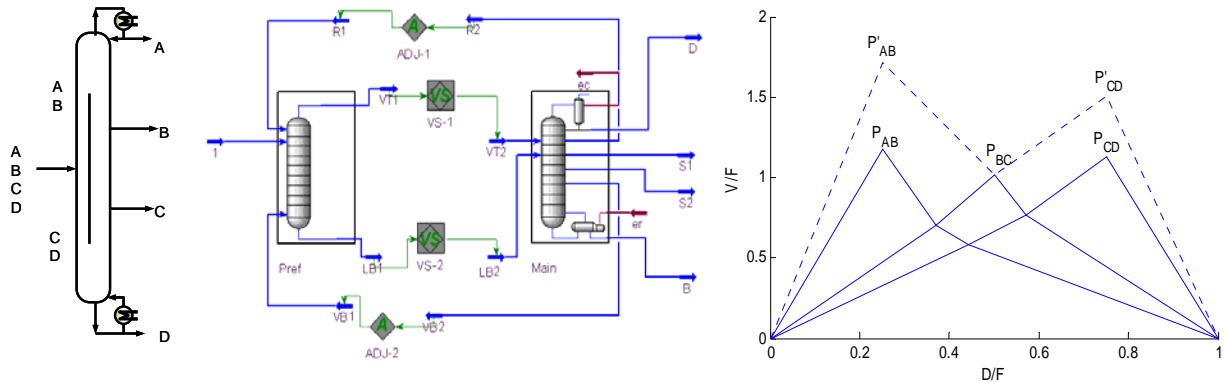


Figure 1. Kaibel column schematic (right), HYSYS simulation to use the information from V_{min} diagram as initial estimate, V_{min} diagram

The peaks at the dashed lines give the vapor flow rate requirement to separate A/B and C/D in a Kaibel column, when the prefractionator does a sharp AB/CD split. The highest peak (here P'_{AB}) determines the overall energy consumption of the Kaibel column, so the lower part of the column has more energy available than required. This can be utilized to obtain somewhat higher purity or to reduce the number of stages. The other point is that unlike Petlyuk column where we normally have a certain slack in the prefractionator operation regarding distribution of the intermediate component (B), the Kaibel-column prefractionator must perform a relatively sharp split between component AB and CD, given by the P_{BC} in the V_{min} -diagram. We can find a certain slack if we allow nonsharp split, but this is limited by the product specifications. Prefractionator operation with higher vapor rate than at P_{BC} could give us some slack also for sharp AB/CD split, but this will lead to higher vapor requirement to split A/B and C/D in the succeeding sections.

Visualization of the cost function gives a qualitative insight into the problem at hand. Since there are two optimization variables, the solution surfaces can be shown in 2-dimensional plots. As it is shown in figure 2, there exists multiplicity in the solution. This is due to two different ways for impurity flows to go to products - namely from top or bottom of the prefractionator.

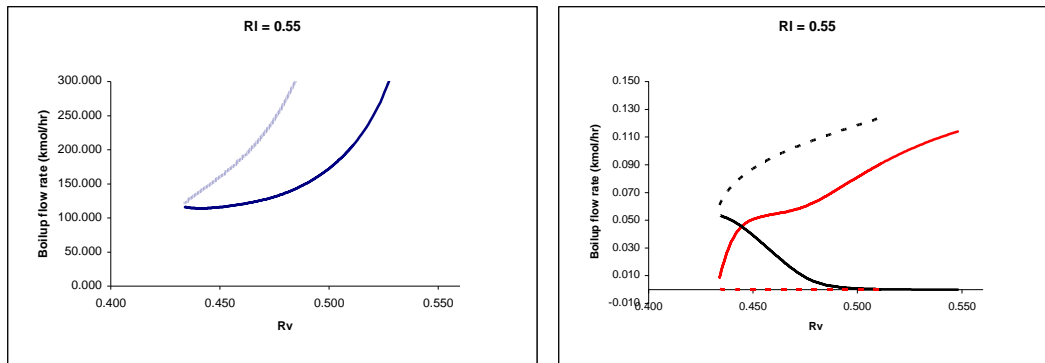


Figure 2. Boilup rate as a function of liquid and vapor splits at constant product purities (left). Impurities of C2 and C3 in the ends of prefractionator (right), red for C3 and black for C2 respectively. The solid lines in the right figure correspond to the solid line in the left figure

Figure 3 (left) shows the dependency of boilup rate to the vapor split as liquid split changes in a wide range. It shows the general trend of change of the minimum vapor as the splits are changing and the span for one split value in which there is a feasible solution as the other one is fixed. Also, the location of minimum is clearer in this figure. The contours of the objective value are shown in Figure 3 (right). In the 3-dimensional graph, they are like thin bended cones. The cross-sectional area of the cone will increase as boilup flow rate increases. This figure also shows that for the case which feed quality is zero, RI is greater than Rv, especially near the optimal point. The opposite rule applies for $q=1$. The reason is quite obvious (e.g. for $q = 0$, since a part of vapor needed for separation is provided by the feed itself, so it needs more liquid than vapor to contact)

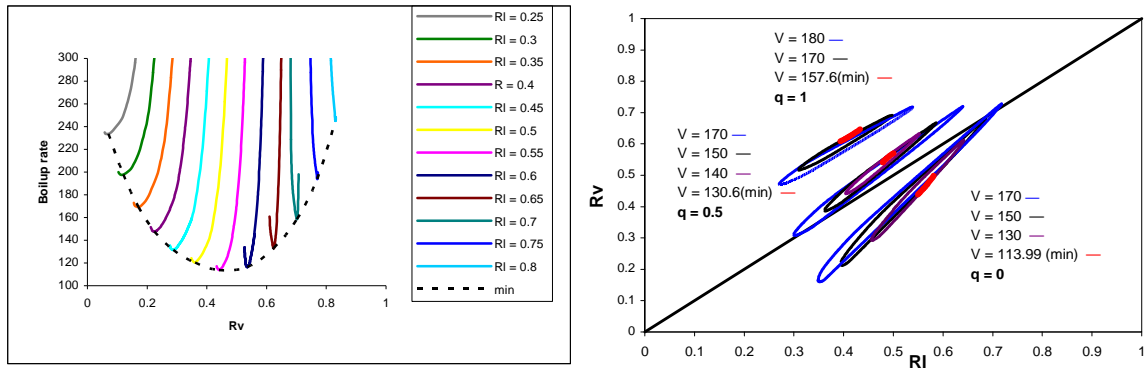


Figure 3. Boilup rate versus vapor split at different values of liquid split ($q = 0$) (left), Contours of Boilup as a function of splits (right)

In industrial practice it is not common to adjust the vapor split online. It will normally be given by the dividing wall placement and flow/pressure characteristics of the packings and the liquid load on each side. The results show that the optimal region is narrow and we are actually forcing the process to go through a very restricted area to reach the purities set. So, the liquid split has to be adjusted carefully to obtain minimum energy.

Note that it is possible to increase some of the products purities with the same amount of vapor flow rate as it is shown in figure 4. This is clearer when we continue with the case where we fix the vapor rate and minimize the sum of impurities in the following section. Some of the products will then easier obtain higher purity than the other. This is due to both the actual selected number of stages and to the extra energy available in the parts of the column related to the lowest peak in the V_{min} -diagram (here the bottom split related to P'_{CD}). Thus, this should be considered when specifying the individual product purities with the minimum energy objective since only the most difficult splits are actually setting the energy requirement.

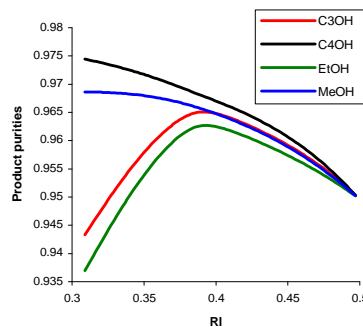


Figure 4. Product composition change with change of splits at fixed boilup rate ($V = 170$ kmol/hr)

3. Maximizing product purities with fixed boilup rate

The Objective function is defined to produce the purest products possible while the boilup flow rate is fixed. Two different cases will lead to this kind of definition.

1. If all the prices for the products are equal and we only get paid for the main component. J is then the loss compared to the pure products.
2. If products 2 (first side stream) and 4 (the bottom product) are as valuable as feed and the distillate and second side stream are the valuable products. In this case, loss compared to the ideal profit (pure products) is defined as the previous case.

The optimal steady state solution is reached with a specified boilup rate and with the other degrees of freedom optimized such that the products will be as pure as possible. Table 1 shows the results of the two cases studied in this paper. The numbers in bold in each column are fixed during the optimization. The optimal composition profile for the nominal case and the optimal temperature profiles for the nominal case and different disturbances are shown below (Figure 5). It is seen that the temperatures in the middle trays (trays 15-33) of main column and middle of the prefractionator remain constant after applying disturbances. So, these temperatures are good candidates to be control variables. Combinations of measurements which show self-optimizing properties can be also considered as control variables⁷.

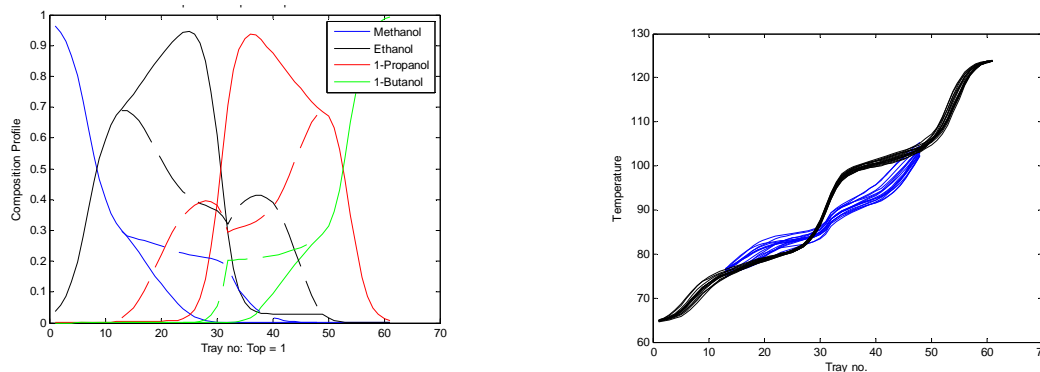


Figure 5. Optimal composition profile (left) and Optimal temperature profiles for various disturbances in feed compositions (5%), liquid fraction (10%) and boilup flow setpoint (5%) (right)

Table 1. Optimal steady-state solution (equimolar feed of 100kmol/hr which is saturated liquid)

	Case 1 (min. boilup rate)	Case 2 (max. product purities)
R_L	0.41	0.4009
R_V	0.623	0.6179
Reflux Ratio	5.97	6.375
S1 flow rate	24.24	24.93 kmol/hr
S2 flow rate	24.53	26.22 kmol/hr
V	157.77	157 kmol/hr
Objective value	157.77	0.00108
Methanol	95	98
Ethanol	95	94
1-Propanol	95	94
1-Butanol	95	99

For control purposes it is interesting to know how different manipulated variables affect the process. The following figures show the dependency of product compositions and the objective value to each of the manipulated variables while all the others are kept constant at their nominal point. The objective value shows a linear dependency on the manipulated variables away from the optimum. The degree of effect of a change in each variable on the objective value is clear in these figures. For example, the deviation of S1 from the optimal point has more effect on the objective value than S2. It can be seen

that any change in Reflux and side streams flow rates will affect the purities below. For example a change in S1 flow rate does not have any effect on the purity of the distillate stream. Likewise, the change in S2 flow rate does not have any effect on the purity of the distillate and S1 streams. By considering each of the 4 parts as a separate column, we can easily confirm the results by analyzing the amounts of internal flows in each part and how it affects the separation. Often in distillation, the internal flows, reflux and boilup, are used as control degrees of freedom. In a two-product multi-component distillation column, the effect of changing an internal flow on the concentration profile is to move the whole profile; one product tends to get purer, whereas the other gets less pure. However, the effect of changing the external flows is much larger, if one draws a lot more in the top stream as there is light component in the feed, it is obvious that the product purity will be lower. The use of external streams as controlled variables is limited, because they are often needed in order to stabilize levels in the reboiler and reflux drum.

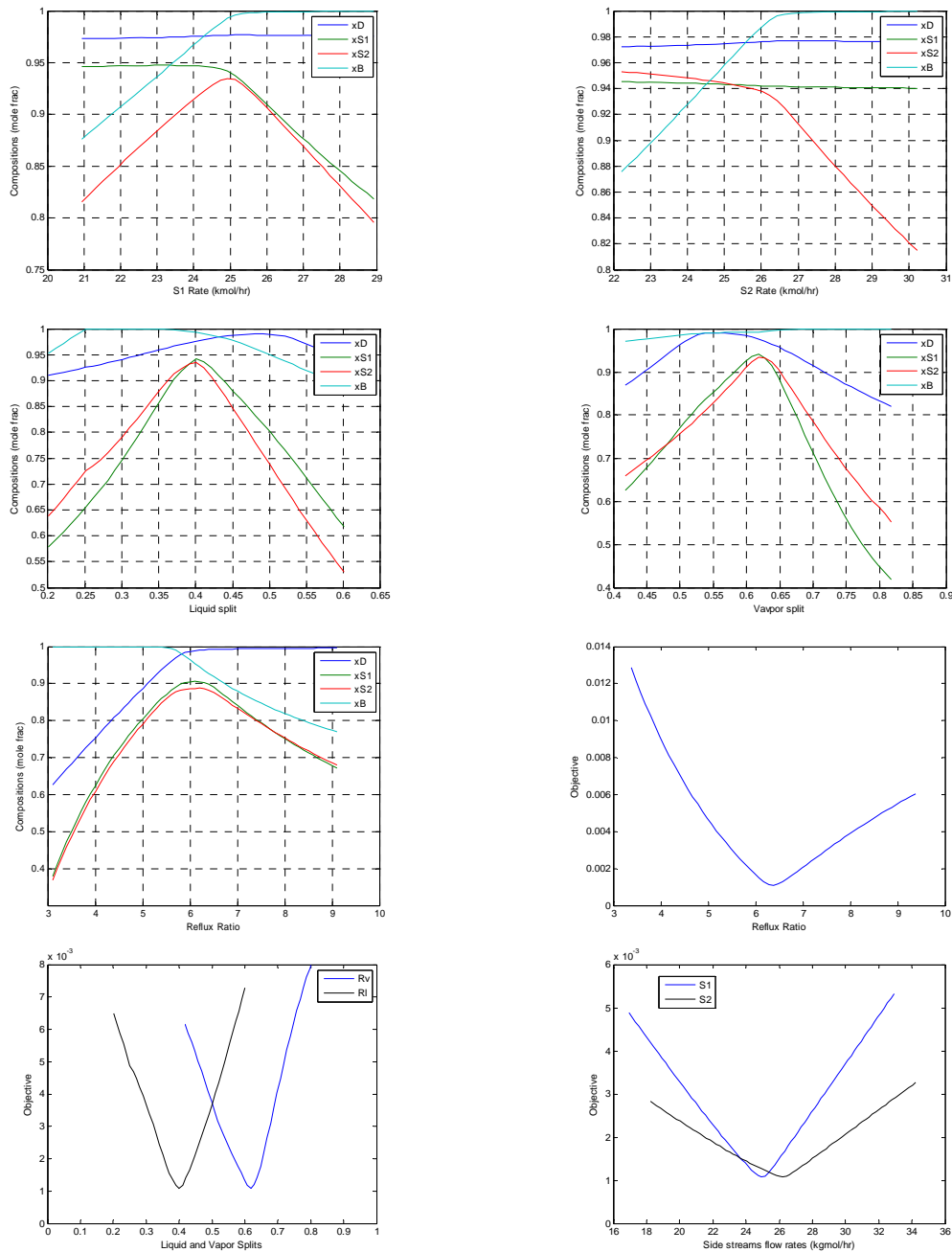


Figure 6. Optimal Functionality of the objective value and products compositions of manipulated variables, one at a time

Since there are five manipulated variables, it is difficult to sketch the solution surface in this case. The following figures are 3-dimensional surfaces which show how the objective value is affected by splits and side stream flow changes. Like the previous case, there is bad direction for both of them along which a small change in one of the variables will result in a large change in the objective value.

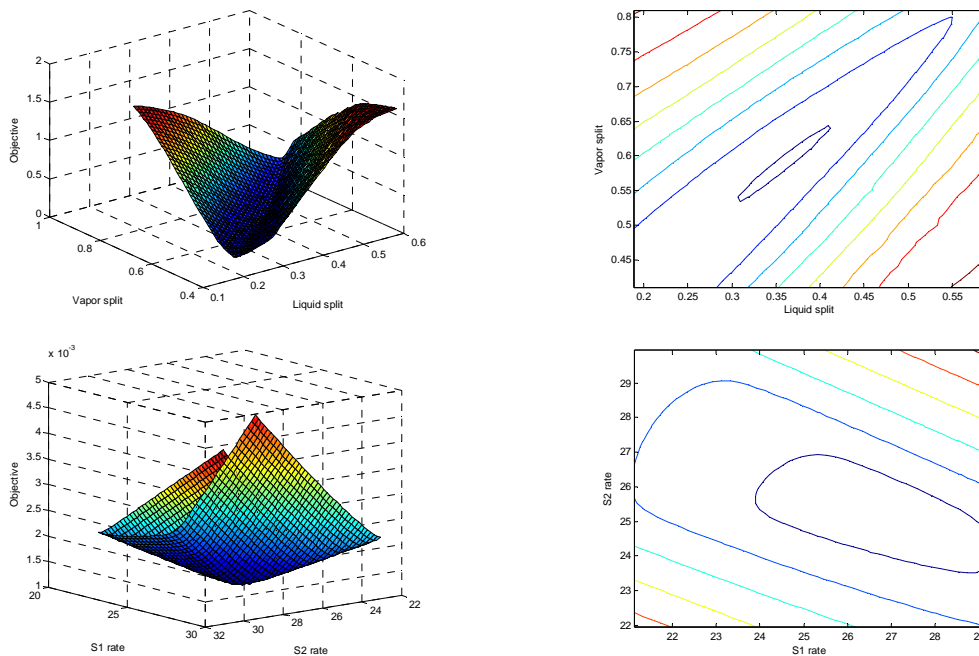


Figure 7. 3-D surfaces and contour plot of objective functions as a function of manipulated variables, the other variables are fixed at optimal value

4. Conclusions

In this paper, two alternatives for operating a Kaibel column are studied. By comparing two cases, it is shown that the first option which is minimizing vapor flow rate at constant product purities is the more difficult case to handle. This difficulty is due to the very narrow solution surface and also multiplicity problem. This case has been more attractive by researchers so far. However, the second case is more interesting in practice.

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