Paper 5a

Improved Analysis and Understanding of the Petlyuk Distillation Column

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Extended Abstract

The Petlyuk (Petlyuk 1965) arrangement for separation of a ternary mixture into three pure product streams has the potential of 20-50% energy savings compared to conventional distillation sequences. However, very few are in industrial use. The reasons for this have been listed as lack of established design procedures and difficulties in control. In this paper, the minimum energy requirement have been analyzed for columns with infinite number of stages.

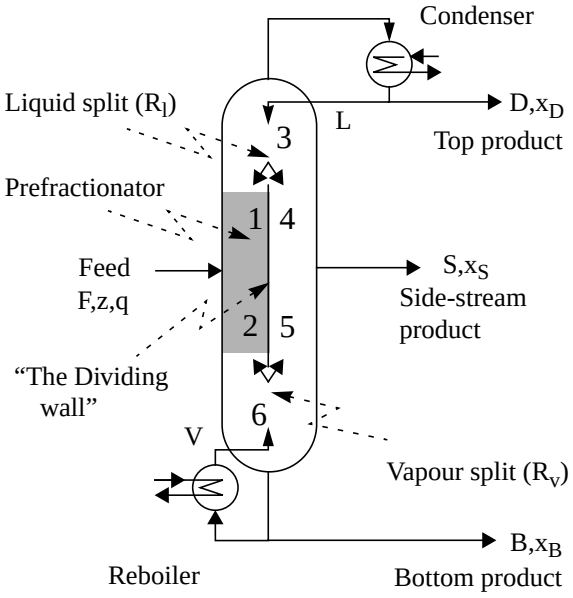

Fig. 1 The Petlyuk distillation arrangement implemented as a Dividing Wall Column

The Petlyuk column, shown in Fig. 1, has at steady state five degrees of freedom, which may be selected as the following manipulated input variables: Boilup (V), reflux (L), mid product side-stream flow (S), liquid split ($R_l=L_1/L$) and vapour split ($R_v=V_2/V$). There are three main product purity specifications: Top (x_{Da}), bottoms (x_{Bc}) and side-stream (x_{Sb}). A very important issue is then that we have more degrees of freedom (5) than product specifications (3 in this example). The two extra degrees of freedom can be used for optimization purposes, like minimization of the energy consumption. When the column is operated optimally, the infinite staged Petlyuk column always consumes less energy than the corresponding

conventional solution, (Fidkowski 1986). However, this optimal operation may be difficult to achieve in practice since the optimal operation depends strongly on the feed properties and the remaining degrees of freedom (Halvorsen and Skogestad 1999a).

A new approach based on the methods of Underwood (Underwood 1946 1948) have been developed. The methods apply to cases with constant relative volatilities and constant molar overflow. Two important extensions compared to earlier work is that we consider non-sharp product splits and that we consider the energy usage in a larger region of operation parameters.

With the presented method it is possible to handle any multi component feed and compute the minimum energy requirement for an arbitrary specification of the three product streams. For example for a 5 component feed with the components ABCDE, we may specify A as the light key, BC as the middle keys and D as the heavy key, thus the three product streams will consist of A,BC and DE. We may also specify non-sharp product splits. A more detailed treatment of the Underwood approach is found in (Halvorsen and Skogestad 1999b)

It is shown that the minimum energy solution for the whole Petlyuk arrangement can be found directly from the Underwood roots for the feed entering the system.

The Petlyuk arrangement has more degrees of freedom than required to specify the product compositions and maintain pressures and liquid levels in the reboiler and accumulator. With three product specifications we usually have two remaining DOFs when all these specifications are met. There are several alternative choices for the remaining DOF variables. We have used the liquid and vapor split ratios (R_l,R_v), but any two independent manipulated variables can be used. The overall energy consumption will then be a function of the degrees of freedom (R_l,R_v), the feed properties (z,q) and the product specifications (x_{Da}, x_{Bc}, x_{Sb}). We choose to use the reboiler vapour flow V as a measure of the energy consumption.

The minimum energy solution can only be obtained for the optimal values of the remaining DOFs. Several authors, (Fidkowski 1986) and (Carlberg and Westerberg 1989) have shown that optimal operation for sharp product split and infinite number of stages is obtained in a region along a certain straight line in a plane spanned by the two remaining DOFs. One endpoint of this optimality region (line) is characterized by operating the prefractionator at absolute minimum energy consumption (point P in figures 2-5), denoted preferred split (Stichlmair 1988), and the other by equal reflux requirement in the upper and lower part of the main column, which we denote a balanced main column (point R in figures 2-5).

However, very little attention have been given to study the performance of the column for expected deviations from a nominal operating point in presence of realistic disturbances and uncertainties. The behavior of the energy consumption for deviations from the optimal values of the remaining DOFs, is very important for operation of a real industrial column. The results in (Halvorsen and Skogestad 1999) show that the energy consumption may get far above the optimal value it the column is not properly operated.

In Fig. 2 and Fig. 3 we show the energy consumption as a function of the liquid and vapours splits. The optimality region is found at the straight line segment from P to R.

We also presented new analytic methods for computation of the energy consumption as function of the liquid and vapor splits for any set of feed conditions and for sharp product splits.

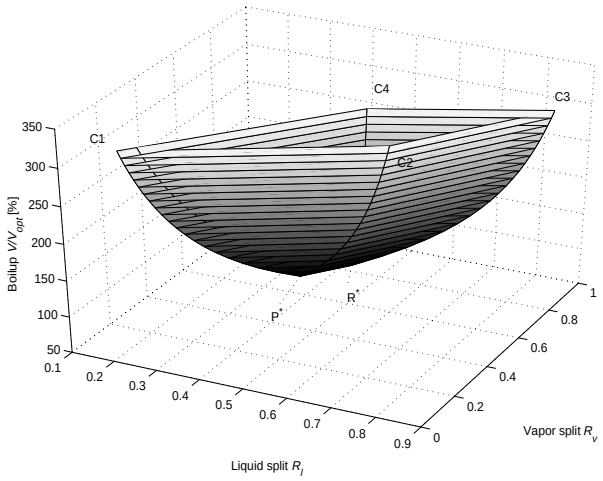

Fig. 2 The solution surface $V(R_l,R_v)$ for the case with infinite stages and sharp splits

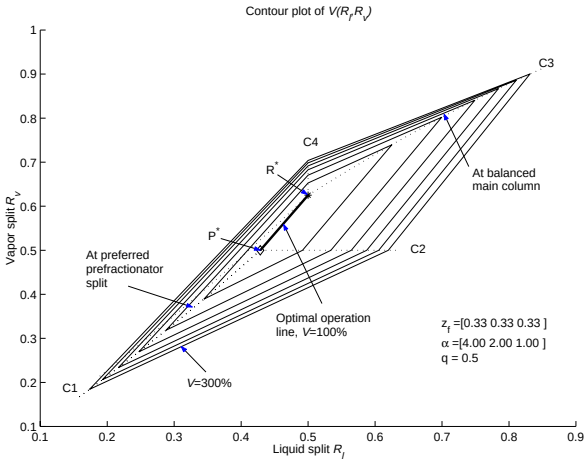

Fig. 3 The contour lines for $V(R_l,R_v)$ are straight lines between the four characteristic corners.

Interestingly, the critical feed conditions where we do not have any flat optimality region is also the region where the potential energy savings is largest (Halvorsen and Skogestad 1999a). So from the energy savings point of view, we would like to operate there, but such operation sets higher requirements to the control strategy compared to the conditions where the flat optimality region is wide. Fig. 4 illustrates the theoretical savings as a function of feed composition for three separation cases

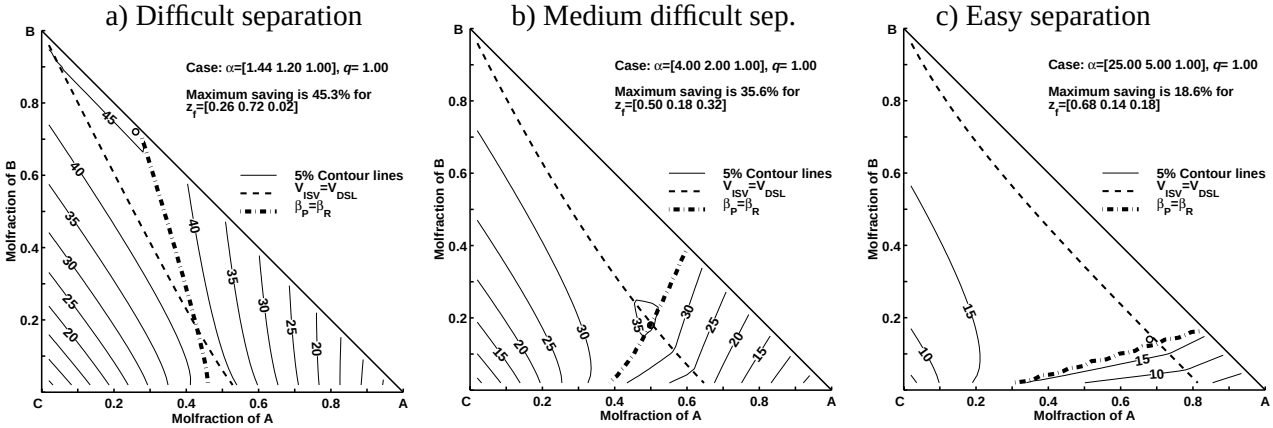

Fig. 4 Contour plots of the savings as function of feed composition with the Petlyuk column compared to the best of the conventional direct split or indirect split configurations. The curve denoted $\beta_P = \beta_R$ in the legend is at feed conditions where the preferred split (P) coincide with a balanced main column (R).

In this work we extend these methods to handle cases with non-sharp product specifications. Then we find that minimum energy now can be obtained in a parallelogram-shaped region in the DOFs plane. And the width of this region is directly related to the purity specification of the side-stream product. This result also explains that it may be difficult to obtain high purity in the side stream if the DOFs are not set properly, and the energy is limited.

The area of this flat optimality region in terms of the two remaining DOFs is very important for the control requirements. If the region is wide in both directions, me may keep both the remaining DOFs constant, and if it is narrow me may require on-line adjustment of both DOFs in order to achieve the potential energy savings. If the optimality region is flat in only one direction, we may keep one DOF constant, but on line adjustment of the other is probably required.

It is shown that the parallelogram-shaped area of the flat optimality region is determined by two factors, one for each direction of the parallelogram.

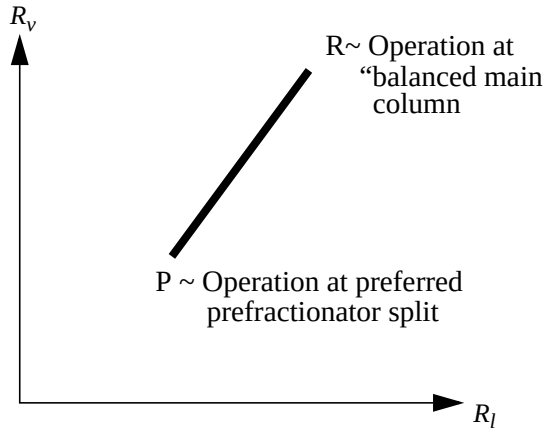

Fig. 5 a) The optimality region is found along a straight line in the (R_l,R_v)-plane for a high purity sidestream product (sharp splits).

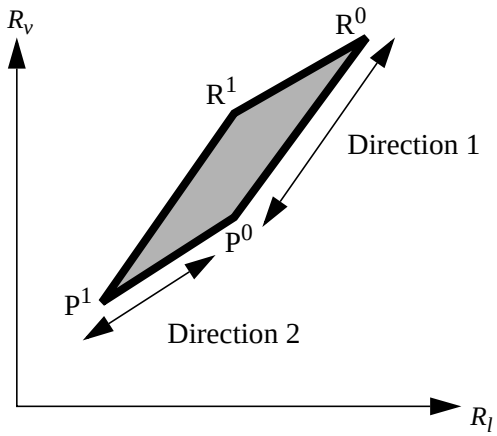

Fig. 5 b) The optimality region "opens" up to a parallelogram shaped area when we allow impurities in the sidestream product.

Direction 1:

We get a large flat region when the feed conditions (composition, liquid fraction and relative volatilities) is far from the boundary where the operating points for a preferred prefractionator split coincide with a balanced main column. (This boundary is illustrated in Fig. 4 as the curves where $\beta_P = \beta_R$ for the three cases).

Direction 2:

Low purity in the side-stream product gives a large flat region. In this case the "preferred split" will be along the line P^0P^1, where P^0 is the "old" preferred split based on sharp heavy/light split in the prefractionator, and P^1 corresponds to operation at the minimum prefractionator energy when all the impure component to the sidestream is coming from a nonsharp split in the prefractionator. Similarly the "balanced" operation point R for sharp product splits, will become the line R^0R^1, dependent on which path the sidestream impurity takes from the feed to the sidestream (above or below the dividing wall).

Based on our results it is better understood why we may get control problems and difficulties in obtaining the energy savings in practice. And we can explain why we in some cases cannot obtain the specified purity, especially in the sidestream, even if the energy input is above the theoretical minimum.

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Several publications are available at these web pages:

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