IFAC-symposium DYCORD+95 Denmark, June 95

COMPARISON OF INVERTED AND REGULAR BATCH DISTILLATION

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Abstract. Several alternative strategies have been suggested to increase the productivity of batch distillation columns. One is the use of inverted columns where the feed is charged to the condenser drum instead of to the reboiler. We find that an inverted column is best for separations with small amounts of light component in the feed. The reason is that it takes a long time to move this small amount from the reboiler to the top before removal when a regular column is used. The regular and the inverted column are found not to be mirror images of each other. This is because the inverted column considered in this study is *not* the true inverse of the regular column since the feed and product are in liquid phase. The ideal inverted column with feed in vapor phase is briefly discussed.

Key Words. Batch distillation; optimization; inverted vs. regular coloumn

1. INTRODUCTION

The use of an *inverted* or stripping column where the feed is charged to the condenser instead of the reboiler, was originally proposed by Robinson and Gilliland (1950). They stated that the main advantage with this configuration was that the most volatile components would be collected in the condenser drum in high purity. They briefly discussed the possibility of running the column first in a normal batch fashion to remove the lighter components and then inverted to remove the heavier constituents. They also discussed a combined operation where the feed was added to the middle of the column and the light and heavy components were taken off simultaneously over the top and bottom respectively.

The combined operation was studied by Hasebe at al. (1992) who denoted this column configuration a *complex column*. They also discussed the difference between regular and inverted columns. They claimed that a regular column always has a better separation efficiency than an inverted column if the separation conditions are the same and the relative volatility is constant ("inverted" separations). The conclusion was based on a comparison between the equilibrium curves and operation lines for a regular and an inverted column with all other conditions equal.

Mujtaba and Macchietto (1992) discussed use of a complex column to improved the operation of reactive batch distillation. They found that this column configuration improved conversion and product yield significantly when the reaction products had two extreme boiling points (highest and lowest in the reaction mixture). The use of an inverted column for cases where the reaction product had a higher boiling point than the reactants was suggested but no examples where given. Mujtaba and Macchietto (1994) discussed use of inverted and complex columns for an example with reactive batch distillation. For this example the inverted column gave a lower conversion than the regular column. This was explained in terms of the difference in relative volatility between the heavy components compared to between the light ones.

Chiotti and Iribarren (1991) presented simplified models for binary batch distillation in both regular and inverted columns. They included an intermediate cut which was recycled to the next feed charge. Their models were based on the assumption of pseudo-steady-state in the column. Numerical integration was thereby avoided. They stated that the inverted column was more economical than the regular one for heavy products of high purity. They presented two numerical examples where they optimized the total annual cost for two separations in both an inverted and a regular column. Chiotti *et al.* (1993) extended these models to multicomponent mixtures. They also considered columns which could be used for both rectification (regular column) and stripping (in-

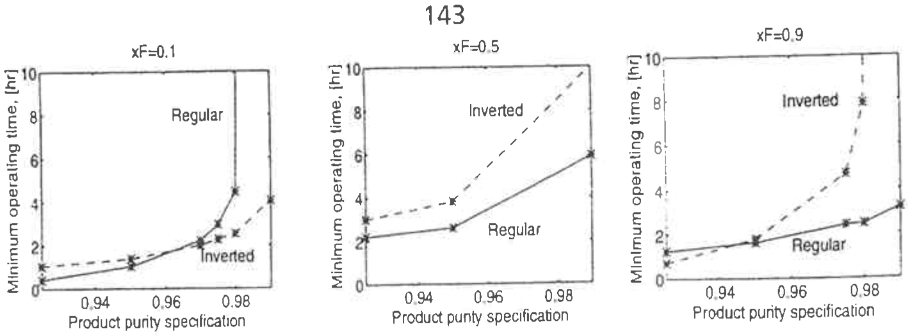

Fig. 2. Minimum operating time t_f as a function of purity specifications x^{spec} for a regular and an inverted column.

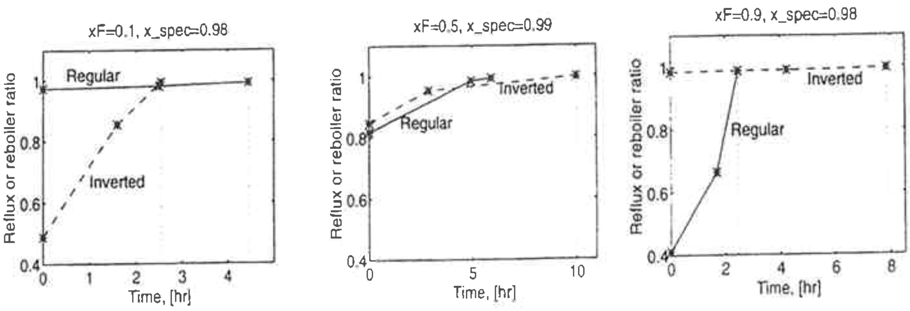

Fig. 3. Optimal reflux ratio R and reboiler ratio R_B.

Table 2 Minimum operating time t_f for varying purity specifications x^{spec} for regular and inverted column (Same purity specification x^{spec} for both products).

Purity specification x^{spec}	Minimum operating time inverted column t_f, hr	regular column t_f, hr
	Feed composition $x_F = 0.1$	
0.925	1.043	**0.409**
0.950	1.369	**1.024**
0.975	**2.264**	2.940
0.980	**2.532**	4.448
0.990	**4.041**	>100
	Feed composition $x_F = 0.5$	
0.925	3.022	**2.200**
0.950	3.807	**2.610**
0.990	10.010	**5.905**
	Feed composition $x_F = 0.9$	
0.925	**0.709**	1.248
0.950	1.791	**1.630**
0.975	4.691	**2.410**
0.980	7.856	**2.462**
0.990	>100	**3.192**

able is involved, several local minima may exist.

2.3. *Results*

We consider 13 cases with different values for the feed composition and product specifications (Table 2). Other operating parameters are as given before (Table 1). The minimum operating time is presented for the 13 cases in Table 2 and shown graphically in Figure 2. The corresponding optimal reflux and reboiler ratios are shown for three of the cases in Figure 3 and details on how the compositions change with time are shown in Figure 4 for one case.

From Table 2 and Figure 2 we see that the inverted column has indeed a shorter operating time than the regular column for some separations. We find that the inverted column is better for cases where the products are to be recovered at high purity from a feed *low in light component* ($x_F = 0.1$), whereas the regular column is best for cases where the products are to be recovered at high purity from a feed *rich in light component* ($x_F = 0.9$). The regular column is found to be better than the inverted column for all symmetrical separations, $x_F = 0.5$. However, more importantly, for some specifications the inverted column gives a moderate operating time when the separation is not even possible in the regular column (e.g. $x_F = 0.1$ and $x^{spec} = 0.999$). The inverted column is best when x_F is small because it takes a long time to "move" a small amount of light component from the reboiler to the top of the column when a regular column is used.

The reflux and reboiler ratios in Figure 3 are very close to 1 for separations where a small amount of product is to be withdrawn from the column leaving a large amount of the other product as residue (e.g. $x_F = 0.1$ in the regular column and $x_F = 0.9$ in the inverted column). The compositions of the products in the residual and the accumulator are given in Figure 4 for a case when the inverted column is best ($x_F = 0.1$ and $x^{spec} = 0.98$). For the regular column, the accumulator composition is

From Figure 5 it can be seen that, for the case with a small amount of "withdrawn component", the product composition for the inverted column drops below the specification $x_{B,heavy}^{spec} = 0.9$ very quickly. For the regular column however, the separation is satisfactory. On the other hand, from Figure 6 we see that for the case with a large amount of "withdrawn" product, the specification for the product composition is held longest for the inverted column.

Conclusion:

- The regular column has a faster approach to equilibrium than the inverted column for "inverted" separations with a *small* amount of "withdrawn" component in the feed (light in the regular column and heavy in the inverted column).
  The regular column is able to maintain a high product composition for a longer period, which again will result in either a larger amount of on-spec product or a shorter operating time for this column.
- For "inverted" separations with a *large* amount of "withdrawn" component in the feed (light in the regular column and heavy in the inverted column), the situation is the opposite. A faster approach to equilibrium and a longer on-spec period is found for the inverted column. The conclusion by Hasebe *et al.* (1992) that the regular column always has a better separation efficiency than the inverted column is thereby found to be incorrect.

4. IDEAL INVERTED COLUMN

The true inverse of a regular batch column is denoted an ideal inverted column in the following. It has the following properties:

- The liquid feed in the reboiler of the regular column is vapor feed in the condenser of the ideal inverted column
- The liquid holdup in the condenser of the regular column is vapor holdup in the reboiler of the ideal inverted column
- The product is taken out as liquid in the top of the regular column but as vapor from the bottom of the ideal inverted column
- The trays are filled with liquid in the regular column but with vapor in the ideal inverted column
- The vapor holdup is neglected in the regular column but the liquid holdup is neglected in the ideal inverted column (with our model assumptions)
- The vapor flow is specified in the regular column but the liquid flow is specified in the ideal inverted column

Finally, for constant relative volatility the separation is equivalent provided the liquid mole fraction of light component in the regular column is the mole fraction of heavy component in the inverted column. This follows since

$$\frac{y_{light}/x_{light}}{y_{heavy}/x_{heavy}} = \alpha = \frac{x_{heavy}/y_{heavy}}{x_{light}/y_{light}} \quad (5)$$

Note that one may directly obtain operational data for the ideal inverted column from data for a regular batch column. One then needs to reverse the data as follows:

$$L^{inv} = V^{reg}, \quad y_F^{inv} = 1 - x_F^{reg},$$
$$y_A^{inv} = 1 - x_A^{reg}, \quad y_R^{inv} = 1 - y_R^{reg} \quad (6)$$

(We use y_F, y_A and y_R to denote that these are vapor phase compositions.)
The data in the right column of Table 2 which are for a regular column with vapor flow $V_B = 10$ $kmol/hr$, will therefore correspond to data for an ideal inverted column with reflux flow $L = 10$ $kmol/hr$. For example, for the case with $x_F = 0.9$ and $x_A^{spec} = 1 - x_R^{spec} = 0.99$ the minimum operating time is 3.19 hr when vapor flow is fixed at $V_B = 10$ $kmol/hr$. Thus, with $y_F = 0.1$ (feed is vapor), $y_A^{spec} = 1 - y_R^{spec} = 0.01$ and *reflux flow* L fixed at 10 $kmol/hr$, the minimum operating time in an ideal inverted column is 3.19 hr. (If we instead fixed the vapor flow at 10 $kmol/hr$ then the operating time would be even shorter.) It is interesting to note from Table 2 that in a practical inverted column this separation needs 4.04 hr which is significantly higher.

5. CONCLUSION

In this paper we have compared a regular and an inverted column in terms of dynamic behavior and optimal operation. The inverted column is found to yield the shortest operating time for separations where the light component is present in a small amount in the feed. This is because in a regular column, the relatively small amount of light component must be moved through the column from the feed end to the withdrawal end which is more time consuming since a very high reflux ratio must be used.
Note that Robinson and Gilliland (1950), who originally proposed the use of inverted columns, stated that the main advantage was that the light component would be collected in the condenser drum in high purity. This is confirmed in this paper.
We have found that the steady state profiles are equal, but the approach to equilibrium is different, for "inverted" binary separations (removal of light component in a regular column and of heavy component in an inverted column). This is because the inverted column is not the true inverse