회분식 증류공정의 최적성

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Optimality for Batch Distillation Configurations

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Introduction

Batch distillation is a popular separation process, especially in the fine chemicals and the pharmaceutical industries. Among the advantages of this separation technique is the ability to separate mixtures with a wide variety of number of components, compositions and degree of difficulty of separation in one column. Operation and control of the process are also relatively simple.

The oldest and most common batch distillation column is known as batch rectifier (Fig. 1a). The initial mixture is loaded into the reboiler and the products are drawn from the condenser. Robinson and Gilland (1950) proposed an inverted batch distillation design, the batch stripper (Fig. 1b), where the initial mixture is loaded into the condenser and the products are drawn from the reboiler. Sorensen and Skogestad (1995) found that the stripper is better than the rectifier, in terms of requiring less operating time, when the light component is present in small amounts.

It appears that Bortolini and Guarise (1970) were the first to propose a new batch distillation design - a column built up from two separation sections and a vessel in between (Fig 1c,d). The mixture to be separated is loaded into the middle vessel and the products are simultaneously withdrawn from the top and the bottom of the column. This column is a combination of a batch rectifier and a batch stripper and can be easily transformed to either one of them by setting one of the product flows to zero. Two modifications of the column concerning the design of the middle vessel can be considered. In the first case (Fig. 1c), the middle vessel can be considered as a feed tank (Hasebe et al., 1992) with the liquid in the feed tray recycled to the feed tank so that the composition of the liquid in the feed tank is close to that on the feed tray. In the second case (Fig. 1d) the middle vessel can be used as an additional condenser or reboiler by removing and supplying heat.

The batch rectifier and batch stripper have been studied extensively. Less work has been done on the column with a middle vessel. Devyatikh and Churbanov (1976) showed advantages over conventional batch distillation for some special examples. Hasebe et al. studied some of the characteristics of the column and presented results of simulations for binary and ternary mixtures with constant relative volatilities. Recently, Hasebe et al. (1995) proposed a multi-effect batch distillation system which can be viewed as a column with multiple intermediate vessels. A through analytical investigation of the minimum reflux model of the column with a middle vessel for mixtures with constant relative volatilities was carried out in a series of papers by Davidyan et al. (1991,1994).

The present work examines a new type of a batch distillation column consisting of two separation sections with a vessel in between. The behavior of the column is analyzed using the minimum reflux models. Using the minimum reflux model, the optimal control problem is solved when both products are pure throughout the separation process. It is shown that the minimum reflux/reboil ratio policy is optimal for the separation of an ideal mixture or any binary mixture. Based on the optimal operation policy and the minimum reflux model, various batch configurations are compared in minimizing separation time.

Minimum reflux conditions

The minimum reflux conditions allow us to obtain quantitative results in order to (1) find the optimal operating strategy of the column with a middle vessel and (2) study the dynamics of batch configurations and compare the performance of the different batch distillation configurations.

Operating strategy for the column with a middle vessel

We show that the minimum reflux/reboil ratio policy is optimal for the separation of an ideal mixture or any binary mixture in minimizing separation time.

Comparison of batch configurations

1. Binary mixtures

We compare the separation of the same amount of a binary mixture at minimum reflux conditions in three columns: batch rectifier, batch stripper and the column with a middle vessel. In order to equalize energy consumption the boilup in each of three columns is assumed to be the same. The composition of the distillate and the bottom products is specified. We find that:

1) Separation in the column with a middle vessel requires always less time than in a batch stripper or rectifier.

2) The relative separation time for the rectifier decreases while the one for the stripper increases as the relative volatility increases. This is because the rectifier becomes better than the stripper as the asymmetry of the vapor-liquid equilibrium curve increases.

3) Batch rectifier and batch stripper require more relative separation time as the product specification increases.

The comparison between rectifier and stripper in term of optimal operation is also studied. The stripper is better than the rectifier:

1) when the light component mole fraction in the initial charge is small and the product purity specification is relatively high.

2) when the light component mole fraction in the initial charge is large and the product specification is low or when the light component mole fraction in the charge is close to the product specification.

2. Ternary mixtures

We examine the region of optimality for the batch configurations. Four operating strategies (combinations) using conventional batch columns are available for the separation of ternary mixtures: rectifier and rectifier (RR); rectifier and stripper (RS); stripper and rectifier (SR); stripper and stripper (SS).

The column with a middle vessel is shown to be better than the RR configuration when the intermediate component is small. Surprisingly, when the intermediate component is large, that is, the light and heavy impurities are small, the new column is worse than the RR scheme. The RR scheme is preferred for the region where the light component is plentiful but the SS scheme is better where the heavy component is large. As the relative volatility increases, the optimality region for the RR scheme becomes larger. This is because as the relative volatility increases, the rectifier becomes better than the stripper due to the asymmetry of the vapor-liquid equilibrium curve similar to the binary case.

These results indicate that a separation scheme performs best when the final holdups of each of the two separation steps are small, i.e., the RR scheme performs best when the amount of the light component is large and the amount of the heavy component is small; the SS scheme performs best when the amount of the heavy component is large and the amount of the light component is small; the column with a middle vessel performs best when the amount of the intermediate component is small.

We propose the following heuristics for choosing the batch configuration for high purity separations: 1) Remove most plentiful component first; 2) Easy separation first. When the desired product purity is low, we should choose the scheme that puts the feed composition closer to the product specification. These ideas can be extended to the case of multicomponent mixtures.

Conclusions

The behavior of the column with a middle vessel and conventional batch distillation configurations were analyzed using the infinite separation and the minimum reflux models.

The optimal control problem for the column with a middle vessel was solved using the minimum reflux model. It was shown that the minimum reflux/reboil ratio policy is optimal for the separation of an ideal mixture or any binary mixture provided that both products are pure. The optimal operation was shown to be at the steady state for a binary separation when there is no tangent pinch.

Based on the optimal operation policy and the minimum reflux model, various batch configurations were compared in minimizing separation time. General guidelines were provided which configuration is best for a given mixture and the reasons for selecting a particular batch scheme were analyzed. Two heuristics were proposed for choosing the batch distillation configurations for the high purity separations: 1) Remove most plentiful component first; 2) Easy separation first.

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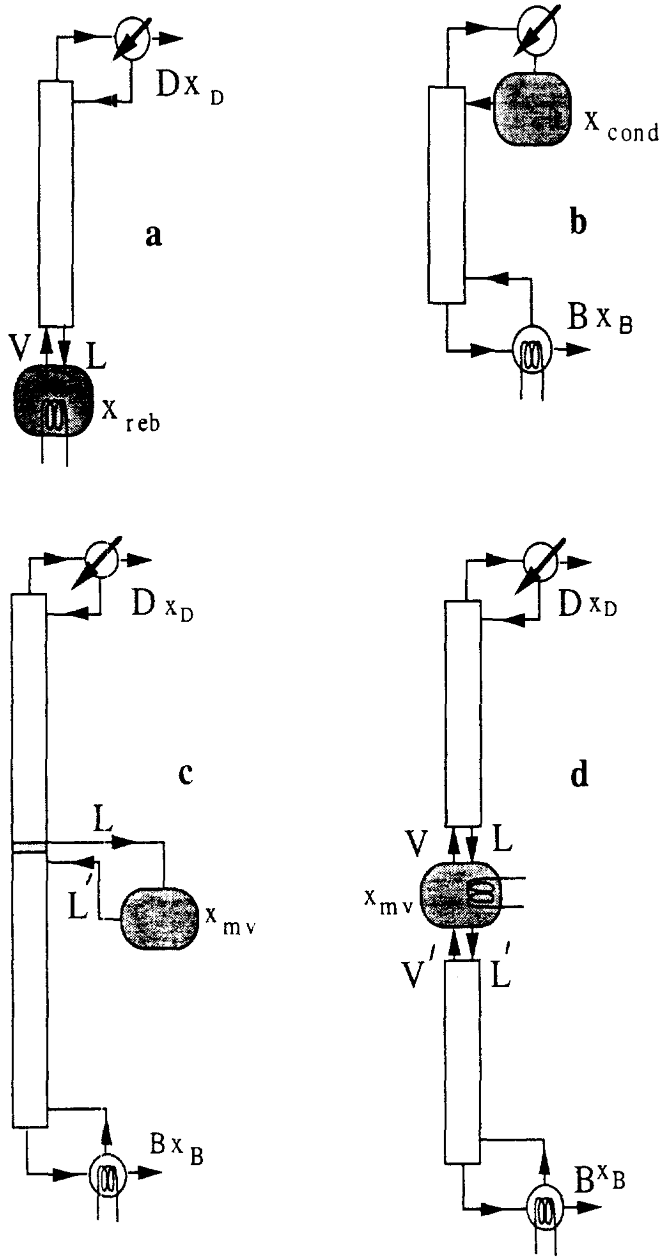

Figure 1: **Batch distillation design.**

a. Batch rectifier. **b.** Batch stripper. **c,d** Column with a middle vessel.