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A simplified and general approach to distillation with parallel streams: The cases of para- and metastillation

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ABSTRACT

This work presents a general approach for calculating the total number of ideal stages in para- and metastillation. The proposed methodology is based on the adaptation of the original McCabe-Thiele methodology. Parastillation involves the division of vapor phase, at the bottom of the column, into two or more streams that flow upward along the equipment, contacting, in alternate trays, the whole of the liquid phase flow. On the other hand, metastillation corresponds exactly to the opposite case: the division of liquid phase into two or more streams and their contact with the entire vapor phase in alternate trays. The methodology for calculating the operating and feed lines is presented in detail for para- and metastillation in case of dividing the respective phase in two streams. Afterwards the approach is generalized for any integer number of divisions. A specific discussion is dedicated to the feed plate in order to develop a simplified but coherent representation of the feed line. Based on the calculated results for different binary mixtures' volatilities, the advantages of distillation with parallel streams are discussed.

1. Introduction

Distillation with parallel streams is a research subject scarcely explored in the literature. Nevertheless, available references point out that parastillation, corresponding to the division of the vapor flow into two or more streams, is capable of reducing energy consumption and/or equipment cost [1–5]. In fact, these works on parastillation emphasize the higher number of stages that can be arranged, keeping the same column height and tray spacing used in conventional distillation columns [3,4], as well as the lower tray area required [4] in this type of process. Furthermore, parastillation trays can be arranged in a way to cause a lower total pressure drop, particularly in case of lower column heights. This occurs because every vapor stream flows upward through the lower number of trays arranged along the corresponding column side. This capacity of combining a higher total number of trays and lower total pressure drop is particularly important in the case of separating mixtures with relative volatility not far from 1.0 and/or mixtures whose distillation must be conducted under low pressure, as highlighted by Guerreri [6] and by Meszaros and Fonyo [7]. Note that this can be the case for some systems of great importance nowadays, such as thermosensitive mixtures containing fatty acids [8] and esters [9], whose components exhibit low vapor pressures and may have relative volatilities close to 1.0. In the same way, the purification step related to the methanol stripping in the production of neutral bioethanol is a possible application case, since this pure alcoholic product requires a very low contamination with that component and the relative volatility methanol/ethanol is around 1.7 [10].

The literature work on metastillation is even scarcer than in the case of parastillation. Heucke [5] highlights that it can allow a reduction of tray area, with the corresponding reduction in equipment weight. According to him, this can occur under high pressure operating conditions, since in this case the liquid stream is particularly important for determining column design. Mizney et al. [11] suggest that metastillation increases the number of theoretical stages roughly by 50%, but in contrast tends to increase, in a significant way, the tray efficiency. Gouvêa [12] confirmed the occurrence of higher efficiency values for metastillation trays.

Furthermore, most researchers on parastillation point out that tray efficiency is higher because the stages are constructed in such a way that the liquid and vapor flow patterns correspond to case II in the classification proposed by Lewis [13], allowing a better distribution of the mass transfer driving force along tray area.

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Nevertheless, in the case of parastillation the theme is subject to some controversy. Based on experimental and simulation results Canfield [3] concluded that, for columns operating under total reflux, tray efficiencies are higher in parastillation. On the other hand, Meszaros and Fonyo [7] stated that, under partial reflux conditions, the efficiencies of parastillation trays are lower because the ratio of vapor to liquid flows along the column is lower than for distillation trays. Gouvêa [12] and Gouvêa et al. [4] confirmed this conclusion, but the calculated efficiency values for parastillation are in average only 5% lower than for distillation trays.

Besides the Lewis effect, Meszaros and Fonyo [7] reported that, according to Canfield [3], another advantageous effect of parastillation is the so called Jenkins effect. This effect states that $2 \cdot N$ ideal parastillation stages cause more separation than N ideal distillation stages. Considering that this effect occurs even in the case of ideal stages, it is clearly unrelated to improving tray efficiency. In fact, the tray arrangement used in parastillation may improve the mass transfer driving force, since the liquid flowing over any tray contacts the vapor phase that comes from two trays below, so that the difference between the concentrations of the input streams feeding any parastillation tray is higher than the corresponding values in a distillation tray.

Gouvêa [12] compared meta-, para- and distillation columns in relation to equipment height, pressure drop and tray area. For height and pressure drop, he reported the same trend, with metastillation having higher values and distillation columns assuming an intermediate position in both cases. Concerning to the tray area, metastillation exhibits intermediate values and parastillation maintains the lowest ones. Such results highlight additional advantages of parastillation.

Simulation works on para- [4,7] and metastillation [12] used rigorous methods based on the MESH equations and no simplified approach was published in the literature. Calculation methods based on simplifying assumptions may allow a better understanding of the main process features and permit the formulation of general conclusions, since they focus on the essential aspects of the mentioned process. In addition, they enable rapid calculation of distillation columns and other processing unities that may help in optimizing and intensifying chemical processes, as well as provide a powerful learning tool for teaching the design of downstream equipment [14–18].

In the present work a new McCabe-Thiele based methodology is developed for calculating para- and metastillation of binary mixtures involving β equal partitions of the vapor or liquid streams, respectively, where β is a real integer such as $\beta \geqslant 2$. The detailed approach will be presented in the case of $\beta = 2$ and afterwards generalized for higher β-values. The obtained results for different relative volatilities are discussed and compared with the traditional distillation.

Heucke [5] presented operating lines for the enriching section of para- and metastillation columns with two partitions, but did not develop the full set of balance equations, for instance, the stripping and feed lines. Furthermore, he suggested a stepping of ideal stages that, besides being restricted to the column top, does not differentiate, in a correct way, the roles of the equilibrium and balance equations. This can be easily confirmed by comparing the drawing of stages proposed in the present work and the stepping suggested by Heucke [5] only for the column top.

The approach developed in the present work contains the total set of balance equations for two and more partitions of the vapor or liquid streams, a coherent treatment for the feed line and the correct way of stepping the ideal stages for any number of partitions. In addition, the results obtained for binary mixtures with different volatilities allow deducing a set of original conclusions for distillation with parallel streams.

2. Model development

The model development is based on the traditional McCabe-Thiele assumption of constant molar overflow, meaning that both components have the same molar enthalpy of vaporization, changes of enthalpy due to concentration and temperature variations along the column as well as heats of mixing are insignificant in comparison with the latent heat values, and heat losses to the environment are negligible. Furthermore, it is assumed that the column operates under uniform pressure (no pressure drop along the equipment), and the trays work as ideal stages.

2.1. Column configuration and the feed region

Figs. 1 and 2 show the column configurations that will be considered in the derivation of the McCabe-Thiele approach for $\beta = 2$ and possible designs of trays for two and three vapor stream partitions.

In most works on parastillation found in the literature, it seems that the binary mixture feeds the equipment on a unique

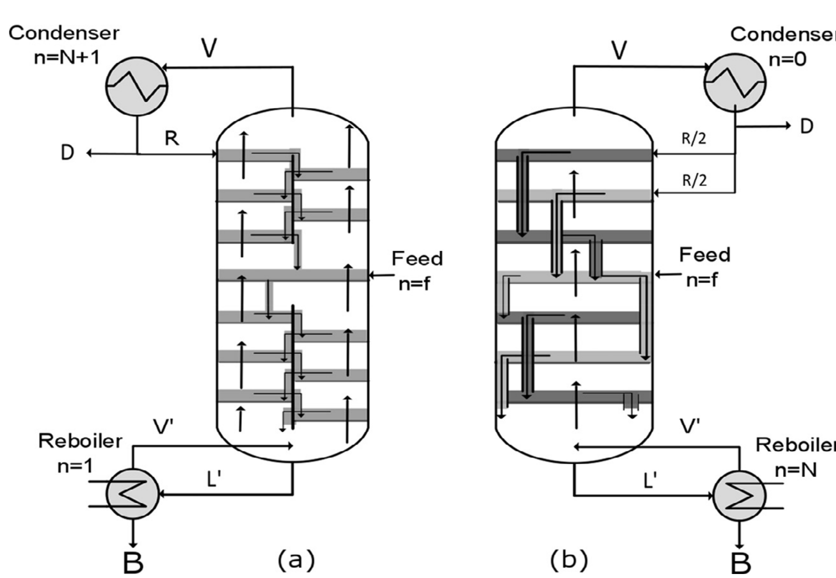

Fig. 1. Scheme of (a) para- and (b) metastillation columns.