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Synthesis of intensified simple column configurations for multicomponent distillations

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ABSTRACT

The synthesis of intensified simple column configurations (ISC) for multicomponent distillations is presented. The ISC configurations use less columns and less heat exchangers than the traditional distillation configurations (TDC), while they keep the similar structural simplicity as the TDC configurations that each column produces an overhead product with a condenser and a bottoms product with a reboiler. For an N-component zeotropic mixture, an easy-to-use procedure is first formulated to generate the ISC configurations from the simple column configurations (SC) with only sharp splits. Then, the procedure is generalized to produce the ISC configurations from any traditional distillation configurations (TDC) with both sharp and sloppy splits. It is demonstrated that the procedure can explicitly modify the TDC configurations step-by-step to systematically generate all the possible ISC configurations. The ISC configurations have the potential to reduce both energy consumption and capital costs than the TDC configurations, at the same time, they have the similar structural simplicity in terms of systems design, control and operation as the traditional distillation configurations. Therefore, they constitute an advantageous alternatives subspace when looking for an optimal system for a specific application in both new design and retrofit of distillation plants.

1. Introduction

Distillation has been the widely used separation method and is still the main workhorse in petroleum, chemical, petrochemical and many other process industries. In the transition from fossil-based feedstocks to biomass-based feedstocks manufacturing, distillation is still among the most important separation methods in many new process industries, including bioethanol, biodiesel and many other biochemicals and natural products manufacturing. The reason is that whenever applicable distillation is advantageous for any fluid materials separation especially in large capacity. Therefore, new distillation processes and equipment are very significant technology for future manufacturing processes, as well as for retrofitting the existing production processes. On the other hand, to pursue sustainable development of our economy and society, we need maximum improve the applied technology to save resources and protect environment.

Due to the intrinsic characteristics of distillation separations, efforts to improve distillation technology are still in twofold: one is to reduce the energy consumption and the other is to reduce the capital investment. This calls for process intensification principles to achieve intensified distillation systems to save both energy and capital costs. While in industrial situations, the mixtures to be separated very often are multicomponent, which usually call for several columns in the distillation processes. The intensified distillation systems should remain less complex to favor their design, control and operations. As indicated by Caballero and Grossmann [1], in mixtures involving more than three components, the first concern is identifying the space of all the alternative configurations in order to extract a good (ideally the best) configuration with savings in energy and/or capital costs without increasing the operational and control complexities.

To separate a multicomponent mixture with N components into N pure products, there need several columns in a distillation configuration. The well-known multicomponent distillation configurations are called simple column configurations (SC). For an N-component mixture, there is a certain number of such simple columns configurations, which can be predicted from the equation of Thompson and King [2]. Fig. 1 presents the two simple column configurations for a ternary mixture. Such simple column

Abbreviations: DSS, distinct separation sequence; DWC, dividing wall column; HITC, heat-integrated thermally coupled configuration; ISC, intensified simple column configuration; OTC, original thermally coupled configuration; SC, simple column configuration with sharp splits; TDC, traditional distillation configuration with both sharp and nonsharp splits; TES, thermodynamically equivalent structure; TSR1, one way transport-side-rectifier; TSR2, two way transport-side-rectifier; TSS1, one way transport-side-stripper; TSS2, two way transport-side-stripper.

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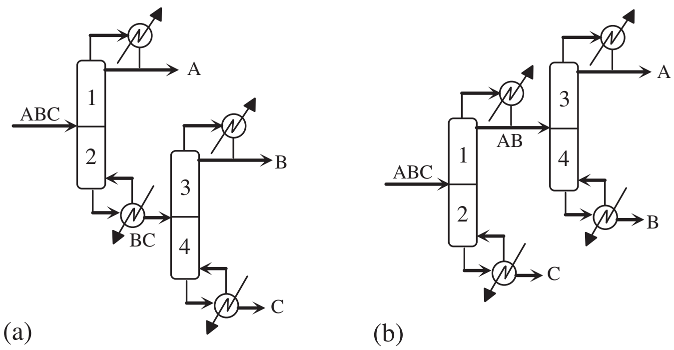

Fig. 1. The two simple column configurations for ternary separations: (a) direct sequence and (b) indirect sequence.

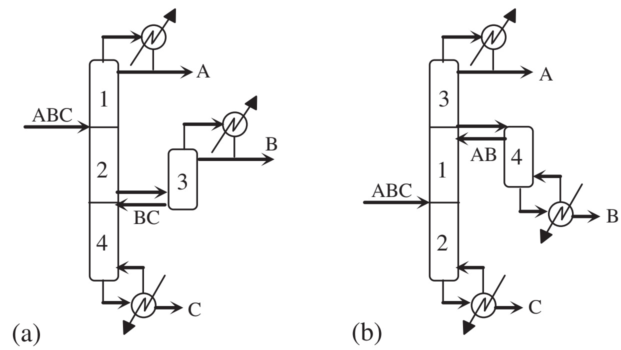

Fig. 3. The thermodynamically equivalent structures for the OTCs in Fig. 2.

configurations were widely studied in the early stage of process synthesis [2–7], they are also the popular configurations in industrial distillation plants due to their simplicity in design, control and operations.

For an N-component mixture, there need N-1 columns in such simple column configurations. In each of such simple column configurations, there need N-1 condensers for the N-1 rectifying sections and N-1 reboilers for the N-1 stripping sections. These simple column configurations are suffered from high energy consumption and large capital investment. The question is can we achieve intensified distillation configurations from such simple column configurations which can keep similar structural simplicity in terms of design, control and operations, while they have the potential to save both energy and capital costs? If so, can we develop a systematic procedure to synthesize such intensified simple column configurations for any N-component mixture?

To answer these two questions, let us first see how we can change the simple column configurations shown in Fig. 1 which favor both energy savings and capital cost reduction. It is known that for the SC configurations, the condensers and reboilers associated with submixtures can be eliminated and replaced with thermal coupling streams, which can produce the original thermally coupled configurations (OTC) [8]. For example, Fig. 2 presents the two thermally coupled configurations for the two SC configurations shown in Fig. 1. For certain cases, such thermally coupled configurations can reduce both energy consumption and capital cost [9].

It is also known that after introduced thermal couplings, some of the column sections in the OTCs are movable and can be rearranged to produce thermodynamically equivalent structures (TES) [10]. For example, Fig. 3 presents the two TESs for the OTCs shown in Fig. 2.

The distinct feature of the TES structures from the OTCs is that there exist different side columns connected to the main column. The TES shown in Fig. 3a is the well-known side-rectifier column, in which there is a single-section side column to produce the middle product B, which we call it *a product-side-rectifier-column*. Also, the TES shown in Fig. 3b is the well-known side-stripper column, in which there is a single-section side column to produce the middle product B, which we call it *a product-side-stripper-column*. We will show in the following that for four-component mixtures, we can produce TES structures in which there contains *nonproduct-side-column* which only serves as the transport of the intermediate submixture between the columns, from which we can produce the intensified simple column configurations.

Similar as for ternary mixtures, the thermal coupling technique can be used to change any traditional distillation configurations for four or more component mixtures, from which we can produce the original thermally coupled configurations and thermodynamically equivalent structures. For example, Fig. 4 presents two SC configurations for a four-component distillation, and the following Figs. 5 and 6 are the generated OTC configurations and TES structures.

From the TESs in Fig. 6, it is observed that all the side columns do not produce any products, they mainly function as transport of the intermediate submixture between the columns. In Fig. 6a, the side-rectifier transports the submixture BC in one-way after the condenser, we define it as *a one-way transport-side-rectifier (TSR1)*. While in Fig. 6b, the side-rectifier transports the submixture BC in two-way through thermal coupling streams, we define it as *a two-way transport-side-rectifier (TSR2)*. Similarly, in Fig. 6c, the side-stripper transports the submixture BC in one-way after the reboiler, we define it as *a one-way transport-side-stripper (TSS1)*. While in Fig. 6d, the side-stripper transports the submixture BC in two-way through thermal coupling streams, we define it as *a two-way transport-side-stripper (TSS2)*.

Functionally, the side rectifiers in TSR1 and TSR2 in Fig. 6a and b are for the further rectifying the heaviest component D so that a mixture with only intermediate components B and C is transported to the next column. However, depending the relative volatilities of the feed components and product purity requirements, when the relative volatility between C and D is large and separation between C and D is easy, a mixture with only B and C can be withdrawn

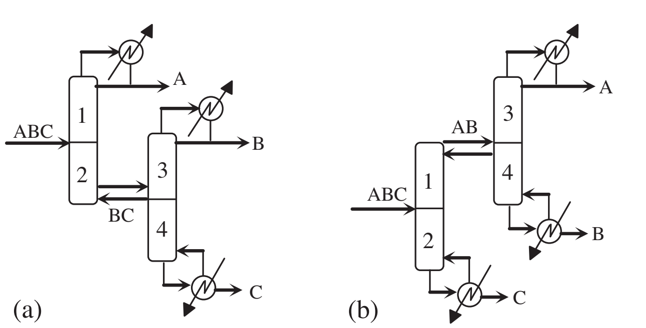

Fig. 2. The original thermally coupled configurations for the SCs in Fig. 1.

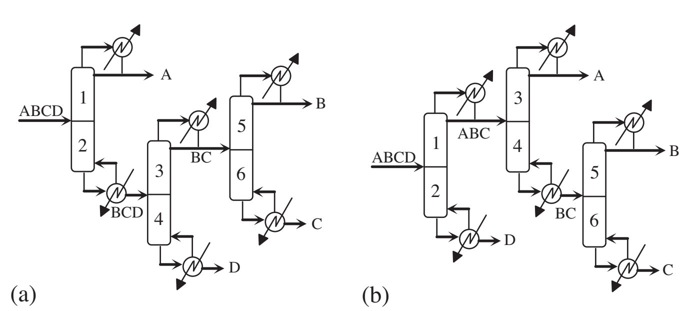

Fig. 4. Two SC configurations for a four-component mixture.