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Design of an energy-efficient side-stream extractive distillation system

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ABSTRACT

A novel extractive distillation system is presented. The proposed separation system evolves from an extractive thermally coupled system with a side rectifier. Specifically, the modification involves substituting the thermal coupling, i.e., the vapor-liquid interconnection, by a liquid side stream fed to a modified second column of the arrangement. The design procedure and performance on energy consumption and CO_2 emissions of the proposed structure is illustrated with three case studies, which involve bioethanol dehydration and the separation of acetone-methanol and heptane-toluene mixtures. The results show that the proposed system can be more energy efficient and provide a more sustainable option when compared to conventional extractive distillation or thermally coupled sequences. We also show how the implementation of heat integration between columns of the proposed structure can be considered for additional savings on energy and CO_2 emissions.

1. Introduction

Distillation systems are highly energy-intensive operations, a characteristic that affects both the process economy and the environment. The search for more energy-efficient distillation systems has been an active effort in this field. In addition to the separation of ideal or nearly-ideal mixtures, an important class of separation problems is that of azeotropic mixtures. The separation of these types of mixtures requires special separation techniques since they cannot be separated by conventional distillation systems. These cases typically require the use of an entrainer that modifies the relative volatility of the mixture to aid its separation. The separation of mixtures with close-boling points can also be enhanced through the use of an entrainer. We concentrate in this paper in the separation of these types of mixtures, and propose a novel separation arrangement that contributes to the energy consumption and environmental impact by the energy savings it provides with respect to the use of conventional extractive distillation systems of the type shown in Fig. 1.

The energy inefficiency of conventional distillation sequences for the separation of ternary mixtures is related to the remixing effect of the intermediate component, and designs that overcome this problem, particularly through the implementation of thermal couplings, have been proposed (e.g. Glinos and Malone, 1988; Fidkowski and Krolikowski, 1990; Triantafyllou and Smith, 1992; Wolf and Skogestad, 1995; Hernández and Jiménez, 1999; Caballero and Grossmann, 2004, 2014). Potential operating problems of thermally coupled systems have given rise to modified structures, such as the ones proposed by Agrawal (2000) and Agrawal and Fidkowski (1998, 1999), who presented several thermodynamically equivalent distillation system to thermally coupled columns for non-azeotropic mixtures to obtain structures with a reduction or elimination of thermal couplings that were expected to be easier to operate.

The remixing problem of the intermediate component is also observed in the first column of extractive distillation systems, so Hernández (2008) proposed the use of thermally coupled systems with side rectifiers and dividing-wall columns, which proved to be more energy efficient than the conventional extractive distillation scheme. Kiss and Suszwalak (2012) showed that energy savings can also be obtained through the use of an extractive dividing-wall column.

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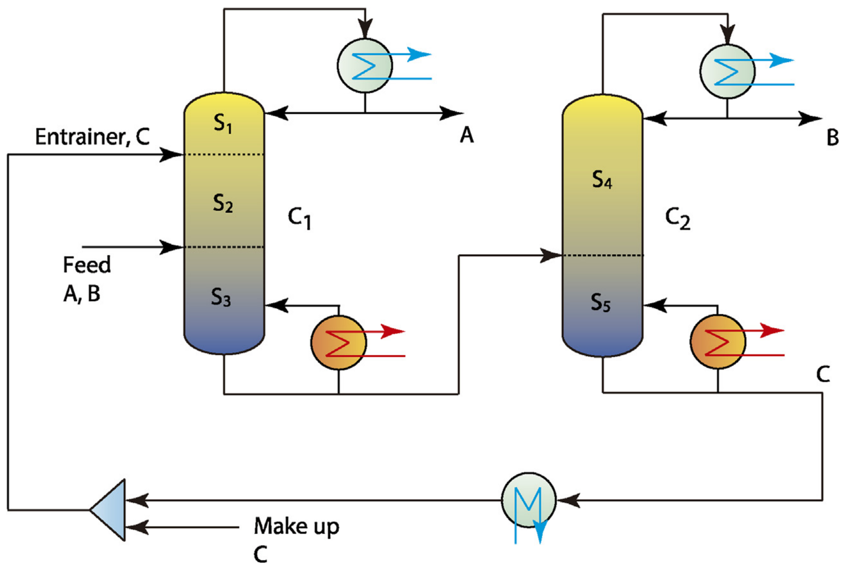

Fig. 1. Conventional extractive distillation system.

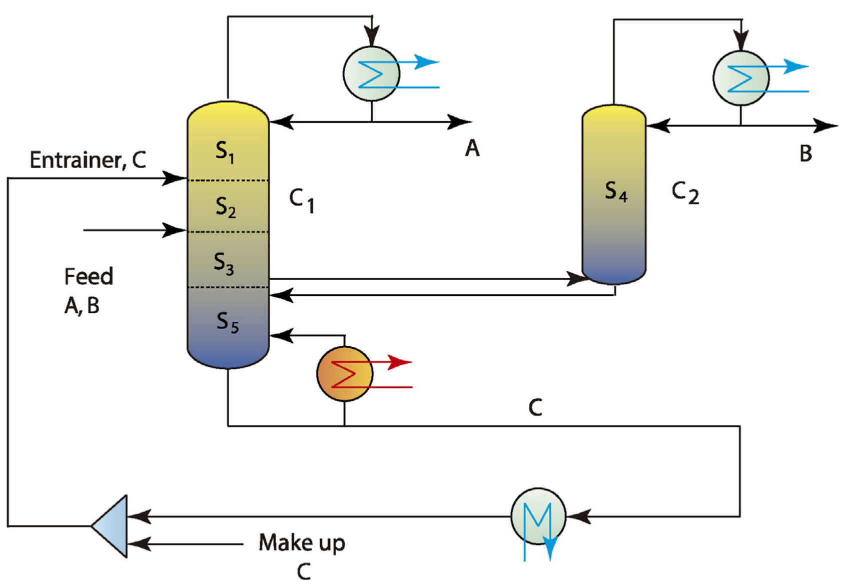

Fig. 2. Extractive distillation system with thermal coupling based on a system with side rectifier.

The new structure presented here is motivated by extending the ideas of Agrawal (2000) and Agrawal and Fidkowski (1998, 1999) to extractive distillation systems; thus, a thermally coupled distillation system with a side rectifier previously proposed for the separation of azeotropic mixtures (Hernández, 2008; Van Duc Long and Lee, 2013) (Fig. 2) is taken as a basis, and an alternative system without thermal coupling is produced (Fig. 3). The vapor-liquid interconnection is substituted by a single feed to the second column, and the side rectifier is complemented with a stripping section to achieve the separation task. The first column (C_1) of the resulting sequence is now a sidestream column, from which the lightest component is removed as the distillate product, and the second column (C_2) produces the intermediate product as a top stream. The bottom streams from the first and second columns contain the solvent that is recycled to aid the separation. A column section analysis shows that the conventional and thermally coupled distillation schemes have five sections, while in the new alternative configuration there are six sections. The additional section (labeled S5′ in Fig. 3) has the same task as the bottom section of the thermally coupled system, which is the purification of the entrainer, so the same number of stages are used in both sections. The remixing problem of the conventional configuration is avoided in the proposed structure by a proper location of the side stream tray.

The aim of this work is to analyze and design the new alternative extractive distillation system. Three different case studies are considered for the application of the proposed distillation structure, two of which are based on azeotropic mixtures and the other one on a near-boiling point mixture. A comparison is made with the use of conventional and extractive thermally coupled distillation systems. As the proposed structure can be designed so as to allow heat integration between columns, such implementation is analyzed for the separation of one of the azeotropic mixtures.

2. Case study 1: ethanol dehydration

The first case study considers the ethanol purification step that is part of a typical bioethanol process, whose importance has been