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Design/optimization of energy-saving extractive distillation process by combining preconcentration column and extractive distillation column

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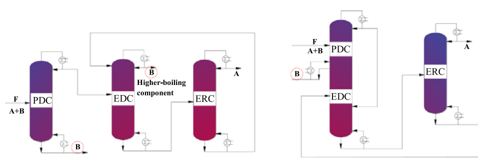
HIGHLIGHTS

- An innovative two-column extractive distillation process was developed.
- The new process is energy efficient with lower capital investment.
- Two systems were investigated to verify the energy and economic advantages.

GRAPHICAL ABSTRACT



Path from conventional setup to energy-saving new process.

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ABSTRACT

In extractive distillation, the addition of entrainer may reverse the relative volatility of the feed components causing the component with higher-boiling point to be removed as the distillate from the extractive column. In this study, the energy saving possibility of a three-column extractive distillation system was studied when this phenomenon occurred. Based on a three-column conventional extractive distillation system, an innovative energy-saving extractive distillation process with lower capital investment was developed by combining preconcentration column and extractive distillation column. Two important case studies were investigated to verify the above-mentioned energy and economic advantages: the separation of *n*-propanol-water using *N*-methyl-2-pyrrolidone (NMP) as entrainer and the separation of ethyl acetate–ethanol using furfural as entrainer. In order to separate these two mixtures, first a three-column extractive distillation sequence including a preconcentration column was applied to diluted fresh feedstock. Then, based on this three-column conventional extractive distillation system, an innovative energy-saving distillation process was developed. For the two separated mixtures, based on the method of global economic optimization, a scheme with optimum design variables was developed for both of the conventional distillation and the new proposed distillation processes. Results revealed that the new process offered 22.76% and 17.25% energy-savings respectively. Similar percentage of reduction in total annual costs (TAC) can also be obtained when compared to the conventional distillation process.

1. Introduction

Distillation is by far the most important separation process in chemical engineering, and it exploits the relative volatility difference of the components to achieve desired separation. However, for systems with close boiling point or azeotropic systems, a separation by conventional distillation process becomes difficult or even impossible. For these systems, several nonconventional techniques such as heterogeneous azeotropic distillation, pressure-swing distillation, and extractive distillation have been proposed (Doherty and Malone, 2001; Seader and Henley, 1998). However, the pressure-swing option is not economically feasible if

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the azeotropic composition is not sufficiently sensitive to pressure, and some complexities of dealing heterogeneous azeotropic distillation, such as multiple steady states, parametric sensitivity that were clearly illustrated by many authors which consequently make the design and control challenging (Doherty and Malone, 2001; Seader and Henley, 1998; Widagdo and Seider, 1996).

Extractive distillation is the most widely used form of homogeneous azeotropic distillation due to the low energy consumption and flexible selection of the possible entrainers (Lei et al., 2003; Sucksmith, 1982). In extractive distillation, a heavier entrainer that has different interaction with the azeotropic components is added to alter the relative volatility of the components, thereby effectively “breaking” the azeotrope. Nowadays, extractive distillation with ionic liquids or the mixture of ionic liquids and solid inorganic salt as entrainers attracted more and more attention (Lei et al., 2014a, 2014b).

An important and special aspect of extractive distillation is that we are not free to pick which of the components in the feed will be the distillate from the extractive column. For a given entrainer, one and only one of the feed components can be recovered in the distillate from the extractive column, and it is not always the component with the lowest boiling point. For example, the separation of methanol and acetone using chlorobenzene causes higher-boiling methanol to be recovered as the distillate from the extractive column, and the lower-boiling acetone to leave in the bottom stream with chlorobenzene. Other entrainers, such as water, dimethyl sulfoxide (DMSO) causes acetone to be recovered as the distillate from the extractive column (Kossack et al., 2008; Luyben, 2008a, 2008b; Kotai et al., 2007; Modla and Lang, 2012, 2011; Langston et al., 2005; Gil et al., 2009). It is important to know which of the feed components will appear in the distillate stream from the extractive column in order to design the equipment. Isovolatility curve and pseudo-binary (entrainer-free) equilibrium diagram are reliable ways. (Doherty and Malone, 2001; Hsu et al., 2010).

Extractive distillation is widely used in a number of processes (Lladosa et al., 2011; Pacheco-Basulto et al., 2012; Arifin and Chien, 2008; Abushwireb et al., 2007; Wang et al., 2012; Gil et al., 2012; Xu and Wang, 2006; Hsu et al., 2010), but it is still energy intensive, different methods to overcome the drawback of energy intensive have been reported. Process integration is a useful option and it has been proven that the process integration leads to a significant reduction in energy consumption compared to conventional process with no integration. Doherty et al. (Knapp and Doherty, 1990) developed thermally-integrated extractive distillation sequences for the separation of ethanol from water using ethylene glycol as entrainer and methanol from acetone using water as entrainer, results showed that thermally-integrated extractive distillation system greatly reduced the energy consumption. Abushwireb et al. (2007) investigated the recovery of aromatics from pyrolysis gasoline using *N*-methylpyrolidone as entrainer, the results presented in their report proved that the heat-integrated extractive distillation system was the best candidate. Luyben (2008b) also studied the heat-integrated extractive distillation system for the separation of acetone–methanol using water as entrainer, 27% reboiler duty was saved as compared to the two-column sequence without thermal integration. In recent years, the use of dividing wall columns has drawn considerable attention. Kiss and Suszwalak (2012) studied bioethanol dehydration by extractive dividing-wall column (E-DWC) system, which led to 10% energy savings. In our previous study, the E-DWC system was used to separate methylal–methanol mixture, results showed that 8% reboiler duty could be saved (Xia et al., 2012). Wu et al. (2013) made a critical assessment of the energy-saving potential of E-DWC, they found that the energy-saving potential of E-DWC was limited.

Although the methods mentioned above are energy efficient, they have some defects along the way. For example, heat-integrated extractive distillation systems lead to high investment cost (Knapp and Doherty, 1990). E-DWC has not been widely used in industry yet due to the complexities of design and control. As stated by Errico et al. (2013a, 2013b, 2013c), many studies just focus on extractive distillation column and entrainer recovery column without considering the preconcentration column. The preconcentration column of the process, which in fact is commonly used in extractive distillation system especially for diluted fresh feed should also be considered since they are also energy intensive.

This paper intends to investigate the energy-saving possibility of extractive distillation system when the adding of the high-boiling solvent reverse relative volatility of feed components. Based on a three-column conventional extractive distillation system, an innovative extractive distillation process will be developed. Two case studies will be used as demonstrating examples to verify the energy and economic advantages of the new process. In the studies, based on global economic optimization procedure, an optimum design for both conventional and innovative process will be investigated.

2. Problem statement and process synthesis procedure

In general, for diluted two-component mixtures, the extractive distillation process is made up of three columns: preconcentration

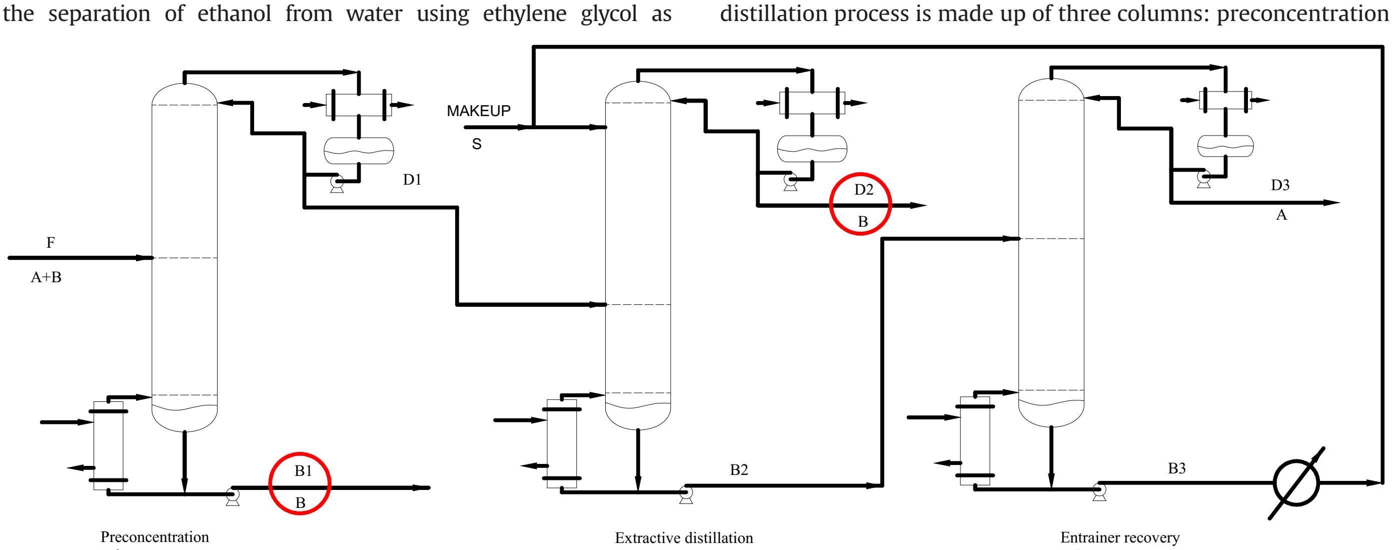

Fig. 1. Sketch of conventional extractive distillation process.