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Economic evaluation of energy saving alternatives in extractive distillation process

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ABSTRACT

Until now, there has not been consensus about the superiority of thermally coupled sequence over the conventional sequence in the extractive distillation process. In this sense, the main goal of this paper is to analyze three approaches for saving energy in the extractive distillation process: optimization, thermal integration and thermal coupling. Three azeotropic mixtures were investigated: ethanol and water (M1); tetrahydrofuran and water (M2); and acetone and methanol (M3). The solvents were ethylene glycol for M1 and M2, and water for M3. The results are shown in terms of the total annual cost (TAC) and specific energy consumption (SEC), and revealed that a thermally coupled extractive distillation sequence with a side rectifier did not always present the best results. Taking the case studies from literature as a starting point (without thermal integration), the optimization procedure used in this work found that TACs are always lower. The inclusion of thermal integration in configurations led to reducing TAC for all mixtures under investigation when compared to the sequences without this integration. When comparing two modifications in the layout of extractive distillation, it can be seen that it is more advantageous to use the preheating of the azeotropic feed with the recycle stream from the recovery column of the conventional sequence than using a thermally coupled sequence.

1. Introduction

Even though the first distillation column was designed as long ago as 1813 (Gorak and Sorensen, 2014), these devices still account for more than 90% of all separations. Furthermore, they consume about 3% of the total energy consumption in the United States, which corresponds to 2.87×10^{18} J per year. Capital investment in these distillation systems reaches about \$8 billion USD (Caballero, 2015).

As to the separation of mixtures which include azeotropes or close boiling components, energy consumption is even more critical. Methods such as extractive or azeotropic distillation, pressure swing, pervaporation and hybrid methods (a combination of the previous ones) have been used to perform these separations. However, until now, extractive distillation is still the best choice for use on an industrial scale (Márquez et al., 2013).

The major intrinsic obstacles to this process are related to the high energy consumption and the large space for possible solutions. This latter problem is a result of two additional decision variables: the solvent feed and the stage at which the solvent should be introduced. Several studies have been published in the last 30 or so years to overcome these obstacles, among which are: how to choose the most appropriate solvent, the best operating point and the best design.

As for finding the best operating point, the literature reports the use of simulators, graphical methods, sensitivity analysis, optimization techniques, heuristic and stochastic methods (Lynn and Hanson, 1986; Meirelles et al., 1992; Bruggermann and Marquardt, 2004; Gil et al., 2008; Utaiwan et al., 2008; Czuczaia et al., 2008; Emhamed et al., 2008; Kossack et al., 2008; Bravo et al., 2010; Figueirêdo et al., 2011; Duenas et al., 2011; Lastari et al., 2012; Bessa et al., 2012; Shirsat et al., 2013; Ojeda et al., 2013).

Beyond the two strategies used with the aim of reducing energy consumption by extractive distillation (process optimization and thermal integration procedure), the process intensification technique, such as the use of divided wall column (DWC) and thermal coupling of columns (TCS), is considered by several researchers as the most promising alternative to reduce the energy consumption of distillation processes, which can be extended to the extractive distillation process (Hernández, 2008; Bravo et al., 2010; Wang et al., 2010; Duenas et al., 2011; Errico and Rong, 2012; Kiss and Suszwalak, 2012; Long and Lee, 2013b; Xia et al., 2012; Modla, 2013; Tututi-Avila et al., 2014). These alternative configurations

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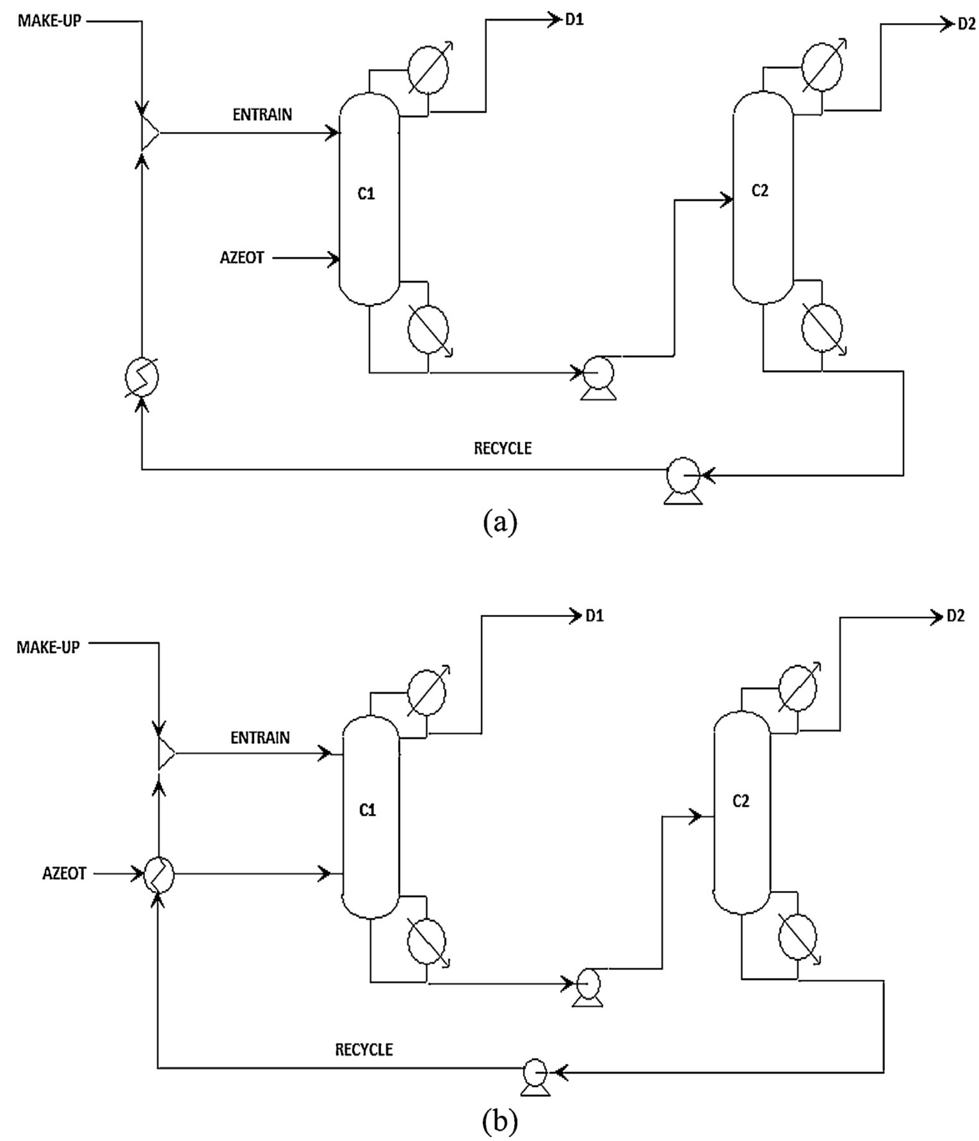

Fig. 1. Conventional extractive distillation sequence: (a) without thermal integration (CS-) and (b) with thermal integration (CS +).

aim to reduce the number of reboilers and/or condensers of distillation columns by using vapor streams and/or liquid, which can result in up to 30% reductions in energy consumption (Triantafyllou and Smith, 1992; Gutiérrez-Guerra et al., 2009; Kiss and Suszwalak, 2012). Some researchers also suggest thermal coupling adaptations (retrofit) in existing hardware (Long and Lee, 2014).

2. Problem definition

The use of thermal coupling is still questionable and there is no potential consensus regarding the reduction of total costs for extractive distillation systems. The work of Wu et al. (2013) put in question if thermal coupling is, in fact, the best option to reduce costs of the extractive distillation process, since for certain chemical systems, higher TAC values were observed in TCS and DWC when compared to conventional sequences, even with a reduction in reboiler heat duty. The authors reported the necessity of using high boiling point solvent in the extractive distillation process as the main reason, which requires high pressure steam in a solvent recovery column.

Sun et al. (2014) also agree that despite being a promising technology for reducing energy use, TCS and DWC have limited energy savings potential. The results obtained by these authors show that a reduction in reboiler heat duty does not necessarily imply in a decrease or a proportional decrease in terms of TAC. Therefore, in addition to the total heat duty, the cost with steam and TAC should be carefully checked in the design of thermally coupled sequence.

Recently, Figueirêdo et al. (2015a,b) included a new parameter to evaluate the extractive distillation process; the solvent content. This parameter corresponds to the solvent liquid composition of its feed stage. Specifying the number of stages of each column, the authors proposed a systematic procedure that makes use of this parameter to find the range of all possible solutions, which necessarily includes the global optimum point of operation. The evaluation of solvent content simultaneously considers two variables that dictate the feasibility of separation and the costs of extractive distillation process: the reflux ratio (R) of the extractive column and the solvent flowrate (S).

In addition to the optimization procedure, Figueirêdo et al. (2015b) used the preheating of the azeotrope feed stream by the heat integration with the bottom stream of the recovery column. This change resulted in reducing specific energy consumption (SEC) by 17.9% and the total annual cost (TAC) by 21.9%, compared to the configuration without thermal integration.