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Sustainable process design & analysis of hybrid separations

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ABSTRACT

Distillation is an energy intensive operation in chemical process industries. There are around 40,000 distillation columns in operation in the US, requiring approximately 40% of the total energy consumption in US chemical process industries. However, analysis of separations by distillation has shown that more than 50% of energy is spent in purifying the last 5–10% of the distillate product. Membrane modules on the other hand can achieve high purity separations at lower energy costs, but if the flux is high, it requires large membrane area. A hybrid scheme where distillation and membrane modules are combined such that each operates at its highest efficiency, has the potential for significant energy reduction without significant increase of capital costs. This paper presents a method for sustainable design of hybrid distillation-membrane schemes with guaranteed reduction of energy consumption together with two illustrative examples.

1. Introduction

Distillation is one of the most used separation techniques in chemical process industry. As a separation technique, it is also one of the most energy intensive, while from an efficiency point of view, it is among the processes having the least thermal efficiency (Pellegrino et al., 2004). Thermal efficiency is defined as the ratio of the net work supplied to the heat supplied by combusted fuel. Table 1 lists the thermal efficiencies of a selected set of manufacturing equipment.

Even though distillation is ranked among the processes with the least thermal efficiency, nearly 80% of all vapor-liquid separations in chemical process industries are performed by distillation (Wankat, 2007). According to the US Department of Energy, separation technologies from all the manufacturing industries used nearly 150 million kW in 2005 (Angelini et al., 2005), out of which, distillation (49%), drying (20%) and evaporation (11%) accounted for more than 90% of the total energy consumption. Fig. 1 highlights the relative energy consumptions of various separation technologies used in the manufacturing industries, where thermally driven technologies (for example, vaporizing a feed stream) consume the highest energies.

It is estimated that the United States alone has more than 40,000 distillation units operating in more than 200 different processes (Angelini et al., 2005), which clearly points to distillation as a significant contributor to the overall energy consumption. Therefore, design of new vapor-liquid separation systems or retrofitting existing systems must be considered for more energy efficient options and sustainable solutions. One such option is to use hybrid separation systems, which combine one or more low energy consuming separation techniques with the higher energy consuming distillation in such a way that a target separation can be achieved at significantly lower energy consumption. Hybrid schemes involving membrane-based separation with distillation have been proposed by many. For example, Stephan et al. (1995), Pettersen et al. (1996), Davis et al. (1993), Moganti et al. (1994) and Caballero et al. (2009) proposed hybrid schemes for recovery of olefins. Also, Rautenbach and Albrecht (1985) highlighted the application of hybrid schemes for separation of an azeotropic mixture of benzene-cyclohexane, while Goldblatt and Gooding (1988) highlighted the application of hybrid schemes to separate an azeotropic mixture of ethanol-water. The main question, however, is when such hybrid schemes should be applied, what characteristics the separation problem should have, what the configuration should be and how much improvement can be expected.

In this paper, a general method for synthesis-design of hybrid distillation-membrane based separation schemes is proposed taking into account the mixture to be separated, the difficulties of using only distillation or membrane-based operations to achieve the desired separation, the optimal distillation-membrane based hybrid scheme, the potential for energy saving without compromising the product specifications, and the capital and operating costs.

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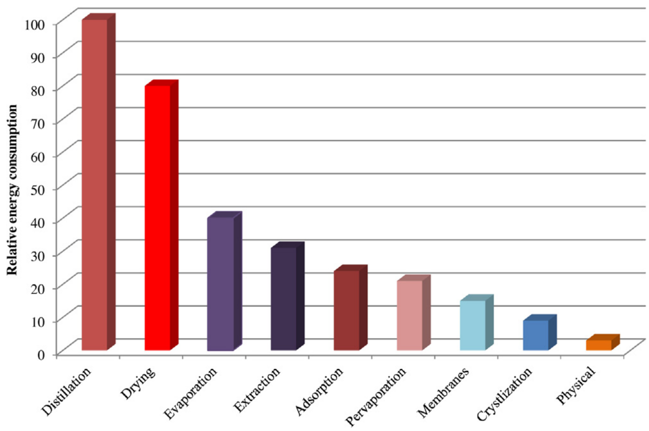

Fig. 1. Relative energy consumption by various separation technologies.

Table 1
Thermal efficiencies of selected energy systems and manufacturing equipment (adopted from Pellegrino et al. (2004)).

Equipment type	Thermal efficiency
Power Generation	25–44%
Steam Boilers (natural gas)	80%
Steam Boilers (coal and oil)	84–85%
Waste Heat Boilers	60–70%
Thermal Cracking (refineries)	58–61%
EAF Steelmaking	56%
Paper Drying	48%
Kraft Pulping	60–69%
Distillation Column	25–40%
Cement Calciner	30–70%
Compressors	10–20%
Pumps and Fans	55–65%
Motors	90–95%

Several application examples are given to highlight the applicability of the proposed method.

2. Concept

2.1. Separation by distillation

Operational costs of distillation columns are proportional to the energy requirements in the reboilers, which vaporize a part of the liquid product coming out of the bottom stage of the column. This vapor stream travels up through the column during which the more volatile compounds in the stream are enriched by being stripped from the liquid flowing down. So the amount of vapor generated, or the reboiler duty, is directly proportional to the required enrichment, or distillate product purity. A relationship between reboiler duty and distillate purity is established by carrying out a simulation based analysis of different binary mixtures of varying degrees of separability (measured in terms of relative volatility). That is, if the driving force (Bek-Pedersen and Gani, 2004) is large, the separation is easy, while if the driving force is small the separation is difficult. Therefore, for the same product purity, as shown by Gani and Bek-Pedersen (2000), the mixture with the larger driving force will require lower energy.

Here, the concept of driving force (DF_{ij}) mentioned is defined as the difference in the liquid (x_i) and vapor (y_i) compositions of a component i in two coexisting phases for property j. Mathematically, it is written as shown in Eq. (1). As the driving force approaches its maximum value, the separation becomes easier. Therefore, from a process design point of view, a separation process should be designed/selected at the highest possible driving

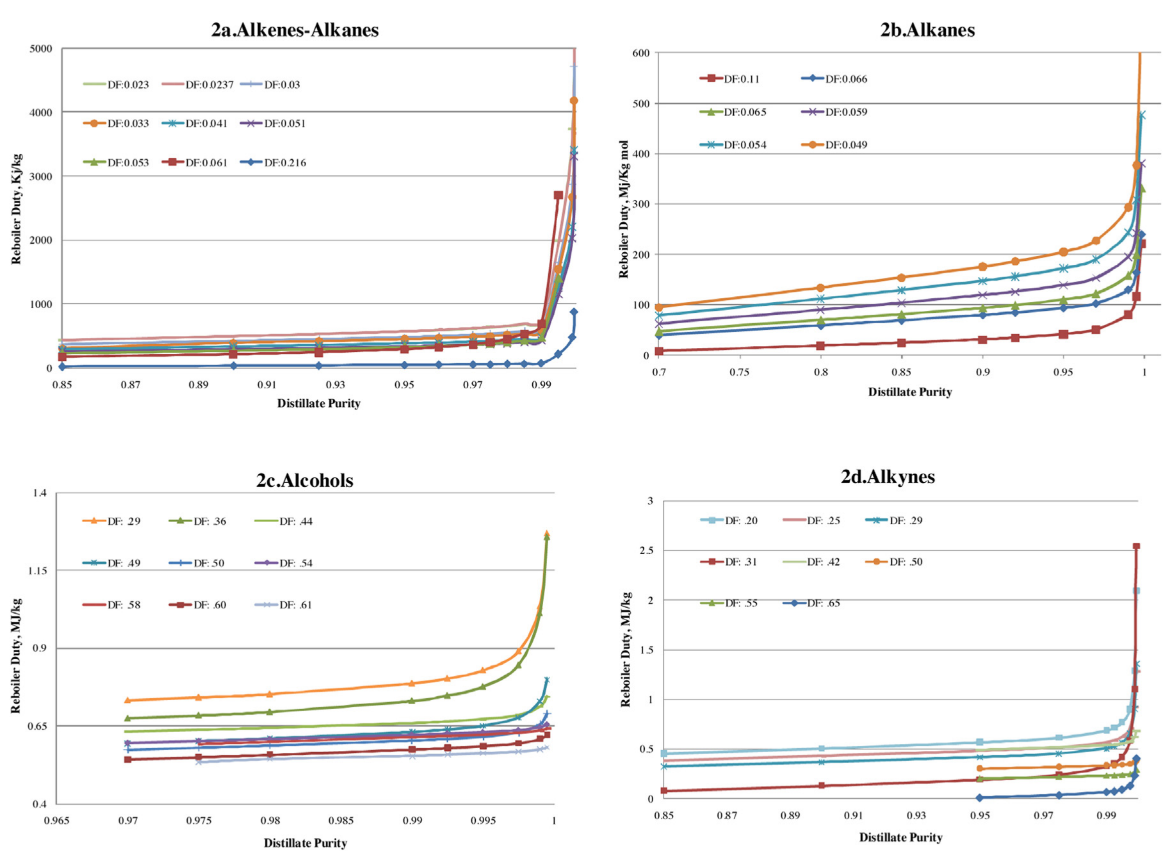

Fig. 2. Reboiler duty versus distillate product purity for different compound classes.

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