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Research paper

Assessing the performance improvement of an intensified heat integration scheme: Reactive pressure-swing distillation

Bandaru Kiran, Amiya K. Jana*

Energy and Process Engineering Laboratory, Department of Chemical Engineering, Indian Institute of Technology, Kharagpur 721 302, India

HIGHLIGHTS

- We develop an intensified heat integration scheme.
- It introduces vapor recompression in an internal heat integration configuration.
- An open-loop control mechanism is devised for optimal use of internal heat sources.
- A pressure-swing distillation is simulated to illustrate the intensified scheme.

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ABSTRACT

Declining petroleum reserves, increasing fuel demands and environmental problems have attracted increasing research attention in improving the energetic potential of separation processes dominated by distillation. In this contribution, we develop an intensified thermal integration scheme for a pressure-swing distillation (PSD) by combining the internally heat integrated distillation column (HIDiC) and the vapor recompression column (VRC), thereby acquiring the benefit of both of them. Since the PSD process typically combines a low-pressure (LP) and a high-pressure (HP) distillation unit, the possibility of thermal coupling arises between the HP column (heat source) and the LP column (heat sink) within the framework of HIDiC scheme. Aiming to further reduce the consumption of external energy in the PSD system, the overhead vapor of HP column is proposed to act as a heat source for bottom liquid reboiling in the LP column by the application of VRC mechanism. By this way, the HIDiC-VRC combination gets the shape of an intensified structure and it is capable of providing an enhanced energy efficiency potential. For a reactive pressure-swing distillation (reactive PSD), the proposed HIDiC-VRC configuration is shown to be more energy efficient and cost-effective compared to the HIDiC-alone scheme.

1. Introduction

Separation processes dealing with the azeotropic mixtures are conveniently lumped into two categories [1]: (i) azeotropic (or extractive) distillation and (ii) pressure-swing distillation (PSD). In the former scheme, a suitable solvent (entrainer) is added to enhance the relative volatility of the species to be separated. This leads to the use of a second separation unit for the regeneration of solvent. On the other hand, a pre-requisite for the PSD scheme is that the azeotrope separated should be sufficiently pressure sensitive. Actually, a PSD system combines a low-pressure (LP) and a high-pressure (HP) distillation towers to circumvent the azeotropic point. Although both of these alternative schemes usually consist of two distillation units, the PSD configuration is becoming increasingly important compared to the azeotropic column because the use of a solvent in the latter scheme may give rise to serious environmental concerns [1]. Despite the fact that the pressure sensitivity of azeotropes has been known since the 1920s, the pressure-swing distillation has not been broadly used in the chemical industry.

In recent years, the reactive distillation (RD) has emerged as an attractive alternative to the conventional sequential approaches. When the chemical reactions are equilibrium limited, the use of RD column, which couples the reaction and separation in a single unit, leads to offer a number of potential advantages. Most notable ones include [2]: improved selectivity, increased conversion, efficient temperature control, effective utilization of reaction heat and avoidance of azeotropes. The present work is concerned with a

* Corresponding author. Tel.: +91 3222 283918; fax: +91 3222 282250.
E-mail address: akjana@che.iitkgp.ernet.in (A.K. Jana).

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continuous flow reactive pressure-swing distillation (reactive PSD) that enjoys the benefit of both reactive and pressure-swing distillation. So far, a very few studies report the reactive PSD scheme (e.g., [3,4]).

Separation processes dominated by distillation are the main user of energy and they account for an about 40–70% of both capital and operating costs in a typical chemical plant [5]. By the virtue of its design, the distillation is an energy inefficient process. This is because the heat is supplied in the reboiler at a high temperature level and almost the same amount of heat is rejected in the overhead condenser at low temperature level. It clearly indicates that distillation involves the degradation of heat from a higher temperature to a lower temperature level in order to perform the work of separation. It is reported [6] that a conventional distillation can typically provide a thermodynamic efficiency in the range of 5–20%.

Today, economic factors along with environmental concerns (e.g., greenhouse gas emissions) are playing a key role in reviving interest in the thermal efficiency of distillation columns. Process intensification has emerged as an effective way of cutting the greenhouse gas emissions through the improvement of thermodynamic efficiency. In the last few decades, great efforts have been made in developing the two thermally coupled distillation configurations, namely vapor recompression column (VRC) [7–9] and dividing wall column (DWC) [10,11]. However, there is another configuration with great potential of energy efficiency that is slowly gaining a great interest from the scientific community, this is internally heat integrated distillation column (HIDiC) [12–15]. There are several variants of these heat integrated distillation schemes, which have been described in some detail in recent review articles [16,17].

The integration of an additional heat pump system with HIDiC presents an intensified HIDiC-VRC structure whereby the performance of the HIDiC can be significantly enhanced by further utilizing the internal heat source through the VRC scheme. Aiming to acquire the benefits of both the HIDiC and VRC systems, Mane and Jana [18] were the first to propose a hybrid configuration by combining both of them. Subsequently, Kiran et al. [15] have adopted and further evaluated this HIDiC-VRC column by a nonreactive multicomponent system, showing a significant improvement in energy efficiency and cost compared to the traditional HIDiC (or HIDiC-alone) scheme.

As far as the pressure-swing distillation is concerned, so far the energy performance is tested by the application of HIDiC configuration [1]. With this status, the present work aims at exploring the feasibility of the intensified HIDiC-VRC scheme on a reactive PSD column for the production of ethyl acetate. Performing a number of numerical simulations, this intensified configuration is shown to be more energy efficient and cost-effective compared to the HIDiC-alone scheme. Based on our knowledge, this is the first work of thermal integration on the pressure-swing distillation column that combines the VRC and HIDiC columns together, thereby acquiring the benefit of both of them.

This article is arranged as follows. Section 2 briefly highlights the conventional operation of a pressure-swing distillation column. In Section 3, the basic configuration and operating principle of the VRC, HIDiC-alone and the intensified HIDiC-VRC scheme are presented and then extended to the PSD column. An open-loop control policy is also devised in Section 3 for the intensified scheme of PSD system. Subsequently, the HIDiC-alone and its intensified configuration are illustrated in Section 4 by a simulated reactive PSD column for the production of ethyl acetate. A quantitative evaluation is also made in the same section for a systematic comparison in the aspects of energy consumption and cost. Some concluding remarks are finally drawn in the last section of this article.

2. Conventional pressure-swing distillation (PSD) process

Conventional pressure-swing distillation (PSD) is perhaps the most simple and economical approach for separating a binary homogeneous azeotrope. As indicated earlier, a strict requirement of employing this PSD process is that the azeotropic composition should be sensitive enough to the changes in operating pressure. This typical process can be adopted when the azeotropic composition varies at least of 5 mol% (preferably 10 mol% or more) over a moderate pressure range (about 10 atm between the two pressures) [19].

Fig. 1 illustrates a conventional PSD process used for the fractionation of a typical minimum-boiling azeotrope. Obviously, this PSD flowsheet consists of two distillation columns. Among them, one operates at low-pressure (LP) (say at P_1) and the other one at relatively high pressure (HP) (say at P_2). As can be seen, the fresh feed (F) is mixed with the recycle stream from the second (HP) column to form the feed stream (F_1) to the first (LP) column. Among the two constituent components of feed mixture, one is taken out almost in its pure form as a bottom product of the LP column. At the same time, a mixture near the azeotropic composition at pressure P_1 leaves the first column as distillate. Changing the pressure of vapor distillate to its desired level (i.e., from P_1 to P_2), it is fed to the second column. From the bottom of this HP column, the second constituent component is withdrawn in almost pure form and a near azeotropic mixture becomes the distillate for recycling to the first column. It should be pointed out that for the binary homogeneous maximum-boiling mixture, an analogous procedure can be used.

3. Thermal integration schemes: basis configuration and working principle

Distillation is most widely used separation process in chemical and allied industries. In an adiabatic column, the thermal energy is added at the highest temperature point for bottom liquid reboiling and almost the same amount of energy is thrown away at the lowest, often useless temperature level. It results in a degradation of energy associated with the temperature difference between the reboiler and condenser of a distillation column, which leads to a low thermodynamic efficiency.

To enhance the energy efficiency of the conventional distillation column (CDiC), several technologies by means of process integration have been developed and implemented during recent decades. Among them, the vapor recompression column (VRC) and internally heat integrated distillation column (HIDiC) have emerged as the promising alternatives to the CDiC.

3.1. Vapor recompression column (VRC)

As indicated earlier, distillation is achieved by introducing thermal energy at the highest temperature and throwing it away at the lowest temperature point. However, if the thermal energy is even recovered at the condenser, it cannot be readily used to heat up any part of the same distillation column because of its lowest temperature level. It clearly indicates the necessity of temperature rise of the heat source before thermally coupling it with a heat sink. In order to achieve this goal, a compressor needs to be installed to generate a thermal driving force.[1] Actually, the pressure (or temperature) is to be elevated by means of a compressor such that the latent heat of compressed overhead vapor (heat source) can be

[1] Throughout this study, we assume a minimum temperature difference ( ) of 20 K required for condensation of compressed vapor in thermal coupling [22].