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A hybrid heat integration scheme for bioethanol separation through pressure-swing distillation route

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A R T I C L E I N F O

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A B S T R A C T

In this contribution, a hybrid thermal integration scheme is proposed for a pressure-swing distillation (PSD) column by combining an internally heat integrated distillation column (HIDiC) with vapor recompression column (VRC). The purpose of this article is three fold: first, it designs a HIDiC for a PSD system with a reduced number of internal heat exchangers. Second, it develops a hybrid column configuration by integrating that HIDiC, which is devised based on the thermal driving force existed between the two diabatic columns, and VRC that is devised based on the thermal driving force existed between the top and bottom of the same high pressure column, yielding an ideal HIDiC–VRC configuration. Third, it provides a comprehensive comparison between the HIDiC-alone and its hybrid HIDiC–VRC structure with reference to a conventional standalone PSD column. To evaluate the performance of all these configurations, we estimate the two performance indexes, namely energy consumption and total annual cost, for an example of a bioethanol dehydration system.

1. Introduction

It is estimated that global energy consumption in 2040 will be almost 30% higher than the one in 2010 [1]. Because of the exponential growth in energy consumption, production of petroleum from large oil fields has already started declining at the rate of 4–5% annually [2]. The world production of oil is expected to peak in coming years. A worrying statistic is that global production rate is approaching its maximum level and the world is now finding one new barrel of oil for every four it consumes [3]. With this status, along with searching a new sustainable environment-friendly energy vector, the improvement of energy efficiency of the existing and matured process technologies has attracted the interest of research communities.

Declining petroleum reserves, increasing energy demands and environmental problems are rising the interest of finding the renewable alternative energy sources, such as bioethanol and biodiesel. Among the various renewable feedstocks, sugar cane and corn are typically used to feed the human populations. Moreover, the sugar cane plantation requires a huge land, which in turn leads to deforestation that has again a negative impact on the environment. Therefore, the transformation of biomass feedstocks into ethanol has gained the research attention in recent years [4,5]. It is interesting to note that the last step of this biological ethanol production route involves the ethanol dehydration that is not an easy separation technique due to the existence of a homogeneous minimum-boiling azeotrope in a width range of pressures.

According to the recent regulations, the ethanol used in the transportation sector should feature high purity ($\geqslant$99.5 mol%) [6]. As indicated before, the ethanol/water system forms an azeotrope having an ethanol composition of 87.2 mol% at 1 atm. For separating this homogeneous minimum-boiling azeotropic mixture, there are several options open, including azeotropic distillation, membrane separation and pressure-swing distillation (PSD). Presenting a systematic comparison between all these separation techniques, Mulia-Soto and Flores-Tlacuahuac [6] have proposed the PSD as an attractive proposition for bioethanol dehydration.

Like the azeotropic distillation, the PSD system includes two separation units, featuring it as an energy demanding process. Aiming to improve the energy efficiency performance, the application of an internally heat integrated distillation column (HIDiC) approach [7–9] in PSD system is proposed in open literature. Huang et al. [10] have designed the HIDiC column by thermally coupling the bottom of low pressure (LP) column with the top of high pressure (HP) column for dealing with the separation of a minimum-boiling azeotrope. As far as the fractionation of maximum-boiling azeotrope is concerned, the reverse combination of thermal pairing is suggested by them. Through the separation of a binary azeotropic mixture (acetonitrile/water), it has been

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demonstrated [10] that the general HIDiC (or HIDiC-alone) column helps to improve the process design in not only thermodynamic efficiency but also capital investment. Recently, Mulia-Soto and Flores-Tlacuahuac [6] have extended the HIDiC technology to a PSD system by coupling the whole portion of both columns. The authors have used the Aspen flowsheet simulator for process dynamics and control studies.

The major complexity involved in operation and design of the HIDiC configuration is associated with the internal heat integration arranged between the whole/major part of the rectifier and that of the stripper. Therefore, in spite of the encouraging outcomes from the standpoint of both capital investment and energy consumption [11], it has not yet found wide applications in the process industries. Keeping this practical concern in mind, Chen et al. [12] have explored the possibility of using a reduced number of vertically arranged internal heat exchangers (internal HE). Subsequently, Harwardt and Marquardt [13] have formally used the optimization technique for HIDiC to establish a systematic design methodology driven by economics to find the optimal number of internal HE. In this article, we have attempted to reduce the number of internal HE in HIDiC without compromising much of its overall performance in the aspect of both energy consumption and cost.

In this contribution, we propose a hybrid heat integration scheme for a PSD column by combining a HIDiC and vapor recompression column (VRC). There are typically two possible approaches to hybridize the general HIDiC column with the VRC scheme. These approaches are based on the way the thermal coupling is made between: (i) the overhead vapor with the bottom liquid of the same HP column, and (ii) the overhead vapor of HP column with the bottom liquid of LP column. When the HIDiC is in ideal form (i.e., no entropy generation) or it does not require any external heat for the LP column reboiler, the first option is applicable for further reduction of utility consumption in the HP column of PSD configuration. Similarly, for the nonideal HIDiC case (i.e., irreversible process), the second option makes sense in hybridizing the HIDiC with VRC.

This work investigates the techno-economic feasibility of a hybrid heat integrated structure for a bioethanol PSD column. For the representative system, the HIDiC is proposed to hybridize by thermally coupling the overhead vapor and bottom liquid of the same HP column under the framework of VRC system, yielding an ideal HIDiC–VRC configuration. Furthermore, aiming to make this heat integration technology one step ahead toward its implementation in industrial scale, attempts are made to design the hybrid configuration, in which, the HIDiC column includes a small number of internal HE. The performance of all these options is quantified and analyzed in terms of both the energy savings and total annual cost.

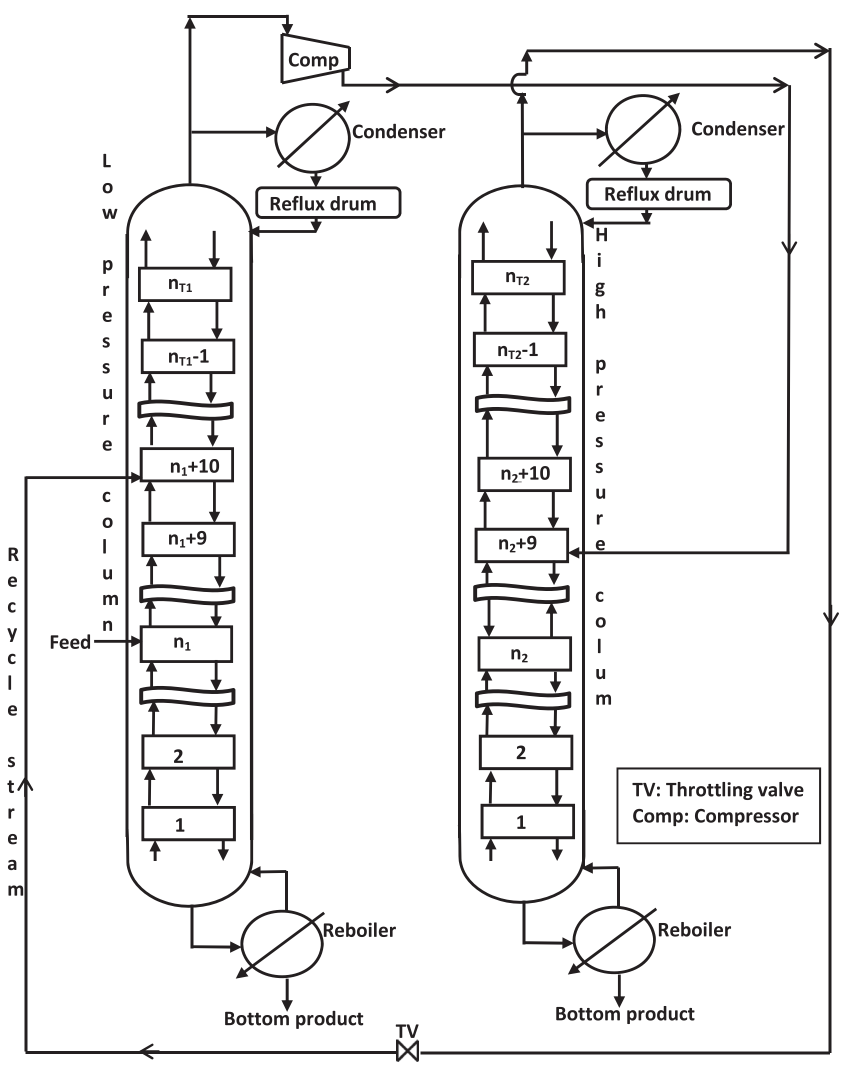

Fig. 1. Schematic representation of a conventional PSD column.