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Research Paper

# Systematic design of the integrating heat pump into heat integrated distillation column for recovering energy

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## HIGHLIGHTS

- Compare CDiC, VRC and basic HIDiC with the super cooled feed of propylene-propane.
- Detail optimizing procedure of the int-HIDiC was presented.
- A novel simplified HIDiC was developed based on the results of int-HIDiC.

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## ABSTRACT

Many developed energy efficient configurations based on heat-integrated distillation column (HIDiC) have been proved to be attractive separation alternatives for saving energy. The key limitation of heat integrated technology is how to build splendid schemes for the heat integrated distillation column. In this work, the overall economic evaluation of conventional distillation column (CDiC), basic heat-integrated distillation column (basic HIDiC) and vapor recompression column (VRC) were executed systematically. Based on the comparison of results, by coupling the basic HIDiC with heat pump technology, a new distillation process model was developed as an intensified HIDiC (int-HIDiC) configuration for propylene-propane splitter. By this enhanced heat integration, the reboiler and the low pressure steam were no longer needed in the process. Meanwhile, the heat distribution proportion and the corresponding operating conditions of this int-HIDiC were optimized through vast simulations and computations. Finally, based on the above optimization results, we developed a simplified HIDiC configuration with two separated columns. The results show the better economic and energy performances than all the other energy-saving schemes including VRC.



## 1. Introduction

Distillation is a simple and effective method in chemical separation process. However, it has a major drawback of enormous energy requirements. Distillation process costs for the degradation of energy and the rejection of low quality energy leading to a low thermodynamic efficiency [1]. Consequently, several technologies have been proposed in recent decades to reduce the energy consumption and improve economic performance [2–6].

As shown in Fig. 1, the vapor recompression column (VRC), also called heat pump column, is a well-known energy-saving technology especially for the separation of close-boiling mixtures [7]. The exploration of its wider and more appropriate application has always been a topic of great concern for chemical engineering reseachers [8–10]. Recently, Felbab et al. provided a new synthesis tool to assess rapidly whether VRC is more thermodynamically favorable than conventional distillation for a given split [11]. Waheed et al. developed various models for the enhancement of VRC and the result showed that strategies could reduce the total annual cost and gas emission rate [12].

Further energy saving improvement is expected from the so-called heat-integrated distillation column (HIDiC), which would also show great promise when separating mixtures with low relative volatility [13,14]. Its theoretical schematic is shown in Fig. 2. The rectifying section and the stripping section are separated, and heat transfer takes place between two columns via heat-exchange devices. The rectifying column is operated at a

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**Nomenclature**

| | |
|---|---|
| A | heat transfer area of the exchangers [$m^2$] |
| D | diameter of column [m] |
| H | height of column [m] |
| M&S | Marshall & Swift economic factor |
| $N_F$ | feed stage in the column |
| $N_R$ | total number of rectifying stages |
| $N_S$ | total number of stripping stages |
| $N_T$ | total number of stages in the column |
| $P_{rec}$ | pressure of rectifying section [bar] |
| $P_{str}$ | pressure of stripping section [bar] |
| $Q_C$ | condenser duty [kW] |
| $Q_{comp}$ | compressor duty [kW] |
| $Q_E$ | total energy consumption [kW] |
| $Q_R$ | reboiler duty [kW] |
| $Q_T$ | heat load per stage [kW] |

*Greek letters*

| | |
|---|---|
| $\theta$ | Service cycle of the equipment [years] |

higher pressure thus it could provide the necessary temperature difference for heat transfer. By this way of internal energy recycling, the duties of both reboiler and condenser can be reduced greatly, and even reflux-free or boilup-free operation can be obtained [5,15,16].

In reported literatures, the energy-intensive propylene-propane splitter was always chosen for the case study of VRC and HIDiC [17–21]. In this work, we also selected this classic compound and carried out our research mainly about HIDiC on the basis of previous studies of Olujic et al. and Suphanit et al. [17,18]. Olujic et al. presented a detail design of a concentric tray column with PP-splitter [17]. As shown in Fig. 3, the integrated part have been arranged into two concentric columns with the changing diameter. The internal diameter decreases gradually from bottom to top while the interlayer space increases accordingly. Such a configuration is to meet the need of the changing vapor flow rates, which indicates the nature of this type of internally heat-integrated column [17]. Later in 2009, Suphanit et al. investigated the optimization of this construction [19]. The result proved that this top-integrated scheme in which all the stripping section stages are thermally coupled with the equivalent number of stages in the upper part of the rectifying section performs the best, when comparing to the middle or bottom type. Furthermore, the conclusion was under the pattern of uniform heat distribution per stage [19]. However, all the above works were based on the same preconditions so that other possible HIDiC configurations suitable for PP-splitter under different separation conditions were not fully explored yet.

Our work developed a series of novel HIDiC configurations based on new separation conditions. The modified (Fig. 4) and the intensified (Fig. 5) HIDiC models were proposed and optimized for the total annual cost (TAC) successively. Finally, we put forward a simplified HIDiC configuration with two separated columns and made the overall comparison of all the energy-saving processes.

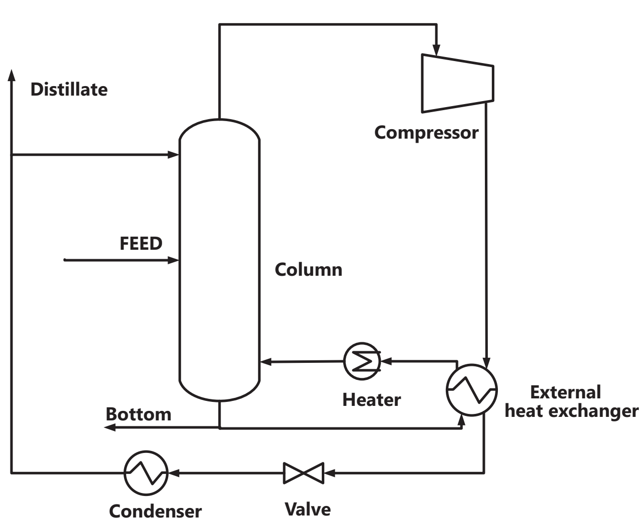


**Fig. 1.** The vapor recompression column (VRC) configuration in this work.

## 2. Cost estimation method

In this work, the main objective function is the total annual cost (TAC) which consists of the annual capital cost (ACC) and the annual operating cost (AOC). The ACC of HIDic process mainly contains the average cost of column shell, tower internals, reboiler, condenser and compressor in its service cycle, while the AOC includes the annual cost of electricity, steam and condensate water. When evaluating the economic efficiency of our HIDic models, the AOC was calculated when executing the models in Aspen Plus, and the ACC was calculated with reference to the following cost correlations given by Douglas [22].

Annual cost of column shell (ACSC, \$/year):

$$ACSC = 4059.96\frac{M\&S}{280\theta}D^{1.066}H^{0.802} \quad (6.8\ \text{bar} < P < 13.6\ \text{bar}) \tag{1}$$

Annual cost of tray (ATC, \$/year):

$$ATC = 136.14\frac{M\&S}{280\theta}D^{1.55}H \tag{2}$$

Annual cost of heat exchanger (AHEC, \$/year):

$$AHEC = C'\frac{M\&S}{280\theta}A^{0.65} \tag{3}$$

The value of $C'$ depends on the form of exchanger. When applied for reboiler, condenser and heat panel, $C'$ is equal to 1775.26, 1609.13 and 1466.72 respectively.Annual cost of compressor (ACPC, \$/year):

$$ACPC = 2047.24\frac{M\&S}{280\theta}Q_{comp}^{0.82} \quad (22 < Q_{comp}\ (\text{kW}) < 7457) \tag{4}$$

For calculating Eqs. (1)–(4), the diameter of stripping section and rectifying section $D$(m) the height of column $H$(m), and the area of exchangers $A$($m^2$) were determined when executing the HIDic models in Aspen Plus. The $M\&S$ presents the Marshall & Swift economic factor, while $\theta$(year) is the service cycle of the equipment. Moreover, other economic basis such as cost index, heat transfer coefficient (U) values, utility costs etc. are almost the same as those applied by Olujic et al. [17] and they are shown in Table 1. In our work, the heat transfer between the corresponding stages of two sections was carried out by heat panels inside the concentric column. In HIDiC and VRC, the U value and cost coefficient of the heat exchangers, which were arranged outside the column, are assumed as same as those of reboiler. We call them the external heat-exchangers.