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HIDiC Configuration Selection Based on Exergetic Analysis

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The present study shows an exergy-based strategy for defining the type of Heat Integrated Distillation Column HIDiC, most suitable for separating the propylene-propane system. For comparing and validating the results, the analysis was performed on conventional column, vapor recompression column (VRC) and several HIDiC configurations: Top, Bottom, Basic, Optimal and Total. Uniform heat transfer area was used for the heat distribution between the internal and external column sections. As main result, it was found that Top HIDiC has the best performance among the HIDiC configurations with a 66.4% of exergy saving compared to a conventional column, followed by the Total HIDiC with a 43.4%. In fact, Top HIDiC shows better exergetic behavior than VRC (55.0% of exergy saving), which is currently used in the industry for the separation of the studied system. Additionally, results confirm that the selection of the configuration for energy integration is not an obvious task and that the presented strategy can be applied for the analysis of the separation of other mixtures.

1. Introduction

Conventional distillation columns tend to have low second law efficiencies. An important condition that reduces the column efficiency is the way heat load is distributed through the column. In a conventional column heat input and output are located at the hottest (reboiler) and the coldest (condenser) points of the distillation column, demanding higher exergetic quality of the heating input in the reboiler and withdrawing lower exergetic quality heat in the condenser, if compared to diabatic columns that allow heat distribution in the internal stages of the column (Mendoza and Riascos, 2011).

The HIDiC is a non-conventional distillation column developed from the diabatic distillation concept; in a HIDiC (Figure 1), heat is transferred from stages located in rectification zone to stages located in the stripping zone. The temperature difference between the rectification and stripping stages is achieved operating each distillation zone at different pressure, while heat transfer is allowed by heat exchangers located in the stages.

The internal heat transfer reduces the heat demand in the condenser and reboiler, in an ideal HIDiC (i-HIDiC) the external heat transfer is not necessary; while in a partial HIDiC (p-HIDiC) only a part of the required heat is internally transferred, therefore the use of the external reboiler and the condenser is still necessary. Detailed descriptions of HIDiC technology and some implementations are presented elsewhere (Kiss and Olujic 2014). The energy saving, compared to conventional columns, estimated by several authors (Nakaiwa et al., 1997, 2001; Liu and Qian, 2000, Matsuda et al., 2010) are from 52 to 90%, these studies considered systems with relative volatilities from 1.15 (propylene-propane) to 2.40 (benzene-toluene).

Within the concentric type HIDiC there are several configurations (Figure 2), which can be grouped in symmetric and asymmetric. In the symmetric HIDiC stripping and rectifying sections are the same size, symmetric configurations are: Basic, Feed Optimum and Total. The Basic HIDiC has equal number of trays in both columns (annular and internal), the rectification zone is only the internal column and the stripping zone is only the annular one, allowing tray to tray heat transfer. In the Optimum Feed HIDiC, part of the rectification zone is in the annular column at a lower pressure, i.e. the rectification zone has more trays than the stripping one, both columns (annular and internal) have equal number of trays, thus heat is transferred tray to tray.

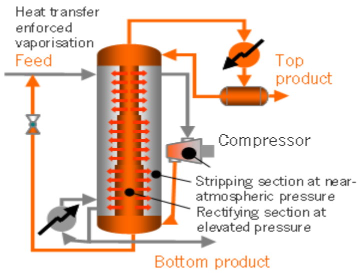

Figure 1: Concentric HIDiC scheme. (Source: Process Systems Enterprise).

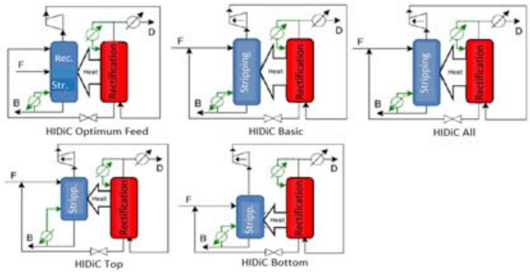

Figure 2: Configuration options schematic for concentric HIDiC columns. (Pulido, 2008).

On the other hand, in asymmetric HIDiCs, the sizes of the annular and internal columns are different and heat integration is performed into a part of the internal column and the whole annular one. Within this type of columns the most common are the Top and Bottom HIDiCs. In these configurations, the name refers to the section in which the heat transfer is made (Pulido 2008). There are many other possibilities for asymmetric HIDiCs (Suphanit 2010), however, for this study, only we will analyze the Top and Bottom ones.

Propylene is a key component for the petrochemical industry; in a general way, it is obtained in mixture with propane from 40 to 60%, depending on the process, and propylene is commonly purified to three different grades: refinery (> 60%), chemical (> 92%), and polymer grade (> 99.5) (Plaza et al., 2012). Due to the low relative volatility, this mixture is separated using distillation columns (C3 splitter or PP splitter) with high reflux ratio and large number of theoretical steps (above 100), generating huge capital and energy costs (Mendoza et al., 2013). Thus, by adopting the HIDiC concept, the energy required in a column could be reduced about 50% compared to the recompression column (VRC), which uses one sixth of the energy required in a conventional distillation column (Olujić et al., 2006). In that way, the energy requirement in HIDiC could be close to the theoretical limit.

Despite the high number of studies on Basic HIDiCs, currently, there is no detailed information on the energy efficiency of other HIDiC configurations for the separation of propane-propylene. Thus, we perform an exergy analysis for selecting the more suitable type of HIDiC for separation of propane-propylene.

2. Methodology

The aim is to perform an exergy analysis for the separation of the propylene propane mixture using not only the basic HIDiC configuration but other configurations, such as: Total, Optimal Feed, Bottom and Top and compare them with the conventional column and the VRC. This analysis will be carried out globally on each column using the following methodology: (1) A vapour recompression column was taken as base case with data supplied by Olujić et al. (2006). (2) The characteristics of the studied HIDiCs were determined. (3) The heat distribution schemes in the HIDiCs were defined, and (4) the exergy loss in each HIDiC were estimated.

2.1 Base case

The operational conditions of the base case (VRC) are shown in Table 2.

Table 2: VRC operational conditions (*Olujić et al., 2006*)

Feature	Value
Rectification section pressure (bar)	11.2
Stripping section pressure (bar)	11.2
Number of stages rectification section	165
Number of stages stripping section	66
Feeding stage	165
Rectification section pressure (bar)	11.2
Feed flow (kg/h)	112000
Feed mole fraction (propylene)	0.53
Feed thermal condition feed (q)	0.37
Distillate mole fraction (propylene)	0.996
Bottoms mole fraction (propylene)	0.011

2.2 HIDiC designs

The characteristics of the five compared HIDiC designs are shown in Table 3.

Table 3: Operational conditions of the different studied HIDiC configurations

Characteristic	Top HIDiC	Bottom HIDiC	Basic HIDiC	Total HIDiC	Opt. Feed HIDiC
Rectification section pressure (bar)	14.6	14.6	14.6	14.6	14.6 – 11.2
Stripping section pressure (bar)	11.2	11.2	11.2	11.2	11.2
Rectification section stages	170	170	115	170	170
Stripping section stages	61	61	115	61	61
Feeding stage	171	171	116	171	171
Trays in the Concentric Column	169	169	115	169	114
Trays in the Annular column	60	60	115	60	114
Feed flow (kg / h)	112000	112000	112000	112000	112000
Feed mole fraction (propylene)	0.57	0.57	0.57	0.57	0.57
Feed thermal condition (q)	0.37	0.37	0.37	0.37	0.37
Distillate mole fraction (propylene)	0.996	0.996	0.996	0.996	0.996
Bottoms mole fraction (propylene)	0.011	0.011	0.011	0.011	0.011

2.3 Heat distribution scheme

The scheme selected for the heat distribution between the rectification and the stripping sections was the uniform heat transfer area adapted from the procedure by Suphanit (2010), which is summarized in the following steps: (1) to define the feed, the pressures, the number of stages and the products specifications; (2) to obtain the total amount of heat rejected from the rectifying section, Q_R, the total amount of heat required in the stripping section, Q_S, and the temperature driving force at any stage location, ΔT_i, along the column without integration; (3) to calculate the heat transferred in each tray, Q_i, by the Equation 1; (4) to perform the simulation with heat integration and input the values of each, Q_i, on the respective stage within each HIDiC and to recalculate Q_R, Q_S and the temperature driving force, ΔT_i.

$$Q_i = \Delta T_i \left[\frac{Q_T}{\sum_{i=1}^{n} \Delta T_i} \right] \tag{1}$$

where Q_T is the smallest value between Q_R and Q_C.

2.4 Calculation of the destroyed exergy

The exergy calculation was performed by first making an entropy balance on each column, Equation 2, and then using the relationship between destroyed exergy and entropy generated, Equation 3:

$$FS_F + V_i S_{Vi} + A_i S_{Ai} + S_{gen} = DS_D + V_o S_{Vo} + A_o S_{Ao} + WS_W \tag{2}$$

where F is the feed, S_F is the entropy of the feed, V_i and S_{Vi} are the steam flow and the entropy at the reboiler inlet; A_i and S_{Ai} are the flow of cooling water and entropy at the condenser inlet; S_{gen} is the entropy generated in the column; D and S_D are the distillate flow and its entropy; V_o and S_{Vo} are the steam flow and the entropy at the exit of the reboiler; A_o and S_{Ao} are the flow of cooling water and entropy at the condenser outlet; W and S_W are the flow of bottoms and their entropy respectively.

$$X_{destroyed} = T_o S_{gen} \tag{3}$$

where $X_{destroyed}$ is the exergy destroyed and T_o is the temperature of the environment (298.15 K).
The simulation of both the VRC and the HIDiC were carried out using Aspen Plus^{TM}. The thermodynamic model used for the system was Peng-Robinson. The exergy analysis of each column was performed through the interaction of ASPEN^{TM} and Excel^{TM}.

3. Results and analysis

Figures 3 and 4 show the destroyed exergy and exergy saving for the VRC column and the different HIDiC configurations, related to the conventional column. It is observed the columns with the lowest exergy losses are the VRC and the Top HIDiC. The Top HIDiC has the best performance among the HIDiC configurations with a 66.4% of exergy saving, followed by the Total HIDiC with a 43.4%. In the other way, the VRC, which is currently used in the industry for the separation of the studied system, achieve 55.0% of exergy saving. The other types of HIDiC configuration, from the exergy point of view, seem to be less favourable than the VRC for the study case. It should be noted that the HIDiC configuration that presents the most exergetic loss is the Bottoms one, due to the large flows of steam and cooling water required in the external exchangers.

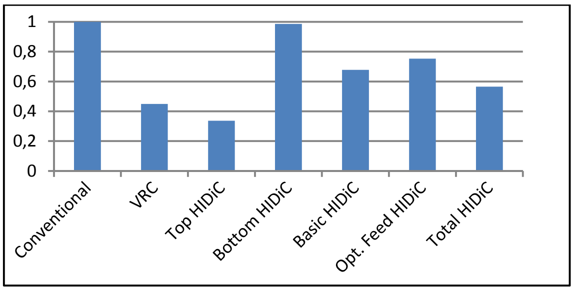

Figure 3: Relative exergy destroyed by column type

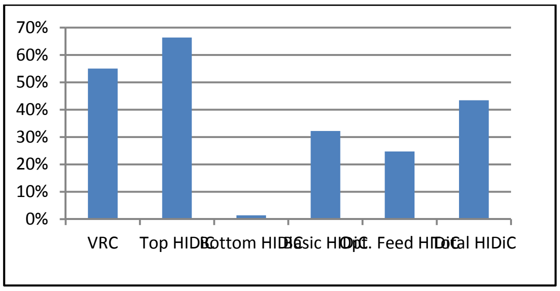

Figure 4: Exergy saving regarding to conventional column

Below is a comparison of the temperature profiles by column type, only in the thermally coupled stages, grouped into two groups, the first (Figure 5) where the Top, Bottom and Total HIDiC are found, corresponding to the HIDiC where heat transfer is carried out in all 60 trays of the stripping section; the second group (Figure 6) corresponds to those configurations where the annular section of the HIDiC column has 115 trays and on these the heat transfer is carried out, which is the case of the Basic HIDiC and Optimal Feeding.

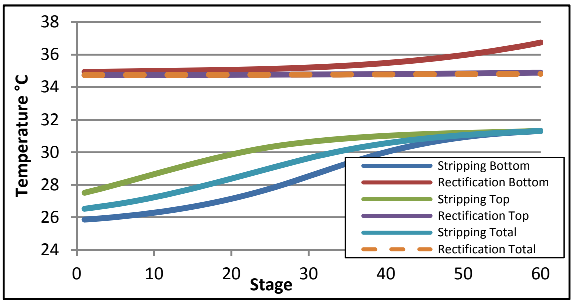

Figure 5: Temperature profiles of thermally coupled sections of Top, Bottom and Total HIDiC

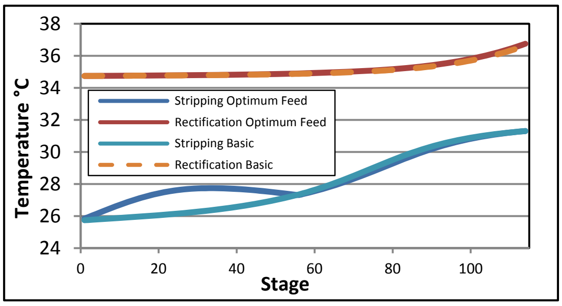

Figure 6: Temperature profiles of thermally coupled sections of Opt. Feed and Basic HIDiC

As shown in Figure 5, the temperature of the rectification zone is always higher than the temperature of the stripping zone, favoring a consistent design where heat exchange is from rectification to stripping. In Figure 6 a similar behavior to the one described above is presented except for the presence of a different trajectory in the first stages of the annular column of the Optimal Feeding HIDiC because this column contents the stripping zone (first 61 trays) and part of the rectification zone (remaining trays of the annular column).

The HIDiC with the highest temperature differences is the Bottom one (between 5.04 and 9.08 °C), Figure 7, which favor the heat transfer rate. On the other hand, the configuration with the lowest temperature difference is the Top HIDiC ($\Delta T \sim$ 3.6 °C) being less effective for a heat flow, however, this benefit of the Bottoms column is not reflected in the exergy, since irreversibility associated to heat transfer increases as temperature difference does.

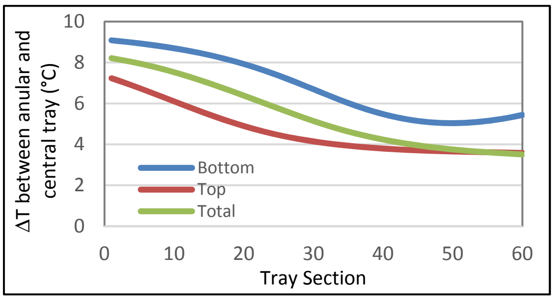

Figure 7: Temperature difference profiles for Top, Bottom and Total HIDiC

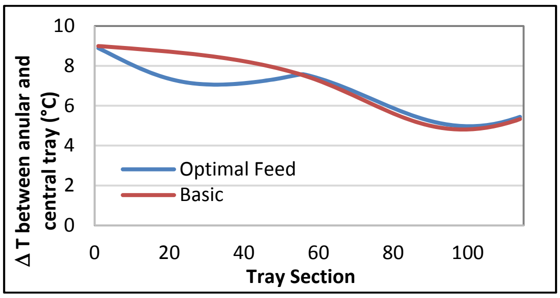

Figure 8: Temperature difference profiles for the Optimum Feed and Basic HIDiC

In Figure 8 a significant difference in the temperature driving force profile is observed for the Optimum Feed configuration in relation to the other HIDiCs is observed, this because a part of the plates in the rectification

section are in the annular column, which operates at a lower pressure (11.2 bar) than the central column (14.6 bar).
In order to deepen the analysis for the selection of the HIDiC type, the temperature profiles in the stripping zones for each configuration before and after the energy integration were also determined (Figures 9 to 13), with the purpose to verify if, after the integration, the heat flow from the highest-pressure section to the lowest one will occur.
As shown in Figure 9, the energy integration increased the temperature throughout the stripping section corroborating a suitable integration. On the other way, when the integration is made in the bottom HIDiC, in the first 25 stages, cooling occurs implying that the flows at these stages are losing heat and becoming colder, contrary to what is wished in this section (Figure 10). This is a consequence of the fact that due to insufficient separation in the rectification section, the upper stages of the stripping section contain relatively much more propylene and consequently have a lower temperature at the same pressure. Due to the above, more heat needs to be transferred between the two sections to reduce the demand on the reboiler. Similar to the bottom HIDiC, the same problem occurs in the Basic and Total ones but in a lesser degree, as shown in Figures 11 and 12.

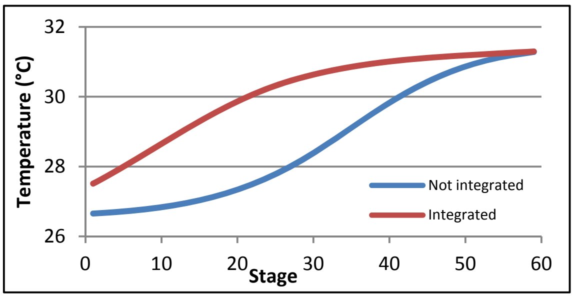

Figure 9: Temperature profiles before and after integration in stripping section of the Top HIDiC

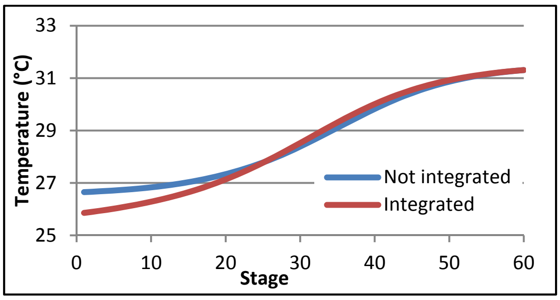

Figure 10: Temperature profiles before and after integration in stripping section of the Bottom HIDiC

The Optimal Feed HIDiC (Figure 13) does not have the cooling disadvantages of the aforementioned ones, however it is observed that it presents a temperature drop between trays 30 to 55 in the stripping section after the energy integration, different from the normal behavior in columns that, as it descends through the plates, the temperature increases. This is due to the fact that the first 56 trays of this column are located before the feeding plate producing a cooling effect in the upper plates.

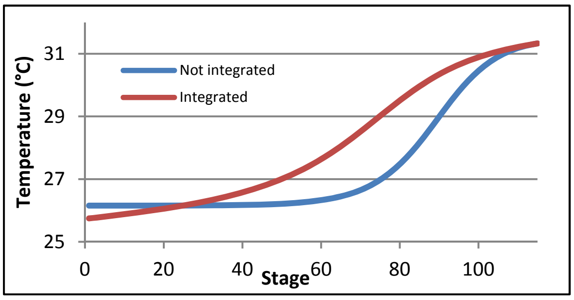

Figure 11: Temperature profiles before and after integration in stripping section of the Basic HIDiC

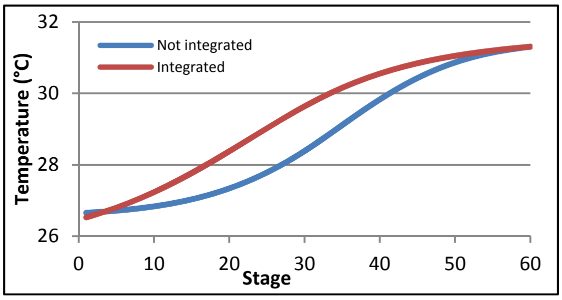

Figure 12: Temperature profiles before and after integration in stripping section of the Total HIDiC

Figure 14 shows the mole fraction of propylene in the liquid per stage, for the different HIDiC configurations. In Bottom HIDiC it is observed that most of the separation is concentrated in the thermally coupled zone (last 60 stages), the distribution of the separation task is increased in the following order: Total HIDiC, basic HIDiC, Optimum Feed and finally the Top HIDiC where the separation is more efficiently distributed. As mentioned in previously, the Optimum Feed HIDiC presents a behavior different from the others, in this column there is a drop in the propylene fraction between plates 170 to 150, returning again to an increase in the propylene fraction as ascending in the column, it occurs because part of the rectification section is in the annular column, as is characteristic of this type of columns.

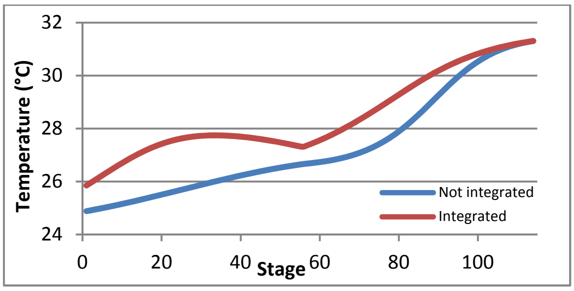

Figure 13: Temperature profiles before and after integration in stripping section of the Opt. Feed HIDiC

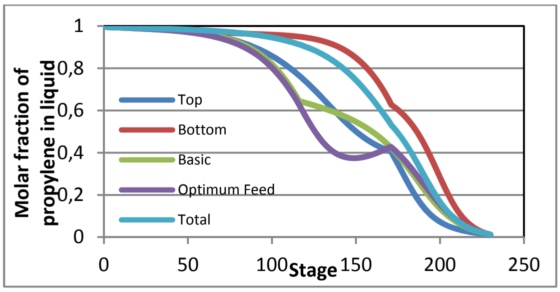

Figure 14: Molar fractions of Propylene in liquid per stage for the different HIDiC configurations

4. Conclusions

According to the study carried out, the type of HIDiC has a strong effect on the energy efficiency that can be achieved and should be considered in the selection of these systems.

For the case study, it can be concluded that among the various HIDiC studied configurations, the one with the best benefits from the exergy point of view is the Top one. It is also important to mention that this configuration presented better exergetic behavior than the column usually used for the separation of propylene-propane system (vapor recompression column), therefore it can be concluded that the Top HIDiC would be a good option for the separation of the study system improving its energy efficiency.

It is clear that although the other HIDiC configurations did not show good results, they should not be ruled out for other systems, since it is always necessary to carry out previous studies with these configurations like the one performed here and verify if they are efficient or not from the point of energetic and operational view.

The Optimum Feed HIDiC presents a different behavior, it is due to the changes in heat transfer direction along the column: one part of the rectification section receives energy and the other part gives it.

Acknowledgments

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