Enhancing Thermodynamic Efficiency of Energy Intensive Distillation Columns via Internal Heat Integration*

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As demonstrated in the present simulation study, taking propylene/propane splitter as base case, an internally heat integrated distillation column (HIDiC), with rectification section operating at higher pressure and temperature than the stripping section, offers significant potential for energy saving compared to energy requirements associated with operation of conventional and heat-pump assisted distillation columns. The rectification section of a propylene/propane splitter contains usually two times more stages than the stripping section, implying a number of heat coupling possibilities, which appears to be strongly influencing the thermal efficiency of the HIDiC. The configuration with the stripping section stages thermally interconnected with the same number of stages in the upper part of the rectification section emerged as the most efficient configuration, allowing a reduction in energy use in the range 30 to 40 % compared with a state of the art heat-pump assisted column, depending on the trade off between the operating compression ratio and the heat transfer area requirement, the latter one being the key limiting factor.

Key words:
Distillation columns, energy saving, HIDiC, heat pump, vapour recompression

Introduction

Distillation column, the workhorse of process industries, is notorious for the inefficiency with respect to energy consumption.[1] It is well-known, since long, that this problem can be solved effectively at its source by implementing a vapour recompression system.[1,2] However, these capital-intensive designs proved to be economically viable in a limited number of large scale, close boiling separations only;[1,3] stand-alone propylene/propane (PP-) splitters being the most prominent applications. The key variable appeared to be the compression ratio, which however depends strongly on the column pressure drop. Since the most interesting applications are high-pressure distillations, with rather large liquid loads, the trays appeared to be the only viable option as vapour/liquid contacting devices for a PP-splitter. However, the pressure drop of presently widely demanded high capacity trays is so large that it discourages the implementation of conventional vapour recompression systems in these applications. A possibility for a breakthrough in this direction is the adoption of the internally heat integrated distillation column concept known presently as HIDiC,[4,5] which allows operation at much lower operating compression ratio.

Fig. 1 illustrates schematically the operating principles of a conventional column (CC), a column with the direct vapour recompression system (VRC) and a HIDiC, respectively. Compared to a VRC, a HIDiC allows a substantial reduction of the compression ratio, because the vapour leaving the stripping section is compressed, which implies much less effort with respect to reaching the temperature level required in the reboiler. In case of a HIDiC,

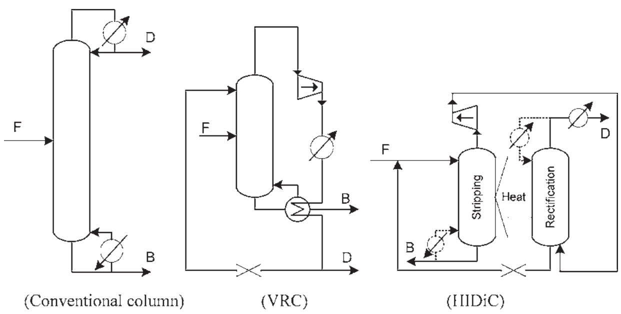

Fig. 1 – *Schematic of the operating principle of a conventional column, a column with direct vapour recompression (VRC) and a HIDiC*

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the rectification section operated at elevated pressure/temperature fulfils the role of a reboiler. Namely, the heat released during continuous vapour condensation along the rectification section is used to effect a roughly same amount of progressive evaporation of liquid to maintain continuously increasing vapour traffic along the stripping section. With such a continuous condensation/evaporation along the column a quasi-reversible operation may be approached similar to that encountered in a "Diabatic Column" which contains a continuous condenser integrated within the rectification section and a continuous reboiler integrated within the stripping section.[6]

In general, a distinctive feature of HIDiC is the fact that it combines advantages of direct vapour recompression and diabatic operation at a significantly reduced total column height and therefore may be considered as an example of a most compact, and with respect to thermal energy conservation potential, an ultimate design of a distillation column. Backgrounds and potential of HIDiC are thoroughly described elsewhere.[4,5] The paper by Nakaiwa *et al.*[4] is a comprehensive review of modelling and experimental efforts carried out over the years by a Japanese research consortium, which was completed by a successful implementation, i.e. building a demonstration unit for the separation of 1.5 t h^{-1} of a multicomponent mixture in industrial environment and operating this unit for more than 4000 hours, confirming the practical feasibility and usability of HIDiC concept. Details on design and operation of this unit can be found elsewhere.[7,8] The main goal, i.e. an energy saving above 30 per cent with respect to conventional column was reached and well exceeded (44 per cent saving in average), however the capital investment associated with construction of this plant was not revealed so far, so that it is difficult to evaluate the economic effectiveness, i.e. pay back time for such a HIDiC. The adopted design is a concentric packed column of unit size, with the partition wall as the surface for heat transfer, which requires placing a number of columns in parallel, within one shell, to achieve desired production capacity. This means that by the virtue of chosen design the desired capacity is achieved by placing a number of basic units in parallel, which implies linear increase in capital costs, and makes this proven design less suitable for common, large scale distillation applications, which are, in turn, most amenable for energy saving considerations.

The paper by Olujic *et al.*[5] demonstrates the energy saving potential of HIDiC and indicates clearly that similar to vapour recompression (heat pump) applications, the separations of close boiling mixtures represent the most attractive candidates for industrial implementation. Taking a PP-splitter as the base case, a comparison was made of performances of conventional, heat pump and HIDiC designs, indicating that the major gain of HIDiC comes from a rather low compression ratio, which however cannot be minimized because minimizing the temperature difference implies maximizing the area needed to transfer the heat from the high pressure (hot) rectification into low pressure (cold) stripping section along the whole length of the column.

A HIDiC could be arranged as a concentric column or a single cylindrical shell, separated by a divider into two semi-cylindrical sections, with heat transfer elements penetrating from the rectification into the stripping section or vice versa. One should note that by placing two column sections in parallel the total height could be nearly halved, which is important gain regarding the fact that PP-splitters and similar columns are exceptionally tall (up to 110 m). Relevant references and patents are cited elsewhere.[5] Most recent patent of this kind introduces a feasible design with flexible heat transfer area for a HIDiC equipped with trays in both sections.[9] In principle, both sections can contain trays or packings; also, the rectification section could be equipped with packings and the stripping section with trays or vice versa. The actual design challenge is to integrate heat transfer devices without affecting adversely hydraulics' and the mass transfer performance of trays and/or packings.

This important equipment performance related consideration was the subject of TU Delft based work within a comprehensive research effort devoted to HIDiC, carried out in co-operation with a multi-partner consortium, including research institutions specialised in energy/exergy conservation and heat transfer, equipment manufacturers and end users from refining, petrochemical and chemical process industries. The total reflux distillation experiments carried out with cyclohexane/*n*-heptane system at atmospheric pressure have shown that an annular sieve tray with outer diameter of 0.8 m and inner diameter of 0.3 m operates with heat transfer panels placed above the active area in a smooth way, with negligibly increased pressure drop and significantly improved efficiency with respect to that of the same tray without heat transfer panels. Details on this and other HIDiC performance related aspects are elaborated in greater detail in the PhD thesis by de Rijke.[10] Most importantly these experiments confirmed the average value of heat transfer coefficient used to design an industrially viable HIDiC version of a state of the art propylene splitter. The actual plant data formed the basis for the techno-economic evaluation, which indicated that with increasing energy prices HIDiC could become an economically attractive option for new designs.[11]

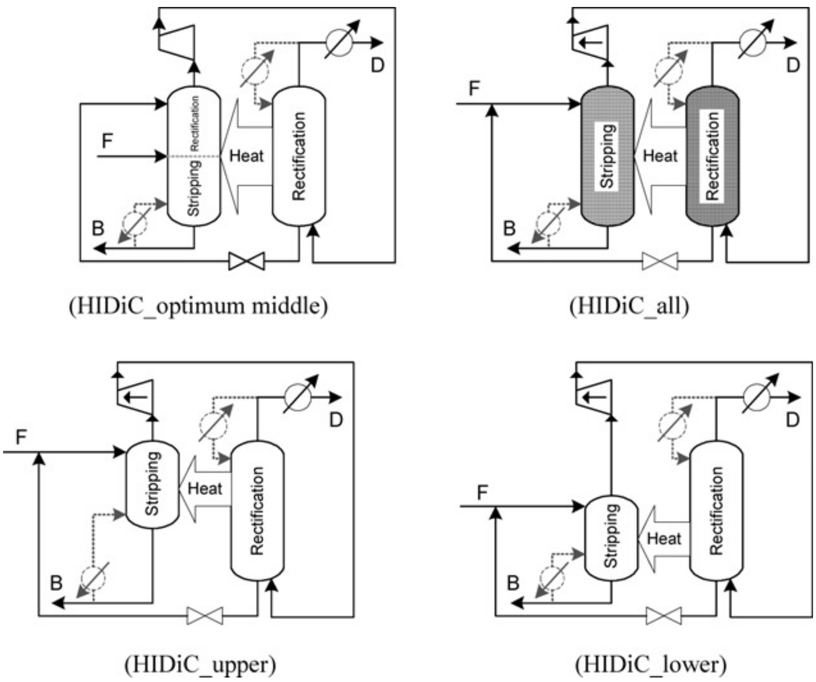
Considering HIDiC as two parallel series of interconnected heat exchangers, Gadalla *et al.* demonstrate the usability of pinch analysis as a tool for screening, i.e. identification of economically interesting configurations for HIDiC applications,[12] and, in another paper,[13] introduce a model that enables quantification of emission levels as well as generation of design options for direct reduction of the carbon dioxide emissions associated with operation of a HIDiC. Most recent paper by Gadalla *et al.*[14] introduces an engineering tool to assess the feasibility of a HIDiC, i.e. to indicate heat integration configurations that satisfy both heat transfer area- and tray hydraulics requirements.

In the previously mentioned simulation study,[5] a column for upgrading the chemical grade propylene into polymer grade propylene was taken as the base case, which is an example of the lightest feed encountered in practice. Certainly, the lighter the feed the lower is the reflux requirement and this suggests that less energy should be consumed, however one forgets often that the quantity of the distillate is proportional to its feed content which finally may mean that such a separation is even more energy intensive than one with a much heavier feed. So in the present paper an attempt is made to evaluate the effect of feed composition as well as the feed thermal condition. The previous study was carried out assuming a constant pressure operation, with the number of theoretical stages close to the maximum, which is the most beneficial condition with respect to energy/exergy conservation. To be more realistic in this respect, this study includes the pressure drop effect and to allow for a wider range of operating conditions a column with a lower number of theoretical trays was taken as basis.

Another potential problem with practical implementation of HIDiC is the fact that an ideal HIDiC inherently requires symmetrical distribution of stages, i.e. equal number of stages in both sections. Namely, this is conflicting with optimum feed position, which in turn is governed by the feed composition, feed thermal condition and products specification. In case of PP-splitters, usually only the distillate (propylene) is required at high purity, which implies that practically all columns of this type contain more stages in rectification than in the stripping section. In the cases evaluated in this and previous studies, approximately one third of stages are contained in the stripping section and other two thirds in the rectification section. It must be noted that with respect to optimum feed position a HIDiC does not differ from conventional column. So the main conceptual design concern is how to arrange a HIDiC with different number of stages in rectification and stripping sections.

Heat integration configurations

Possible configurations, compared in this study are shown in Fig. 2. The basic configuration called *HIDiC_middle*, shown in Fig. 1, is the fully symmetrical configuration structure as known from the



F i g . 2 – *Other possible configurations of the HIDiC, in addition to that (HIDiC_middle) shown in Fig. 1* literature,[4] which, regarding the present base case implies operation with a feed introduced well above the optimum location. In this way, each stage in the rectification section is connected through a heat exchanger with a corresponding stage in the stripping section. *HIDiC_optimum middle* is the modification of *HIDiC_middle* where the feed is introduced on the stage, which represents the optimum one of a conventional column (minimum energy requirement). In order to get the same number of stages in the low- and high pressure/temperature sections of the column, a number of rectification section stages is placed directly above the stripping section. This means that a certain number of rectification section stages operates at lower pressure, which is beneficial, i.e. increases relative volatility and reduces reflux requirement accordingly.

HIDiC_upper and *HIDiC_lower* represent two extreme asymmetric configurations, with the stripping section stages connected with the same number of stages in the rectification section in the respectively upper and lower part of the rectification section. In these cases, a part of the rectification section resembles conventional column design.

Finally, a HIDiC with a smaller number of stages in stripping than in rectification section can be arranged to have equal length of the sections, simply by adapting the stripping section tray spacing accordingly. This configuration, called *HIDiC_all* implies the heat exchange between each of stripping section stages with one or more stages in the corresponding segment of the rectification section. Furthermore, one should note that only an ideal HIDiC does not require a reboiler and a condenser. These are however needed and will be most probably significantly larger for start-up purposes than those needed to sustain HIDiC operation (a minimum reboiler and a condenser to liquefy the distillate and provide initial reflux).

The objective of the current work is to present the results of a thermal analysis study indicating a strikingly strong effect of HIDiC configuration on the energy/exergy consumption of a PP-splitter. This will be followed by a general discussion of the relation between the compression ratio and the heat transfer area requirement, as well as an evaluation of possible effects of variations in feed composition and thermal condition.

Design cases

Table 1 summarizes operating conditions of a conventional, a VRC PP-splitter, and five HIDiC configurations compared in this study. In order to illustrate the magnitude of the compression ratio effect, two stripping section pressures (13 and 15 bar) are considered for each of HIDiC configurations studied, in conjunction with a constant pressure at the top of the rectification section (18.34 bar), which corresponds to the pressure at the outlet of compressor of the base case VRC (actual plant data) and is representative of the top pressure encountered in water cooled conventional columns. The top of the VRC operates at 9.15 bar, and the pressure drop effect is also considered to account properly for variations in heat duty associated with the pressure drop encountered in PP-splitters. A pressure drop of 8 mbar per theoretical stage is assumed

Table 1 – *Operating conditions of various PP-splitter configurations*

Configurations		CC	VRC	HIDiC_middle	HIDiC_opt. middle	HIDiC_upper HIDiC_lower HIDiC_all
No. of stages	Rectification section	138	140	91	91	138
	Stripping section	44	42	91	91	44
Feed stage		139	141	92	125	139
Top pressure of rectification section, p/bar		18.34	9.15	18.34	18.34	18.34
Top pressure of stripping section, p/bar				13, 15	13, 15	13, 15
Pressure drop per stage, Δp/bar		0.008	0.008	0.008	0.008	0.008
Feed flow rate, F/kmol h^{-1}		100	100	100	100	100
Feed mole fraction of propylene, x		0.5	0.5	0.5	0.5	0.5
Feed thermal condition, q		1	1	1	1	1
Overhead propylene mole fraction, x		0.995	0.995	0.995	0.995	0.995
Bottom propylene mole fraction, x		0.04	0.04	0.04	0.04	0.04

here as a reasonable (worst case) estimate for the purposes of this study. Thus, the compression ratio as used throughout this study is the ratio of the top pressure of the rectification section increased by the pressure drop of this section and the top pressure of the stripping section, i.e. $(p_R + \Delta p_R)/p_S$.

Base case number of theoretical stages is 182 and the feed stage that differs slightly for CC and VRC represents the optimal one for given feed composition, feed thermal condition and product specifications. The exception in this respect is the conventional HIDiC configuration (*HIDiC_middle*) only. In general, a HIDiC behaves similar to a column with vapour recompression (heat pump) system and they both differ to some extent from the conventional column with respect to effects of variations in common design and/or operating variables. Operating ranges of PP-splitters delivering polymer grade propylene (> 99.5 mol per cent) vary considerably regarding the feed rates (from 10 to 100 t h^{-1}), feed composition (from 40 to 95 mol per cent propylene) and feed condition (vapour fraction up to 50 mol per cent). Usually propylene recovery is above 98 mol per cent, however in some complex plants bottoms of a PP-splitter can contain a substantial quantity of propylene, and a few percent of heavies can always be found in the bottoms. This comparative study considers a binary mixture and bottoms specification is set at 4 mol per cent propylene, i.e. 96 mol per cent propane. An overview of the state of the art of PP-splitter technology can be found in a recent conference paper by Reid.[15]

Since the energy/exergy consumption changes linearly with the feed flow rate and the present paper aims at a comparison of the relative performances only, the base-case flow rate of an equimolar feed was taken to be F = 100 kmol h^{-1}. Certainly, this is on the low side, regarding the capacity of the state of the art PP-splitters but this choice is of no consequence to the results of this study.

The conventional distillation column uses the heat added into the reboiler as the separating agent. In case of both the VRC and HIDiC, the only energy supplied from outside is the electrical energy used to drive the compressor. To account properly for the difference in the qualities of thermal and electric energies the exergy analysis was adopted. The exergy of compressor work equals to the work itself while the exergy of heat equals to the maximum work that can be recovered when heat is converted into work in a Carnot process. Following relation was used to convert the heat added in the reboiler into exergy:

$$Ex_R = \dot{Q}_R \left(1 - \frac{T_0}{T_B + \Delta T}\right) \qquad (1)$$

where Ex_R is the exergy of reboiler, $\dot{Q}_R$ is the reboiler duty, T_0 is ambient temperature, T_B is bottoms temperature, and ΔT is the temperature difference in the reboiler. A constant temperature difference of 30 K or °C was used for all external reboilers and the HIDiC related heat transfer area calculations were based on a constant value of the overall heat transfer coefficient of 1000 W m^{-2} K^{-1}, which appeared to be a realistic number according to own experimental evidence.[10,16]

Simulation tool

The thermal analysis of the PP-splitter configurations evaluated in this study was carried out using ASPEN Plus facilities. The thermal operation of HIDiC was simulated as a pair of interconnected parallel columns/sections, each at its operating pressure, with the number of thermally interconnected stages according to given configuration. Corresponding heat transfer area requirements were evaluated by an interactive sequential calculation effort, by combining ASPEN Plus with Excel.

Results and discussion

Fig. 3 shows the energy and exergy consumptions of the VRC (column with vapour recompression system) and the HIDiC relative to that of the conventional column. As expected a VCR enables a huge energy saving with respect to conventional column and the asymmetric HIDiC with upper part of rectification section coupled thermally to the stripping section seems to be the best configuration in this respect. As expected, each of HIDiC configurations with lower compression ratio (HIDiC(15), p_R/p_S = 1.2) consumes less energy/exergy than its counterpart operating at the higher compression ratio (HIDiC(13), p_R/p_S = 1.4). Interestingly the performances of five compared configurations of HIDiC differ significantly and some of them, with larger compression ratio (*HIDiC(13)_middle and HIDiC(13)_lower*) which is however lower than that of VRC (2.0 in present study), appeared to be less favourable than the VRC itself. This may not be so surprising if we consider the fact that the HIDiCs in question are that with feed stage far from optimum and the one with a number of rectification stages placed in the low-pressure part of the column.

Striking is the extent of bad performance of the HIDiC with the bottom part of the rectification section coupled to the stripping section (*HIDiC_lower*). The relative exergy consumption plot shown in Fig. 3 indicates that the exergy efficiency of this configuration is more than factor two worse than that of the conventional column. An explanation for the

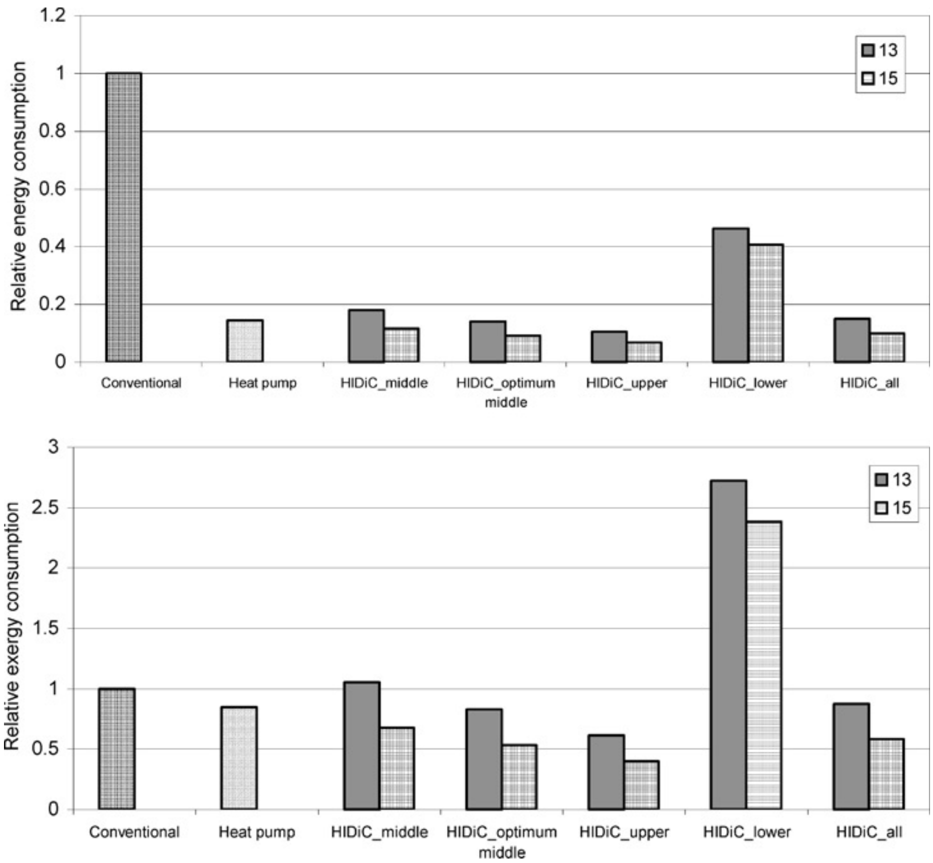


Fig. 3 – *Relative energy (upper) and exergy (lower) consumption compared to the conventional column (HIDiC with bottom section pressure of respectively 13 and 15 bar)*

difference in the performance of five HIDiC configurations, particularly the extreme one, is suggested in Fig. 4 which shows vapour flow rate profiles for each configuration, with stage number increasing from the top to the bottom of the column. Namely, in addition to the compression ratio, which is equal for all HIDiC configurations, the compressor duty depends also on the mass flow rate of the vapour. As indicated in Fig. 4 the latter one varies considerably, in one case extremely, depending on the configuration.

It should be noted that the vapour flow rate in a HIDiC increases from zero at the bottom of stripping section to the maximum at the top of the stripping section. The additional increase in vapour flow of the feed stage indicated by the vertical part of the profile occurs through partial evaporation (adiabatic flash) of the liquid from the rectification section passing through the throttling valve on its way to the top of the stripping section. The vapour flow that enters the rectification section starts to decrease continuously while ascending through the rectification section reaching the minimum rate at the top, which is equivalent to that of the distillate product.

The peaks of vapour rate curves shown in Fig. 4 indicate the compressor load associated

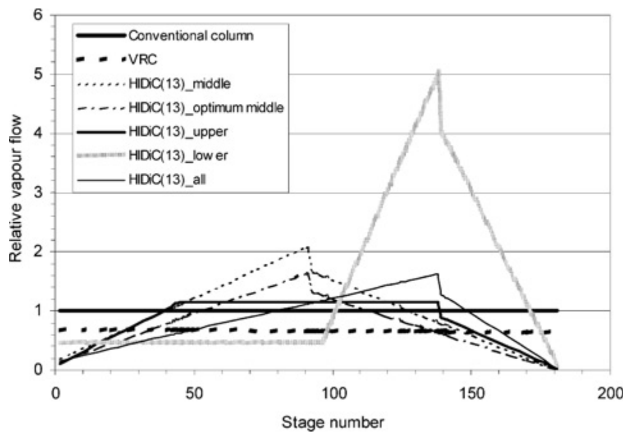
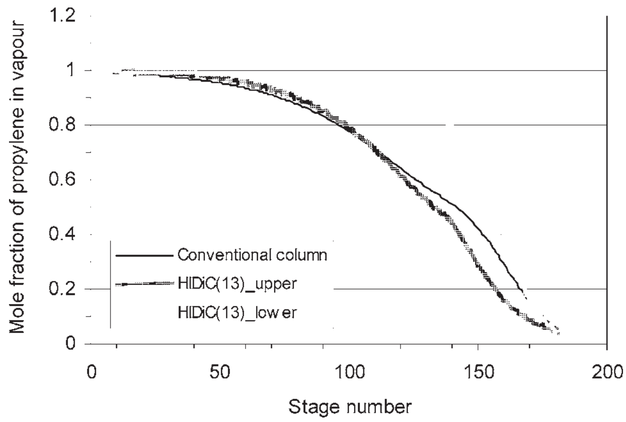


Fig. 4 – *Comparison of vapour flow profiles for the high compression ratio HIDiC*

with HIDiC configurations considered here. It can be seen that the vapour flows through compressors of *HIDiC(13)_upper*, *HIDiC(13)_optimum middle*, *HIDiC(13)_all*, *HIDiC(13)_middle* and *HIDiC(13)_lower* are 1.7, 2.4, 2.4, 3.1 and 7.5 times of that of the VRC, respectively. This observation reveals a latent weak point of HIDiC, i.e. a relatively much larger vapour load of the compressor compared to that of the VCR. Therefore it is not surprising that in some cases a HIDiC consumes more energy/exergy than the VRC. According to Fig. 4, *HIDiC(13)_all* and *HIDiC(13)_optimum middle* exhibit the same vapour load peak, which is that high that it leads to approximately equal energy/exergy consumption as in the case of VRC (see Fig. 3). Such a strongly pronounced deteriorating effect of the vapour load could be reduced to some extent by increasing appropriately the number of stages. Anyhow, to perform better than the VRC these configurations should be operated at a lower compression ratio, which, as it will be shown later on, is associated with a heat transfer area requirement that may become impractical.

Certainly the configurations with the feed stage far from optimum (*HIDiC(13)_middle*) and the stripping section trays thermally coupled to the trays in the lower part of the rectification section (*HIDiC(13)_lower*) perform even much worse. On the other hand, as mentioned before, both configurations of the *HIDiC_upper* perform the best, by saving respectively 27 per cent and 40 per cent exergy compared to the VRC.

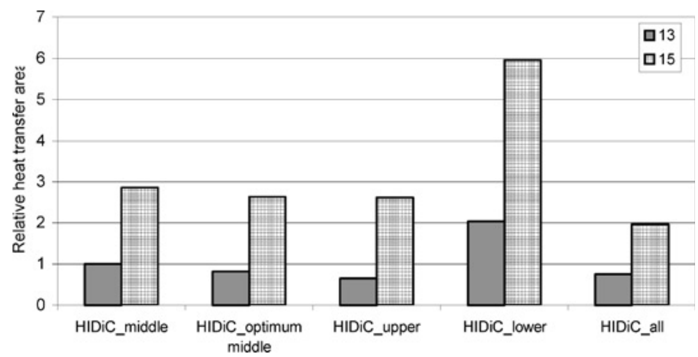
The flat part of the vapour flow profiles, of two asymmetric HIDiCs indicates a constant flow rate operation, similar to that of the conventional column and the VRC. Indeed, this is so, and the extremely bad performance of the *HIDiC(13)_lower* can be attributed to the fact that the upper, normal column part of the rectification section operates at a constant internal reflux ratio equivalent to the distillate flow rate, which is roughly factor three lower than that encountered in respectively the VRC and the conventional column. An inspection of the propylene composition profile along the column for two asymmetric HIDiCs and the conventional column shown in Fig. 5 indicates that in case of *HIDiC(13)_lower* the required separation effort is concentrated in the thermally coupled part of the column. In fact, this part of the column operates with a rather low number of theoretical stages, which must be compensated by correspondingly increased internal reflux ratio (roughly 75!). This is needed to compensate effectively for highly inefficient performance of the upper, strongly under-refluxed part of the rectification section, which uses more than 100 stages to bring the distillate to the specification. On the other hand, the separation performance of *HIDiC(13)_upper* resembles that of the conventional column. As shown in Fig. 4, the vapour flow in the normally operating lower part of the rectification section is somewhat larger indicating correspondingly larger internal reflux (around 24.5). As indicated in Fig. 5, this leads to somewhat enhanced separation performance in this part of the column, which compensates certain loss in the thermally coupled part of the column.



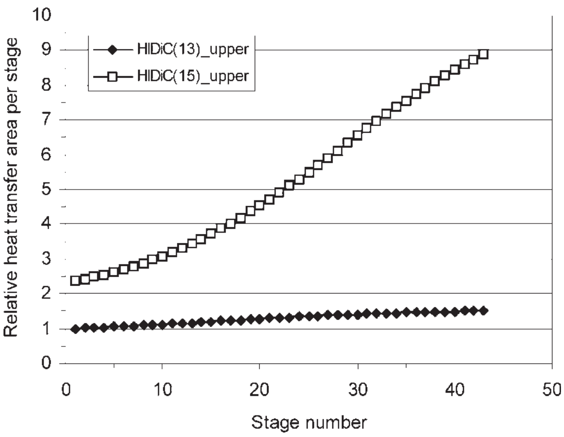
F i g . 5 – *Comparison of propylene fraction in vapour along the conventional column, HIDiC_upper and HIDiC_lower*

This clearly indicates that the performance of a HIDiC strongly depends on the heat integration configuration chosen. From thermal integration point of view, the asymmetric HIDiC with upper part of rectification section interconnected thermally with stripping section appears to be the best option. However, as mentioned before, the heat transfer area, which is for a given heat transfer duty and the overall heat transfer coefficient directly proportional to the temperature difference along the column must be reasonable to make a HIDiC feasible.

In general, heat transfer duties of low compression ratio (higher bottoms pressure/temperature) design in all cases appeared to be slightly higher and the lowest one was that associated with *HIDiC_upper*. This suggests that accordingly, this configuration will require the lowest heat transfer area, which however appeared to be strongly sensitive to the compression ratio. An indication of the heat transfer requirements relative to that of the high compression ratio option of the fully symmetric HIDiC (*HIDiC(13)_middle*) can be obtained from Fig. 6. Interestingly, the effect of the compression ratio is most pronounced in case of the thermally best HIDiC configuration (*HIDiC_upper*). In fact,



F i g . 6 – *Heat transfer area relative to the HIDiC(15)_middle*



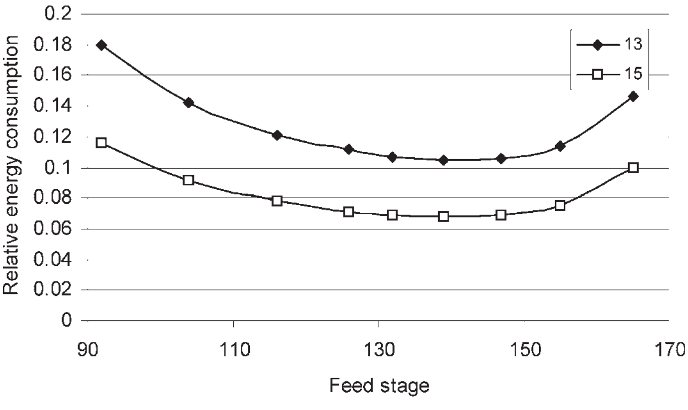
F i g . 7 – *Effect of the compression ratio on the heat transfer area for HIDiC_upper*

the low compression ratio configuration (*HIDiC(15)_upper*) requires nearly four times more heat transfer area than the high compression ratio configuration (*HIDiC(13)_upper*), which is a really profound effect. In fact, as indicated in Fig. 7, the heat transfer area increases towards the bottom of the stripping section following the reduction in temperature difference, and in case of the lower compression ratio the increase is so steep that it ends in the numbers, which may represent a technical barrier. Namely, considering the fact that the heat is transferred from rectification to the stripping section, it looks quite appealing to consider the installation of the heat transfer devices on the trays in the stripping section. On the other hand, the vapour flow is at its minimum in the bottom part of the stripping section, which implies that a rather large heat transfer area should be installed on trays with smallest cross-sectional area. This is hurting, even in the case of the configuration allowing the use of extra large tray spacing in the stripping section (*HIDiC_all*) and could effectively be overcome by placing heat transfer devices in the rectification section. This means that a portion of liquid from stripping section should be transported (by gravity) into the internal part of the heat transfer device placed on the rectification tray, and after evaporation brought back to the same stripping section stage. It should be noted however, that due to a counter-current flow situation this appears to be difficult to realize in an effective way, and, therefore should be avoided.

A practical remedy for low cross sectional area trays in the bottom part of stripping section is to consider installation of allowable heat transfer area anticipating a lower heat transfer duty, as suggested by Gadalla *et al.* in a paper discussing the benefits of so-called variable heat transfer area design approach.[14] Since a too large heat transfer area requirement poses a practical threat for HIDiC, choosing a higher compression ratio operation needs to be considered too, because increasing the temperature difference leads directly to reduction of required heat transfer area. The only one option looking well at a low compression ratio is the expanded stripping section configuration (*HIDiC(15)_all*), which requires the lowest area, because it operates at a somewhat higher temperature difference. Obviously, a thorough optimization effort is needed to arrive at the best combination of heat integration configuration and operating conditions.

Feed stage effect

Fig. 8 shows the relative energy consumption of the thermally best option of the HIDiC (*HIDiC_upper*) as a function of the feed stage location, for two compression ratios. In both HIDiC cases as well as for the conventional column the stage 139 appeared to be the optimum feed stage. In fact, the feed point could be placed 10 stages above or below the optimum one without causing higher energy/exergy consumption. This provides some degree of design flexibility, i.e. it allows making the thermally interconnected part of asymmetric HIDiC larger or smaller, depending on the potential benefit. Certainly, by moving the feed further "upward" the stage count the performance becomes to deteriorate and by placing the feed on the stage 92, *HIDiC_upper* becomes *HIDiC_middle*. Finally, Fig. 8 indicates clearly that *HIDiC_upper* could enable a PP-splitter operation using 7 to 10 per cent of the energy consumed in the operation of the conventional column, depending on the compression ratio chosen.



F i g . 8 – *Relative energy consumption for HIDiC_upper with different feed stages compared to the conventional column*

Feed composition/condition effect

In view of the fact that the construction of a HIDiC does not allow much flexibility regarding the feed location, it is interesting to see how sensitive is a HIDiC PP-splitter with respect to possible variations in feed composition and/or feed thermal

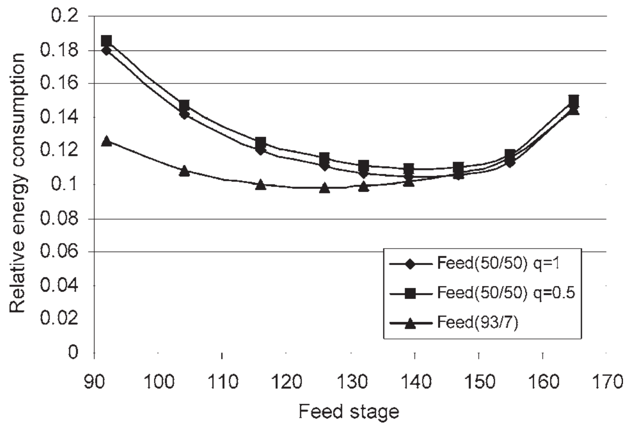


Fig. 9 – *Effect of feed composition and feed thermal condition on the relative energy consumption of the HIDiC(13)_upper*

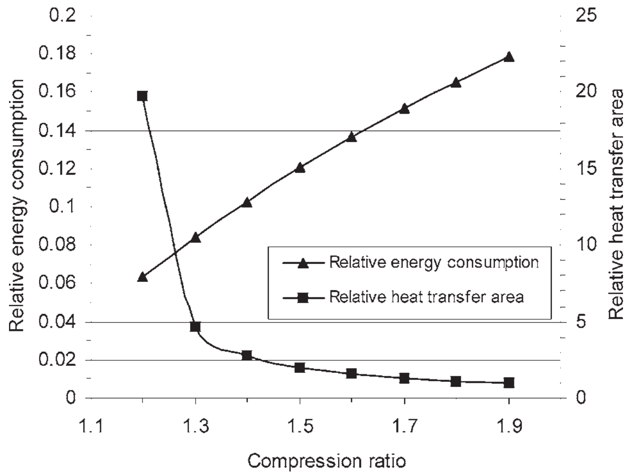


Fig. 10 – *Effect of the compression ratio on the heat transfer area and the relative energy consumption of the HIDiC_upper*

condition. Relative energy consumption curves for *HIDiC(13)_upper* shown in Fig. 9 indicate a pronounced effect of the feed composition limited however to the rectifying part of the column. As expected, for a light feed (93 mol per cent propylene) the optimum feed stage shifts accordingly, which results in a relatively shorter rectification section. The feed condition effect is independent of the feed location and does not affect greatly the energy consumption. Interestingly, in contrast to the conventional column, a partly vaporized feed in case of HIDiC leads to a small increase in the energy consumption. This may be attributed to a relatively larger vapour flow entering the compressor. It must be noted here that dealing with a partially vaporised feed is inherent to the nature of HIDiC operation, due to adiabatic flashing of the liquid transported from the rectification to the stripping section. So, there are some peculiarities related with the process behaviour of HIDiC and these should be accounted for properly before a design is fixed conceptually. A practical solution for excessive vapour flow rate could be placing a flash drum immediately after the throttling valve and subsequent condensation of separated vapour prior to adding it as saturated liquid to column feed.

In summary, the configuration of HIDiC with stripping section stages thermally interconnected with the same number of stages in the upper part of the rectification section (*HIDiC_upper*) is expected to have a lower energy demand than other HIDiC PP-splitter configurations. The challenge is to find an optimum, i.e. a sound balance between compression ratio and the heat transfer area. An indication in this direction is given in Fig. 10, which shows relative energy consumption and the heat transfer area as a function of the compression ratio, and suggests that a *HIDiC_upper* operated at compression ratio around 1.3 would nearly maximize energy saving while retaining the required heat transfer area on low side. Indeed, as demonstrated elsewhere,[11] with increasing energy costs HIDiC could emerge as an cost effective alternative for common vapour recompression systems as encountered in energy intensive distillation of close-boiling mixtures. It should be noted that capital intensive heat pump systems are considered only in stand-alone applications, i.e. if there is no waste heat- or enough low pressure steam available in an industrial plant.

Concluding remarks

Using propylene/propane separation, an industrially important, thermodynamically highly inefficient distillation process, as the base case, a conventional column and a column with direct vapour recompression are compared with five different configurations of a HIDiC. With respect to the stages to reflux ratio relation, a HIDiC behaves similar to the conventional column. The main advantage of a HIDiC with respect to a column with direct vapour recompression is that it allows operation at a significantly lower compression ratio, which, however, cannot be minimized because it maximizes the heat transfer area required for internal heat integration, which, in turn needs to be feasible with respect to available cross sectional area dictated by tray hydraulics considerations. Another limitation in this respect may arise from the fact that a HIDiC delivers more vapour to compressor than a VRC.

The performance of a HIDiC with different number of stages in rectification and stripping section depends strongly on the configuration chosen. For the PP-splitter base case considered here, the best option appeared to be a configuration with stripping section stages thermally interconnected with a corresponding number of stages in the upper part of the rectification section, with the lower part of rectification section operating as a normal column, i.e. with a constant liquid to vapour flow ratio, somewhat larger than the reflux ratio of the conventional column.

From the process design point of view, a trade-off between energy saving and the heat transfer area requirement is the main concern and in this case a compression ratio of 1.3 seems to be the best choice. Certainly, this could change to some extent if a lower operating pressure would be chosen for the rectification section. In general, a better overall performance can be expected of a HIDiC operated at the same compression ratio but with the stripping section pressure equal to that encountered in a VRC. This, i.e. optimal design of a HIDiC for a real life application is the subject of an ongoing study. The most important data, heat integrated tray efficiency, pressure drop and turndown as well as the overall heat transfer coefficient will be obtained experimentally, using a pilot scale HIDiC. Also, it is expected that this study will provide answers to all practical questions regarding the potential technical barriers for tray columns, as well as to provide a basis for establishing the reliable capital cost estimate, which, in turn is considered as a key to appraising properly the industrial viability of HIDiC.

Finally, attractiveness of this, essentially most energy-efficient distillation system, could increase significantly, if it could be implemented in retrofit situations, which may prove feasible and consequently lead to a significant expansion of the HIDiC application window.

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Notation

B – bottoms flow rate, kmol h^{-1}
D – distillate flow rate, kmol h^{-1}
Ex – exergy, kJ
F – feed flow rate, kmol h^{-1}
p_R – rectification section pressure, bar
p_S – stripping section pressure, bar
$\dot{Q}_R$ – reboiler duty, kW
q – feed thermal condition, –
T_B – bottoms temperature, K
T_0 – surroundings temperature, K
Δp_R – pressure drop of the rectification section, bar
ΔT – temperature difference, K
x – mole fraction, %

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