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Design of a commercial-scale heat-integrated distillation column based on plate-fin heat exchangers

J.A. Hugill

E.M. van Dorst

G. de Jong

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ABSTRACT

The Heat-Integrated Distillation Column (HIDiC), in which heat is transferred directly from the rectification section to the stripping section of the column, has higher energy efficiency than either a conventional distillation column or a vapour-recompression column. Although the HIDiC concept has been researched for a number of years, it has not yet been commercialised. However, a HIDiC based on a plate-fin heat exchanger has advantages of compactness, a closer temperature approach, modular structure, flexibility in design, and low pressure drop.

A case study for a commercial-scale propane-propene splitter has shown that the plate-fin HIDiC can save 35% in primary energy and 10% in Total Annual Cost compared to a vapour-recompression column. Savings compared to a conventional distillation column are even higher.

The propane-propene splitter case was worked out in more detail with the use of 3-dimensional Computer Aided Design. This demonstrated the feasibility of connecting plate-fin modules in series and in parallel in order to construct a large-scale plant. A complete plant including all major equipment items and pipework was visualised, and compared to equivalent designs for a conventional column and a vapour-recompression column. This confirmed that the HIDiC plant is more compact than the alternatives. Issues for future attention include the liquid distribution within each plate-fin module, and the apparent necessity of a large flash vessel to facilitate liquid distribution over several modules.

THE HEAT-INTEGRATED DISTILLATION COLUMN

About 40% of the energy use in the chemical and refinery industries is associated with separation by distillation. A conventional distillation column (Fig. 1) has a very low energy efficiency. Heat is supplied to the reboiler at a relatively high temperature and recovered from the condenser at a relatively low temperature, the distillation column itself being adiabatic. Many ideas have been proposed to improve this, but very few have been implemented.

One idea that has sometimes been implemented is that of the vapour-recompression column (VRC) shown in Fig. 2. In this scheme, the top stream from the column is compressed so that it can be condensed at a higher temperature, enabling the condenser and reboiler to be integrated together as a single heat exchanger. The reboiler heat duty is eliminated, but energy is required for the compressor, which is also a significant cost item. In practice, applications of the VRC have been limited to distillations in which the mixture has a relative volatility close to unity (i.e. close-boiling mixtures) so that the compressor has a reasonably low compression ratio.

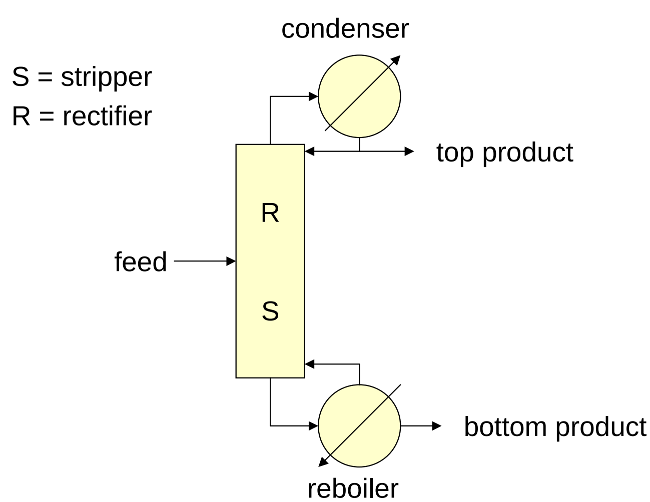

Fig. 1. Conventional distillation column.

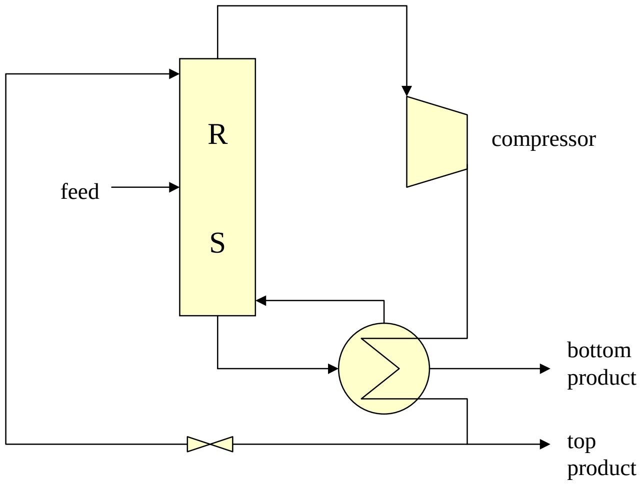

Fig. 2. Vapour-recompression column.

The basic idea of the Heat-Integrated Distillation Column (HIDiC), which has not yet been commercially applied, is shown in Fig. 3. The HIDiC is similar to the VRC insofar as a compressor is used, but now the compressor is placed mid-way in the column, just above the feed inlet. The stripping section (S) of the column (below the feed inlet) is operated at a relatively low pressure while the rectification section (R) of the column (above the feed inlet) is operated at a relatively high pressure. The pressure differential implies a corresponding differential in operating temperature, which in turn enables heat to be transferred directly from the rectification section to the stripping section. Both the reboiler and the condenser heat duties can be greatly reduced - in theory either the reboiler or the condenser can be eliminated. Although energy is required for the compressor, overall the efficiency is improved.

The history of the HIDiC has been described elsewhere (Nakaiwa et al., 2003; Olujic et al., 2003). The most interesting applications are similar to those of a VRC, for close-boiling mixtures. However the HIDiC can lead to even

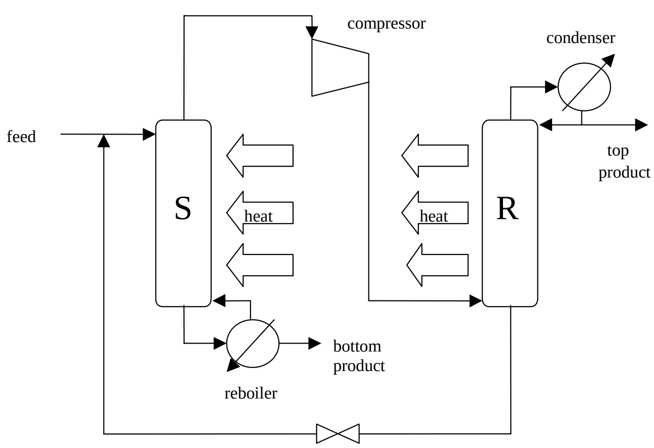

Fig. 3. HIDiC concept.

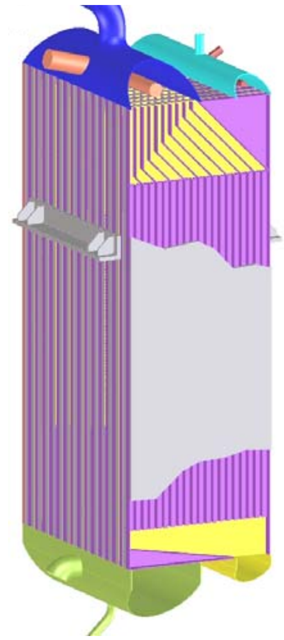

Fig. 4. Plate-fin heat exchanger for HIDiC.

higher energy savings than the VRC (Sun et al., 2003). Total primary energy savings in the Netherlands, Western Europe, and the world have been estimated to be respectively in the ranges 11-25, 60-140, and 370-860 PJ/y (Hugill and Van Dorst, 2005a). The most promising applications in terms of total energy savings in the Netherlands are the propane/propene-splitter, ethane/ethene-splitter, and cryogenic air separation.

THE PLATE-FIN HIDiC

In an earlier publication we described the option of basing a HIDiC design on a plate-fin heat exchanger (PFHE) (Hugill and Van Dorst, 2005b). The advantages of using PFHEs include compactness, a closer temperature approach, modular structure, flexibility in design, and low pressure drop. A PFHE (Fig. 4) consists of a number of parallel flat plates with intermediate corrugated plates (fins). The flat plates separate the process streams and provide primary heat-transfer surface. The fins provide secondary heat-transfer surface. In a HIDiC application, the PFHE is arranged for parallel vertical flows in alternating stripper and rectifier layers. In each layer there is a countercurrent flow of vapour and liquid, with the liquid flowing downwards as a film on the walls. Within each layer, the fins may (depending on the type of fin) divide the space into a number of parallel passages.

A feature of the HIDiC is that the vapour and liquid flows change significantly with height (Fig. 5). Use of a constant cross-section and constant hydraulic diameter for the rectifier or the stripper would imply that the cross-section is determined by the approach to the countercurrent flooding limit at the point of maximum vapour and liquid

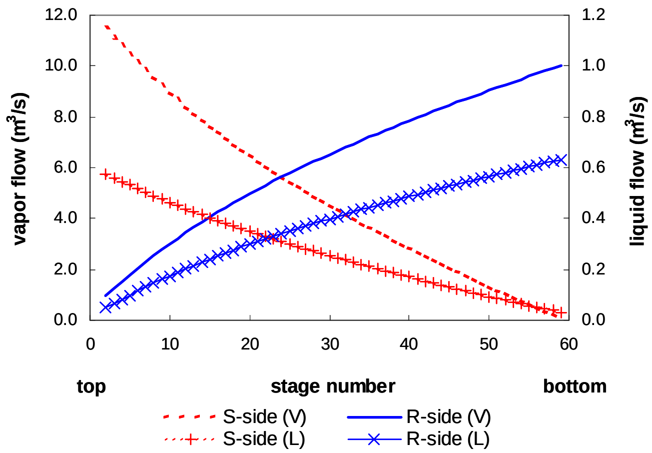

Fig. 5. Volumetric flows versus stage number.

flows (i.e. at the top of the stripper or the bottom of the rectifier). This would lead to relatively low vapour velocities at the bottom of the stripper and the top of the rectifier. This in turn implies relatively poor heat and mass transfer between the phases, leading to a loss of efficiency. With a PFHE design there are various possibilities to change the cross-sectional area, and also the hydraulic diameter, with height. One option is to vary the fin-strip length and fin spacing (Fig. 6). An alternative idea, which deviates more from current PFHE designs, is to use non-parallel plates with a constant fin spacing (Hugill, 2003; Hugill and Van Dorst, 2005a).

DESIGN MODEL AND RESULTS

In an earlier paper we reported the first version of our design model and its application to a preliminary case study of a propane-propene (PP-)splitter (Hugill and Van Dorst, 2005b). Subsequently the design model was refined, and the case study was extended (Hugill and Van Dorst, 2005a).

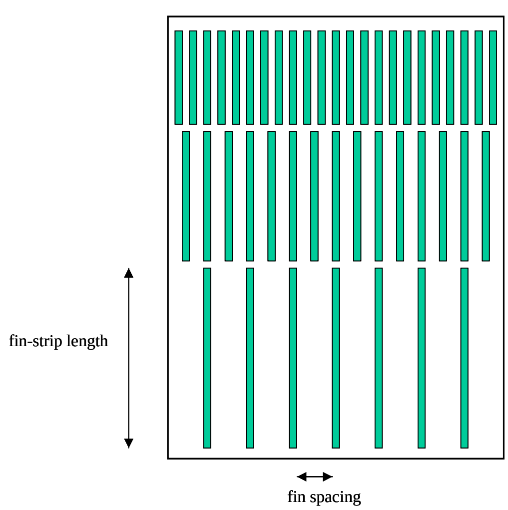

Fig. 6. Variable fin-strip length and fin spacing (rectifier side).

Here we present a few aspects of that earlier work, together with some more recent results, updates, and comparisons.

The basis of design for the PP-splitter case study has been described elsewhere (Olujic et al., 2006). The base case corresponds to an existing large commercial plant, which is a VRC equipped with conventional trays. The base case (with optimum position of the feed inlet) has 154 equilibrium stages in the rectifier and 57 in the stripper (Schmal, 2004). In the HIDiC design the 57 stripper stages are integrated with the top 57 stages of the rectifier (Olujic et al., 2006; Sun et al., 2003). The remaining rectifier stages are implemented as a conventional column. The complete HIDiC flowsheet, including an additional flash vessel that will be discussed later, is shown in Fig. 7.

Here we report results for the following case, which corresponds to case B in our previous publication (Hugill and Van Dorst, 2005a):

- The design is based on parallel plates
- The equilibrium-stage height is 0.32 m
- The fin-strip length is equal to the equilibrium-stage height, so that the fin spacing could vary from stage to stage (Fig. 6)
- The maximum plate spacing is 30 mm
- The minimum temperature difference (approach) between rectifier and stripper is 1 K
- The material of construction is aluminium.

The assumed equilibrium-stage height of 0.32 m is conservative compared to available lab-scale data (Tung et al., 1986) but may be more consistent with industrial experience with dephlegmators (reflux condensers), which are similar to the rectifier section of the HIDiC. The use of this stage height, together with the maximum height of 6-8 m for the heat-transfer core of a commercial PFHE module, implies that 3 or 4 modules are required in the vertical direction. We have conservatively assumed that 4 modules are required.

The design procedure aimed to accommodate the large changes in flow (Fig. 5) and to approach as closely as possible to 70% of countercurrent flood at every height in the column. This was achieved by varying both the plate spacing and the fin spacing, as illustrated in Fig. 8 and Fig. 9.

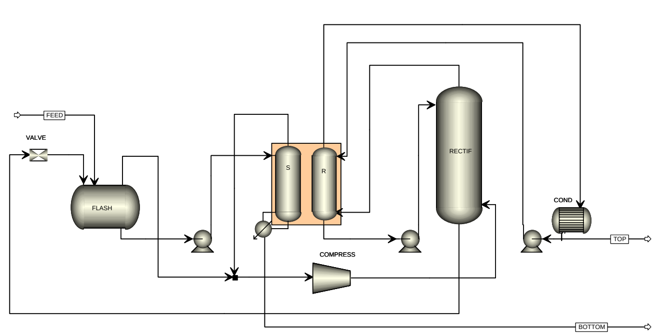

Fig. 7. Complete HIDiC flowsheet for PP-splitter case.

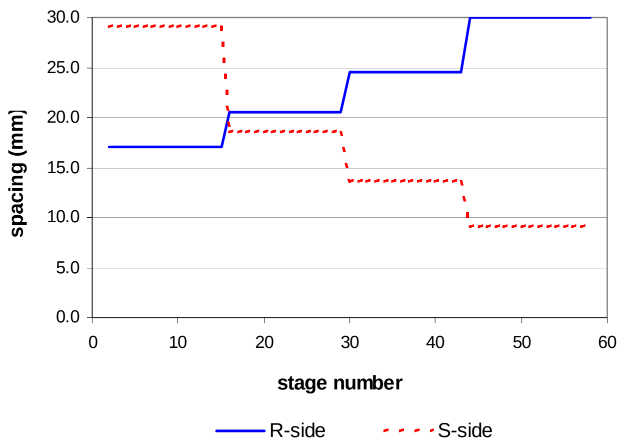

Fig. 8. Plate spacing versus stage number.

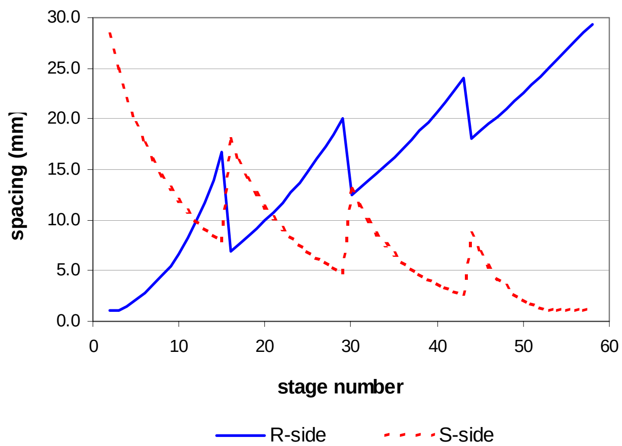

Fig. 9. Fin spacing versus stage number.

Some further results are shown in Table 1. The HIDiC design is compared to the VRC base case and also to an equivalent conventional column (CC).

Comparing to the VRC base case, we see that the compressor duty (i.e. energy requirement) is reduced by 35%. Also the column height is significantly reduced. The column diameter (calculated for the PFHE modules as an equivalent circular diameter) is slightly increased. The equivalent diameter far exceeds the normal dimensions of a PFHE module, so that in practice several modules will have to be connected in parallel to accommodate this very large-scale application.

Table 1. Results of the PP-splitter design case.

		CC	VRC	HIDiC
P drop /stage	Pa	619	619	95-110
Compression ratio	-	-	1.62	1.30
Compressor duty	%	-	100	65
Column height	m	110	110	53 + 34*
Column diam	m	8.1	6.5	8.1 + 7.3*

* conventional rectifier + PFHE modules

The primary energy savings of HIDiC compared to the conventional column are even greater than those compared to the VRC.

DETAILED DESIGN

The basic design described above was worked out in more detail with the aid of standard sizing correlations and 3-dimensional Computer Aided Design software. This was done not only to visualise the complete commercial-scale plant, but also to help identify issues that might be encountered at a later stage in the development of this technology.

Attention was paid to the detailed design of a single PFHE module and to the way in which modules can be combined in series and parallel to construct a large-scale plant. Plausible solutions for the distribution of liquid and vapour phases within a module and among a number of modules were developed. Sizing calculations were done for the other equipment items in the plant (compressor, pumps, flash vessel, reboiler and condenser) and for the pipework connecting all the equipment items (Sinnott, 2005). The reboiler, although in theory eliminated in the HIDiC design, was included in the plant for the purpose of start-up. For the purpose of comparison with the plate-fin HIDiC, equivalent designs were made for a VRC and for a CC.

Distribution of liquid and vapour within a single module

A single PFHE module is shown in Fig. 4. Details of the headers and distributors are shown in Fig. 10 and Fig. 11 for respectively the top and the bottom of a module. (N.B. For the purpose of clarity, plate and fin spacings are not to scale in these Figures).

The liquid distribution at the top of the module, for both the stripper and the rectifier sections, is done in two stages (Fig. 10). In both stages, allowance must be made for a significant counter flow of vapour, and entrainment of liquid in the vapour flow must be avoided. In the first stage, liquid must be distributed evenly over the layers of the module. This can be done by means of a distributor similar to those used in conventional distillation columns that are equipped with structured packing. Various types of distributor are commercially available for this service, however this is indicated only very schematically in the Figure. In the second stage, within each layer, liquid must be distributed evenly over the channels between the fins. This can be done by means of distributor fins similar to those already used in commercial PFHEs, shown schematically in the Figure. Experience with countercurrent two-phase flow in conventional PFHE applications is relatively limited. For a HIDiC application the design challenge is probably greater, especially at the top of the stripper where the flows are largest. Accordingly we feel that the detailed design of the liquid distribution is a major issue for future development.

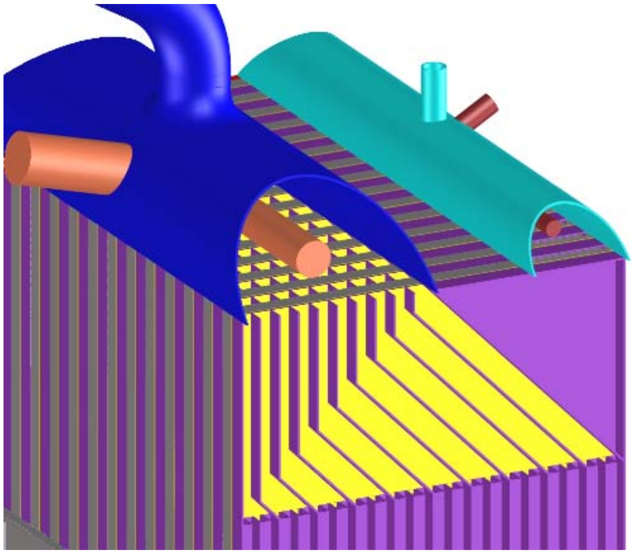

Fig. 10. Detail of headers and distributors at top of module.

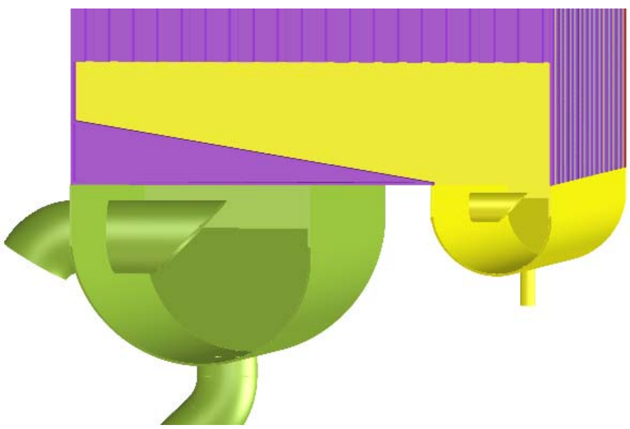

Fig. 11. Detail of headers and distributors at bottom of module.

Distribution of vapour at the bottom of the module is also done in two stages (Fig. 11). For the time being we have assumed that the vapour distribution can be achieved simply on the basis of a low pressure drop, and that no specific distributor hardware is required. However, this assumption should be checked at a later stage of the equipment development. If required, the first stage of distribution could be achieved by means of a distributor similar to those used in conventional distillation columns that are equipped with structured packing. For the second stage, past experience with dephlegmators is relevant; for example various ideas have been proposed to ensure smooth disengagement of liquid and thereby avoid local flooding and vapour maldistribution at the bottom of the heat-transfer fins.

Another feature of the header at the bottom of the module is that room has been made for a hold-up volume of liquid in the bottom of the header, similar to the liquid volume normally present in the bottom of a conventional distillation column.

Connection of modules in parallel

As already mentioned above, in practice several modules must be connected in parallel to provide the required capacity (throughput). This can be achieved by the use of manifolds as shown in Fig. 12. It was assumed that the maximum dimensions of a single module were a stack height of 3 m and a width of 2 m. This implies that six modules must be connected in parallel as shown in Fig. 12. The maximum width of currently available commercial PFHE modules may be slightly less than 2 m (say 1.5 m), in which case more than six modules would be required; however this does not change the principle involved. It is expected that larger modules may be available by the time such a plant is actually built. The design of the manifolds must ensure a uniform distribution of liquid and of vapour to the modules. However this distribution problem is less difficult than the distribution problem within each module, because in each manifold there is only one phase (either liquid or vapour) flowing.

Connection of modules in series

As already mentioned above, we assumed that four modules must be connected vertically in series to provide the required number of equilibrium stages. This can be achieved in a rather simple manner as shown in Fig. 13. It should be noticed that the horizontal manifolds that connect the modules in parallel are present only at the top and bottom of such a vertical series.

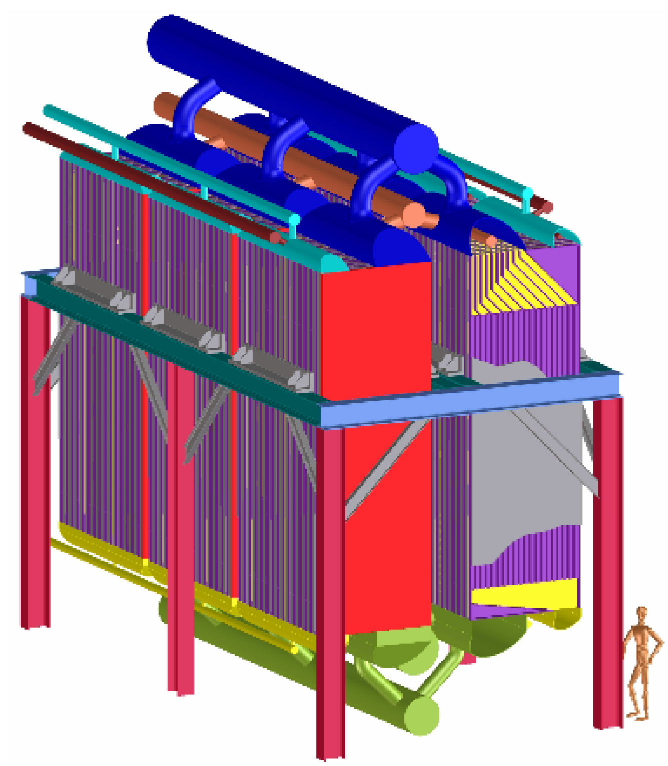

Fig. 12. Connection of modules in parallel.

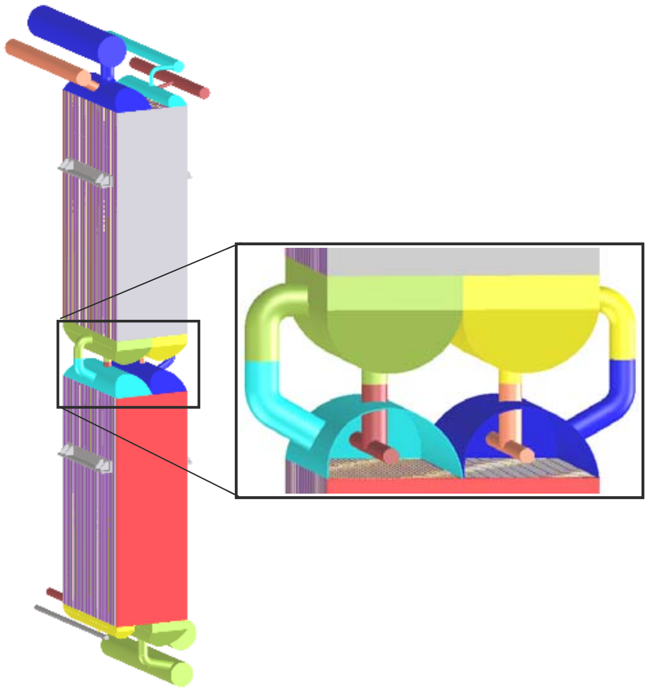

Fig. 13. Connection of modules in series.

The complete HIDiC plant

The complete HIDiC plant, corresponding to the flowsheet of Fig. 7, is shown in Fig. 14 and Fig. 15. It can be seen the stack of 24 PFHE modules (constituting 57 rectifier stages and 57 stripper stages) is relatively small compared to the conventional rectifier section (97 stages), which confirms the potential of the HIDiC concept to give a more compact plant. However, it can also be seen that the flash vessel (the horizontal vessel coloured brown in the drawings) is conspicuously large. This deserves further comment.

The flash vessel

The flash vessel was not present in the initial conceptual design (Fig. 3). The necessity for this vessel emerged at a later stage, when it became clear that a number of PFHE modules would have to be connected in parallel (Fig. 12). This introduced a new problem concerning the stream to the top of the stripper section (see Fig. 3), which is a mixed liquid-vapour stream. If this feed is to the top of a single PFHE module, the required disengagement of the liquid and vapour phases can be allowed for in the design of the header and the liquid distributor. However, if the liquid must be distributed equally over a number of parallel PFHE modules, then the obvious conventional solution is to introduce a flash vessel as indicated in the complete flowsheet (Fig. 7). The liquid phase is then distributed to the modules, while the vapour phase is routed directly to the compressor. However, when the flash vessel is designed according to standard design rules (Sinnott, 2005), a vessel

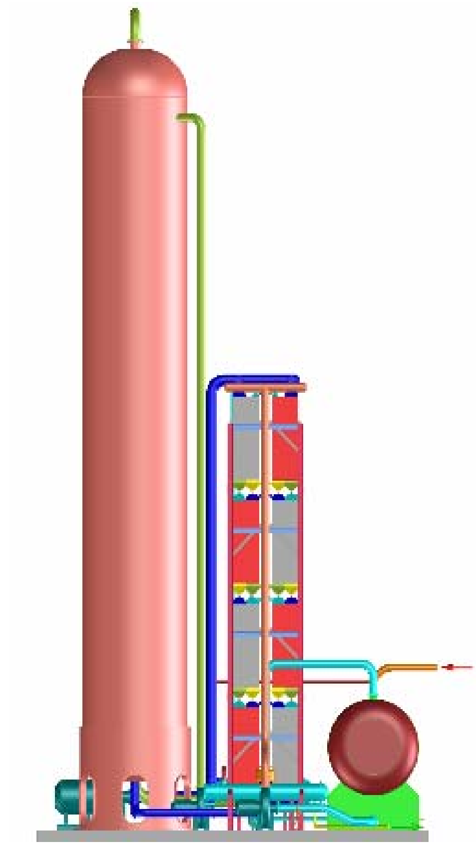

Fig. 14. The complete HIDiC plant (side view).

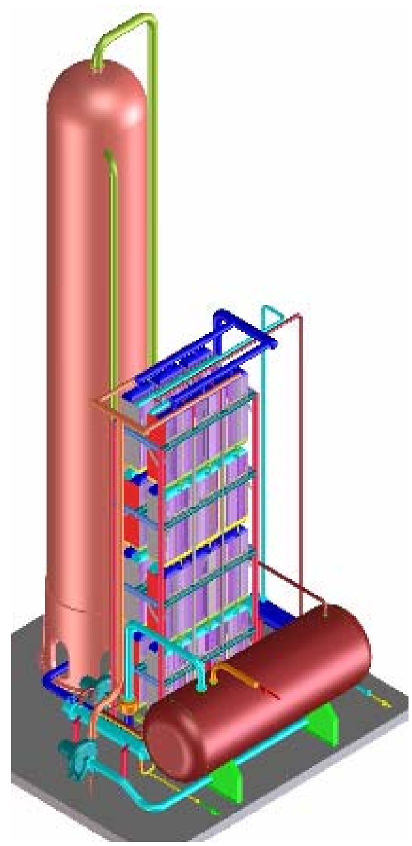

Fig. 15. The complete HIDiC plant (general view).

is obtained that is large compared to most of the other equipment items. Fortunately the impact on the investment cost is not so great (see below). Nevertheless this could be an issue for the future HIDiC development: are there alternative devices to a flash vessel, or could the flash vessel actually be made smaller than the standard rules suggest?

Comparison with VRC and CC

In Fig. 16 we see the comparison between the complete HIDiC plant, the VRC, and the CC. This again confirms that the HIDiC plant is significantly more compact than the alternatives.

ECONOMIC EVALUATION

The cost estimating procedure and economic evaluation for a generic HIDiC design had previously been implemented in an Excel spreadsheet (Olujic et al., 2006). For our purpose it was only necessary to add cost estimates for the PFHE modules. The purchase cost of each module was estimated based on tabulated cost data (Shah and Sekulic, 2003). The installed cost was then estimated assuming a Lang factor of 2, which is commonly applied for plate heat exchangers (Hesselgreaves, 2001).

The relative contributions to the total annual cost (TAC), assuming a 10-year project lifetime, are given in Table 2. The economic picture is dominated by the electricity cost, but the PFHE modules are also a significant cost item. Compared to the other cases, the HIDiC design saves energy but this is partly offset by the higher capital cost: the TAC is 90% of the value for the VRC. It should be noted that the uncertainty in the estimated installed cost of the PFHE modules is high. A 50% higher cost would cause the TAC for HIDiC to equal that of the VRC. On the other hand, the TAC of the plate-fin HIDiC has not yet been optimised with respect to compression ratio.

Table 2. Contributions to total annual costs for HIDiC.

	% of TAC
Column shell (rectifier)	6.8
Trays (rectifier)	1.4
PFHE modules	26.2
Condenser	0.7
Reboiler	0.7
Compressor	5.7
Flash vessel	1.9
Cooling water	2.1
Electricity	54.6
TOTAL	100.0

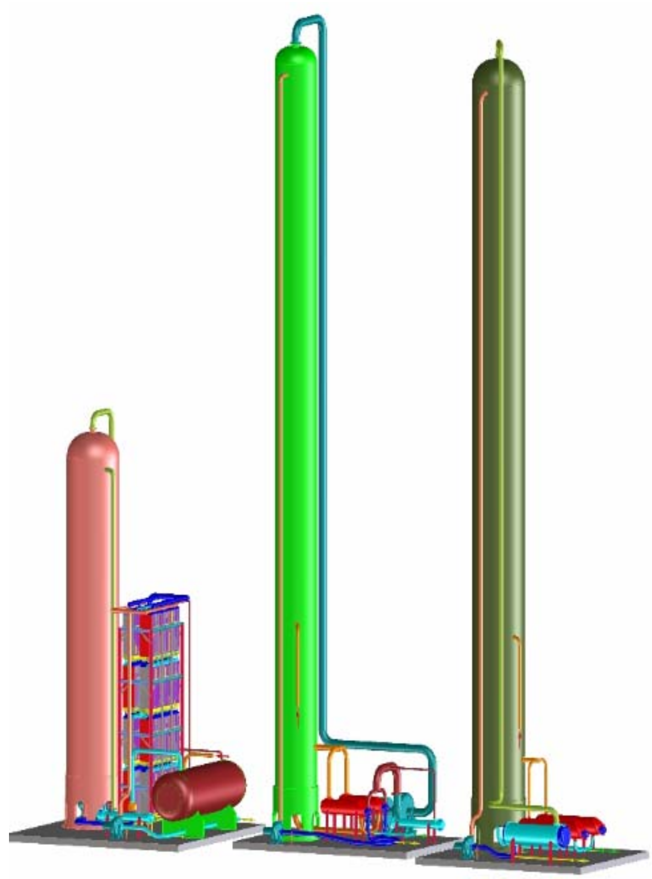

Fig. 16. Comparison of the HIDiC (left) with the VRC (middle) and the CC (right).

CONCLUSIONS

The case study for a PP-splitter has shown that the plate-fin HIDiC can save 35% in primary energy and 10% in Total Annual Cost compared to a vapour-recompression column. Savings compared to a conventional distillation column are even higher. The HIDiC plant is also more compact.

The detailed design has demonstrated the feasibility of connecting PFHE modules in series and in parallel in order to build such a large-scale plant. Issues for future attention include the liquid distribution within each module, and the apparent necessity of a large flash vessel to facilitate liquid distribution over several modules.

NOMENCLATURE

CC	Conventional (distillation) Column
HIDiC	Heat Integrated Distillation Column
PFHE	Plate-Fin Heat Exchanger
PP	Propane-Propene
TAC	Total Annual Cost
VRC	Vapour-Recompression Column

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