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THE USE OF COMPACT HEAT EXCHANGERS IN HEAT-INTEGRATED DISTILLATION COLUMNS

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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 a much higher energy efficiency than either a normal 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. Recent literature describes an embodiment of the concept, which resembles a shell-and-tube heat exchanger. However an alternative embodiment based on a compact (plate) heat exchanger has several potential advantages over the shell-and-tube design. These advantages include compactness, a closer temperature approach, modular structure, and flexibility in design.

In order to investigate the feasibility of a HIDiC design based on a plate-fin heat exchanger, a computer program has been developed. This approach is based on an existing model for conventional distillation, coupled to a spreadsheet program that incorporates correlations for such factors as flooding, wetting, and fin efficiency, and that takes account of geometric constraints in the plate-fin design. The software was applied in a preliminary case study for a propane-propene splitter. This confirmed the scope for energy savings, with energy savings of about 37% compared to a vapour-recompression column. First indications suggest that the economics may also be favourable. It was concluded that the plate-fin design is feasible in principle. However the required hydraulic diameter was larger than currently available in commercial plate-fin heat exchangers.

THE HEAT-INTEGRATED DISTILLATION COLUMN

About 40% of the energy use in the chemical and refinery industries is associated with separation by distillation. It is well known that a conventional distillation column 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. The decrease in temperature level implies a low (exergetic) efficiency. 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. 1. 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, so that the compressor has a reasonably low compression ratio.

The basic idea of the Heat-Integrated Distillation Column (HIDiC), which has not yet been commercially

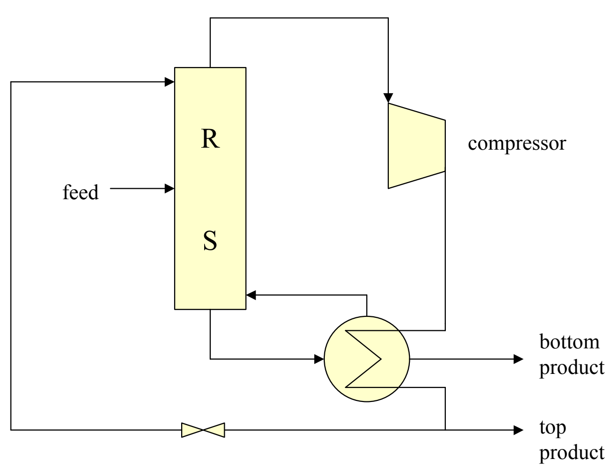

Fig. 1. Vapour-recompression column.

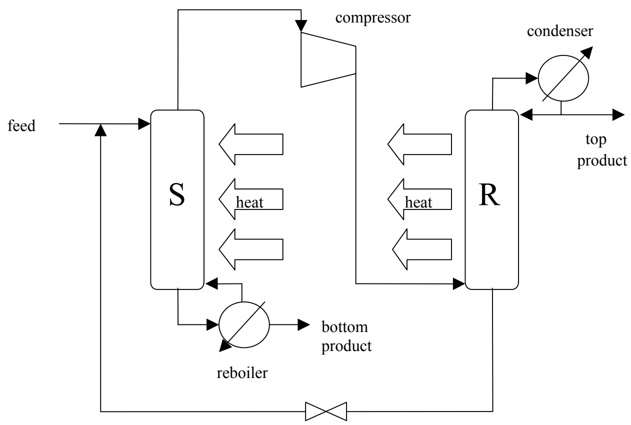

Fig. 2. HIDiC concept.

applied, is shown in Fig. 2. 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 name "HIDiC" was coined by a Japanese consortium, which has published a large number of papers on this subject over the last few years (Nakaiwa et al., 2003). However the concept was previously investigated by others. The history of the HIDiC has been described elsewhere (Olujic et al., 2003). Recent work at the Technical University of Delft has shown that the most interesting applications are similar to those of a VRC, for mixtures with relative volatilities close to unity. However the HIDiC can lead to energy savings of about 50% compared to a VRC (Sun et al., 2003).

Over the years many specific implementations have been proposed for the HIDiC. Broadly two types of implementation are possible:

- distillation columns modified to allow heat transfer,
- heat exchangers modified to allow fractionation.

Recent developments in the first type of implementation have been described elsewhere (Olujic et al., 2004). In this paper we focus on the second type of implementation.

COMPACT HEAT EXCHANGERS APPLIED TO THE HIDIC

The Japanese consortium mentioned above has developed an example of the second type of implementation, in which the stripping and rectification sections are combined in an apparatus, which closely resembles a vertical shell-and-tube heat exchanger (Aso et al., 1998). Both sides of the heat exchanger may contain internals such as regular or irregular packing. Here we consider the possibility of using a compact heat exchanger instead of a shell-and-tube heat exchanger.

Compact heat exchangers (CHEs) are heat exchangers in which the heat-exchange surface area per unit volume of the equipment is significantly higher than in a conventional shell-and-tube exchanger, i.e. greater than about 400 m^2/m^3. Most compact designs are based on a structure of parallel flat plates. Various types are commercially available and have been described in the literature (Hesselgreaves, 2001; Reay, 1999; Reay and Pritchard, 1998) e.g. plate-frame, brazed-plate, or welded-plate heat exchangers, printed-circuit heat exchangers, or plate-fin heat exchangers (PFHEs).

The feasibility of applying compact heat exchangers to the HIDiC concept is partly based on the recognition that the rectification section of the HIDiC is essentially equivalent to a reflux condenser. Reflux condensers (or dephlegmators) are well known in the literature and have been commercially applied. In this equipment the condenser (heat exchanger) is arranged in such a way that countercurrent two-phase flow occurs in the condenser, as in a distillation column, and thereby a degree of component separation is achieved which is greater than in a normal overhead partial condenser (single equilibrium stage). Although shell-and-tube heat exchangers can be used, compact heat exchangers (especially PFHEs) have been found to have advantages in this service (Bernhard et al., 1986).

Fig. 3 shows a PFHE suitable for a HIDiC application. A PFHE 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

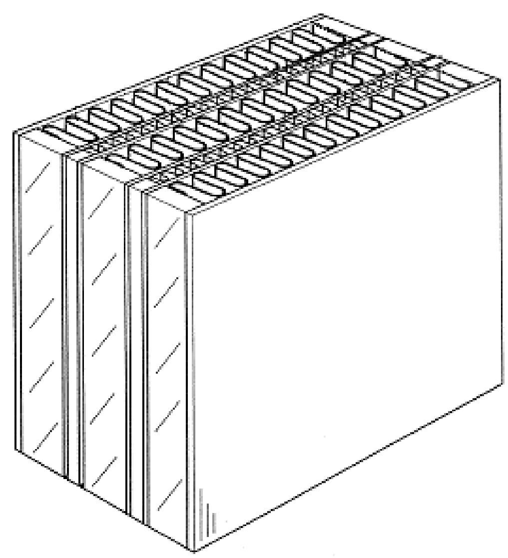

Fig. 3. Plate-fin heat exchanger for HIDiC.

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 gas and liquid, with the liquid flowing downwards as a film on the walls. In the figure, the alternate layers are shown with significantly different widths (plate-to-plate distances); however this width difference can vary from one design to another. Within each layer, the fins may (depending on the type of fin) divide the space into a number of parallel passages. The headers and liquid and gas distributors are not shown in the figure.

Previous work

Haselden et al. published a series of papers and patents in the period 1956 – 1983 concerning the HIDiC (or very similar) concepts, mainly applied to air separation where oxygen of medium purity (< 98%) was required. His early work was concerned with plate designs with "overflow packing" (Gee and Haselden, 1968; Haselden, 1958; Haselden et al., 1960; Haselden and Winteringham, 1965; Platt and Haselden, 1965; Winteringham and Haselden, 1966) that was patented in 1956-57 (Haselden, 1956; Haselden, 1957). Although there is some resemblance to commercial PFHEs, overflow packing has the following specific features:

- The corrugated plate has horizontal corrugations (fins).
- Liquid is deliberately held up in small reservoirs at each corrugation.
- Holes in the corrugated plate allow liquid to overflow from the reservoirs and gas to pass upward.

Overflow packing was tested in a lab-scale unit with nitrogen-oxygen mixtures. Heights of transfer unit were observed in the range 7 – 21 cm.

Mah et al. published a series of papers (1977- 1986) on the Secondary Reflux and Vaporisation (SRV) concept, which is equivalent to HIDiC (Mah et al., 1977). The idea of implementing SRV in a plate-fin structure was put forward in 1980 (Mah, 1980). Lab-scale experiments (evaporation and condensation separately) were done with a plate-fin design. With toluene-hexane mixtures, heights of transfer unit in the range 12 – 25 cm were measured (Tung et al., 1986).

An Air Products patent from 1997 (Herron et al., 1997) is basically an update of Haselden's patents but with a PFHE instead of overflow packing.

Advantages and disadvantages

The advantages of the plate concept (specifically compared to the shell-and-tube design) are as follows:

- *Commercial experience* with PFHEs in dephlegmator applications should lead to easier acceptance by industry.
- *Compactness*: A higher heat exchange area per unit volume of equipment, possibly combined with higher heat-transfer coefficients. This can lead to more compact equipment and/or a closer temperature approach.
- *Closer temperature approach*: The temperature approach (temperature difference between hot and cold sides of the heat exchanger) is typically 10 - 20 K for a shell-and-tube heat exchanger, but may be as low as 1 K for a PFHE. Applied to HIDiC, a lower temperature approach implies a lower pressure differential between the stripping and rectification sections, which in turn implies *a smaller (less costly) compressor and lower energy use*.
- *Modular structure*: Once the design of a single plate is fixed, the overall capacity (throughput) of the equipment can be easily modified by adjusting the number of plates.
- *Flexibility in design*:
- *Cross-sectional area and hydraulic diameter*: The use of a plate geometry enables us to propose alternative (potentially more effective/cheaper) ways of changing the cross-sectional area and/or hydraulic diameter with height, as explained in the next section.
- *Heat/mass transfer ratio*: A crucial factor in a HIDiC application is the balance between heat transfer and mass transfer in the equipment. This is largely determined by the ratio between the heat transfer surface and the mass transfer surface. The plate geometry, especially in the plate-fin embodiment with a variable design distance between the plates, has greater flexibility in this respect than the shell-and-tube design.

Further advantages, shared with the (packed) shell-and-tube design, compared to a distillation column with trays are:

- low liquid hold-up,
- low pressure drop.

Disadvantages of (or issues to be addressed with) the plate design are:

- a need for complex distributors,
- PFHE module size limitation (maximum height about 6 - 8 m, width about 2 m),
- flooding limitation with high liquid loads,
- turndown (surface wetting),
- limited flexibility under a range of operating conditions (matching heat/mass transfer on the two sides).

The last issue may well be a problem with other HIDiC concepts as well.

Change of cross sectional area and hydraulic diameter with height

A feature of the HIDiC is that the gas and liquid flows change significantly with height (Fig. 4). 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 gas and liquid flows (i.e. at the top of the stripper or the bottom of the rectifier). This would lead to relatively low gas velocities at the bottom of

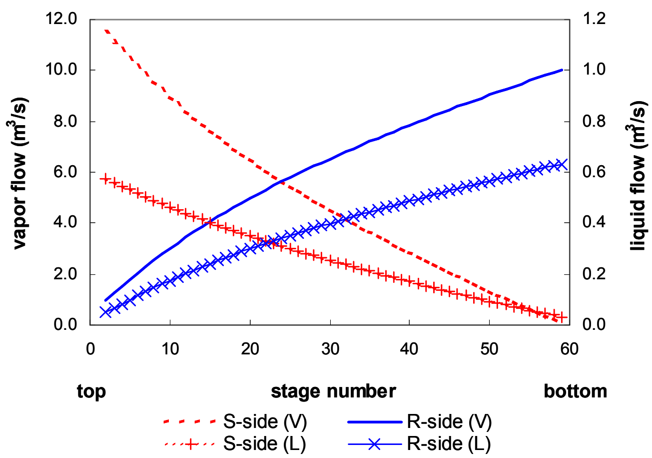

Fig. 4. Volumetric flows versus stage number (Case 1).

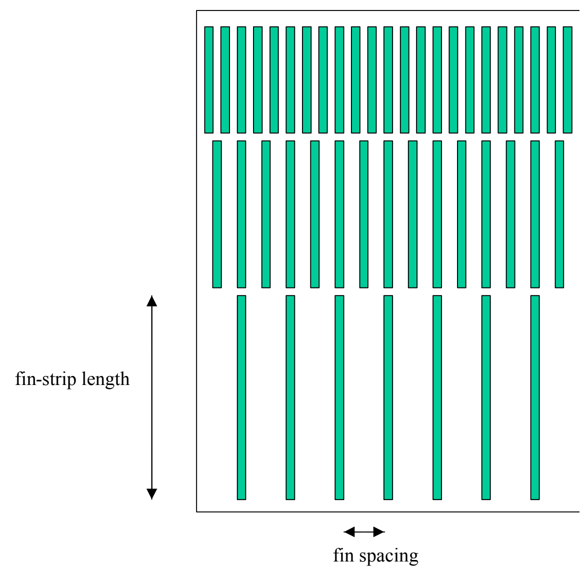

Fig. 6. Variable fin-strip length and fin spacing (rectifier side).

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. This is known to be a problem in dephlegmators (Jibb and Droegemueller, 1999).

The shell-and-tube design (Aso et al., 1998) includes various ways of changing the cross-sectional area of the tubes with height. With a plate design there are various possibilities to change the cross-sectional area, and also the hydraulic diameter, with height. One option might be to use non-parallel plates (Fig. 5) (Hugill, 2003) although this is a significant deviation from current PFHE designs and it remains to be seen whether this construction is viable in practice. Another possibility, which has already been suggested for dephlegmators (Bakke, 1997) is to vary the fin-strip length and fin spacing (Fig. 6); in this case it is mainly the hydraulic diameter rather than the cross-sectional area, which is changed. This enables the design to approach the local flooding point at every height in the exchanger, so that greater heat/mass-transfer area can be installed higher in the rectifier (and lower in the stripper).

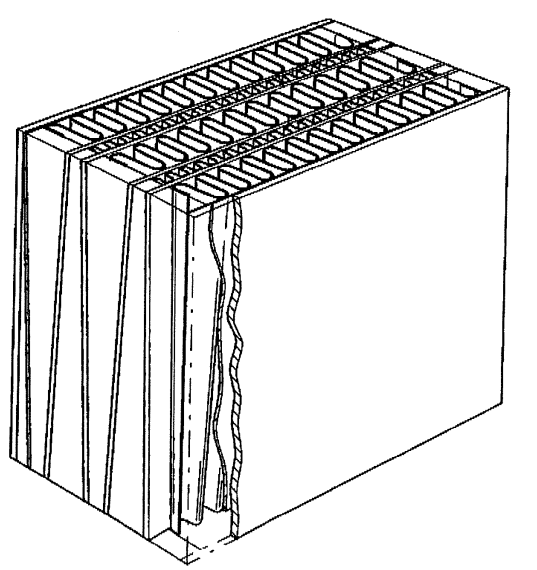

Fig. 5. Plate-fin design for HIDiC (non-parallel plates).

A MODEL FOR DESIGN

In order to investigate the technical feasibility of a plate-fin HIDiC design, we have developed a computer model. This is based on a commercially-available model for conventional distillation, namely the equilibrium-stage model RADFRAC, which is part of the Aspen Plus flowsheeting program. This model had previously been extended to a generic HIDiC design by coupling with an Excel spreadsheet (Olujic et al., 2004). We have further extended this approach to describe a

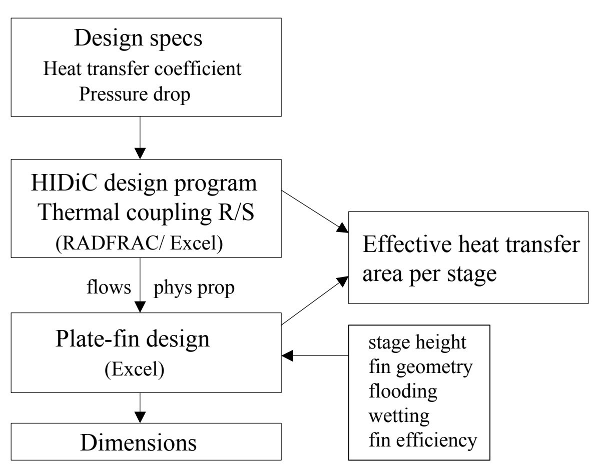

Fig. 7. Structure of design model.

plate-fin design. The overall structure of the software is shown in Fig. 7. The spreadsheet includes parameters or literature correlations to describe the required properties, e.g. the Wallis flooding correlation (Hewitt et al., 1994), fin efficiency (Shah and Sekulic, 2003), and wetting (Ponter et al., 1967). The initial design objective is to approach as closely as possible to 70% of the flooding limit at every equilibrium stage on both the rectifier and stripper sides, based on flow-rates and physical-property data from the RADFRAC simulation. This objective is subject to geometrical constraints imposed by the plate-fin design (e.g. minimum and maximum values for module height, plate spacing, fin spacing, and fin thickness). The resultant geometric heat-transfer area on each stage (on both the rectifier and stripper sides) is corrected for the effects of fin efficiency and wetting, giving an effective heat-transfer area. This effective area per stage is averaged between the rectifier and stripper sections by use of a simple approximation. The overall effective area is then multiplied by the temperature difference and by an estimated value for the overall heat-transfer coefficient to yield a value for the heat transfer per stage, which can be compared to the value used in the RADFRAC simulation. Using an iterative procedure a consistent design can be achieved.

RESULTS

We report some preliminary results for a case study of a propane-propene (PP-)splitter. The basis of design has been described elsewhere (Olujic et al., 2004). 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., 2004; Sun et al., 2003). The remaining rectifier stages are implemented as a conventional column, which is not further considered here. For the plate-fin HIDiC design only the parallel-plate option (Fig. 3) was considered. The fin-strip length was assumed equal to the equilibrium-stage height, so that the fin spacing could vary from stage to stage (Fig. 6). We report three cases:

- Case 1: effective heat-transfer area per stage about 400 m^2, pressure drop per stage as in the VRC.
- Case 2: minimum temperature difference 1 K, pressure drop per stage as in the VRC.
- Case 3: minimum temperature difference 1 K, pressure drop per stage realistic for a PFHE.

In these calculations the height of an equilibrium stage was put equal to 0.16 m. This was consistent with the available experimental data (Tung et al., 1986) but may be optimistically small compared to experience with commercial dephlegmators. The overall heat-transfer coefficient between the rectifier and the stripper was assumed to be 1000 W K^{-1} m^{-2}. Plain fins were considered, as shown in Fig. 3.

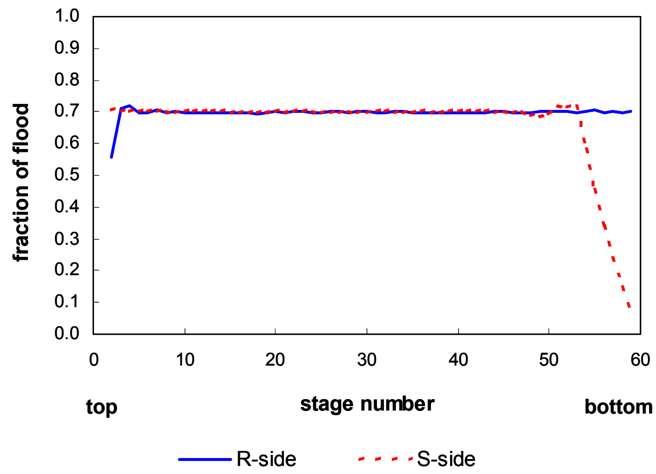

Fig. 8. Fraction of flood versus stage number (Case 1).

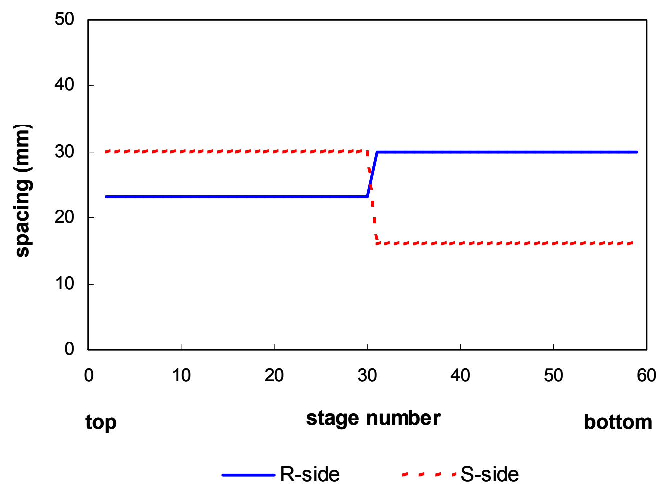

Fig. 9. Plate spacing versus stage number (Case 1).

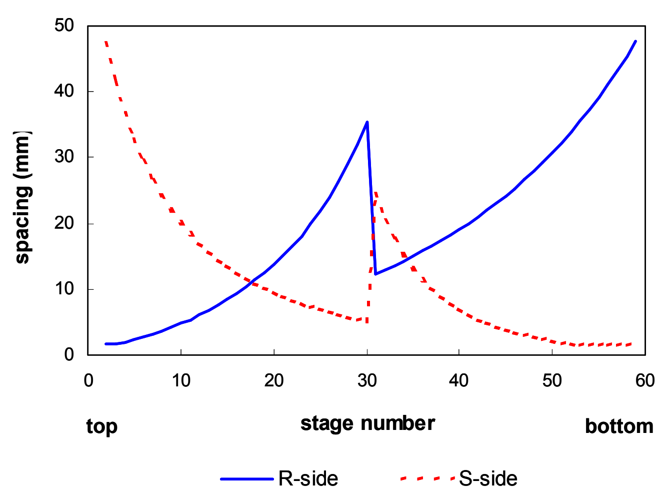

Fig. 10. Fin spacing versus stage number (Case 1).

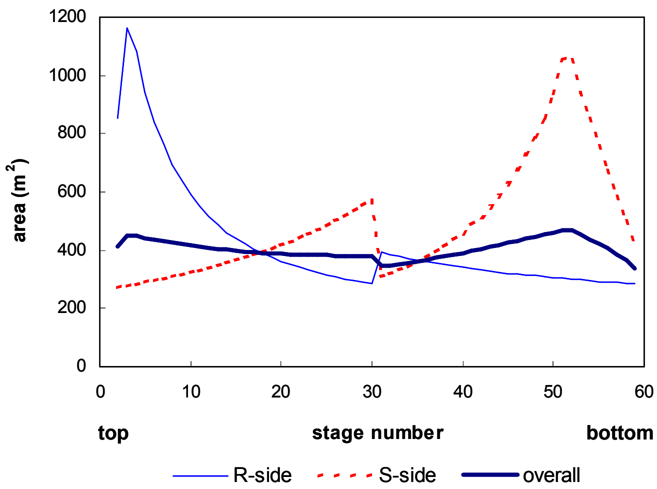

Fig. 11. Effective heat-transfer area versus stage number (Case 1).

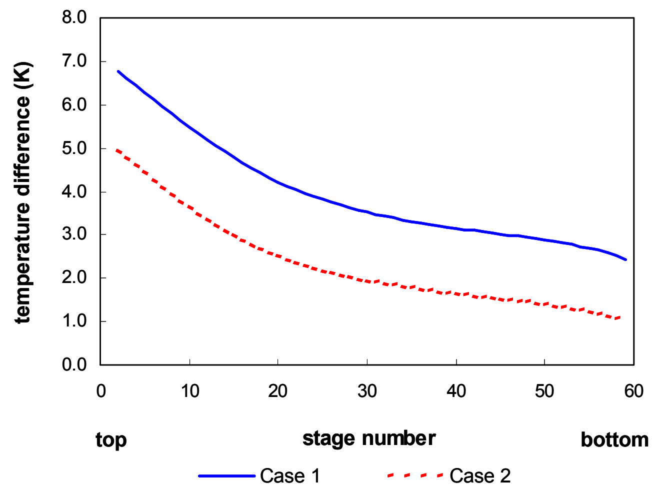

Fig. 12. Temperature difference versus stage number.

Some typical results are illustrated for case 1 in the figures where various quantities are plotted as a function of stage number. Fig. 4 shows the volumetric flows - the essence of the HIDiC design problem. Fig. 8 shows the fraction of flood - it can be seen that the design is successful in approaching 70% of flood over most of the column height. Fig. 9 shows the plate spacing - it can be seen that the column has been split into 2 modules. Within each module, the plate spacing is different for the rectifier and the stripper. A maximum plate spacing of 30 mm has been assumed, which is about a factor 3 higher than currently applied in commercial PFHEs. Fig. 10 shows the fin spacing - in places this far exceeds the values currently applied. Fig. 11 shows the effective heat transfer area - because the area on the rectifier side is nearly a mirror image of that on the stripper side, it turns out that the overall effective area is fairly constant through the column.

Some further results for all three cases are shown in Table 1. Comparing case 1 to the VRC base case, we see that the compressor duty (i.e. energy requirement) is reduced by 23%. Also the column height is greatly reduced, although this may be optimistic because of the possibly low value used for the equilibrium stage height. The column diameter (calculated for the two 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 would have to be connected in parallel to accommodate this very large-scale application.

Comparing case 2 to case 1, we see the effect of decreasing the temperature approach from 2.4 to 1.0 K. (The temperature-difference profiles for the column are shown in Fig. 12). This involves increasing the effective heat transfer area per stage from 403 to 703 m^2. This leads to additional energy savings, and lower values of the hydraulic diameter (which is related to plate spacing and fin spacing). The hydraulic diameter still in places exceeds values currently applied in commercial PFHEs (about 8 mm). The effective column diameter is increased.

Comparing case 3 to case 2, we see the effect of using a more realistic value for the pressure drop per stage. The energy savings are increased still further, now amounting to about 37% compared to the base case.

A detailed economic evaluation has yet to be made for the plate-fin design. However, first indications are that the overall economics are dominated by the operating cost (mainly electricity for the compressor) and the capital cost of the compressor (Olujic et al., 2004). This suggests that any increased capital cost for the heat-exchange area involved in the plate-fin design may be outweighed by the decreased compressor duty.

Table 1 Results of design cases

		VRC	Case 1	Case 2	Case3
Heat transfer area per stage	m^2	-	403	711	739
Pressure drop per stage	Pa	620	620	620	50-60
Temp. diff. (average)	K	-	3.9	2.3	2.2
Temp. diff. (min)	K	-	2.4	1.0	1.0
Compression ratio	-	1.62	1.38	1.34	1.30
Compressor duty	%	100	77	70	63
Column height	m	53*	9.2	9.2	9.2
Column diameter	m	6.5	6.8 - 7.1	7.8 - 8.3	7.9 - 8.7
Hydraulic diameter	mm	-	2 - 35	2 - 22	2 - 22

* excluding the conventional part of the rectifier

CONCLUSIONS

It was concluded that the plate-fin design is feasible in principle, in the sense that a consistent design can be made. The potential for energy saving was confirmed. However for the case of a PP-splitter the required hydraulic diameter is in places larger than currently available in commercial plate-fin heat exchangers.

NOMENCLATURE

CHE	Compact Heat Exchanger
HIDiC	Heat Integrated Distillation Column
PFHE	Plate-Fin Heat Exchanger
PP	Propane-Propene
SRV	Secondary Reflux and Vaporisation
VRC	Vapour-Recompression column

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