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Design of a heat-integrated distillation column based on a plate-fin heat exchanger

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Abstract

The Heat-Integrated Distillation Column (HIDiC) has a higher energy efficiency than either a normal distillation column or a vapour-recompression column. The potential energy savings in the Netherlands are estimated to be in the range 11-25 PJ/y. Although the HIDiC concept is well known, it has not yet been commercialised. In order to investigate the feasibility of a HIDiC design based on a plate-fin heat exchanger, a computer program has been developed and applied in a case study for a propane-propene splitter. Compared to a vapour-recompression column, energy savings are about 35 % and the total annual cost may be lower.

Notation

A	Effective heat-transfer area per stage	m^2
h	Heat-transfer coefficient	$W.m^{-2}.K^{-1}$
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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1. 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 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 Figure 1.1. 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.

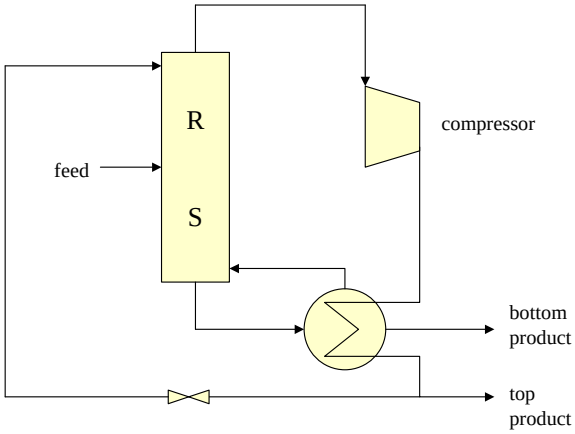

Figure 1.1 *Vapour-recompression column*

The basic idea of the Heat-Integrated Distillation Column (HIDiC), which has not yet been commercially applied, is shown in Figure 1.2. 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.

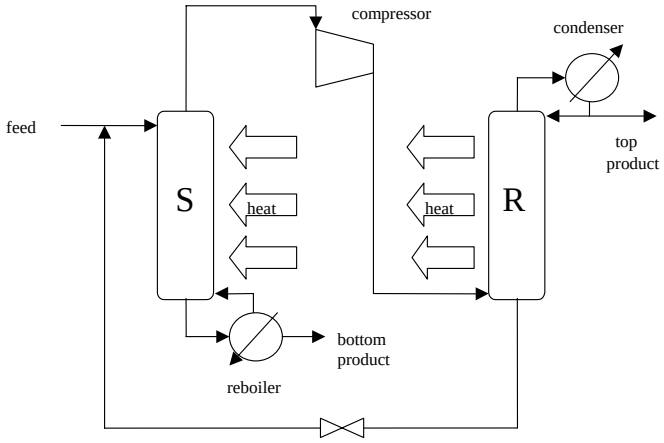

Figure 1.2 *HIDiC concept*

The history of the HIDiC has been described elsewhere (1,2). 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 (3). In order to quantify the potential energy savings of the HIDiC, the ECN database of distillation columns in the Netherlands has been screened to identify potential applications. Assuming that 50 % of primary energy can be saved for these applications, the total savings in the Netherlands are in the range 11-25 PJ/y. Rough estimates of savings for Western Europe and the world are respectively 60-140 PJ/y and 370-860 PJ/y. 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.

In an earlier publication we described the option of basing a HIDiC design on a plate-fin heat exchanger (PFHE) (4). A PFHE (Figure 1.3) 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 gas 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. The headers and liquid and gas distributors are not shown in the figure.

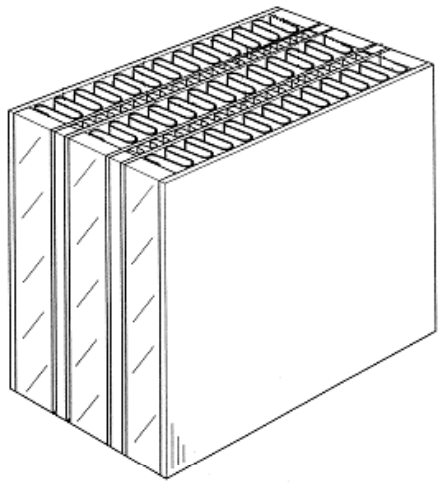

Figure 1.3 *Plate-fin heat exchanger for HIDiC*

A feature of the HIDiC is that the gas and liquid flows change significantly with height (Figure 1.4). 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 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 (Figure 1.5). An alternative idea, which deviates more from current PFHE designs, is to use non-parallel plates with a constant fin spacing (Figure 1.6) (5).

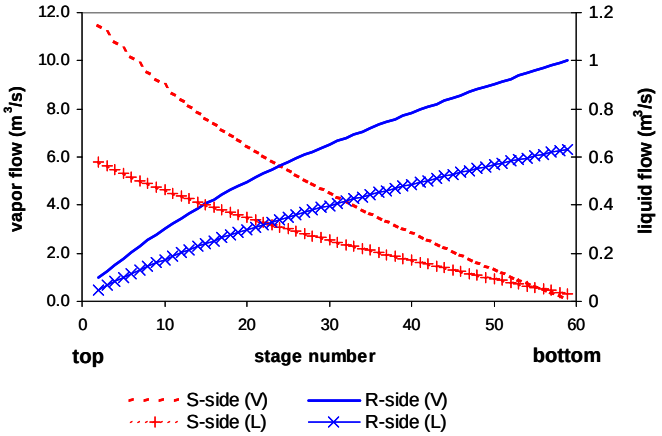

Figure 1.4 *Volumetric flows versus stage number*

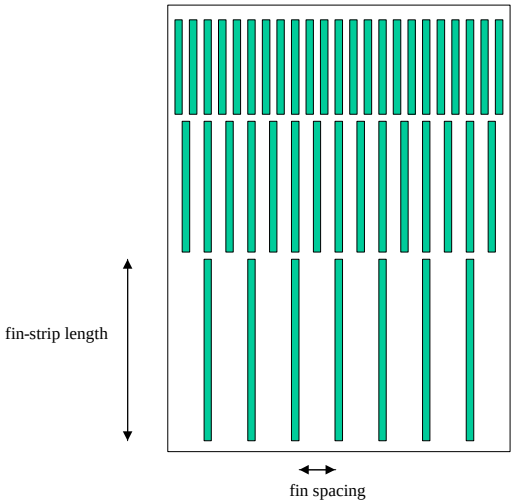

Figure 1.5 *Variable fin-strip length and fin spacing (rectifier side)*

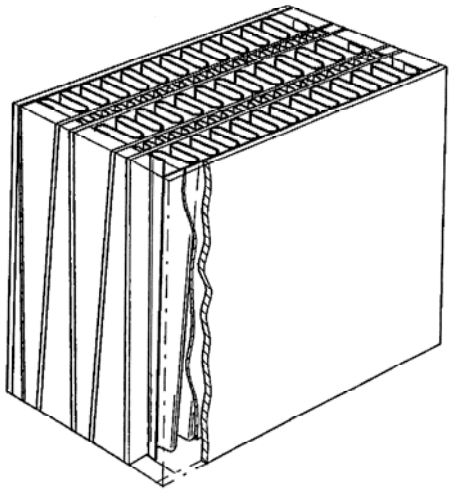

Figure 1.6 *Plate-fin design for HIDiC (non-parallel plates)*

2. 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 (6). We have further extended this approach to describe a plate-fin design. The overall structure of the software is shown in Figure 2.1. The spreadsheet includes parameters or literature correlations to describe the required properties, e.g. flooding, fin efficiency, wetting, and heat-transfer coefficients (7). The initial design objective for the plate-fin HIDiC 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). For the case of non-parallel plates, an extra parameter is introduced, namely the angle between the plates; for a given module design, there is a maximum value to this angle determined by the minimum and maximum values of the plate spacing. 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. The effective heat-transfer area A is then multiplied by the heat-transfer coefficient h. The product Ah is thereby determined separately for the rectifier side (R) and the stripper side (S) of each stage. An overall value $(Ah)_O$ can then be calculated from the usual formula:

$$(Ah)_O = 1/\{ (A_R h_R)^{-1} + (A_S h_S)^{-1} \}$$

The product $(Ah)_O$ is equal to the heat transfer per unit temperature difference on the stage. This can be compared to the value used in the RADFRAC simulation. Using an iterative procedure a consistent design can be achieved.

An earlier version of this model was described in our earlier publication (4). The main difference is that the calculation of the heat transfer per stage has been improved. The earlier version made use of a guestimated constant value for an overall heat transfer coefficient, which also necessitated the use of an approximation for an overall effective heat-transfer area per stage.

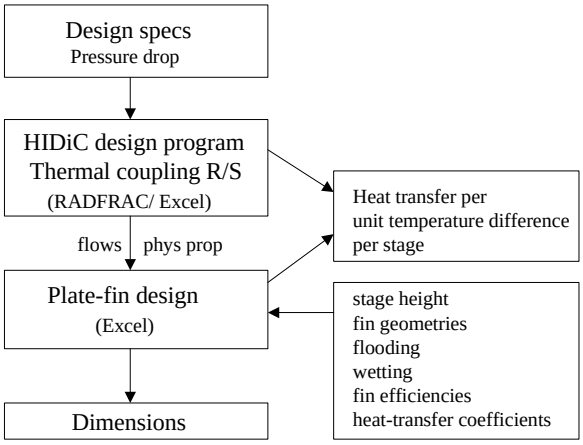

Figure 2.1 *Structure of design model*

3. Results

We report some results for a case study of a propane-propene (PP-)splitter. The basis of design has been described elsewhere (6). 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 (8). In the HIDiC design the 57 stripper stages are integrated with the top 57 stages of the rectifier (3,6). The remaining rectifier stages are implemented as a conventional column, which is not further considered here, except in the economic evaluation.

We report three cases:

- Case A: Parallel-plate design (Figure 1.3 and Figure 1.5) with an equilibrium stage height of 0.16 m.
- Case B: Parallel-plate design with an equilibrium stage height of 0.32 m.
- Case C: Non-parallel-plate design (Figure 1.6) with equilibrium stage height of 0.16 m.

All three cases have a minimum temperature difference of 1 K. The material of construction was assumed to be aluminium. For the parallel-plate option (Figure 1.3) the fin-strip length was assumed equal to the equilibrium-stage height, so that the fin spacing could vary from stage to stage (Figure 1.5). For case C, the angle between the plates was arbitrarily set to half of the maximum value, and the fin spacing was set equal to the minimum plate spacing.

Some typical results are illustrated for case A in the Figures where various quantities are plotted as a function of stage number.[1] Figure 1.4 shows the volumetric flows - the essence of the HIDiC design problem. Figure 3.1 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. Figure 3.3 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. Figure 3.4 shows the fin spacing. Figure 3.5 shows the values of Ah - because the rectifier side is nearly a mirror image of the stripper side, it turns out that the overall value $(Ah)_O$ is fairly constant through the column.

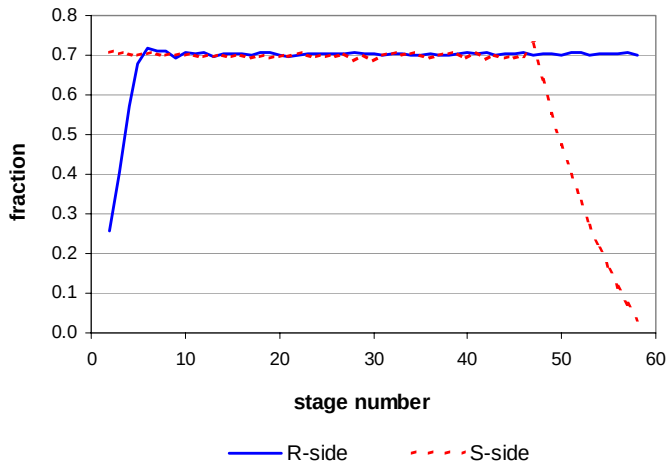

Figure 3.1 *Fraction of flood versus stage number (Case A)*

[1] Case A is similar to "case 3" in our earlier publication (4). However the improved version of the model has now been used.

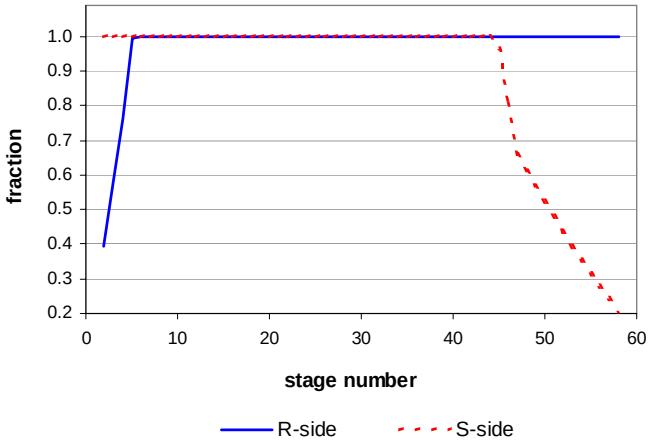

Figure 3.2 *Wetting versus stage number (case A)*

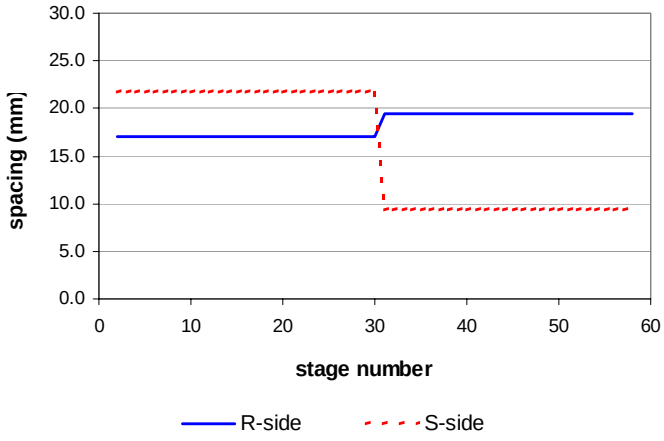

Figure 3.3 *Plate spacing versus stage number (Case A)*

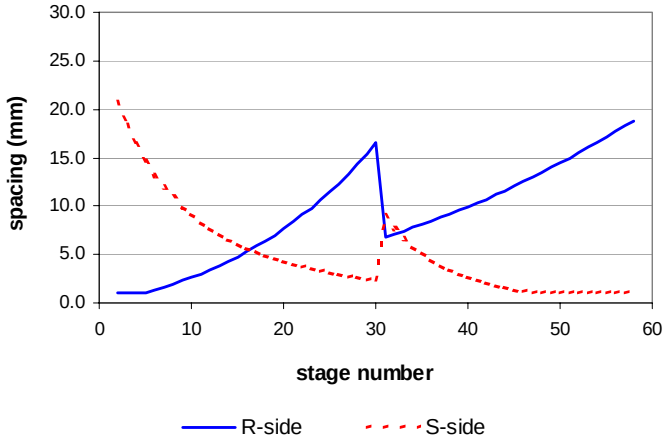

Figure 3.4 *Fin spacing versus stage number (case A)*

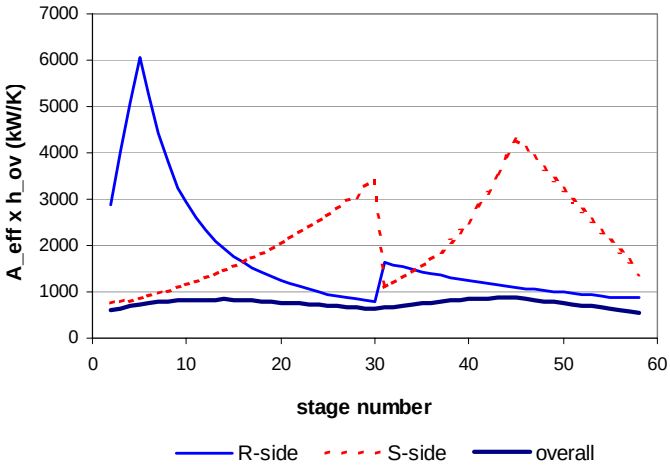

Figure 3.5 *Heat transfer per unit temperature difference versus stage number (Case A)*

Some further results for all three cases are shown in Table 3.1.

Table 3.1 *Results of design cases*

		VRC	Case A	Case B	Case C
Eq. stage height	m		0.16	0.32	0.16
No. of modules	-	-	2	4	2
P drop /stage	Pa	619	50-60	95-110	50-60
Ah per stage	kW/K	-	750	764	750
Comp. ratio	-	1.62	1.30	1.30	1.30
Compressor duty	%	100	65	65	65
Column height	m	53*	9.1	18.1	9.1
Column diam	m	6.5	8.3-8.8	6.9-7.6	8.3-8.7
Hydraulic diam (mean)	mm	-	9	14	10
Hydraulic diam (range)	mm	-	2 - 21	2 - 29	5 - 16

* Excluding the conventional part of the rectifier.

Comparing case A to the VRC base case, we see that the compressor duty (i.e. energy requirement) is reduced by 35 %. 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 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.

3.1 Case B compared to case A

For case A, an equilibrium stage height of 0.16 m had been assumed. Although this is in line with the available lab-scale data (9) it may be an underestimate compared to industrial experience with dephlegmators. To investigate the sensitivity of the design with respect to the equilibrium stage height, case B was defined. Case B is identical to case A except that the equilibrium stage height is now 0.32 m instead of 0.16 m. This leads to 4 modules being required instead of 2, and the height of the column doubles. The pressure drop per stage is also doubled.

However because the design criterion (a temperature approach of 1 K) remains the same, $(Ah)_O$ has to stay about constant at about 750 kW/K per stage (there is a small change due to the different pressure drop). This is achieved by increasing the plate spacing and fin spacing as shown

in Figure 3.6 and Figure 3.7. This implies an increase in hydraulic diameter, which in turn implies (because of the flooding condition) a decrease in the effective column diameter. The increased hydraulic diameter and decreased column diameter more than compensate for the effect of an increased stage height, so that the geometric surface areas per stage are decreased slightly. Taking into account small increases in fin efficiency and wetting, and a decrease in heat transfer coefficients, the end result is that $(Ah)_O$ per stage stays about constant.

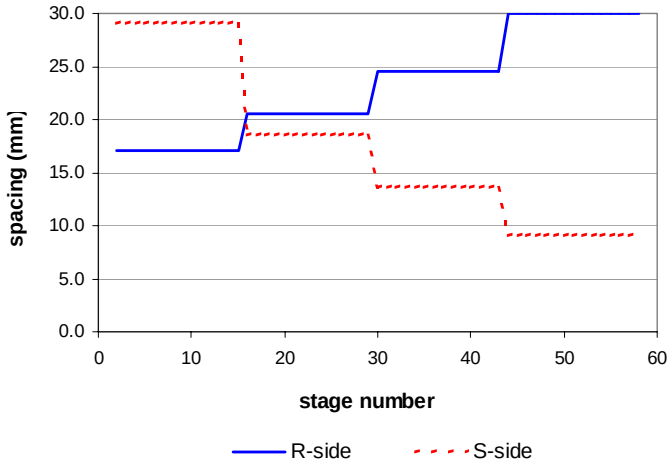

Figure 3.6 *Plate spacing versus stage number (Case B)*

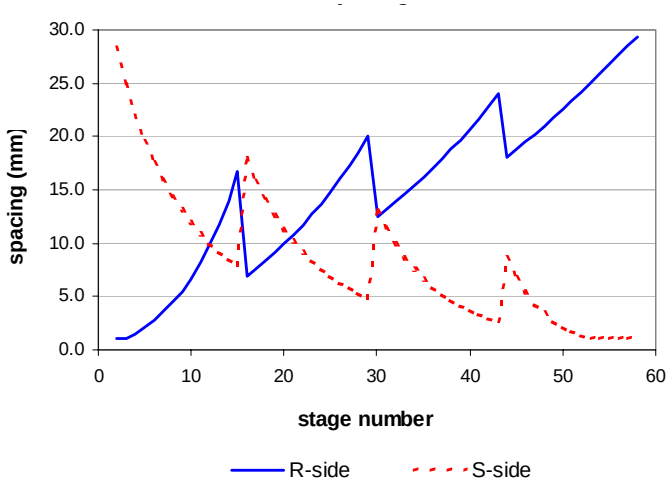

Figure 3.7 *Fin spacing versus stage number (case B)*

Another difference between the two designs is that in case B, the flooding and wetting are improved at the top of the rectifier and the bottom of the stripper (i.e. they come closer to 70 % and 100 % respectively). This results from the greater flexibility achievable when more modules are used. The ratio between the plate spacing on the rectifier side to that on the stripper side can now reach higher values at the bottom of the column, and lower values at the top of the column, than was possible in case A (Figure 3.3 and Figure 3.6).

3.2 Case C compared to case A

For case C, the flooding criterion cannot be fulfilled over the whole column (Figure 3.8). Although there is some scope for optimisation by adjustment of the plate angle, it seems that the non-parallel plate design has an inherent inflexibility compared to the parallel-plate design. This can be understood in terms of the number of adjustable parameters that are available. For case

A, the plate spacings are constant for each module (Figure 3.3) but the fin spacings can be varied independently on each stage, albeit subject to some constraints (Figure 3.4). For case C, the fin spacings are constant in each module (Figure 3.11) but the plate spacings cannot be varied independently on each stage, because the plate spacing must be a linear function of stage number (Figure 3.10).

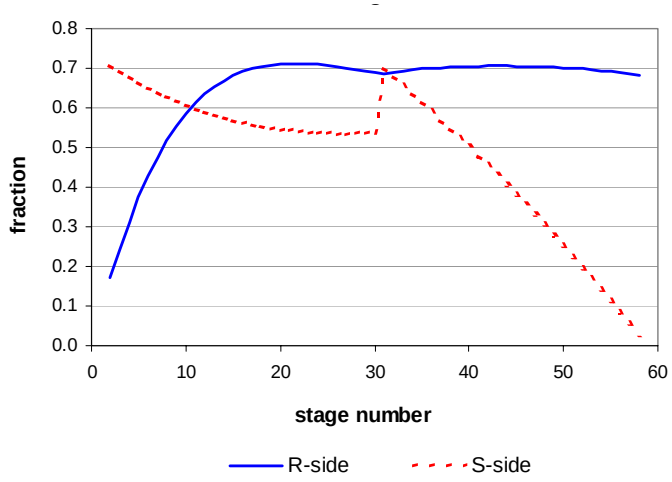

Figure 3.8 *Fraction of flood versus stage number (Case C)*

However the wetting behaviour is actually better (Figure 3.9). This is due to the fact that the hydraulic diameter in the top of the rectifier and in the bottom of the stripper is restricted by the above-mentioned geometrical constraints and is "too large" compared to an ideal value. This results in a too low fraction of flood but also in a better wetting (due to a smaller perimeter length).

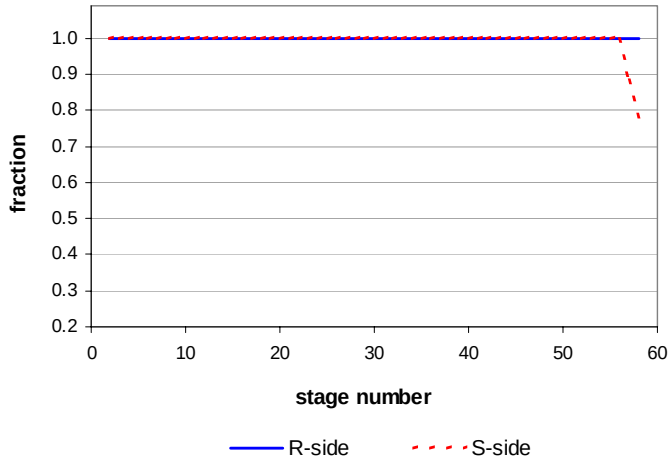

Figure 3.9 *Wetting versus stage number (case C)*

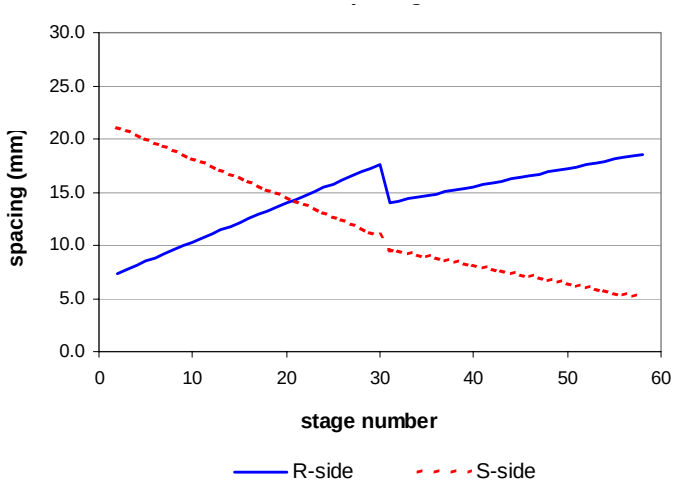

Figure 3.10 *Plate spacing versus stage number (Case C)*

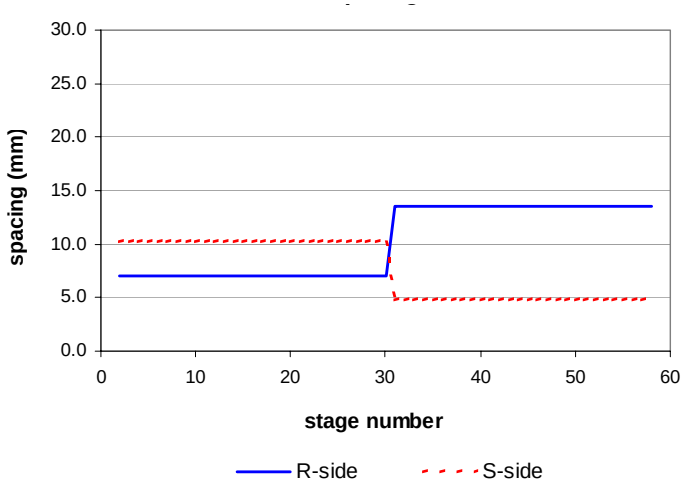

Figure 3.11 *Fin spacing versus stage number (case C)*

The heat transfer per unit temperature difference for the individual sides (R and S) is now more evenly distributed over the column (Figure 3.12, compare Figure 3.5). This results from the fact that the change of geometric surface area per stage through each module (increasing with increasing plate spacing) is nicely balanced by an opposite trend in the fin efficiency (decreasing with increasing plate spacing). Such an even distribution may indicate a more robust design.

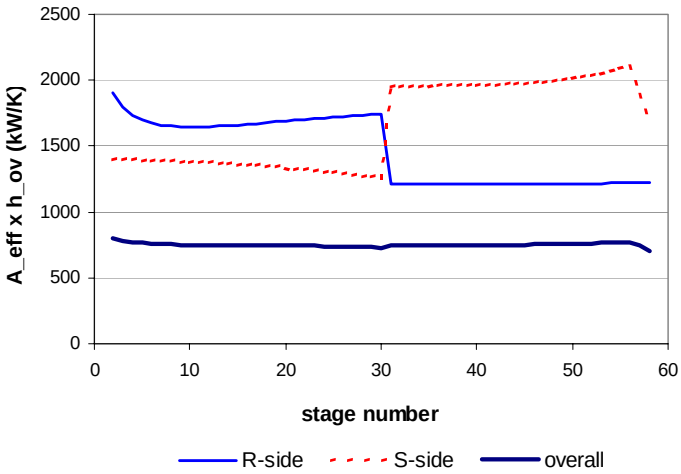

Figure 3.12 *Heat transfer per unit temperature difference versus stage number (Case C)*

A further advantage of the non-parallel plate design (not indicated in the simulations) is that it avoids the problem of internal distribution that is encountered in the stripper section of the parallel plate design due to the decrease in fin spacing as liquid flows down the column.

It should also be pointed out that the Figure 1.6 greatly exaggerates the extent to which the plates deviate from being parallel. The absolute change in the plate spacing is actually very small compared to the height of the module: for module 1 the change is 9.1 mm over a height of 4.6 m, for module 2 the change is 4.2 mm over a module height of 4.5 m.

3.3 Economic evaluation

The cost estimating procedure and economic evaluation for a generic HIDiC design had previously been implemented in an Excel spreadsheet (6). For our purpose it was only necessary to add cost estimates for the PFHE modules. This has been done for cases A and B, but not for case C because the non-parallel plate design deviates significantly from current commercial PFHEs. Each module (height about 4.5 m) was assumed to be divided into a number of parallel "sub-modules", each with a maximum width of 2 m and a maximum breadth of 2 m, so that each sub-module had a size comparable with current commercial PFHE designs. The purchase cost of each sub-module was estimated based on tabulated cost data (10). The installed cost was then estimated assuming a Lang factor of 2, which is commonly applied for plate heat exchangers (11).

It was found that the total cost of the PFHE modules for case B was only about 5 % higher than that for case A, despite the much greater column height. This resulted from the fact that the estimated purchase cost is mainly dependent on the "thermal size" $(Ah)_O$, which is similar for the two cases. The overall economics are therefore not very sensitive to the equilibrium stage height.

The relative contributions to the total annual cost (TAC) for case B, assuming a 10-year project lifetime, are given in Table 3.2. The economic picture is dominated by the electricity cost, but the PFHE modules are also a significant cost item. Compared to the VRC base case, the HIDiC design saves electricity but this is partly offset by the higher capital cost: the TAC for case B is 88 % of the TAC of 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 case B 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 3.2 *Contributions to total annual costs for case B*

	% of TAC
Column shell (rectifier)	6.5
Trays (rectifier)	1.4
PFHE modules	25.3
Condenser	0.7
Compressor	11.5
Cooling water	2.0
Electricity	52.7
TOTAL	100.0

4. Conclusions

The model for plate-fin HIDiC designs has been improved and extended. Simulation results for a PP-splitter case have shown that an increase in the equilibrium stage height leads to an increase in hydraulic diameter and a decrease in column diameter, and to only a slight increase in installed cost. The design with non-parallel plates has less flexibility to meet the flooding criterion than the design with parallel plates, but may in some other respects be a more robust design. The total annual cost of the plate-fin HIDiC may be somewhat lower than that of the VRC.

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