European Symposium on Computer Aided Process Engineering – 15
L. Puigjaner and A. Espuña (Editors)

# A new approach to the design of internally heat-integrated tray distillation columns

M. Gadalla, Z. Olujic[*], A. de Rijke and P. J. Jansens
Laboratory for Process Equipment
Delft University of Technology, Leeghwaterstraat 44, 2628 CA Delft, Netherlands

## Abstract

Internally heat integrated distillation column has received a great attention lately because of its ultimate potential for energy savings. Typical conceptual design of such columns is based on constant heat transfer duties along the column stages. This paper introduces more effective approach to conceptual design of heat integrated distillation columns based on constant available heat transfer areas. This design scenario implies changing stage heat transfer duties. The procedure has been implemented into a commercial simulation package in such a way that it allows simultaneous problem solutions.

**Keywords**: **HIDIC, Heat Integration, Distillation, Energy saving, Vapour recompression**

## 1. Introduction

Internally heat integrated distillation column, known as HIDiC (Nakaiwa et al., 2003; Olujic et al., 2003) is a design concept which offers ultimate potential for energy saving related to the operation of single distillation columns, i.e. far beyond that achieved with columns employing well established but capital intensive direct vapour recompression systems. A recent simulation study (Sun et al., 2003) has indicated that a propylene-propane splitter (PP-splitter) designed as a HIDiC could be realized at a cost lower than that associated with a state of the art vapour recompression system. This study also indicated that for columns with a pronounced difference in the number of stages in the two column sections, it is important to identify the most suitable coupling, and in the case of a base case PP-splitter (Sun et al., 2003; Olujic et al., 2004) this proved to be a configuration where sixty stages of the stripping section are coupled with the equivalent number of stages in the upper part of the rectification section, leaving the lower part of the rectification section to operate as a normal column. In this study, a constant heat duty per stage was assumed, which implies that in the bottom part of the stripping section with lower temperature difference a relatively large heat transfer area is required, where, due to rather low vapour load, the available cross

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[*] Author to whom correspondence should be addressed: z.olujic@wbmt.tudelft.nl

section area of a tray is at its lower end. Namely, in order to realize the required heat transfer duty, corresponding heat transfer area should be available, which, as proposed recently (de Graauw et al., 2003), should be installed above the active area of a tray, i.e. in the space in between two trays. This could be accounted for accordingly, if a constant area approach could be implemented. This implies an operation under a variable heat transfer duty mode, which, in turn, provides a certain degree of flexibility regarding the fact that available cross section area increases toward the top of the stripping section. In this paper, the design approach of constant area is tackled, as is its implementation in the existing simulation packages. This preferably provides a faster approach to optimal design.

## 2. HIDiC design scenarios

Design of heat-integrated distillation columns is normally carried out using rigorous simulations, in which the column configuration and data are specified, as are the product specifications. At first, no heat integration is considered and the reboiler and condenser duties are calculated. Then, heat integration calculations are performed by adding a specific amount of heat to each stage of the stripping column and withdrawing the same amount from the rectifying column stages. This represents the heat transfer from the hot rectifying stages to the cold stripping stages. Heat transfer duty is kept constant throughout all column stages; this will facilitate the simulation calculations. Then, the heat transfer rate across stages is increased gradually until the reboiler duty or the condenser duty reaches a very small value (duty ≈ 0, an ideal HIDiC). Heat transfer area on each stage is then calculated separately by dividing the heat duty by the temperature difference and the overall heat transfer coefficient. So, the calculated heat transfer area is expected to vary from one stage to another for a constant heat transfer rate since the temperature driving force changes. The constant heat duty design represents a simple and easy scenario for HIDiC designs. However, it may result in an impractical solution due to large heat transfer areas required for particular stages, especially for those stages which have small temperature differences. Alternatively, the HIDiC design may be achieved by installing a practical and constant heat transfer area on each stage. This approach is more reasonable and relevant to designers, i.e. practical compared to the previous one because of the fact that the designer starts his tasks by knowing the stage diameter and hence the physical space area and not the heat transfer duties. Moreover, this space area does not necessarily meet the heat transfer duty requirements if the design was handled using the constant heat duties (the first design approach). This new design can be performed by transferring different heat transfer duties on stages of rectifying and stripping columns. In this scenario, the heat transfer duties will be calculated by knowing the amount of area that can be installed on each stage. The main challenge of this design scenario is that the calculated heat duty is a function of the temperature driving force, which in turn changes with the heat duty transferred on column stages. Consequently, the design procedure should be completed simultaneously with the column simulation. However, the design can be done differently by assuming that the temperature difference obtained from constant heat duty scenario does not change when heat duty is varied. The procedure for this design is illustrated using the base case described in Table 1, as follows:

1. HIDiC is designed based on a constant heat duty, $Q_{const,}$, across all stages. The temperature driving forces across all stages are determined.

2. Heat transfer area on each stage ($A_{stage}$) is calculated by Equation 1, and then can be plotted versus stage numbers (Figure 1). As shown, the heat transfer area required for some stages is very large compared to others. This reveals the impracticality of the constant heat duty design scenario. Figure 1 shows the results for a propylene-propane splitter. Problem data and design specifications are summarised in Table 1.

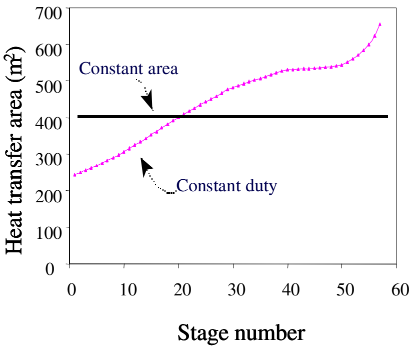

*Figure 1. Heat transfer area for a constant heat duty scenario (stages are from top to bottom)*

3. An average heat transfer area is selected from the plot of the variable heat transfer area versus stage number, as shown in Figure 1. This value must be achievable by the physical space available according to the HIDiC hydraulic design. In this example, the constant heat transfer area, $A_{const}$, is set to 400 $m^2$.

4. Assume that the stage temperature difference is that determined by the constant heat duty scenario ($\Delta T_{min}$). Then, the heat transfer duty across each stage ($Q_{new}$) can be calculated from Equation 2. This will result in new variable heat duties that can be transferred for the assumed constant transfer areas.

5. HIDiC is then resimulated by specifying the new heat duties obtained for every stage.

6. The values of the new heat duties may need adjusting during simulation in order to adjust the reboiler duty to be zero. This is due the assumption made for the temperature driving force. When simulation converges, the new temperature differences ($\Delta T_{min}^{new}$) for each stage are obtained.

7. An adjusted heat transfer area, $A_{stage}^{adjust}$, is then calculated for each stage from the new values of the heat duties and the new temperature differences by Equation 3.

$$A_{stage} = \frac{Q_{const}}{U\Delta T_{\min}} \tag{1}$$

$$Q_{new} = UA_{const}\Delta T_{\min} \tag{2}$$

$$A_{stage}^{adjust} = \frac{Q_{new}^{adjust}}{U\Delta T_{\min}^{new}} \tag{3}$$

where $A_{stage}$ is heat transfer area on a stage ($m^2$), $Q_{const}$ is constant heat transfer rate per stage (kW), $U$ is overall heat transfer coefficient (kW/ $m^2$ °C), $\Delta T_{min}$ is minimum difference temperature approach ($^{o}$C), $Q_{new}$ is new heat transfer rate on stages (kW), $A_{const}$ is constant heat transfer area on a stage (m$^2$), $A_{stage}^{adjust}$ is adjusted constant heat transfer area on a stage (m$^2$), $A_{new}^{adjust}$ is adjusted new heat transfer rate on stages (kW), and $\Delta T_{min}^{new}$ is new minimum difference temperature approach ($^{o}$C). Figure 2 summarises the procedure discussed above.

*Table 1. Base case HIDiC design specifications*

| Column specification | | |
|---|---|---|
| Feed | | propylene-propane |
| Composition | propylene mole % | 50 |
| Flow rate | t/h | 111.6 |
| Pressure | bar | 12.2 |
| Temperature | $^{o}$C | 31.7 |
| Rectifying pressure | bar | 19.2 |
| Stripping pressure | bar | 12.2 |
| Rectifying stages | - | 154 |
| Stripping stages | - | 57 |
| Top product purity | propylene % | 99.6 |
| Stripping stages | propylene % | 1.1 |

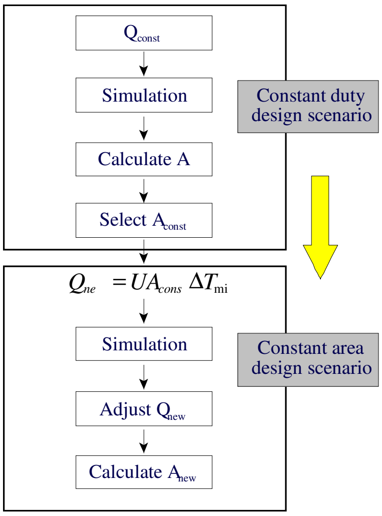

*Figure 2. Procedure for HIDiC design*

## 3. Results and discussion

Figure 3 shows the results of the new heat duties obtained for all stages; it is clear that the heat duty varies throughout the column stages. The horizontal line indicates the heat duty (1817 kW) for the constant heat rate design. Figure 4 shows the results of the adjusted heat transfer areas. The adjusted heat transfer area can be seen as almost constant (≈ 450 m$^2$). The temperature difference on stages for the new design is given in Figure 5, and compared with those for the constant heat duty design.

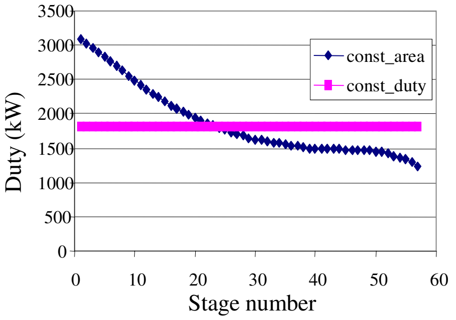

*Figure 3. Heat transfer rate for constant area design scenario*

A comparison of the overall results of the two designs is given in Table 2. The constant area design does not incur a significant increase to the compressor duty; however, the total heat transfer area is almost identical for the two designs. It is obvious that the constant area design is more practical compared to the constant duty scenario. The heat transfer area required per stage is constant and relatively smaller than that required by the constant duty design on some particular stages. In addition, the total heat transfer area is still the same as for the constant duty design.

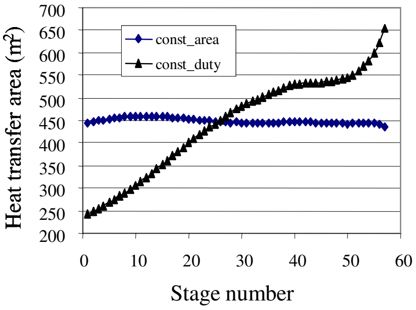

*Figure 4: Heat transfer areas for constant duty and area scenarios*

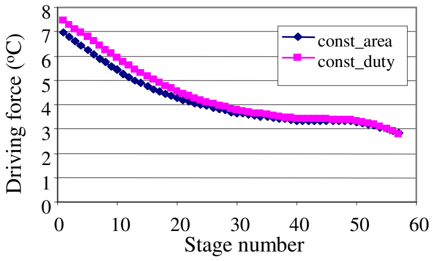

*Figure 5: Temperature differences for constant duty and area scenarios*

*Table 2. Design results for constant duty and area scenarios*

| Design specification | | Constant duty | Constant area |
|---|---|---|---|
| Stage duty | kW | 1817 | variable |
| Heat transfer area | $m^2$ | variable | 450 |
| Reboiler duty | kW | 0 | 0 |
| Condenser duty | kW | 5782 | 6160 |
| Compressor duty | kW | 7489 | 7729 |
| Total heat transfer area | $m^2$ | 25364 | 25582 |

The procedure given in Figure 2 has been successfully implemented into HYSYS simulation software (HYSYS, 2002), in which the assumption of temperature driving forces is not needed since the actual online temperature differences are considered. This is done by embedding Equation 2 into the software equation facilities (Spreadsheet). So, the temperatures of the liquid streams and vapour streams flowing through the stripping and rectifying stages, respectively, are extracted from the simulation results to a spreadsheet specified to implement Equation 2. Then by specifying a reasonable overall heat transfer coefficient, the heat transfer duty that can be transferred across each stage can be calculated for the available space area which is specified in the same spreadsheet. This space area should be available by the hydraulic design of the column stages (Gadalla et al., 2004). The values of the heat duties calculated for each stage are simultaneously exported to be applied to the stripping and rectifying column stages. By doing so, there is no need for any assumption with respect to the temperature difference.

## 4. Summary and conclusions

A systematic design procedure has been presented for HIDiC design with constant heat transfer area throughout all column stages. This design approach is practical and guarantees that the physical space constraints are fulfilled. Proposed design procedure has been implemented in a commercial simulation package which provides a new modelling facility by which the column design and heat integration tasks are handled simultaneously.

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### Acknowledgement

The authors are grateful to EET (Energy, Ecology, Technology - SenterNovem) for the financial support of the multi-partner HIDiC research project. Also we are grateful to Borealis Group for providing actual plant data for the purpose of our comparative studies.