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A design method for internal heat integrated distillation columns (iHIDiCs)

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Abstract

Distillation of close-boiling mixtures, such as propylene-propane and ethyl benzene-styrene systems, is an energy intensive process. Vapor recompression (VRC) techniques and heat pumping-assisted columns have been adopted for such applications for their high potential of energy savings. In direct vapor recompression columns, the vapor leaving the top of the distillation column is compressed and then it is condensed in the reboiler of the same column, providing the heat needed for vapor generation. Internal heat integrated distillation columns (iHIDiCs) also use the concept of vapor recompression. These column configurations combine the advantages of both direct vapor recompression and adiabatic operation, and can have significantly lower energy demands than common VRC columns. In iHIDiCs, rectifying column is operated at a higher pressure and temperature than the stripping, and therefore its heat can be used to generate vapor in stripping section. The paper presents a hierarchy design procedure for iHIDiCs in two phases: thermodynamic and hydraulic analysis. In the thermodynamic design, the temperature profiles for both column sections are used as a design tool to generate design alternatives. In addition the model is proposed based on hydraulic calculations and tray geometry analysis, to quantify the column capacity for heat transfer.

1. Introduction

Distillation is an old separation process and has broadly been used in most chemical and petrochemical industries. The high energy consumption of distillation processes is the main disadvantage, and it becomes extremely important for mixtures with low relative volatilities, such as propylene-propane. The energy inefficiency of distillation has urged the industry's interest towards the implementation of advanced technologies with better efficiencies. As a result, thermal coupling, heat integration, vapor recompression and heat pumps were adopted as new developments to increase the distillation efficiency [1-3]. In vapor recompression designs, the vapors leaving the top of the distillation column are compressed and then are condensed in the reboiler of the same column, providing the heat needed for vapor generation. Internal heat integrated distillation columns (iHIDiCs) are further intensifications of vapor recompression principle. These columns combine the advantages of both direct vapor recompression and adiabatic operation and can have significantly lower energy demands than common vapor recompression distillation columns or heat pumps [4-6].

The concept of iHIDiCs was introduced by Mah and co-workers [7, 8] under the name 'Secondary Reflux and Vaporization' (SRV). Seader [9] and Glenchur and Govind [10] suggested different column configurations for iHIDiCs implementation. Also, a shell and tube-type packed column was presented by Aso *et al.* [11]. Recently, a group of Japanese researchers [4, 5, 12, 13] studied iHIDiCs; their results indicated energy saving up of up to a 60%. Among the research of previous work, few design aspects have been reported. Nevertheless, most simulation studies were performed without guidelines. In this work, more attention is directed to the systematic design of iHIDiC and the evaluation of design feasibilities with respect to thermal and physical space capacities.

2. Simulation background of iHIDiCs

A schematic diagram for an internal heat integrated distillation column is illustrated in Fig. 1. Configurations of iHIDiC comprise two separate distillation columns, stripping and rectifying. There is a pressure difference between the two columns; the overhead vapor of the stripping column is compressed before entering at the bottom of the rectifying column. The rectifying column therefore operates at a higher pressure (*i.e.,* higher temperature). The liquid from the bottom of the rectifying column is fed into the top of the stripping column. The two columns are configured in a particular way so that the energy of the hot rectifying column can be used to heat the stripping column. The amount of heat transfer between the two columns can vary, and correspondingly the reboiler

duty changes. When no heat is transferred, the reboiler duty is equivalent to conventional design (maximum duty). Heat is transferred on each column tray through an indirect contact of the rectifying hot vapor and the stripping cold liquid streams. This implies that a continuous condensation of the vapor phase occurs along the rectifying column and continuous evaporation (*i.e.*, vapor generation, takes place in the stripping column). This heat transfer is achieved in an external medium (device), such as heat panels. Heat panels are placed either on the rectifying side or stripping side of the column trays. As a result, the energy requirement in the reboiler is reduced. iHIDiCs can be partial, when the reboiler energy consumption is reduced, compared to that in a conventional column, or ideal, when the reboiler duty is reduced to zero. For ideal iHIDiC, the reboiler unit is not needed since all the energy required for vapor generation is provided by the rectifying section.

Design of iHIDiCs is typically performed using process simulations (*e.g.* Aspen Plus®, Hysys.Plant®). The design task includes the calculations of the compressor, condenser and reboiler duties, stage heat transfer rates and the heat transfer area required.
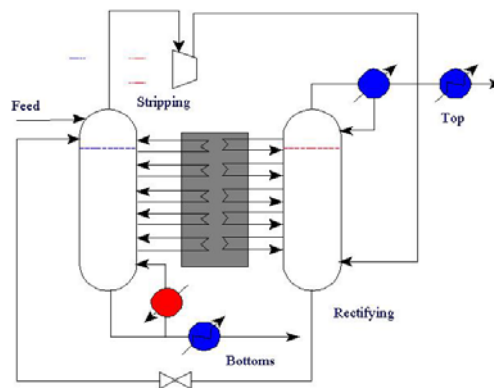

Figure 1. Superstructure for the hydrodealkylation of toluene.

3. Hierarchy for design of iHIDiCs

Based on available conventional calculations, a design hierarchy is proposed (Fig. 2) for internal heat integrated distillation columns. This hierarchy guides the designer to perform a systematic design and provides valuable insights for optimum results. The design procedure starts by simulating a conventional column for the given design problem. Required data for simulation are typically the feed flow rate and conditions, components composition, product and separation requirements, column pressure, etc… Simulated design parameters are the number of stages in each column section, reboiler and condenser duties, and product compositions. For systems where heat pumps are adopted, the

column configuration is simulated to calculate compressor electricity consumption and working pressure ratio. First, an iHIDiC is simulated using the column configuration given previously in Fig. 1 without any heat transfer between the two columns (basic design). Then, a complete iHIDiC with full heat integration is carried out by increasing the level of heat transfer between the individual columns step by step until the reboiler duty is reduced to zero (ideal iHIDiC). Basic assumptions had to be taken into account for both design cases, such as the feed location in iHIDiC configuration, number of stages in each column and the pressure before and after the compressor. The conventional column is splitted around the feed entrance into two separate columns for iHIDiC, rectifying and stripping. The relative feed location is kept unchanged, (*i.e.,* the feed enters the stripping column at the top stage). The pressure in the rectifying column is assumed to be as high as the pressure of the bottom of the conventional column with respect to the top. On the other hand, the pressure of the stripping column can be taken to be the same for the conventional top section. Therefore, a preliminary value for the pressure ratio can be obtained. A reasonable pressure drop per stage is assumed for both columns. As an approximate assumption, the number of stages of the stripping section is supposed to be the same as for the stripping column and similarly for the rectifying column. Fig. 3 shows a basic iHIDiC for separating methanol-water system. Design assumptions made based on a conventional design (confidential) are: 1.2 and 1.6 bars for the stripping column top and bottom respectively and 1.8 and 2.6 bars for the rectifying column respectively. Working pressure ratio is of 2.1. Number of stages for the stripping column is 30, while the rectifying column has 65 stages. It may be noted that the reboiler and condenser duties of basic iHIDiC are close to those of conventional column (40 MW for condenser, 45 MW for reboiler).

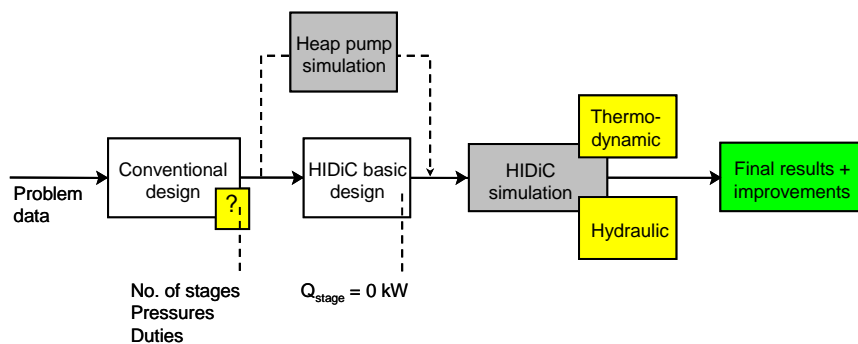Two design stages, thermodynamic and hydraulic, are suggested in the hierarchy for full iHIDiC design.

Fig. 2. A hierarchy for iHIDiC design

3.1. Thermodynamic design of iHIDiCs

In the thermodynamic design, stage temperature profiles of basic iHIDiCs are a key for heat integration. The temperatures profiles are plotted against the stages number for both the rectifying and stripping columns. For a possible heat transfer between the two columns, the temperature profile of the rectifying column must be above (hotter) the stripping temperature profile. Therefore, there should be a positive temperature driving forces between the rectifying and stripping columns. The variation of the temperature differences of both profiles corresponds to the distribution of the heat transfer between the columns. The amount of heat that can be transfer on stages varies according to the temperature difference. On the other hand, stages with minimum temperature differences are limiting stages and define the key bottleneck for heat integration. Temperature profiles can also determine the minimum pressure ratio that allows heat transfer. Heat integration is unfeasible on stages with negative temperature differences. Various iHIDiC designs can be achieved by changing the heat transfer distribution according to temperature profiles.
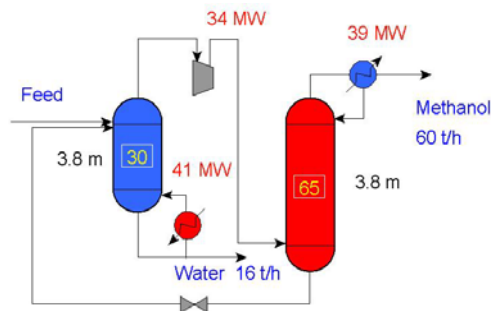

Fig. 3 Basic iHIDiC for methanol-water separation (no heat exchange)

3.2. Hydraulic design of iHIDiCs

A hydraulic model is proposed to calculate the heat panels transfer area available by the column stages. This model is based on the hydraulic diameter obtained from flooding limits, configuration of the rectifying and stripping sections, and the area of the heat panels. The calculations also depend on the layout of the panel placed on the column stages and its dimensions. The model can calculate all the physical space areas that can be used to place the heat panels. Heat panels can be placed in the stripping side or in the annular space outside the rectifying column. This is determined by the space available inside the column. Designs of iHIDiCs are hydraulically feasible when the heat transfer area available by the column stages is less than the area required by simulation results.

The initial design obtained from the hierarchy after the thermodynamic and hydraulics steps can then be improved by for example increasing number of stages, adding pre-flash vessel after the throttling valve (see Fig. 1) or by changing the heat integration scheme [14].

The results of the methanol-water iHIDiC column are: optimum heat transfer rate: 1150 kW/stage, reboiler duty: 19.5 MW, electricity requirement: 3.51 MW, condenser duty: 17.9 MW. The optimum iHIDiC design has a total annualized cost of 7.22 M$/yr, compared with a 7.98 M$/yr for the conventional column

4. Conclusions

A systematic design hierarchy has been proposed for iHIDiCs, including thermodynamic and hydraulic approaches. Starting from a conventional design, a full iHIDiC design can be achieved by performing basic design assumptions to conventional data. Temperature profiles are a key for heat integration, while hydraulic calculations are necessary to quantify the ability of a column design to place heat panels.

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