Economic Performance Assessment for an Internal Thermally Coupled Distillation Column

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Abstract: Economic features of an internal thermally coupled distillation column (ITCDC) are investigated and compared to a conventional column and a commercial column with vapour recompression system (VRC) for the separation of propylene-propane mixture. The study indicates that ITCDC has 10 – 20 % total annual cost (TAC) saving associated with VRC, which appeared to be strongly sensitive to the pressure ratio.

Key words: Distillation, Thermally coupled, ITCDC, Economic optimization

1 Introduction

Conceptually, An internal thermally coupled distillation column (ITCDC) is a column with vapor leaving the stripping section, compressed to a higher pressure, which upon entering the rectification section starts to condense and in this way provides the heat duty for evaporation in the stripping section[1,2]. An internal thermally coupled distillation column (ITCDC) offers maximum potential for energy saving in distillation. As demonstrated earlier[1], by adopting the ITCDC concept, the energy requirement of a heat pump assisted propylene-propane splitter (PP-splitter), which uses one sixth of the energy required in a conventional steam heated column, could be reduced by nearly 50%, i.e.to the values close to theoretical limit. However, such a gain is at the expense of increased design complexity

For the implementation of industrially feasible ITCDC, in this paper comparative studies were made with conventional distillation column (CC) and a column with a vapor recompression system (VRC) taking a PP-splitter as the base case. Economic study was carried out. Column layout and dimensions were also presented.

2 Design case

2.1 The base case

As the base case, the stand alone, heat pump assisted PP-splitter is used, considered in a previous study[3]. It is one of the largest columns of this sort, 110 m tall, with an internal diameter of around 6.5 m, containing 230 four pass sieve trays. This column operates at an overall efficiency of around 91%, which means that at given reflux ratio (16.8) 211 theoretical trays (equilibrium stages) are contained in the column, 47 in stripping section and 164 in the rectification section. Feed flow rate of a partly vaporized feed (vapour fraction = 0.37) is around 112 t/h. Overall composition of the vapor and liquid feed mixture is: 52 mole % propylene, 47 mole % propane and a small fraction, say around 1 mole % of isobutane and heavier components. The top product is polymer grade propylene (99.6 mole %), and only 1.1 mole % propylene is allowed in bottoms, which contains mainly propane (96.5 mole %). Top pressure is around 11.2 bar, and the column pressure drop is around 6 mbar per stage, which results in a column pressure drop of approximately 1.2 bar. The compressor ratio employed in this case is around 1.7, which means that the top vapor is compressed to around 18 bar. This results in a temperature increase of roughly 21 ^{o}C, i.e. a vapor temperature of 45 ^{o}C at the reboiler inlet.

2.2 simulation tools

The simulation of separation performances of the base case and the ITCDC PP-splitters was performed using ASPEN Plus facilities.

2.3 Cost estimation procedure

By adopting the column efficiency and tray design and spacing of the base case VRC, and assuming the same for ITCDC, the basic dimensions, column diameter(s) and height(s) are easily calculated. Table 1 summarizes main simulation results. As indicated in Table 1, optimized ITCDC operates with a compression ratio of 1.3 and contains few more stages, with feed location moved

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upwards accordingly. Some peculiarities related to sizing are discussed later on, under results.

Table 2 Characteristic parameters of the compared PP-splitter designs

	VRC	ITCDC
Rectification section top pressure (bar)	11.2	14.6
Stripping section top pressure (bar)		11.2
Pressure drop per stage (mbar/stage)	6.2	6.2
Number of stages/trays, rectification section (-)	164/179	170/185
Number of stages/trays, stripping section (-)	47/51	61/66
Total number of stages/trays (-)	211/230	231/251
Feed stage/tray (-)	165/180	171/1860

To enable updating of installed cost estimates based on correlations proposed by Douglas (1988), Marshall and Swift index (*M&S* = 1115.8) was used (Chemical Engineering, 2003). The installed cost of the column shell, made of carbon steel, is estimated as a function of column diameter, d_{col} (m), and the total column (tangent to tangent) height, h_{col} (m):

$$CSC_{inst} = (\frac{M\&S}{280}) \cdot C \cdot d_{col}^{1.066} \cdot h_{col}^{0.802} \tag{1}$$

where the coefficient C varies, depending on the pressure range. In fact, the values of these coefficients, given in Table 2, include both the correction factors for the pressure effect and the construction material. The latter one is 1, because the column shell is built of carbon steel. Additional complexity of ITCDC is accounted for by multiplying the value obtained from Eq. (1) by a factor of 1.5.

Table 2 Coefficients of Eq. (1)

Pressure range (bar)	C
6.8 – 13.6	4059.96
13.6 – 20.5	4106.85

The tray cost is estimated as a function of column/section diameter and the height of the column occupied by trays, h_{tray} (m):

$$TC_{inst} = \left(\frac{M\&S}{280}\right) \cdot 97.243 \cdot d_{col}^{1.55} \cdot h_{tray} \cdot F_C \tag{2}$$

The overall correction factor comprises contributions of the construction material (0), the type of tray (0) and for tray spacing (1.4): $FC = 0 + 0 + 1.4 = 1.4$.

The calculation of the heat transfer area is straightforward from the duty, Q (kW or MW), temperature difference, ΔT (K), and the overall heat transfer coefficient, U (kW/m2):

$$A = \frac{Q}{U \cdot \Delta T} \tag{3}$$

Depending on the type of the device, constant values of heat transfer coefficients are used, as generally employed for kettle reboilers (1000 W/m^{2}K), thermosyphon reboilers (1200 W/m^{2}K), and condensers (800 W/m^{2}K), respectively. For heat transfer panels installed in the ITCDC, a similar value was assumed (1000 W/m^{2}K). The installed cost was estimated as a function of the heat transfer area, A (m2), using:

$$HEC_{inst} = \left(\frac{M\&S}{280}\right) \cdot c \cdot A^{0.65} \tag{4}$$

The values of the coefficient c are shown in Table 3.

Table 3 Coefficients of Eq. (4)

Heat exchanger	c
Thermosyphon reboiler	1799.00
Kettle reboiler	1775.26
Condenser	1609.13
ITCDC panel	1466.72

The installed cost of the centrifugal compressor, driven by an electro-motor, is based on the brake power only:

$$CC_{inst} = \left(\frac{M\,\&\,S}{280}\right) \cdot 2047.24 \cdot bp^{0.82}$$

(5)

This expression is valid in the range of: 22 < *bp* (kW) < 7457. The value of the coefficient includes corrections for the type (centrifugal, with electro-motor), construction material and the pressure range.

2.3 Economic evaluation

In order to evaluate properly the economic feasibility of ITCDC, it is chosen here to compare total annual costs (TAC) of two compared designs, which includes both the yearly operating costs and 10% of capital cost, according to assumed plant life time of 10 years. The capital cost is obtained by summing up individual equipment costs. Also, for the sake of simplicity, operating costs are taken to be identical to utility costs, i.e. the number resulting from the summation of electricity (0.1 $/kWh), low pressure steam (13 $/ton) and cooling water (0.03 $/ton) costs for a year containing 8000 operating hours. Practically no steam is required during the operation of VRC or ITCDC and some water is needed to produce minimum reflux required to initiate liquid flow at the top tray.

3 Results and discussion

3.1 Parametric study

In order to arrive at optimum operating conditions, and to be able to make a comparison to VRC, the operating compression ratio was varied. However the absolute values were kept between the stripping section pressure (11.2 bar) and the compressor outlet/reboiler inlet pressure of the VRC (18.1 bar), which corresponds with the rectification section pressure of a conventional column. Column/section pressure drop was considered in all simulations.

Fig. 1 shows relative operating, capital and total annual costs as a function of the compression ratio based on the upper limit operating pressure (rectification section). Obviously, all costs increase with increasing compression ratio, the capital cost less pronounced than the operating costs, i.e. the cost of utilities. The relative contribution of main components of overall annual costs is shown in Table 4, which indicates that the cost of compressor is the largest among the capital cost components and that the cost of electricity is by far the largest contributor. Roughly, operating costs make nearly 72 % of total annual cost. It is interesting to note that the cost of heat transfer panels is appreciably larger than the tray cost, however, in absolute sense, it is not so high to be of significant influence on total costs. This means that costs related to increased complexity of construction of a ITCDC are not a crucial factor, which implies that the cost of heat transfer devices and associated installation costs should not be considered as a real barrier for implementation of ITCDC concept in practice.

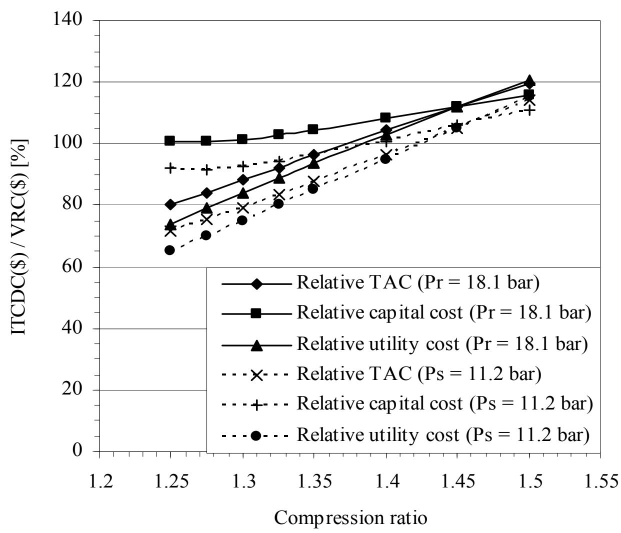

Fig. 1 Annual costs as a function of the compression ratio, for high and low (dotted lines) operating pressure, respectively

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Table 4 Relative contributions (in percents) of main components of capital and operating costs to total annual cost (TAC)

Cost component	P_r = 18.1 bar	P_s = 11.2 bar
Column shell	8.89	8.60
Tray	1.72	1.57
Panel	2.54	2.85
Condenser	0.54	0.94
Reboiler	0.00	0.00
Compressor	14.45	14.60
Electricity	69.34	68.63
Cooling water	2.52	2.81
Steam	0.00	0.00
Total	100.00	100.0

As indicated by dot lines in Fig. 1, the costs of a full scale ITCDC can be pushed down significantly if operating pressure is minimized, in this case that based on the stripping section pressure of 11.2 bar. This results, at the same compression ratio, in a lower rectification section pressure (14.6 bar). Comparison of total annual costs for these two options indicates that TAC for low operating pressure option is some 10 % lower and that the break-even point is pushed to higher compression ratio (above 1.4). This is mainly because of the fact that at fixed number of stages the reflux ratio will decrease with decreasing operating temperature/pressure, and this is directly reflected in decreasing operating costs. It should be noted that a 14 bar vapor leaving at the top of the column (35 ^{o}C at compression ratio of 1.3) still can be condensed using water, at the expense of using a larger condenser to compensate for a reduced temperature difference. However, this is of no impact on overall costs. The corresponding column shown in Table 4 indicates that the relative change in contributions of different components of total annual costs is rather small, and the relatively nearly doubled condenser contribution still so low that it does not affect the overall cost at all. Therefore, the low operating pressure version of ITCDC is chosen for further considerations.

Operating a conventional column, a VRC or a ITCDC at maximum number of stages will force the operating costs, which dominate the overall annual costs of both VRC and ITCDC, to decrease. This is illustrated for VRC and ITCDC version of the PP-splitter in Fig. 2, which shows the relative TAC and the average heat transfer area per stage as a function of the number of stages. The asymptotic trend in TAC at high end indicates that a ITCDC with 230 stages should be considered as reasonable choice.

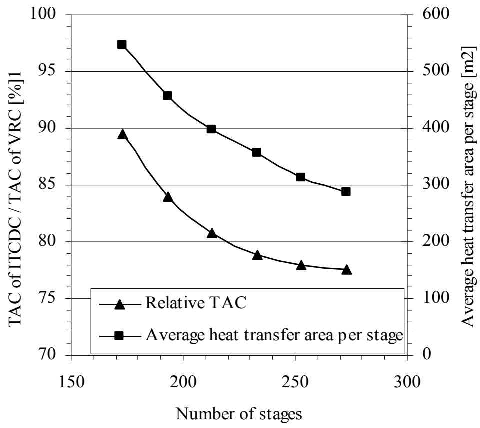

Fig. 2 The effect of the number of stages on relative TAC and the average heat transfer area per stage (P_s=11.2 bar, P_r/P_s=1.3)

4 Conclusions

Based on the simulation results we may conclude that ITCDC could be competitive to a VRC. A PP-splitter could be designed as a one-shell column, with the ITCDC part placed above the part of rectification section operating as a normal column.

It is clear that compression ratio is the most important variable that influences the performance of ITCDC. Lower compression ratio means higher energy efficiency, but that will inevitably require higher heat transfer area, which would threaten the feasibility of ITCDC. A trade off between the heat transfer area and the compression ratio is required.

This study indicates that relative gain in total annual cost could be up to 20 %. Compressor capital cost and strikingly large operating cost are the main factor affecting the economy of a ITCDC. Both, the increasing number of stages and decreasing compression ratio and operating pressure of the top of the column are beneficial in this respect.

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