Sensitivity Analysis of an Internal Thermally Coupled Distillation Column

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Abstract：Sensitivity analysis was performed for an industrially viable internal thermally coupled distillation column (ITCDC) and comparative studies were made with conventional distillation column (CC) and a column with a vapor recompression system (VRC) taking a propylene/propane splitter as the base case. Thermal efficiency of the ITCDC appeared to be strongly sensitive to the compression ratio between rectification section and stripping section.

Keywords: Distillation; Thermally coupled; ITCDC; Propylene splitter

1 Introduction

A ITCDC, i.e. an internally heat-integrated distillation column, which combines advantages of a low compression ratio vapor recompression system with a diabatic operation, offers ultimate potential for energy saving in distillation [1,2]. A conventional column (CC), a column with vapor recompression system (VRC) is shown schematically in Fig. 1 together with its ITCDC counterpart. Conceptually, a 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. This implies that the vapor load in rectification section decreases steadily downward the column/section, while the vapor load increases correspondingly upwards the stripping column/section. In this way some sort of a continuous operating line is obtained, which follows in parallel the equilibrium line at a minimum distance, ensuring nearly a reversible operation, as expected in diabatically-operated distillation columns [3]

Because of the unequal number of stages in the stripping section and the rectification section there are five options to coupling the two sections. It was proved that the best option is that where stripping section stages are thermally coupled with the equivalent number of stages in the upper part of the rectification section[4], which was taken as basis for design of a ITCDC PP-splitter.

For the implementation of industrially feasible ITCDC, in this paper sensitivity analysis was performed for ITCDC and 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.

2 Simulation tools

The simulation of separation performances of CC, VRC and ITCDC PP-splitters was carried out using AS-PEN Plus facilities. The ITCDC part of the alternative design (called generally ITCDC) was simulated as a pair of thermally interconnected columns/sections. In this case, the stripping section stages were thermally integrated with the equivalent number of the stages in the upper part of the rectification column. Lower part of the rectification column, operates as a normal column at given operating pressure. The heat transfer area requirement of the ITCDC was estimated by an interactive sequential calculation effort, by combining ASPEN and Excel.

3 Sensitivity analysis

3.1 Base case configurations

Table 1 summarizes operating conditions of three PP-splitter configurations compared in this study. In this study, two stripping section pressures (13 and 15 bar) are considered for each of ITCDC configurations studied, in conjunction with a constant rectification section pressure (18.34 bar), which corresponds to the top pressure of the conventional column. The VRC operates at 9.15 bar, and

a pressure drop of 8 mbar per theoretical stage is assumed here. Thus, the compression ratio as used throughout this study is the ratio of the top pressure of

the rectification section increased by the pressure drop of this section and the top pressure of the stripping section, i.e. $(P_r+\Delta P_r)/P_s$.
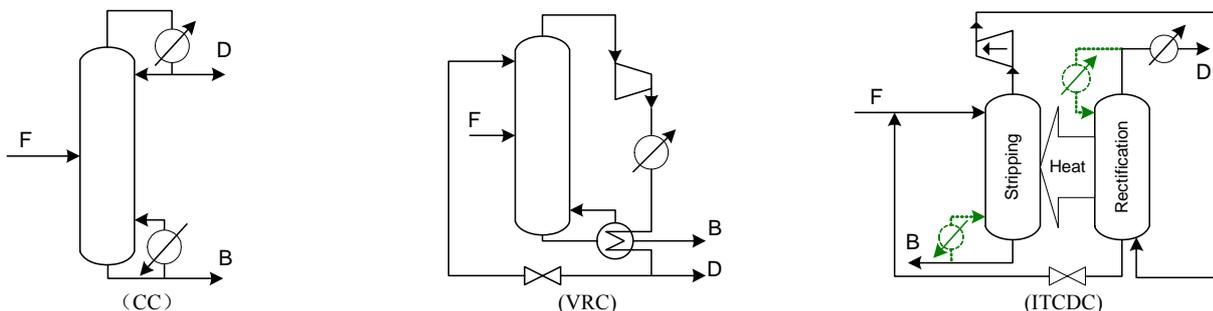
Fig. 1 Schematic illustration of the operating principle of a conventional column(CC), a column with the direct vapour recompression (VRC) and a ITCDC

Table 1 Operating conditions of the conventional distillation columnVRC and ITCDC for the base case

Configurations	CC	The column with vapour recompression	ITCDC
No. of stages Rectification section	138	140	138
	44	42	44
Stripping section			
Feed stage	139	141	139
Top pressure of rectification section [bar]	18.34	9.15	18.34
Top pressure of stripping section [bar]			13, 15
Pressure drop per stage [bar]	0.008	0.008	0.008
Feed flow rate [kmol/hr]	100	100	100
Feed mole fraction (Propylene)	0.5	0.5	0.5
(Propane)	0.5	0.5	0.5
Feed thermal condition	1	1	1
Overhead propylene mole fraction	0.995	0.995	0.995
Bottom propylene mole fraction	0.04	0.04	0.04

Base case number of theoretical stages is 182 and

the feed stage that differs slightly for CC and VRC represents the optimal one for given feed composition, feed thermal condition and product specifications. In general a ITCDC behaves similar to a column with vapour recompression (heat pump) system and they both differ to some extent from the conventional column with respect to effects of variations in common design and/or operating variables. Operating ranges of PP-splitters delivering polymer grade (>99.5 mole %) propylene vary considerably regarding the feed rates (10 – 100 t/h), feed composition (40 to 95 mole % propylene) and feed (vapour fraction up to 50 mole %) condition. This comparative study considers a binary mixture and bottoms specification is set at 4 mole % propylene, i.e. 96 mole % propane. And the base case flow rate of an equimolar feed was taken to be 100 kmol/h.

In case of both the VRC and ITCDC, the only energy supplied from outside is the electrical energy. The exergy of compressor work equals to the work itself while the exergy of heat equals to the maximum work that can be recovered when heat is converted into work in a Carnot process. Following relation was used to convert the heat added in the reboiler into exergy:

$$Ex_R = Q_R(1-\frac{T_0}{T_B+\Delta T}) \qquad (1)$$

where Ex_R is the exergy of reboiler, Q_R is the reboiler duty, T_0 is ambient temperature, T_B is bottoms temperature, and ΔT is the temperature difference in the

reboiler. A constant temperature difference of 30 0C was used for all external reboilers and the ITCDC related heat transfer area calculations were based on a constant value of the overall heat transfer coefficient (1000 W/m2 K).

3.2 Effect of compression ratio

In this study the top pressure of rectification section is kept constant so that of compression ratio on ITCDC. Fig. 2 shows the effects of compression ratio on relative exergy consumption. The top pressure of stripping section were varied to investigate the effect the relative exergy consumption of ITCDC increases with increasing compression ratio. Up to the compression ratio of 1.83 and 1.65 the advantage of ITCDC on exergy consumption was lost respectively compared to CC and VRC, because the compressor of ITCDC consumes too much electricity.

Fig. 3 shows the heat transfer duty and area of ITCDC for varied compression ratio. It can be seen that the heat transfer duty and area decrease as the compression ratio increases. From Fig. 2and Fig. 3 it can be concluded the appropriate range of compression ratio for the case studied here is from 1.3 to 1.6 which could save 20~50% and 10~40% exergy compared to the conventional column and VRC respectively and requires reasonable heat transfer area.

In the following parts the ITCDC with the compression ratio of 1.2 and 1.4 were taken as an example, which are denoted by ITCDC(15) and ITCDC(13) respectively.

Fig. 4 shows the effects of the number of stages on relative exergy consumption of ITCDC and VRC compared to CC. The exergy consumption of compressor decreases with increasing number of stages. This occurs because of the decrease in reflux ratio with 显示桌面.scf increasing number of stages. The exergy consumption of ITCDC decreases in the same rate to that of CC but faster than that of VRC as the number of stages increases. As a result the relative exergy consumption of ITCDC is nearly unaffected by the number of stages and that of VRC will increase with increasing number of stages. It is anticipated that up to a certain number of stages the potential of exergy saving will be totally lost for VRC.
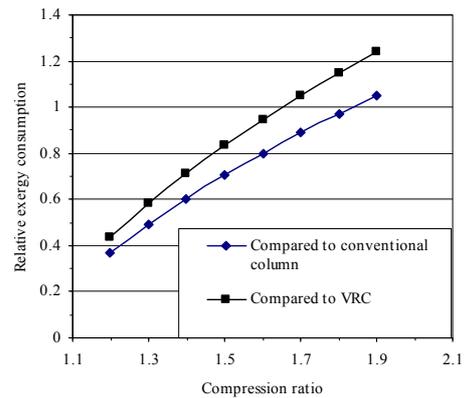
Fig. 2 The effect of pressure ratio on relative exergy consumption of HIDiC compared to the conventional distillation column and VRC
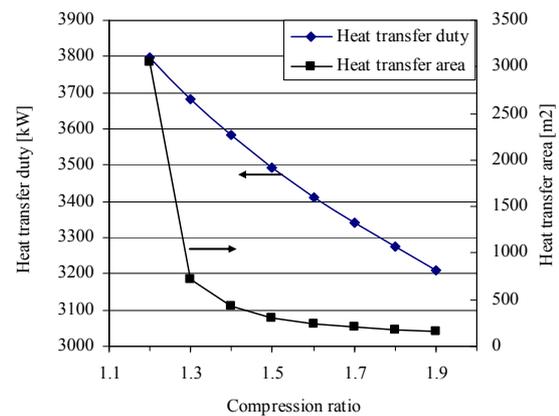
Fig. 3 The effect of pressure ratio on heat transfer duty and area of ITCDC

3.3 Effect of number of stages
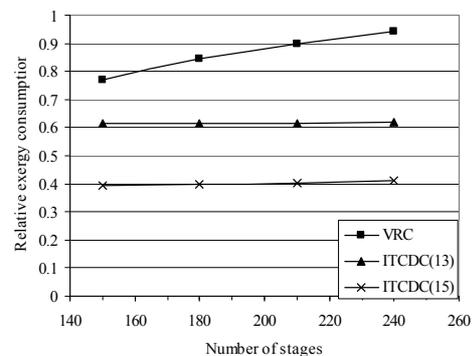
Fig. 4 The effect of number of stages on relative exergy consumption of ITCDC and VRC compared to CC
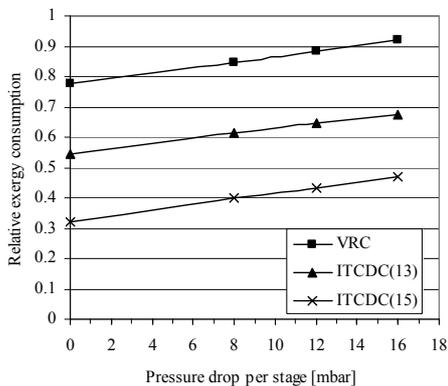
Fig. 5 The effect of pressure drop on the relative exergy con-
sumption of ITCDC and VRC compared to CC

3.4 Effect of pressure drop

The effects of pressure drop on the relative exergy consumption of ITCDC and VRC compared to CC are presented in Fig.5.

Both reflux ratio and compression ratio of compressor will increase a little as pressure drop increases. It indicates that the exergy consumption of these three columns increases with increasing pressure drop while the exergy consumption of VRC and ITCDC increase faster than that of CC.

3.5 Effect of feed composition

Fig. 6 shows the effects of the feed composition on relative exergy consumption of VRC and ITCDC. The exergy consumption CC, VRC and ITCDC increases with increasing feed composition, because this leads to an increase in the vapour flow. As a result the relative exergy consumption of ITCDC is not affected by the feed composition. For VRC, as can be readily seen, around the region of feed composition equaling 0.5, the relative exergy consumption reaches its minimum value. Away from 0.5 it gradually increases.

3.6 Effect of feed thermal condition

Fig. 7 shows the effects of feed thermal condition on relative exergy consumption of VRC and ITCDC.

The system of propylene and propane has a low relative volatility and is difficult to separate which results in a high reflux ratio. So the feed thermal condition can

only have little influence on the exergy consumption of columns. As result the exergy consumption of CC increases slightly with increasing feed thermal condition while those of ITCDC and VRC remain constant which accounts for the fact that the relative exergy consumption of ITCDC and VRC decreases slightly as the feed thermal condition increases. So it is reasonable to consider that feed thermal condition will not influence the process energy efficiency and economic performance of ITCDC substantially.
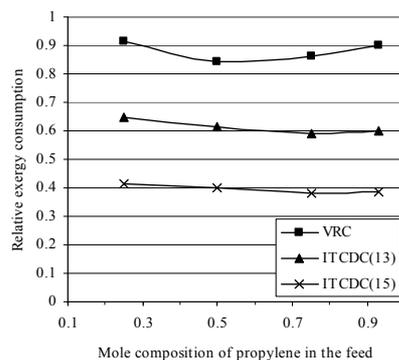
Fig. 6 The effect of feed composition on relative exergy consump-
tion of ITCDC andVRC compared to CC
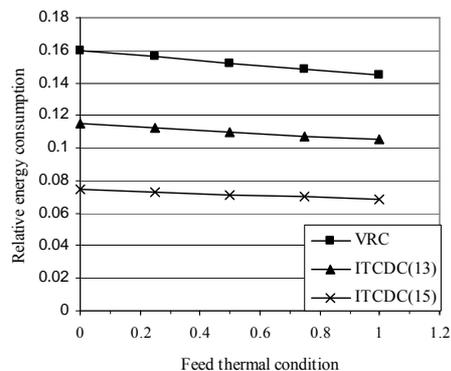
Fig. 7 The effect of feed thermal condition on relative exergy
consumption of ITCDC and VRC compared to CC

5 Conclusions

Based on the simulation results presented in this study we may conclude that ITCDC is feasible and could be competitive to a VRC. 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.

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