Structure Study of Internal Thermally Coupled Distillation Columns

Lanyi Sun, Cheng Zhai, Hui Zhang, Qingsong Li

State Key Laboratory of Heavy Oil Processing, China University of Petroleum, qingdao, Shandong 266555,China

sunlanyi@163.com

Abstract: Possible structures for an Internal Thermally Coupled Distillation Columns (ITCDC) are suggested and compared to a conventional column and a column with a vapour recompression system (VRC) taking a propylene/propane splitter as the base case. Thermal efficiency of the ITCDC appeared to be strongly sensitive to column structure and a highly efficient asymmetrical structure with stripping section stages thermally interconnected with the same number of stages in the upper part of the rectifying section emerged as the most promising one. The relationships among pressure ratio of rectifying section to stripping section, energy consumption and heat transfer area were also discussed.

Keywords: heat integrated distillation column; structure; energy consumption

Distillation column, the workhorse of process industries is notorious for the inefficiency with respect to energy consumption. A possibility for a breakthrough in this direction is the adoption of the internally heat integrated distillation column concept known as ITCDC[1-3], a well known but due to complexity never implemented column structure.

Fig. 1 illustrates schematically the operating principles of a conventional column (CC), a column with the direct vapour recompression system (VRC) and an ITCDC. In case of an ITCDC, the rectifying section operated at elevated pressure/temperature fulfils the role of a reboiler. Namely, the heat released during continuous condensation along the rectifying section is used to effect a roughly the same amount of progressive evaporation of liquid to maintain continuously increasing vapour traffic along the stripping section.

A potential problem with practical implementation of ITCDC is the fact that an ideal ITCDC inherently requires symmetrical distribution of stages, i.e. equal number of stages in both sections. Namely, this is conflicting with optimum feed position. In case of PP-splitters, usually only the distillate (propylene) is required at high purity, which implies that practically all columns of this type contain more stages in rectifying than in the stripping section. So the main conceptual design question is how to arrange an ITCDC with different number of stages in rectifying and stripping sections. Possible structures, compared in this study are shown in Fig. 2.

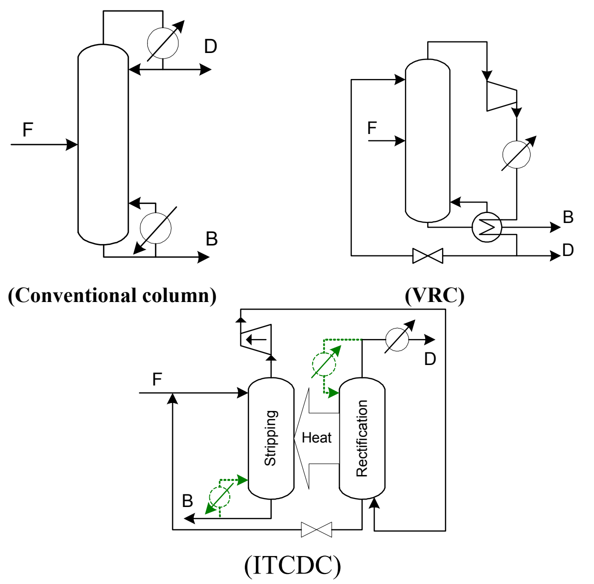
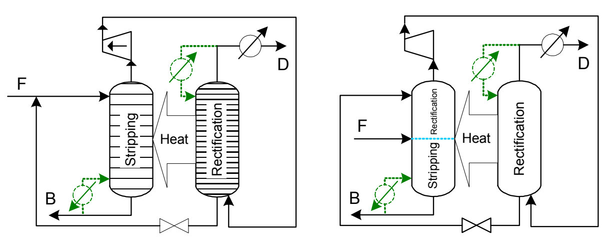
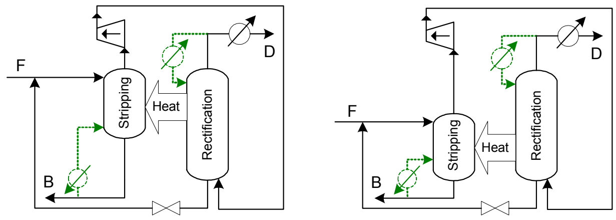


Fig.1 Schematic illustration of the operating principle of a conventional column, a column with the direct vapour recompression (VRC) and an ITCDC



(ITCDC_all) **(ITCDC_optimum middle)**

978-1-935068-37-2 © 2010 SciRes.



(ITCDC_upper) (ITCDC_lower)

Fig. 2 Other possible structures of the ITCDC, in addition to that (ITCDC_middle) shown in Fig. 1

ITCDC_middle, shown in Fig. 1 is the fully symmetrical structure structure as known from the literature[1-2]. ITCDC_optimum middle is the modification of ITCDC_middle where the feed is introduced on the stage, which represents the optimum one of a conventional column. ITCDC_upper and ITCDC_lower represent two extreme asymmetric structures, with the stripping section stages connected with the same number of stages in the rectifying section in the respectively upper and lower part of the rectifying section. Finally, ITCDC_all can be arranged to have equal length of the sections, simply by adapting the stripping section tray spacing accordingly.

The objective of the current work is to present the results of a thermal analysis study indicating a strikingly strong effect of ITCDC structure on the exergy consumption of a hypothetical PP-splitter.

1. Base case structures

Table 1 summarizes operating conditions of seven PP-splitter structures compared in this study. The thermal analysis of the PP-splitter structures evaluated in this study was carried out using ASPEN Plus facilities.

The conventional distillation column uses the heat added into the reboiler as the separating agent. In case of both the VRC and ITCDC, the only energy supplied from outside is the electrical energy used to drive the compressor. To account properly for the difference in the qualities of thermal and electric energies the exergy analysis was adopted employing the following relation:

Tab. 1 Operating conditions of the ITCDC

Structures	CC	VRC	ITCDC_middle	ITCDC_opt. middle	ITCDC_upper ITCDC_lower ITCDC_all
No. of stages Rectifying section	138	140	91	91	138
Stripping section	44	42	91	91	44
Feed stage	139	141	92	125	139
Top rectifying pressure, $P_R/10^{-1}$MPa	18.34	9.15	18.34	18.34	1.834
Top stripping pressure, $P_S/10^{-1}$MPa			13, 15	13, 15	1.3, 1.5
Pressure drop per stage/ 10^{-3}MPa	8	8	8	8	0.008
Feed flow rate/(kmol/s)	100	100	100	100	100
Feed mole fraction (Propylene)	0.5	0.5	0.5	0.5	0.5
(Propane)	0.5	0.5	0.5	0.5	0.5
Feed thermal condition， q	1	1	1	1	1
Top propylene mole fraction	0.995	0.995	0.995	0.995	0.995
Bottom propylene mole fraction	0.04	0.04	0.04	0.04	0.04

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

where ExR is the exergy of reboiler [kW], QR is the reboiler duty [kW], T0 is ambient temperature [K], TB is bottoms temperature [K], and ΔT is the temperature difference in the reboiler [K].

2. Results and discussion

Fig. 3 shows the energy and exergy consumptions of the VRC (column with vapour recompression system) and the ITCDC relative to that of the conventional column. As expected a VCR enables a huge energy saving with respect to conventional column and the asymmetric ITCDC with upper part of rectification section coupled thermally to the striping section seems to be the best structure in this respect. As expected, each of ITCDC structures with lower compression ratio (ITCDC(15), PR/PS = 1.2) consumes less energy/exergy than its counterpart operating at the higher compression ratio (ITCDC(13), PR/PS = 1.4). Interestingly the performances of five compared structures of ITCDC differ significantly and some of them, with larger compression ratio (ITCDC(13)_middle and ITCDC(13)_lower) which is however lower than that of VRC, appeared to be less favourable than the VRC itself. Striking is the extent of bad performance of the ITCDC with the bottom part of the rectification section coupled to the stripping section (ITCDC_lower). The relative exergy consumption plot shown in Fig. 3 indicates that the exergy efficiency of this structure is more than factor two worse than that of the conventional column. An explanation for the difference in the performance of five ITCDC structures, particularly the extreme one, is suggested in Fig. 4 which shows vapour flow rate profiles for each structure, with stage number increasing from the top to the bottom of the column. Namely, in addition to the compression ratio, which is equal for all ITCDC structures, the compressor duty depends also on the mass flow rate of the vapour. As indicated in Fig. 4 the latter one varies considerably, in one case extremely, depending on the structure. It should be noted that the vapour flow rate in an ITCDC increases from say zero at the bottom of stripping section to the maximum at the top of the stripping section. The vapour flow that enters the rectification section starts to decrease continuously while ascending through the rectification section reaching the minimum rate at the top, which is equivalent to that of the distillate product.

The peaks of vapour rate curves shown in Fig. 4 indicate the compressor load associated with ITCDC structures considered here. It can be seen that the vapour flows through compressors of ITCDC(13)_upper, ITCDC(13)_optimum middle, ITCDC(13)_all, ITCDC(13)_middle and ITCDC(13)_lower are 1.7, 2.4, 2.4, 3.1 and 7.5 times of that of the VRC, respectively. Therefore it is not surprising that in some cases an ITCDC consumes more energy/exergy than the VRC. On the other hand, as mentioned before, both structures of the ITCDC_upper perform the best, by saving respectively 27% and 40% exergy compared to the VRC.

An inspection of the propylene composition profile along the column for two asymmetric ITCDC's and the conventional column shown in Fig. 5 indicates that in case of ITCDC(13)_lower the separation effort is concentrated in the thermally coupled part of the column. In fact, this part of the column operates with a rather low number of theoretical stages, which must be compensated by correspondingly increased internal reflux ratio (roughly 75!). This is needed to compensate effectively for highly inefficient performance of the upper. On the other hand, the separation performance of ITCDC(13)_upper resembles that of the conventional column. As shown in Fig. 4, the vapour flow in the normally operating lower part of the rectification section is somewhat larger indicating correspondingly larger internal reflux (around 24.5). As indicated in Fig. 5, this leads to somewhat enhanced separation performance in this part of the column, which compensates certain loss in the thermally coupled part of the column.

In general, heat transfer duties of low compression ratio design in all cases appeared to be slightly higher and the lowest one was that associated with ITCDC_upper. This suggests that accordingly, thisstructure will require the lowest heat transfer area, which however appeared to be strongly sensitive to the compression ratio. An indication of the heat transfer requirements relative to that of the high compression ratio option of the fully symmetric ITCDC (ITCDC(13)_middle) can be obtained from Fig. 6. The low compression ratio structure (ITCDC(15)_upper) requires nearly four times more heat transfer area than the high compression ratio structure (ITCDC(13)_upper) .In fact, as indicated in Fig. 7, the heat transfer area increases towards the bottom of the stripping section and in case of the lower compression ratio the increase is so steep that it ends in the numbers, which may represent a technical barrier.

Since the integration of a large heat transfer area poses a practical threat for ITCDC, the high compression ratio structure requiring much less area may be a

978-1-935068-37-2 © 2010 SciRes.

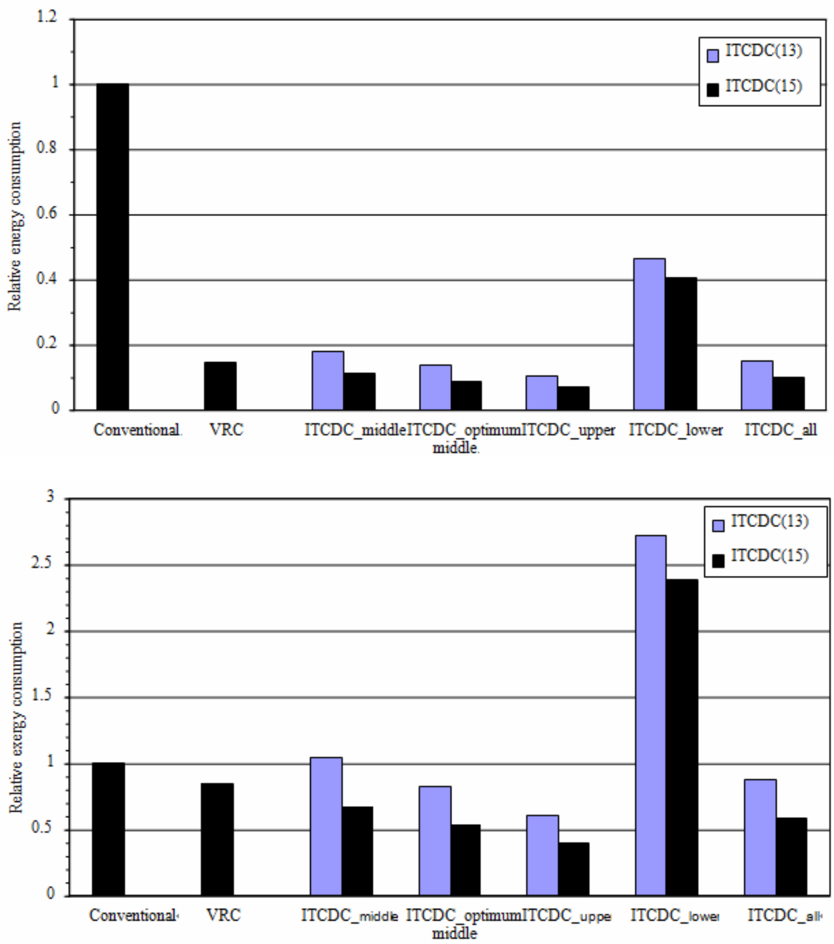


Fig.3 Relative energy (left) and exergy (right) consumption compared to the conventional column (ITCDC with bottom section pressure of respectively 13*10-1MPa and 15*10-1MPa).

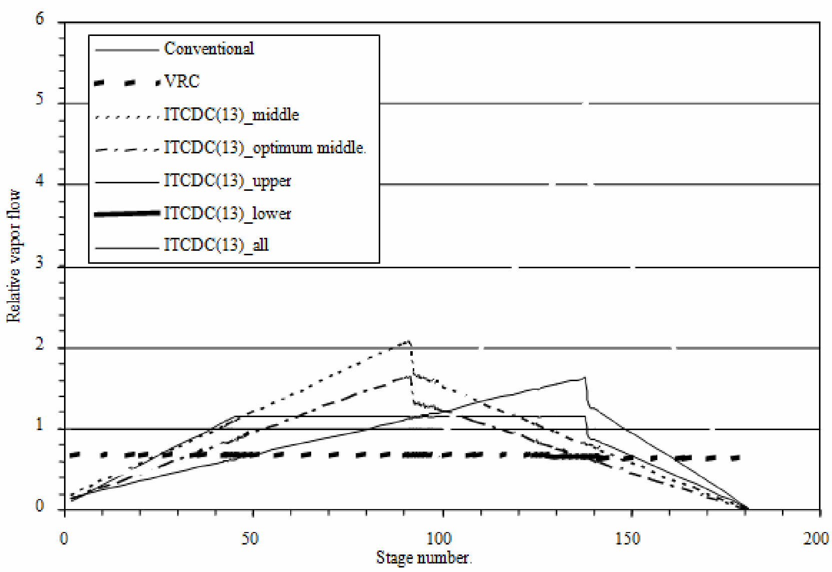


Fig.4 Comparison of vapour flow profiles for the high compression ratio ITCDC in vapour along the column

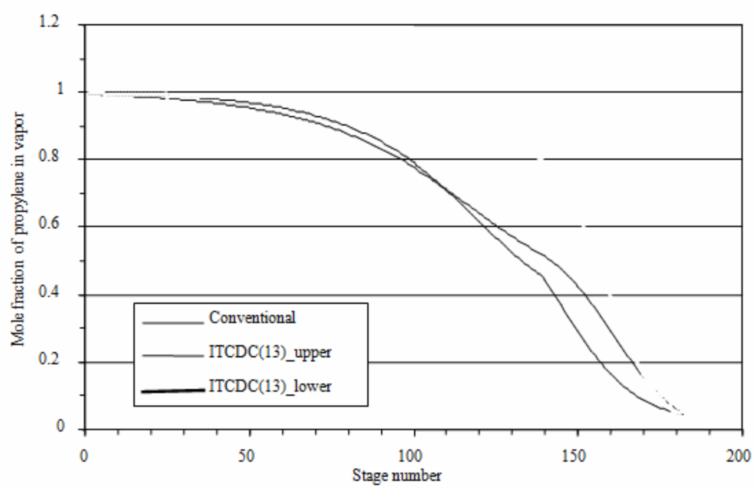


Fig. 5 Comparison of propylene fraction

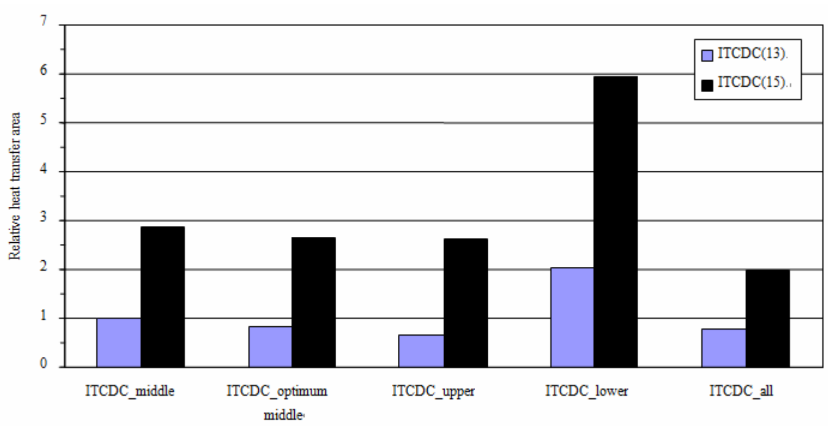


Fig. 6 Relative heat transfer area

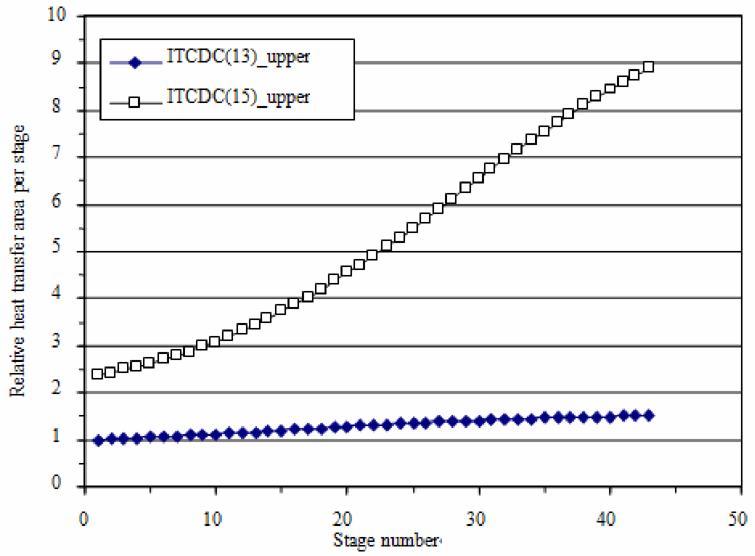


Fig. 7. Effect of the compression atio on the heat transfer area

more realistic choice. The only one option looking well at a low compression ratio is the expanded stripping section structure (ITCDC(15)_all), which requires the lowest area, because it operates at a somewhat higher temperature difference. Obviously, a thorough optimisation effort is needed to identify the best structure as well as to find the optimum compression ratio, which implies a trade-off between energy saving (operating cost) and the heat transfer area (capital cost).

3 Conclusions

The performance of an ITCDC with different number of stages in rectifying and stripping section depends strongly on the structure chosen. For the PP-splitter, the best option appeared to be a structure with stripping section stages thermally interconnected with a corresponding number of stages in the upper part of the rectifying section, with the lower part of rectification section operating as a normal column.With this structure it appears possible to reduce the energy consumption associated with a heat-pump distillation column by nearly 25~40%.

ITCDC with low compression ratio consumes less energy/exergy than structures with high compression ratio at the cost of higher heat transfer area which varies along the column.

References

[1] M. Nakaiwa *et al.* Internally Heat Integrated Distillation Columns: A Review [J], Trans IchemE, Part A, Chem. Eng. Res. Des. 81 (2003) 162-177.

[2] Z. Olujic *et al.* Internal heat integration – the key to energy-conserving distillation column [J], J. Chem. Technol. Biotechnol. 78 (2003) 241-248.

[3] P. J. Jansens, et al. Energy saving potential of a heat integrated distillation column, Proceedings of the Topical Distillation Symposium, AIChE 2001 Spring National Meeting, Houston, 22-26 April 2001, 19-25