

Pressure Swing Thermal-Dividing Wall Integrated Light Hydrocarbon Distillation Design and its Control

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Light hydrocarbon separation has received much attention due to its high energy consumption. In this paper, a novel five-column pressure swing thermal-dividing wall (PSTDW) integrated light hydrocarbon separation process is designed to replace the conventional six-column scheme and its control structure is proposed to effectively intensify the integrated distillation process. First, dividing wall column (DWC) as an energy-saving technology is introduced in the distillation process, which can save energy by 13.49 MW. Second, the heat duty between ethylene column and propylene column in the process is matched by means of thermal integration to further improve thermal integration efficiency, with energy saved by 33.7 %. Finally, one control strategy of the PSTDW process is designed to guarantee the product purity qualification. Its dynamic simulation results show that the control structure can effectively make the process back to a steady state in the face of disturbance.

1. Introduction

The efficient separation of light hydrocarbon has greatly promoted energy saving and sustainable production. Light hydrocarbon mixture, which typically separated by distillation process are major chemical raw material for the petrochemicals production (Pivovarova, 2019). Its main products, ethylene, and propylene, are the most indispensable chemicals used to produce polymers, plastics, membranes, rubbers, and chemical intermediates in many industries. Their separations are difficult because of low relative volatility and high energy consumption. For example, Methanol to Olefins (MTO) distillation as an important part of MTO process to obtain pure ethylene and propylene through separation, consumes two-thirds of the energy of MTO process. A new energy-saving process for separating light hydrocarbon mixture is thus the key to improve the market competitiveness.

As a representative of energy-saving equipment, the Dividing Wall Column (DWC) has the advantages of low energy consumption and capital cost (Feng et al., 2018). Dividing wall column can achieve multi-component separation through a single column. It not only reduces equipment investment but also improves thermal efficiency. Compared with a conventional distillation column, DWC can achieve 10 – 60 % energy savings and 10 – 50 % capital cost savings (Li et al., 2019).

In addition, thermal integration has been widely used in energy conservation as a kind of process integration (Patrascu et al., 2018). For example, pressure-swing heat integration can achieve energy integration by adjusting the operating pressure of column and changing the temperature of condenser and reboiler (Wang et al., 2018). Lü et al. (2018) proposed a pressure-swing distillation to separate a minimum-boiling azeotropic system of ethyl acetate and n-hexane, which can reduce the energy cost and Total Annual Cost (TAC) by 62.61 % and 49.26 % respectively compared with continuous homogenous azeotropic distillation process.

The dynamic controls for distillation processes have been widely studied in recent years, but there is relatively little research for the control study of the light hydrocarbon distillation with high purify requirement. Wang et al (2018) proposed the optimal design and control of the Kaibel and multi-side stream column for separating five-component hydrocarbon mixtures, and the control structure of KDWC can handle feed disturbance more effectively with the purity was closer to the design value. Design and control of DWC for the separation of

hydrocarbon mixtures was studied by Kim (2016), in which the controllability of DWC was improved by utilising the side-rectifier.

Ma et al. (2017) optimised front-end depropanisation process through thermal integration between columns, which can reduce the energy consumption by 38.8 %. However, the hydrocarbon separation process still has great energy-saving potential. In this work, a novel integrated light hydrocarbon distillation process is proposed to replace the conventional distillation scheme, which can greatly reduce energy consumption and meet high purify requirement. To improve the stability of the new process, a control structure of the high integration process is developed, which can effectively handle feed disturbance, and the purity is closer to the design value.

2. Pressure swing thermal-dividing wall (PSTDW) integrated distillation process

2.1 The conventional six-column separation process

The conventional distillation flowsheet is shown in Figure 1. The hydrocarbon mixture is fed into depropaniser *via* drying and pressurising operation. The bottom product of depropaniser enters into the debutaniser to separate C4 components from C5 and other heavy components, and the top product is compressed into demethaniser to remove methane and other light gases. The bottom product of demethaniser is introduced into deethaniser to separate C2 and C3. The mixture of ethane and ethylene obtained from the top of deethaniser enters into ethylene distillation column to realise ethylene refining, and the bottom stream of deethaniser is introduced into propylene distillation column to obtain pure propylene.

In the distillation process, the propane obtained from propylene distillation column is used as absorbent in the demethaniser to make the operating temperature not too low and avoids cryogenic process. Owing to the quite close boiling points of propylene and propane, a large number of trays and extensive energy are required to separate them. Hence, column with heat pump as an energy-saving technology is used in this process. The top stream of the column is taken as heat source for the column reboiler. Composition of the hydrocarbon mixture is listed in Table 1. Product purity specifications of the important components are: ethylene and propylene more than 99.95 % and 99.6 %. The content of C4 components in C4 stream exceeds 95 %, and the content of C5 components in C5+ stream is more than 95 %.

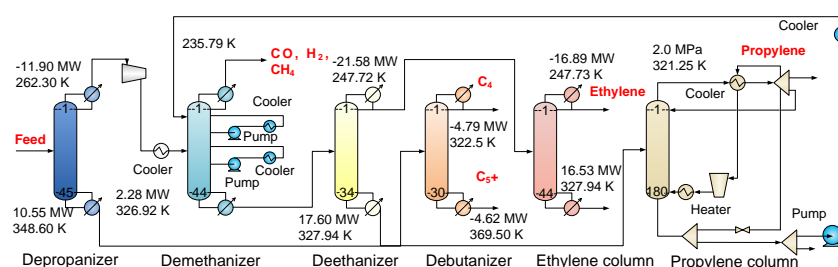


Figure 1: Process flow diagram of the pre-depropanation separation process

Table 1: Composition of hydrocarbon mixture

Component	Mass fraction %
H ₂	0.18
CO	0.19
N ₂	0.19
CH ₄	1.76
C ₂ H ₄	41.27
C ₂ H ₆	0.79
C ₃ H ₆	40.32
C ₃ H ₈	2.81
C ₄	10.45
C ₅ +	2.04

2.2 The novel Multi-olefin distillation process based on dividing wall column (MODP-DWC)

The distillation column sequence is designed based on relative volatility of the components. The phase equilibrium constant and relative volatility of the light hydrocarbon mixture is listed in Table 2. It can be seen that the relative volatility between C₄H₁₀-01 and C₅H₁₀-01 is the highest, so C₄H₁₀-01 and C₅H₁₀-01 should be

separated first. However, the contents of C4 and C5 components are the lowest. It is unreasonable to separate the C4 and C5 components firstly. The separation of CH₄ and C₂H₄, C₂H₆ and C₃H₆, C₃H₈ should be carried out first.

Table2: The phase equilibrium constant and relative volatility of the components

Component i	CH ₄	C ₂ H ₄	C ₂ H ₆	C ₃ H ₆	C ₃ H ₈	C ₄ H ₈ -01	C ₄ H ₁₀ --01	C ₅ H ₁₀ -01	C ₅ H ₁₂ -01
K_i	5.16	3.22	2.95	1.12	0.96	0.44	0.39	0.15	0.16
α_{ij}	1.60	1.09	2.64	1.16	2.18	1.13	2.68	0.93	

Process flow diagram based on MODP-DWC system is shown in Figure 2. The process involves five columns, namely, dividing wall column, ethylene distillation column, depropaniser, propylene distillation column, and debutaniser. Light hydrocarbon mixture is fed into dividing wall column (DWC) to separate C₁, C₂ and C₃ components. Lighter components (CO, H₂, CH₄) are left from the top of the dividing wall column, while C₂ components are extracted from the side of DWC and enter ethylene distillation column to obtain pure ethylene. The bottom products of DWC containing C₃, C₄, and C₅ components are introduced into depropaniser for separating C₃ components from C₄ and C₅ components, and the mixture of propylene and propane obtained from the top of depropaniser are fed into propylene distillation column for propylene purification. The bottom products of the depropaniser are introduced into debutaniser to separate C₄ and C₅ components.

The mass fraction and feed flow rate of major streams are summarised in Table 3. It can be seen that the PSTDW process can realise light hydrocarbon product separation while saving heat public utility and cool public utility by 8.73 MW and 4.76 MW.

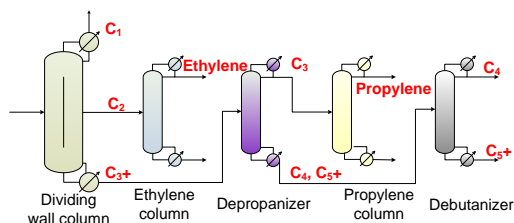


Figure 2: Process flow diagram based on dividing wall column

Table 3: The mass fraction and feed flow rate for the system

Stream	C ₁	Ethylene	Propylene	C ₄	C ₅ +
Flowrate/ kg/h	2,447.37	39,318.00	37,157.29	10,051.05	2,055.54
wt/ %					
H ₂	7.21	0	0	0	0
CO	7.61	8.76e-12	0	0	0
N ₂	7.61	7.93e-13	0	0	0
CH ₄	69.68	0.05	0	0	0
C ₂ H ₄	7.89	99.95	2.92×10 ⁻⁷	0	0
C ₂ H ₆	2.35×10 ⁻⁴	2.61×10 ⁻⁴	6.39×10 ⁻⁶	0	0
C ₃ H ₆	1.38×10 ⁻⁹	2.10×10 ⁻¹⁵	99.99	6.28×10 ⁻³	4.39×10 ⁻¹³
C ₃ H ₈	5.75×10 ⁻¹²	9.18×10 ⁻¹⁹	5.16×10 ⁻³	3.80×10 ⁻⁴	2.71×10 ⁻¹²
C ₄ H ₁₀ -01	7.29×10 ⁻¹⁹	3.67×10 ⁻³⁰	7.59×10 ⁻³²	4.02	2.72
C ₄ H ₈ --01	2.30×10 ⁻¹⁸	3.47×10 ⁻³⁰	5.75×10 ⁻³⁶	95.98	48.64
C ₅ H ₁₀ -01	5.23×10 ⁻²⁹	1.19×10 ⁻⁴⁶	2.22×10 ⁻⁸⁰	2.95×10 ⁻⁴	48.64
C ₅ H ₁₂ -01	6.20×10 ⁻³¹	1.09×10 ⁻⁴⁹	4.71×10 ⁻⁸⁸	2.44×10 ⁻⁵	0.01

2.3 Feasibility analysis of thermal integration in MODP-DWC system

There are five columns in MODP-DWC system. The feasibility of thermal integration for the five columns is shown by T-H diagram in Figure 3. The x-coordinate represents the heat load, the y-coordinate represents the temperature, and the energy input and output of five columns are represented by quadrilateral. The ethylene distillation column and propylene distillation column consume a large amount of heat which can only be provided by public utility. Thus, the two distillation columns cause a lot of energy consumption. The overhead stream temperature of the propylene distillation column is 278 K, 2 K higher than the bottom temperature of ethylene distillation column (276 K). In addition, the heat load of ethylene distillation column is close to the cold load of propylene distillation column. The heat integration between the two columns could be realised by adjusting their operating pressure.

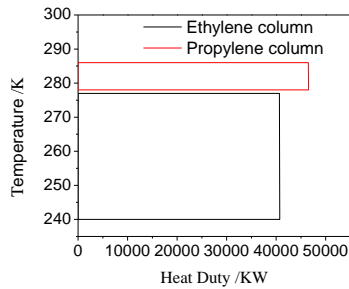


Figure 3: T-H diagram of distillation system

The relation between ethylene mass fraction and operating pressure of the ethylene column are shown in Figure 4(a). The mass fraction of ethylene is decreased from 0.999502 to 0.99949 when the operating pressure of the ethylene column is increased from 1.4 to 2.6 MPa. When the pressure approaches to 2.05 MPa, the mass fraction of ethylene reduces to 0.9995. Thus, the upper pressure limit of ethylene column is set at 2.05 MPa to meet the quality of ethylene.

The relation between temperature and operating pressure of the ethylene column are shown in Figure 4(b). The operating pressure of ethylene column is in a range of 1.5-2.05 MPa, and the pressure of the propylene column is in a range of 0.5-1.1 MPa. In pressurised heat integration process, the operating pressure of the ethylene distillation column is 2.05 MPa and the bottom temperature of the ethylene distillation column is 282 K. In order to heat the reboiler by using the top stream of propylene distillation column, the top stream temperature of the propylene distillation column should be set at least 292 K, 10 K higher than that of the reboiler temperature of ethylene column with a corresponding pressure of 1.02 MPa. In depressurised heat integration process, the minimum operating pressure of ethylene distillation column is 1.5 MPa and its corresponding reboiler temperature is 268 K. The condenser temperature of the propylene distillation column should be higher than 278 K to keep 10 K difference with the reboiler of ethylene distillation column. There are a lot of combinations of heat integration in this pressure range discussed above. Although the depressurised heat integration process has advantages in equipment investment and operating cost, it has higher requirements for refrigerant of ethylene distillation column condenser. Consequently, in pressurised heat integration process, the pressure of ethylene column is increased to 2.01 MPa, and the matching scheme realises heat integration between propylene column and ethylene column.

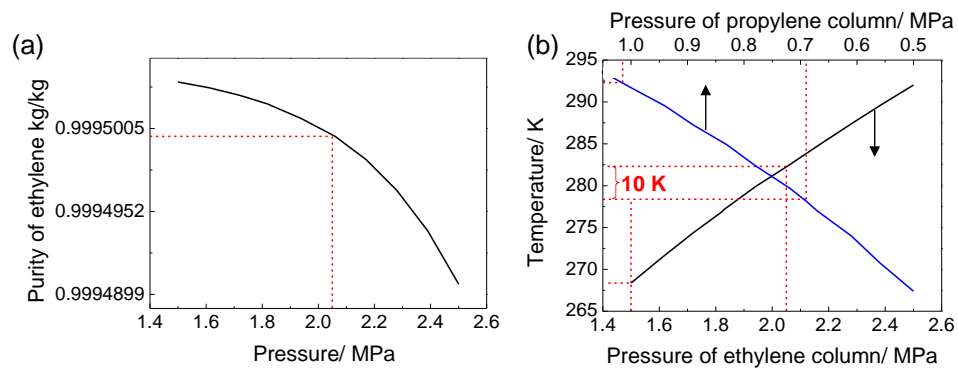


Figure 4: (a) The relation between ethylene mass fraction and operating pressure of the ethylene column; (b) The relation between temperature and operating pressure of the ethylene column

2.4 The PSTDW integrated distillation process

In the MODP-DWC system, when the pressure of ethylene distillation column is increased to 2.01 MPa, the corresponding heat load of ethylene column reboiler is 38.88 MW. When the propylene distillation column is increased to 1.02 MPa, the corresponding heat load of propylene column condenser is reduced to 43.39 MW, and the remaining heat of propylene column condenser is removed by cold public utility. Process flow diagram of the MODP-DWC heat integration process is shown in Figure 5. Compared to the integrated conventional distillation process, the PSTDW process can save 73.47 MW energy.

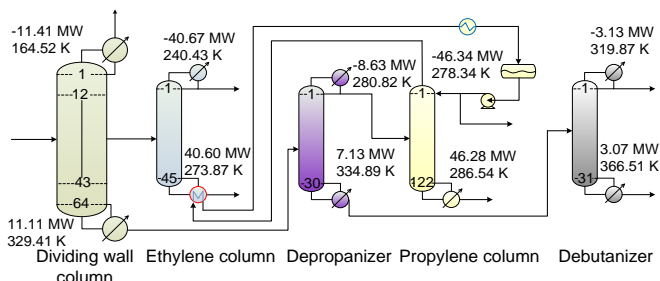


Figure 5: The PSTDW distillation system

3. Plant wide control for the PSTDW distillation system

The control structure is shown in Figure 6. According to the basic principles of the control design methodology, some conventional controllers, such as flow controller (FC), level controller (LC), temperature controller (TC), and pressure controller (PC), should be arranged first to establish the control structure. The controllers added in the control scheme are summarised as follows:

- (1) The flow controller is employed to adjust the feed flow rate (reverse acting);
- (2) The operating pressure of column is controlled by condenser heat removal (reverse acting);
- (3) The flow rates of distillate and bottom product are used as manipulated variables to control the levels of column sump and reflux drum, respectively (direct acting);
- (4) The return flow rate of column is proportional to the feed flow rate;
- (5) The temperature of sensible stage is adjusted by manipulating condenser or reboiler heat duty (reverse acting).

For flow controller, the default adjustment constant gain is 0.5, the integration time is 0.3 min. For temperature controller, the tuning parameters are $K_c = 2$ and $T_i = 10$ min (Luyben, 2013). The default gain and integration time of other controllers are given similarly.

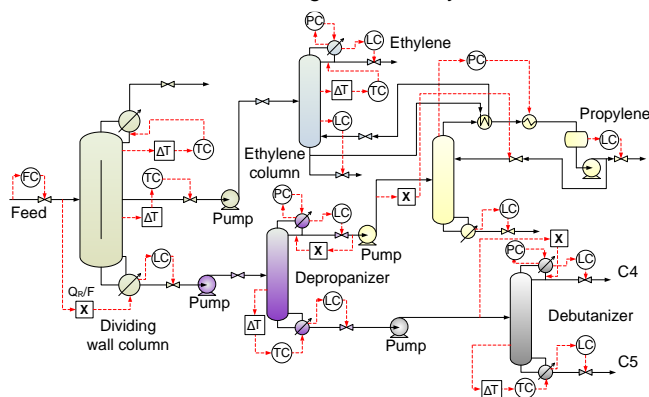


Figure 6: Control scheme of PSTDW distillation system with top temperature controller

After the dynamic running 3 h, the $\pm 10\%$ feed flow rate disturbances are added to investigate the stability of the control structure. Figure 7 shows the response curves for the control scheme. It can be seen that the desired product purities at the new steady state can be achieved after 8 h. At the new steady state, the purities of ethylene and propylene are 99.92% and 99.99% corresponding to the 10% flow rate increase in feed, whereas they are 99.98% and 99.99% corresponding to the 10% flow rate decrease in fresh feed. And the purities of the C4 and C5 are quickly stabilised above 95%. These results demonstrate that the proposed control structure can achieve the controllable operating of the PSTDW distillation system.

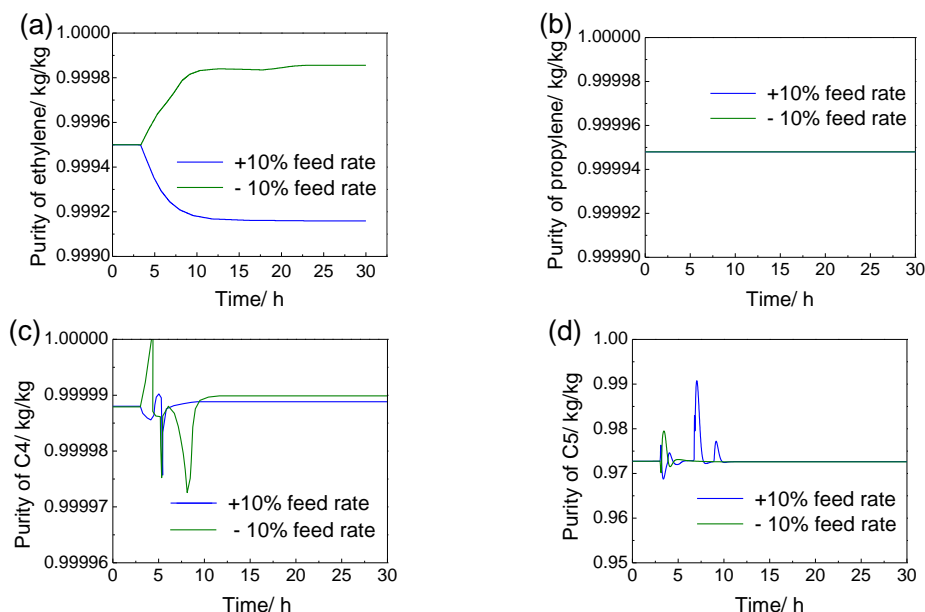


Figure 7: Dynamic responses of the control scheme. (a) Purity of ethylene; (b) Purity of propylene; (c) Purity of C4; (d) Purity of C5

4. Conclusions

In this work, a novel pressure swing thermal-dividing wall integrated distillation process is proposed to replace conventional six-column scheme for separating light hydrocarbon mixture. Dividing wall column is introduced to improve thermodynamic efficiency. In order to further save energy consumption of this system, the overhead steam of the propylene distillation column is used to heat the reboiler of the ethylene distillation column, which reduces energy consumption by 33.7%. Finally, one control strategy of the PSTDW distillation system is established, which can resist $\pm 10\%$ fresh feed flow rate disturbances effectively. The economy of the PSTDW process will be taken into consideration in the near future.

Acknowledgements

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References

- Feng S., Ye Q., Xia H., Chen J., Liu T., Wu W., 2018. Controllability comparisons of a reactive dividing-wall column for transesterification of methyl acetate and isopropanol. *Chemical Engineering Research and Design*, 132, 409-423.
- Kim Y.H., 2016. Design and control of energy-efficient distillation columns. *Korean Journal of Chemical Engineering*, 33(9), 2513–2521.
- Li J., Zhang F., Pan Q., 2019. Performance enhancement of reactive dividing wall column based on self-heat recuperation technology. *Industrial and Engineering Chemistry Research*, 58(27), 12179-12191.
- Ma Z., Duan M., Zhang Z., Qiao X., Zhang J., Ma X., 2017. Heat integration in methanol to olefins separation process. *Computer and Applied Chemistry*, 34 (10), 809-814. (in Chinese)
- Patrascu I., Bildea C., Kiss A., 2018. Enhanced biobutanol separation by a heat pump assisted azeotropic dividing-wall column. *Chemical Engineering Transactions*, 69, 2283-9216.
- Pivovarov N.A., 2019. Use of wave effect in processing of the hydrocarbon raw material (review). *Petroleum Chemistry*, 59(6), 559-569.
- Wang X., Yu X., Xie L., Li M., Zhang Y., 2018. Energy-saving columns: Design and control of a Kaibel and a multi-sidestream column for separating hydrocarbon mixture. *Chemical Engineering and Processing-Process Intensification*, 133, 66–82.
- Wang Y., Ma K., Yu M., Dai Y., Yuan R., Zhu Z., Gao J., 2018. An improvement scheme for pressure-swing distillation with and without heat integration through an intermediate connection to achieve energy savings. *Computers and Chemical Engineering*, 119(2), 439-449.