INVESTIGATION OF MATERIAL COST OF A PROPANE-PROPYLENE RECTIFICATION COLUMN

Viktória Kállai
senior lecturer, University of Miskolc, Institute of Energy Engineering and Chemical Machinery
3515 Miskolc-Egyetemváros, e-mail: viktoria.kallai@uni-miskolc.hu

Péter Mizsey
professor, University of Miskolc, Institute of Chemistry
3515 Miskolc-Egyetemváros, e-mail: peter.mizsey@uni-miskolc.hu

Gábor L. Szepesi
professor, University of Miskolc, Institute of Energy Engineering and Chemical Machinery
3515 Miskolc-Egyetemváros, e-mail: gabor.szepesi@uni-miskolc.hu

Abstract
In this study a propane-propylene rectification column was investigated in terms of diameter of the column, number of trays, reflux ratio and the construction material costs of the column. During the calculations the reflux ratio was modified between 8 and 30. The chosen material of the column and trays was 1.4404 grade austenitic steel.

The calculation has shown that with higher reflux ratio the diameter of the column and the number of trays were changing. Next, the necessary wall thickness of the shell of the column was determined with strength calculation.

A material cost function was also determined with these parameters applying various reflux ratio values. From the results it can be concluded that the optimal reflux ratio is 12, because in this case the material cost function has a minimum point.

Keywords: *material cost, propane-propylene rectification column, reflux ratio*

1. Introduction

Propylene is one of the most important products of the petrochemicals industry. It serves as a basic material of many other products. The separation of propane and propylene is an energy-intensive procedure, since the boiling points of these two components are near to each other (at atmospheric pressure the difference between the boiling points of the components is approximately 5.5 °C), therefore the difference between their relative volatility is also low. The other reason of the high energy demand is due to the fact that these components are gases at atmospheric pressure and ambient temperature (J. R. Alcántara-Avila et al., 2014).

Process simulator softwares, such as UniSim Design® are suitable tool for the investigation of distillation technology in case of low carbon content of carbohydrates with Soave-Redlich-Kwong (SRK) equation of state (A. Jalali et al., 2019; E. C. Carlson, 1996).

2. The method of the investigation

During the study the first step was the calculation of the required number of theoretical trays with the so-called tray-by-tray method (Földes and Fonyó, 1978) in case of different values of reflux ratio.

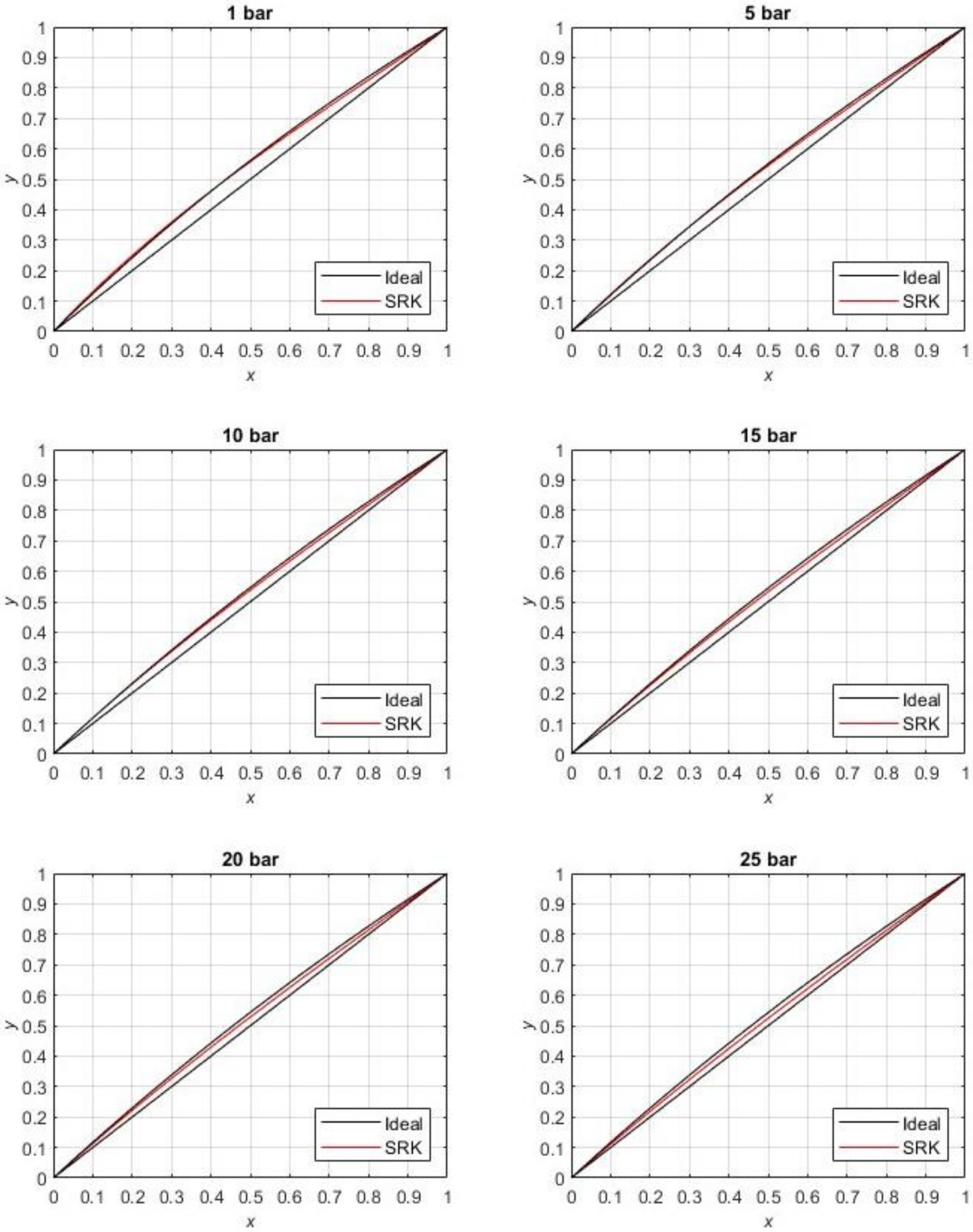

Figure 1. *Equilibrium diagrams of propane-propylene at different pressures*

Using the results from the above mentioned calculation, the mass flow of the vapour and liquid streams in the column, and the mole fraction of the light component in the bottom product were determined. The equations of the system were solved tray-by-tray than. This is an approximation method, where all trays can be calculated with one iteration. The calculation started on both ends of the column, the stream and composition parameters were assumed and with this data the parameters of the next tray can be calculated (Földes and Fonyó, 1978).

During the study the propane-propylene mixture was treated as an ideal one, as from the equilibrium diagram it can be apparent that between the results of ideal and SRK equation of state there are lower differences than 5% *(Figure 1)*. In case of higher pressure the deviation between the investigated cases is also higher.

In the *figure 1* the abscissa is *x*, it is the mole fraction of the propylene in the liquid phase, while the ordinate is *y*, it is the mole fraction of the propylene in the vapour phase.

The column diameter was calculated with the so-called Souders-Brown-Fair method with the Fair diagram *(Figure 2)*. The tray spacing was 0.457 m in the column (Fonyó and Fábry, 1998; Perry, 2008). For the calculation some parameters of the streams should be known, such as the density of liquid and vapour streams, the surface tension of liquid stream. During this study these parameters were determined by UniSim Design® (UniSim Design, 2009) process simulator software using SRK equation of state (Jaubert and Privat, 2010; Némethné, 2013).

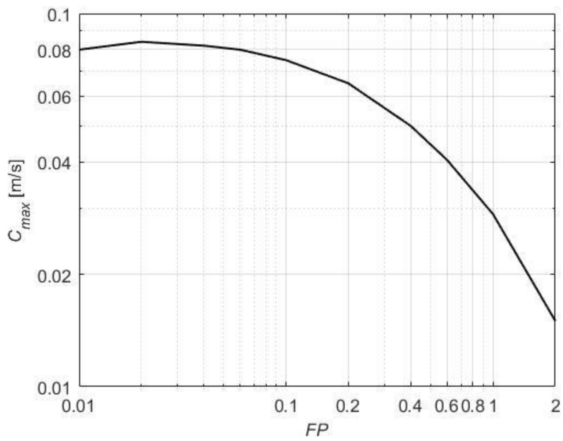

Figure 2. *Fair load capacity diagram* (Fonyó and Fábry, 1998; Perry, 2008)

The abscissa of the curve in *figure 2* is the *FP* parameter which is the flow parameter, it should be calculated with the following equation:

$$FP = \frac{L}{V} \cdot \sqrt{\frac{\rho_V}{\rho_L}}, \tag{1}$$

where *L* is the mass flow of liquid stream inside the column [kg/h], *V* is the mass flow of vapour stream inside the column [kg/h], ρ_V is the density of the vapour phase [kg/m^3], ρ_L is the density of the liquid phase [kg/m^3].

The maximum vapour velocity for flooding is determined with the ordinate parameter (C_{max}) of the curve in *figure 2* using the Souders-Brown-Fair method:

$$v_{max} = C_{max} \cdot \left(\frac{\sigma}{0.02}\right)^{0.2} \cdot \sqrt{\frac{\rho_L - \rho_V}{\rho_V}}, \tag{2}$$

where v_{max} is the maximum vapour velocity for flooding [m/s], C_{max} is the capacity parameter from *figure 2* [m/s], σ is the surface tension of the liquid phase [N/m].

The allowable vapour velocity (v_a [m/s]) is approximately 60–80% of maximum vapour velocity (Perry, 2008). In this study the allowable vapour velocity is the 70% of maximum vapour velocity:

$$v_a = 0{,}7 \cdot v_{max} \tag{3}$$

The cross-section of the tray can be calculated with the following equation.

$$A_t = \frac{V_V}{v_a}, \tag{4}$$

where A_t is the cross-section of a tray [m^2], V_V is the internal vapour flow rate [m^3/s].

Due to the tray has downcomer, a 1.2 times allowance is required to calculate the cross-section of the column:

$$A_c = 1.2 \cdot A_t, \tag{5}$$

where A_c is the cross-section of the column [m^2]. Thus, the diameter of the column (D [m]) can be calculated:

$$D = \sqrt{\frac{A_c \cdot 4}{\pi}}. \tag{6}$$

Furthermore, the required thickness of the wall of the column was calculated using the given operating parameters with strength calculation. These calculations based on the standard of MSZ EN 13445-3:2014 and the material properties are described with the standard of MSZ EN 10028-7:2001.

In case of higher reflux ratio, a lower required number of trays are essential. These are used to reach the given purity of the overhead product, and therefore simultaneously the diameter of the column will be higher, which will increase the required wall thickness. Taking these modifications into account, the material cost of a given column was calculated in case of different reflux ratio values and 1.4404 grade austenitic steel material.

The volume of a tray can be calculated by the following equation, where thickness of the trays was 5 mm:

$$V_t = A_t \cdot t_d, \tag{7}$$

where V_t is the volume of a tray [m^3], t_d is the thickness of a tray [m].

The mass of a tray is given by multiplication of its volume and density:

$$m = V_t \cdot \rho_{steel}, \tag{8}$$

where m is the mass of a tray [kg] and ρ_{steel} is the density of the1.4404 grade austenitic steel [kg/m^3].

During this study the headers of the column are not take into account, only the trayed part of the column was investigated (as shown in *figure 3*, the calculated part of the column is framed with red), thus the height of this part is determined with the following equation:

$$H = N_t \cdot t_d + (N_t - 1) \cdot t_t, \tag{9}$$

where H is the height of the column [m], N_t is the theoretical number of trays, t_t is the tray spacing [m].

The volume of the column can be calculated with the following equation:

$$V_c = \left(\frac{D_e^2 \cdot \pi}{4} - \frac{D_i^2 \cdot \pi}{4}\right) \cdot H, \tag{10}$$

where V_c is the volume of the column [m^3], D_e is the external diameter of the column [m], D_i is the internal diameter of the column [m].

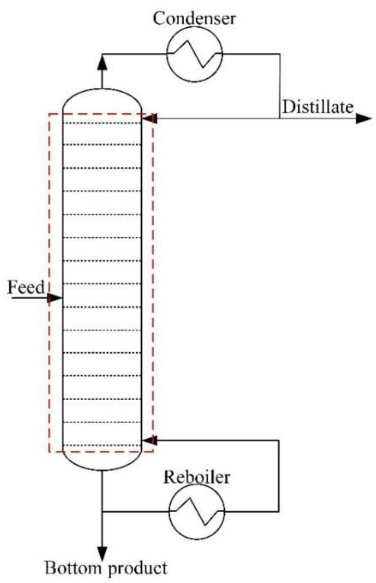

Figure 3. *Schematic figure of a distillation column*

The above mentioned material costs of trays and columns can be calculated using the described parameters. The price of the chosen material (1.4404 grade austenitic steel) was determined according to the referenced website (http://www.estainlesssteel.com/usstainlesssurcharges.shtml., 26. 04. 2022).

3. The investigated system

3.1. Propane-propylene rectification column

Parameters of the feed and products of the propane-propylene column are summarized in *table 1*.

Table 1

Parameters of the feed and the products of the propane-propylene rectification column

	Feed	Distillate	Bottom product
Temperature [°C]	52.60	46.65	57.29
Pressure [bar]	20.68	19.31	20.68
Molar flow [kmol/h]	612.40	351.50	260.90
Propylene [mole%]	60.00	98.95	7.51
Propane [mole%]	40.00	1.05	92.49

In *figure 4* the effect of the reflux ratio on the diameter of the column and the number of trays was plotted. With higher reflux ratio the number of trays is lower, while the diameter of the column is higher.

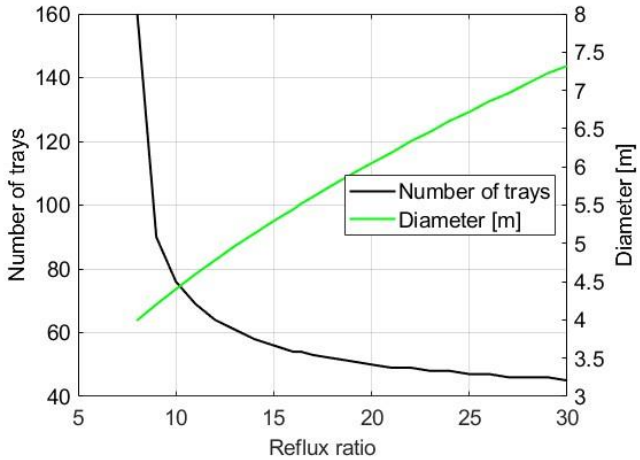

Figure 4. *Effect of the reflux ratio on the number of trays and the diameter of the investigated propane-propylene rectification column*

The relationship between reflux ratio and diameter of the column can be described by the following second-degree polynomial function according to the curve described in *figure 4*.

$$D = -2.033 \cdot 10^{-3} \cdot R^2 + 0.2266 \cdot R + 2.3386. \tag{11}$$

Figure 5 shows the relationship between reflux ratio and material cost of the trays in the investigated propane-propylene rectification column. It is seen in the diagram that in case of reflux ratio 12 the material cost has minimum point.

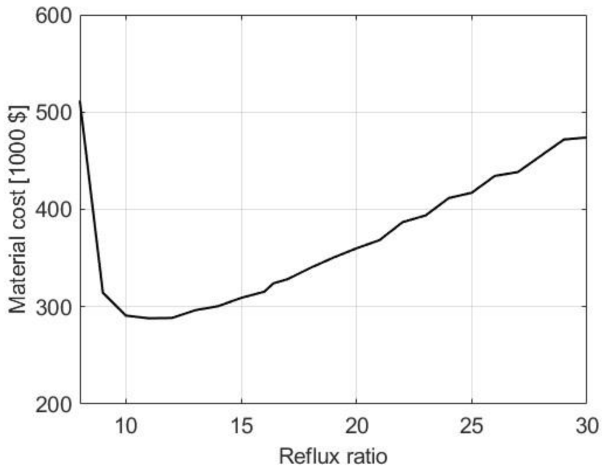

Figure 5. *The effect of the reflux ratio on the material cost of the investigated propane-propylene rectification column*

3.2. Comparison of cost functions

According to J. M. Douglas (Douglas, 1998) the purchase cost of columns can be calculated with the following function:

$$PC = \frac{M\&S}{280} \cdot 101.9 \cdot D^{1.066} \cdot H^{0.82} \cdot F_c, \tag{12}$$

where *M&S* is the Marshall and Swift cost index [–], its value was 2171.6 in 2020 (Camaraza-Medina et al., 2020). *D* is the diameter of the column [ft], *H* is the height of the column [ft] and F_c is calculated by the following equation:

$$F_c = F_m \cdot F_p, \tag{13}$$

where F_m is the factor which takes into account the quality of the material [–], in case of 1.4401 grade austenitic stainless steel its value is 3.67, F_p is the factor which consider the pressure of the column, in case of the investigated system it is 1.2.

The purchase and material costs of the propane-propylene column are demonstrated in case of different reflux ratio values in *figure 6*. The material cost includes only the price of the material of the column based on the calculation showed previously, while the literature context gives the total purchase cost of the column. In both cases the cost functions have a minimum point, where the value of the reflux ratio is optimal. In case of material cost the optimal reflux ratio is 12, while in case of purchase cost the optimal reflux ratio is 14. It can be concluded that within the studied reflux ratio interval, the total purchase cost of the column is on average 8.3 times higher than the material cost of the investigated propane-propylene column.

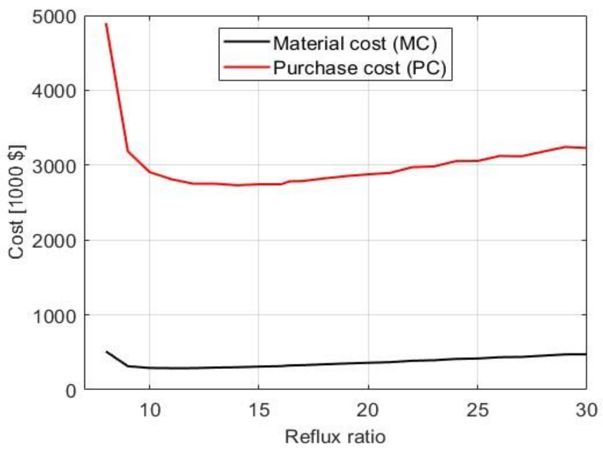

Figure 6. *Relationship between costs and reflux ratio for propane-propylene column*

4. Summary

In this study a propane-propylene rectification column was investigated in the viewpoint of relationship between reflux ratio and material cost. The material of the column is 1.4404 grade austenitic steel. It can be concluded that the optimal reflux ratio value is 12, because in this case the material cost function has a minimum point.

Not only material cost but also purchase cost was studied for the column. During the study the utility cost was not investigated. The purchase cost based on literature correlation and both cost functions have the similar nature. From the results it can be determined that in the investigated reflux ratio interval the total purchase cost of the column is averagely 8.3 times higher than the calculated material cost of the investigated system. The described calculation can be the basis of the cost calculation of the examined system, because cost reduction and optimization play a significant role.

References

[1] Alcántara-Avila, J. R., Gómez-Castro, F. I., Segovia-Hernández, J. G., Sotowa, K. I., Horikawa, T. (2014). Optimal design of cryogenic distillation columns with side heat pumps for the propylene/propane separation. *Chemical Engineering and Processing: Process Intensification*, 82, pp. 112–122. **https://doi.org/10.1016/j.cep.2014.06.006**

[2] Jalali, A., Shafiee, M., Iranshahi, D., Mohammadi, A. H. (2019) *Simulation and energy optimization of a reformate stabilizer unit in a petrochemical plant*. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 42, 1, **https://doi.org/10.1080/15567036.2019.1587058**

[3] Carlson, E. C. (1996), *Don't gamble with physical properties for simulations*. Chemical Engineering Process

[4] Földes P., Fonyó Zs. (1978). *Rektifikálás*. Műszaki Könyvkiadó, Budapest.

[5] Fonyó Zs., Fábry Gy. (1998). *Vegyipari művelettani alapismeretek*. Nemzeti Tankönyvkiadó, Budapest.

[6] Perry, J. H. (2008). *Chemical engineers' handbook*, eighth edition. The McGraw-Hill Companies, Inc.

[7] *UniSim Design*. User Guide (2009), Honeywell.

[8] Jaubert, J., Privat, R. (2010) Relationship between the binary interaction parameters (kij) of the Peng-Robinson and those of the Soave-Redlich-Kwong equations of state: Application to the definition of the PR2SRK model. *Fluid Phase Equilibria*, 25, pp. 26–37. **https://doi.org/10.1016/j.fluid.2010.03.037**

[9] Némethné S. J. (2013) A Vegyipari szimulációs programok működéséhez alkalmazható termodinamikai modellek. *Anyagmérnöki Tudományok*, 38 (1), pp. 231–243.

[10] http://www.estainlesssteel.com/usstainlesssurcharges.shtml (26. 04. 2022).

[11] Douglas, J. M. (1998). *Conceptual design of chemical processes*. McGraw-Hill Book Company.

[12] Camaraza-Medina, Y., Sánchez-Escalona, A. A., Retirado-Mediaceja, Y., García-Morales, O. F. (2020). Use of Air Cooled Condenser in Biomass Power Plants: A Case Study in Cuba. *International Journal of Heat and Technology*, 38 (2), pp. 425–431. **https://doi.org/10.18280/ijht.380218**