Energy Reduction in a Divided Wall Distillation Column

RALUCA ISOPESCU*, ALEXANDRU WOINAROSCHY, LOREDANA DRĂGHICIU
University „Politehnica” of Bucharest, Department of Chemical Engineering, 1-7 Gh. Polizu Str., 011061 Bucharest, Romania

The paper presents the analysis of the thermal efficiency of a dividing wall distillation column and the influence of the feed composition on the reduction of energy consumption compared to a classical scheme of multicomponent mixture separation. The study relays on rigorous simulations in HYSYS^{TM} using thermodynamically equivalent schemes. A case study is presented for the separation of a hydrocarbon mixture: benzene, toluene, ethylbenzene, o-xylene separated in three products in a dividing wall column. The dividing wall column solution led to about 40 % energy saving. The efficiency of a dividing wall column increases when the middle component is in large amount in the feed.

Keywords: divided wall distillation column, energy savings, thermal coupling

Distillation is the most commonly used method for multicomponent mixture separation in chemical and petrochemical industries. The main disadvantage of this operation is its large energy requirements; distillation processes represent more than 40 % of the total energy consumption in these industries. Multiple mixtures separation sequences are generally designed considering some empirical rules that can make the operation more efficient from economical point of view: (a) the light component is separated first, (b) the component in the greatest amount is separated first, (c) the difficult separations are left at the end of the sequence, etc. Considering for instance a mixture of three components, A, B and C, where A is the lightest and C is the heaviest, the separation into pure products is commonly performed using simple column sequencing. For some mixtures, and especially when B is the major component, these solutions are not thermally efficient. The remixing effect that occurs in a conventional distillation sequences is associated with higher energy consumption [1]. In the conventional direct separation sequence the concentration of component B in the first column reaches a high value below the feed stage and then decreases towards the bottom of the column as the concentration of the heavy component increases. In the second column, a supplementary amount of energy is required to concentrate component B as a top product. In a thermally coupled distillation scheme this effect is diminished and a higher efficiency in energy use can be realised. Typical thermally coupled solutions are the side striper, side rectifiers, already in large use in oil refineries, and the Petlyuk column, which is a total thermal coupled solution (fig. 1a). The Petlyuk column is a well-known concept [2] but the practical solution that includes the prefractionater and the main column in a single shell is a new and challenging design option for distillation systems. This solution (figure 1b) represents the dividing wall distillation column (DWC) and it saves both energy and capital costs. A DWC column looks like a common distillation column with a side-draw. In reality it is a column that has a vertical separating wall for a given part of its length, which defines the “prefractionating” region and the “main column” region. The reflux that comes from the condenser will split on both sides of the separating wall and will make the reflux in the two parts of the distillation column. The vapour from the reboiler will also split, in the lower part of the column, in accordance with the liquid split and hydrodynamic conditions on both sides of the dividing wall.

The main advantage of a DWC is that the middle component B splits in the prefractionator section, so that a high composition of B can be reached in the middle product that is drawn out from a given tray on the right hand side of the dividing wall. Assuming that the heat transfer across the dividing wall is negligible, DWC is thermodynamically equivalent to the Petlyuk column. When compared to conventional two-column system a capital cost saving of up to 40% can be expected [3].

To evaluate if DWC is a good solution, the thermodynamic properties of the components and the composition of the feed and products must be considered. Some guidelines are proposed concerning product purity requirements and feed composition.

-Product purity: the purity of the middle product is higer then can be achieved in a simple side draw column. The DWC is a good solution when high purity of the middle product is required;

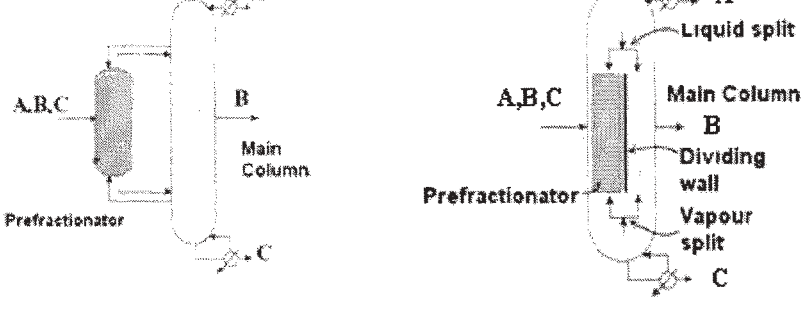

Fig. 1. Fully thermally compled sequence
a) Petlyuk Column
b) Dividing Wall Column

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* email: r_isopescu@chim.upb.ro,

-feed composition: if component B is a major component the energy reduction compared to classical separation schemes is more evident

Mathematical modelling

The mathematical model for a DWC is based on the representation of the complex distillation column by several tray section interconnected by vapour and liquid streams to represent the real flow distribution as in a DWC. Such internal structures can be built out of two, three, four or six column sections [4]. A short-cut design step is required to give an initial reliable solution containing design elements (number of trays, feed and side-draw location) to start a rigorous modeling using HYSYS™ simulator. Several short-cut methods can be used by coupling the specific equations used in the design of simple columns with mass balances equations that describe the interconnection between the tray sections [1, 3, 5]. The short-cut method used in the present work considered Fenske-Underwood-Gilliland model for a three columns equivalent scheme and is implemented in COLOM (software DPI-UMIST). A detailed description of the mathematical model is presented in [3]. Antoine type equations were chosen to represent the liquid-vapor equilibrium for the components considered in the mixture.

HYSYS simulation

The short-cut design was implemented in HYSYS™. A sub – flowsheet was considered to represent the top, the right hand side, the left hand side and the bottom of the column. Applying the subflowsheet facilities, the connection between the tray sections in the DWC are realised without "cutting" the recycle loops and adding a recycle unit to assure the convergence of the final solution. This way, it is not necessary to initialize the internal flowrates, and the refining of the final solution is straightforward. The four-column model, as implemented in HYSYS™ is presented in figure 2. The tray section denoted by "Top" represents the DWC section which is above the dividing wall, the "Prefractionater" corresponds to the left hand side of the dividing wall (fig. 1), the "Side-draw" sections is the tray section placed on the right hand side of the dividing wall while "Bottom" denotes the part of the DWC below the dividing wall.

The structure defined by the DWC has five degrees of freedom, compared to three degrees of freedom for a simple distillation column with a side draw. As mentioned before in literature [7, 8], this gives a larger variety of operational alternatives in the production of specified products but also may increase the difficulty in the design of control schemes. The topology of the simulation scheme was based on the short-cut method design considering also some corrections. The most important one was to set equal the number of trays in the column sections that represent the two sides of the dividing wall in order to ensure the same pressure drop leading to a feasible practical implementation of this structure. During the simulation step the liquid and vapour split are automatically adjusted to reach a convergent steady state solution. The three products' purities can be adjusted by modifying the reflux, the feed and side draw locations. By a trial and error method the feed and side draw locations were fixed to realize the desired separation with minimum energy consumption.

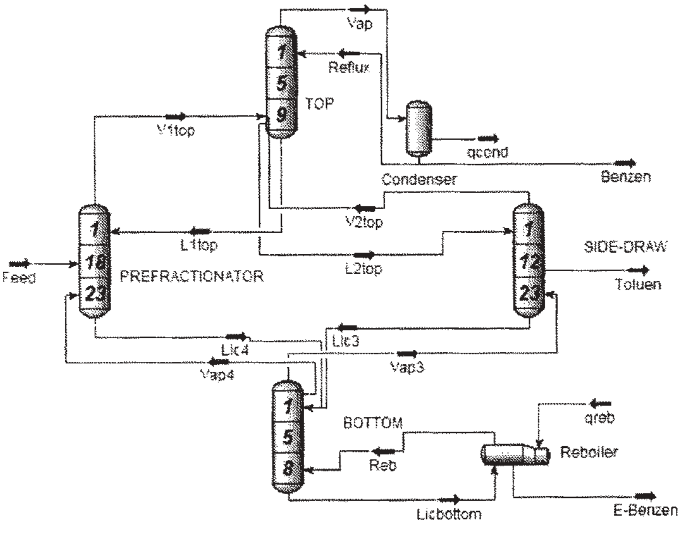

Fig. 2. The four tray sections flowsheet model in HYSYS™

Case study

The present paper studies the possibility of using a DWC for the separation of a hydrocarbon mixture (benzene, toluene, ethylbenzene, *o*-xylene) in three products. The light product contains benzene (> 95 % mol), the middle product is toluene (> 92 % mol) and the heavy product is ethylbenzene and o-xylene (> 95 % mol). The common separation sequence is composed of two distillation columns: the first column separates benzene at the top (column 1 fig. 3) and the second column has toluene as top product (column 2 in figure 3). The working pressures considered are 1.4 bar in the first column and 1.2 bar in the second column. A feed flow of 200 kmole/h was taken as an example. The molar feed composition in this case study is 30 % benzene, 30 % toluene, 10 % ethylbenzene and 30 % o-xylene. Considering the specified products' purities a short cut design for the two columns was easily performed and the structure was then adjusted in the frame of HYSYS™ simulator.

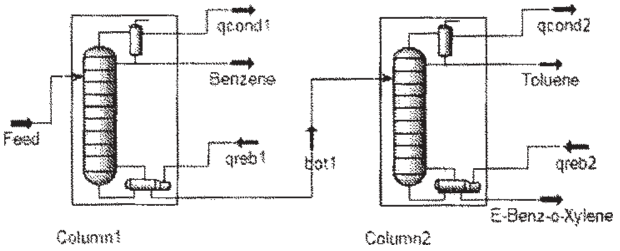

Fig. 3. Separation flowsheet using a classical sequence of simple columns

The molar concentration of toluene in the first column is presented in figure 4 and it reveals the so called "remixing problem" consisting in the increase of toluene concentration from tray 9 (the feed tray) up to 50 % on tray 17, and then decreasing to 40% in the bottom of the column. The second column aims to concentrate toluene in the top and will thus require a greater energy consumption.

The DWC will replace the two columns from the separation scheme. In this case study the feed of the DWC is at 1.4 bar and the composition and flowrate have the same values as in the two columns sequence case.

In order to study the possible influence of feed composition on the thermal efficiency of the DWC, several simulation were done, for variable toluene molar fractions in the feed. The toluene content varied in the range 10 % to 70 % (mol).

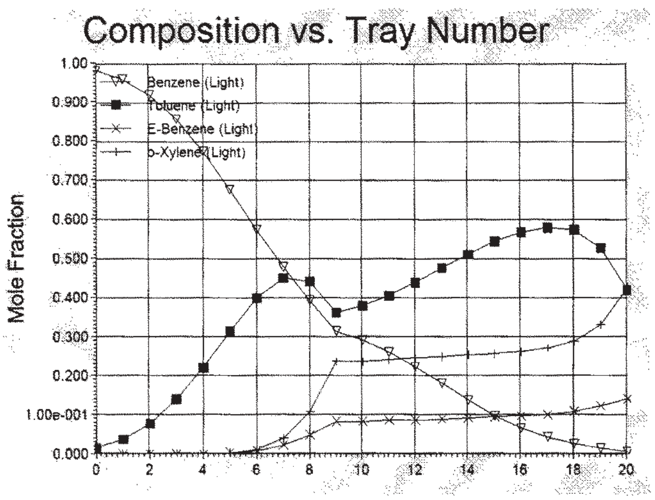

Fig. 4. Composition along the trays in the first column of the sequence

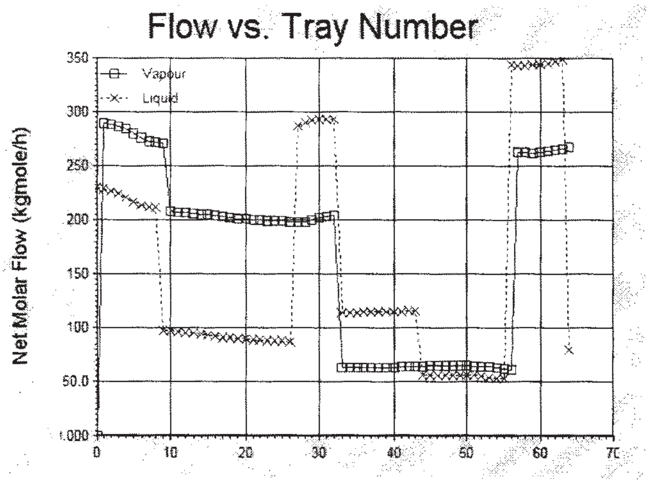

Fig. 5. Molar liquid and vapour flows in the DWC

Results and discussions

Main comparative results between the classical two columns sequence and a DWC are presented in table 1.

For the DWC case, the internal liquid and vapor flowrates are represented in figure 5. The number of trays is considered in a "continuous way" on this diagram. Consequently, trays numbered from 1 to 9 represent the top region, trays number 10 to 32 represent the prefractionator (tray 27 is the feed tray), trays number 33 to 55 correspond to the right hand side of the dividing wall (tray 45 is the side draw location), and the last trays (56 to 63) are the bottom region of the DWC. The liquid flowrate denotes a steep increase with 200 kmole/h on tray 27 corresponding to the feed and a steep decrease on tray 45 due to the side draw. As figure 5 shows, for the convergent solution obtained in the frame of HYSYS$^{\text{TM}}$ simulator, the liquid flowrate on the two sides of the dividing wall are almost equal while the vapour flowrate in the prefractionator is much higher than the vapour flowrate in the right side of the dividing wall. That will correspond to a larger cross section in the prefractionator region. Concerning the variation of composition along the trays of the DWC, the top of the column is characterized by high concentration of benzene (98%), while in the bottom of the column ethylbenzene and o-xylene are over 95 % (fig. 6). The maximum value of toluene concentration is around tray number 45 which is the location of the side draw stream. According to figure 5, the concentration of benzene and toluene increases from the feed position towards the top of the prefractionator (from tray number 27 towards tray 10) while the concentration of toluene and heavy compounds increase towards the bottom of the prefractionator (from tray 27 to tray 31). The distribution of toluene between the top and the bottom region leads to an important energy reduction for the global separation process. As regarding the temperature profile (figure 7), it has larger gradients were the composition varies significantly and is close to the products boiling point at the trays were products draw is located. For our case study, the temperature on trays located on each side of the dividing wall are almost equal (trays 10 to 32 representing the prefractionater, and trays 33 to 55 representing the side draw region respectively). In this case the hypothesis that no heat transfer occurs through the dividing wall is very close to reality.

Energy consumption analysis

The reboiler duty for the DWC is 2457 kW while for the sequence with two simple columns the reboilers duties are 1677 kW for the first column and 1858 kW for the second column which means that a reduction of about 31 % is obtained using the DWC instead of the simple column sequence. The advantages concerning lower energy consumption recommend the DWC for possible retrofit in the oil refineries [5, 6, 9]. A generally accepted disadvantage of the DWC solution concerning the energy consumption is the higher temperature required in the DWC reboiler compared to a two columns system. This issue is linked with the pressure distribution required for a multiple mixture separation. In a two columns system the first column works at a higher pressure to assure a convenient condensation temperature in the condenser, while the second column where the heavy component is obtained can operate at a lower pressure and thus the boiling point in the reboiler is decreased. In a DWC a single operation pressure is defined and, consequently, the boiling point in the reboiler will be higher. This side effect is more pregnant if the light component has a low boiling point that requires high operating pressures. This is the case in light hydrocarbon separation flowsheets [3, 7] were the light components as ethane or butane require high pressure to ensure convenient temperatures in the condenser, while heavier fraction can be separated at

Table 1

COMPARATIVE MAIN RESULTS

	DWC	Two columns sequence	
		Column 1	Column 2
Tray number	40	19	21
Reflux ratio	3.8	2.07	2.31
Reboiler duty, kW	2457	1677	1858
Temperature in the reboiler, C	163.5	135.4	162.5
Product purity	Benzene 98 % Toluene 97% Ethylbenzene +o-xylene 98%	Benzene 99%	Toluene 97% Ethylbenzene +o-xylene 97.8%

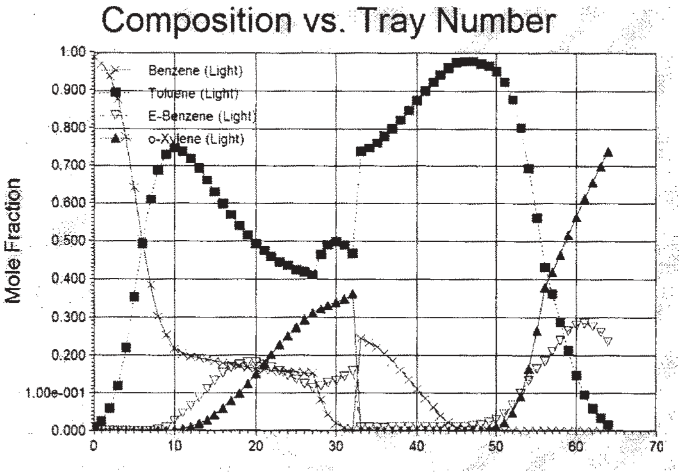

Fig. 6. Component distribution along DWC

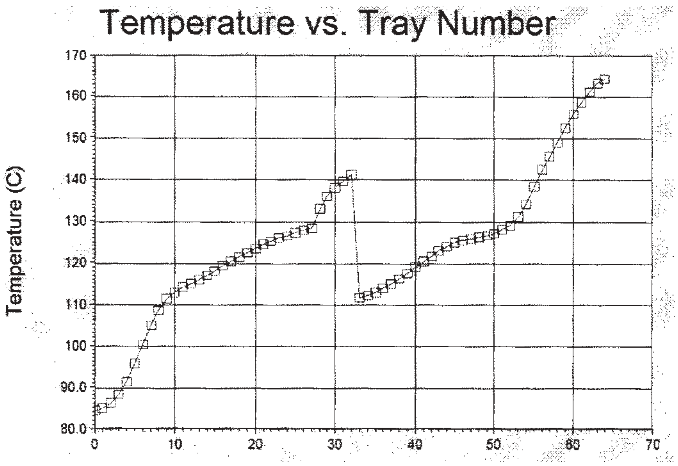

Fig. 7. Temperature profile along the DWC

Table 2

ENERGY REDUCTION FOR A DWC FOR VARIABLE MIDDLE COMPONENT FEED CONCENTRATION

Toluene feed concentration, % (mol)	Reboilers' duty for two colums system, kW	Reboiler duty in a DWC, kW	Energy reduction, %
10	3416	2551	25
20	3160	2480	21
30	3535	2457	30
40	3808	2626	31
50	4423	2852	36
60	4834	2663	45
70	5062	2724	46

lower pressures. In our case study, were the operating pressure is close to the atmospheric pressure, the difference in heavy product boiling point in a simple column sequence and in the DWC is not very important. The fact that all the thermal duty is to be realised with steam corresponding to the boiling temperature of 163.5°C in a DWC, while in the classical system almost half of the reboilers' duty is provided for a boiling point of 135°C will not significantly increase the cost of the steam.

In order to analyse the possible influence of feed composition, upon the thermal efficiency of the DWC, several simulation have been performed by varying the concentration of middle component that has to be concentrated in the side-draw stream which is toluene. The same topology of simple columns and DWC were used and simulations were performed in the framework of HYSYS^{TM} simulator. The results are presented in table 2.

As revealed by table 2, the same general structure of a DWC can be used to separate mixtures of variable feed compositions, while the energy reduction increases with the middle component concentration.

Conclusions

The present work investigates some possibilities to analyse the separation of a multiple mixture using thermal integration and complex columns using short-cut design and a rigorous simulation with HYSYS^{TM}. As results demonstrate, a DWC can be a good solution for reducing the energy consumption. The DWC is more efficient in terms of energy requirement in the case were the middle component is in large amount in the feed stream.

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