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Special theme research article

Improved energy efficiency in debottlenecking using a fully thermally coupled distillation column

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ABSTRACT: Increasing the throughput of an existing distillation process has received considerable attention due to the higher market demand for products derived therefrom. However, this could create a bottleneck in the column. The main objective of this work is to systematically identify bottlenecks in distillation columns and propose a strategy related to dividing wall column (DWC) use for debottlenecking within the column, as well as for energy saving. To optimize the DWC, the internal recycle flow distribution around the dividing wall was investigated as a primary optimizing variable. Several cases were analyzed to show that use of the DWC is a promising method for debottlenecking, as well as investment cost and energy consumption saving. © 2011 Curtin University of Technology and John Wiley & Sons, Ltd.

KEYWORDS: distillation; dividing wall column; debottlenecking; fully thermally coupled distillation column

INTRODUCTION

For ternary separations, either direct or indirect sequences with two conventional columns are typically employed to separate the mixture according to product specifications. Although the control and operation strategy for conventional columns is simple, it is inefficient in terms of energy due to mixing entropy by an irreversible split.[1] Therefore, various strategies have been applied to improve the energy efficiency of such distillation systems. Many studies confirm that the fully thermally coupled distillation system (FTCDS) or the Petlyuk column offers a great chance at reduced energy consumption.[2–6] In the Petlyuk column arrangement, reversible splits are possible and no part of the separation is performed twice, which mainly attributes superior energy efficiency for separation over other column configurations.[7]

Instead of having an external prefractionator, the prefractionator can be incorporated into a single shell arrangement by installing an internal wall, dividing it into the prefractionator and main section, as seen in Fig. 1. This arrangement is referred to as a dividing wall column (DWC), which is conceptually the same as the Petlyuk column given the thermodynamically equivalent arrangements[8] and thus, expected to be similar in terms of energy savings. However, the DWC offers further benefits in terms of capital cost saving. Its single shell feature, single reboiler and condenser can typically reduce capital expenditures by 30% compared to the conventional two-column sequence. But the DWC design is more complex than a simple column because of more degrees of freedom (DFs) that need to be specified. Key variables and parameters, such as number of trays of the column, liquid and vapor splits into each side of dividing wall, feed and side tray locations and dividing wall section must be established. These DFs all interact with each other and need to be optimized simultaneously to obtain the best design. Since the number of stages is an integer variable, column optimization falls into a class of mixed integer nonlinear programming problems (MINLP),[9] which cannot be done within commercially available process simulators. Another main reason for slow acceptance of DWC in the process industry was the fear of expected control-related problems. Substantial work was done in this area and a large number of papers published, addressing mainly three component and products separation. The feedback control of DWCs has been focused.[4] The DWC has five DFs or five manipulated variables: boil up (heat input), reflux ratio, side product rate, vapour and liquid split. Since three DFs are enough to manipulate three controlled variables (process set points), two additional DFs can be used for minimizing operating cost. The most recent contribution is a control structure that is capable of simultaneously controlling all

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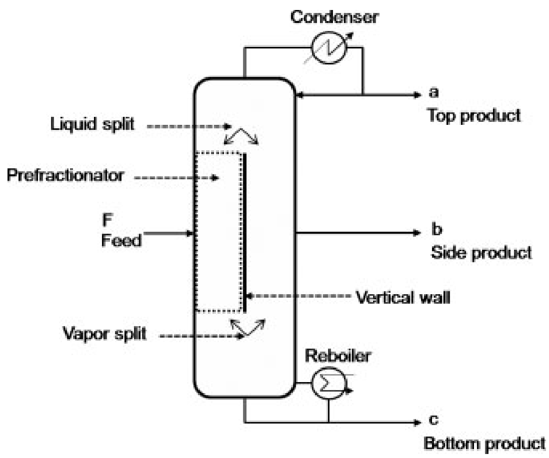

Figure 1. Schematic diagram of a dividing wall column.

three products' compositions and minimizing energy consumption.[10]

In recent years, there has been a great incentive to increase the throughput of the existing process, which causes some challenges related to removal of the flooding phenomenon in the column, as well as improving energy efficiency. It has been estimated that, at the end of the 1980s, 70–80% of capital investment projects in the processing industry were retrofit projects.[11] When the throughput of an existing distillation process is increased, entrainment flooding may create a bottleneck in the column. The goal of retrofit design is to identify and remove such a bottleneck. The main objective of this work is to identify bottlenecks in the distillation process and propose a systematic strategy related to the use of a fully thermally coupled distillation column, including the DWC for debottlenecking within the column, as well as for energy saving. This allows a promising design option to be identified systematically, easily and quickly.

DEBOTTLENECKING METHOD

Definition and assumptions

For an existing distillation process with a given feed composition, there will be a maximum feed flow rate that can be separated to meet some fixed product specifications.[11] The bottleneck of the process is that part of the installed equipment cannot accommodate higher flows than those associated with this maximum feed flow rate. In this case, the column-producing main product may no longer be able to perform as it is required to, or the downcomers in the column may flood, etc.

There are two main approaches that are adopted to the retrofit design of distillation processes for throughput increase:

1. Replacing existing internals with high capacity and/or high efficiency internals
2. Revamping the process by improving the utilization of existing equipment and making relatively minor modifications, including adjusting the operating conditions, adding equipment, etc.

In this paper, the retrofit project purpose is throughput increase to produce the bottleneck problem, with the following assumptions:

1. Throughput increases by 25% over the existing one.
2. Existing columns are already operating with the highest performance internals.
3. Tray flooding, or entrainment flooding, constrains the production capacity of an existing distillation column.
4. All condensers and reboilers are fully utilized.
5. The recovery and purity of main products are kept constant.
6. The operating velocity of all columns is nearly 85% of the flooding velocity.

Most retrofit practices in distillation have emphasized column internals that not only promote separation but also govern the column hydraulic performance.[12] However, using better internals in debottlenecking distillation columns is not the only design option, nor is it always the most cost effective.[11] In some cases, this does not improve the energy efficiency of the system and could subsequently prevent a large increase in capacity.[13] Furthermore, in the case where the column already has a high efficiency internal, the potential for capacity increases by replacing the existing column internal with a new one is very limited.

Configurations explored for debottlenecking

The key to a successful retrofit lies in maximizing utilization of the existing equipments, while simultaneously minimizing the new hardware so as to abbreviate capital costs. It is important to remember that these modifications require plant downtime. In many retrofit projects, downtime is the largest economic factor as it leads to a loss of production and an interruption in product supply to customers.[12] However, this retrofit should be considered based on specific conditions of each particular case, such as component characteristics, operating conditions, number of trays, equipment lifetime, construction material, as well as feed composition. There are some rules for utilizing thermally coupled distillation columns in debottlenecking:

1. DWC could be utilized for retrofitting when the remixing occurs in the conventional column sequence and the intermediate component composition in the feed stream is larger than 30%.
2. When the construction material is different for each column, causing differences in the lifetime, it provides a suitable opportunity to change to a new column in a retrofit, especially a totally new DWC. One of the main ideas is to shift the increased load into the subsequent columns and to have the DWC address the extra load.[14]
3. Since the DWC shows different performances, which depend on the component composition in the feed stream, a new DWC should be rearranged with existing columns to obtain the best arrangement.
4. Integrating columns of largely different operating pressures is found impractical.
5. For sharp separation of n products, adding new columns in parallel with an existing sequence to take care of the extra load is preferred due to a lower feed rate, which subsequently decreases investment cost.
6. DWC should be added in the section having no corrosion phenomenon and low operating pressure to reduce the investment cost or make relatively minor modifications.
7. When the cooling sources in the two columns, including one source coming from refrigeration, are different and the refrigeration cost is quite high, it is not desirable to integrate two columns to one DWC. The top dividing wall column (TDWC) has to be considered.
8. Using a bottom dividing wall column (BDWC) could take advantage of the thermally coupled effect when the temperature difference between the overhead and the bottom of column is small and the heat load is high.
9. If there is more than 50% of intermediate component in the feed, the side-draw that is withdrawn as a liquid from above the feed tray or as a vapor from a tray below the feed tray is utilized depending on the composition of light and heavy components.[15] However, the purity of the side stream product is restricted by thermodynamics and by the nature of the distillation process.[16] Thus, retrofitting the side stream column to the DWC could be promising for saving energy and increasing the purity.
10. When the number of trays in the columns is small or the lifetime of the columns is not much, the complex column arrangements, such as a prefractionator arrangement,[12] a side stripper or a side rectifier, could be proposed for retrofitting. This sequence is much simpler to design, control and operate.
11. Likewise, addition of a new column, such as a postfractionator or a prefractionator, could also provide a process debottlenecking option.[17]
12. The extractive top dividing wall column (ETDWC) could make the separation of an azeotropic mixture feasible and save much energy consumption compared to the conventional two-column sequence.[18]

On the basis of the above-mentioned rules, several potential configurations are proposed as shown in Fig. 2 and evaluated for process debottlenecking, as well as investment and energy savings. These include the following:

- Retrofitting all the existing columns to DWCs
- Retrofitting a part of the sequence to DWC and adding a new DWC in parallel or series
- Rearranging the existing column sequence into a complex arrangement, such as a prefractionator arrangement, a side rectifier and side stripper, and adding a new DWC in parallel or series
- Keeping the existing column sequence and adding a new DWC to handle the increased load
- Keeping the existing column sequence and adding new conventional columns in parallel or series

Hydraulic performance indication and bottleneck phenomenon determination

Column hydraulics, as well as flooding, has to be considered. When the downcomer is small or the downcomer backup is high, downcomer flooding occurs, causing liquid accumulation in the tray above, while the rising of the vapor velocity causes entrainment. To determine the flooding of a particular column, the rating mode is simulated with column internal specifications such as type of trays, column diameter, tray spacing and number of passes.

With the increase in the daily production rate by 25%, firstly a new base is simulated using the old sequence. Consequently, the bottleneck problem could be identified based on the indication of hydraulic performance. The best option to remove the bottleneck problem depends on the particular case and could be determined by evaluating every possible option aforementioned.

Structure design

The shortcut design procedure,[6,8,14] based on the conventional column configuration shown in Fig. 3, was applied for the initial design of the DWC structure. In this conventional configuration, the first column corresponds to the prefractionator section in the DWC. The rectifying section of the second column and the stripping section of the third column represent the top and bottom sections of the DWC, respectively. Both the stripping section of the second column and the

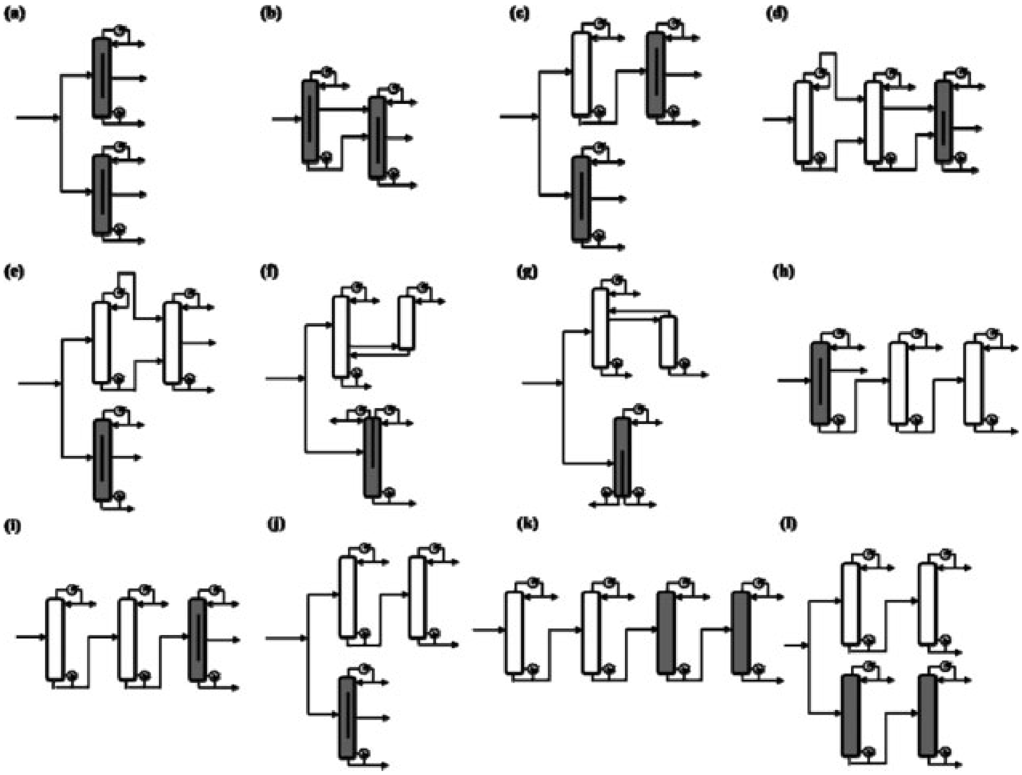

Figure 2. Separation trains explored for debottlenecking a conventional distillation sequence with two columns. All the gray columns are new columns or existing columns retrofitted to a DWC.

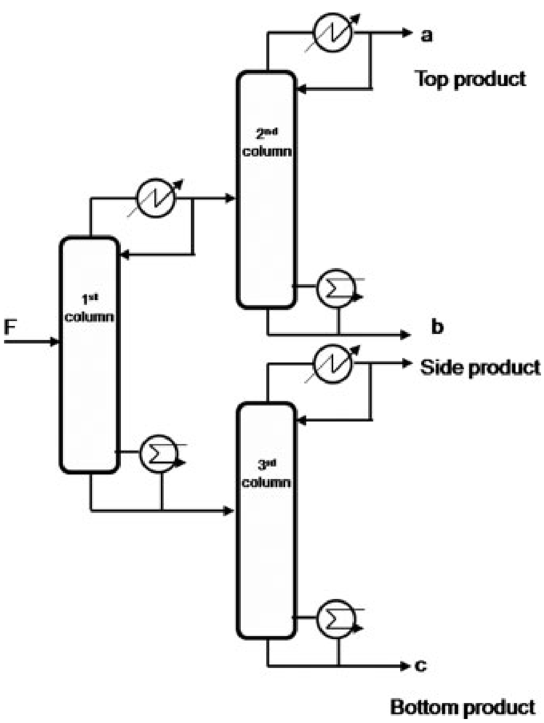

Figure 3. Schematic diagram of a three-column distillation system for initial design of a DWC structure.

rectifying section of the third column were equivalent to the divided wall section of the DWC. Furthermore, both the bottom stream from the second column and the top stream from the third column refer to the side stream of the DWC. Consequently, the structure of the DWC can be divided into four sections: the prefractionator section for the feed mixture, the top and bottom sections above and below the divided wall, and the divided wall section.

Optimization

The total number of trays, feed tray location, side tray location and the dividing wall section were also investigated to establish an optimal DWC structure. For each chosen DWC structure, the internal vapor and liquid flow to the prefractionator were varied to optimize energy consumption, which bears significant influence on overall plant profitability.

All columns were designed with the maximum flooding being nearly 85%, to prevent flooding in the columns. The cross-sectional area of the middle section of the new DWC is the sum of the prefractionator section area and the middle section area of the main fractionator.[14,19] The diameter of the middle section can be calculated from the cross-sectional area of

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the middle section. On the basis of the results of the diameter of the top, middle and bottom sections of the DWC, the largest dimension will be chosen as the diameter of the DWC.

Note that in all the works related to estimation of investment costs, Guthrie's modular method was applied.[20] The investment cost for conventional distillation is the total cost of the column and auxiliary equipment, such as reboiler and condenser, while for the DWC it entails the additional dividing wall cost. In this study, for cost updating, the Chemical Engineering Plant Cost Index of 575.4 was utilized.

CASE STUDY

Natural gas liquid (NGL) recovery process

Existing process

Figure 4 illustrates the existing separation sequence and its current operating conditions. Since the critical temperature of ethane is nearly 32 °C, the deethanizer column requires a refrigerated condenser for producing relatively pure ethane. In order to minimize refrigeration costs, the deethanizer was designed and operated for relatively high pressures of approximately 31 bars. The resulting condenser temperature of approximately 13 °C (for relative pure ethane) is also high enough to preclude formation of hydrates that can plug equipment. The deethanizer column with 18 theoretical stages produces ethane as an overhead vapor stream, which is partially condensed in a condenser. While the depropanizer, possessing 34 theoretical stages, was designed and operated for nearly 18 bars as commercial propane can be condensed with cooling water at this pressure.[21] The feed composition, temperature and pressure are described in Table 1. The simulation work was performed using the simulator Aspen Hysys V7.1. The Peng-Robinson equation of state was used for the prediction of vapor–liquid equilibrium (VLE) of these simulations.[22] Table 2 presents the conditions and product specifications for each column in the existing column sequence. The energy consumption of the deethanizer and depropanizer were 24.91 and 18.52 Gcal/h, respectively.

With the 25% increase in capacity of the process, both the columns were bottlenecked because each column produces its own main products (maximum floodings were 107.11 and 103.92%, respectively). It is not wise to retrofit a deethanizer to a DWC because of the small number of trays. In addition, the retrofit of the depropanizer to DWC, while keeping the deethanizer, is not recommended because the ethane composition in the stream feeding into the retrofitted DWC is small, causing the low energy savings shown in Fig. 5. Furthermore, integrating the deethanizer and depropanizer into a prefractionator arrangement is not preferred, although it is possible to save 20.60% of the

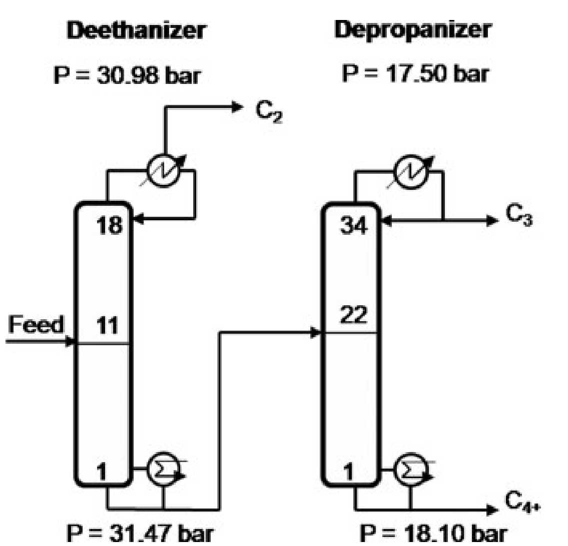

Figure 4. Simplified flow sheet illustrating the existing separation train of deethanizer and depropanizer.

Table 1. Feed conditions of the mixture.

	Feed conditions	
Component	Mass flow (kg/h)	Mole fractions (%)
Methane	991.66	0.86
Ethane	87179.69	40.45
Propane	87268.17	27.61
i-Butane	26803.59	6.43
n-Butane	57180.35	13.72
i-Pentane	20649.83	3.99
n-Pentane	14600.65	2.82
n-Hexane	17559.16	2.84
n-Heptane	9099.56	1.27
Temperature (°C)	55.83	
Pressure (bar)	31.37	

Table 2. Column hydraulics, energy performance and product specifications of the existing column sequence.

	Deethanizer	Depropanizer
Number of trays	18	34
Tray type	Sieve	Sieve
Column diameter (m)	6.2	4.9
Number of flow paths	1	1
Tray spacing (mm)	609.6	609.6
Max flooding (%)	85.99	83.51
Condenser duty (Gcal/h)	12.63	22.40
Reboiler duty (Gcal/h)	24.91	18.52
Purity of C_2 (mole fractions %)	94.43	
Recovery of C_2 (%)	94.58	
Purity of C_3 (mole fractions %)	90.29	
Recovery of C_3 (%)	92.47	

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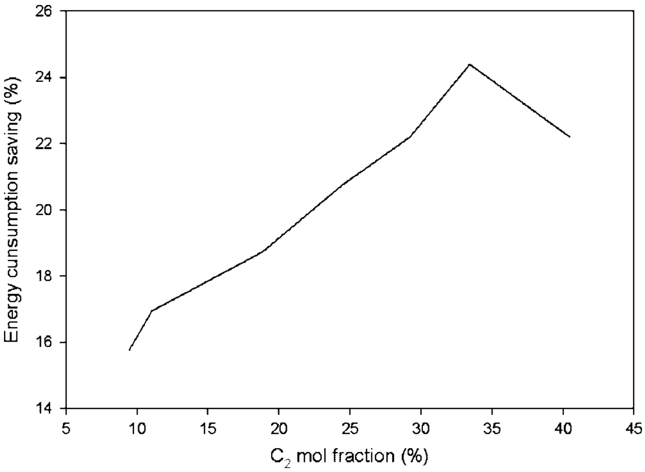

Figure 5. Effects of C_2 mol fraction on the energy consumption savings of the TDWC.

reboiler energy consumption, as it causes an additional high cost refrigeration of 6.11 Gcal/h compared with the conventional sequence. Thus, new columns should be added to achieve the required capacity, recovery and purity. Adding new columns in series could cause significant energy consumption due to a large feed flow rate. Instead, two new columns are added in parallel, or one TDWC is added in parallel to address the load.

Proposed modification

When the capacity is up, adding new columns in parallel and series has to be first considered in order to choose the best sequence. Figure 6a and 6b illustrate the schematic diagram of the separation train showing two new columns added in parallel and in series with an existing sequence, respectively. In the case of multiple main products, adding a new column in parallel is usually preferred because of a smaller feed rate. This tendency can be also seen from investment costs and energy consumption, since adding new columns in parallel are nearly 34.34 and 22.74% lower, respectively, than those in series. However, adding two new conventional columns is not preferred for energy savings and investment costs. Nevertheless, this type of conventional column sequence is considered as a base case to evaluate retrofit efficiency.

In the NGL recovery process, operating pressure is an important factor in processing costs. Increasing the column pressure increases the temperature of the top vapor stream, thus decreasing refrigeration costs. However, it gives rise to the reboiler and condenser duty as well as the thickness of walled vessels with relatively large diameters. Therefore, the optimum pressure of the integrated column is found by balancing the investment and operating costs. It has been discovered that remixing of propane and butane in the bottom of the deethanizer can be eliminated by reducing the deethanizer pressure to match the depropanizer, and by thermally coupling the two columns. It is known that the deethanizer, with a relatively low pressure (~18 bars), requires more refrigeration utilities, but has a much smaller diameter and requires less reboiler duty than one with a relatively high pressure (~31 bars). In addition, the wall thickness, weight and cost of the column will be further reduced because of lower operating pressures.[21] Thus, the DWC, operated at 18 bars, was applied to minimize the investment cost and energy consumption. Furthermore, as the cooling sources in the two columns, including one source coming from refrigeration, are different and the refrigeration cost is quite high, it is not desirable to integrate two columns to one DWC with one condenser. Thus, to decrease the refrigeration cost and investment costs, a TDWC has to be considered. The system in Fig. 7 is built by moving the wall up to the top of the column to separate the column into three sections: one is the prefractionator section for feeding the mixture with its own condenser (C1) to produce ethane; another is the bottom section below the divided wall; the last is the divided wall section with a condenser (C2) to produce propane.

As a result, the refrigeration cost decreases compared with the conventional column sequence. In particular, the TDWC requires less than 0.11 Gcal/h. Furthermore, the condenser (C2) and reboiler duty can save 50.17 and 25.97%, respectively. In addition, the purity and recovery of ethane also increase from 94.43 to 96.39% and 94.58 to 97.35%, respectively, as compared with the conventional column sequence. With a TDWC diameter of 3.0 m, it is possible to save up to 36.60% in investment costs over the conventional column sequence.

Acetic acid purification process

Existing process

Acetic acid (AA) is an important industrial commodity chemical, with many industrial uses and a world demand of nearly 6 million tonnes per year.[23] The preferred industrial method for its manufacture is carbonylation of methanol, accounting for approximately 60% of the total world manufacturing capacity, whereby a mixture of crude AA and contaminants is separated in a series of distillation columns.[24] Figure 8 illustrates the existing AA purification sequence and current operating conditions. The existing system has three valve-trayed columns of 4.2, 2.8 and 3.6 m diameters, with 17, 50 and 65 trays, respectively. The role of the fractionation column is removal of light components and portions of water in the mixture, while treating both water and formic acid (FA), along with propionic acid (PA), are the purpose of the dehydration column and refining column, respectively. In the production of AA, electrochemical corrosion can occur in iodide-containing AA media, damaging the fractionation and dehydration columns.[25] It is thus expedient to use zirconium alloys.[26] In this

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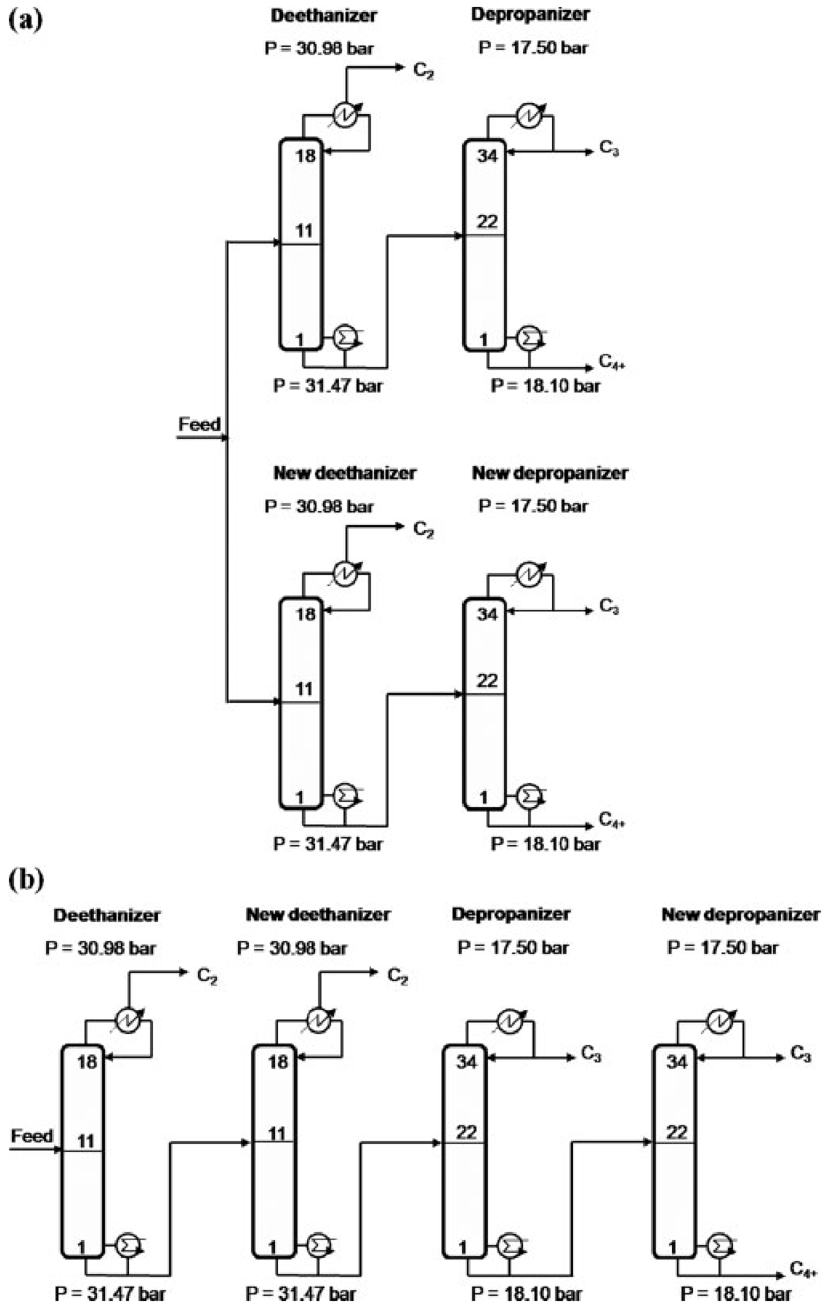

Figure 6. Simplified flow sheet illustrating the separation train showing: (a) four conventional columns, including two new columns added in parallel with the existing sequence; (b) four conventional columns, including two new columns added in series.

design, the fractionation and dehydration columns are constructed of zirconium, while the refining column is constructed of 316SS as almost all iodide ion is removed before entering this column.

The NRTL-HOC property method that uses the Hayden-O'Connell equation of state as the vapor phase model and NRTL for the liquid phase was used for prediction of the VLE of these simulations. The Hayden-O'Connell equation reliably predicts the solvation of polar compounds and dimerization in the vapor phase that occurs with mixtures containing carboxylic acids.[27] It shows that the energy consumption of three columns is 15.67, 11.70 and 17.38 Gcal/h, respectively, when the production rate is 1000 tonne/day AA.

Proposed modification

By shifting the increased load into the subsequent columns, bottleneck problems occur only in the refining column. Note that the bottlenecked column is the column purifying the main product. When the lifetime

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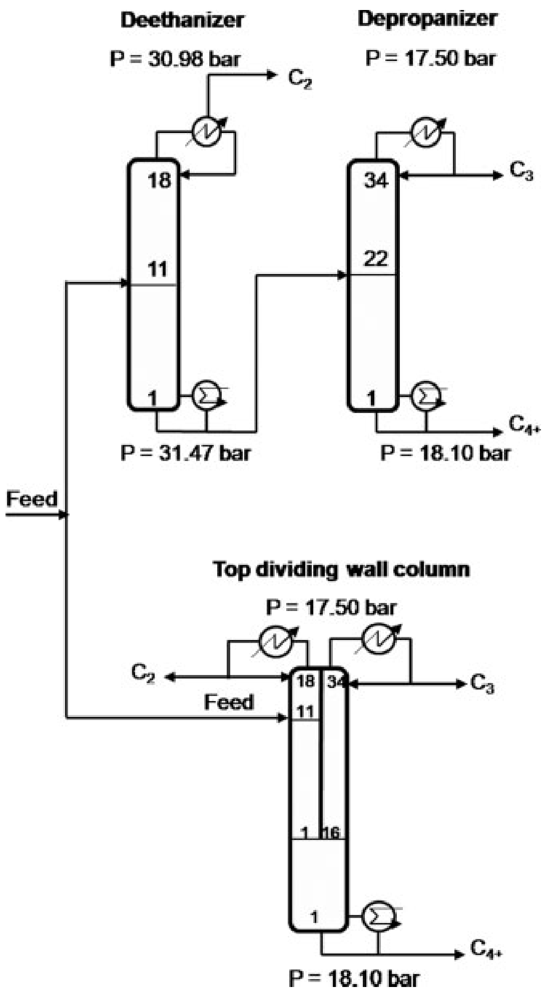

Figure 7. Simplified flow sheet illustrating the separation train, including two conventional columns and one additional TDWC system.

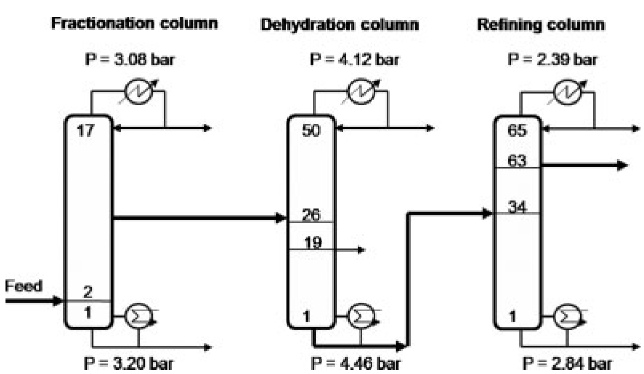

Figure 8. Simplified flow sheet illustrating the existing acetic acid separation train of three conventional columns.

of the refining column still remains, retrofitting this column to the DWC can be used for debottlenecking.[14]

It is important to remember that these modifications require plant downtime, which leads to a loss of production and interruption of product supply to customers. Another important factor is that the refining column material (stainless steel) has a shorter lifetime compared with the fractionation and dehydration column material (zirconium). In this case study, it is assumed that the lifetime of the refining column is almost over. In this case, it provides a suitable opportunity to change to a new column in a retrofit. Figure 9a and 9b illustrate the separation train, added with two conventional distillation columns and one new DWC, respectively. Although both can be utilized for debottlenecking, adding one new DWC into the sequence is preferred because of the saving of both investment and operating costs. Furthermore, savings in terms of space could be obtained by reducing the number of columns, as well as the number of condensers, reboilers, pumps and supports.

With an energy consumption of 21.28 Gcal/h, the DWC system saves up to 37.96% on energy consumption compared with that of the conventional sequence. Moreover, by using one DWC replacing two new columns, it is possible to save up to 31.14% on investment costs over the conventional column sequence.

Methanol–acetone separation process

Existing sequence

The DWC can be applied for debottlenecking of extractive distillation columns employed to separate azeotropic mixtures. In extractive distillation, a heavy component is added to the mixture to increase the relative volatility of the original components.

Acetone and methanol are popular solvents and reagents in organic chemistry. Acetone is extensively used in industry to dissolve plastics, like a drying agent, and is a primary component in nail polish remover. Methanol is also a commonly used solvent, and its mixtures with acetone are usually observed, being necessary to separate these volatile solvents for future applications.[28] The acetone-methanol system has a minimum boiling point azeotrope, and the extractive distillation is a possible method used to separate this azeotropic mixture. The entrainer selection is an important step because the separation effectiveness largely depends on the interactions between this component and the azeotropic mixture.[28–30] Many works have studied the vapor-liquid equilibrium of this system and suggest water as an entrainer.[31–35] The process flow diagram of the existing extractive distillation process is presented in Fig. 10. The process has two columns, one for extractive separation and the other for solvent recuperation. The optimum design had a 57-stage extractive column and a 26-stage methanol column, both operating at 1.01 bar. Note that the solvent is fed to the extractive column on a tray above the feed tray and below the top of the column so that high-purity acetone can be produced in the distillate.[36]

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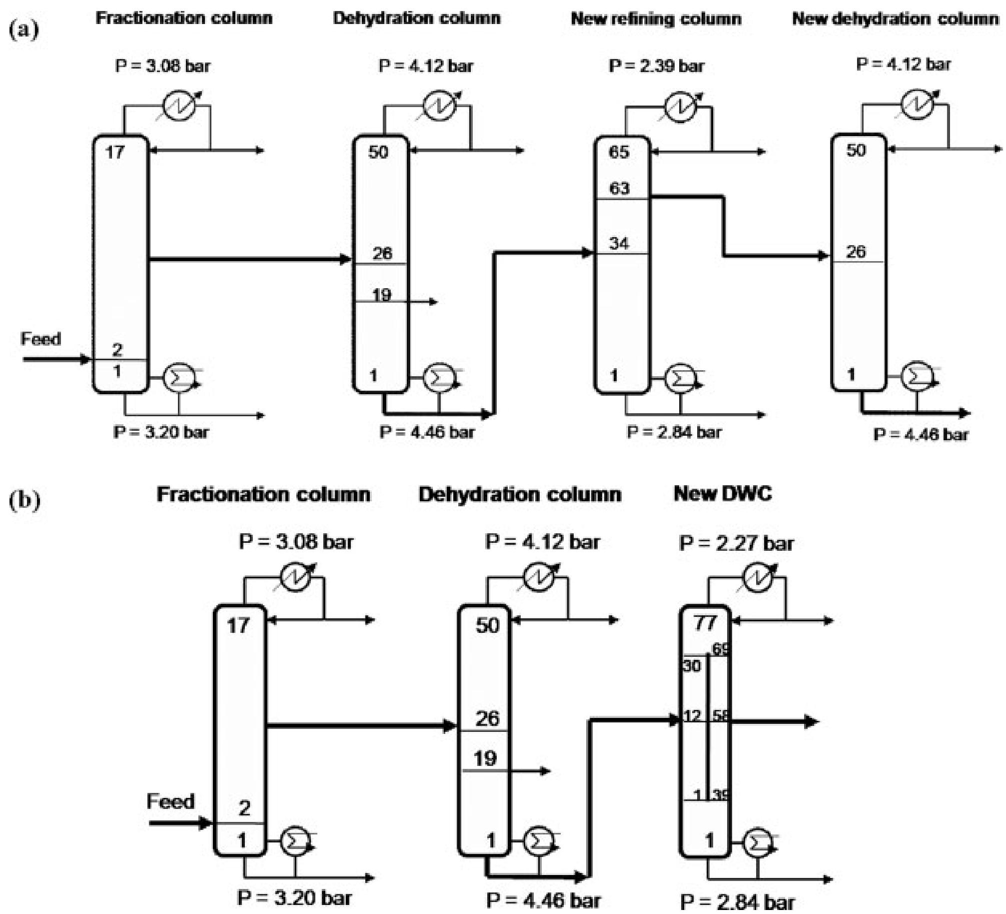

Figure 9. Simplified flow sheet illustrating the separation train showing: (a) four conventional columns, including a new refining column and one new dehydration column added in series; (b) three columns, including one DWC system.

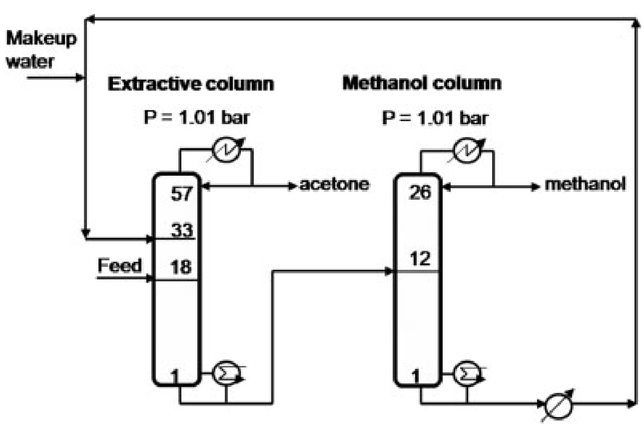

Figure 10. Simplified flow sheet illustrating the existing methanol–acetone separation train of two conventional columns.

The UNIQUAC physical property package is used in this work. To achieve the desired 99.5 mol% acetone purity, the solvent flow rate must be 1100 kmol/h.[36] The results show that it takes 10.33 and 6.13 Gcal/h in extractive and methanol column, respectively.

Proposed modification

Just as with other cases, the process needs to increase production of acetone and methanol by 25% over the existing one. To obtain the desired product, as well as utilize the existing equipment at its maximum, a sequence including two columns is installed in parallel with the others. Figure 11a shows the separation train involving four conventional columns that is applied to separate methanol and acetone. The energy consumption of the two new columns is 2.58 and 1.54 Gcal/h, respectively. This option is considered as a base case.

In the proposed modification, the existing columns are still utilized but integrated as shown in Fig. 11b. Instead of using two new columns to remove the bottleneck in the column, the ETDWC offers a great chance for replacement by reducing investment and operating costs, as well as space. For the ETDWC configuration, the number of trays, feed and solvent tray locations, dividing wall section, solvent/feed ratio and solvent type are considered optimization variables.

By integrating the conventional sequence, as well as adding a new ETDWC, it is possible not only to debottleneck but also save 16.57 and 5.79% in terms of

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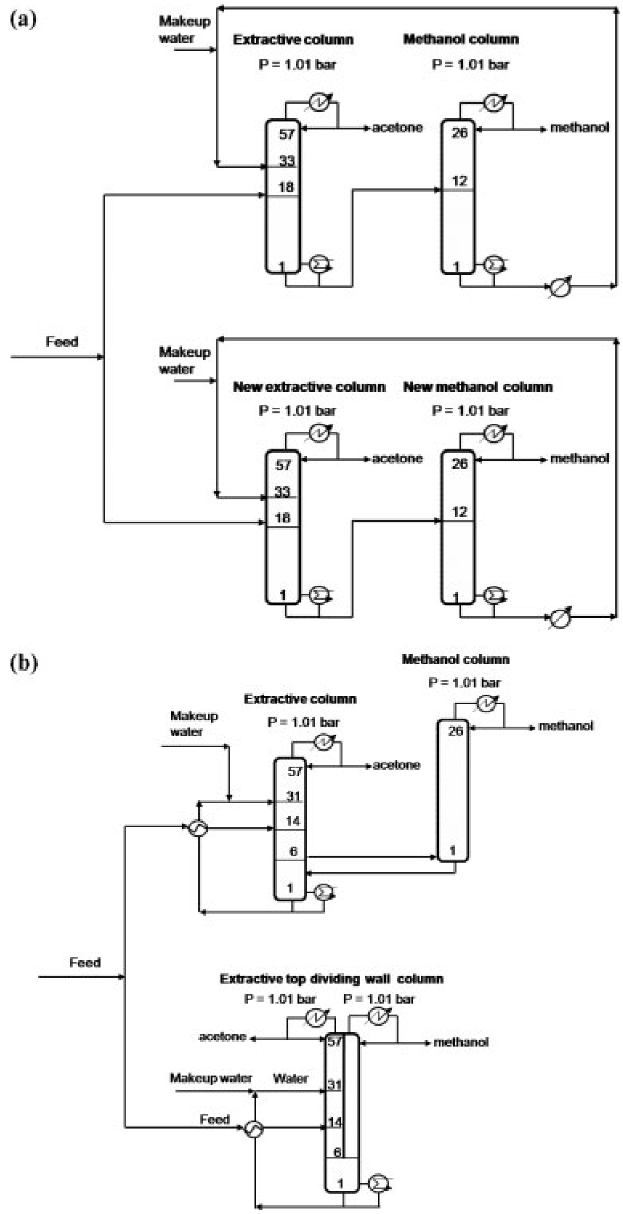

Figure 11. Simplified flow sheet illustrating the separation train showing: (a) four conventional columns, including two new columns added in parallel with the existing sequence; (b) three columns, including integration of two conventional distillation columns and one ETDWC system.

energy consumption and investment costs, respectively. Furthermore, *in lieu* of using a solvent flow rate of 1100.00 and 275.00 kmol/h in the conventional column sequence, it is possible to use a flow rate of 888.60 and 224.70 kmol/h in the retrofitted column with a side rectifier and the ETCWC, respectively.

CONCLUSIONS

Systematic identification and design of column sequences involving the DWC have been considered for removing the column bottleneck problem due to throughput increase. To debottleneck the column, various possible configurations, such as adding new columns, re-arranging the existing column sequence to a complex arrangement, retrofitting the column to a DWC and replacing the existing column with a DWC have to be evaluated based on the specific conditions of each particular case. Operating conditions, construction material, lifetime, component characteristics, separation feasibility, number of trays, as well as the effect of feed composition on the DWC performance need to be considered to determine the best options. The results show that the DWC could give apparent benefits in terms of investment costs, energy consumption and space saving when used to remove the bottleneck problem. The DWC can be applied for debottlenecking in azeotropic separation. By using the ETDWC and integrating the existing columns, not only can energy and investment costs be saved but the entrainer can also be reduced 19.03% compared to a conventional column sequence.

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