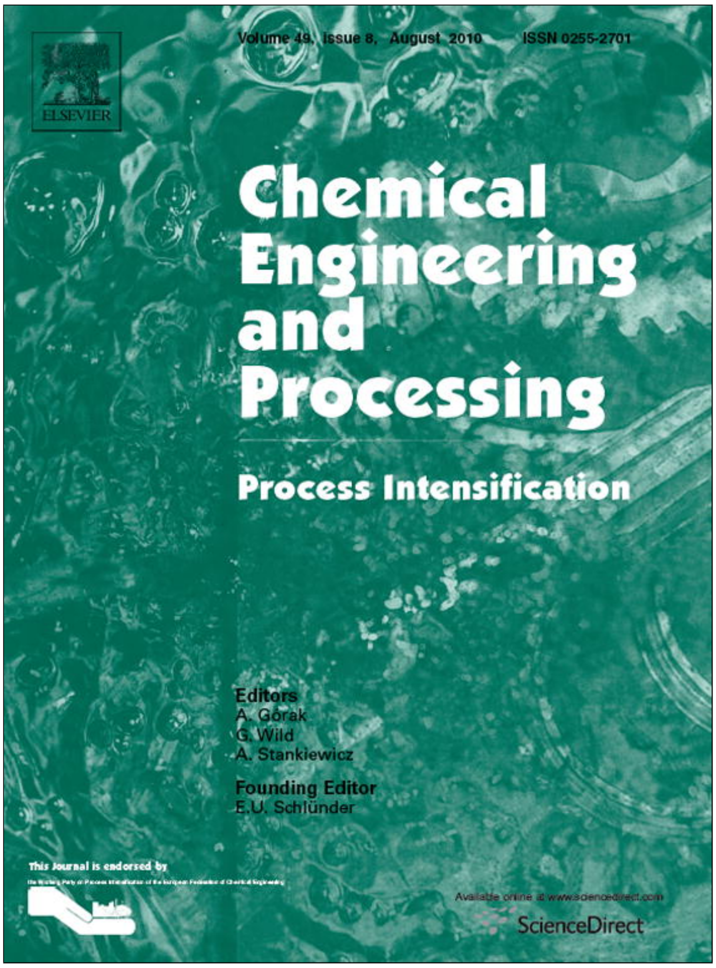
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Design and optimization of a dividing wall column for debottlenecking of the acetic acid purification process

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ABSTRACT

The dividing wall column (DWC) has gained increasing application in a variety of chemical processes because of its potentiality in energy and capital cost savings in multicomponent separations. The main objective in this work is investigation of its use for removing the bottleneck phenomenon within the column when increasing the throughput of an existing distillation process, particularly, the acetic acid (AA) purification process. Optimal column sequence design, involving both conventional and DWC, is considered. The internal recycle flow distribution around the dividing wall was investigated as a primary optimizing variable. Several column arrangements were analyzed to show that the DWC requires less investment and energy costs than conventional distillation, the Petlyuk column, or the prefractionator arrangement.

1. Introduction

It is well-known that distillation plays an important role in the chemical process industries and consumes the largest amount of energy with an estimated 3% of the world's energy consumption [1]. Development of a new type of column and/or performance enhancement of existing distillation processes for improved energy efficiency have been imperative issues associated with distillation [2].

For ternary separations, either the 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 the conventional columns is simple, it is inefficient in terms of energy due to the mixing entropy by irreversible split [3]. Therefore, various strategies have been applied to improve the energy efficiency of such distillation systems. One in particular is thermal coupling, whereby the transfer of heat is achieved by a direct contact of material flow between the columns [4–6]. Many studies confirm that the fully thermally coupled distillation system (FTCDS) or the Petlyuk column offers a great chance at reduced energy consumption [7–11]. In lieu of two condensers and two reboilers as the normal two column sequence, the Petlyuk column has only one condenser and one reboiler due to full integration of the prefractionator and main column, schematically drawn in Fig. 1a. In the Petlyuk column arrangement, reversible splits are possible and no part of the separation is performed twice, which mainly attribute superior energy efficiency for separation over other column configurations [12].

However, the Petlyuk column undergoes strong interactions between the two columns because of their thermal integration, which causes some difficulties in design and operation. To solve this problem, as well as reduce the capital cost, a vertical wall is installed in the central section of the column, dividing it into the prefractionator and the main section, as seen in Fig. 1b. This arrangement is referred to as the dividing wall column (DWC), which is conceptually the same as the Petlyuk column given the thermodynamically equivalent arrangements [6], and more than 90 applications in commercial scale are known [3].

When the throughput of an existing distillation column sequence increases, entrainment flooding may create a bottleneck in the column. The goal of a retrofit design is identification and removal of such bottlenecks [13]. Most retrofit practices in distillation have emphasized column internals that not only promote separation, but also govern the column hydraulic performance [14]. However, using better internals to debottleneck distillation columns is not the only design option, nor is it always the most cost effective [13]. In some cases, this does not improve the energy efficiency of the system and could subsequently prevent a large increase in capacity [15]. 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.

The key to a successful retrofit lies in maximizing utilization of the existing equipment, while simultaneously minimizing the new hardware so as to abbreviate capital costs. Re-arrangement of existing columns to complex column arrangements, such as the

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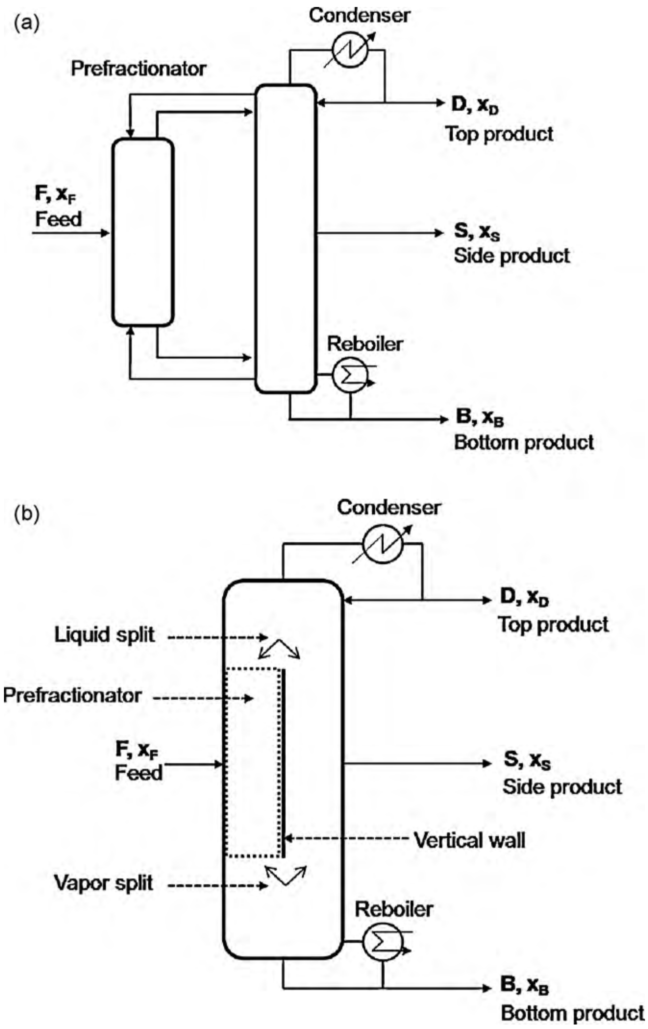

Fig. 1. Schematic diagram of: (a) Petlyuk column and (b) dividing wall column.

Petlyuk column and the prefractionator arrangement, has been proposed for retrofitting [14]. Likewise, addition of a new column, such as a post-fractionator or prefractionator, could also provide a process debottlenecking option [16]. Accordingly, construction material for the new column must be considered, which is related directly to investment cost and corrosion phenomenon. While some modification methods have been successfully proposed to reduce investment and operating costs, it is nevertheless necessary to consider each particular case based on realistic conditions.

The main objective of this work is to introduce how the DWC can be utilized for removing the bottleneck phenomenon as well as improving energy efficiency, particularly, in the acetic acid purification process comprising series of distillation columns when increasing the throughput. One of main ideas is to shift the increased load into the subsequent columns and to have the DWC take care the load. Various possible distillation arrangements as well as the DWC configuration were studied and evaluated to find the best option in a systematic manner.

The shortcut method utilizing a three conventional column configuration was used to find the initial DWC structure in a simple manner. The optimal design of the DWC was considered in terms of the total number of trays, feed tray location, and side tray location, as well as the dividing wall section. In addition, the internal recycle flow distribution around the dividing wall was investigated as the main optimizing variable. The study was performed using Aspen HYSYS V7.1. These results were then compared to the performance of the conventional column sequence and the Petlyuk column, as well as the prefractionator arrangement.

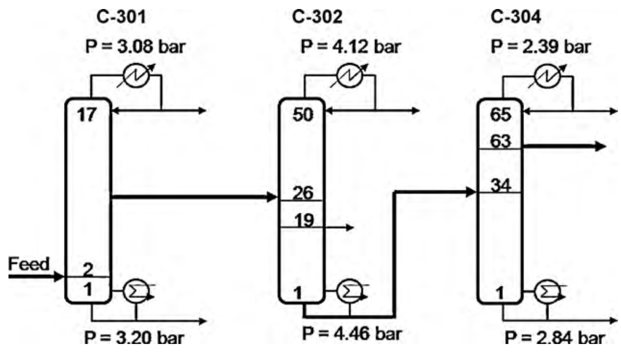

Fig. 2. Simplified flow sheet illustrating the existing separation train of three conventional columns.

1.1. Existing process configuration

Acetic acid (AA) is an important industrial commodity chemical, with many industrial uses and a world demand of nearly six million tonnes per year [17]. 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 [18]. Fig. 2 illustrates the existing distillation column sequence and current operating conditions. The existing system has three valve-trayed columns of 4.4, 3.0, and 3.8 m diameters, with 17, 50, and 65 trays, respectively. The production medium for the acetic acid in the purification stage at 130–200 °C contains up to 16% water, 26% methyl iodize, and other components such as methyl acetate, methanol, hydrogen iodide, formic acid (FA), and propionic acid (PA). The role of the C-301 fractionating column is removal of the light components and portions of water in the mixture, while treating both water and FA, and PA, are the purpose of the C-302 dehydration column and the C-304 refining column, respectively.

In the production of AA, the construction material has to be considered carefully because of corrosion. Usually, nickel–molybdenum alloys (Hastelloy B and Hastelloy B-2) are employed in this very aggressive media for production of synthetic acetic acid. However, equipment made of Hastelloy is subject to enhanced corrosion [19,20]. Electrochemical corrosion can occur in iodide-containing AA media, damaging the fractionation and dehydration columns [21]. It is thus expedient to use zirconium alloys [20]. In this design, the fractionating C-301 and dehydration C-302 are constructed of zirconium, while the refining C-304 is constructed of 316SS as almost all iodide ion is removed before entering this column.

The feed composition, temperature, and pressure are described in Table 1. The simulation work was performed using simulator Aspen HYSYS V7.1. 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 the prediction of the vapor–liquid equilibrium (VLE) of these simulations. Dimerization affects VLE, vapor phase properties, such as enthalpy and density, and liquid phase properties, such as enthalpy. 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 [22]. Table 2 presents the conditions and product specifications for each column in the existing column sequences. From the base case simulation model, it shows that the energy consumption of three columns are 17.39, 13.05, and 19.06 Gcal/h, respectively.

Table 1
Conditions of the feed mixture.

Feed conditions		
Component	Mass flow (kg/h)	Mass fraction (%)
Carbon-monoxide	1105.42	0.60
Hydrogen iodide	36.29	0.02
Methyl iodide	48808.40	26.50
Methyl acetate	3683.21	2.00
Methanol	183.71	0.10
Formic acid (FA)	736.64	0.40
Water	30037.65	16.31
Acetic acid (AA)	98778.92	53.63
Propionic acid (PA)	810.58	0.44
Temperature (°C)	166	
Pressure (bar)	5.50	

1.2. Existing column hydraulics

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 max 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. Table 2 lists parameters necessary to define the existing hydraulic features of the columns. All columns were designed with a load which is at near 85% of the load at the flooding point to prevent flooding in the columns.

2. Increasing daily production

In the retrofit design to increase throughput of distillation processes, existing internals are usually replaced with high capacity or high efficiency internals; the process could also be revamped by improving the utilization of existing equipment and making relatively minor modifications, including adjusting operating conditions and adding equipment [13]. In this paper, the retrofit project purpose is throughput increase to produce the bottleneck problem, with the following assumptions:

a. AA production must increase by 25% over the existing one.
b. The existing columns are already operating with the highest performance internals.
c. All condensers and reboilers are fully utilized.
d. The recovery of AA is kept constant.
e. The operating velocity of all columns is near 85% of the flooding velocity.

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

	C-301	C-302	C-304
Number of trays	17	50	65
Tray type	Valve	Valve	Valve
Column diameter (m)	4.4	3.0	3.8
Number of flow paths	1	1	1
Tray spacing (mm)	609.6	457	457
Max flooding (%)	85.95	84.26	87.03
Condenser duty (Gcal/h)	49.26	25.71	20.01
Reboiler duty (Gcal/h)	17.39	13.05	19.06
Recovery of acetic acid (%)	65.41	80.17	88.77
Purity of acetic acid (%)	82.50	98.92	99.92
FA amount in final product stream (ppm)	580 (<1000 ppm)		
PA amount in final product stream (ppm)	49 (<300 ppm)		
Production rate (ton/day)	1105		

Table 3
Column hydraulics, energy performance, and product specifications upon increasing the AA daily production rate by 25%.

	C-301	C-302	C-304
Number of trays	17	50	65
Tray type	Valve	Valve	Valve
Column diameter (m)	4.4	3.0	3.8
Number of flow paths	1	1	1
Tray spacing (mm)	609.6	457	457
Max flooding (%)	86.30	85.60	103.23
Condenser duty (Gcal/h)	51.56	20.66	25.26
Reboiler duty (Gcal/h)	11.30	7.60	24.39
Recovery of acetic acid (%)	65.41	80.16	88.77
Purity of acetic acid (%)	80.77	96.93	98.44
FA amount in final product stream (ppm)	5522 (>1000 ppm)		
PA amount in final product stream (ppm)	300		
Production rate (ton/day)	1380		

f. Specification of product:
  - FA and water concentration must be less than 1000 ppm.
  - PA concentration is less than 300 ppm.
g. To evaluate the energy saving of the methods compared, the total energy of all columns, except C-301, was used.

With a target production at 1380 ton/day AA, the new base was simulated using the old process configuration, whereby all columns (C-301, C-302, C-304) were utilized to obtain the product. For process simulation, all columns were adjusted for the same recovery of AA for each column and a load which is at near 85% of the load at the flooding point. Table 3 presents the column hydraulics, energy performance, and product specifications when increasing the daily production rate of AA by 25%. Unfortunately, the results show that it is impossible to use the existing column sequence, the reason being that when increasing the throughput, the impurity amount is also concomitantly increased. Columns C-301 and C-302 could not operate sufficiently to remove the contaminants. Therefore, more impurity, including FA, water, and PA, enters refining column C-304, causing not only the amount of FA in the final product stream to be 5522 ppm, significantly higher than the allowable impurity level in the product (must be less than 1000 ppm), but also flooding in C-304 as the column is bottlenecked. The retrofitting opportunity for replacing internals with new ones is excluded in this study since the columns are already operated with the highest performance internals.

Thus, to obtain requirements of product in terms of productivity, recovery, and purity, several potential configurations were proposed for energy saving and process debottlenecking, as shown in Fig. 3. These include re-traying the existing column, adding a new column, re-arranging the existing column into a complex arrangement, retrofitting the existing column to a DWC, and using a new DWC.

Adding a new pre-treatment column upstream of C-302 could be used for debottlenecking. The construction material for pre-treatment must be considered because electrochemical corrosion can occur in iodide-containing AA media. This is economically unfeasible, however, given the costly metals required, particularly zirconium. Hence, adding a new column downstream is preferred.

The combination of two columns to produce a complex arrangement often proves beneficial. Since there is no remixing in C-301, integration of C-301 and C-302 is not a good option, although they are of the same construction material. The other option is combination of C-302 and C-304. However, another problem occurs related to the corrosion phenomenon. The construction material of the column, combined with C-302 to obtain the required product performance, must have a corrosion resistance aptitude. Thus, it is unwise to combine C-302 and C-304 to create either the Petlyuk

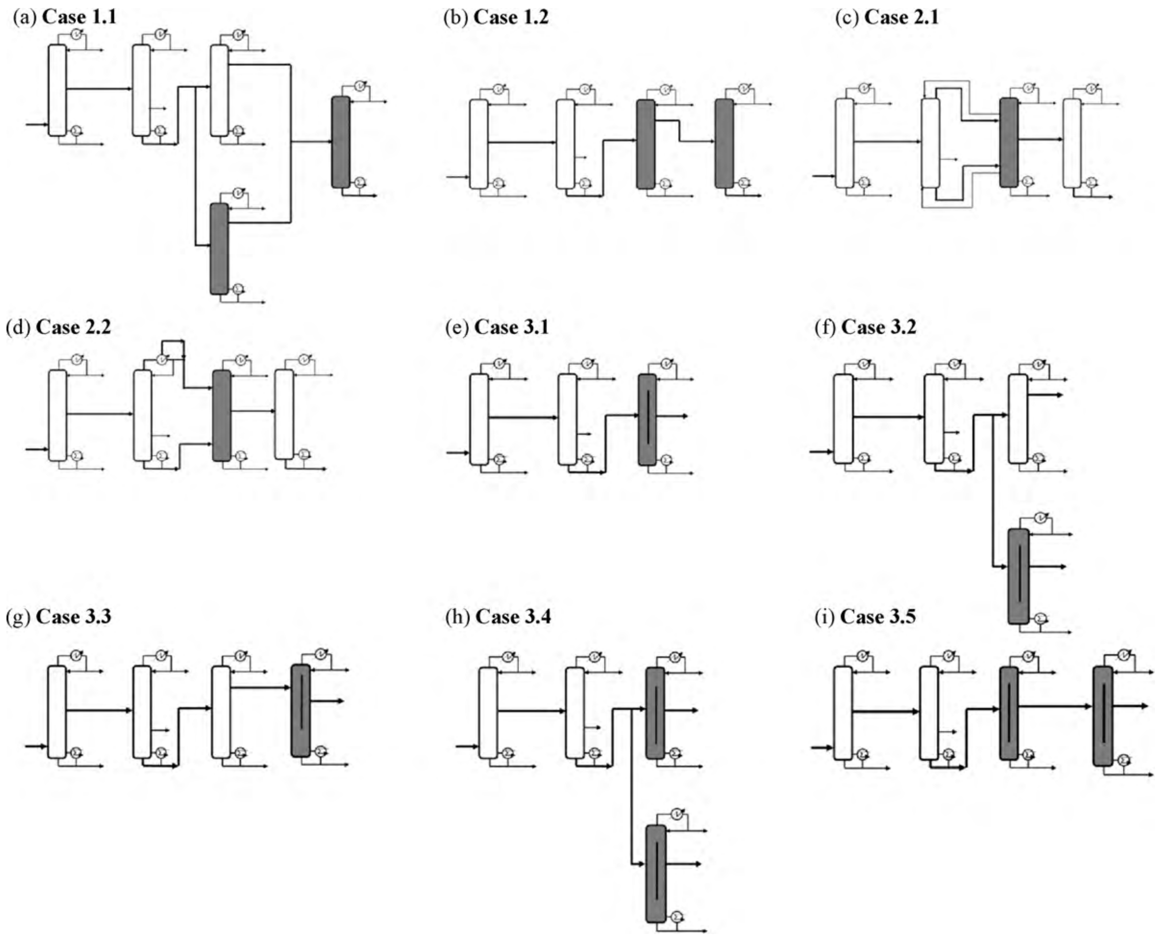

Fig. 3. The nine separation trains explored for column debottlenecking. All the gray columns are new columns or existing columns retrofitted to a DWC.

or prefractionator arrangement. Instead, the new column, the same material as C-302, is added. However, this option may require significant investment costs. In this study, the complex systems were investigated to compare with other cases.

Fortunately, because the iodide ion is almost completely removed by the C-301 and C-302 columns, the existing C-304 or new additional columns can be constructed with stainless steel 316SS, except for the new additional column, which is combined with C-302 to produce the complex arrangement.

Note that in the whole of works related to estimation of investment costs, Guthrie's modular method was applied [23]. The investment cost for conventional distillation is the total cost of the column and the 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.

The cost of energy consumption depends on the temperature. Since the temperatures on the bottom section of the columns for various configurations were similar enough, the analysis based on the energy consumption still leads to acceptable comparison of these configurations and can be considered as a good index for annual cost.

3. Proposed modifications

3.1. Conventional column sequence

3.1.1. Case 1.1 – adding two new columns

To obtain the required product performance, the conventional column sequence is first investigated, thoroughly utilizing the old system. In order to increase throughput, the max flooding of each column, as well as acetic acid recovery, needs to be kept constant. Fig. 4a shows the separation train involving five conventional columns that is applied to purify AA from contaminants when C-304 is bottlenecked. Note that the purpose of column C-306 is to remove FA and water. Adding two new conventional distillation columns can be utilized for process debottlenecking; however, it is not preferred for saving on energy and investment costs. Nevertheless, this case is considered as the base case to evaluate retrofitting efficiency when exploitation of C-304 is continued.

3.1.2. Case 1.2 – replacing C-304 and adding one new column

The retrofit of an existing plant is usually carried out after the starting time for some of the objectives, such as process debottlenecking, in order to increase capacity or energy savings. Replacement of the existing column can be a good option when the lifetime of the column is over or little time remains on it. Hence, for obtaining the required product performance, another conventional column sequence is investigated, one which replaces C-304 with a new column possessing a larger diameter and adds one more column C-306. Fig. 4b shows the separation train, involving four conventional columns, employed to purify acetic acid from contaminants when C-304 is bottlenecked. All new columns were based upon the optimal design. This case is considered a base case for comparison with others when C-304 is replaced with a new column. Based upon the simulation, the new column (diameter of 4.3 m) is used to replace C-304, while another column C-306 (diameter of 2.9 m) is required to remove the water and FA. The energy consumption of the two new columns is 24.45 and 13.97 Gcal/h,

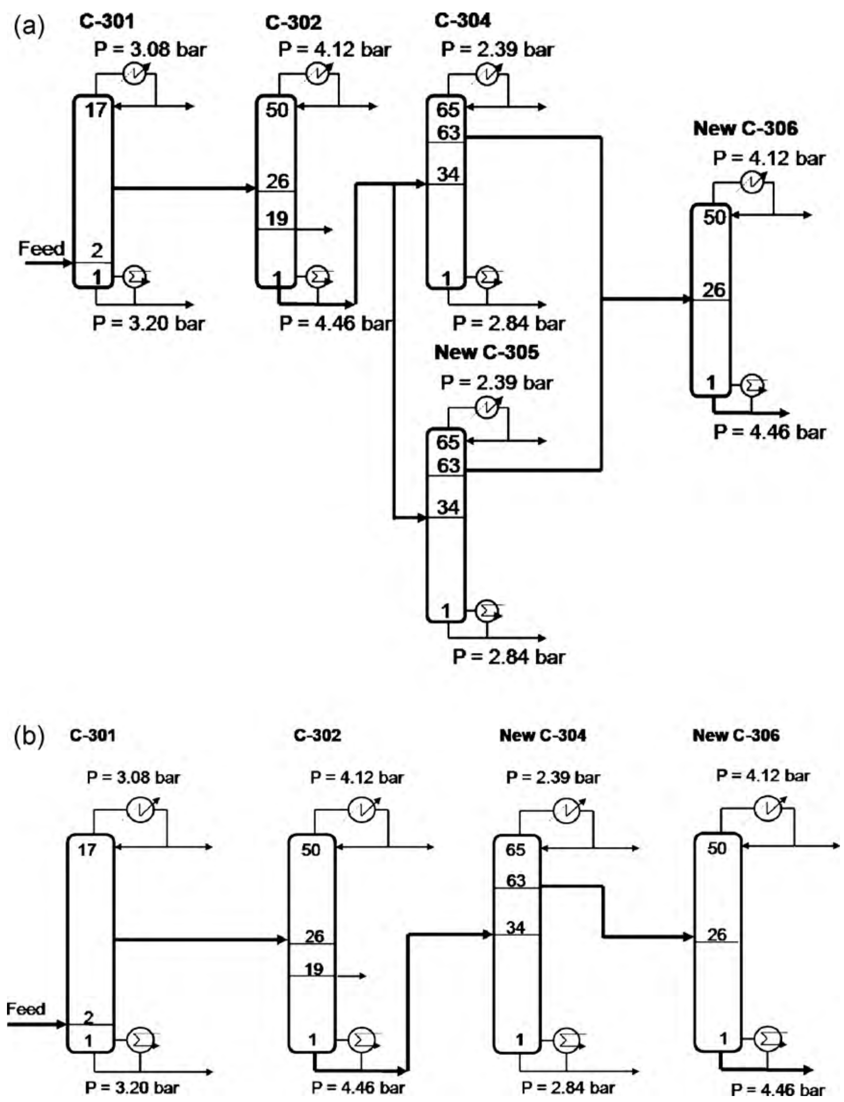

Fig. 4. Simplified flow sheet illustrating the separation train showing: (a) five conventional columns, including one new column added in parallel with C-304 and another added in series and (b) four conventional columns, including a new C-304 and one new column added in series.

respectively. This option can be utilized for process debottlenecking; however, it is not preferred for saving on energy.

3.2. Re-arranging the existing column into a complex arrangement

3.2.1. Case 2.1 – re-arranging the existing column into a Petlyuk column arrangement

Some authors [14,24] have proposed the Petlyuk column configuration, equivalent to the dividing wall column, as a route to take advantage of the two existing columns. With this arrangement, the column with fewer trays becomes a prefractionator while the other acts as the main column. However, this can be applied when the two existing columns are of the same construction material. Unfortunately, those of C-302 and C-304 are different, the former being made of zirconium and the latter stainless steel. Hence, a new zirconium-column was added to combine with the C-302 to produce a Petlyuk column arrangement whose side stream enters the C-304 to remove FA and water, as shown in Fig. 5a. Furthermore, a new condenser and reboiler, constructed of zirconium, were required as they are bottlenecked. With this new configuration it was possible to save 28.0% on energy consumption when compared to the conventional column sequence (case 1.1). However, even if only one new column was added, the investment cost was almost 4.1 times higher than the conventional column sequence case due to such expensive material. In addition, the Petlyuk column arrangement is not recommended in practice as it possesses strong interactions between the two columns that can cause some difficulties in the design and operation.

3.2.2. Case 2.2 – re-arranging the existing column into a prefractionator arrangement

A prefractionator arrangement was also studied for a retrofit. By adding one new column constructed of zirconium, the prefractionator arrangement can be produced. This prefractionator arrangement takes advantage of control and operation, whereby control of the external flows from the reboiler and condenser of C-302 is facile. The prefractionator configuration is advantageous to conventional distillation schemes and shows a better energy performance [14].

The design of the prefractionator arrangement is shown in Fig. 5b. Rigorous simulation based on the equilibrium-stage model was performed for this arrangement by adjusting the flow of AA in the bottom stream of the C-302, as well as the feed tray location of the new column, to maximize use of the existing column and minimize the size of the new column and total energy consumption

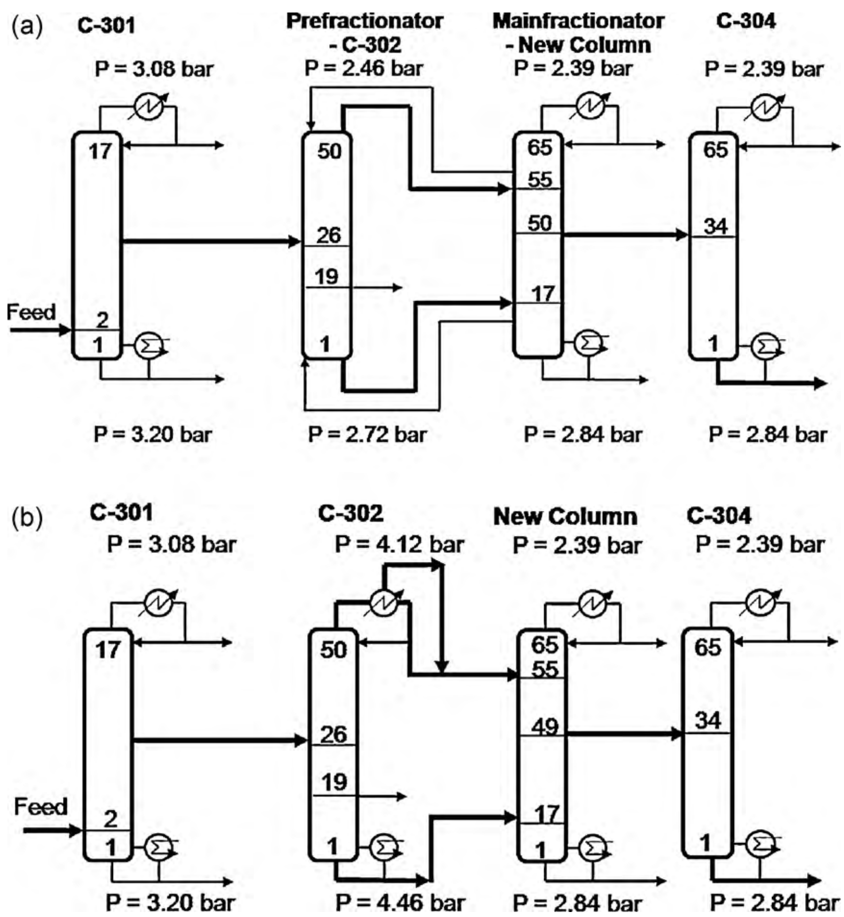

Fig. 5. Simplified flow sheet illustrating the separation train, including: (a) the Petlyuk arrangement and (b) the prefractionator arrangement by adding a new column.

of the system. The energy savings evaluated from this arrangement were 26.4% compared to the conventional column sequence (case 1.1). However, investment in new columns is costly, nearly 3.9 times more when compared to the conventional sequence. As such, the prefractionator arrangement bears some advantages in terms of investment costs compared to the Petlyuk system due to utilization of the condenser and reboiler in the C-302. In turn, the required condenser and reboiler in the main column become smaller than those in the Petlyuk system. The condenser type here is a partial condenser, with a liquid stream entering the new column. For a more thermodynamically equivalent set up compared to the Petlyuk system, a type of full reflux condenser, in which all liquid from the overhead receiver is refluxed back to the C-302 while only vapor product from the reflux drum enters into the new column, is applied in the prefractionator C-302. As a result, the prefractionator arrangement and Petlyuk system show similar advantages in energy savings at 27.7 and 28.0%, respectively. Nevertheless, this option remains unfavorable due to the high investment costs for new column material.

3.3. Debottlenecking using dividing wall column

Several cases were investigated using the dividing wall column for retrofit.

3.3.1. Case 3.1 – replacing the two new columns with a new DWC

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 interruption of product supply to customers [14]. Another important factor is that the C-304 material (stainless steel) has a shorter lifetime compared to the C-301 and C-302 material (zirconium). When the lifetime is almost over, it provides a suitable opportunity to change to a new column in a retrofit, especially a totally new DWC. Fig. 6 illustrates the separation train, including two conventional distillation columns and one DWC. This option is attractive due to the saving of investment and operating costs. Furthermore, savings in terms of space could be obtained by reducing the numbers of columns, as well as the numbers of condensers, reboilers, pumps, and supports.

For the initial design of the DWC structure, it was applied the shortcut design procedure [6,25] based on the conventional column

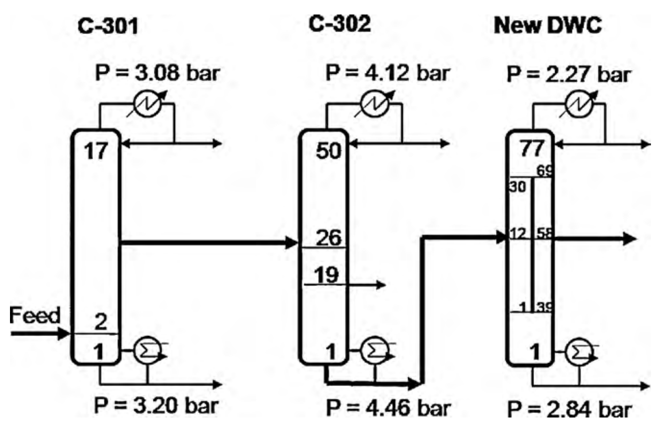

Fig. 6. Simplified flow sheet illustrating the separation train, including a two conventional column distillation and one DWC system.

configuration shown in Fig. 7. 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 rectifying section of the third column are 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 [25]. 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; the divided wall section.

As mentioned previously, the main concern of the DWC application was not only to debottleneck the column, but also save on energy consumption and investment costs. Therefore, the design of the dividing wall column will be described in detail. After the DWC structure design procedure, the internal recycle flows to the prefractionator were optimized as shown in Fig. 8a. The circle symbol is the optimal point. Then, the total numbers of trays, feed tray location, side tray location, as well as the dividing wall section, were also investigated to establish an optimal DWC structure. For each chosen number of trays, feed and side tray location, and dividing wall section, the internal vapor and liquid flow to the prefractionator were varied to optimize energy consumption, which bears significant influence on overall plant profitability.

Fig. 8b shows the effect of the tray number on the reboiler duty. It is clearly seen that reboiler duty rapidly decreases when the number of trays increases from 71 to 75, and slightly decreases when

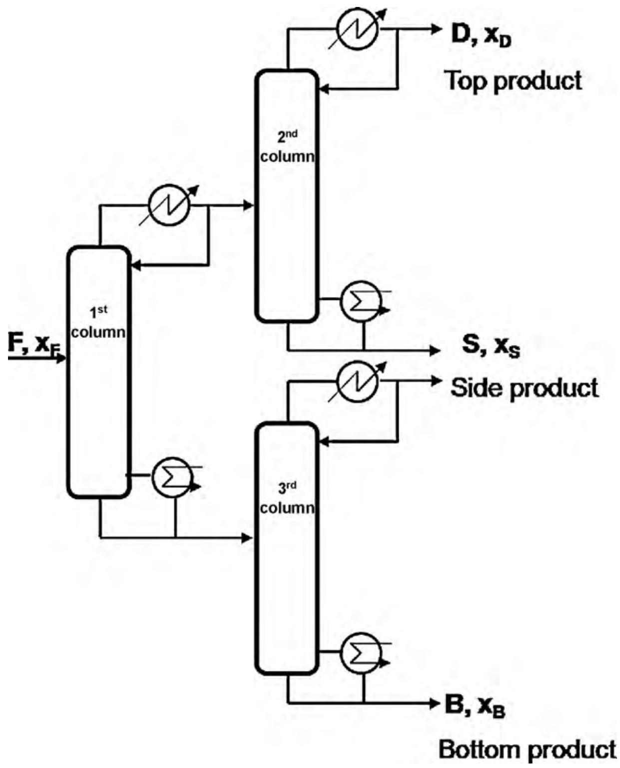

Fig. 7. Schematic diagram of a three-column distillation system for initial design of DWC structure.

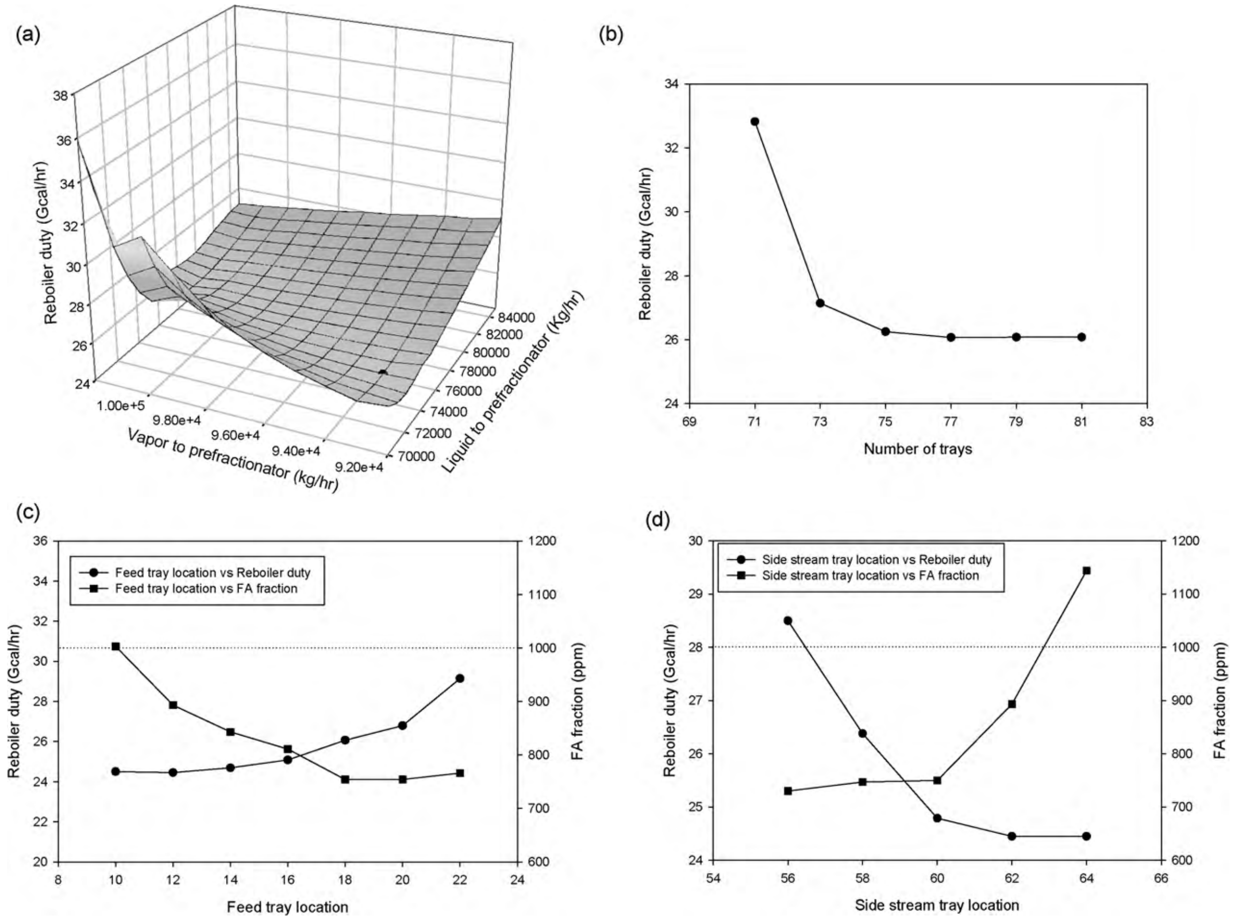

Fig. 8. Effects of: (a) liquid and vapor flow into the prefractionator section; (b) the number of trays of the main fractionator; (c) the feed tray location; and (d) the side tray location on the reboiler duty of the DWC.

Table 4
Effects of the dividing wall section on the reboiler duty of the DWC.

Dividing wall section	(35, 65)	(37, 67)	(39, 69)	(41, 71)	(43, 73)	(45, 75)
Reboiler duty (Gcal/h)	24.28	23.91	23.91	23.93	24.45	24.68
FA fraction (ppmw)	712	714	711	780	893	1149

Table 5
Diameter of the DWC for a required maximum flooding.

	Prefractionator	Mainfractionator (middle)	DWC (middle)	DWC (top)	DWC (bottom)	DWC
Diameter (m)	2.4	3.2	4.0	4.0	4.0	4.0
Max flooding (%)	83.30	82.31		85.11	84.79	
Position of section		40th tray–69th tray		70th tray–79th tray	1st tray–39th tray	

it increases from 75 to 77. Then, the reboiler duty remains stable when the number of trays continues to increase. Therefore, 77 trays were employed in the design of the DWC.

In an optimal distillation design, the composition of the feed tray was required to be close to the feed composition in order to eliminate irreversible mixing at the feed tray [26]. To examine the effects of the feed tray on energy consumption, a number of simulation runs were carried out by varying the feed tray location from the 10th tray to the 22nd tray. As seen in Fig. 8c, the feed must be fed into the 12th tray to achieve the lowest reboiler duty and meet the required product specifications in terms of impurity concentration.

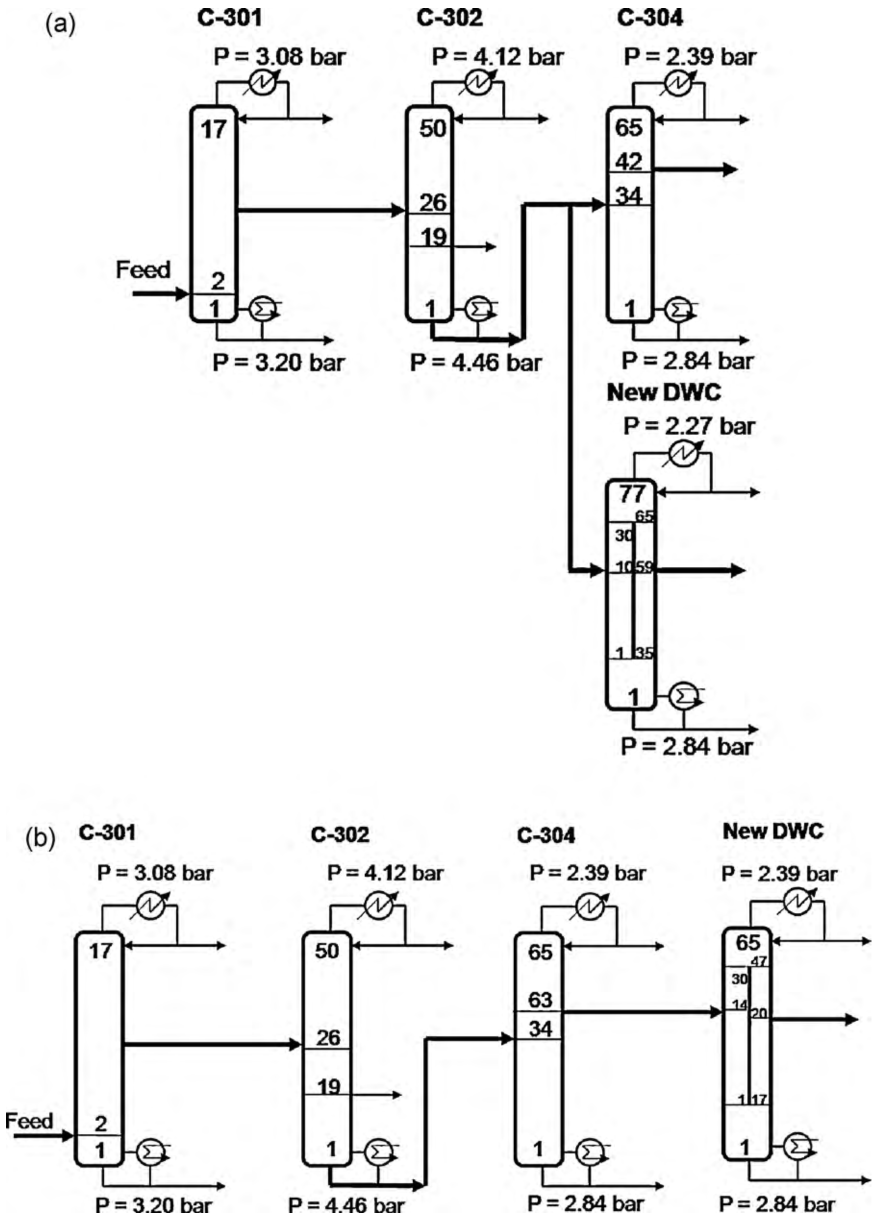

Fig. 9. Simplified flow sheet illustrating the separation train, showing four columns, including the additional DWC: (a) parallel with C-304 and (b) in the series.

Similarly, the side tray location and dividing section were also examined to find out the optimal structure of the DWC. Fig. 8d and Table 4 show the effects of the side tray location and dividing section, respectively. According to the simulation results, the liquid split ratio (R_L) and vapor split ratio (R_V) were 2.42 and 1.68, respectively. By this sequence, the FA and PA concentrations were 711 and 300 ppm, respectively. With an energy consumption of 23.91 Gcal/h, the DWC system saves up to 37.8% on energy consumption compared to conventional sequences (case 1.2).

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. The diameter of the middle section can be calculated from the cross-sectional area of the middle section. Table 5 shows the diameter of the top, middle, and bottom sections of the DWC. Based on the results in Table 5, a length of 4.0 m was chosen as the diameter of the DWC. With this, it is possible to save up to 31.0% on investment costs over the conventional column sequence.

3.3.2. Case 3.2 – re-traying C-304 and adding a new DWC in parallel with C-304

Instead of adding two new columns (C-305 and C-306), another option, including re-traying C-304 and adding a new DWC in parallel with C-304, was studied. Herein, the DWC was employed primarily to debottleneck the distillation column and fully employ the existing columns. As shown in Fig. 9a, the bottom stream of C-302 was divided into two streams. The first was pumped to C-304 for purification of the acetic acid to obtain the required impurities concentration. The existing C-304 is generally not optimize and thus needs to be. The side stream location is varied to achieve the lowest reboiler duty and satisfy the fixed maximum flooding. The second divided stream enters the new dividing wall column, parallel with C-304. Due to the large energy consumption of the conventional C-304, the overall energy saving is minimal, 6.2%. However, an extra 3.8% of investment cost is required compared with the conventional column sequence. One interesting point is that C-304 is fully utilized in this case. Reducing the feed rate of C-304 decreases total energy consumption, and until that value is

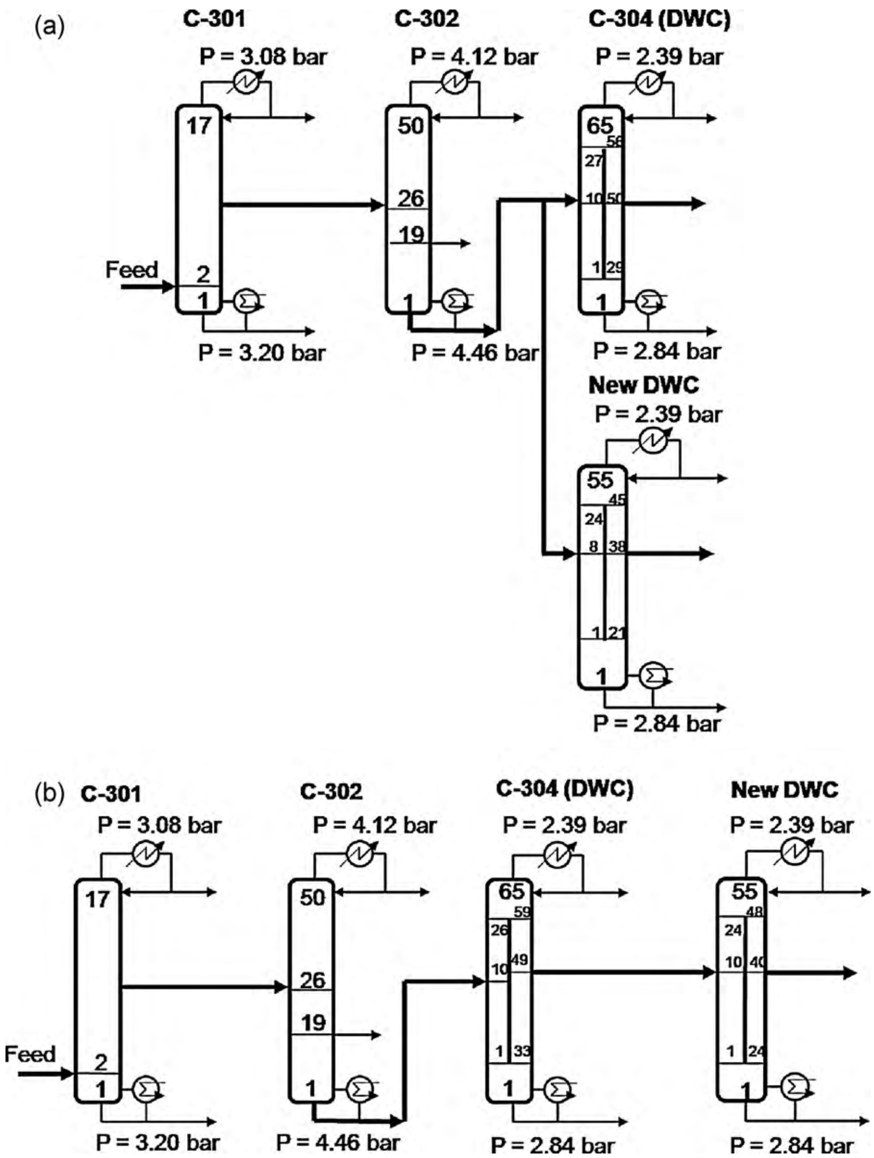

Fig. 10. Simplified flow sheet illustrating the separation train showing: (a) two conventional distillation columns and two DWC systems, including one from retrofitting C-304 and one new DWC, parallel with the C-304 and (b) two conventional distillation columns and two DWC systems, including one from retrofitting C-304 and one new DWC in series.

zero, case 3.2 approaches case 3.1, where C-304 is replaced by a new DWC. However, decreasing the feed rate into C-304, such as increasing the feed rate into the new DWC, gives increased investment costs. Therefore, the optimum feed rate ratio is ascertained by balancing investment and operation costs, demonstrating that maximizing utilization of the existing equipment is not always the best solution. To debottleneck the column, it is necessary to consider the whole process, including column internal, column hydraulics, operating conditions, equipment lifetime, construction material, and feasibility of a combination of columns to make a complex re-arrangement and retrofit to the DWC.

3.3.3. Case 3.3 – adding a new DWC in series

In the literature, there is little data regarding the influence and comparison of energy consumption by adding new columns in parallel/series with an existing column. Thus, to debottleneck the column, another option, adding a new DWC in series, is employed and shown in Fig. 9b. Case 3.3 brings the respective savings up to 33.4 and 15.0% in investment and operating costs. From this, adding a new DWC in series with a conventional column sequence is better than adding in parallel with an existing sequence. In fact, in the case of adding a new DWC in parallel, it requires extensive energy to purify the AA in the 3-products-conventional C-304 due to increased impurity. Furthermore, because of the upper limitation of the maximum flooding in the column and to achieve the required product purity, C-304 can treat about 1/5 of the bottom flow of C-302, while the remaining 4/5 of that stream enters the new DWC. For increased savings on investment costs, as well as operating costs, retrofitting of C-304 to the DWC must be considered.

3.3.4. Case 3.4 – retrofitting C-304 to a DWC and adding a new parallel DWC

In this section, the option of retrofitting C-304 to a DWC and adding a new DWC in parallel with a C-304, schematically drawn in Fig. 10a, is considered. Here, the existing C-304 from the process can be retrofitted to a DWC to separate a portion of the bottom stream of C-302; the remaining flow is then fed into the new DWC. The C-304 is now modified by adding a wall in the middle section while maintaining the same number of trays. The existing reboiler and condenser should be checked to verify reuse or not.

For retrofitting this column, the operating velocity was fixed at 85% of the flooding velocity. The existing reboiler and condenser can be re-used as their duties are 19.87 and 20.40 Gcal/h, respectively. Thus, only the additional wall was counted for in retrofitting C-304 to the DWC. As a result, the existing columns were maximally utilized and new capital expenditures minimized.

After the design and optimization procedures, the new DWC in parallel had 55 stages. Moreover, the feed stage of the DWC was the eighth stage and the divided wall was located from the 21st to the 45th stage, while the side stream was drawn from the 38th stage. Here, it is assumed that all the columns possess an efficiency of 100%. The duty of the condenser and reboiler were 6.10 and 5.93 Gcal/h, respectively. Retrofitting C-304 to a DWC and adding one more new DWC can save 57.9 and 31.0% in terms of investment cost and energy consumption, respectively. The chemical/petrochemical plants usually have an annual maintenance period of 10–14 days, during which major repair and replacement are carried out. The retrofitting discussed above has been assumed to take place within this maintenance period, thus production loss during the retrofitting time is not considered [27].

3.3.5. Case 3.5 – retrofitting C-304 to a DWC and adding a new DWC in series

To compare with adding a new DWC in parallel with existing columns, another study was carried out with retrofitting C-304 to a DWC and adding a new DWC in series. The equipment to be retrofitted, as well as the equipment/systems connected with it, should be checked/monitored for their condition to perform the new operations. If any of them is unsuitable from the point of process/thermal design and/or mechanical stability/integrity, then such equipment needs to be considered for modification and added to the cost [27].

Table 6
Summary of relative performances for various arrangements.

	% of energy usage	% of investment usage
C-304 is replaced		
Case 1.2. Replacing C-304 and adding one new column (base case 2)	100.0	100.0
Case 3.1. Replacing two new columns with a new DWC	62.2	69.0
C-304 is utilized		
Case 1.1. Adding two new columns (base case 1)	100.0	100.0
Case 2.1. Re-arranging the existing one into Petlyuk column arrangement	72.0	410.0
Case 2.2. Re-arranging the existing one into prefractionator arrangement	72.3	390.0
Case 3.2. Re-traying C-304 and adding a new DWC in parallel with C-304	93.8	103.8
Case 3.3. Adding a new DWC in series	85.0	66.6
Case 3.4. Retrofitting C-304 to a DWC and adding a new parallel DWC	69.0	42.1
Case 3.5. Retrofitting C-304 to a DWC and adding a new DWC in series	78.7	59.9

Fig. 10b illustrates the schematic diagram of the separation train showing two conventional columns and two DWCs in series. By this option, 40.1 and 21.3% improvement in terms of respective investment and operating costs could be obtained. Compared with adding the DWC in parallel, adding the new DWC in series required larger columns and increased energy consumption due to a larger feed rate, which subsequently increased investment cost. Adding in series and parallel could save 21.3 and 31.0% in terms of energy consumption, respectively, and improve 40.1 and 57.9% in terms of investment costs, respectively. This interesting aspect can be further studied and developed by investigating other mixtures.

Table 6 summarizes the results concerning the energy and investment cost performances for all distillation arrangements studied in this work. The results indicate that the dividing wall column can be efficiently applied to replace and retrofit a conventional column for debottlenecking of distillation processes while requiring less investment and energy costs than the conventional distillation, the Petlyuk column, and the prefractionator arrangements.

4. Conclusions

This paper has focused upon the design of column sequences involving the DWC for removing the column bottleneck problem inherent to increased throughput of the acetic acid purification process. The shortcut method, utilizing the three conventional column configuration structurally equivalent to the DWC, was used to determine the proper initial structure for each DWC in a simple manner. The optimal structure design of the DWC has been considered in terms of the total number of trays, feed tray location, side tray location, and dividing wall section. The internal recycle flow distribution around the dividing wall was also investigated as the main optimizing variable.

In addition, re-traying the column, adding a new column, re-arranging the existing column sequence to a complex arrangement, retrofitting the column to a DWC, and replacing the existing column with a DWC were applied for debottlenecking of the column. Several cases were analyzed and the results showed that the dividing wall column is the best retrofit option. The DWC leads to significantly reduced investment and energy costs over conventional distillation and Petlyuk and prefractionator arrangements.

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Appendix A. Nomenclature

AA	acetic acid
B	bottom product flow
D	top product flow
DWC	dividing wall column
F	feed flow
FA	formic acid
PA	propionic acid
R_L	liquid split ratio
R_V	vapor split ratio
S	side product flow
VLE	vapor liquid equilibrium

Subscripts and superscripts

L	liquid
V	vapor

References

[1] G. Hewitt, J. Quarini, M. Morrell, More efficiency distillation, Chem. Eng. (October) (1999).
[2] Z. Olujic, M. Jödecke, A. Shilkin, G. Schuch, B. Kaibel, Equipment improvement trends in distillation, Chem. Eng. Process. 48 (2009) 1089–1104.
[3] N. Asprion, G. Kaibel, Dividing wall columns: fundamentals and recent advances, Chem. Eng. Process. 49 (2010) 139–146.
[4] R. Agrawal, A method to draw fully thermally coupled distillation column configurations for multicomponent distillation, Trans. IChemE 78 (Part A) (2000) 454–464.
[5] J.G.S. Hernández, S. Hernández, V.R. Ramírez, A. Jiménez, A comparison of the feedback control behavior between thermally coupled and conventional distillation schemes, Comput. Chem. Eng. 28 (2004) 811–819.
[6] K.A. Amminudin, R. Smith, D.Y.C. Thong, G.P. Towler, Design and optimization of fully thermally coupled distillation columns. Part 1: preliminary design and optimization methodology, Trans. IChemE 79 (Part A) (2001) 701–715.
[7] A. Jiménez, N. Ramírez, A. Castro, S. Hernández, Design and energy performance of alternative schemes to the Petlyuk distillation system, Trans. IChemE 81 (Part A) (2003) 518–524.
[8] I.J. Halvorsen, S. Skogestad, Minimum energy consumption in multicomponent distillation. 2. Three-product Petlyuk arrangements, Ind. Eng. Chem. Res. 42 (2003) 605–615.
[9] E.A. Wolff, S. Skogested, Operation of integrated three-product (Petlyuk) distillation columns, Ind. Eng. Chem. Res. 34 (1995) 2094–2103.
[10] I.J. Halvorsen, S. Skogestad, Optimal operation of Petlyuk distillation: steady-state behavior, J. Process Control 9 (1999) 407–424.
[11] I.J. Halvorsen, S. Skogestad, Shortcut analysis of optimal operation of Petlyuk distillation, Ind. Eng. Chem. Res. 43 (2004) 3994–3999.
[12] N. Poth, D. Brusis, J. Stichlmair, Minimaler Energiebedarf von Trennwandkolonnen, Chem. Ing. Tech. 76 (2004) 1811–1814.
[13] Z.Y. Liu, M. Jobson, Retrofit design for increasing the processing capacity of distillation columns 1. A hydraulic performance indicator, Trans. IChemE 82 (2004) 3–9.
[14] K.A. Amminudin, R. Smith, Design and optimization of fully thermally coupled distillation columns. Part 2: application of dividing wall columns in retrofit, Trans. IChemE 79 (2001) 716–724.
[15] D.B. Manley, Capacity expansion options for NGL fractionation, in: Proceedings of the 77th GPA Annual Convention, Gas Processors Association, 1998, pp. 114–119.
[16] K. Liebman, Integrated crude oil distillation design, Ph.D. Thesis, UMIST, Manchester, UK, 1991.
[17] J.H. Jane, The Cativa™ process for the manufacture of acetic acid, Platinum Metal Rev. 44 (2001) 95–105.
[18] PEP Report, Acetic Acid by Low Pressure Carbonylation of Methanol, November 1994.
[19] A.N. Kuzyukov, L.V. Zaitseva, A.N. Kuzyukova, V.I. Romaniv, Corrosion of nickel–molybdenum alloys in media involved in acetic acid production, Khim. Prom. 7 (1985) 22–24.
[20] E.K. Malakhova, A.N. Kuzyukov, A.V. Meshcheryakov, Corrosion resistance of zirconium alloys in acetic acid media, Chem. Petrol. Eng. 31 (1995) 3–4.
[21] L.M. Pischik, A.I. Tsinman, M.I. Balvas, Use of titanium in the manufacture of equipment for acetic acid production, Chem. Petrol. Eng. 19 (1983) 200–202.
[22] Aspen Technology, Aspen Physical Property System, Version Number V7.1, 2009, January.
[23] L.T. Biegler, I.E. Grossmann, A.W. Westerberg, Systematic Methods of Chemical Process Design, Prentice Hall Inc, New Jersey, 1997, pp. 110–141.
[24] C. Triantafyllou, The design optimization and integration of dividing wall distillation columns, Ph.D. Thesis, UMIST, Manchester, UK, 2001.
[25] S.H. Lee, M.Y. Lee, The study of structure design for dividing wall distillation column, Korean Chem. Eng. Res. 45 (2007) 39–45.
[26] C. Triantafyllou, R. Smith, The design and optimization of fully thermally coupled distillation, Trans. Inst. Chem. Eng. 70 (Part A) (1992) 118–132.
[27] R. Premkumar, G.P. Rangaiah, Retrofitting conventional column systems to dividing wall columns, Chem. Eng. Res. Des. 87 (2009) 47–60.