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Hydraulic design, technical challenges and comparison of alternative configurations of a four-product dividing wall column

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ABSTRACT

This study addresses technical feasibility related aspects of multi-partition wall alternatives for a four-product dividing wall column, which, although highly beneficial, have not been yet attempted in industrial practice. Utilizing an industrially relevant aromatics processing plant case as basis for design and evaluation of cost-effectiveness of alternative configurations, this paper focuses on the hydraulic design and dimensioning of a minimum energy configuration with two overhead product streams. DWC technology related issues are discussed, which can help to distinguish what makes sense and what not when dealing with practical implementation of multi-partition wall configurations.

1. Introduction

Striving towards greater sustainability drives the process industries to look for opportunities to improve the energy efficiency of distillation columns and sequences. Numerous academicians and practitioners are active in this field and utilize various approaches to provide theoretically sound conceptual, technology advancing solutions. Most of the academic effort is spent on column sequencing and heat coupling and in the literature there is every year a considerable number of publications introducing advances in this respect. These efforts are summarized in a book by Kiss, published last year [1]. However, few papers are concerned with finding adequate technical solutions that could be implemented in industrial practice in a cost-effective way.

A real technology breakthrough in this respect occurred recently by successful industrial implementation of so-called "dividing wall column" (DWC), i.e. a fully thermally coupled, single shell distillation column that minimizes energy and capital requirement as well as plot area, compared to that required by conventional two column sequences for obtaining three pure products [2–4]. Although DWCs are a proven technology, designers and users, confronted with increased complexity and related uncertainties, still hesitate to make the next, highly rewarding step, i.e. to build and operate DWCs with four products.

A conventional sequence for obtaining four specified products from a multicomponent aromatics plant feed (see Table 1) is shown in Fig. 1a [5]. In an alternative new design, this particular sequence could be replaced by a combination of a three-product DWC and a conventional column as shown in Fig. 1b. Some other possibilities are mentioned in a paper by Errico et al. [6]. However, this is of little relevance here, and the configuration shown in Fig. 1b is considered just as an example of an appropriate intermediate solution, because a four-product DWC is without doubt the most beneficial configuration for this separation task [5]. A partial confirmation is provided by Kiss et al. [7], who show that a conventional column combined with a single-partition, four-product DWC (so called "Kaibel column") requires less energy for separation of a five component aromatics mixture into five products than any conventional or other sequences, including two conventional DWCs connected in series.

The first packed, single-partition wall, four-product DWC was taken into operation in 2002 in a BASF SE plant [8]. This configuration (denoted "2-4"), shown in Fig. 2a, is less efficient than its fully thermally coupled equivalent ("2-3-4") shown in Fig. 2b. Namely, in such a case a certain amount of component remixing occurs in between two side- product draw-offs on main column side leading to undesired entropy formation. To avoid this, i.e. to implement a full (Petlyuk) thermal coupling, three sections need

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Table 1
Base case feed and product streams specifications.

Stream name	Feed (F)	C5-C6 (A)	BRC (B)	Toluene (C)	Heavies (D)
Flow rate [t/h]	31.7	7.45	3.87	7.97	12.44
Mass fractions (rounded)					
n-Butane	0.019	0.083	–	–	–
i-Pentane	0.064	0.273	–	–	–
n-Pentane	0.045	0.193	–	–	–
2-Methylpentane	0.080	0.341	0.003	–	–
N-Hexane	0.043	0.098	0.160	–	–
Benzene	0.086	0.013	0.675	–	–
3-Methylhexane	0.020	–	0.162	0.002	–
Toluene	0.247	–	–	0.984	0.001
Ethylbenzene	0.035	–	–	0.006	0.086
p-Xylene	0.042	–	–	0.003	0.107
m-Xylene	0.122	–	–	0.005	0.307
o-Xylene	0.055	–	–	–	0.140
m-Ethyltoluene	0.047	–	–	–	0.120
1-3-5-Trimethylbenzene	0.077	–	–	–	0.197
1-4-Diethylbenzene	0.017	–	–	–	0.043

to be arranged in parallel in the central part of the column shell, as shown schematically in Fig. 2b. A packed version of a DWC with a "2-3-4" configuration could be installed using available know-how and proven non-welded partition wall technology [5,9]. A major concern related to design and operation of such a complex DWC stems from the need to arrange properly and maintain during operation three vapour splits, while the "2-4" configuration requires only one.

Hydraulic design is the key to arranging required liquid to vapour flow rate ratio (L/V) on both sides of partition wall in each of partitioned sections. In other words, during design the vapour flow resistances in the parallel sections, for given liquid loads and packed bed heights, need to be arranged carefully to ensure obtaining the required vapour splits. For single and multi- partition DWCs, this can be done using methods described in detail elsewhere [10,11].

The problem is to maintain stable situation, because, local pressure drop disturbances may propagate and force the vapour splits to change and detrimentally affect the separation performance. A corrective action could be imposed by adjusting the liquid splits in a co-ordinated way. This is effective, and sensitivity in this respect should be examined by process simulation studies. The results of dedicated process control studies, performed using experimentally validated predictive models, indicate that both a single partition wall ("2-4") and a complex three partition walls four-product column ("2-3-4") could be controlled in an effective way [12–15].

Related malperformance risks could be lessened significantly if one of the required vapour splits could be avoided. As elaborated in detail elsewhere [16], a *Vmin*-diagram based analysis revealed a number of possibilities in this respect. Two simpler internal configurations, where in both cases one vapour split is eliminated and which exhibit the same performance and are thermodynamically equivalent to fully thermally coupled "2-3-4" DWC, have been identified and evaluated in detailed simulations carried out using commercial software package CHEMCAD [16,17]. The configuration on the left-hand side of Fig. 3 is referred to as ("s-2-3-4"), because it represents a simplified version of the "2-3-4" configuration. Here the middle and the main column sections are separated by a single, long partition wall, with only a fraction of the liquid going from the middle to the main column section side. The so-called ("2-2-4") configuration, shown on right hand side of Fig. 3, employs two liquid splits and two vapour splits. This even simpler version of a four-product DWC contains only a short segment of total height arranged as three sections in parallel.

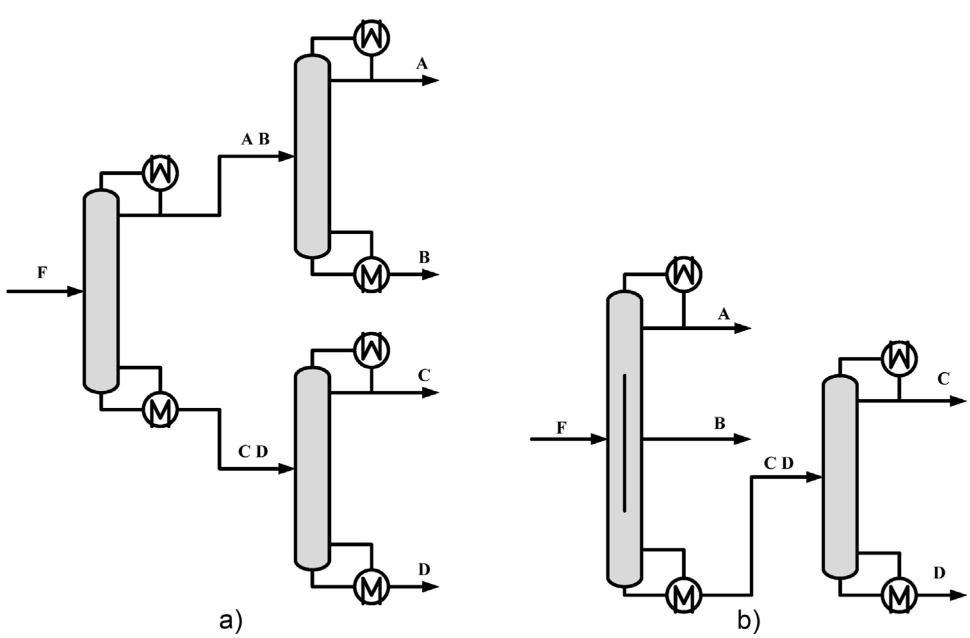

Fig. 1. Schematic representation of a conventional three-column sequence and an alternative configuration employing a three-product DWC connected in series with a conventional distillation column (CC).

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A	cross-sectional area (m^2)
A,B,C,D	products/fractions in order of volatility
B	bottoms flow rate (kmol/h)
D	distillate flow rate (kmol/h)
d	diameter (m)
F	feed or feed flow rate (kmol/h)
F_G	($F_G = u_G(\rho_G)^{0.5}$) vapour load ($Pa^{0.5}$)
h	packed bed height (m)
L	liquid flow rate (kmol/h)
N	number of equilibrium stages or theoretical plates (#)
P	operating pressure (bar)
u_L	specific liquid load ($m^3/(m^2$ h))
V	vapour flow rate (kmol/h)

Greek letters

Δp	pressure drop (mbar, or mbar/m)
φ	fraction free area
ρ_G	vapour density (kg/m^3)

Subscripts

A,F,G,H,I,X,Y	sections in parallel
CC	chevron collector
CT	chimney tray collector

Acronyms

BRC	benzene rich cut
C1/C2/C3	columns in conventional three column sequence
C5-C6	hexane and lighter components
DWC	dividing wall column
TAC	total annualized costs

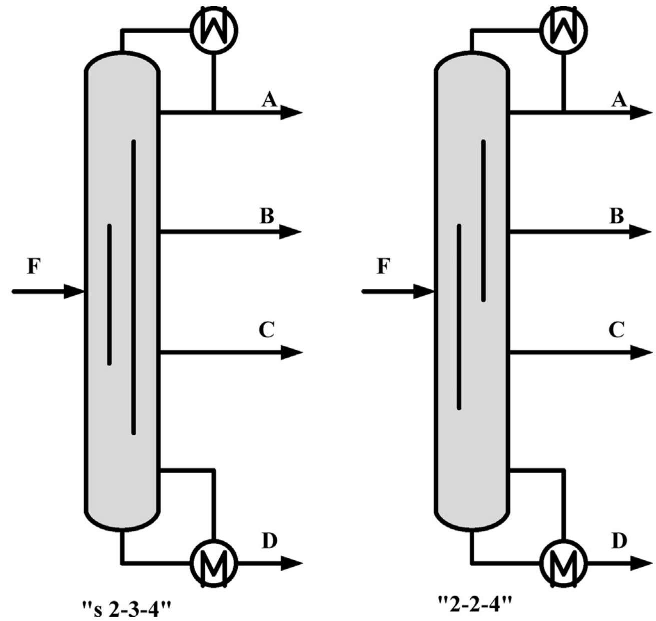

Fig. 3. Schematic representation of two simplified four-product DWCs with two vapour splits.

A further elaboration of possibilities along this line generated an innovative configuration, denoted here as "2-3-3" (see Fig. 4), with the top position of the partition wall separating middle from the main column section [17,18]. This configuration employs two liquid splits and three vapour splits and it delivers two overhead product streams at the same energy and total stage requirement as other energy efficient four-product configurations. An important, process control related potential benefit of this configuration is reflected in the fact that it allows the upper section vapour split to be varied to certain extent by adjusting accordingly the top pressure, i.e. condenser duty. An indication on the range of disturbances in feed rate and/or compositions that could be smoothed out in this way could be obtained from process simulation studies.

The present paper provides the first detailed description of the hydraulic design and column dimensioning for this remarkable four-product DWC configuration. Since this and other energy efficient four-product DWCs are similar with respect to

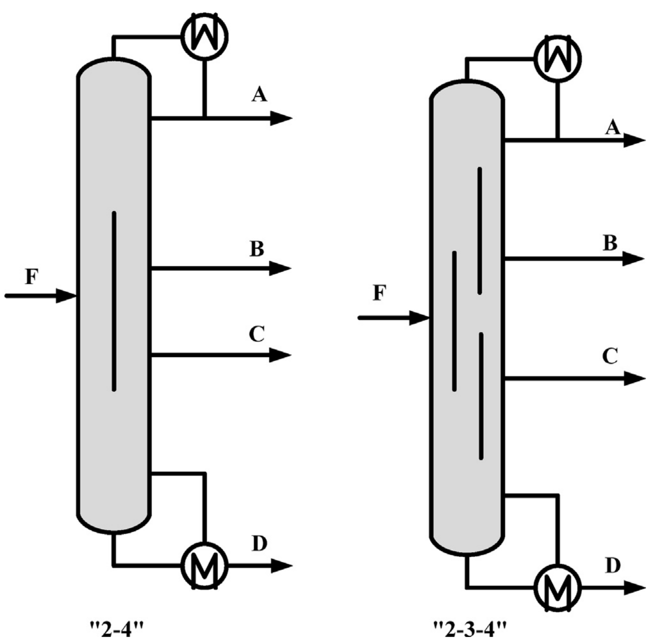

Fig. 2. Schematic representation of a single-partition ("2-4" or Kaibel column) and a multi-partition fully coupled ("2-3-4" or Sargent column) four-product DWC.

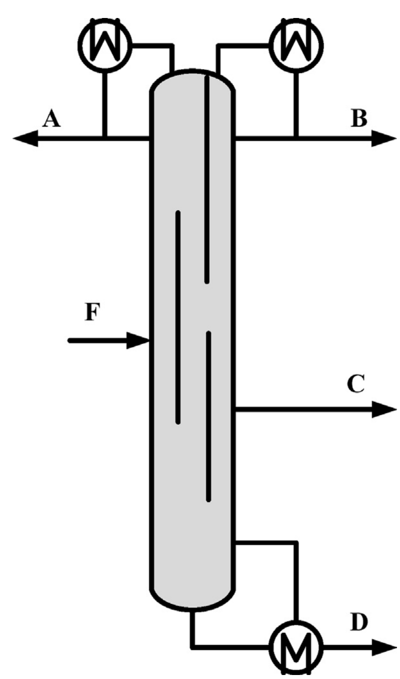

Fig. 4. Schematic representation of the four-product DWC "2-3-3", with two overhead products.

cost-effectiveness, this paper emphasises and discusses thoroughly the technical aspects of importance for decision making regarding the choice of a multi-partition four-product DWC configuration for industrial implementation.

2. Alternative designs of a four-product DWC

The energy and stage requirements of the five DWC configurations shown in Figs. 2–4 are summarized and compared to that of conventional three-column sequence in Table 2. Being an interesting option, the configuration combining a three-product DWC and a conventional column (Fig. 1b) is also included. The design case is an aromatics plant situation with feed and product specifications as given in Table 1 [5].

According to the numbers shown in Table 2, the multi-partition designs, including “2-3-3” configuration are most energy efficient and the savings are more than 50% compared to the conventional, three-column sequence. As expected, the configuration combining a three-product DWC and a conventional column is more energy efficient than the conventional sequence (41%), however it is less than that achievable with the proven, single partition wall, “2-4” (Kaibel) configuration (48%). One should note that the total reboiler duty for the conventional, three column sequence is 11.1 MW, and not 10 MW as given in previous publications (5,11), where the benzene-rich fraction was erroneously set to 63 mass% instead to 67.5 mass%. This implies higher energy and capital savings than found previously.

The total number of stages and that determining the column height are shown separately in Table 2. It is interesting to note that the number of stages determining column shell height is lowest for the configuration with two condensers (“2-3-3”). Fewer stages suggest a correspondingly reduced column shell height, but this is not straightforward, as it will be shown in the following section describing column dimensioning.

3. Dimensioning a “2-3-3” four-product DWC

Details related to hydraulic design and dimensioning of DWCs with “2-4”, “2-3-4” and “2-2-4” configurations can be found elsewhere [11]. Internally, the “s-2-3-4” configuration resembles that of “2-3-4” DWC, requiring, due to an increased vapour flow rate, a somewhat larger cross sectional area in the upper part of the middle section.

The basic information required for dimensioning a DWC with the “2-3-3” configuration is summarized in Fig. 5, indicating vapour and liquid flow paths and related inlet and outlet mass flow rates as well as the number of stages contained per packed bed in each section. The corresponding numbers have been extracted from the results of detailed simulation of the “2-3-3” configuration using adequate flowsheet [17].

3.1. Packed “2-3-3” DWC height

To have the same basis for comparison with other options, the “2-3-3” configuration was sized utilizing Montzpak B1-350MN. This is a high-performance structured packing with a specific geometric area of 350 m^2/m^3, which is expected to deliver 2.5 equilibrium stages per metre bed height. This corresponds to a HETP (height equivalent to a theoretical plate) of 0.4 m; a value that was used for dimensioning of other configurations [11]. As done previously, the maximum single bed height has been set to 20 equilibrium stages (theoretical plates) per bed.

It is interesting to mention that the number of the theoretical plates determining the shell height of the “2-3-3” configuration is not 116 (Table 2) as anticipated from the preliminary dimensioning [18], which uses the middle column based stage count, but 124. To see this, consider Fig. 6, which shows a detailed drawing of internal configuration of the “2-3-3” DWC, indicating that the supports of three packed beds in the lower part of the column are at the same elevation. Since the middle section (2.3) is shorter than that on the main column side (3.2), the height of the middle segment of the column with the three sections in parallel is dominated by the number of stages on the main column side. The bed on the main column side contains 8 more stages than that on the middle column side. The former, including the spacing for the liquid redistribution section, determines the height of this segment of the column. Using the same packing, the space above the shorter beds in the middle section and on the prefractionator side will be empty. This could be useful, because it allows access to sections in parallel through only one manhole, provided the other one is installed in the partition wall separating the prefractionator and middle section of the column. Also a coarser packing could be used in these sections if the main column experiences capacity limitation.

The enlarged number of stages (124), multiplied with a chosen HETP of 0.4 m, gives the shell height (49.6 m) required to accommodate the total bed height. As indicated in Fig. 5, the total bed height needs to be arranged in 7 beds, separated by 6 liquid redistribution sections. The standard spacing, i.e. distance between two packed beds, needed to accommodate a liquid redistribution section is 2 m (this can be reduced to the amount considered safe during detailed design), which means that in the present case the effective height of the column shell would be 61.6 m ($49.6 + 6 \times 2$). Adopting 5 m as additional height for vapour-liquid disengagement space at the top and bottom of the column, the tangent to tangent height of a shell incorporating the “2-3-3” configuration (see Fig. 6) would be 66.6 m. According to the data shown in Table 4, this is less than required [11] for configurations “2-4” (68.6 m), “2-3-4” (69 m) and “2-2-4” (69 m), but the column shell height reduction of 2 m–2.4 m is less pronounced than anticipated from the numbers (116 vs 130 stages) given in Table 2. This suggests that a certain degree of rigour in equipment dimensioning is required during the conceptual design phase to allow a fair comparison of alternatives based on their cost-effectiveness and practicality.

3.2. Packed “2-3-3” DWC shell and partitioned sections diameters

Regarding the fact that the reboiler duty is the same, the shell diameter of the “2-3-3” DWC is equal to that of alternative multipartition configurations. However, the cross sectional areas of three sections in parallel will differ to comply with the distribution of vapour and liquid loads. This dictates the lateral positioning of partition walls, and to arrange this properly within a given shell diameter, accurate balancing of flow resistances in parallel sections is needed. This is done according to the pressure drop situation shown schematically in Fig. 7. Here symbols P1–P6 denote the absolute pressure at a given level. Note that the top pressures P5 and P6 could be chosen to be different, if appropriate. However, in the present study, the same top pressure is chosen for both sections in the partitioned top of the “2-3-3” column, equal to that of the alternative configurations.

With the same top pressures (P5 = P6), the situation depicted in Fig. 7 is similar to that of the “2-3-4” configuration [11], except that vapour streams leaving the middle and main column sections do not merge, but leave the column as overheads product streams through separate nozzles.

Since the spontaneous adjustment of three vapour splits ensures pressure equalization in parallel column sections, the following conditions need to be satisfied:

$$\Delta p_I + \Delta p_H = \Delta p_Y \quad (1a)$$

Table 2
Energy and stage requirement of different configurations considered in this study.

DWC configuration	Conventional	3P DWC + conventional	"2-4"	"2-3-4"	"s-2-3-4"	"2-2-4"	"2-3-3"
Total reboiler duty (MW)	11.11	6.56	5.82	4.81	4.81	4.81	4.81
Energy saving (%)	–	41	48	57	57	57	57
Number of stages (total)	116	124	169	202	202	174	202
Number of stages (main column)	–	–	129	130	130	130	116

$$\Delta p_H + \Delta p_G = \Delta p_A \quad (1b)$$

$$\Delta p_G + \Delta p_F = \Delta p_X \quad (1c)$$

where Δp (mbar) is the pressure drop and the subscripts indicate the respective column sections shown in Fig. 7.

As a check, the pressure drop of the partitioned part of "2-3-3" column, which extends from the top of the column to the lower end of the lowest partition wall, must be equal for each of three vapour flow paths, i.e.:

$$\Delta p_I + \Delta p_A + \Delta p_F = \Delta p_I + \Delta p_H + \Delta p_G + \Delta p_F = \Delta p_Y + \Delta p_X \quad (2)$$

Iterative pressure drop calculations are carried out using the Excel Solver, which includes adjustment of the cross sectional area requirement in sections arranged in parallel. The working equations of the pressure drop method used for this purpose can be found elsewhere [10]. The starting shell diameter is based on the position with maximum vapour and liquid loads, which, in the

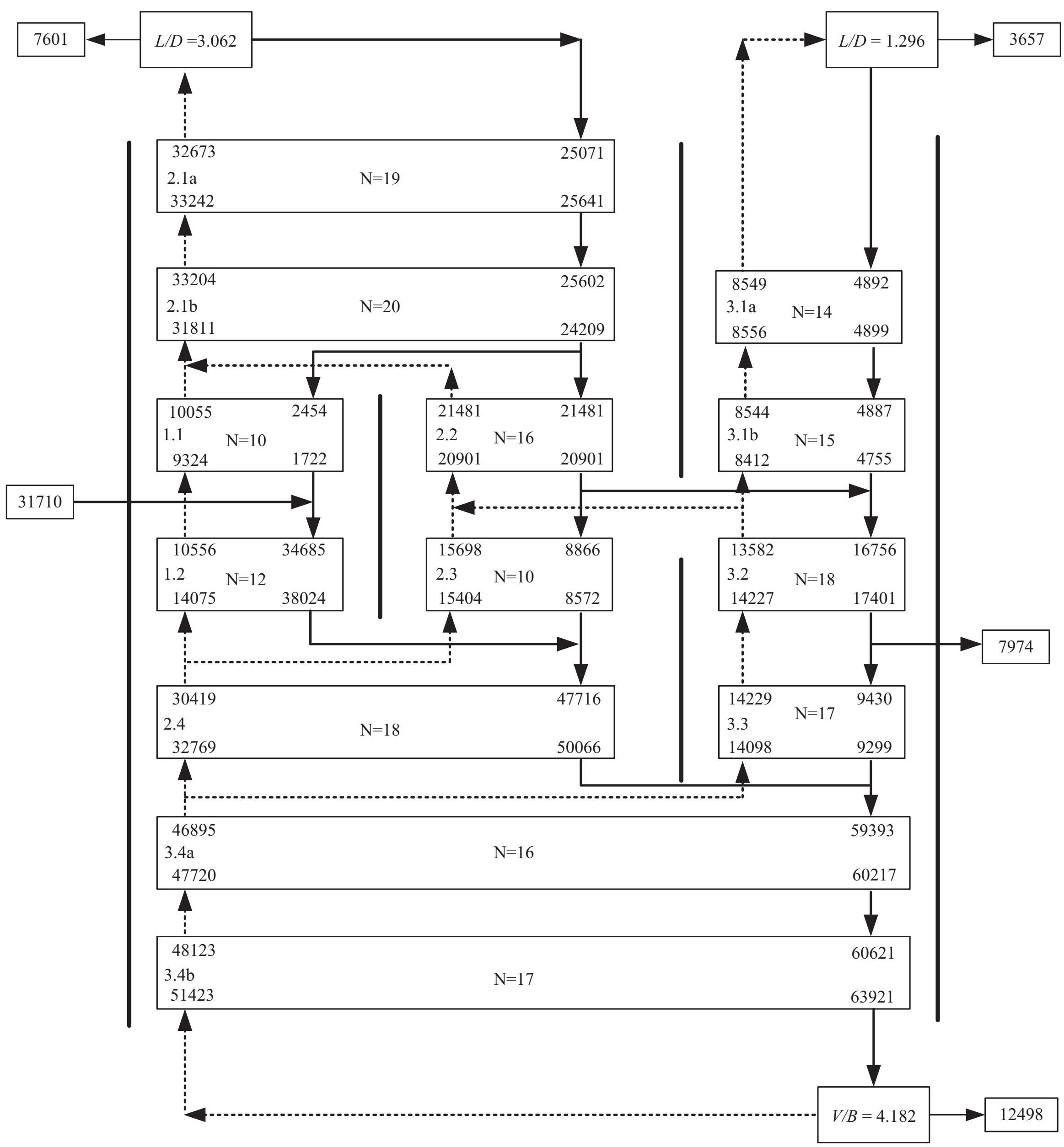

Fig. 5. Stage requirement per section and corresponding vapour and liquid mass flow rates and patterns for "2-3-3" four-product DWC shown in Fig. 4.

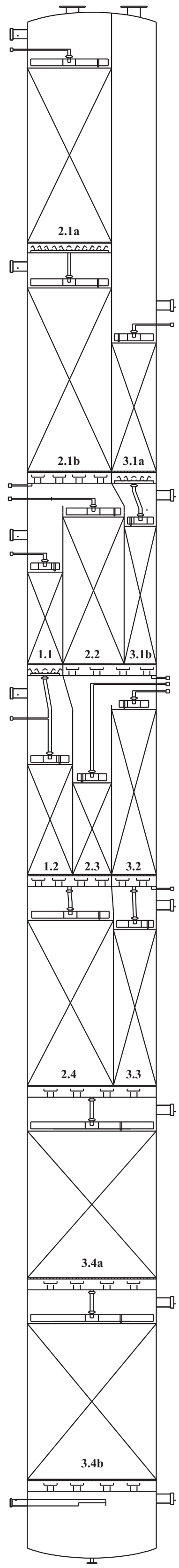

Fig. 6. Detailed drawing of the “2-3-3” four-product DWC.

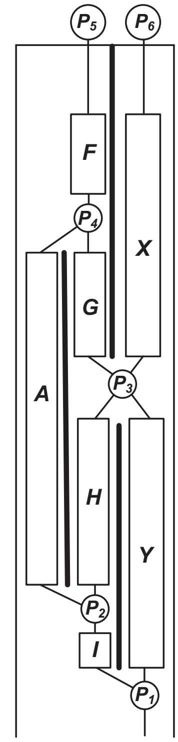

Fig. 7. Schematic representation of the pressure drop situation in the “2-3-3” four-product DWC shown in Fig. 4.

present case, with above atmospheric pressure and a slightly subcooled liquid feed is at the bottom stage. As a design value, i.e. the criterion for establishing the shell diameter as well as equivalent diameters of partitioned sections, a maximum pressure drop of 3 mbar per metre bed height is chosen, which corresponds roughly to a vapour load at 75% of the flood point in an irrigated packed bed equipped with conventional corrugated sheet structured packings. With a high-performance packing, allowing a design pressure drop of 5 mbar/m, the shell diameter could be further reduced, provided a higher pressure drop is affordable in the given application. This however is something to be considered and worked out during detailed design.

With the DWC shell diameter set to be equal to that required at the bottom, calculations move upward to the point where partition walls separate available cross sectional area first into two sections, then three sections in parallel and in the upper part of the shell again to two sections in parallel extending to the top of the column. Initial guesses for cross section areas of partitioned sections can be set to be equivalent to the ratio of corresponding fractions of total vapour flow rate. If the pressure drop in one of these sections exceeds 3 mbar/m, the cross sectional area of this section is gradually increased at the expense of the neighbouring section with the lowest vapour load.

When this is done, the pressure drop of the irrigated packed beds in each section is fixed. Since the number of required stages and corresponding bed heights differ as well as specific liquid and vapour loads per section, the pressure drop caused by packed beds may differ considerably in parallel sections. To allow adequate pressure equalization, the amount of missing pressure drop needs to be provided by arranging the free area of liquid collectors and distributors in these sections accordingly.

To get a clear picture in this respect, Fig. 6 shows a detailed drawing of the internal structure of a packed “2-3-3” DWC, indicating for each section the type of auxiliary equipment used. Note that a distinction is made between a so-called “chimney tray” type- and

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a “chevron” or “vane” type liquid collector. The former are more suitable to deal with larger liquid loads and are a preferred choice at side-product draw-off locations, while the latter, more streamlined ones, are generally preferred at specific liquid loads below 20 $m^3/(m^2 h)$ [11,19]. State of the art gravity liquid distributors are of the narrow trough type and offer more free area (up to 50%) for passage of vapour than chimney and chevron type liquid collectors (up to 30%). The pressure drop for these devices, as well as for irrigated packed beds containing conventional and high performance or capacity structured packings can be estimated with enough confidence for preliminary design and cost estimation purposes using methods described in details elsewhere [10,11].

Regarding pressure equalization calculations, Eq. (1a) is solved first, by adjusting the free area of liquid collectors that are contained in sections corresponding to pressure drops Δp_I, Δp_H, and Δp_Y. Next, Eq. (1b) is solved, utilizing Δp_H from Eq. (1a) and required free area of liquid collectors involved. In the final step, Eq. (1c) is solved keeping Δp_G constant. A final check is done by summing up per section the individual pressure drops, from column top to the bottom end of the lowest partition wall. As mentioned before, the resulting number must be equal for all three vapour flow paths, i.e. Eq. (2) must be satisfied. By adding the pressure drop of the conventional, bottom section (beds 3.4a and 3.4b including auxiliary equipment), the total pressure drop is obtained.

3.3. Total annualized cost estimation

The total annualized cost (TAC) is obtained by summing up the annual utility related expenses and adding a 10% of installed equipment cost. The capital costs for column shells, shell and tube type condensers and reboilers as well as fired heaters required are estimated using the SI version installed cost correlations given in textbook by Douglas [10,20]. These are actualized to the year 2012, using the corresponding value (1545.9) of the Marshall & Swift Index, which was published monthly in Chemical Engineering until mid-2012, and which is presently available as a product on commercial basis from an independent source (www.equipment-cost-index.com). Details on correlation-based estimates of installed costs of main process equipment, including the purchased costs and corresponding installation factors for sieve trays, structured packings, liquid collectors, liquid distributors and packing support rings used in this and previous studies, as well as the yearly operation time and utility prices for water, steam and fuel oil required to reach required temperature level in reboilers of the three columns in conventional sequence as well as DWC configurations considered, can be found elsewhere [10].

4. Results and discussion

4.1. Hydraulic design

The results of the detailed pressure drop calculations for “2-3-3” DWC are summarized in Table 3, separately for (a) packed beds, (b) liquid distributors, and (c) liquid collectors. Each of these subtables contains required input data per section. Similar tables for “2-4”, “2-3-4” and “2-2-4” configurations can be found in [11].

In Table 3a, which shows the pressure drop of installed packed beds, the sections are denoted by the corresponding bed number (see Figs. 5 and 7), starting from the top of the column. Table 3 includes information on bed height, *h*, cross-sectional area, *A*, and equivalent diameter, *d*, of each section. The shell diameter is equal to the internal diameter of the conventional bottom section. It is 2 m, which is the same as previously established for “2-3-4” and “2-2-4” columns [11]. The estimated pressure drops are arithmetic averages of the values corresponding to the conditions at the top and the bottom of the bed.

Table 3b, which shows the pressure drop of the liquid distributors, includes the vapour loads expressed as F-factors corresponding to that leaving the bed below. Here each individual device is indicated by its corresponding bed number, starting from the top of the column. The liquid distributor considered in all cases is a common narrow trough distributor with a free area of 40%.

Table 3c, which shows the pressure drop of the liquid collectors, includes in addition to the given *F*-factor (vapour leaving the bed below), F_G, also the specific liquid load, u_L, for each section and indicates the type of liquid collector used. Symbols “CC” and “CT” denote chevron collector and chimney tray collector, respectively. As mentioned before, the initial value of free area, φ, was 0.25, and a different number generated by Excel solver indicates the value that needs to be implemented by design to get the pressure drop equalized.

An inspection of the values given in these tables shows that the pressure drop of the liquid distributors (which have a free area of 40%) is much lower than for the packed beds and liquid collectors. Also, it appears that a balanced pressure drop in the sections in parallel is achieved by adjusting the free area of collectors within the given range. Critical locations, i.e. those in need of additional amount of pressure drop, are the top bed in the main column section and the lowest beds in prefractionator and middle column sections, where the free area of liquid collectors below these beds has been reduced to 6% to generate required pressure drop.

The total pressure drop of the “2-3-3” DWC is 114.5 mbar, and the contributions of liquid distributors and collectors are about 12%. According to the numbers shown in Table 4, the “2-2-4” DWC has the lowest pressure drop, and the reduction of 8–10% compared to other configurations may be considered as a positive factor in favour of this particular configuration. Anyhow, the overall pressure drop of all compared alternatives is rather low; less than 2 mbar per metre column height.

4.2. Column dimensioning and cost evaluation

The main dimensions and column pressure drops for all alternatives are summarized in Table 4, including information on the number of packed beds and liquid collectors installed. One should note that the number of liquid distributors and bed supports is equal to the number of packed beds, while the number of collectors deviates from this, because in some cases (see Fig. 6) one collector serves two beds. This is of importance for cost estimation because the installed equipment cost factor for internals depends on the complexity of internal configuration, i.e. it is somewhat larger for column segments containing two partition walls in parallel than for single partition wall situations [10].

As expected, a DWC is considerably taller than any of the columns from conventional sequence, because it needs to accommodate many more stages. The shell height itself, which is up to 69 m, is not a concern, but the height to diameter ratio (>30) certainly is. Such, quite slender column shells require substantial shell thickness in the lower part and appropriate support structure to sustain wind-imposed loads. However, in case of plants with larger capacities, i.e. substantially larger column diameters, this would not be a concern.

Interesting to note here is that the energy efficient DWCs reduce the vapour flow rate to such an extent that that it requires a diameter which is equal to that of the two larger columns in conventional sequence. This suggests that two existing columns could be considered as candidates for revamp, because two shells connected in series provide more than enough height to accommodate the required number of stages. This, primarily energy saving retrofit option will be elaborated in detail in a forthcoming study.

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Table 3
Basic data and pressure drop of packed beds, liquid distributors and liquid collectors of the “2-3-3” DWC.

(a) Packed beds

Section	1.1	1.2	2.1a	2.1b	2.2	2.3	2.4
h (m)	4.0	4.8	7.6	8.0	6.4	4.0	7.2
A (m^2)	0.70	0.98	2.16	2.16	1.82	1.18	2.22
d (m)	0.95	1.12	1.66	1.66	1.52	1.23	1.68
Δp (mbar)	8.8	10.1	20.5	15.5	10.3	8.2	17.8

(a) Packed beds

Section	3.1a	3.1b	3.2	3.3	3.4a	3.4b
h (m)	5.6	6.0	7.2	6.8	6.4	6.8
A (m^2)	0.98	0.61	0.98	0.92	3.14	3.14
d (m)	1.12	0.88	1.12	1.08	2.00	2.00
Δp (mbar)	5.1	13.9	18.6	18.5	16.8	19.4

(b) Liquid distributors

Position	2.1a	2.1b	3.1a	1.1	2.2	3.1b	1.2	2.3	3.2	2.4	3.3	3.4a	3.4b
F_G (Pa$^{0.5}$)	1.51	1.60	0.91	1.52	1.24	1.47	1.02	1.40	1.46	1.43	1.60	1.53	1.55
Δp (mbar)	0.06	0.06	0.02	0.06	0.04	0.05	0.03	0.05	0.05	0.05	0.06	0.06	0.06

(c) Liquid collectors

Position	2.1a	2.1b	3.1a	1.1	2.2 + 3.1b	1.2 + 2.3	3.2	2.4 + 3.3	3.4a	3.4b
u_L (m^3/(m^2 h))	19.7	15.0	7.0	3.5	14.4	29.7	24.0	25.7	26.3	28.5
Type	CC	CT[a]	CC	CC	CT[a]	CT	CT	CT	CT	CT
$\varphi_{cc/ct}$	0.05	0.08	0.30	0.30	0.20	0.06	0.30	0.25	0.25	0.25
F_G (Pa$^{0.5}$)	1.66	1.02	0.93	1.41	1.27	1.40	1.56	1.53	1.58	1.70
Δp (mbar)	19.13	3.61	0.13	0.29	0.70	11.60	0.45	0.65	0.69	0.80

[a] CT in this position because of the liquid product draw-off.

While having an equal (“2-3-4”, “s-2-3-4” and “2-2-4”) or even lower (“2-3-3”) height, the two- or three partition walls DWCs require a 10% smaller diameter than the less energy efficient “2-4” configuration. This demonstrates clearly that in the case of a DWC, energy saving translates directly into a significant reduction of column diameter, i.e. a considerable capital saving.

With its reduced height requirement, the “2-3-3” configuration appears to be most beneficial. However, the potential gain is compromised to certain extent by the additional costs for two condensers and more internals in the partitioned part of the column.

4.3. Cost effectiveness of compared configurations

Table 5 compares total annualized costs (TAC) of the alternative configurations. As expected, the conventional three-column sequence has the by far highest TAC, followed by the combined three-product DWC and conventional column, and the single-partition wall (Kaibel) DWC. As expected, the lowest costs are associated with the four-product DWCs. The TAC for the “2-3-3” configuration is somewhat lower than for the fully integrated “2-3-4” and similar “s-2-3-4” configuration, and almost identical to the simplest “2-2-4” DWC.

Compared to the single-partition “2-4” Kaibel DWC, multi-partition configurations use approximately 18% less energy, and this brings a nearly equal TAC benefit. This is substantial, but the “2-4” Kaibel DWC itself has an energy saving of 50% compared to conventional sequence. This should move practitioners to consider first the industrially proven “2-4” Kaibel DWC. However, in large-scale applications, the additional gain of more than 15% could be appealing enough to consider practical implementation of one of complex, multipartition wall DWC configurations.

The final choice needs to be based on a thorough technical evaluation of design, construction, installation, operation, and control related issues. These are same for both conventional three-product DWCs and four-product DWCs, but appear, as it will be indicated in what follows, more pronounced and thus a greater concern for the latter.

5. Design and operation issues and concerns

5.1. Off-centre welded/non-welded partition walls

If the vapour and liquid loads of prefractionator and the partitioned part of the main column differ significantly, a conventional,

Table 4
Dimensions, internals, operating pressures and pressure drops of conventional three-column sequence, combined 3-product DWC + conventional column, single (“2-4”) and multiple (“2-3-4”, “2-2-4”, “2-3-3”) partition wall DWCs considered in this study.

Configuration	Conventional	3P DWC + conventional	“2-4”	“2-3-4” “s-2-3-4”	“2-2-4”	“2-3-3”
Column	C1/C2/C3	DWC/C3	DWC	DWC	DWC	DWC
Internals	Sieve trays	B1-350MN/Sieve trays	B1-350MN	B1-350MN	B1-350MN	B1-350MN
Shell height (m)	40.5/39.5/39.5	39.3/39.5	68.6	69.0	69.0	66
Shell diameter (m)	2.0/2.0/1.8	1.7/1.8	2.2	2.0	2.0	2.0
Packed beds, t/p (#)	–	–/2	10/7	13/10	11/8	13/11
Collectors, t/p (#)	–	–/2	9/5	12/8	9/5	10/8
Top pressure (bar)	2.7/1.7/1.013	2.7/1.013	2.5	2.5	2.5	2.5
Pressure drop (bar)	0.313/0.272/0.244	0.044/0.244	0.114	0.116	0.105	0.111

t/p refers to total/partitioned, i.e. to the number of devices contained in total and in partitioned sections of a DWC, where, in some cases, one collector serves two beds.

Table 5
Capital, operating and total annualized (TAC) of column configurations considered in this study.

Configuration	Conventional	3P DWC + conventional	"2-4"	"2-3-4" "s-2-3-4"	"2-2-4"	"2-3-3"
Column	C1/C2/C3	DWC/C3	DWC	DWC	DWC	DWC
Internals	Sieve trays	Sieve trays/B1-350MN	B1-350MN	B1-350MN	B1-350MN	B1-350MN
Equipment (US $)	$4,365,759	$2,890,988	$3,184,699	$2,931,466	$2,703,305	$2,878,370
Saving (%)	–	34%	27%	33%	38%	34%
Utilities (US $)	$1,796,596	$954,325	$838,742	$681,778	$683,526	$681,461
Saving (%)	–	47%	53%	62%	62%	62%
TAC (US $)	$2,233,171	$1,243,424	$1,157,212	$974,925	$953,856	$969,298
Saving (%)	–	44%	48%	56%	57%	57%

three product DWCs will require an off-centre positioning of the partition wall to allow minimization of the shell diameter. This is even more probable in the case of a single-partition wall, four-product DWC and is practically inevitable in case of multi-partition wall designs. Off-centre positioning of the partition wall is relatively easy if there is no need to weld it to the column wall over its entire length. If there are reasons (e.g. ppm-level or higher product purity required) to choose welded partition walls, then construction and installation of a DWC becomes more demanding and certainly costlier.

Non-welded partition wall is a proven technology for packed columns. As summarized by Kaibel [9], the effort, time and costs associated with construction and installation of a new packed DWC or revamp of an existing column into a packed DWC are comparable to those associated with conventional column (re)design. As proven in an early revamp case, a non-welded partition wall can be arranged with ease also in a tray column [21].

Concerns regarding installation of a non-welded wall are related to the possibility of either phase to go to the other side of the wall, through the gaps between the partition wall and column walls. The feed location is a sensitive place, particularly in the case of a two-phase or flashing feed mixture, where both phases may appear partly as strong jets hitting the walls. Welding a short section of the partition wall within the reach of entering feed could be a safe solution to avoid this. The same should be done in the side product draw-off zone.

Another potential driving force that may move vapour to the other side is a local pressure difference due to unequal distribution of pressures on two sides of the partition wall. This could occur if, for instance, the bed height on one side is much lower than that on other side and the free area of the liquid collector above the short bed reduced accordingly to generate missing pressure drop. From Fig. 3b it can be seen that such a situation could develop around the feed inlet zone for a "2-2-4" configuration, or in top segment of a "2-3-3" DWC (see Fig. 6). On the side with the highest packed bed there will be a linear pressure profile, while on the side with an empty space above the shorter bed, the pressure profile will change stepwise.

If this is a rather short section, welding could provide remedy. Anyhow, to fully utilize the advantages of a non-welded partition wall, effective sealing means are required, that, attached to the side ends of the partition wall would keep both the vapour and the liquid on their side of the wall. Relevant patents (until 2010) addressing related inventions are mentioned elsewhere [2].

5.2. Control of vapour splits

The hydraulic design of a "2-3-3" DWC, as documented in Table 3, reflects the nominal design load. However, during operation, the pressure balance of a DWC will vary, imposing changes in vapour splits. Therefore the possibility to control the vapour splits by changing two condenser duties, i.e. the top pressures is an interesting option for the "2-3-3" DWC. This however may require welding of the partition wall to eliminate potential risk of vapour leakage and product contamination due to pressure difference at two sides of the partition in the column top.

In general, adequate mechanical provisions for adjusting the vapour flow resistance in parallel sections during operation are necessary to deal properly with multiple vapour split situations. These should be remotely controlled devices capable of reducing the free area for vapour flow to required extent, placed on dry locations, such as below the liquid collectors. A practical, common technical sense solution is a bubble cap tray with variable clear liquid height.

5.3. Top and bottom temperatures

In a four-product DWC a rather large number of stages needs to be accommodated, which implies a relatively larger spread of the temperature, from top to bottom, compared to individual columns in a three columns sequence. Fig. 8 shows for the "2-3-3" DWC temperature profiles separately for the prefractionator, middle section and main column side. The gaps in profiles correspond with positions and the height of liquid redistribution sections.

According to Fig. 8, the temperature difference between the top and bottom is of about 105 °C. The bottoms temperature of about 185 °C requires a fired heater as a reboiler. A potential cost-effectiveness related problem arises in situations when implementing a DWC would require higher temperature hot utility and/or refrigeration.

5.4. Temperature difference across the partition wall

If a welded partition wall is utilized, a large temperature difference across the partition wall, say above 30 °C, may induce local thermal stresses and cause partition wall deformation. In addition, thermal expansion of shell on the hot side may cause tilt, which could affect detrimentally both packings and trays. Uncertainties related to thermal stresses should be evaluated by construction material specialists through devoted simulations studies. Practically, a deformation of partition wall is avoided if a non-welded partition wall is utilized.

However, even a low temperature difference between parallel sections may induce some adverse effects on processing side. In the present case (Fig. 8) the largest temperature difference across the partition wall (17–19 °C) is observed between the hotter top bed (3.1a) of the main column section and the cooler second bed from the top in the middle section (2.1b). In the middle part of the column, with two times three sections in parallel, the temperature tends to decrease from the main column section towards the prefractionator column section and the differences are more pronounced between the middle section and the prefractionator.

Packed columns are more sensitive to potentially adverse effects of a temperature difference than are trayed columns. This is mainly because of inevitable development of strong wall effects. For instance, on high-temperature side, due to strong condensation effect the partition wall is covered by a thick liquid layer. The

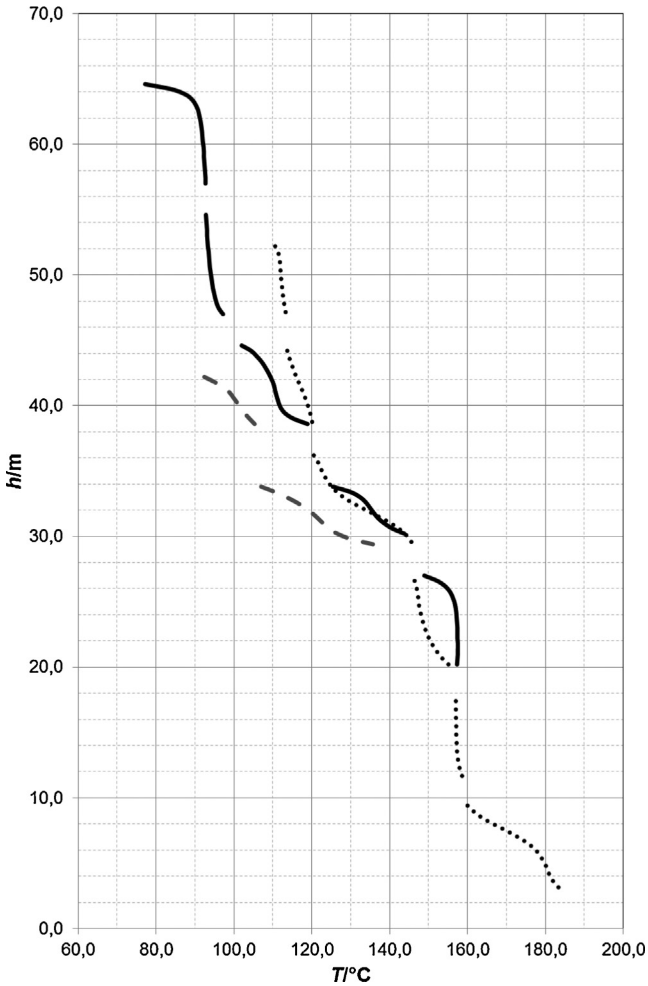

Fig. 8. Temperature profiles along the prefractionator, middle section and main column of a "2-3-3" DWC.

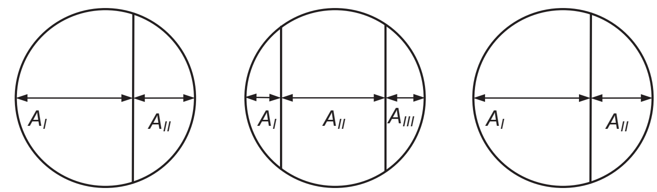

Fig. 9. Cross sectional areas of partitioned sections as encountered in DWC shown in Fig. 6.

partition wall on the cooler side may remain dry, if the wall temperature is higher than the bubble point temperature of the liquid film. This needs to be accounted for in the detailed design phase, and the insulation of the whole or a part of the partition wall is an option. However, in the case of large temperature differences, an insulated partition wall may minimize heat leak to cooler side, but column shell will conduct the heat to an extent that will rise the inner temperature of the shell on the cooler side above the bulk temperature, causing excessive evaporation of liquid in the wall zone. With this in mind, the periphery of packings needs to have effective provisions that will ensure removal of excessive liquid on wet side- and provide for enough wetting on dry side of the partition wall.

Also, one should not ignore the possibility that a pronounced temperature difference could cause a significant vapour density difference on the two sides, providing conditions for natural convention to occur. As mentioned before, an effective sealing is needed to prevent possible transport of vapour and liquid to the other side of a non-welded partition wall.

5.5. Noncircular cross-sectional areas

With two partition walls in parallel, different shapes of the cross-sectional area emerge, including a practically rectangular one in the central zone (see Fig. 9). Deviations from the common cylindrical bed layout may cause some performance deterioration. In the present case with a small shell diameter, the wall area to packing volume ratio in the partitioned sections of a packed DWC is rather large. Therefore, it is necessary to prevent bypassing of liquid and/or vapour along the walls, which requires installing highly effective wall wiper systems. Trays are much less sensitive in this respect.

5.6. Tray DWCs

A trayed DWC is also an option for industrial application considered in present study, which could certainly be an interesting alternative if much larger column diameter would be required than that required in the present design case, provided a relatively much larger pressure drop could be afforded in given situation. Sieve trays should be taken as basis for preliminary design purposes, because of the availability public domain models for hydraulic design and prediction of pressure drop. The first new designs of a trayed DWC have been for two large columns installed in a SASOL plant in South Africa [22]. One of these, with a tangent to tangent height of 100 m, and an internal diameter of 5.2 m, is one among the tallest single shell distillation columns ever built.

As demonstrated in the case of the revamp of an existing refinery column [21], partition walls in trayed columns can also be positioned off centre, fixed to bolt-bars welded on both sides of the column, and sealed with PTFE gasket. An advantage from the mechanical design, i.e. tray construction point of view, is the possibility to use partition walls to arrange tray support without interfering with the operation of the tray.

The established column manufacturers have knowledge and skill to assemble the required internal configurations. However, the mechanical design approaches and solutions are increasingly protected by patents; that given in [23] is a typical example in this respect.

A DWC with three sections in parallel would require trays with different shape of tray decks, the middle one nearly rectangular and the prefractionator and main column section ones with a pronouncedly curved side. The tray efficiency estimation should be based on experience with similar conventional columns. Safety margins need to account for potentially detrimental flow patterns, including back mixing, or even longer liquid flow paths, which may generate higher efficiencies than expected. Such situations belong to typical process design challenges within the existing know-how and industrial practices that need to be thoroughly evaluated for each case.

5.7. Control issues

Many practitioners are sceptical when it comes to the practical operation and control of DWCs, especially with fluctuations in feed flow rate and composition as experienced in practice. We believe that control issues can be solved by implementing available knowledge. One may not be able to obtain in practice the full energy savings, but these are already so large that a slight reduction in the gain is acceptable. As suggested elsewhere [12–15] an active vapour

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split manipulation, not available industrially at this moment, is the key to achieve in practice the full energy savings.

6. Concluding remarks

Implementing a four-product dividing wall column (DWC) instead of conventional three column sequences for a refinery aromatics processing plants could bring savings in both energy and total annualized cost of about 45–55%.

The energy and TAC savings associated with the simpler, industrially proven, single-partition wall DWC ("2-4") are about 50%. This is more than appealing, and could move practitioners to prefer implementation of this configuration. The additional complexity associated with arranging three sections in parallel, which implies accommodation and handling of three liquid and three vapour splits, is probably too risky for industrial implementation at this stage of DWC technology development.

As shown in this paper, a number of simplifications of the internal configuration are possible without affecting the energy efficiency adversely. The newest among these, worked out in greater detail here, is a DWC with two overhead product streams ("2-3-3" configuration).

Predictive tools developed to facilitate design and control of complex DWCs, used in conjunction with available simulation packages, can help to arrive at sound conceptual designs. A hydraulic design approach for multi- partition wall packed DWCs has been demonstrated for a packed, two overhead products ("2-3-3") four-product DWC.

In terms of cost-effectiveness, which is excellent in general, all compared minimum-energy configurations are close. This means that the choice among potential alternatives should be based on a thorough technical evaluation of all issues. Regarding the complexity of minimum energy configurations considered and evaluated here, the "2-2-4" configuration, with two liquid and two vapour splits and a rather short segment of column containing three sections in parallel, appears to be, from both process and mechanical design standpoint, the most suitable candidate for detailed design consideration. Such a configuration could be installed as a packed column, using existing design and construction know-how. More demanding, but feasible in case of larger shell diameters, would be the design and installation of a four-product DWC employing trays.

To ensure proper controllability, i.e. to provide for certain flexibility with respect to potential fluctuations in operating conditions, a multi-partition wall DWC should have the capability to vary the pressure drop at suitable locations by changing the vapour flow resistances.

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