

## Cost-effective design of energy efficient four-product dividing wall columns

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Potential alternatives for a fully thermally coupled four-product dividing wall column are addressed, emphasizing hydraulic design and column dimensioning aspects of importance for practical implementation of multi-partition wall configurations. Utilizing an industrially relevant aromatics processing plant case for evaluation and comparison of the cost-effectiveness of alternative configurations, this paper focuses on a new, minimum energy, four-product dividing wall column with two overhead product streams.

### 1. Introduction

As demonstrated in a simulation study based on an actual aromatics processing plant base case, a single-partition wall four-product dividing wall column (DWC), similar to that applied in practice (Olujic et al., 2009), would significantly reduce both energy requirement and capital costs compared to a conventional three columns sequence (Dejanović et al., 2011a). However, to minimize the energy requirement in such a case, a four-product DWC should be arranged internally to utilize fully the thermal coupling. To achieve this, three sections need to be arranged in parallel in the central part of the column shell (Asprion and Kaibel, 2010). A schematic representation of these two configurations, called here respectively “2-4” and “2-3-4”, assembled as packed columns, is given in Figure 1. The numbers denoting given configuration refer to the number of products of the columns connected in series in a flowsheet suitable for detailed calculation of optimum stage and reflux requirement. In the literature, the “2-4” and “2-3-4” configurations are often referred to as the “Kaibel column” and the “Sargent column” (Yildirim et al., 2011).

In both cases, off-centre positioning of the partition wall is required to minimize column diameter. This can be arranged in practice by utilising well-established non-welded partition wall technology, developed jointly by BASF SE and Julius Montz GmbH (Olujic et al. 2009). An additional difficulty associated with the quite complex internal configuration “2-3-4” is the need to arrange three liquid and three vapour splits, while the “2-4” configuration requires only one of each.

In spite of the recent advances in the design of four-product DWCs (Olujic et al., 2012) and the control of both the “Kaibel column” (Dwivedi et al., 2012) and the “Sargent column” (Dwivedi et al., 2013), as well as the certainty that packed versions of multi-partition wall DWCs can be installed using available know-how and proven non-welded partition wall technology, practitioners still have good reasons to be sceptical regarding the prospects for successful practical implementation of such complex configurations. It is the risk of malfunction of such a complex DWC, associated with the fact that an internal configuration with three partition walls involves three vapour splits. In absence of an adjustable vapour-split, the key to success in this respect is to arrange properly the flow resistances in the parallel sections during the design of the column (Olujic et al., 2012).

The related uncertainties could be lessened significantly if one of the required vapour splits could be avoided or controlled adequately. As elaborated in detail elsewhere (Halvorsen et al., 2011), a  $V_{min}$

diagram-based analysis brought the outcome in this respect, confirming the versatility and usability of this simple and effective design tool (Halvorsen and Skogestad, 2011). Most recently, Halvorsen et al. (2013) revealed that a four-product DWC with two overhead product streams could be an interesting alternative option, due to availability of two condensers, which allows certain flexibility with respect to control of vapour splits.

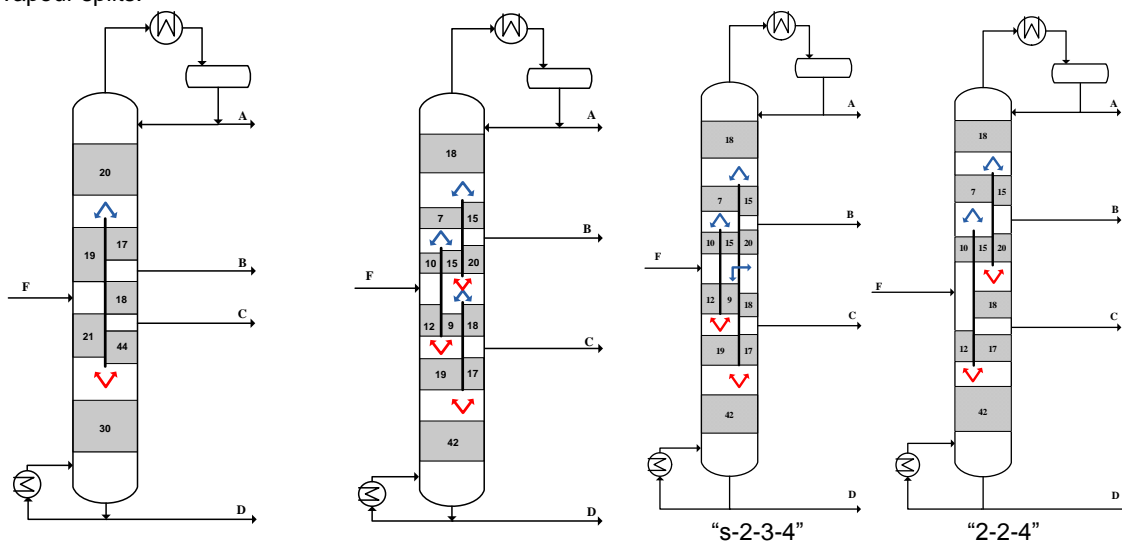


Figure 1: A single- (“2-4”) and a multi-partition (“2-3-4”) four-product DWC (Halvorsen et al., 2013)

Figure 2: Alternative, two-vapour splits four-product DWCs (Halvorsen et al., 2013)

The objective of this paper is to compare alternative design options and to discuss potential benefits and dimensioning-related aspects of a four-product DWC with two separate overhead product streams. Contrary to popular belief that DWCs with two overhead products or two bottom products cannot bring any energy saving compared to conventional sequences (Kaibel, 2007), the four-product DWC with two overhead products allows for more than halving the energy requirement compared to the conventional three-column sequence.

## 2. Previous work

As elaborated in greater detail elsewhere (Halvorsen et al., 2011), there is some flexibility in arranging the separation requirements and the related vapour and liquid flows within a full Petlyuk sequence representing a fully thermally coupled four-product DWC. Moreover, it appears possible to eliminate one vapour split, without affecting adversely the separation and overall energy demand.

Figure 2 shows schematically the internal configurations of two feasible variations of the “2-3-4” configuration, each employing two vapour splits. The positions and relative length of partition walls are indicated in the Figure 2, as well as the distribution of packed sections including stage requirement according to the outcome of detailed calculations.

The configuration on the left in Figure 2 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 a fraction of the liquid going from the middle to the main column section side. The so-called “2-2-4” configuration, shown on the right in Figure 2, employs two liquid splits and two vapour splits.

A further elaboration on the possibilities along this line of development (Halvorsen et al., 2013) resulted in a potentially interesting design, denoted here as “2-3-3” (see Figure 3), with the top position of the partition wall separating the middle from the main column section. This configuration employs two liquid splits and three vapour splits and it delivers two overhead product streams with the same energy and total stage requirement as other energy efficient four-product configurations (see Table 1).

It is interesting to mention here that the non-optimal, but very practical, “2-4” configuration allows energy savings of about 50 % compared to that of a conventional, three columns sequence. However, this is 18 % less than the achievable with a complex, fully thermally coupled configuration or its somewhat simpler alternatives. It is also interesting to note that the number of stages determining the column shell height is lowest for the configuration with two condensers (“2-3-3”). Unlike other options, this configuration is

characterised by a more equal distribution of stages between the middle and the main column sections, and the most demanding part of the separation effort is concentrated in the middle section of the column.

Table 1: Energy and stage requirement of different four-product DWC configurations considered in this study

DWC configuration	Conventional	"2-4"	"2-3-4"	"s-2-3-4"	"2-2-4"	"2-3-3"
Column	C1 / C2 / C3	DWC	DWC	DWC	DWC	DWC
Reboiler duty (MW)	3.8 / 3.1 / 3.1	5.82	4.81	4.81	4.81	4.81
Stages (total)	40 / 38 / 38	169	202	202	174	202
Stages (main column)	-	129	130	130	130	116*

\*In this particular case it is the middle column!

### 3. Dimensioning a "2-3-3" four-product DWC

The results of detailed simulations give all internal vapour and liquid flows, as well as physical properties of the two phases according to the pressure profile and related temperatures as established along different column sections. These serve as a basis for more detailed column dimensioning, providing diameter and tangent to tangent height of the DWC shell as well as relevant dimensions of each internal section. With this, a basis is provided for estimation of related capital costs using a validated method (Dejanović et al., 2011b) with accuracy as required in the preliminary design phase. The fraction of the estimated capital costs corresponding to the chosen life time (10 y) is added to the yearly operating costs to find the total annualized cost (TAC), which serves as basis for evaluation of the cost-effectiveness of various alternatives.

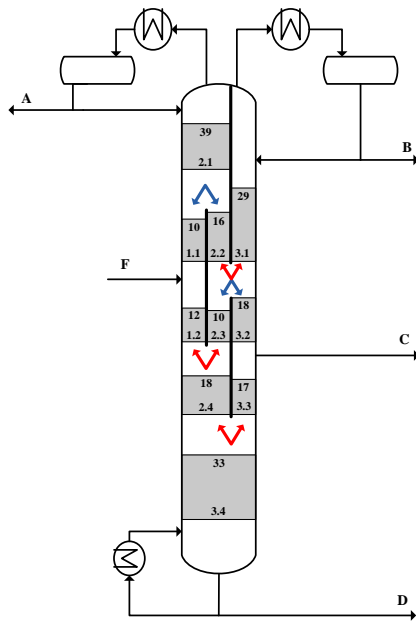


Figure 3: The "2-3-3", two overhead products four-product DWC

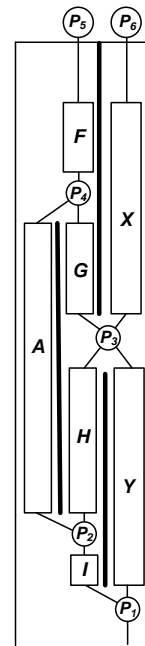


Figure 4: Pressure drop paths in the "2-3-3" DWC

The details related to the hydraulic design and dimensioning of DWCs with the "2-4", "2-3-4" and "2-2-4" configurations can be found elsewhere (Olujić et al., 2012). Internally, the "s-2-3-4" configuration resembles that of "2-3-4", employing, due to an increased vapour flow rate (no vapour split between middle and main column sections), a somewhat larger cross sectional area in the upper part of the middle section at the cost of that of the main column section. Therefore, the emphasis in the present work is on challenges and peculiarities associated with the design of a four-product DWC with two top products ("2-3-3" configuration).

To have a consistent basis for comparison with other options, the Montz-pak B1-350MN packing is taken as a basis for dimensioning of this column. It has a HETP (Height Equivalent to a Theoretical Plate) of 0.4 m, a value that was used during the dimensioning of other configurations (Olujić et al., 2012). The number

of theoretical plates (stages) is largest along the middle section of the column (116), which multiplied with the chosen HETP value gives the total bed height. The maximum single bed height has been set to be equivalent to 20 equilibrium stages (theoretical plates) per bed. Therefore, 116 stages need to be arranged in 7 beds, separated by 6 liquid redistribution sections. Standard spacing, i.e. distance between two packed beds, needed to accommodate a liquid redistribution section is 2 m, which means that in the present case the effective height of the column shell would be 58.4 m ( $0.4 \cdot 116 + 6 \cdot 2$ ). Adopting additional 5 m 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 would be 66.6 m. This is respectively 2 m and 2.4 m less than the height required for the “2-4” (68.6 m), “2-3-4” (69 m) and “2-2-4” (69 m) configurations (Olujic et al., 2012).

Since the reboiler duty is the same as in other multi-partition wall cases (see Table 1), the “2-3-3” DWC shell diameter should be the same. However, the cross-sectional areas of the three sections in parallel will differ, as given by the design imposed distribution of vapour and liquid loads. This dictates the lateral positioning of partition walls, and to arrange this properly within the given shell diameter, accurate balancing of the flow resistances in parallel sections is needed, according to the situation shown schematically in Figure 4. Here, symbols P1 – P6 denote absolute pressure at given level, and having P5 and P6 shown separately at the top of the column implies that the top pressures could be different, if appropriate. However this requires installation of a welded partition wall, which is impractical. Therefore the same top pressure is chosen for both sections in the “2-3-3” column, equal to that of the other configurations.

The pressure drop of the partitioned part of the “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.:

$$\Delta p_I + \Delta p_A + \Delta p_F = \Delta p_I + \Delta p_H + \Delta p_G + \Delta p_F = \Delta p_Y + \Delta p_X \quad (1)$$

Iterative pressure drop estimations were carried out using Excel Solver, including the adjustment of the cross-sectional area requirement in the parallel sections. The starting shell diameter is based on the position with maximum vapour and liquid loads, which, in the present case (above atmospheric pressure and slightly sub-cooled liquid feed) is 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 pressure drop of 3 mbar per unit bed height is chosen. This corresponds roughly to a vapour load about 25 % below the flood point of an irrigated packed bed equipped with conventional corrugated sheet structured packings. The initial guesses for the cross-sectional areas of the partitioned sections can be set to be equivalent to the corresponding fractions of the total vapour flow rate. These are transformed into equivalent cylindrical column diameters, which serve as a basis for estimating the related irrigated packed bed pressure drop. If one of these exceeds 3 mbar/m, the cross - sectional area is gradually increased at the expense of the neighbouring one, until the desired pressure drop is achieved.

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 the 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.

One should note that the number of liquid collectors and distributors, as well as the bed supports, is equal to the number of packed beds. Note that a distinction is made between the so-called “chimney tray” type- and “chevron or vane” type liquid collectors. The former are more suitable for large liquid loads and are the preferred choice at side-product draw-off locations, while the latter more streamlined ones, are generally preferred at lower specific liquid loads ( $< 20 \text{ m}^3/\text{m}^2\text{h}$ ). 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 of these devices, as well as for the 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 (Dejanović et al., 2011b). The pressure drop of packing support is negligible. However these devices are taken into account when determining the capital costs.

In the present study, the total annualized cost (TAC) is that corresponding to the sum of annual utilities costs and a 10 % of installed equipment cost. The details on empirical correlations for installed costs of the main process equipment (columns shells, condensers, and reboilers), including the unit prices 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 (Dejanović et al., 2011b).

#### 4. Results and discussion

The main dimensions and column pressure drops for a conventional three column sequence and for five options for a four-product DWC are summarized in Table 2, including information on the top pressure of each column and the total pressure drop. As expected, a DWC is considerably taller than any of the columns from a conventional sequence, because it needs to accommodate much more stages, i.e. all the stages required to arrive at given specification. The height required in the present case study is not a concern, but the height to diameter ratio ( $> 30$ ) is. Such a slender column requires a substantial shell thickness in the lower part and an appropriate support structure to sustain the wind loads. However, for plants with larger capacities and larger column diameters, this would not be a concern.

It is interesting to note that the energy-efficient DWCs reduce the vapour flow rate to such an extent that it requires a diameter which is the same as that of the largest of individual columns in conventional sequence. This suggests that existing columns could be considered as candidates for revamping. However, to accommodate necessary stage requirement within the available height, two or three existing shells should be connected in series.

With 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-wall DWCs require a 10 % lower diameter than the less energy efficient "2-4" configuration. This demonstrates clearly that in the case of a DWC, energy savings translate directly into a reduction of column diameter, i.e. into a significant capital saving.

*Table 2: Dimensions, internals, operating pressures and pressure drops of conventional three-column sequence, single ("2-4") and multiple ("2-3-4", "2-2-4", "2-3-3") partition wall DWCs considered in this study*

Configuration	Conventional	"2-4"	"2-3-4" "s-2-3-4"	"2-2-4"	"2-3-3"
Column	C1/C2/C3	DWC	DWC	DWC	DWC
Internals	Sieve trays	B1-350MN	B1-350MN	B1-350MN	B1-350MN
Shell height (m)	40.5 / 39.5 / 39.5	68.6	69.0	69.0	66.6
Shell diameter (m)	2.0 / 2.0 / 1.8	2.2	2.0	2.0	2.0
Top pressure (bar)	1.7 / 2.7 / 1.013	2.5	2.5	2.5	2.5
Pressure drop (bar)	0.313/0.272/0.244	0.114	0.117	0.105	0.114

Regarding the height requirement, the "2-3-3" configuration appears to be the most beneficial one. However, this configuration requires two condensers and more internals in the partitioned part of the column and this compensates for the gain due to lower shell height.

The pressure drop of the "2-2-4" DWC is the lowest. However, in all cases, the overall pressure drop is rather low, less than 2 mbar/m column height, and therefore it is not considered in the present case to be a parameter of importance for decision making in this respect.

*Table 3: Capital, operating and total annualized cost (TAC) of four-product column configurations considered in this study*

Configuration	Conventional	"2-4"	"2-3-4" "s-2-3-4"	"2-2-4"	"2-3-3"
Column	C1/C2/C3	DWC	DWC	DWC	DWC
Internals	Sieve trays	B1-350MN	B1-350MN	B1-350MN	B1-350MN
Equipment (US \$)	4,428,790	3,095,474	2,865,042	2,622,230	2,737,485
Saving (%)	-	30	35	41	38
Utilities (US \$)	1,678,523	838,742	687,557	683,526	682,227
Saving (%)	-	50	59	59	59
TAC (US \$)	2,121,402	1,148,290	974,061	945,749	956,026
Saving (%)	-	46	54	55	55

According to the numbers shown in Table 3, the total annualized cost (TAC) for the "2-3-3" design is somewhat lower than that for the "2-3-4" or the "s-2-3-4" configuration, but slightly higher than that of the simpler "2-2-4" DWC. Compared to the single-partition "2-4" DWC, the maximum energy efficiency configurations are approximately 18 % more cost-effective. Since the operation of an industrially proven single-partition wall four-product DWC brings an energy saving benefit of 50 % and nearly equal TAC benefit, the additional 18 % saving may not appear appealing enough to justify a more complex configuration. Nevertheless, in larger scale applications, an 18 % benefit may turn out to be attractive enough to consider implementation of such complex configurations.

The “2-2-4”, with two short partition walls and two liquid and two vapour splits, appears to be the simplest, and thus the most practical one. However, the “2-3-3” configuration, with two condensers offers some flexibility on operating side. Hydraulic design and detailed column design are subjects of a forthcoming publication, and the final choice will be based on a thorough technical evaluation of design, construction, installation and operation-related issues.

## 5. Concluding remarks

Implementing a four-product dividing wall column (DWC) instead of conventional three column sequences in the aromatics processing plant of a complex refinery could bring a benefit in energy and total annualized cost saving of about 45 - 55 %, depending on the chosen internal configuration.

Comparison of the estimated column heights and diameters clearly demonstrates that a single-partition wall DWC needs much less equipment volume than a conventional sequence for the same separation. Implementing the full thermal coupling gives further reduction in column diameter.

The energy and TAC savings associated with industrially proven, single-partition wall DWC (“2-4”) are more than appealing, and could move practitioners to prefer implementation of this less energy efficient configuration instead of going for the maximum, which could be achieved with a fully thermally coupled configuration (“2-3-4”). The additional complexity associated with the need to arrange three sections in parallel, which implies three liquid and three vapour splits, is at this stage of the DWC technology development a serious disadvantage.

As shown in this paper, a number of simplifications of the internal configuration of a four-product DWC are possible without affecting the performance adversely. One of these, worked out in greater detail here, is the two-overhead product configuration (“2-3-3”).

Regarding the complexity of the minimum-energy configurations considered here, the “2-2-4” configuration, with two liquid and two vapour splits and a rather short segment of the column containing three sections in parallel, appears to be, from both the process and mechanical design standpoint, the most promising candidate for detailed design considerations. Such a configuration could be installed as a packed column, using existing design and construction know-how.

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