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Dividing-Wall Column for Fractionation of Natural Gas Liquids in Floating Liquefied Natural Gas Plants

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The development of floating liquefied natural gas (FLNG) plants has resulted in a focus on reducing the weight and size of the topside processing facilities for these units. The conventional fractionation of natural gas liquids (NGL) in LNG plants implies a direct sequence of three or more conventional distillation columns requiring different levels of refrigeration. The results of a feasibility study are described, indicating that a packed three-product dividing-wall column (DWC) could replace conventional de-ethanizer and depropanizer columns. This could provide significant energy, hardware, weight, and footprint benefits, but, very likely, at the expense of an unaffordable cold utilities demand.¹⁾

Keywords: Distillation, Dividing-wall columns, Liquefied natural gas, Structured packings

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1 Introduction

Natural gas liquids (NGL) fractionation plants, stand-alone or as an important component of onshore as well as floating natural gas liquefaction facilities, employ sequences of three or more distillation columns to separate C1 to C5+ hydrocarbons according to specific site requirements. Since such processes are capital- and energy-intensive, both globally and regionally operating natural gas processing industries are interested in approaches that would reduce energy requirements and related environmental emissions as well as the size of equipment involved.

As well-known and proven in industrial practice [1,2], dividing-wall column (DWC) technology has a considerable potential in this respect. However, there are various technical barriers that need to be addressed to provide a proper basis for evaluation of technical feasibility and cost-effectiveness of the application of DWCs in offshore oil and gas processing plants. No installations of DWC have been reported in the literature for NGL fractionation, apart from a few academic simulation studies reported by Lee and co-workers [3–5]. Indeed, as indicated in these references, NGL fractionation provides opportunities for improved energy efficiency and cost-effectiveness using DWC technology. The potential for reduced plot area

and weight of equipment as well as the need to minimize energy-intensive refrigeration are of particular interest to Statoil and other companies installing NGL fractionation plants on floating facilities. The latter implies additional design- and operation-related concerns. However, conventional DWC equipment may be used in conjunction with know-how and experience gained with conventional NGL fractionation columns.

NGL fractionation plants installed on barges or FPSOs (floating production, storage, and offload vessel), the latter being increasingly used in place of fixed platforms, differ in some aspects considerably from conventional onshore facilities. On the processing side, most specific of the challenges are due to motion of a floating facility. If excessive, motion could affect detrimentally liquid distribution and efficiency of distillation columns. As reported in [6], even with extensive use of compartmentalized active or bubbling areas, trays are difficult to operate reliably under moving conditions. Similar difficulties apply for random packings, while structured packings appeared to be least sensitive in this respect. Structured packings are therefore used instead of trays in high- and intermediate-pressure columns as employed in floating NGL fractionation plants. Relevant details and peculiarities of the relation between packed column motion-induced liquid maldistribution and the resulting drop in efficiency are described in a recent paper writ-

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ten by ExxonMobil specialists [7], suggesting conservative designs. Most importantly, packed high-pressure distillation columns have been installed and operate on barges and FPSOs [6]. However, being appreciably taller than any of individual columns from a conventional sequence, a DWC might be more pronouncedly sensitive to various forms of movement experienced on a floating facility.

This and other concerns of particular importance for design and operation of packed DWCs on floating facilities are addressed in this paper, which explores the opportunities for incorporating a DWC into an NGL fractionation unit as encountered in floating liquefied natural gas (FLNG) plants. The results of this preliminary feasibility study confirm that a DWC provides a significant energy benefit of thermal coupling with a reduced equipment weight, indicating an increased cold utilities demand as a potential constraint in this respect.

2 The Floating Natural Gas Liquids Fractionation Plant Base Case

An FLNG processing plant is considered where the main stream of methane is separated as overhead product in a primary demethanizer (scrub) column, and bottoms' product is sent to NGL fractionation to be separated into four fractions according to given product specifications. The NGL-rich liquid feed, available at 34 bar at 54 °C, consists of practically negligible quantities of nitrogen and higher concentrations of methane (C1), ethane (C2), propane (C3), butanes (*i*-C4 and *n*-C4), pentanes (*i*-C5 and *n*-C5), and a remaining mix of *n*-C6 and heavier alkanes and aromatics. Tab. 1 shows specifications (rounded numbers) of the feed and four product streams as well as operating conditions as encountered in a direct three-columns sequence (Fig. 1) typically employed to separate the given feed into four product streams. These are denoted in the flowsheet in Fig. 1 as A, B, C, and D, and represent a C1-rich (A), a C2-rich (B), a C3+C4 (C), and a C5 and heavier alkanes and aromatics (D) fraction, respectively.

The product formulation C1-rich implies that a certain small amount of C2 is acceptable. This stream is recompressed and eventually liquefied to LNG. Similarly, a small amount of methane on the light side and propane on the heavier side is allowed in C2-rich stream. This stream is used as refrigerant make-up. The depropanizer top product is a mixture of propanes and butanes and is either used as refrigerant or exported. With regard to their main purpose, these columns from the sequence shown in Fig. 1 are referred to as the demethanizer, de-ethanizer, and depropanizer columns, respectively. The operating pressure for the first column will be close to the feed pressure, i.e., 34 bar. Regarding the fact that the third column delivers as top product a liquid mixture of propanes and butanes, the most reasonable choice is the operation at lowest pressure that allows condensing at approximately sea water temperature.

The top product of the second column is an ethane-rich product, which, similar to methane, requires the use of cold utilities (refrigerants). The operating pressure of the de-ethanizer column depends on the temperature level of available cold utilities, and this allows some flexibility, i.e., reduction

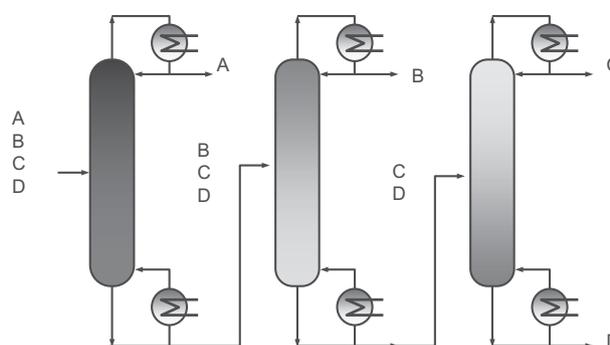


Figure 1. Conventional 4-p direct-split distillation sequence.

with respect to the value (17 bar) chosen for the conventional three-column sequence. For demethanizer, de-ethanizer, and depropanizer columns operated at 34, 17, and 7 bar, required cooling temperature levels are -91, -40, and +40 °C, respectively. Since the considered NGL fractionation plant is situated within a FLNG facility, even the coldest utility is available. However, any saving in this respect would be beneficial. A feature of the present situation is that the methane recovered from the demethanizer can be delivered as gas, and the cold from the liquefaction cycle can be used to liquefy the amount required as reflux for the demethanizer column.

3 Design Approach and Methods

The tool used for the purposes of preliminary assessment is the V_{\min} -diagram method [8], which has been proven in different applications [8–10]. It is a rather simple, robust, and reliable conceptual performance evaluation method that, based on feed composition and relative volatilities of key components at given pressure and temperature, allows estimation of minimum vapor rates in a complex, fully thermally coupled extended Petlyuk arrangement and its modifications. This applies for any number of components (fractions) and products. The ratios of molar overhead vapor flow and feed flow rates (V/F) for each configuration are estimated and compared on the same basis, revealing configurations most promising from an energy-saving standpoint. Regarding the fact that a four-product situation is considered, the number of potential heat-coupling arrangements was rather large.

Upon preliminary screening, eight potentially interesting configurations involving a DWC have been evaluated in greater detail and compared to the conventional direct-split three-column sequence which serves as reference. These include three different four-product (4-p) DWC configurations and five configurations combining a three-product (3-p) DWC and a conventional column. The first include two different designs of a multi-partition 4-p DWC: one with liquid side-products, another one with two top condensers, and one single-partition 4-p DWC with a side condenser. The two-column sequences include a DWC and a conventional column, and a conventional column and a DWC, without or in combination with side condensers or a vaporous side-product stream.

Table 1. Feed and product specifications.

	Feed	C1+C2	C2-rich	C4-rich	C5+
Temperature [°C]	54.0	-91.7	-26.6	25.0	151.5
Pressure [bar]	34	34	17	7	7
Vapor mole fraction [-]	0.09	0.00	0.00	0.00	0.00
Molar flow rate [kmol h ⁻¹]	108.5	17.4	9.2	29.9	52.0
Mass flow rate [kg h ⁻¹]	6951.0	282.0	270.8	1560.1	4838.1
Liquid flow rate [m ³ h ⁻¹]	11.5	0.9	0.8	2.8	6.9
Vapor flow rate (std) [m ³ h ⁻¹]	2432.0	390.4	206.1	670.9	1164.6
<i>Composition [mol %]</i>					
Nitrogen	0.00	0.01	0.00	0.00	0.00
Methane	16.38	98.97	5.80	0.00	0.00
Carbon dioxide	0.00	0.00	0.00	0.00	0.00
Ethane	8.19	1.02	92.82	0.58	0.00
Propane	11.73	0.00	1.38	42.08	0.00
<i>i</i> -Butane	6.08	0.00	0.00	22.04	0.00
<i>n</i> -Butane	9.81	0.00	0.00	34.87	0.41
2,2-Dimethylpropane	0.46	0.00	0.00	0.42	0.72
<i>i</i> -Pentane	6.45	0.00	0.00	0.01	13.46
<i>n</i> -Pentane	4.76	0.00	0.00	0.00	9.93
<i>n</i> -Hexane	6.00	0.00	0.00	0.00	12.54
Benzene	0.62	0.00	0.00	0.00	1.29
<i>n</i> -Heptane	20.07	0.00	0.00	0.00	41.91
Toluene	0.59	0.00	0.00	0.00	1.24
<i>n</i> -Octane	0.88	0.00	0.00	0.00	1.83
Ethylbenzene	5.90	0.00	0.00	0.00	12.33
<i>p</i> -Xylene	0.00	0.00	0.00	0.00	0.00
<i>m</i> -Xylene	0.48	0.00	0.00	0.00	1.00
<i>n</i> -Nonane	1.59	0.00	0.00	0.00	3.31
<i>n</i> -Decane	0.01	0.00	0.00	0.00	0.03

All DWC configurations considered in this study allow side condensers on side-product draw-off positions. This option enables reducing the superfluous vapor flow rate towards the top, and thereby reduces the top condensing duty as well as the top section diameter. This is particularly important when the top condenser needs expensive cold utilities. The optimal change in the vapor rate across the side stream is given by the difference in height of the peaks in the V_{\min} -diagram. Taking out the side stream as vapor may be a simple option when the optimal vapor flow rate change is similar in magnitude to the side stream itself.

For illustration, Figs. 2 and 3 show V_{\min} -diagram boundaries for a single-partition 4-p DWC and an alternative sequence

consisting of a conventional demethanizer column and a 3-p DWC. The latter includes the conventional sequence situation for reference. Three individual vapor per unit feed flow rate (V/F) peaks in this V_{\min} -diagram indicate minimum vapor load related to sharp binary separations between C1/C2+, C2/C3+, and (C3+C4)/C5+. The latter is the most demanding one, which determines the total vapor load and consequently energy (heat) requirement of a DWC. This depends on the configuration, and in all cases considered (Tab.2) it is lower than that of the conventional sequence ($V/F = 1.1$). Indeed, the vapor load is directly related to the reboiler duty, i.e., energy requirement, but in the present case, with top side product temperatures below -30°C , it may appear misleading because

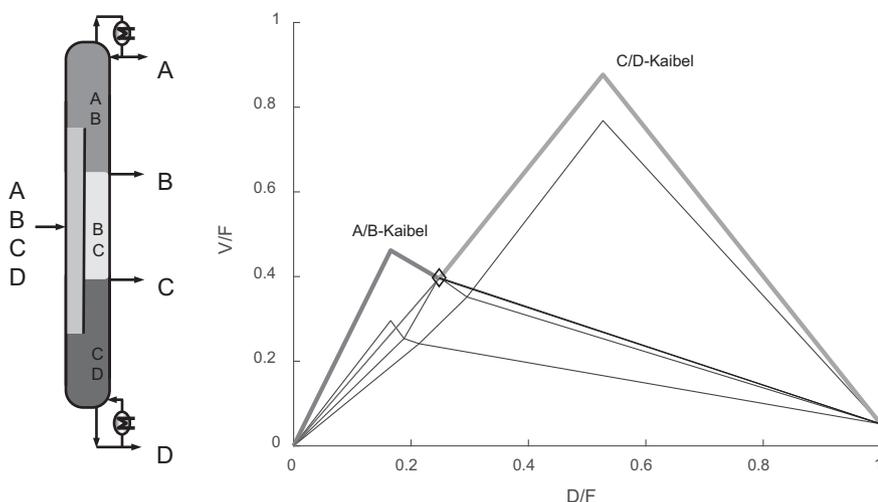


Figure 2. V_{\min} -diagrams of a single-partition 4-p DWC, replacing the conventional three-column sequence shown in Fig. 1.

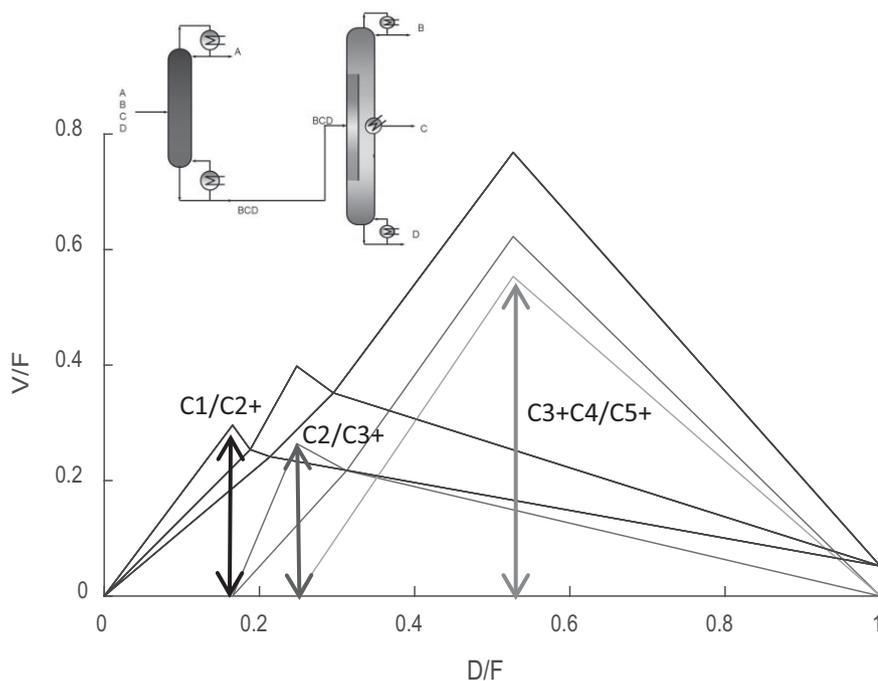


Figure 3. V_{\min} -diagram of an alternative configuration combining the conventional demethanizer and a 3-p DWC. Minimum vapor loads of each of the three columns from the conventional sequence are displayed for reference.

the costs of required cold utilities (refrigerants) are a dominating factor in NGL fractionation plants.

The stage and reflux requirements for the chosen configurations and all internal vapor and liquid flows were obtained by detailed simulations. All columns in the present study were dimensioned as packed columns using a validated method that allows hydraulic design of complex DWCs with an accuracy sufficient for purposes of preliminary design, i.e., feasibility studies [11, 12]. The packing chosen for this purpose (Montz-Pak B1-350MN) is well-established in DWC applications. The

internal shell diameter is based on the allowable vapor throughput, which is chosen to be on conservative side by setting the pressure drop of 3 mbar m^{-1} as upper limit. With this, the internal vapor load of all conventional columns and critical sections of a DWC was well below the flood limit.

The height of a DWC depends on the number of stages in conventional sections plus the largest number of stages contained in the sections arranged in parallel. The single bed height is limited to maximum 20 stages, which is 8 m in the present case. This is based on the adopted HETP (height equivalent to a theoretical plate) value of 0.4 m. Note that, worried about the potential performance deteriorating effect of liquid maldistribution that tends to rise with increasing bed depth, some designers considering other packing types and/or sizes may be more conservative in this respect. Anticipating a certain loss of efficiency, in the present study a HETP of 0.5 m has been used for sections with a specific liquid load exceeding $30 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$.

The height required for installation of a liquid redistribution section was chosen to be 1.5 m, and 2.0 m was taken as the height required for vapor-liquid disengagement at the top of the column, which is a reasonable choice for column diameters considered in the present study. The height of the bottom (sump) of the column was determined in conjunction with a given internal diameter assuming the liquid retention time of 5 min and surge time of 1 min, respectively.

Additional dimensioning effort was needed to arrive at the required weight of the compared configurations. Stainless steel was chosen as construction material for shell and column heads. The minimum wall thickness for shell and heads was calculated according to well-established ASME (American Society of Mechanical Engineers) codes and procedures [13, 14]. The weight of packing and auxiliary internal equipment was added to get the total weight of installed columns. The weight of the supporting structure, external piping, reboilers, condensers, and reflux accumulators, as well as the weight of the liquid inventory during operation was not considered here.

Table 2. Relative vapor load, shell weight, and cold utilities and water cooling demand of DWC configurations compared to conventional three-column sequence as reference.

No.	Configuration	Relative V/F [-]	Relative weight [-]	Condensing duties [kW]		
				-91 °C	-40 °C	40 °C
1	Conventional direct-split sequence	1.00	1.00	-91	-164	-513
2	4-p DWC with liquid side-products	0.69	-			
3	4-p DWC with two top condensers	0.69	-			
4	4-p Single-partition DWC + side condenser	0.79	-			
5	3-p DWC + conventional column (CC)	0.86	1.46	-133	-	-513
6	3-p DWC with vaporous side-product + CC	0.86	1.40	-113	-	-513
7	3-p DWC + side condenser + CC	0.86	-			
8	CC + 3-p DWC	0.83	0.95	-91	-371	-
9	CC + 3-p DWC with vaporous side-product	0.83	0.91	-91	-265	-

4 Results and Discussion

4.1 Comparison of Chosen Configurations

Tab. 2 summarizes the overall V/F values and relative weights for a number of DWC-based configurations, using the conventional sequence as reference. As expected, the largest energy savings are achieved with a multi-partition, 4-p DWC configuration (not yet attempted in practice), followed by the single-partition one, which is less energy-efficient due to a certain amount of inevitable remixing of components in the space between two side-product draw-offs. Although potential energy savings are appealing and the know-how required to design, install, and operate a single-partition wall 4-p DWC as packed column is proven [15], excessive height, bottoms temperature, and full refrigeration requirement make it unsuitable for an application as considered here.

The main reason for this is the rather large spread of boiling points among the components. In a conventional three-column sequence, each column can be operated close to optimum pressure for the given products. This is impossible to accommodate in a 4-p DWC, which can have only one operating pressure. If operated at the same top pressure as the demethanizer (34 bar), the top and bottoms temperature will differ by more than 300 °C. The bottoms temperature will exceed the critical temperature of pentanes and heavier components.

However, these obstacles could be avoided by connecting a conventional column (CC) and a 3-p DWC in series. This allows running either the demethanizer or depropanizer at the most suitable pressure, while that of the DWC could be operated at another pressure to best suit the needs of its separation.

As shown in Tab. 2, the configurations consisting of a conventional column and a DWC perform better than a conventional sequence, but appear to be less efficient than a 4-p DWC. The combination of a 3-p DWC and a depropanizer column is in all variations less efficient than a combination of a demethanizer and a 3-p DWC. In case of the latter, a DWC in

conjunction with the vaporous side-product stream (case 9 in Tab. 2) minimizes the cold utilities demand for ethane condensation, which makes it the most promising arrangement for a given separation task. Most importantly, as shown in the second column of Tab. 2, this configuration with the DWC operated at 8 bar enables an appreciable weight reduction compared to the conventional three-column sequence.

Additionally, a considerable weight benefit would result from the reduced number of reboilers, condensers, and reflux accumulators, which will also further reduce the required footprint. In addition to the equipment weight saved, the weight related to structural steel and piping is avoided.

Indeed, the configuration combining a conventional demethanizer and a 3-p DWC reduces the total energy requirement of the NGL fractionation process significantly, but at the expense of a somewhat larger cold utilities demand at -40 °C (Tab. 2). Being rather high, the cold utilities cost is the dominating factor, and the cooling temperature level penalty in the present case is such that the operating cost of this in many respects advanced and highly beneficial configuration could exceed that of the conventional sequence.

A thorough elaboration on the impact of thermal coupling on utility demands and temperature levels and the need to consider properly the energy quality and quantity when evaluating design alternatives with respect to energy efficiency, as well as on performance characteristics and DWC design and operation-related concerns can be found elsewhere [16–18].

4.2 Concerns Regarding the Most Promising Configuration

A schematic drawing of the chosen configuration consisting of a conventional demethanizer and a three-product DWC is presented in Fig. 4, including operating pressures and corresponding temperatures at critical places. One should note that pre-cooling the feed to a reasonable temperature could reduce the

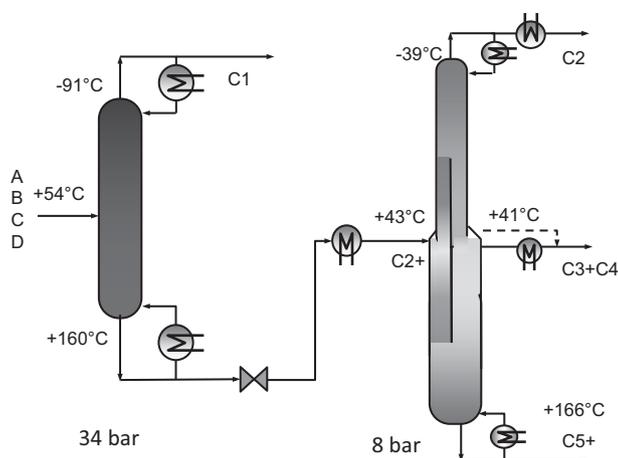


Figure 4. Schematic representation of a conventional demethanizer and a 3-p DWC as an alternative for the conventional three-column sequence.

condenser duty. This, however, is at the cost of an increased reboiler duty, but, as mentioned before, the costs associated with the former, i.e., the very expensive cold utilities required, are the dominating factor in the present case. It is also important to avoid feed temperature variations in order to better maintain optimal operation of the DWC. In order to obtain the most adequate control strategy (structure), sensitivities in this respect should be evaluated in a separate dynamic simulation study.

Since in a DWC with a side-stream condenser or a vapor-side draw the vapor load is effectively reduced, the shell diameter of the upper part of the DWC can be significantly diminished with respect to the part below the feed. In the present case it is 0.45 m, while the internal diameter of the lower part is 1.05 m. With 48 stages contained at the main column side the total shell height is 31 m, which largely exceeds that of individual conventional columns. This will inevitably lead to an increased extent of movement, causing a more pronounced deviation from the vertical with a certain frequency. Since trays, even specially designed ones, do not eliminate potential reduction of efficiency due to moving-induced liquid maldistribution that induces and stimulates vapor maldistribution, these high-pressure distillation columns need to be equipped with packings. Namely, both random and particularly the structured packing are much less sensitive in that respect. One should note that in case of an enduring tilt, e.g., if winds blows for a longer period from the same direction, the structured packing is a preferred choice. In addition, a structured packing equipped with robust and effective wall wipers avoids appearance of excessive wall flow, which affects efficiency adversely. From these reasons, a structured packing well-proven in DWC applications onshore was chosen for the purposes of this comparative study.

Nevertheless, such a slender DWC with a height-to-diameter ratio around 30 as considered here would require a heavy frame (additional weight!) to ensure the required mechanical stability and rigid enough shell, to avoid additional more pronounced movement of the upper part, which is expected to be induced by the motion of the moving floating platform (barge, FPSO). This could eliminate the potential gain in weight

(Tab. 2) with respect to that of the conventional three-column sequence.

One of the main design and operation concerns is related to the packing efficiency achievable under high-pressure distillation conditions as encountered in common NGL separation plants. Since the distillation columns are usually designed for as high as reasonable vapor load (80% of flood), the specific liquid loads in high-pressure columns are rather high, well above those considered sound for the common size of structured packings. From this reason, in the present study, the diameters of all columns in conventional three-column sequence have been based on $30 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$ as maximum specific liquid load. This means employing larger column diameters than required in the case of trays. It implies also an increased weight, however, this is not prohibitive in the present case, where, due to a rather small plant capacity (feed stream $\approx 7 \text{ t h}^{-1}$), the diameters of all conventional columns are below 1 m. As mentioned before, only in critical sections of a DWC higher liquid loads (up to $50 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$) have been allowed assuming that this will introduce a 25% efficiency loss which was compensated by a corresponding increase in the design HETP value.

Since something like this has not been yet attempted in practice, further detailed technical evaluation of the chosen configuration is required addressing all design, construction, installation, and operation uncertainties and issues in order to mitigate potential risks, particularly those associated with movement of the columns, prior making a decision on implementation of such a DWC-based configuration into a floating natural gas processing plant environment.

5 Conclusions

A conventional demethanizer combined with a 3-p DWC, operated at a moderate pressure, appears to be a promising alternative to the conventional three-column sequence as encountered in NGL fractionation plants. In addition to the overall energy saving, such a configuration enables also weight and footprint reduction, which makes it particularly interesting for application in FLNG facilities. However, though it reduces the total vapor load and cooling requirement, the DWC employed in the present case requires more cold utilities than the de-ethanizer in the conventional sequence, and the accompanying temperature penalty may render it industrially unviable. An increased operating pressure is not the solution in the present case, and it is expected that fine-tuning the feed thermal condition and prefractionator preferred split could reduce the cold utilities demand accordingly.

Being taller than any of conventional columns, the DWC employed in this case is prone to detrimental effects of movements as experienced on a floating facility. To minimize potential loss of separation efficiency, structured packings need to be used instead of trays or random packings, which are preferred internals for high- and moderate-pressure columns onshore. Uncertainties remain regarding the expected level of separation performance of structured packings under high-pressure distillation conditions.

Since design safety in this respect implies additional shell height/weight, quantitative benefits of implementation of a

DWC in this particular application could be outweighed by detrimental effects of additional refrigeration demand.

The authors have declared no conflict of interest.

Symbols used

D	$[\text{kmol h}^{-1}]$	distillate flow rate
F	$[\text{kmol h}^{-1}]$	feed flow rate
V	$[\text{kmol h}^{-1}]$	vapor flow rate

Abbreviations

A, B, C, D	components of feed mixture
CC	conventional column
DWC	dividing-wall column
FLNG	floating liquefied natural gas
FPSO	floating production, storage, and offload vessel
HETP	height equivalent to a theoretical plate
LNG	liquefied natural gas
NGL	natural gas liquids
3-p DWC	three-product DWC
4-p DWC	four-product DWC

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