

Dividing Wall Columns for Natural Gas Liquefaction Plants

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In order to meet current carbon dioxide emissions reduction challenges, natural gas processing and refining industries have to find the ways to minimize energy requirements of distillation operations. Building on foundations laid down in a preceding effort, this paper shows that this could be achieved in a cost-effective way in natural gas liquids fractionation plants and that a conventional demethanizer column combined with either a thermally coupled direct sequence of deethanizer and propane-butane recovery columns or a dividing wall column produces expected savings in capital and hot utilities costs as compared to conventional direct sequence, without any temperature penalty on cold utilities side. The choice between available options will largely depend on important process considerations that may differ for offshore and onshore plants to the extent depending on specific site requirements.

1. Introduction

Modern floating and on-land natural gas liquefaction (NGL) plants employ direct sequences of three or more distillation columns to recover C1 to C5+ hydrocarbons according to specific site requirements. In a recent paper addressing potential for energy conservation in a floating NGL fractionation complex (Halvorsen et al, 2016) it is shown that replacing conventional de-ethanizer and depropanizer columns by a three-product dividing wall column (DWC) could lead to substantial overall energy saving as well as significant weight and footprint benefits. However, this was achieved at the expense of an increased cold utility demand with respect to that of a conventional de-ethanizer column in a direct three columns sequence. Indeed, being a dominating factor, an increase in refrigeration costs may render a DWC industrially unviable in this and similar applications.

Present paper explores means and configurations that could help to overcome this, refrigeration demand related burden and open the door for implementing thermal coupling and DWC technologies in NGL fractionation plants in a cost-effective way, both as new design and a retrofit option. The latter is particularly interesting because it provides natural gas processing and refining industries with an opportunity to meet legislation imposed energy and carbon dioxide reduction challenges in existing NGL fractionation plants.

2. Previous work

Details including a table with feed and product specifications for a natural gas liquids (NGL) fractionation complex within a state-of-the-art floating liquefied natural gas (FNLG) plant can be found elsewhere (Halvorsen et al, 2016). The natural gas liquids rich feed is available at 35 bar and 54 °C, and is to be separated into four fractions: a methane rich stream (C1+), an ethane rich stream (C2+), a propane and butane rich stream (C3+C4), and a pentanes and heavier stream (C5+). Common approach in this case is to utilize a direct three column sequence (Figure 1), and in previous detailed simulation study the operating pressure at the top (condenser) of the demethanizer was 34 bar, that of deethanizer column was 17 bar, and that of propane-butane column was 7 bar. As it can be seen from Table 1, containing feed and product specifications for this case, the corresponding condenser temperatures are -91 °C, -27 °C, and 25 °C,

respectively, which implies that refrigeration is required in condensers of demethanizer and deethanizer columns.

As described in Halvorsen et al. (2016), to arrive at a feasible energy saving option the thermal coupling should consider second and third column only, leaving demethanizer column as it is. Among a number of options considered and evaluated, the arrangement utilizing a conventional demethanizer column combined with a conventional three-product DWC, operated at 8 bar, appeared to be the most promising in this respect. This arrangement with a centrally placed partition wall, called “full DWC” in further text, is shown schematically in Figure 2. The overheads vapor enters partial condenser that liquefies only the fraction of vapor required as reflux. In other words, the top product is a vapor stream. Also the side stream, i.e. (C3+C4) fraction, which is three times larger than ethane rich stream was drawn off as vapor. This effectively reduces the vapor load above the side product draw-off stage but remaining vapor mixes above the upper end of partition wall with that coming from the prefractionator; thus the condenser receives more vapor and more cold utilities are needed to liquefy the excessive vapor, i.e. -265kW compared to -164 kW in case of conventional deethanizer column.

Table 1: Feed and product specifications for NGL fractionation in a floating LNG plant

| Stream Name | Feed | C1 | C2 | C3+C4 | C5+ |
|---------------------------------------|--------|-------|-------|--------|--------|
| Temperature, °C | 54.0 | -91.7 | -38.9 | 33.6 | 154.0 |
| Pressure, bar | 34.0 | 34.0 | 8.0 | 7.0 | 7.3 |
| Vapor mole fraction, - | 0.09 | 0.00 | 1.00 | 1.00 | 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 | 1559.7 | 4838.5 |
| Composition, mole % | | | | | |
| 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 | 42.09 | 0.00 |
| I-Butane | 6.08 | 0.00 | 0.00 | 22.04 | 0.00 |
| N-Butane | 9.81 | 0.00 | 0.00 | 34.87 | 0.40 |
| 2-2-Dimethylprop | 0.46 | 0.00 | 0.00 | 0.39 | 0.74 |
| I-Pentane | 6.45 | 0.00 | 0.00 | 0.02 | 13.46 |
| N-Pentane | 4.76 | 0.00 | 0.00 | 0.00 | 9.93 |
| N-Hexane | 6.00 | 0.00 | 0.00 | 0.00 | 12.54 |
| Benzene | 0.62 | 0.00 | 0.00 | 0.00 | 1.29 |
| N-Heptane | 20.07 | 0.00 | 0.00 | 0.00 | 41.90 |
| Toluene | 0.59 | 0.00 | 0.00 | 0.00 | 1.24 |
| Heavies | 8.86 | 0.00 | 0.00 | 0.00 | 18.50 |

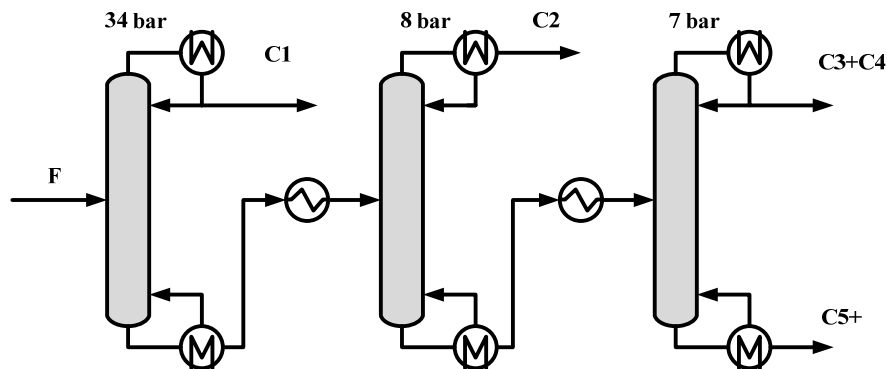


Figure 1: Direct three column sequence

Following the suggestion from previous paper (Halvorsen et al., 2016), it appeared that by subcooling the feed to 28 °C (in previous case it was 43 °C) and increasing the number of stages in prefractionator and main column the cold utilities demand in this case could be reduced to -175 kW. This, however, is still more than

required in case of conventional deethanizer operated at 17 bar, and a somewhat colder cooling utility is needed at 8 bar to operate partial condenser at a considerably lower temperature, i.e. -39°C . Note that if the conventional deethanizer would be designed to operate at same absolute top pressure as DWC, i.e. 8 bar in the condenser, the condenser duty would drop to -52 kW . This number is considered as proper target for thermal coupling effort. Therefore the direct sequence with the deethanizer and (C3+C4) recovery column operated at top pressures of 8 bar and 7 bar, respectively, has been taken as base case configuration for present study. Important design and operating parameters for this case are shown in Table 2.

Table 2: Operating conditions and design data for direct sequence and thermally coupled direct sequence (TCDS)

| | Deethanizer | (C3+C4) | TCDS | |
|---------------------------|-----------------------|----------------------|-----------------------|------------------|
| | column | column | Prefractionator | Main column |
| Feed temperature | 28°C | 78°C | 28°C | - |
| Feed cooler duty | -643 kW | -43 kW | -643 kW | - |
| Condenser pressure | 8 bar | 7 bar | 8 bar | 8 bar |
| Condenser temperature | -39°C | 45°C | -39°C | 50 |
| Condenser duty | -52 kW | -236 kW | -52 kW | -157 kW |
| Distillate vapor fraction | 1 | 1 | 1 | 1 |
| Reboiler duty | 315 kW | 606 kW | 830 kW | |
| Total reboiler duty | 921 kW | | | |
| Number of stages | 20 (18) | 56 (54) | 17 (15) | 54 (52) |
| Feed stage | 6 (5) | 14 (13) | 5 (4) | 20 (19) |

According to the required duty, subcooling the deethanizer feed is quite demanding, however the temperature level of the feed as well as overheads vapor leaving the top of the (C3+C4) recovery column is that high that required temperature drop can be easily achieved using sea water as cooling medium. Note that both columns are equipped with a partial condenser and a partial reboiler, which, by virtue of their nature, act as external equilibrium stages. The numbers in parentheses correspond to the number of stages installed within column shell

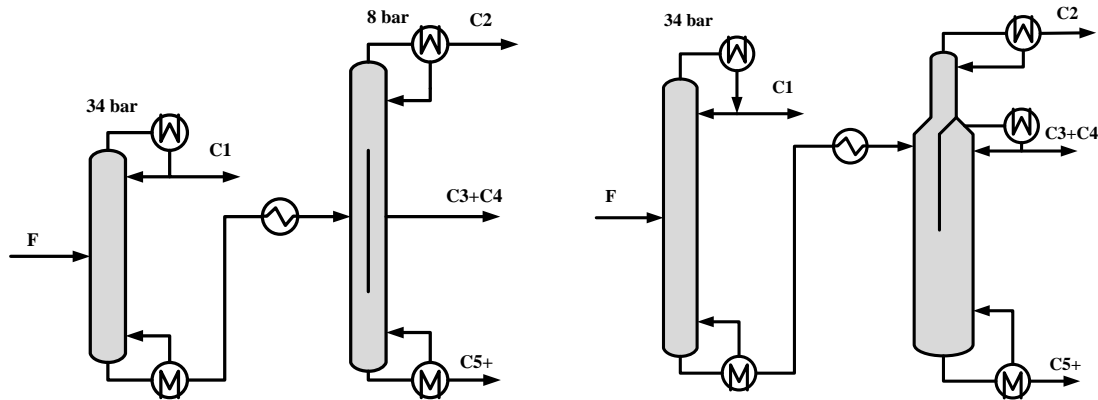


Figure 2: Conventional demethanizer & full-DWC Figure 3: Conventional demethanizer & modified full-DWC

3. Effective thermal coupling arrangements

As mentioned above, main prerequisite for minimization of cold utilities demand in a thermally coupled arrangement is assuring by design that only the vapor from prefractionator operated at conditions resembling those of conventional deethanizer is delivered to the refrigerated condenser at the top. As indicated during preliminary evaluations using V_{\min} diagram method (Halvorsen and Skogestad, 2011) and confirmed by detailed simulation, this could be achieved by rearranging the main column side of the full DWC (Figure 2) to include an intermediate condenser immediately above side product (vapor stream) draw-off, to condense remaining vapor that would ascend towards the column top, transforming it into an internal reflux (liquid) stream on main column side. This, however, would require incorporation of an additional condenser and additional shell height to install it.

Related constructional and operational complexities and expenses could be completely evaded, simply by installing a lateral, sloped partition wall on main column side immediately above the draw-off stage and using

an external, water cooled condenser to generate amount of reflux required to reach given side product specification. Being useless, the complete section of the main column above the draw-off can be omitted. This, as shown schematically in Figure 3, would allow a significant reduction in shell diameter above the side-product draw-off position, to be dimensioned just to accommodate rectification section of the prefractionator. This implies that the modified full DWC will be taller than any of two conventional columns. However this will be not so pronounced because the rectification section of the prefractionator contains five stages only. Most importantly, in such an arrangement very cold part of the column is placed above the hot part of the column. In the latter, the temperature difference over the partition wall is not that large that it could induce performance deteriorating effects. This could even turn into an intrinsic advantage, i.e. improved overall thermodynamic efficiency of the process. Namely, analogously to operation of an internally heat integrated distillation column (HIDiC, Kiss and Olujić, 2014) the heat transferred through the partition wall from the hotter main column could facilitate evaporation on colder prefractionator side to certain extent.

On the other hand, modified DWC shown schematically in Figure 3 represents a different arrangement of internal thermal coupling compared to that of a conventional DWC with a centrally placed partition wall. If we consider fundamental concepts of thermal coupling (Agrawal, 2001),(Smith, 2005), it appears that the thermal coupling arrangement of modified full DWC from Figure 3 is equivalent to a thermally coupled direct sequence (TCDS). In a TCDS arrangement, shown schematically in Figure 4, the reboiler of the first column in the direct sequence is omitted and the vapor required by this column is supplied by the reboiler of the second column.

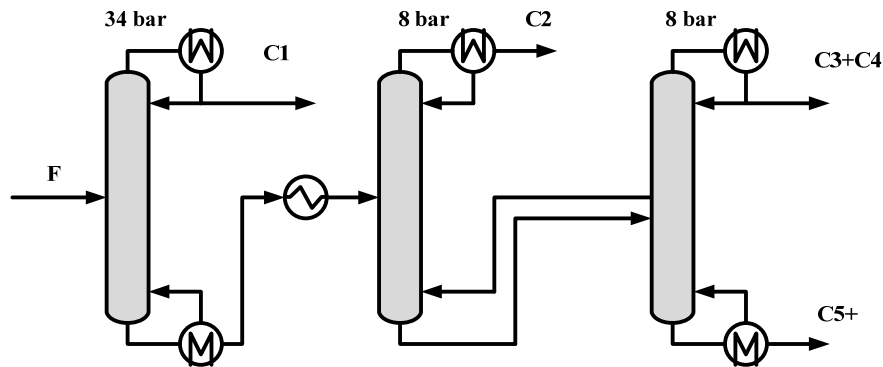


Figure 4: Conventional demethanizer & TCDS arrangement

This, however, was since long considered by Manley (1996, 1998), under the name “recycle coupled deethanizer and depropanizer”, as an opportunity for improvement of energy efficiency of conventional, on land NGL fractionation complexes. He evaluated various options in this respect, and in his 1998 publication he proposed a highly thermally integrated four column sequence, with ethane, propane, n-butane, iso-butane and C5+ fraction (natural gasoline) as products, combining external and internal thermal coupling. Revival in this direction occurred recently; however, focus is on further elaboration of thermal coupling and DWC arrangements suitable for recovery of propane and heavier components (Long and Lee, 2014). It appears that thermal coupling including cold deethanizer column is not considered in general literature as promising in this respect, which, as shown in what follows, may be considered as a wrong perception.

Indeed, as ascertained by detailed simulation, with same subcooled feed and stage requirement the TCDS arrangement can achieve same product specifications at the same cold utilities requirement as a conventional deethanizer operated at same top pressure. Overall mass balance and internal liquid and vapor flows as well as stage requirement per section are shown in Figure 5, including reboiler and condenser duties. These, compared with those of direct sequence in Table 2, indicate that thermal coupling in this unfriendly case (a very wide boiling mixture) requires some 10 % less hot utilities, without any penalty on cold utilities demand side.

A thermodynamically equivalent alternative for this configuration is so called side-rectifier arrangement (TCSR), where the vapor required by the second column is supplied by the reboiler of the first column (Smith, 2005). Both configurations imply draw-off and transport of a vapor stream from one shell to the other, by arranging the operating pressures accordingly, and the additional pressure drop needs to be accounted for appropriately to ensure maintenance of required vapor split. Importantly, this arrangement allows control of vapor split by balancing condenser duties, which is a prerequisite for a smooth operation of the prefractionator at the preferred split. A second advantage is in simplicity of the construction, with two shells in parallel. On land this allows utilization of proven tray designs, while in case of a floating LNG plant, a lower shell height makes a column less prone to motion-induced liquid maldistribution and accompanying column efficiency

reduction effect. Last but not the least, both TCDS and TCSR could be highly interesting as retrofit option for existing NGL fractionation plants. This, however, may require installation of an additional, larger diameter column to accommodate appropriately increased vapor volume associated with low pressure operation of pre-fractionator, i.e. deethanizer.

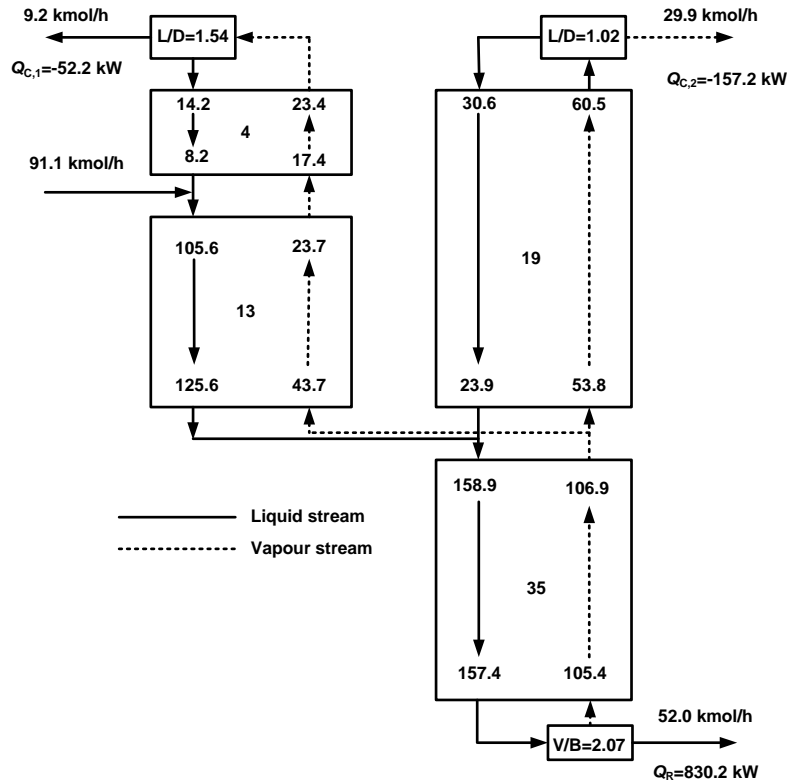


Figure 5: Material and energy balance of TDCS arrangement with internal molar liquid and vapor flow rates, and stage requirement per section according to detailed simulation.

Added value of a side-rectifier arrangement is that it can be constructed as a single shell column, i.e. as a dividing wall column with partition wall in upper section of the column (Smith, 2005). This partitioned side-rectifier arrangement (SR-DWC), shown schematically in Figure 6, ensures additional plot area and weight benefits, and being accommodated in a shorter shell than partitioned TCDS could make it to a preferred choice for floating LNG plants.

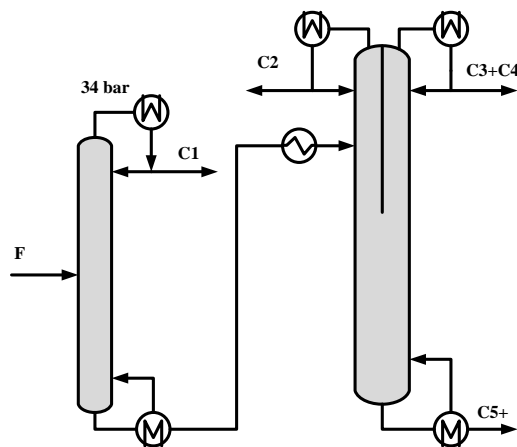


Figure 6: Conventional demethanizer & partitioned side-rectifier DWC (SR-DWC)

However, unlike partitioned TCDS shown in Figure 4, this arrangement, with a very large temperature difference over the partition wall (> 50 K), may not function properly without adequate insulation. Some solutions in this respect can be found in a patent by G. Kaibel (1998). Certainly, it is a challenge to ensure mechanical integrity of the construction with a welded partition wall in case of such a large temperature difference, and further concern in this respect is the extent of thermal expansion of the shell on the hot side, which, if significant, needs to be accounted for during installation of internals to ensure proper levelness under operating conditions (B. Kaibel, 2014, Jansen et al., 2014). This is demanding and related uncertainties may emerge as a reason to decline this compact construction and choose for somewhat taller DWC shown in Figure 3.

Both, external (TCDS) and internal (SR-DWC or partitioned TCDS) thermal coupling arrangements, if primarily considered for installation on a floating facility, should utilise packed columns, as discussed in elaborated way elsewhere (Halvorsen et al., 2016). In a similar onshore plant, with a relatively much larger capacity and equipment size, tray columns would be a preferred choice. A detailed description of a trayed SR-DWC can be found in a patent by Ognisty and Manley (1998). Practical implementation is going slowly, but there is evidence that the number of trayed DWCs as well as related construction and installation knowhow is increasing steadily (Bhargava et al., 2016).

4. Concluding remarks

The energy efficiency of NGL fractionation plants as encountered in natural gas liquefaction plants, offshore and onshore, could be significantly improved by implementing thermal coupling where appropriate. As demonstrated in this study, combining a conventional demethanizer with a thermally coupled direct sequence (TCDS) replacing conventional deethanizer and (C3+C4) recovery columns provides a realistic opportunity for natural gas processing and refining industries to achieve significant energy savings, e.g. carbon dioxide emissions reduction, in a cost-effective way. This simple and effective thermal coupling arrangement is amenable for both new designs and as a retrofit option, and a thermodynamically equivalent partitioned-TCDS or side-rectifier arrangement (SR-DWC), latter utilizing a well-insulated dividing wall in upper part of the shell, would ensure further weight and plot area benefits. Final choices in this respect, including choice of most appropriate column internals, will largely depend on important design, construction, and operation considerations that may differ for offshore and onshore plants to the extent depending on specific site requirements.

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