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Application of a divided wall column for gas separation in floating liquefied natural gas plant

Ho Hwan Chun* and Young Han Kim,†**

*Department of Naval Architecture & Ocean Engineering, Pusan National University, Busan 609-735, Korea
**Department of Chemical Engineering, Dong-A University, Busan 604-714, Korea

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Abstract−A divided wall column (DWC) has widely been utilized as an energy-efficient distillation column. When it is applied to the offshore floating liquefied natural gas (FLNG) plant, its compactness can provide a favorable distillation system for the unconventional plant on top of its high energy efficiency. We investigated the design characteristic, cost evaluation and operation difficulty of the DWC at its utilization in the FLNG plant. The results from the HYSYS simulation of the DWC were compared with those of the conventional distillation system, and the following was found from the study. The DWC replacing the depropanizer and debutanizer of the conventional distillation system requires 12.5% less investment cost. While the saving of 25% in steam cost is expected from the DWC, the total utility cost including the refrigerant cost is reduced by 20.2% due to the lower cost reduction of refrigeration in the DWC.

Key words: Divided Wall Column, Energy-efficient Distillation, Floating Liquefied Natural Gas Plant, Thermally-coupled Distillation

INTRODUCTION

As the production of natural gas onshore and from shallow continental shelf is waning, its offshore production from deep water is gaining more attention. Due to the varying production sites the quality of the produced natural gas becomes diverse, but its quality is strictly controlled for safety concern. The calorific value between 950 and 1,150 Btu/ft^3 is one of the controlled specifications, and dew point requirement is another [1]. To satisfy the specifications the raw natural gas is diluted with nitrogen or carbon dioxide, and otherwise heavy components in the gas are separated using distillation [2]. The separated heavy components, such as ethane and propane, are used as raw material in ethylene and propylene production.

The divided wall column (DWC) shown in Fig. 1(a) has the same principle of ternary separation to the fully thermally coupled distillation column (FTCDC) also known as the Petlyuk column demonstrated in Fig. 1(b). The left hand side of the divided section in the DWC works as a prefractionator in the FTCDC. Actually, the FTCDC was developed as one of the energy efficient distillation systems [3]. Provided that three products can be produced from a single distillation column processing a ternary mixture, a conventional two-column system producing the three products becomes a one-column simple system. The FTCDC is the system. The side product drawn from the middle of the main column of the FTCDC has high composition of the intermediate component among the ternary components, but its composition in feed is much lower than that in the product. Note that the feed also enters at the middle of the column. Therefore, the side product and feed have to be separated. In the conventional column, a composition difference of the feed and side product is not allowed, unless a very large number of trays and almost infinite reflux flow rate are provided. The dividing wall in the DWC vertically separates the middle section of the column for the feed and side draw having different composition to hold them in the same column. In the FTCDC, the separated middle section is composed of the prefractionator and main column.

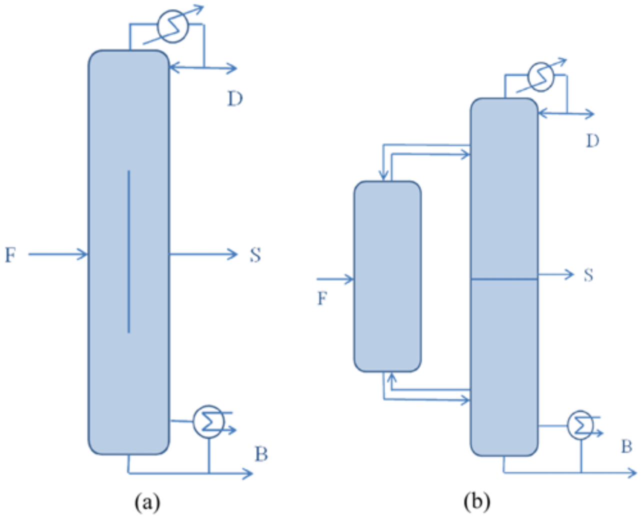

Fig. 1. Schematic diagram of the divided wall column (a) and fully thermally coupled distillation column (b).

A floating liquefied natural gas (FLNG) plant requires compactness of processing equipments due to its nature of offshore operation. The fully thermally coupled distillation column commercialized as the divided wall column (DWC) provides the compactness along with the energy conservation of about 30% over conventional distillation column [4-6]. Fig. 2 shows the existing separation sequence of heavy components from feed LNG in the FLNG plant. When

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†To whom correspondence should be addressed.
E-mail: yhkim@mail.donga.ac.kr

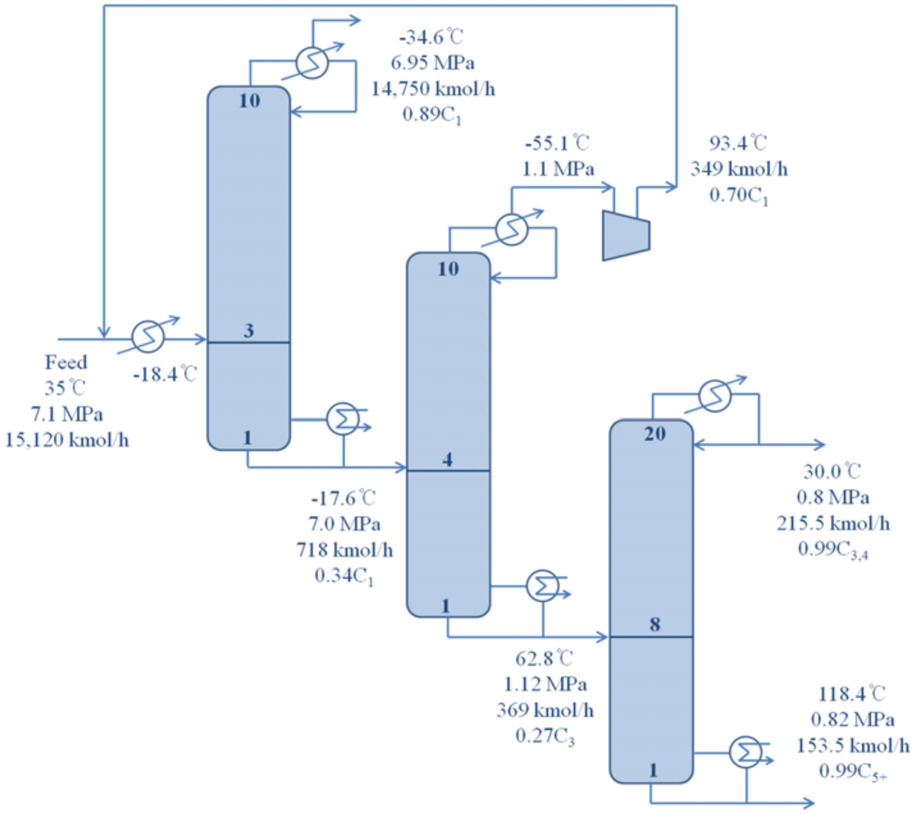

Fig. 2. Schematic diagram of the conventional FLNG plant. The first column is a demethanizer, the second is a depropanizer, and the third is a debutanizer.

its alternative system, the DWC, is utilized in an offshore chemical plant, its compactness and high energy efficiency can attract field engineers' interest. The DWC was applied to the combination of deethanizer and depropanzer in the recovery process of natural gas liquids (NGL) to yield a reduction of 43% reboiler duty, and the modification of the conventional DWC by moving the wall the all the way to the column top (TDWC) was also proposed by Long and Lee [7]. In the study the refrigeration load required for the vapor condensation providing reflux flow was eliminated by utilizing vapor compression and heat integration. Later the TDWC was implemented in the FLNG plant [8].

In this study a modification of the last two columns of the separation process in the FLNG plant into the single DWC is proposed, and its performance and cost are compared with those of the conventional process. Other problems arising from the modification are also discussed to find the possible solutions.

Table 1. List of feed conditions

Name	Value
Temperature (°C)	35
Pressure (MPa)	7.1
Flow rate (kmol/h)	15,120
Composition (% mol fraction)	
Nitrogen	1.54
Methane	86.39
Ethane	6.47
Propane	2.87
i-Butane	0.72
n-Butane	0.82
i-Pentane	0.41
n-Pentane	0.31
n-Hexane	0.31
n-Heptane	0.15

PROCESS DESCRIPTION

A conventional FLNG process was adopted from Lee et al. [8], and the process is demonstrated in Fig. 2. The feed condition is listed in Table 1. The gas feed obtained from the well is pressurized for transportation, and is cooled before entering the first distillation column, demethanizer. Because the methane content in the feed is very high, the methane separation is a relatively simple procedure except the operating pressure is high and a large amount of refrigerant is used in the condenser. Unlike the onshore processing of the feed, most of the ethane is separated together with the methane due to the limitation of column and tray numbers in the offshore operation. The demethanizer of limited tray number does not separate high specification of methane product. Therefore, some of the methane and ethane leave the demethanizer with bottom product. Then the mixture of C_1 through C_3 components is separated from the top of the second column, depropanizer, and recycled to the demethanizer. The third column, debutanizer, produces LPG and C_{5+} products as overhead and bottom products, respectively. The product specifications are 0.89, 0.98 and 0.99 for methane, LPG and C_{5+} product,

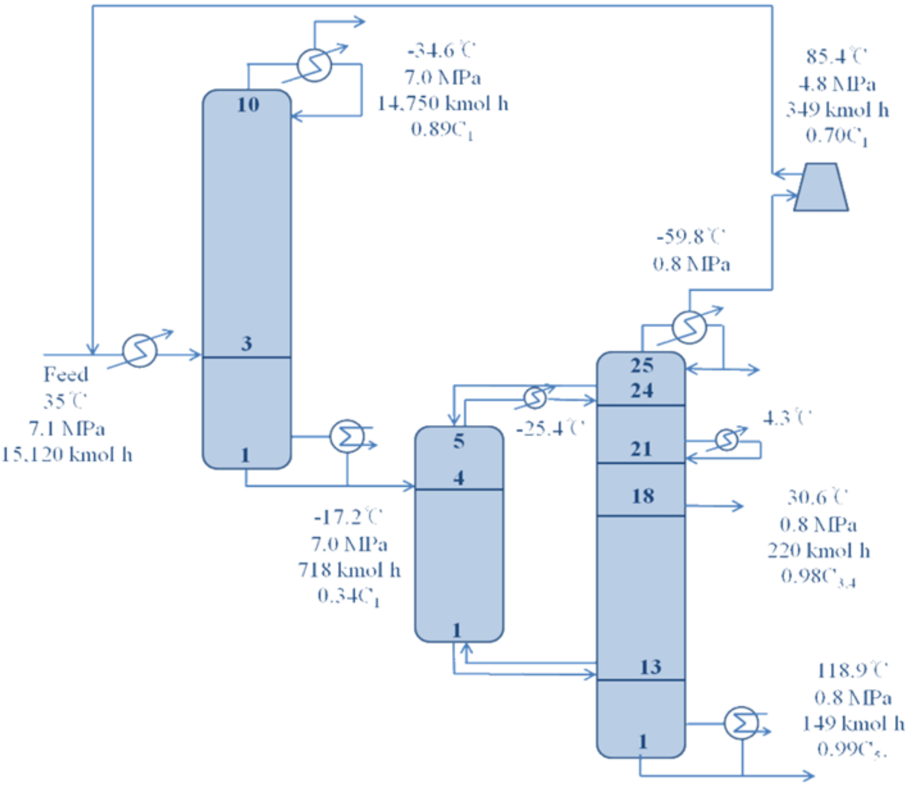

Fig. 3. Schematic diagram of the fully thermally couple distillation column (FTCDC) applied to FLNG plant. The FTCDC is the same to the DWC in principle.

respectively.

Offshore operation requires the compactness of equipment due to limited space and harsh environment. The introduction of the DWC to the offshore LNG plant will give the compactness, and consume less energy demand compared with the conventional FLNG process. Fig. 3 shows the replacement of the last two columns with a fully thermally coupled distillation column (FTCDC), which is built in the form of the DWC for practical application.

FTCDC DESIGN

In the design of distillation column using the commercial design program, the number of trays and column pressure are required to begin the simulation. While changing operating variables, such as reflux flow and vapor boilup rates, the specification of products is examined to match the desired values [9]. The revised structural information is sought to give the minimum reflux flow rate from iterative computation. This design procedure was implemented in the FTCDC design of this study, and the extra structural information of the FTCDC was also found from the iterative simulation.

Because the depropanizer and debutanizer were combined into the FTCDC, the total number of trays of the FTCDC was set to the sum of the two columns. The total number was distributed to the prefractionator and main column as 5 and 25, respectively. The main column may need more trays, but its total height is limited due to the nature of offshore operation. The location of interlinking stages and feed and side product trays was determined for the minimum reflux flow from the HYSYS simulation. The column pressure was set to the pressure of the debutanizer after considering the temperature of reboiler steam. The Peng-Robinson EOS was used for the calculation of vapor-liquid equilibrium in the simulation.

The fully thermally coupled distillation column (FTCDC), also known as the Petlyuk column, has the same principle of ternary separation as the DWC. The design procedure of the FTCDC is used here, but the actual installation of the system is given with the DWC. Because the manipulation of vapor and liquid flows between the interlinking trays of the prefractionator and main column is difficult in the FTCDC, field engineers prefer the DWC to the FTCDC and have successfully implemented it in many applications [4,10]. In addition, the compactness of the DWC is useful for offshore installation.

RESULTS AND DISCUSSION

The design results of the proposed DWC process in the FLNG plant were presented, and its performance improvement over the conventional process was examined as below.

1. Design Analysis

The column structure and operating condition of the conventional FLNG plant are listed in Table 2. The last two columns among the three columns in the conventional system were replaced with the DWC, and therefore the first column, demethanizer, was used in both systems. The total number of trays in the DWC was from the sum of the two columns. The location of feed and interlinking trays was found from the HYSYS simulation for the optimum reflux flow rate. The column pressure was set to the pressure of the debutanizer. The operating conditions, such as vapor and liquid flow rates, were found from the optimum column structure and satisfactory specifi-

Table 2. Structural information, operating conditions and compositions in the conventional and divided wall column distillation systems for the FLNG plant. Tray numbers are counted from bottom

Name	Conventional			DWC	
	DeC_1	DeC_3	DeC_4	Prefract.	Main
Structural					
Number of trays	10	10	20	5	25
Feed/Side draw tray	3	4	8	2	22
Interlinking trays					12/24
Operating					
Pressure (MPa)-top	7.0	1.1	0.8	0.8	0.8
Temperature (°C)					
Overhead	−34.5	−55.1	30.0	−12.9	−59.8
Bottom	−17.6	62.8	118.4	42.6	118.9
Feed (kmol/h)	15,120/349	718	369	718	
Overhead (kmol/h)	14,750	349	215.5	349	
Bottom (kmol/h)	718	369	153.5	149	
Side (kmol/h)				220	
Reflux (kmol/h)	101.5	178	183.2	33	115
Vapor boilup (kmol/h)	1.14	526.5	352.6	380	567.8
Cooling duty (MW)		4.7	1.04	2.02	0.71
Reboiler duty (MW)		0.01	2.85	2.24	3.62
Precooler/Comp. (MW)	14.6	0.52			0.52
Composition (mol frac.)					
Feed	0.93/0.04/0.01	046/0.32/0.18	0/0.58/0.42	046/0.32/0.18	
Product-$C_{1,2}$	0.95		0.95		0.94
-LPG		0.32	0.58	0.99	0.98
-C_{5+}				0.99	0.99

Table 3. Detail of inter-cooler installation for the cooling load alleviation in the DWC

Number	Tray location	Outlet temperature (°C)	Capacity (MW)
I	24	−25.4	0.3
II	21	4.3	0.6

cation of products. One disadvantage of the DWC is the increase of cooling load at low temperature due to the combination of depropanizer and debutanizer into one column. When the low temperature requires a high cost refrigerant as in this study, the elevation of the utility cost is significant. To reduce the cooling load at the condenser of the DWC, two inter-coolers were installed as listed in Table 3. The structural information and operating condition of the DWC are also listed in Table 2.

The utilization of the DWC gives not only the compactness, essential in the offshore FLNG plant, but also energy saving. The reboiler duty of the DWC proposed here is 29% less than the conventional system as listed in Table 2. The energy saving of the DWC in the onshore NGL plant was 43% [7], but the number of trays was much higher than this study due to the nature of onshore operation. The large energy saving of the DWC comes from its high thermodynamic efficiency. While feed composition is not far from the composition of feed tray in binary separation, the feed composition can be far from the tray composition in a ternary system as demonstrated in Fig. 4(a), and it leads to large mixing at the feed tray and the reduction of thermodynamic efficiency owing to the irreversibility of the mixing [11]. The column profile of the DWC is demonstrated in Fig. 4(b), in which the distance between the feed composition and feed tray is shorter than the conventional system. This means that less mixing occurs in the DWC. Secondly, the feed tray mixing occurs at the second column of the conventional two-column system, but there is no second feed in the DWC. Finally, when the column profile of ternary separation in whole is examined, the profile of the DWC is similar to the equilibrium distillation lines illustrated in Fig. 4(c). The curves denote different reflux flow rates, and the curve with high LPG composition comes from more reflux. The profile of the second column in the conventional system is that of a binary system. Because the thermodynamic efficiency of an equilibrium distillation is the highest among possible column profiles [12], the similarity to the equilibrium distillation predicts the higher efficiency of the DWC.

2. Economic Evaluation

For the economic evaluation of the proposed DWC employed in the FLNG plant, the investment and operating costs were calculated by using the following procedure. The cost of distillation column includes the prices of column shell and internals, and the shell cost is given as

$$C_{col}=\left(\frac{M\ \&\ S}{280}\right)C_f D_C^{1.066} H_C^{0.802} C_p \qquad (1)$$

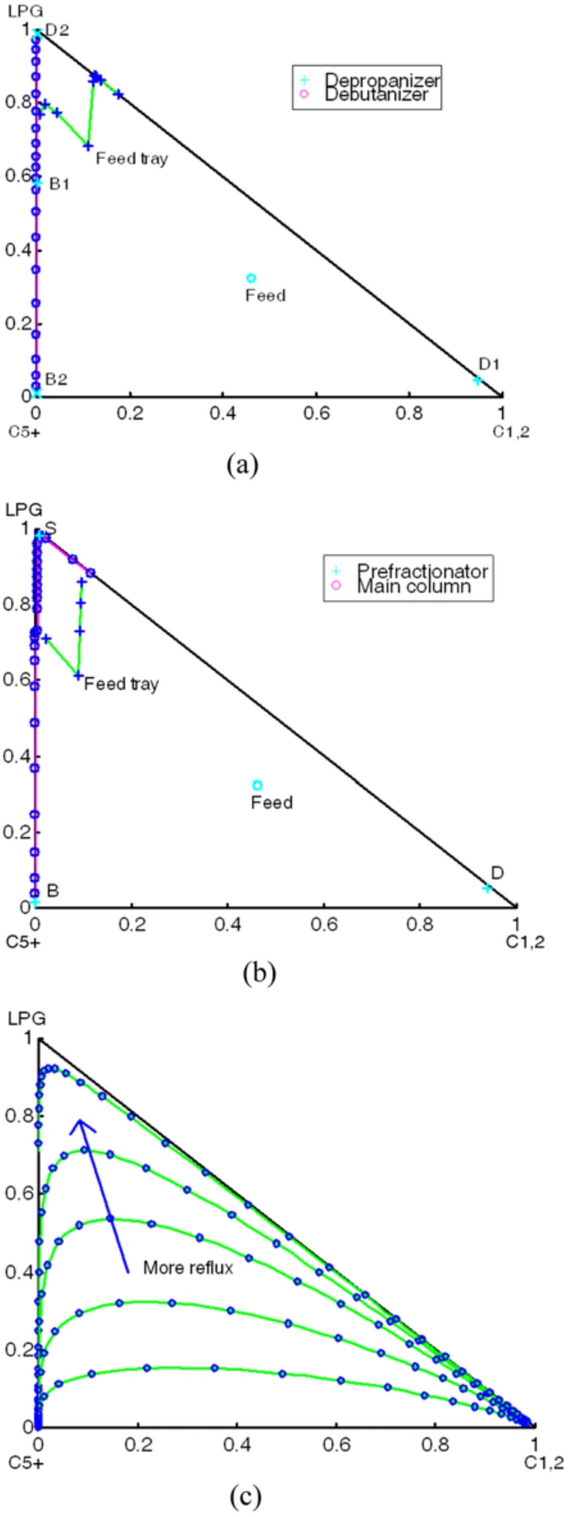

Fig. 4. Column profiles of the sequential binary distillation (a), divided wall column (b), and equilibrium distillation (c).

where the M&S is the Marshall and Swift index, and the value of 4th quarter of 2011 of 1536.5 was used here. The coefficient C_f is given as 3919.32 from Olujic et al. [13], and the pressure related correction C_p is from Douglas [14]. The column diameter is calculated from the maximum vapor flow rate.

$$D_c = 0.08318\sqrt{V} \tag{2}$$

where V is the rate of vapor in kg-mol/h. The height of column H_c is calculated from two feet spacing and the total number of trays.

The cost of column internals is yielded from the tray cost.

$$C_{tray} = \left(\frac{M\,\&\,S}{280}\right) 97.243 D_C^{1.55} H_C F_e \tag{3}$$

where the fabrication coefficient Fc is given in Olujic et al. [13]. From the same reference the heat exchanger cost equation was adopted, and the condenser cost is

$$C_{cond} = \left(\frac{M\,\&\,S}{280}\right) 1609.13 A_C^{0.65} \tag{4}$$

where Ac is the heat transfer area of the condenser in the unit of square meters. Similarly, the reboiler cost is found as

$$C_{reb} = \left(\frac{M\,\&\,S}{280}\right) 1775.26 A_R^{0.65} \tag{5}$$

The investment cost of compressor is calculated from

$$C_{comp} = \left(\frac{M\,\&\,S}{280}\right) 2047.24 b_P^{0.82} \tag{6}$$

where b_P is

$$b_p = \frac{\gamma R T_{in}}{\gamma - 1}\left[\left(\frac{P_{out}}{P_{in}}\right)^{(\gamma-1)/\gamma} - 1\right] V/3600 \tag{7}$$

Table 4. List of utility costs

Name	Price ($/GJ)
Steam	6.08
Cooling water	0.35
Refrigerant (−20 °C)	7.89
Refrigerant (−50 °C)	13.11
Electricity	16.8

Table 5. Economic evaluation of the conventional and DWC distillation systems for the FLNG plant. The utility cost is annual, and the cost of the demethanizer is not counted in the total. Units are in million U.S. dollars

Name	Conventional			DWC	
	DeC_1	DeC_3	DeC_4	Prefract.	Main
Investment					
Column	2.707	0.218	0.294		0.448
Tray	0.165	0.013	0.020	0.005	0.031
Heat exchanger	2.125	0.399	0.393		0.527
Compressor		1.566			1.528
Total			2.903		2.539
Utility					
Steam		0.494	0.389		0.662
Cooling water			0.020		
Refrigerant	1.057	0.388			0.333
Electricity		0.197			0.192
Total			1.488		1.187

The coefficient γ is the ratio of specific heats, and γ=1.4 was used here [15]. The constant R is the ideal gas constant, and T and P are absolute temperature and pressure, respectively. The cost of utilities is from Lee et al. [8], and listed in Table 4. The process operation was assumed to be 330 days per year and 24 hours a day.

The calculated investment and utility costs are listed in Table 5. The demethanizer is utilized in both the conventional and DWC systems; its cost is not included in the total. The investment cost of the DWC is 12.5% less than that of the conventional system. Because of the large compressor cost applied for both systems equally, the reduction of column and heat exchanger cost in the DWC is not significant. On the other hand, the steam cost in the DWC is reduced by 25% noticeably, which is close to the predicted saving for the DWC in other studies [4-6]. But, its saving of total utility cost is 20.2% compared with that of the conventional system. The reduction of steam consumption in the DWC and installing the inter-coolers are responsible for the saving of the total cost. The installation reduced the cooling load at the condenser by 60.6%. Note that the utility cost of the inter-cooling is substantially lower than the condenser cooling at the column overhead due to the high outlet temperature of the inter-cooler.

In the DWC the combined reflux flow of depropanizer and debutanizer requires refrigerant due to its low temperature at the column overhead as shown in Fig. 3. To separate the refrigerant utilization in the DWC, Lee et al. implemented a top divided wall column (TDWC) [8]. In principle, the TDWC is similar to a column with side rectifier. In the design a portion of feed was directly fed to the bottom of the demethanizer to eliminate its reboiler and to reduce the cooling duty at the pre-cooler of the feed by 17%. The DWC structure of this study is similar to the TDWC, because the upper interlinking is almost at the top of the column - one stage below the top - as shown in Fig. 3.

3. Process Operation

The offshore operation of an LNG plant limits the height and number of distillation columns. If a high column is necessary, the column can be separated into two columns with the middle connection of vapor and liquid flows. This arrangement is practiced in many chemical processes in the field. The limitation of column height can be handled in any processes if necessary. On the other hand, the limitation of column number is not simply resolved in the process design. The application of the DWC is a promising solution for the offshore operation seriously requiring the limited column number.

One other problem arising from the DWC utilization is its difficulty of operation. Though wide, successful application of the DWCs in field operations has been reported for many years [16]; the operation of the DWC is more difficult than the conventional system [17]. Especially, the specification control of its side product is troublesome, because no flow control is available at the side product tray except its own production rate. But the flow rate is subject to the total material balance. The overhead and bottom products are adjusted, not only their own flow rates but also the reflux and vapor boilup rates, respectively. This problem can be solved with the sufficient margin of design specification of products as suggested in Wolff and Skogestad [4].

CONCLUSIONS

An offshore floating liquefied natural gas (FLNG) plant requires a small number of distillation columns with limited height for its gas separation due to its harsh condition of process operation. The divided wall column (DWC) provides a reduction of the required column number and investment and utility costs. When the DWC was utilized in the FLNG plant, its design and column efficiency were examined from the simulation results using the HYSYS. In addition, the cost evaluation and column operation were also discussed. When the same number of trays in the depropanizer and debutanizer of the conventional distillation system was implemented to a single DWC, 12.5% less investment cost was required. While a saving of 25% in steam cost was expected, the total reduction of utility cost was 20.2% due to the lower reduction of refrigeration cost in the DWC. The operation difficulty associated with the DWC implementation can be solved by using a wide margin of product specification in the design of the DWC system.

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NOMENCLATURE

A : heat transfer area [m^2]
b : compressor power [kW]
C : equipment cost or cost coefficient [\$]
D : column diameter [m]
f : fabrication coefficient [-]
H : column height [m]
P : pressure [kPa]
T : absolute temperature [K]
V : vapor flow rate [kmol/h]

Subscripts

C : column or condenser
f : fabrication
p : pressure
R : reboiler

Greek Letters

γ : ratio of specific heats [-]

REFERENCES

1. A. J. Kidnay, W. R. Parrish and D. G. McCartney, *Fundamentals of natural gas processing*, 2nd Ed., CRC Press, Boca Raton, FL (2011).
2. S. Baek, G. Hwang, C. Lee, S. Jeong and D. Choi, *Energy Convers. Manage*., **52**, 2807 (2011).
3. Y. H. Kim, *Ind. Eng. Chem. Res*., **50**, 5733 (2011).
4. E. A. Wolff and S. Skogestad, *Ind. Eng. Chem. Res*., **34**, 2094 (1995).
5. M. I. Abdul Mutalib and R. Smith, *Chem. Eng. Res. Des*., **76**, Part A, 308 (1998).
6. S. H. Lee, M. Shamsuzzoha, M. Han, Y. H. Kim and M. Lee, *Korean J. Chem. Eng*., **28**, 348 (2011).
7. N. V. D. Long and M. Lee, *J. Chem. Eng., Japan*, **45**, 285 (2012).
8. S. Lee, N. V. D. Long and M. Lee, *Ind. Eng. Chem. Res*., **51**, 10021

(2012).

9. K. S. Hwang, B. C. Kim and Y. H. Kim, *Chem. Eng. Technol*., **34**, 273 (2011).
10. K. S. Hwang, B. C. Kim and Y. H. Kim, *Korean J. Chem. Eng*., **27**, 1056 (2010).
11. Y. H. Kim, *Ind. Eng. Chem. Res*., **40**, 2460 (2001).
12. S. Widago and W. D. Seider, *AIChE J*., **42**, 96 (1996).
13. Z. Olujic, L. Sun, A. de Rijke and P. J. Jansens, *Energy*, **31**, 3083 (2006).
14. J. M. Douglas, *Conceptual design of chemical processes*, McGraw-Hill, New York (1988).
15. T.-J. Ho, C.-T. Huang, L.-S. Lee and C.-T. Chen, *Ind. Eng. Chem. Res*., **49**, 350 (2010).
16. R. Premkumar and G. P. Rangaiah, *Chem. Eng. Res. Des*., **87**, 47 (2009).
17. H. Cho, Y. Choi, J. Lee, I. Cho and M. Han, *Korean Chem. Eng. Res*., **50**, 815 (2012).