Design and Optimization of NGL Recovery Process in FLNG

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1. Introduction

The primary use of natural gas (NG) is as a fuel; it can also be a source of hydrocarbons for petrochemical feed stocks and a major source of industrially important elemental sulfur [1]. Its clean burning and ability to meet stringent environmental requirements have raised the demand for natural gas [2], which is supporting the rapid growth of liquefied natural gas (LNG) production capacity. Much of the world's gas reserves are in offshore fields [3], though onshore LNG processing is generally favored [4-8]. Recently, offshore FLNG (floating LNG) and LNG-FPSO (floating, production, shipping and offloading) services are beginning to be explored instead of land-based LNG plants [9]. FLNG plants must be safe, compact and energy efficient.

Several analyses of dividing wall columns (DWCs, Figure 1) for ternary separations have shown that they can achieve energy and space savings of up to 30% over conventional direct and indirect distillations [10-12]. DWCs allow reversible splits with no part of the separation performed twice, the main reason for their superior energy efficiency [13]. However, their design is more complex than conventional arrangements because of the greater number of degrees of freedom [14] that interact with each other and need to be optimized simultaneously.

Optimization studies rely on statistical approaches, with response surface methodology (RSM) being routinely used in several biotechnological and industrial multivariable processes [15-16]. In RSM, the Box-Behnken design only has three levels (low, medium, and high, coded as -1, 0, +1) and requires a small number of experiments or simulation runs. It is more efficient and easier to arrange and interpret than other methods.

This work proposes a new, simple, compact and power-efficient NGL recovery sequence for offshore FLNG. In the proposed NGL recovery process, feed splitting and a top dividing wall column were employed to maximize energy efficiency and plant compactness.

2. Proposed base sequence

A new NGL recovery process is proposed for FLNG facilities with the following constraints and assumptions:

a. The maximum allowable number of trays of each column is limited to 21 to limit the motion of wind and waves and to avoid excessive bending moments.
b. All columns are designed as packed type columns for greater stability against motion.
c. The operating velocity of all columns is near 80% of the flooding velocity.
d. The product specifications are as follows:
    - C_1: 89% (top of demethanizer)
    - LPG: 98% (top of debutanizer)
    - C_{5+}: 99% (bottom of debutanizer)

Based on the feed conditions and the product specifications, simulations were performed to quantify energy consumption. The demethanizer, with 10 theoretical trays, was designed for use at 69.5 bar (Figure 1). The sharp separation of methane from C_{2+} increases energy consumption. Therefore, a depropanizer column is used to recycle light components in the bottom stream of the demethanizer. The 20-tray debutanizer column was designed for use at 8.0 bar, as commercial LPG can be condensed with cooling water at this pressure.

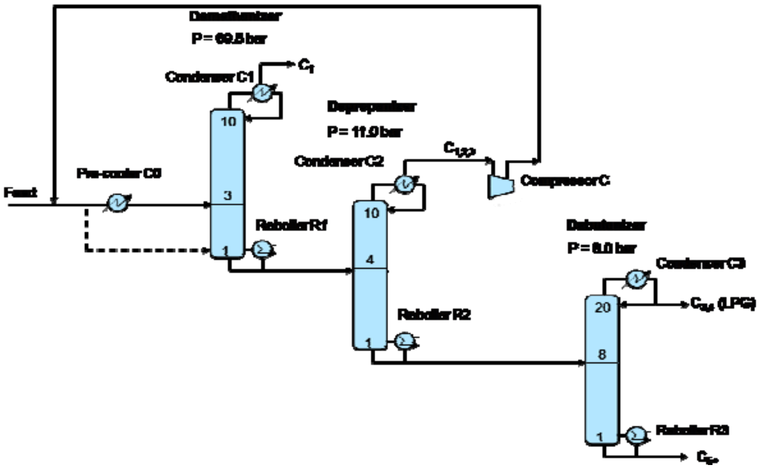

Figure 1. The separation train of three conventional columns.

3. Improvement of proposed base sequence

3.1. Feed split

Instead of pre-cooling the entire feed stream, it can first be divided into two streams: one is cooled before entering the column like a feed, and one that is fed into the column's bottom (dashed line) (Figure 1). This sequence can eliminate one reboiler in the demethanizer and save energy in pre-cooler C0. However, energy consumption is increased in condenser C1 in the demethanizer and the reboiler in the depropanizer. Note that the refrigeration used in precooler C0 and condenser C1 are at low temperatures. Therefore, adjustment of the feed split ratio is important in the optimization. A feed split ratio of 15% is optimal, reducing reboiler duty and operating costs by 47.43% and 9.64%, respectively.

3.2. Top Dividing Wall Column (TDWC)

In this case, two different cooling sources, water and refrigeration, are employed. Due to the high cost of refrigeration, integrating two columns into one dividing wall column with only one condenser is not efficient. Therefore, a top dividing wall column is considered here to integrate the depropanizer and the debutanizer for improved energy efficiency.

3.2.1. Optimization Methodology

The main design variables of internal vapor flow to the prefractionator (F_V), and the numbers of trays in the top (N1), botttom (N2), and feed rectifying (N3) sections were optimized. The objectives of the optimization were the minimization of the total number of trays (N) and the reboiler duty (Q). The optimization was constrained by the product purities and recoveries.

$$\min(Q,N) = f(N1, N2, N3, F_V) \tag{1}$$

Multiple response optimization can be undertaken by forming a constrained optimization problem with one of the responses treated as the objective of a constrained optimization problem and other responses treated as the constraints where the constraints' boundaries are determined by the process design engineers. Here, reboiler duty is considered the objective. The numbers of trays are the constraints and depend on the design engineers. Note that the number of trays in each column must be less than 21 trays.

A Box-Behnken design was employed under the response surface methodology to analyze how the variables interacted and to optimize the system in terms of reboiler duty and the number of trays. After determining the variables' preliminary ranges through single-factor testing, simulation run data were fitted to a second-order polynomial model and regression coefficients were obtained. The generalized second-order polynomial model used in the response surface analysis is as follows:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum\sum_{i<j} \beta_{ij} X_i X_j + \varepsilon \qquad (2)$$

where Y is the predicted response, X_i are the uncoded or coded values of the variables, β_0 is a constant, β_i, β_{ii} and β_{ij} are the coefficients of the linear, quadratic and interactive terms, respectively, and ε is the error term. MINITAB software was used for response surfaces fitting.

3.2.2. TDWC Configuration

After initially setting the TDWC structure using a shortcut method [12,14], it was then optimized using response surface methodology. The DWC parameters were optimized over 15 simulation runs. For each run, the internal vapor flows to the prefractionator were varied to meet the required product purity and recovery. The optimum reboiler duty saving corresponds to the number of trays, increasing rapidly as the number of trays increases from 19 to 22. Therefore the maximum allowable 20 trays were employed in the design of the TDWC.

The greatest reboiler duty saving (11.89%) was predicted to have coded levels of -0.8192, 0.8192, and -1 corresponding to the numbers of trays in the top, bottom, and feed rectifying sections, respectively. The variables' natural values can be derived from the coded levels. The optimized TDWC system (Figure 2) had a simulated saving of 11.79%, in good agreement with the predicted value.

This column can be used to integrate two columns, whose condensers are cooled by different coolants; particularly the the depropanizer requires refrigeration, while the debutanizer can condense the top vapor stream under water cooling. The simulation results show that the TDWC can save up to 35.09% of refrigeration costs compared with a conventional column sequence. The duties of condenser (C3) and the reboiler can be reduced by 21.42% and 11.79%, respectively. Using a 1.5 m diameter TDWC could reduce energy consumption by 15.36% in terms of TAC compared with a conventional column sequence. Therefore, this kind of column can reduce energy consumption (refrigeration energy and reboiler and condenser duty) and investment costs (replacing two columns with one and eliminating a reboiler).

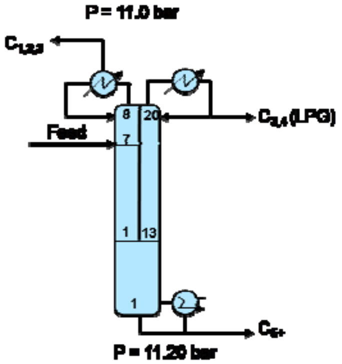

Figure 2. The TDWC system.

4. Conclusions

A new, energy-efficient and compact NGL recovery is proposed for offshore FLNG plants. Feed splitting could eliminate the demethanizer reboiler and reduce precooling energy. Operating costs were minimized at a feed split ratio of 15%. A TDWC allowed more energy-efficient depropanization and debutanization. A shortcut method determined a suitable initial structure of the TDWC, which was then optimized by response surface methodology. The proposed method could be simply and efficiently implemented in HYSYS and Minitab. Simulated results agreed well with predicted values. This kind of column could reduce energy consumption and investment costs. The reduced numbers of columns and reboilers could also make a plant more compact, important for offshore facilities.

Acknowledgements

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