NOVEL NITROGEN REMOVAL SCHEMES FOR LNG PLANTS WITH ELECTRIC MOTOR DRIVE AND VARYING FEED COMPOSITION

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ABSTRACT

There has recently been an increasing interest in using electric motors to drive LNG process compressors, as seen in many land-based small to mid-size LNG projects worldwide and some shale gas export projects in North America. One challenge in these new opportunities is that the nitrogen content in the pipeline feed gas can vary over time. Traditionally, nitrogen was either rejected from the LNG into the fuel system by using an endflash separation drum or a nitrogen stripping column, or was separated and vented into the atmosphere using a dedicated nitrogen rejection unit (NRU). NRU's add process complexity and capital costs while electric motors reduce the fuel requirements and create fuel balance challenges. These issues drive the need for more efficient and cost effective nitrogen removal methods.

A number of novel nitrogen removal systems were developed to tackle the challenges of handling varying nitrogen content, minimizing fuel production and flaring, and maximizing methane recovery. Innovative integration of the nitrogen removal systems with the liquefaction unit can offer more compact and flexible processes with reduced capital cost.

Dynamic simulations were performed to demonstrate that the proposed systems are flexible in handling varying nitrogen content in the feed gas and can maintain good process efficiency with appropriate operational adjustment. The dynamic simulation results helps developing operating guidelines and control schemes that ensure successful implementation. This paper will describe the novel nitrogen removal systems, the results of the dynamic simulations, and how to adjust key operating parameters when the nitrogen content varies.

INTRODUCTION

The feed gas to a Natural Gas Liquefaction facility inevitably contains some level of nitrogen and possibly other light components such as helium, regardless of whether it is taken from a gas well or from a utility pipeline, Typically, the nitrogen in the final LNG product needs to be less than 1-1.5 mol% to avoid storage tank roll-over[1] or per customer specification. Therefore, excess nitrogen must be rejected into a fuel stream or a separate nitrogen vent (Figure 1). Many conventional technologies are available that allow the excess nitrogen to be concentrated and then rejected into a fuel stream or vented to the atmosphere.

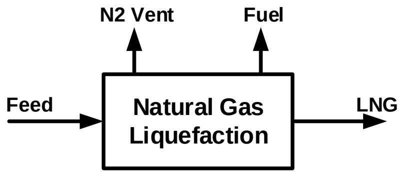

Figure 1. Feed and nitrogen material balances

When the nitrogen concentration in feed is relatively high (e.g., >5 mol%), it is sometimes preferred to separate the excess nitrogen and vent into the atmosphere. Due to environmental regulations and the desire to maximize methane recovery, the vent stream usually needs to contain less than 1 mol% methane. Such separation is difficult and often requires a costly and complex Nitrogen Rejection Unit (NRU) integrated to the cold end of the liquefaction process. When the nitrogen concentration is relatively low (e.g. <5 mol%), the excess nitrogen may be rejected into a fuel stream, as long as the total heating value of the fuel does not exceed the plant's overall fuel consumption needs, which include gas turbines or steam generators, hot oil system for general heating, and regeneration of the acid gas removal solvent.

$$(\text{Fuel flowrate}) \times (\text{Unit heating value of Fuel}) \leq (\text{Plant fuel consumption}) \qquad \text{Eq. 1}$$

Meeting the fuel needs while not having to flare is often achievable if the plant is driven by gas or steam turbines which have a relatively large fuel demand. In order to ensure proper combustion, the fuel stream also has a minimum methane concentration requirement, e.g., more than 65 mol% for driving the gas turbine, more than 30 mol% for steam generator, and more than 15% for general heating service.

$$\text{Methane\%} \geq \text{Minimum concentration required for combustion} \qquad \text{Eq. 2}$$

The technical considerations for a nitrogen removal system can be greatly affected by the type of driver selected and the characteristics of the feed gas.

ELECTRIC MOTOR DRIVE. The use of electric motors decreases the overall scope and footprint of the plant and substantially reduces the maintenance and downtime associated with gas turbines[2]. When used together with a variable frequency drive (VFD), electric motors provide extensive turndown capability and better efficiency over a wide operating range. When electricity is sourced from the grid, the plant fuel consumption is typically an order of magnitude less than required when using gas or steam turbines, making the constraint as set by Eq. 1 much more stringent. It is often preferred to recover as much methane from the fuel so long as the fuel is still combustible.

VARYING FEED GAS COMPOSITION. Most conventional baseload LNG plants process un-treated feed gas from dedicated natural gas wells that maintain relatively constant compositions for years. In contrast, small to mid-size LNG plants and North America shale gas export projects process feed gas from utility pipelines, which can exhibit greatly variable and unpredictable compositions[3]. Changing feed sources, blending of feed gas to adjust BTU values, and supply-demand shifts all cause the pipeline composition to vary. Many natural gas pipelines do not have specific requirement for maximum nitrogen content and the nitrogen concentration in a typical pipeline can vary from almost 0 to close to 10 mol%. The nitrogen mass balance of a LNG plant requires:

$$\begin{aligned}(\mathbf{Feed})\times(\mathbf{N_2\,\%\ in\ feed}) = (\mathbf{LNG})\times(\mathbf{N_2\,\%\ in\ LNG}) + (\mathbf{Fuel})\times(\mathbf{N_2\,\%\ in\ Fuel})\\ + (\mathbf{N_2\ vent})\times(\mathbf{N_2\,\%\ in\ Vent})\end{aligned} \quad \text{Eq. 3}$$

For an LNG plant with potentially varying feed gas composition, the process design and equipment selection are usually based on an average feed gas composition or a composition that the plant will see most frequently. Once the plant is running, the feed nitrogen content may suddenly decrease or increase, resulting in changes of the fuel stream and/or the vent stream, potentially violating the fuel and LNG purity constraints.

NITROGEN REMOVAL SCHEMES

Many conventional nitrogen removal schemes of different complexity are available[4]. However, for projects based upon electric motor drive and variable feed composition, the constraints as set by Eq. (1)-(3) become even more stringent. Therefore, it is important to have a versatile process design with robust control schemes and an operating strategy that provides flexibility in handling nitrogen. The operation goals are always to meet the plant fuel requirement and the LNG purity specification, while maintaining an optimal process efficiency and minimizing wasteful flaring. Recently, some novel nitrogen removal systems were developed to tackle these challenges. The process and operational considerations of the conventional and novel schemes are discussed and compared in this paper.

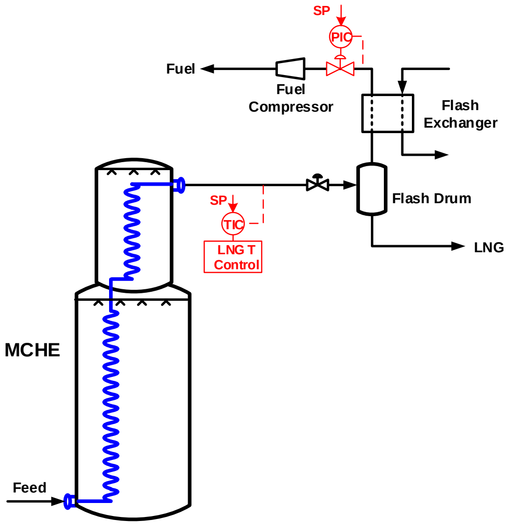

Figure 2. LNG end flash drum

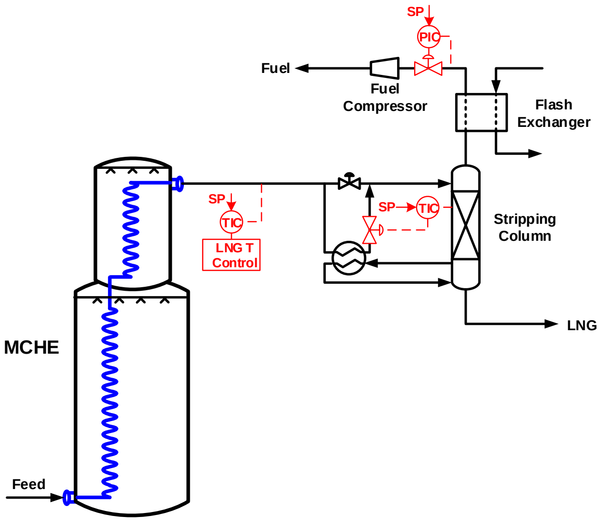

Figure 3. Nitrogen Stripping Column

LNG END FLASH DRUM. The simplest nitrogen removal scheme is an LNG end flash drum as shown in Figure 2. LNG exiting the Main Cryogenic Heat Exchanger (MCHE) is reduced in pressure and separated into a nitrogen-enriched vapor stream and a nitrogen-depleted LNG product stream. The operation of this scheme can be adjusted by two controlled variables: the flash drum operating pressure and the cold LNG temperature from the MCHE. As nitrogen content increases, the LNG temperature may be warmed or the drum pressure may be reduced, and vice versa. For low nitrogen content feed gas (e.g. <2 mol%), it is typically not difficult to meet the fuel requirement and achieve the LNG purity specification. However, since it is only one equilibrium stage of separation, the operational flexibility is limited when the feed nitrogen content increases and the fuel requirement is low. It can lead to an oversupply of fuel gas and make it difficult to reduce the nitrogen content in the final LNG product stream.

NITROGEN STRIPPING COLUMN. The separation effectiveness of the End Flash Drum scheme can be improved by replacing the single-stage flash drum with a multi-stage stripping column. This scheme uses column temperature as another primary controlled variable, allowing the LNG Nitrogen specification to be achieved more easily (Figure 3). By controlling the reboiler duty (as indicated by the column temperature) the amount of stripping gas can be adjusted, which helps to control the nitrogen content in the LNG. Typically, higher concentrations of N2 require more reboiler duty and higher stripping gas flowrates.

Although the stripping column scheme provides additional flexibility to meet the LNG purity specification, it shares one drawback with the End Flash Drum scheme: it is highly limited to adapt to feed gas composition changes and unavoidably produces more fuel gas as the nitrogen content increases in the feed.

NITROGEN RECTIFYING COLUMN. Providing a rectifying section to the column reduces the methane lost overhead and helps maintains the fuel balance. Figure 4 shows a nitrogen rectifying column scheme that is more flexible as it uses column condensing duty (overhead temperature) as one additional controlled variable5. The LNG withdrawn from the warm section of the MCHE is flashed to a lower pressure at the bottom of the rectifying column. The nitrogen-lean LNG stream is subcooled in the cold section of the MCHE while the nitrogen-enriched vapor stream travels upward through the column and is partially condensed by the cold nitrogen-lean

LNG stream produced in the MCHE (or provided by liquefaction refrigerant). By adjusting the cold LNG bypass flowrate around the condenser, the condensing duty can be controlled which in turn determines the methane content and the heating value of the fuel stream. The temperature of the warm LNG stream entering the column bottom and the column operating pressure can be adjusted to control the nitrogen content of the final LNG product.

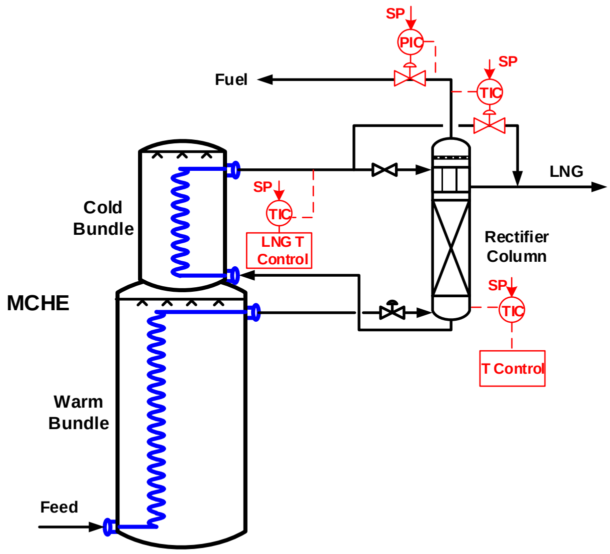

Figure 4. Nitrogen Rectifying Column

If the feed nitrogen content goes up, increasing the temperature of the MCHE warm section and/or decreasing the column pressure can help generate more flash gas and remove more nitrogen from the LNG. To maintain the fuel balance, more condensing duty and a potentially colder LNG temperature from the MCHE are required. More liquefaction power will be consumed as a result. The minimum rectifying column pressure may be set by the fuel gas header. If feed nitrogen content decreases, the opposite changes can be made to achieve better liquefaction efficiency.

Due to the improved operational flexibility and limited capital investment the Nitrogen Rectifying Column scheme can be a good option when the expected nitrogen content variation is small and the efficiency impact can be tolerated.

INTEGRATED NITROGEN REMOVAL WITH DEDICATED COOLING CIRCUITS. A novel and effective way to provide condensing duty is to design the MCHE cold section with a dedicated cooling circuit for direct heat transfer from the refrigerant to the nitrogen-enriched vapor stream[6]. As shown in Figure 5, the LNG from the warm section of the MCHE is flashed to lower pressure in an intermediate drum to generate a nitrogen-lean LNG stream and a nitrogen-enriched vapor stream. Both are sent through the cold section of the MCHE where the LNG stream is subcooled while the nitrogen-enriched vapor stream is partially condensed. The two streams then enter a nitrogen column which has both rectifying and stripping sections. Inside the column, the liquid portion of the nitrogen-lean LNG stream travels down in the stripping section and its nitrogen content is reduced continuously by the stripping gas. The partially condensed nitrogen-enriched stream enters the top stage of the nitrogen column, and the vapor portion is withdrawn from the column as a fuel stream while its liquid portion provides reflux to the rectifying section.

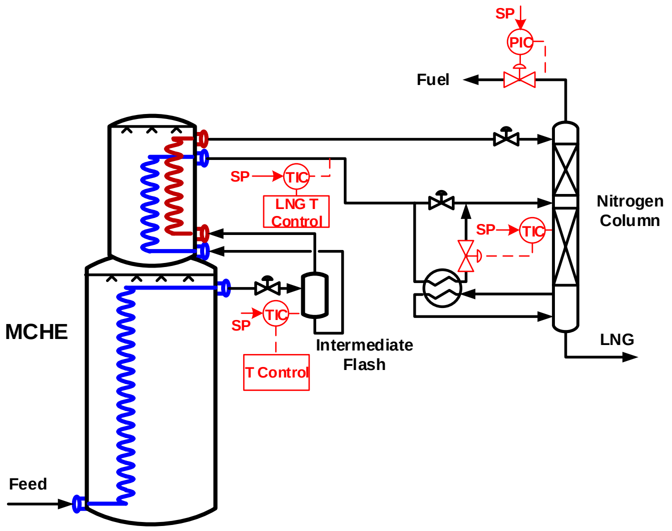

Figure 5. Nitrogen Removal Scheme with Dedicated Circuit for Intermediate Flash (Patent Pending)

This scheme is more efficient than the Nitrogen Rectifying Column scheme for a wider range of nitrogen in the feed gas. It provides one additional equilibrium separation stage to better meet the LNG and fuel purity requirements. The overall scheme requires the same number of primary controlled variables as the Nitrogen Rectifying Column scheme although it is slightly more complex because of the additional flash drum and the dedicated MCHE tube circuit.

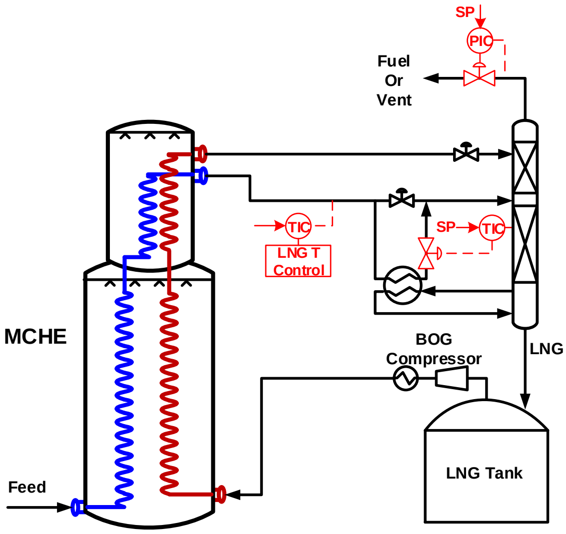

Figure 6. Nitrogen Removal Scheme with Dedicated Circuit for Recycled BOG (Patent Pending)

Figure 6 shows another variation of the novel nitrogen removal scheme with a dedicated cooling circuit[7]. In this scheme, the nitrogen-enriched vapor stream is the recycled boil-off gas (BOG) from the LNG storage tank. A BOG stream in a LNG plant contains higher concentration of nitrogen than the feed natural gas. Conventionally, the BOG is compressed and recycled, entering the MCHE after mixing with fresh dry sweet gas. The mixing of the high nitrogen containing BOG and the fresh feed gas is a large source of inefficiency due to exergy loss. Figure 6 avoids such mixing, instead, it sends the BOG through a dedicated cooling circuit throughout the entire MCHE. Without mixing with the BOG gas, the nitrogen in the LNG stream prior to entering the nitrogen column stays the same as in the fresh feed gas, allowing the LNG purity requirement to be satisfied much more easily. In addition, with the high nitrogen content of the BOG (often >20 mol%), the nitrogen in the final fuel stream is significantly enriched. If preferred, the fuel stream can be enriched to contain >99 mol% nitrogen such that it can be vented. This scheme only requires three primary controlled variables and therefore is more operator-friendly than other conventional schemes.

COMPARISON

The various nitrogen removal schemes discussed above are compared in Table 1. The flexibility of meeting the fuel requirement is judged by the scheme's ability to limit its fuel production with widely varying nitrogen content. The flexibility to meet the LNG purity specification is ranked based on the ability to reject enough nitrogen from the LNG stream when feed gas composition changes. The ability to produce a nitrogen vent is evaluated based on whether the scheme can concentrate the rejected nitrogen to high purity. The simplicity and ease of operation are scored by the number of primary controlled variables.

The Rectifying Column and the two novel schemes shown in Figures 5 and 6 are good options for LNG plants with low fuel consumption and varying feed gas. The ultimate choice will depend on the project specifics and need to balance cost, simplicity and flexibility.

It is worth pointing out that all of these nitrogen removal schemes are independent of the refrigeration system and liquefaction cycle. However, the impact of operational adjustments in the nitrogen removal system on the liquefaction system needs to be carefully evaluated.

Table 1. Comparison of Nitrogen Removal Schemes

Scheme	Flash Drum	Stripping Column	Dedicated NRU	Rectifying Column	Dedicated Circuit with Intermediate Flash	Dedicated Circuit with BOG Recycle
PFD	Figure 2	Figure 3	-	Figure 4	Figure 5	Figure 6
Flexibility of meeting fuel requirements	Low	Low	Highest	Medium	High	Highest
Flexibility of meeting LNG purity specs	Low	Medium	Medium	Medium	Medium	High
Ability to produce a nitrogen vent	None	None	Yes	Yes but difficult	Yes	Yes
Simplicity and ease of operation	Best	Good	Adequate	Better	Good	Good
Cost	Lowest	Low	High	Medium	Medium	Medium

CASE STUDY

PROBLEM DESCRIPTION. A developer is looking to build an LNG plant with the refrigerant compressor to be driven by electric motors. The feed gas is sourced from an adjacent pipeline in which the nitrogen concentration averages around 4 mol% but is expected to vary inconsistently between 1 mol% and 7 mol% throughout the year. The fuel demand is calculated to be 5 MW based on plant utility requirement which is only approximately 2 mol% of the feed gas equivalence on a methane basis. The net-in-tank LNG purity specification requires nitrogen to be less than 1.5 mol%.

The developer carefully reviewed the process technology options and decided to design the nitrogen system based on the average nitrogen content of 4 mol%. They also require that the nitrogen removal scheme be able to handle varying nitrogen content in the feed without violating the product purity specification. The excess nitrogen shall be rejected into a fuel gas. To maximize production, the developer wants to recover as much methane from the fuel as feasible and avoid flaring excess fuel gas. Based on these requirements, a mixed refrigerant based liquefaction cycle with the nitrogen rectifying column scheme shown in Figure 4 is recommended to the developer for its flexibility and simplicity.

DYNAMIC SIMULATION. The operability of the nitrogen removal scheme should be studied in the context of the entire liquefaction process. Using the developer's specific plant parameters, a detailed dynamic simulation flowsheet is developed to encompass the MCHE, refrigerant compressor, and nitrogen rectifying column as shown in Figure 7. The column operating pressure and the column overhead temperature can be operated independently from the liquefaction system. The two LNG temperature controllers (the warm LNG temperature and the cold LNG temperature) rely on the liquefaction process to adjust the amount of refrigeration to each section of the MCHE.

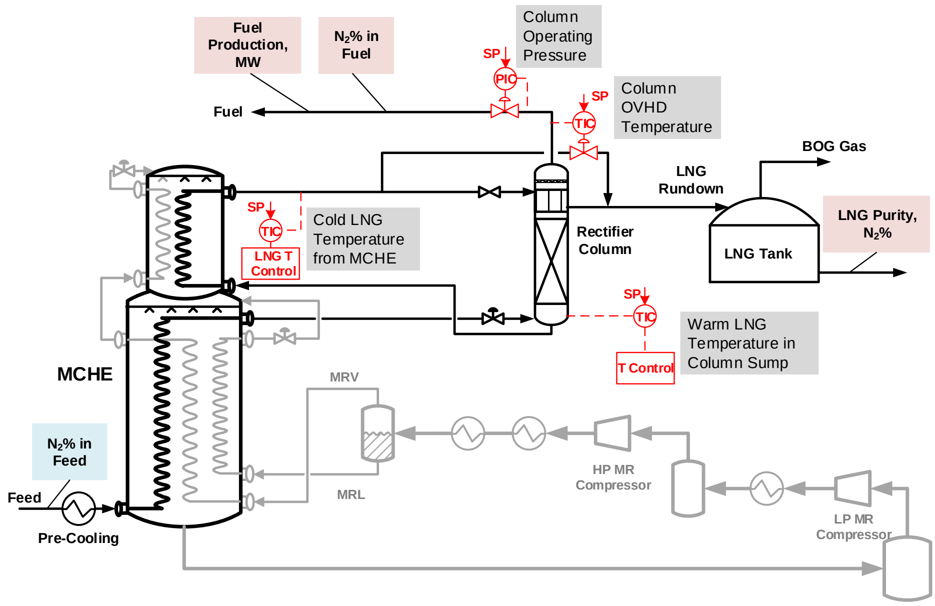

Figure 7. Simplified PFD used in the Dynamic Simulation

As the nitrogen content in the feed gas varies, it inevitably results in changes in fuel composition, fuel flow rate, and LNG product purity specification. If the system is robust and flexible, the set points of the primary controllers can be adjusted by the operator to meet the operating objectives. Two scenarios are considered to study the operability of the system:

1. From the design point of 4%, the nitrogen content in the feed gas increases to 7 mol%.
2. From the design point of 4%, the nitrogen content in the feed gas sequentially decreases to 1 mol% in 1 mol% increment.

RESULTS AND DISCUSSION. To observe the system response after the feed gas composition is changed, the set points of all the controllers are initially held constant. If the fuel balance and product purity exceed operating specifications or the liquefaction efficiency becomes less optimal, the set points are then adjusted to correct for it. This approach was taken to demonstrate that the controllers are able to make adjustments in the process to achieve the desired results.

Figure 8 is the dynamic simulation results of the first scenario and shows of how key process variables changed with time. The x-axis is scaled time that is in the order of hours. The nitrogen content in the feed increased from 4 mol% to 7 mol% at t=2. Shortly after the composition change the LNG purity and the fuel production violated the specifications. Excess fuel was wastefully sent to flare. The warm LNG temperature and the column overhead temperature both cooled slightly due to increased nitrogen content. They slowly warmed up as the two temperature controllers automatically adjusted the refrigeration process to stay close to the set points. As the warm LNG temperature slowly warmed towards its set point, more nitrogen was flashed which helped reduce the nitrogen content in the LNG product.

At t=4 the warming process slowed and the LNG N2 content was still high. At t=5 the warm LNG temperature set point had to be increased manually to remove more nitrogen from the warm LNG. At t=8 the LNG purity specification was met. Due to the higher warm LNG temperature, more fuel was generated with increased methane content resulting in more undesired flaring.

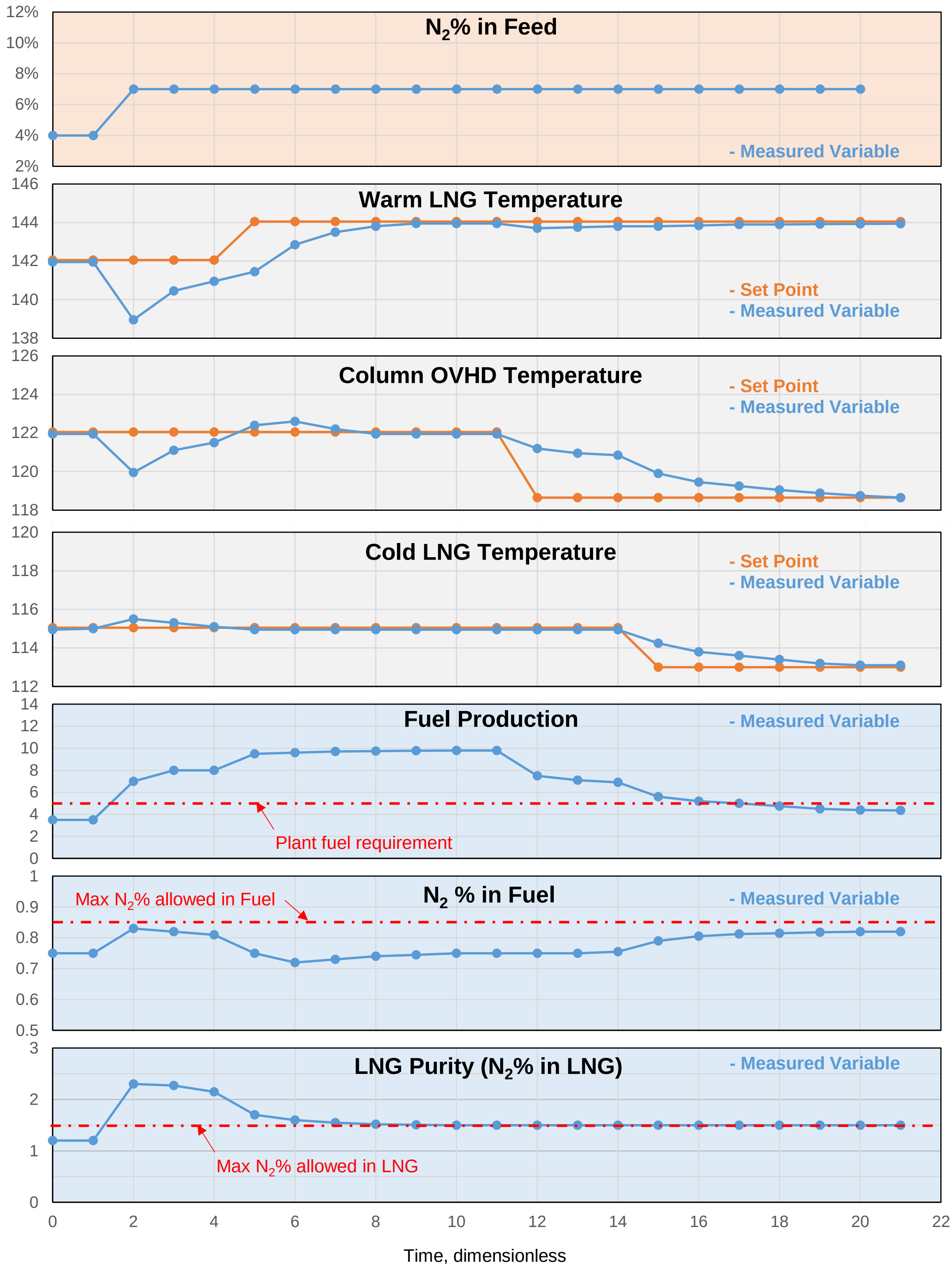

Figure 8. Dynamic behavior of the system with increased nitrogen content in feed gas

To rebalance the fuel production with the plant fuel requirement, two actions were taken. First, at t=12 the set point of the column overhead temperature was decreased. The LNG bypass valve around the column condenser closed slightly and sent more LNG through the condenser, effectively condensing more methane from the fuel stream. This effect diminishes at t=14 as the bypass valve was fully closed and the LNG flow to the condenser was maximized. To further reduce the methane in the fuel stream, the cold LNG temperature set point was decreased. Following this change at t=15 the fuel production and methane content decreased.

Finally, at t=18 all three operation goals were achieved: the fuel production meets the plant fuel requirement; the nitrogen content in the fuel gas is below 85 mol% to keep the fuel combustible; and the nitrogen content in the LNG is kept below 1.5 mol%. During this process, the column operating pressure did not have to be adjusted and therefore was kept constant.

The second scenario where the nitrogen content in the feed sequentially decreases from 4 mol% to 1 mol% is a less complex operation scenario as essentially no set point changes are necessary, except that a small amount of fresh feed gas may need to be sent to fuel to maintain the fuel balance. However, some minor operational adjustments could be made to improve the liquefaction process efficiency. Due to the length limitation of this paper, the detail is discussed in the poster of the same title in LNG 18 conference.

The results show that the rectifying column scheme can respond to operational adjustments within hours and has good flexibility for the expected nitrogen concentration range. With proper training and experience, the operator in the field will be able to monitor key process variables and make the right adjustments as needed.

CONCLUSION

Many nitrogen removal schemes are available and can be integrated with the liquefaction process to reject nitrogen from the LNG product. The selection depends upon two primary factors: the amount of fuel required and the N2 concentration in the feed. This paper reviewed conventional nitrogen removal schemes and introduced three novel integrated processes. The features of each scheme and their applicability and flexibility are discussed and compared in detail. The novel nitrogen removal schemes are particularly suitable for LNG plants with electric motor drive and varying feed gas composition. The operability and flexibility of one of the recommended nitrogen schemes was demonstrated in the case study using dynamic simulation.

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