Plant-wide control for the economic operation of modified single mixed refrigerant process for an offshore natural gas liquefaction plant

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A B S T R A C T

The marine operation of floating liquefied natural gas (FLNG) demands process compactness, flexibility, simplicity of operation, safety, and higher efficiency. The modified single mixed refrigerant (MSMR) process satisfies the FLNG process requirements and is accepted as a suitable technology for FLNG operation. The aim of this study was to develop a plant-wide control structure or strategy that can sustain the economic efficiency of the MSMR process. The NGL recovery and liquefaction units were integrated in the MSMR process to provide a compact plant structure with an efficient operation. Steady-state optimality analysis was intensively conducted in a rigorous dynamic simulation environment to determine the correct variable to sustain the economic efficiency of MSMR process. The results showed that the flow rate ratio of heavy and light mixed refrigerant (HK/LK ratio) is a promising self-optimizing controlled variable. Controlling this variable can sustain the MSMR optimality, even when the process is operated under off-design operating conditions or in the presence of disturbances. Based on the control structure tests, the control configuration with the HK/LK ratio loop showed excellent performance, maintaining the process stability against a range of disturbances. The proposed approach can also be applied to any cryogenic liquefaction technology for determining a possible optimizing controlled variable.

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1. Introduction

Currently, the source of fossil energy is scarce, and the days of ‘easy’ or ‘cheap’ oil and gas are numbered (Gilmour and Deveney, 2010). Fossil fuel resources in less accessible and challenging environments must be explored. Included in this resource is stranded natural gas trapped in unusual sites. Approximately 240,000 billion cubic feet of the world’s natural gas reserves are located in offshore fields (Schafer, 2012); a huge amount of potential energy that should not be left unexploited. Conventionally, offshore natural gas is transported through a pipeline to an onshore plant for further processing according to consumer specifications. This can be less economical because a traditional onshore plant for offshore gas reserves requires constructions in two locations: offshore for exploring and pre-treating the gas and onshore for the liquefaction plant (Lee et al., 2012).

Offshore FLNG emerges as an answer to improve the offshore plant economics by integrating all the necessary steps in processing natural gas (NG) to Liquefied Natural Gas (LNG) at a single site. Selecting the appropriate technology for an offshore LNG plant is a difficult task because of the space limitations and rough marine environment. Ideally, the perfect technology for an offshore plant has small equipment counts and high process efficiency.

Modified Single Mixed Refrigerant (MSMR) is the new proposed technology for offshore natural gas liquefaction plants which developed based on the work of Lee et al. (2012). This technology combines the compactness of Single Mixed Refrigerant (SMR) cycle and the high efficiency of Dual Mixed...
Refrigerant (DMR). Another feature of the MSMR process is the integration between the liquefaction and natural gas liquid (NGL) recovery unit. This integration does not require an external refrigeration utility because the cooled natural gas is used as the reflux for the de-methanizer column. Therefore, the investment and operating cost as well as the space required are reduced.

The MSMR process has been designed to operate under optimal steady-state conditions and show high efficiency. On the other hand, it has not been tested in a dynamic environment, where feed fluctuations and process disturbances can result in poor performance. Therefore, a good plant-wide control scheme that can sustain the economic feasibility of this process is needed.

Most studies mainly discussed the optimal design of LNG processes and their process optimality from a steady-state point of view (Khan et al., 2012; Khan and Lee, 2013a; Khan et al., 2013b). Several papers have discussed the plant-wide control problem with particular focus on economical operation. Jagtap et al. (2013) developed a plant-wide control procedure for near-optimal process operation over a wide throughput range with an expanding active constraint set. Umar et al. (2012) applied the self-optimizing control method for selecting the controlled variables to the case study of a forced circulation evaporator. In terms of a more general subject, many authors have examined plant-wide control problems on a range of processes. Ochoa et al. (2010) examined the plant-wide control problem of a continuous bioethanol process. Huang et al. (2012) studied the plant-wide control of a reactive distillation process. Bao and Xu (2012) used a network approach for designing plant-wide control based on the concept of dissipative systems. The number of applications of plant-wide control technology to industrial processes is still growing. Nevertheless, to the author’s knowledge, there are few papers that have discussed the applications of a plant-wide control methodology for designing control structure of natural gas liquefaction plants.

The aim of this study was to synthesize a plant-wide control structure for economic operation of the MSMR process by adopting the self-optimizing control procedure (Skogestad, 2012). In this framework, the procedure for designing the economic aspect of the control strategy consists of two steps. The first is to define the cost function to be minimized. The appropriate cost function, particularly for the MSMR process, is the total duty/net LNG product because it reflects the economic feasibility of this process. The second step is to determine the optimizing controlled variables that are insensitive to unmeasured disturbances, and variations in their set-points will not affect the cost function significantly. An optimizing controlled variable is a variable that when held constant, can automatically lead to optimal adjustment of the manipulated variables (Morari et al., 1980). The optimizing controlled variable in this study was searched by conducting steady-state optimality analysis.

Most studies that discussed economic plant-wide control analyzed the process optimality from a steady-state point of view. This analysis was conducted mostly with the assumption that all inventories in the plant are perfectly controlled. Consequently, it sacrifices the plant dynamic stability because there is no guarantee that a steady-state analysis for economic purposes will also maintain the dynamic performance of the process (Luyben, 2004).

Simulation in steady-state and dynamic environment is likely to give an inconsistent result due to technical issues in the simulation engine. Therefore because the control structures are developed and tested in dynamic simulation environment, to obtain a more precise data that consistent with the control purpose, all data in the steady-state optimality analysis was also obtained from the dynamic simulation environment.

The HK/LK ratio was selected as the optimizing controlled variable. The HK (heavy key) denotes the flow rate of the refrigerant containing heavier components while the LK (light key) is for the refrigerant with lighter components. The MSMR optimality can be sustained by controlling this variable, even when the process is operated under non-optimal operating conditions. Based on control structure tests, the control configuration that includes the HK/LK ratio loop also shows excellent performance, maintaining the process stability against a range of disturbances.

2. Process description

The MSMR process consists of three main units: mixed refrigerant (MR) compression, liquefaction, and natural gas liquid (NGL) recovery unit (Fig. 1). The high pressure single mixed refrigerant from MR compression is separated into light key (LK) and heavy key (HK) refrigerant streams. In the cryogenic exchanger, the LK plays a dominant role as the precooler, liquefier, and subcooler, whereas the HK also assists the precooling and liquefaction process with a lower refrigeration effect. The smaller flow rate of the HK and the fact that it contains high boiling point components provide it a narrower working temperature compared to the LK. After exiting the liquefaction unit, the LK and HK are compressed separately to reach a particular pressure before being mixed to be compressed simultaneously prior returning to the liquefaction unit. This remixing is a necessary process to allow both the LK and HK to enter liquefaction unit at the same pressure. Because the LK serves as the subcooling agent, it needs to undergo a larger pressure drop through adiabatic expansion to obtain a sufficiently low temperature. Therefore, the LK requires a larger number of compression stages. The different suction pressures between the LK and HK necessitates separate compression stages of the respective streams.

MSMR process combines DMR and SMR cycle by separating a single source of mixed refrigerant into two different compression cycles. The integration of these two liquefaction technologies allows the MSMR process to have a higher liquefaction capacity that is operated using less equipment, which cannot be achieved by a standalone SMR or DMR cycle.

The NGL recovery unit consists of a de-methanizer (De-C1), de-ethanizer (De-C2), and de-propanizer (De-C3) column. To make the process more compact, De-C1 is integrated with the liquefaction unit. Precooled natural gas from MCHE-1 is introduced to the De-C1 column as the main feed. Larger portion of the overhead stream rich in CH₄ is supplied to MCHE-2 to be liquefied, whereas a smaller part of the overhead stream is returned to the receiver tank of De-C1 (RT1). The liquefied natural gas from MCHE-2 is returned to RT1. The higher boiling components are condensed and sent as reflux to the De-C1 column. The vapor stream from RT1 is finally subcooled in MCHE-3 to form the LNG product. A small portion of the LNG product is recycled to RT1. This LNG recycling system is used to stabilize the inventory inside the accumulator.

The integration of liquefaction and the NGL recovery unit reduces the number of necessary auxiliary equipment, which
then reduces the investment cost. MSMR is a simple but effective process that makes it quite suitable for offshore natural gas liquefaction plants.

3. Control structure synthesis for MSMR process

The control structure for the MSMR process is designed by carrying out six main steps (Fig. 2). The highlight of each step is presented as follows:

- The first step is about the formulation control objectives of the MSMR process that cover the controllability and efficient operation. Several constraints to protect the stability of the MSMR process are also discussed in this step.
- The degrees of freedom analysis in the second step aims to locate the available manipulated variables to achieve the objectives devised in the first step.
- Sensitivity analysis in the third step provides information on the input-output relation. Therefore, the appropriate manipulated variable for the main controlled variable can be determined.
- Based on the controllability objectives and process constraints listed in the first step, the necessary regulatory control loops are added to the MR compression and NGL recovery units.
- In the fifth step, steady-state data from the dynamic simulation environment is collected to construct a MSMR process optimality map. This part covers the second step for designing the economic aspects of the control strategy (see Section 1). The process optimality map, as well as the other plots, is the mean for selecting the optimizing-controlled variable.
- In the sixth step, the control structures of MSMR process that include the selected self-optimizing controlled variable are evaluated in terms of both dynamic response and steady-state optimality point of views.

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**Fig. 1 – Conceptual structure of MSMR process.**

**Fig. 2 – Procedure for synthesizing control structure for MSMR process.**
3.1. Control objectives and process constraints

The objectives in the MSMR process are divided into two branches (Fig. 3). The first branch, which is the key operation objective in a typical baseload LNG plant (Mandler et al., 1998), is to produce liquefied natural gas with a pre-specified temperature in a stable manner under operation constraints. The goal in second branch is to operate the process efficiently by minimizing the control cost. To achieve the necessary stable operation, regulatory control loops are added to the MR compression and NGL recovery unit, whereas at least one more auxiliary controlled variable, i.e. optimizing controlled variable, must be designed to minimize the control cost. Nevertheless, in any control configuration, controlling the LNG product temperature is essential, which takes precedence over the other control tasks.

The control cost ($J$) to be minimized is the total compressor duty over the net LNG production. The duty for cooling the compressor outlet streams in the intercooler is not included in the cost function because its value is much lower than the compressor work (Jacobsen and Skogstad, 2013). The price of LNG is also excluded in plant economic analysis because the concern is only in achieving the most efficient plant operation and not the highest total profit. Therefore, the control cost of the MSMR process can be expressed as

$$
\min J = \frac{W_s}{m_{\text{LNG}}}
$$

(1)

where $W_s$ and $m_{\text{LNG}}$ denote the total compressor duties and LNG product flow rate, respectively (in Fig. 1, $m_{\text{LNG}}$ refers to the flow rate of stream ‘LNG’). Reboiler duties are much smaller than compressor duties therefore they are ignored in this equation. The constraints in the liquefaction process are related to the operability and optimality of the particular process unit (compressor minimum surge and suction temperature) and product specification (temperature and composition of LNG). To avoid a surge phenomenon, for the MSMR process, the suction pressure was selected as the constraint to represent the compressor surge. To avoid the surge phenomenon, which can damage the compressor shaft, the suction pressure must not be lower than the constrained value. This pressure should also not be higher than its constrained value because it will reduce the pressure drop of the refrigerant in the cryogenic exchanger, hence decrease the refrigeration effect.

Operating a compressor below the mixed refrigerant dew point temperature must be avoided for safe compressor operation. Therefore, the suction temperature is a critical variable in the operability of a compressor. The suction temperatures of both compressor inlet streams (LK and HK) are totally dependent on heat transfer in the cryogenic exchanger, and based on several tests in a dynamic simulation, these streams will reach the dew point temperature when the process is under extreme conditions, i.e. either when the NG flow rate is very low or the flow rates of the refrigerants are quite large. Hence, the suction temperature constraint is left inactive. The LNG temperature constraint is always active because it defines the product phase. The temperature should be maintained at a certain value, where the LNG product is in the liquid state but not lower than necessary to prevent energy wastage.

Table 1 lists the constraints in the MSMR process and their values.

### Table 1 – Process variables and constraints.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Value</th>
<th>Constraints</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG feed pressure (bar)</td>
<td>62.5</td>
<td>LNG temperature</td>
<td>-150.9</td>
</tr>
<tr>
<td>NG feed temperature (°C)</td>
<td>11.5</td>
<td>Suction pressure (bar)</td>
<td></td>
</tr>
<tr>
<td>NG feed composition</td>
<td></td>
<td>1st HK comp.</td>
<td>1.3</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.047</td>
<td>2nd HK comp.</td>
<td>3.6</td>
</tr>
<tr>
<td>Methane</td>
<td>0.871</td>
<td>3rd HK comp.</td>
<td>10.06</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.051</td>
<td>HK comp.</td>
<td>11</td>
</tr>
<tr>
<td>Propane</td>
<td>0.022</td>
<td>Mix comp.</td>
<td>28</td>
</tr>
<tr>
<td>i-Butane</td>
<td>0.004</td>
<td>LK suction temperature (°C)</td>
<td>31.67</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.004</td>
<td>HK suction temperature (°C)</td>
<td>33.54</td>
</tr>
<tr>
<td>i-Pentane</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. Degrees of freedom analysis

The two branches of control objectives, mentioned in step 1, i.e. stable operation and control cost minimization, divide the degrees of freedom analysis into two parts. The concern is not only to define the control degrees of freedom but also to define the number of optimizing degrees of freedom. The number of control degrees of freedom ($N_m$) can be obtained easily by calculating the number of adjustable valves and the number of adjustable electrical and mechanical variables (Skogstad, 2000). According to this concept, there are 57 control degrees.
of freedom in the MSMR process, and their details are presented in Table 2. The optimizing degrees of freedom \( N_{\text{opt}} \), however, are the control degrees of freedom that affect the cost function. \( N_{\text{opt}} \) can be calculated from Eq. (2).

\[
N_{\text{opt}} = N_{m} - N_0 \tag{2}
\]

\[
N_0 = N_{m0} + N_{y0}, \tag{3}
\]

where \( N_0 \) is the number of variables with no effect on the cost. \( N_{m0} \) and \( N_{y0} \) are the number of manipulated inputs and controlled variable, respectively, with no effect on the cost function. From Eqs. (2) and (3) there are 8 optimizing degrees of freedom available in the MSMR process, which consists of 5 compressor speeds, HK flow rate, LK flow rate, and NG flow rate. Nevertheless, the compressor speeds are used to control the suction pressures of the compressor inlet streams. In addition, two cases of the NG flow rate were considered. In the first case, the NG flow rate was fixed at a certain value, and in the second case, it was considered a disturbance. In any case, the NG flow rate is not available as a degree of freedom for optimization. Therefore, there are only 2 variables remaining as the optimizing degrees of freedom i.e. the HK and LK flow rates. The remaining 49 control degrees of freedom are used as the manipulated variables for the necessary regulatory controls, which will be explained in Section 3.4.

### 3.3. Sensitivity analysis

This analysis aims to provide insights into how the LNG temperature responds to input variations, i.e. HK, LK and NG flow rate. Sensitivity analysis was conducted by increasing the NG, LK, and HK flow rates stepwise by 1% (when one input is stepped up the other inputs are fixed). All outputs in the MSMR process were tightly controlled including the suction pressure, aftercooler temperature and liquid level. The LNG temperature showed significant deviation to the variation of the HK and NG flow rate, and reached a new steady-state value after a relatively short period (Fig. 4B and C). A variation in the HK flow rate, however, generates an insignificant change in the LNG temperature (Fig. 4A) compared to the response due to a variation in the LK and NG flow. These results suggest that compared to the HK, the LK is more suitable as a manipulated variable for controlling the LNG temperature.

### 3.4. Constructing the regulatory control layer

The objective of this layer is to facilitate a smooth operation and not to optimize the objectives related to profit (Hovd and Skogestad, 1993). The regulatory control layers consist of control loops that are developed in the MR compression and NGL recovery units.

#### 3.4.1. Regulatory control for MR compression unit

In the MR compression unit, there are four types of variables that need to be controlled tightly: (i) compressor suction pressures, (ii) compressor anti surge, (iii) compressor outlet temperatures, and (iv) liquid level of the HK-LK mixing tank. By controlling these variables, the liquefaction process is isolated from the disturbances caused by pressure and temperature variations in the HK or LK streams. The regulatory control arrangement in the MR compression unit can be viewed in Fig. 5.

#### 3.4.2. Regulatory control for NGL recovery unit

Four types of control strategies for a conventional distillation column are reported: LV, DV, L/D-V/B, and DB (Skogestad et al., 1990). In the LV structure, reflux flow (L) and boil-up rate (V) is the degrees of freedom for controlling the top and bottom compositions of the distillation column. This structure is a commonly used structure in industrial applications and is used to control the columns in the NGL recovery unit except for De-C1. The configurations of regulatory control for NGL recovery unit are depicted in Fig. 6.

#### 3.4.2.1. Control configuration for De-C1 column

##### 3.4.2.1.1. Column stabilizing control structure

Levels and pressures of distillation columns must be controlled at all times to ensure stable operation (Skogestad et al., 1990), therefore these two loops were configured first. The De-C1 column is heat-integrated with the liquefaction unit (Fig. 1). Liquefied NG from MCHE-2, which flows to RT1, provides cold energy for condensation and removes the need for an external cooling agent. Therefore, the number of degrees of freedom for De-C1 is reduced because the flow rate of cooling agent, i.e. water flow rate, is commonly used as the manipulated variable for controlling the overhead pressure (Skogestad et al., 1990). The split stream of overhead flow (O-2) is used as an alternative variable for controlling the De-C1 top pressure.

The reboiler level is controlled by adjusting the bottom flow rate (B-1). Designing level control loop for RT1, however, requires more analysis. In most cases the liquid level of overhead condenser is controlled by adjusting the flow rate of distillate or reflux. However the distillate (O-1) that goes into MCHE-2 should remain free because assigning it as a manipulated variable could enhance the interaction between the two units. Therefore, the reflux flow (R-1) and LNG-Recycle are the remaining free manipulated variables for controlling the liquid level of RT1.

There are three possible level control loops that can be developed: the liquid level is controlled by (1) R-1, (2) LNG-Recycle, or (3) Split range scenario between R-1 and LNG-Recycle. Two tests were conducted to observe the performance of the three loops in controlling liquid level in RT1. The NG feed flow rate was increased and decreased by 1%, where all the control loops in the MR compression unit were closed and both the HK and LK flow rates were fixed.
This R-1 loop is able to maintain the liquid level in RT1 when the NG flow rate was decreased but failed in the opposite situation (Fig. 7A). When the NG flow rate was increased, it disturbed heat transfer in the cryogenic exchanger, resulting in an increase in the LNG temperature from MCHE-2 that was introduced to RT1. The vapor fraction inside the tank increased and drained the liquid from RT1, even though the reflux flow had decreased to the lowest acceptable value. This shows that the applied control structure for De-C1 is not the correct solution, and a better control configuration is required.

The LNG-recycle loop on the other hand is able to maintain the liquid level when the NG flow rate is changed in a positive direction (Fig. 7B) but fails to maintain the set-point of the liquid level in RT1 when the NG flow rate is decreased (Fig. 7C). The undershoot in the middle (approximately the 400th minute) of the ‘Split Control’ response (Fig. 7B) is due to non-smooth role switching between the reflux pump and the LNG-recycle pump. The reflux pump is the main control element for the liquid level in RT1 and was set to 50% of the maximum duty in a normal operation, whereas the LNG-recycle pump was set to the lowest capacity (1% of the maximum duty). When RT1 was drained after increasing the NG flow rate, the capacity of the reflux pump was switched to the lowest acceptable value, whereas the capacity of the LNG-recycle pump was increased to allow a larger flow rate of the LNG-recycle. The instability shown in Fig. 7B occurs when a process approaches the split range point (between the reflux and LNG-recycle pumps). This phenomenon was not observed when the NG flow rate was decreased (Fig. 7C) because there was no role-switching between the reflux pump and LNG-recycle pump. When the tank was flooded, the necessary control action increased the flow rate of the reflux stream, whereas the LNG-recycle pump remained in its initial low capacity.

Overall, all three scenarios showed similar performance in terms of the cost function. Nevertheless, in the present case, the first priority was to maintain stability in RT1 rather than maximize the efficiency. Therefore, for this process structure, the split range scenario between R-1 and LNG-Recycle was selected to control the liquid level in RT1.

3.4.2.1.2. Product specifications. The composition of methane in overhead and bottom product is indirectly controlled by using secondary measurement that is column stage temperature. De-C1 is consisted with only five stages and reboiler stage. Therefore the appropriate stage for closing the temperature loop can be selected by conducting disturbance tests to see which stage temperature is most affected by the variations in feed conditions (temperature, pressure, and composition). The disturbance test showed that among all stages in De-C1, the temperature of the reboiler stage is most affected

Fig. 5 – Control structure arrangement in MR compression unit.

Fig. 4 – Sensitivity of LNG temperature after 1% increase in (A) HK, (B) LK, and (C) NG flow rate.
by the variations in feed conditions. Therefore the methane mole fraction in the overhead stream is controlled by closing the temperature loop in the reboiler stage with the reboiler duty as the manipulated variable. This configuration (Fig. 6A) is similar to the DV structure (distillate D and boilup V are the degrees of freedom for controlling the top and bottom composition respectively), except that the distillate stream in De-C1 is not assigned to control the top composition.

3.4.2.2. Control configuration for De-C2 and De-C3 column. The LV structure was used to control the De-C2 and De-C3 column (Fig. 8), and was found to be working robustly in this process. These columns had relatively smaller interactions with the liquefaction unit that were considered negligible. The connections between the De-C2 and De-C3 columns and liquefaction unit were only through a C2 and C3+ injection (LPG reinjection) and ‘C4 from bottom De-C3’ stream respectively) to the NG stream, which was much smaller than the NG flow rate. Although some portions of the MR were exchanging heat with the overhead streams from De-C2 and De-C3, tight control of the suction pressure and aftercooler temperature in MR compression unit inhibited any disturbances from the columns to propagate further.

3.4.3. Holdup controls
MR main stream is collected in RT4 prior separating it into vapor and liquid stream. The holdup in RT4 is not controlled (and should not be controlled) because this vessel is a part of the MR closed process loop. The holdup volume inside RT4 must be kept floating at certain range to keep the balance of MR in the process loop. Also in the same liquid line of this vessel there is a valve (V1) that is used as the control element for another control loop. Due to variations in this valve the holdup volume in RT4 will be affected temporarily but once the process reach steady state, the liquid volume in RT4 will also reach particular steady value.

The holdup volume in the vessel at the exit of the liquefaction unit (RT5) is controlled by adjusting the flow rate one of the split streams from liquid line of RT5.

3.5. Steady state optimality analysis
In this step the self optimizing controlled variable for the MSMR process was formulated. The search for this variable was initiated by plotting an optimality map, at five different NG feed flow rate (mLNG), which represents the steady-state correlation between the HK, LK and NG flow rate to the cost function. The optimality map of the MSMR process (Fig. 9) was

Fig. 6 – (A) Initial, (B) first and (C) second alternative control structure for controlling liquid level in RT1.
composed at a given LNG temperature (−150.9 °C) by fixing the NG feed pressure, temperature and composition as well as all the associated regulatory controls in the MR compression and NGL recovery unit. The LNG temperature was fixed at the set point by manipulating the LK flow rate, whereas the HK flow rate was used as a source of input variation.

The shaded area in the center of the map in Fig. 9 shows the region of the optimal operation of the MSMR process in terms of the HK flow rate. The total duty/net LNG is insensitive to variations in the HK flow rate. In this shaded area, even when the HK flow rate was located on the right side of the optimum line, the total duty/net LNG was similar to its optimal value.

The optimality map can be viewed from a different angle (Fig. 10). This map shows the relationship between the total duty/net LNG and HK flow rate variations. In contrast to the variations in the HK flow rate, the same scale of variations in the LK flow rate alter the total duty/net LNG with a larger deviation, thereby creating a distinctive optimal point on each NG flow rate curve. If the LK flow rate is fixed at a constant value when the operating point is moved to a different NG flow rate, the total duty/net LNG is also changing with a significant deviation. This suggests that the HK flow rate is not the appropriate optimizing variable. The HK flow rate in this case will be a better optimizing variable because variations in HK flow rate produce flatter curves of cost function.

The HK flow rate can be derived as another possible optimizing controlled variable i.e. the HK/LK flow rate ratio. In a natural gas liquefaction plant, the ratio between the flow rate of a light and heavy refrigerant can be used as an additional controlled variable to maintain the composition of the MR over.

Fig. 8 – Control structure arrangement for De-C2 and De-C3.
the operating map (Mandler et al., 1998). In addition, maintaining the refrigerant to always have an appropriate mixture of high and low boiling point components will result in a large specific refrigeration effect at relatively low refrigeration temperatures (Venkataraman, 2008).

To select between the HK flow rate and HK/LK ratio, several lines that represent the constant value of each variable, were plotted on the map in Fig. 10. Note that the data for constructing this map were obtained from the same tests, including the data to draw the constant line of the HK flow and HK/LK ratio. The constant line of the HK/LK ratio coincided perfectly with the optimal points, whereas the constant HK flow rate line showed a small deviation at higher NG flow rates. As the operating condition moved to the upper region, only the constant lines of the HK/LK ratio could maintain an almost constant distance to the optimal line at every point of the NG flow rate. On the other hand, the constant lines of the HK flow rate digressed significantly.

The operating condition is not necessarily at the optimal point and can be anywhere in the map within the feasible range. From the optimality map (Fig. 10), maintaining a constant HK flow rate outside the optimal region will likely to bring the MSMR process into inefficiency. This suggests that the HK/LK ratio is more suitable as the optimizing controlled variable under constant NG feed conditions.

The NG feed conditions are subject to variations and the operational map at the new state variables will also change. A proper optimizing controlled variable can also be selected.
by observing how its optimal value is affected by variations
in the NG feed conditions. The optimal value of the optimi-
ing controlled variable must be insensitive to distur-
bances (Skogestad, 2012). A number of tests were conducted to deter-
mine how the optimal HK flow rate and HK/LK ratio respond
to the propagation of disturbances (Fig. 11). These tests were
carried out at a fixed LNG temperature at the base case NG
flow rate ($m_{\text{LNG}} = 264.9$ kmol/h) with the LK flow rate used as
the manipulated variable.

The HK/LK ratio was indifferent to NG feed pressure varia-
tions, whereas the HK flow rate deviated with relatively larger
magnitude (Fig. 11A). The same situation was also applied
to the temperature (Fig. 11B) and composition disturbance
(Fig. 11C). Based on the requirement mentioned previously,
the HK/LK ratio is more suitable as an optimizing controlled
variable compared to the HK flow rate.

Another method for selecting the optimizing controlled
variable is by comparing the profile of $J$ in two systems,
one with a fixed HK flow rate and the other with a fixed HK/LK
ratio, when the disturbances propagate (Fig. 12). The deviations of $J$ due to pressure disturbances in the system with a
fixed HK flow rate and the system with a fixed HK/LK ratio

![Fig. 11 – Deviation of optimum value of optimizing controlled variable candidate ($d_{\text{opt}}$) at $m_{\text{LNG}} = 264.9$ kmol/h after variation in NG feed conditions: (A) pressure, (B) temperature, and (C) mole fraction of CH$_4$.](image)

![Fig. 12 – Deviation of $J$ after variation in NG feed conditions: (A) pressure, (B) temperature, and (C) mole fraction of CH$_4$.](image)

![Fig. 13 – Control structure in liquefaction unit with (A) HK flow rate loop and (B) HK/LK ratio loop.](image)
Fig. 14 – Responses of LNG temperature (in deviation value) after disturbances in NG feed conditions.

were similar (Fig. 12A). On the other hand, for positive pressure deviation, the system with a constant HK flow rate could drive the process to a lower J value. The J values in the three systems were similar despite the variations in the NG feed temperature (Fig. 12B). For a composition disturbance (Fig. 12C), the values of the cost function in the two systems were similar except for the case of a smaller CH₄ mole fraction.

All plots in Fig. 12 suggest that both the HK flow and HK/LK ratio will produce similar solutions, in terms of J, when the disturbances propagate to the process. Nevertheless, an analysis of all results from steady-state optimality analysis showed that the HK/LK ratio is the appropriate optimizing controlled variable for the following reasons:

1. If NG flow rate is considered as a disturbance, where the NG flow rate is subject to variations, then from Fig. 10 in terms of minimizing the cost function, controlling the HK/LK ratio will be more advantageous than controlling the HK flow rate.

Fig. 15 – Responses of J (in deviation value) after disturbances in NG feed conditions.
2. Maintaining the HK/LK ratio imparts a benefit to the operational of MSMR process as explained earlier in this section. Therefore, from steady-state optimality analysis, the HK/LK ratio was selected as the optimizing controlled variable.

3.6. Control structure tests

To validate the conclusion from steady-state optimality analysis, the control performance of the MSMR process with a HK flow rate loop and HK/LK ratio loop was checked. Fig. 13 shows the arrangement of the control structure in a liquefaction unit with two different optimizing variables. Figs. 14 and 15 present the results of applying three kinds of disturbances to both systems. D1 refers to a ±3 bar disturbance in the NG feed pressure, D2 is a ±3 °C disturbance in the NG feed temperature, and D3 is a ±0.03 disturbance in the NG feed CH₄ mole fraction. For D3, when the CH₄ mole fraction is decreased by 0.03, the mole fractions of C₂H₆ and C₃H₈ are increased by 0.015. Qualitatively, the system with a HK/LK ratio loop can reject most disturbances better than a system with a HK flow loop (Fig. 14). This hypothesis was confirmed by the Integral Absolute Error (IAE)
results (Table 3) which showed that by controlling the HK/LK ratio, the LNG temperature can return to its set-point with a smaller error. On the other hand, in terms of the cost function, both systems showed similar performance, where a similar new steady-state value was reached in each system (Fig. 15). These situations were detected previously in the steady-state optimality analysis results described in Fig. 12.

The system with the HK/LK ratio showed better performance than that with the HK flow rate when the NG flow rate was increased by 1%. The system with the HK/LK ratio had a smaller overshoot (Fig. 16A) and also a lower deviation in the cost function (Fig. 16B). Excellent performance of the system with the HK/LK ratio was also observed when the NG flow rate was decreased by 1% (Fig. 17A). This system has a slightly higher IAE than the system with a fixed HK flow. On the other hand, fixing the HK/LK ratio allows the system to have a lower cost function once the NG flow rate is decreased (Fig. 17B). This NG-flow-rate step represents a situation where natural gas is not controlled and is considered a source of disturbance. When there are variations in the NG flow rate, controlling the HK/LK ratio is more beneficial than controlling the HK flow rate because it can minimize the control cost.

4. Conclusions

This paper presented a steady-state optimality analysis to find the self-optimizing controlled variable of the MSMR process. The insensitivity of the total duty/net LNG to variations in the HK flow rate highlights the robustness of the MSMR process. On the other hand, the unconstrained sharp optimum of the cost function due to variations in the HK flow rate indicates that the HK flow rate is unsuitable as an optimizing variable. This variable is instead more suitable as the manipulated variable for controlling the LNG temperature. Further analysis showed that maintaining a constant HK/LK ratio is more beneficial. The HK/LK ratio is insensitive to disturbances and the system with the HK/LK ratio control loop can reject most disturbances better than the system with the HK flow control loop. The system with the HK/LK ratio can also perform a more stable operation with a lower control cost when the NG flow rate is varied. The steady-state optimality method used in this study was developed to determine the optimizing controlled variable in an offshore natural gas liquefaction plant. This method can also be applied to other natural gas liquefaction plants that use different liquefaction technologies or even any plant that includes liquefaction using multi stream cryogenic exchangers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cherd.2013.11.009.

References


