

# Single-cycle mixed-fluid LNG process

## Part II: Optimal operation

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### Abstract

Considering the large amount of work that goes into the design of LNG processes, there is surprisingly little attention to their subsequent operation. This partly comes from the assumption that optimal design and optimal operation are the same, but this is not generally true. In this paper we study the optimal operation of a relatively simple LNG process, namely the PRICO process.

**Keywords:** PRICO, LNG, operation

## 1 Introduction

The process considered in this paper is a single mixed refrigerant process, namely the PRICO process (Stebbing and O'Brien, 1975; Price and Mortko, 1996). This is the simplest configuration used commercially for liquefaction of natural gas and it has been optimized in several publications (Lee et al., 2002; Del Nogal et al., 2005) and in part I, but only with respect to design. Singh and Hovd (2006) study the controllability of the process but they do not consider optimal operation which is the theme in this paper. Figure 1 shows a simplified flowsheet of the PRICO process and a description of the process is given in part I of the paper. We here consider Case 8 from part I, where a liquid turbine is included both in the expansion of natural gas and expansion of the refrigerant. The extra choke valve between the liquid turbine and receiver is to give a safety margin to saturation at the liquid turbine outlet.

An important issue in plantwide control is to find the degrees of freedom that may be used for online optimization (Skogestad, 2002). In our case these are the same as the steady-state operational degrees of freedom and this number is

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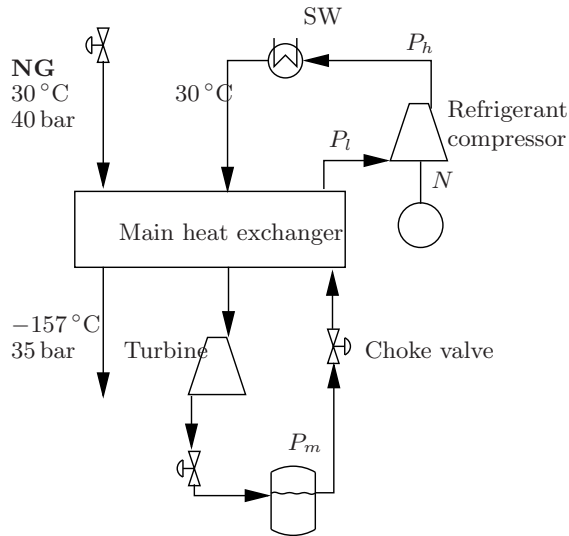


Figure 1: A simplified flowsheet of the PRICO process

important for several reasons. First, it determines the degrees of freedom available for solving the optimization problem. However, more importantly in terms of operation it determines the number of steady-state controlled variables that need to be selected. Optimal operation is normally implemented by keeping the selected variables at constant setpoints. Note that the selection of controlled variables is equally important if we use a model-based control structure such as model predictive control (MPC).

The process, model and software is briefly mentioned in part I of the paper. More details are given in Jensen (2008).

## 1.1 Manipulated inputs

There are 9 manipulated inputs with a steady-state effect (potential control degrees of freedom for control,  $u_0$ ):

- 1 Compressor: rotational speed  $N$
- 2 Choke valve: valve opening  $z$
- 3 Turbine: rotational speed
- 4 Cooler: flow of sea water (SW) in cooler
- 5 Load: Feed flow of natural gas (can also be considered a disturbance)
- 6-9 Composition of refrigerant (5 components give 4 independent compositions). These degrees of freedom are not considered for control, but the compositions are optimized at the design stage.

## 1.2 Operational constraints

In general, there are many constraints (represented by the equations  $c \leq 0$  in the optimization problems) that must be satisfied during operation.

- Super-heating ( $\Delta T_{\text{sup}}$ ): The stream entering the compressor must not contain liquid (but note that this is not necessary an active constraint in this case, because there is internal heat exchange, so it is actually optimal with some super-heating).
- $T_{LNG}^{\text{out}}$ : Natural gas temperature out of the main heat exchanger should be within certain bounds. This temperature sets the amount of flash gas and affects the composition of flash gas and LNG.
- Compressor power ( $W_s$ ): We assume maximum at 120 MW
- Compressor rotational speed ( $N$ ): We assume maximum at 100 %.
- Compressor surge: The compressor may in theory be operated in the surge region using active surge control, but normally one would like to operate with a certain margin to surge. In this paper, we use the value  $\Delta \dot{m}_{\text{surge}} \geq 0.0 \text{ kg s}^{-1}$  (i.e. no back-off). Operation of the compressor is given by compressor maps, see Jensen (2008).

In particular, the cooling water flow has a maximum value, and it is clear from physical insight that maximum cooling is optimal (active constraint). Assuming that we have a large area in this heat exchanger, we will in the following replace this constraint by the following:

- Maximum cooling: Assume refrigerant has  $T = 30^\circ\text{C}$  after SW cooler

With the assumption of  $T = 30^\circ\text{C}$  after the SW cooler (flow of sea water at maximum), we are left with 8 steady-state degrees of freedom (4 for control).

## 2 Objective function

The economic cost function to be minimized during operation is:

$$J_{\text{operation}} = p_{W_s} \cdot W_s - p_{W_{s,\text{turbine}}} \cdot W_{s,\text{turbine}} + p_{SW} \cdot Q_C - p_{LNG} \cdot \dot{m}_{LNG} + p_{\text{feed}} \cdot \dot{m}_{\text{feed}} - p_{\text{fuel}} \cdot \dot{m}_{\text{fuel}} \quad (1)$$

We make the following assumptions:

- Same price for fuel and feed. Then,  $p_{\text{feed}} \cdot \dot{m}_{\text{feed}} - p_{\text{fuel}} \cdot \dot{m}_{\text{fuel}} - p_{LNG} \cdot \dot{m}_{LNG} = (p_{\text{feed}} - p_{LNG}) \cdot \dot{m}_{LNG} = \hat{p}_{LNG} \cdot \dot{m}_{LNG}$
- Neglect income from turbine work,  $p_{W_{s,\text{turbine}}} = 0$  and cost of cooling,  $p_{SW} = 0$

The optimization problem then becomes:

$$\begin{aligned} \min_u \quad & W_s - \hat{p}_{\text{LNG}} \cdot \dot{m}_{\text{LNG}} \\ \text{subject to} \quad & c \leq 0 \end{aligned} \quad (2)$$

Here,  $c \leq 0$  represent the mathematical formulation of the operational constraints and the model equations. One such constraint is  $W_s \leq W_s^{\text{max}}$ . The degrees of freedom  $u$  are 8 in design and 4 during operation.

Depending on product price and other external factors there are two main operating modes:

**Mode I** Given throughput: With a given feed flowrate or given LNG production, the optimization problem simplifies to:

$$\begin{aligned} \min_u \quad & W_s \\ \text{subject to} \quad & \dot{m}_{\text{feed}} = \text{given} \quad (\text{or } \dot{m}_{\text{LNG}} = \text{given}) \\ & c \leq 0 \end{aligned} \quad (3)$$

**Mode II** Maximum throughput: If the LNG price ( $\hat{p}_{\text{LNG}}$ ) is sufficiently high and there is no active constraint related to available feed or product distribution it will be optimal to maximize the production of LNG:

$$\begin{aligned} \min_u \quad & -\dot{m}_{\text{LNG}} \\ \text{subject to} \quad & c \leq 0 \end{aligned} \quad (4)$$

In this case, the constraint on compressor power is active, that is  $W_s = W_s^{\text{max}} = 120$  MW. Note that the operation in this mode may be quite different from the “nominal” optimum found for mode I.

### 3 Nominal optimum

**Mode I:** Since the production rate (or feed rate) is fixed there are 7 steady-state degrees of freedom including the 4 refrigerant compositions. The nominal optimum is found by solving the optimization problem in Equation 3. The results are summarized in the left column of Table 1.

The compressor work was minimized with respect to the 7 degrees of freedom, including the 4 refrigerant compositions. Note that we have assumed that the refrigerant is 30 °C after the SW cooling. The optimal operation of the compressor was found subject to compressor maps (Jensen, 2008). We find that the following constraints are active at the nominal optimum:

1. Temperature of natural gas after cooling at maximum ( $T_{\text{out}} = -157$  °C)
2. Surge margin at minimum ( $\Delta\dot{m}_{\text{surge}} = 0$ )

Table 1: The nominal operating point for: Mode I - Given production. Mode II - Maximum production

		Mode I	Mode II
$W_s$ [kW]	Compressor work	106	<b>120</b>
$P_h$ [bar]	Cycle high pressure	26.8	30.0
$P_l$ [bar]	Cycle low pressure	3.67	4.14
$N$ [%]	Compressor rotational speed	<b>100</b>	<b>100</b>
$\eta$ [%]	Compressor efficiency	82.8	82.8
$\dot{m}_{\text{LNG}}$ [kg s <sup>-1</sup> ]	LNG flowrate	<b>69.8</b>	76.7
$\dot{m}_{\text{REF}}$ [kg s <sup>-1</sup> ]	Refrigerant flowrate	549	614
$\Delta\dot{m}_{\text{surge}}$ [kg s <sup>-1</sup> ]	Surge margin	<b>0.000</b>	<b>0.000</b>
$\Delta T_{\text{sup}}$ [°C]	Super-heating before compressor	12.9	11.3
$T_{\text{out}}$ [°C]	NG temperature after cooling	<b>-157</b>	<b>-157</b>
$x_{\text{CH}_4}$ [mole-%]	Methane in refrigerant	31.9	32.7
$x_{\text{C}_2\text{H}_6}$ [mole-%]	Ethane in refrigerant	35.2	34.3
$x_{\text{C}_3\text{H}_8}$ [mole-%]	Propane in refrigerant	<b>0.0</b>	<b>0.0</b>
$x_{\text{n-C}_4\text{H}_{10}}$ [mole-%]	nButane in refrigerant	24.7	23.3
$x_{\text{N}_2}$ [mole-%]	Nitrogen in refrigerant	8.2	9.7

Boldface: Specifications and active constraints

### 3. Compressor speed at maximum ( $N = 100\%$ )

Thus, at the nominal optimum, the only unconstrained degrees of freedom are the refrigerant compositions.

**Mode II** The LNG production is maximized, see Equation 4. Since the production rate (or feed rate) is free there are 8 steady-state degrees of freedom (with 30 °C after SW cooling).

The nominal optimum, including the optimal composition of the refrigerant, is summarized in the right column of Table 1.

We find that the following constraints are active at the nominal optimum:

1. Compressor work at maximum ( $W_s = 120$  MW)
2. Surge margin at minimum ( $\Delta\dot{m}_{\text{surge}} = 0$ )
3. Temperature of natural gas after cooling at maximum ( $T_{\text{out}} = -157$  °C)
4. Compressor rotational speed at maximum ( $N = 100\%$ )

Note that there are two ‘‘capacity’’ constraints that are active (1 and 4). Again, the only unconstrained degrees of freedom are related to the refrigerant composition.

We have now identified the nominal optimum for the two cases, but how should we control the process to maintain close to optimal operation when the process is exposed to disturbances? This is discussed next.

## 4 Optimum with disturbances

Table 2: Nominal, minimum and maximum values for the disturbances. The numbers in parentheses are for mode I.

	Nominal	Min	Max	Name
$W_s^{max}$ [MW]	120	110	130	$d_1^*$
$P_{feed}$ [bar]	40	35	45	$d_2$
$T_{in}$ [ $^{\circ}$ C] <sup>†</sup>	30	25	35	$d_3$
$x_{CH_4}$ [%]	32.7 (31.9)	29.4 (28.7)	36.0 (35.1)	$d_4$
$x_{C_2H_6}$ [%]	34.3 (35.2)	30.9 (31.7)	37.7 (38.7)	$d_5$
$x_{C_4H_{10}}$ [%]	23.3 (24.7)	21.0 (22.2)	25.6 (27.2)	$d_6$
$x_{N_2}$ [%]	9.7 (8.2)	8.7 (7.4)	10.7 (9.0)	$d_7$
$\dot{m}_{LNG}$ [kg s <sup>-1</sup> ]	69.8	66.5	73.1	$d_8^{\ddagger}$

\*Only used for mode II

†The temperature of natural gas and refrigerant at the inlet to the main heat exchanger

‡Only used for mode I

The next step is to consider optimal operation with disturbances, and we consider the eight disturbance variables given in Table 2. We here fix the refrigerant composition (the composition is treated as a disturbance), see Table 2). With a fixed temperature (30  $^{\circ}$ C) after the SW cooler, there are then 4 remaining degrees of freedom. During operation, it is always optimal to cool the natural gas to  $-157^{\circ}$ C (to avoid product give-away), and, one degree of freedom is spent to set the load:

Mode I The production rate is given

Mode II The compressor is at its maximum ( $W_s = W_s^{max}$ )

Thus, two constraints are always active and this leaves for both modes only 2 steady-state operational degrees of freedom. The optimal results are shown graphically as dots in Figure 2 for mode II.

Recall that the surge margin constraint ( $\Delta\dot{m}_{surge} = 0$ ) and compressor maximum speed constraint ( $N = N^{max}$ ) were active in the nominal point, and we find, as one would expect, that these remain active for most of the disturbances, but not all. Also note that some disturbances are not feasible in mode I, probably because of the fixed refrigerant composition.

To obtain optimal operation, we should always implement the active constraints, and then find "self-optimizing" variables for the remaining unconstrained degrees of freedom in each region. Strictly speaking, we then need to consider four regions:

1.  $N = N^{max}$  and  $\Delta\dot{m}_{surge} = 0$  (no unconstrained variable)
2.  $\Delta\dot{m}_{surge} = 0$  and  $N < N^{max}$  (one unconstrained variable)
3.  $N = N^{max}$  and  $\Delta\dot{m}_{surge} > 0$  (one unconstrained variable)
4.  $N < N^{max}$  and  $\Delta\dot{m}_{surge} > 0$  (two unconstrained variables)

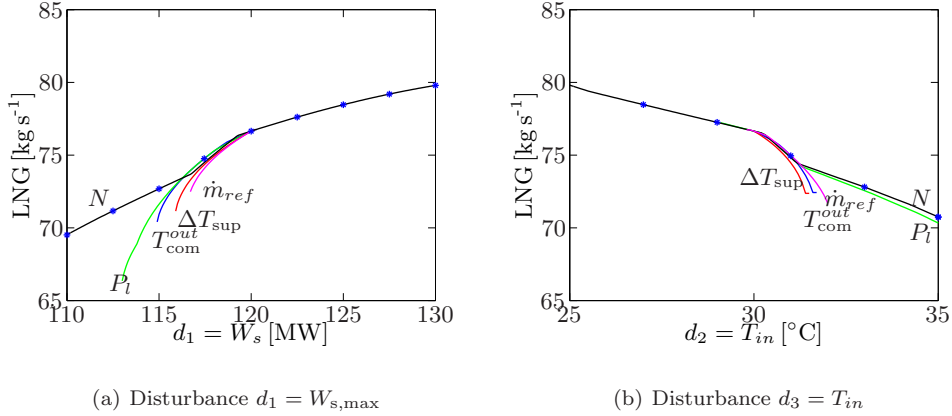


Figure 2: LNG production for different control structures as function of disturbances for mode II. Dots are re-optimized operation with constant composition.

This becomes rather complicated. For practical implementation, we would prefer to have the same controlled variables in all regions, and in our case the obvious policy is to consider keeping the variables at constraint ( $\Delta\dot{m}_{surge} = 0$  and  $N = 100\%$ ) in all regions. Obviously, this is not optimal, but the loss is rather small as discussed next, except for some cases in mode I, where it seems operation is not feasible (without changing the composition or feed rate).

#### 4.1 Selection of controlled variables

A preliminary screening was performed by using the maximum scaled gain method (Halvorsen et al., 2003). Some variables were discarded based on these results (e.g. the degree of sub-cooling, cycle high pressure). Also, we found that the surge margin ( $\Delta\dot{m}_{surge}$ ) is a much more promising controlled variable than any of the alternatives we tested. Thus, we choose to fix  $\Delta\dot{m}_{surge} = 0$  and this gives only minor losses as seen below.

Figure 2 shows LNG production as a function of 2 of the 7 disturbances ( $d_1, d_2, d_4 - d_6$ ) considered for mode II.  $\Delta\dot{m}_{surge} = 0$  and the following alternative controlled variables are tested for the remaining degree of freedom;  $N = 100\%$ ,  $\Delta T_{sup} = 11.3^\circ\text{C}$ ,  $P_l = 4.14\text{ bar}$ ,  $T_{com}^{out} = 124^\circ\text{C}$  and  $\dot{m}_{ref} = 614\text{ kg s}^{-1}$ . The dots show re-optimized operation, where both  $N$  and  $\Delta\dot{m}_{surge}$  has been optimized. The disturbance is plotted on the X-axis and the Y-axis shows the corresponding production rate in  $\text{kg s}^{-1}$ . Note that the composition of the refrigerant is still the same as for the nominal operating point.

$N$  is actually the only feasible control structure for some disturbance directions. This may be seen from Figure 2(a), where all lines except the constant  $N$  line ends at the nominal point (from left to right).

## 5 Conclusion

For both mode I (given feed) and mode II (maximum feed), operating close to surge and at maximum compressor speed ( $\Delta\dot{m}_{\text{surge}} = 0$  and  $N = 100\%$ ) is optimal for the nominal operating point and in some of the disturbance regions. Since maintaining constant  $N$  and  $\Delta\dot{m}_{\text{surge}}$  is also close to optimal for the remaining disturbance regions we propose to use this control structure. The remaining controlled variables are the active constraints; i) maximum sea water cooling (valve fully open), ii)  $T_{\text{LNG}} = -157^\circ\text{C}$  and iii)  $\dot{m}_{\text{LNG}} = 69.8\text{ kg s}^{-1}$  (mode I) or  $W_s = 120\text{ MW}$  (mode II).

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