16th European Symposium on Computer Aided Process Engineering
and 9th International Symposium on Process Systems Engineering
W. Marquardt, C. Pantelides (Editors)
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# Optimal operation of a mixed fluid cascade LNG plant

Jørgen Bauck Jensen[a] & Sigurd Skogestad[a*]

[a]Department of Chemical Engineering, NTNU, Trondheim, Norway

Studies on the operation of complex vapour compression cycles, like the one used for the production of liquefied natural gas (LNG), are not widely reported in the open literature. This is a bit surprising, considering the large amount of work that has been put into optimizing the design of such processes. It is important that the process is operated close to optimum to fully achieve the maximum performance in practice. There are possibilities for savings, both due to (a) identifying the optimal point of operation, and (b) selecting the controlled variables such that the optimal operation depends weakly on disturbances.

In this paper we study the mixed fluid cascade (MFC) LNG process developed by *The Statoil Linde Technology Alliance*. We study the degrees of freedom and how to adjust these to achieve optimal steady-state operation.

**Keywords:** Self-optimizing control, optimal operation, liquefied natural gas

## 1. Introduction

Large amounts of natural gas (NG) are found at locations that makes it infeasible or not economical to transport it in gaseous state (in pipelines or as compressed NG) to the customers. The most economic way of transporting NG over long distances is to first produce liquefied natural gas (LNG) and then transport the LNG by ships. At atmospheric pressure LNG has approximately 600 times the density of gaseous NG.

At atmospheric pressure LNG has a temperature of approximately -162°$C$, so the process of cooling and condensing the NG requires large amounts of energy. Several different process designs are used and they can be grouped roughly as follows:

- Mixed refrigerant: The refrigerant composition is adjusted to match the cooling curve of NG. Some are designed with a separate pre-cooling cycle
- Cascade process (pure fluid): Several refrigerant cycles are used to limit the mean temperature difference in the heat exchange
- Mixed fluid cascade process: Energy efficiency is further improved by using several mixed refrigerant cycles

The process considered in this paper is the Mixed Fluid Cascade (MFC) process developed by *The Statoil Linde Technology Alliance* [1]. The MFC process has three different cycles, all with mixed refrigerant and the first cycle with two pressure levels.

The steady-state model for this plant is implemented in gPROMS [6] resulting in approximately 14000 equations. Optimizing the plant takes in the order of 2 hours on a Pentium 4 computer with 2.8 GHz and 512 MB RAM running GNU/Linux.

## 2. Process description

A simplified flowsheet is given in Figure 1. For more details about the process consult [1], [2] and [3].
Nominal conditions:

- Feed: NG enters with P=61.5 bar and T=11°$C$ after pretreatment. The composition is: 88.8% methane, 5.7% ethane, 2.75% propane and 2.75% nitrogen. Nominal flow rate is 1 kmol/s

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[*] skoge@chemeng.ntnu.no

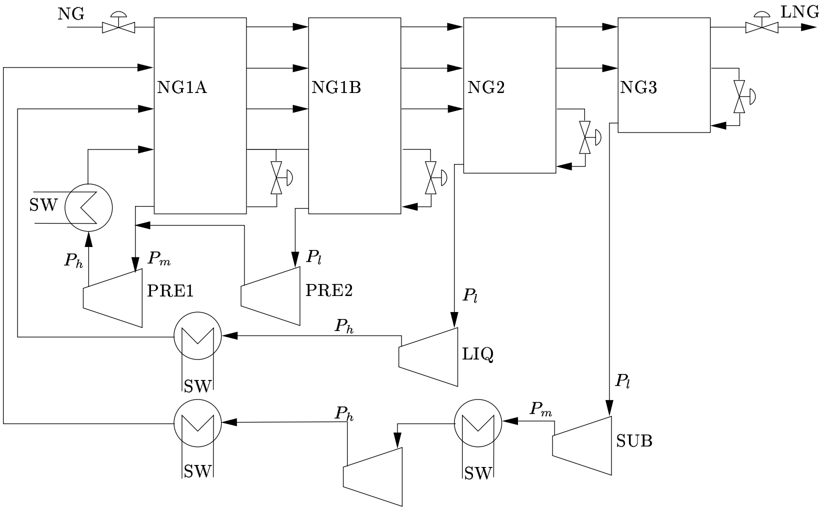

Figure 1. Simplified flowsheet of the MFC process. SUB - sub-cooling cycle, LIQ - liquefaction cycle, PRE - pre-cooling cycle (two stages 1 and 2). NG1A to NG3 are the main heat exchangers. Degrees of freedom associated with variable active charge in each cycle are not shown

- Product: LNG is at P=55.1 bar and T=-155°$C$
- The refrigerants are a mix of nitrogen ($N_2$), methane ($C_1$), ethane ($C_2$) and propane ($C_3$) and the compositions are used in optimization.
- The refrigerant vapour to the compressors are super-heated 10°$C$
- The refrigerants are cooled to 11°$C$ in all sea water (SW) coolers (assumed maximum cooling)
- Pressure drops are 0.5 bar in SW coolers, 0.5 bar for hot flows in main heat exchangers and 0.2 bar for cold refrigerant in main heat exchangers

The SRK equation of state is used both for NG and the refrigerants. The heat exchangers are distributed models with constant heat transfer coefficients. The compressors are isentropic with 90% constant efficiencies.

## 3. Degree of freedom analysis

In this section we present a detailed degree of freedom analysis which is an important result of this work.

In a single simple vapour compression cycle (e.g. a home refrigerator) there are two obvious manipulated inputs, namely the compressor and the valve[†]. In addition, there is a less obvious manipulated variable. This is the "active charge" in the cycle, which may be modified by introducing a unit (tank) with variable holdup [4]. The active charge may be changed by placing tanks at many different locations, but from a simple mass balance it may be verified that for each cycle one may have only one independent variable (tank) associated with the active charge. Thus for the cycles the number of manipulated variables are the number of compressors and valves plus one active charge for each cycle.

Let us now look at the MFC process.

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[†] In addition one might control flow of hot and cold fluid, but this is outside the cycle, so let us overlook that for now

### 3.1. Manipulated variables (MV's)

From the discussion above we find that there are in total 26 manipulated variables (degrees of freedom):

- 5 Compressor powers $W_{s,i}$
- 4 Choke valve openings $z_i$
- 4 SW flows in coolers
- 1 NG flow (can also be considered a disturbance)
- 9 Composition of three refrigerants
- 3 active charges (one for each cycle)

### 3.2. Constraints during operation

There are some constraints that must be satisfied during operation.

- Super-heating: The vapour entering the compressors must be $\geq 10°C$ super-heated
- $T^{out}_{LNG}$: NG Temperature out of NG3 must be $\leq$-155$°C$ or colder
- Pressure: 2 bar$\geq$ P $\leq$60 bar
- NG temperature after NG1A and NG1B (not considered in this paper)
- Compressor outlet temperature (not considered in this paper)

### 3.3. Active constraints

We are able to identify some constraints that will be active at optimum. In total there are 12 active constraints:

- 4 Super-heatings to be minimized (e.g. see [4]), that is $\Delta T_{sup,i}$=10$°C$ at 4 locations
- Excess cooling is costly so $T^{out}_{LNG}$=-155$°C$
- Optimal with low pressure in cycles so $P_l$=2 bar (for all 3 cycles)
- Maximum cooling: Assume T=11$°C$ at 4 locations

### 3.4. Unconstrained degrees of freedom

After using 12 of the 26 manipulated inputs to satisfy active constraints, we are left with 14 unconstrained degrees of freedom. In this work we consider the NG flow given from elsewhere (disturbance to the process), so we are left with 13 degrees of freedom in optimization. For a steady state analysis the pairing of inputs and outputs is insignificant, so say we are left with the following subset of the MV's:

- 3 NG temperatures (after NG1A, NG1B and NG2)
- $P_m$ in SUB
- 9 Refrigerant compositions

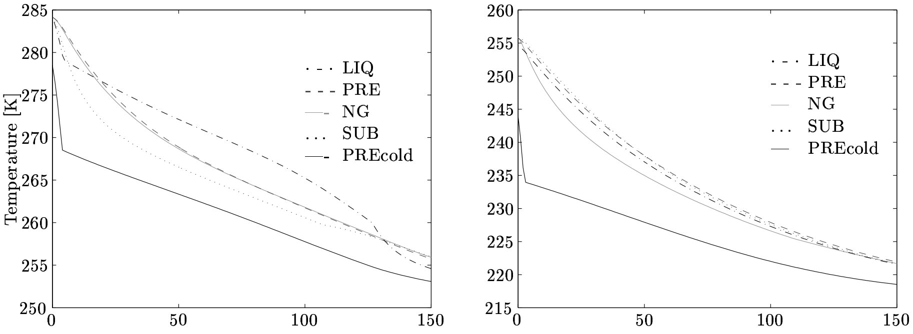
In this paper we will not consider manipulating refrigerant composition in operation (only in the optimization), so of the 13 unconstrained degrees of freedom we are left with 4 during operation.

## 4. Optimization results

In this section we are optimizing on the 13 degrees of freedom given above to locate the optimal operation of a given MFC LNG plant. The resulting temperature profiles for the four main heat exchangers are given in Figure 2. Some key values of the refrigerant cycles are given in Table 1 where the nomenclature is given in Figure 1.

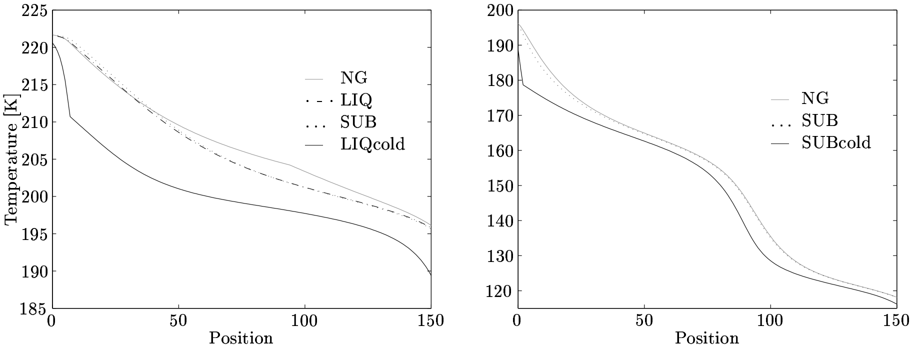
Some remarks:

- The total shaft work is 10.896 MW
- The optimal NG temperature out of NG1A, NG1B and NG2 is 255.9 K, 221.7 K and 196.1 K, respectively
- In the true design there will separators at the high pressure side of the cycles, which has not been considered here. Further work will include an analysis of the effect of this sub-optimal design
- In SUB cycle the pressure ratios over the two compressor stages are far from equal (which is a rule of thumb for compression ratios). This is because the inlet temperature to the first stage (approximately -80$°C$) is much lower than inlet temperature to the second stage (11$°C$)
- Nitrogen is present in SUB only to satisfy the minimum pressure of 2 bar



(a) NG1A

(b) NG1B



(c) NG2

(d) NG3

Figure 2. Temperature profiles

## 5. Control structure design

In the section above we where able to identify the optimum for the process, but how should this optimum be implemented in practice? First we need to control the active constraints:

- Degree of super-heating (4 locations): For this we may use the corresponding choke valve opening
- $P_l$ is for each of the 3 cycles: For this we may use "active charge" (see discussion above)
- Maximum cooling in 4 SW coolers: SW flow at maximum
- LNG outlet temperature at -155°$C$: May use first compressor stage in SUB

The four remaining degrees of freedom should be used to control variables which have good self optimizing properties:

"Self optimizing control is when we can achieve acceptable loss with constant setpoint values for the controlled variables (without the need to re-optimize when disturbances occur)" [5].

Table 1
Optimal operation of a MFC process

| | | PRE1 | PRE2 | LIQ | SUB |
|---|---|---|---|---|---|
| $P_l$ | [Pa] | 6.45 | 2.00 | 2.00 | 2.00 |
| $P_m$ | [Pa] | | 6.45 | - | 28.38 |
| $P_h$ | [Pa] | 15.03 | 15.03 | 20.58 | 56.99 |
| $C_1$ | [%] | 0.00 | 0.00 | 4.02 | 52.99 |
| $C_2$ | [%] | 37.70 | 37.70 | 82.96 | 42.45 |
| $C_3$ | [%] | 62.30 | 62.30 | 13.02 | 0.00 |
| $N_2$ | [%] | 0.00 | 0.00 | 0.00 | 4.55 |
| Flow | [mol/s] | 464 | 685 | 390 | 627 |
| $W_s$ | [MW] | 1.2565 + 2.644 | | 2.128 | 3.780+1.086 |

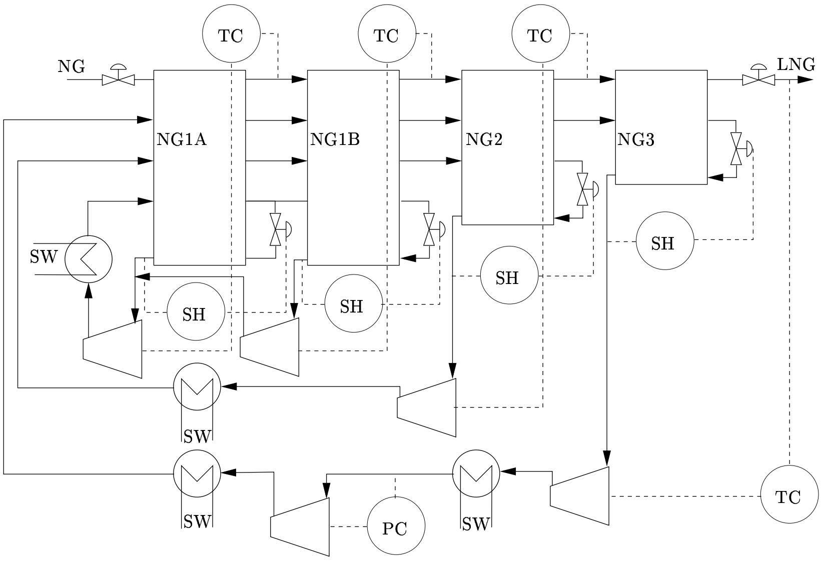


Figure 3. Suggested control structure for the MFC process. SH are degree of super-heating controllers, PC and TC are pressure and temperature controllers respectively. Not shown: Three pressure controllers on the low pressure side using the active charge in each cycle

To evaluate the loss one needs to consider the effect of disturbances and implementation errors. A steady-state analysis is usually sufficient because the economics are primarily determined by the steady-state.

Based on physical insight the following four variables may been suggested

- $T_{NG1A}^{out}$
- $T_{NG1B}^{out}$
- $T_{NG2}^{out}$
- $P_m$

A possible control structure with these four variables and the active constraints controlled is shown in Figure 3. However, note that the "pairings" of controlled and manipulated inputs are included primarily to illustrate that we have available degrees of freedom, as this does not matter for evaluating self-optimizing control at steady-state. It will be the subject of future work to compare this choice of controlled variables with one that follows from a systematic procedure.

## 6. Conclusion

We have shown that the degrees of freedom in vapour compression cycles are equal to the number of compressors and valves plus one. The extra degree of freedom is related to the "active charge" in the system, and a tank with variable holdup should be included to gain this degree of freedom.

A detailed degree of freedom analysis for the MFC process reveals that there are four unconstrained degrees of freedom in operation (not considering manipulating refrigerant compositions). To fully achieve the potentially high thermodynamic efficiency of the MFC process it is important that these four unconstrained degrees of freedom are utilized optimally.

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