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# Constraint Formulations for Optimisation of Dual Mixed Refrigerant LNG Processes

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Optimisation of a dual mixed refrigerant LNG process is challenging due to its rather complex structure. Therefore, appropriate constraint formulations are essential to solve the optimisation problem. In this paper, the AP-DMR process was optimised to minimize the power consumption with different constraints in order to find proper constraint formulations. The case studies indicate that refrigerant superheating does not always increase the power consumption. Instead, the best-known solutions required specific values of refrigerant superheating. Moreover, maximum heat exchanger area constraints for cryogenic heat exchangers delivered higher energy efficiency, compared to the constraints of minimum temperature difference, which is common practice for LNG processes.

## 1. Introduction

Demand for natural gas has increased constantly to mitigate the greenhouse effect as a cleaner fuel. In particular, liquefied natural gas (LNG) produced for long-distance transport has been a major source of natural gas supply, accounting for over 30 % of world trade. To meet such growing demand for LNG, there have been various types of LNG processes suggested for energy efficient production. For a large scale production of LNG, in excess of 2 - 4 Mt/y (MTPA), the dual mixed refrigerant (DMR) process has been considered as a favourable technical solution. This is due to its low specific power, large train capacity and the less flammable refrigerant for its pre-cooling circuit compared to the C3-MR process, which is the current market dominator. The mixed refrigerant (MR) for the pre-cooling circuit also gives better operational flexibility as it can handle the variation of feed gas conditions and ambient temperature. However, the DMR process is not a mature technology since it has been deployed only to a limited number of sites, and with only one of the several suggested configurations realized.

There have been various studies to make the DMR process more energy efficient. The challenge is given by the fact that this system has a complex structure due to multiple circuits with mixed refrigerants. This grants flexibility in its configuration and operating conditions, which makes the system difficult to analyse and optimise due to the large size of the optimisation problem. Thus, several papers have focused on the formulation of the optimisation problem. Nevertheless, there has been less interest in the formulation of constraints that may have a room for energy savings such as refrigerant superheating and maximum heat exchanger area. Therefore, this paper studies constraint formulations of refrigerant superheating in the DMR process, while considering both minimum temperature difference ($\Delta T_{min}$) and maximum heat exchanger area ($UA_{max}$) constraints in the cryogenic heat exchangers. This work also provides the insight on the interaction between the two refrigerant circuits in the DMR process, which is affected by the implemented constraints.

## 2. Superheating in refrigeration cycles

For the typical vapour compression refrigeration cycle, some degree of the refrigerant superheating at the condenser outlet is used for a practical purpose, which is preventing liquid formation at the compressor inlet. However, various experimental works indicate that superheating will decrease the system efficiency (Yang and Yeh, 2015). Even though the superheating allows the refrigerant to take a larger amount of heat in the

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evaporator, the higher temperature and larger volume of the compressor inlet stream will increase compression power, which may exceed the increased refrigeration effect. Nevertheless, the effect of superheating on the refrigeration cycle has not been extensively examined as an optimisation problem. Thus, Jensen and Skogestad (2007) optimised the refrigeration system with a single component refrigerant and proposed that superheating is not encouraged to achieve minimum compressor work. However, they also suggested that refrigeration systems with internal heat exchange between the condenser and the evaporator may need some degree of superheating such as natural gas liquefaction processes.

The characteristics of refrigeration systems with superheating will vary depending on the type of refrigerant and the structure of the process. For refrigeration systems with a mixed refrigerant, the PRICO process was selected and optimised to verify the effect of superheating (Jensen and Skogestad, 2009). Unlike the typical refrigeration cycle, the PRICO process had higher energy efficiency when there is a certain degree of superheating. Processes operated by multiple refrigeration cycles with pure component refrigerants also had a distinctive characteristic with refrigerant superheating (Austbø and Gundersen, 2014). In the case of the pure refrigerant cascade LNG process, maximum refrigerant superheating was required to decrease the power consumption.

Despite the previous studies on superheating, optimisation results of LNG processes are still misinterpreted such that superheating will reduce the energy efficiency, which is a common thought for vapor compression refrigeration (Mortazavi et al., 2016). In addition, fixed or limited bounds of superheating are still used in the optimisation of the DMR processes even though the effect of superheating is determined by the structure of the refrigeration system. Thus, this paper examines refrigerant superheating constraints on an LNG process having multiple cycles with mixed refrigerants. Since the above-mentioned optimisation studies are performed with minimum temperature difference constraints for heat exchangers, maximum heat exchanger area constraints are also tested to see the change in the effect of superheating.

## 3. Design basis and optimisation

The AP-DMR process was studied as a representative of the refrigeration system, having multiple cycles with two mixed refrigerants (Roberts and Agrawal, 2001). The process flow diagram is shown in Figure 1 and the simulation was performed with Aspen HYSYS V8.6. Pre-treated natural gas, having small amounts of heavier hydrocarbons, was assumed as the feed gas and liquefied through the AP-DMR process. The end-flash step for the subcooled LNG was not included in this simulation. Table 1 shows other design conditions and assumptions used in this work.

The simulation model was optimised to minimize power consumption per unit mass of LNG produced. The molar flow rates of components in both the warm mixed refrigerant (WMR) and the cold mixed refrigerant (CMR) were set as variables. The warm mixed refrigerant (WMR) consists of ethane, propane and n-butane, while the cold mixed refrigerant (CMR) contains nitrogen, methane, ethane and propane. In addition, all the pressure levels of the WMR and the CMR and the outlet temperature of heat exchangers HE1 and HE2 in Figure 1 were defined as variables so that the duty of the heat exchangers can be manipulated during optimisation. The optimisation problem applied minimum temperature difference constraints of 3 K for all the heat exchangers. In the heat exchanger models, all outlet temperatures of the hot streams were set to be equal. Minimum superheating was also constrained for the inlet streams of compressors K-1 and K-2 in Figure 1, and various degrees of minimum superheating were tested as case studies.

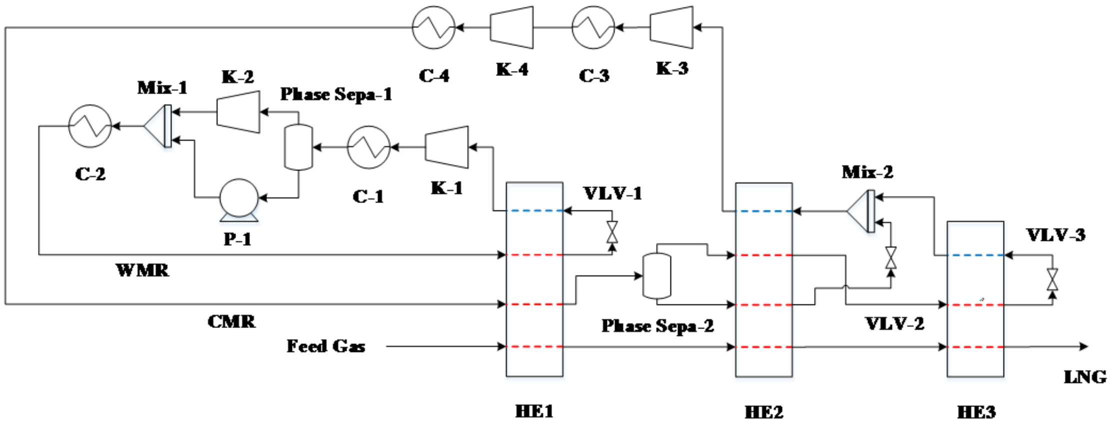

*Figure 1: The AP-DMR process flow diagram.*

*Table 1: Simulation conditions and assumptions.*

| Simulation details | Value |
|---|---|
| Feed gas flow rate | 1 kmol/s |
| Feed gas pressure | 60 bar |
| Feed gas temperature | 22 °C |
| LNG temperature | -148 °C |
| Compressor efficiency | 78 % Polytropic |
| Equation of state | Peng-Robinson |

## 4. Result

### 4.1 Effect of superheating with minimum temperature difference constraints

The AP-DMR process was optimised with different values of minimum superheating on the compressor inlet streams from 0 K to 25 K. As illustrated in Figure 2 (left), the lowest specific power consumption was achieved with the minimum superheating of 0 K and 5 K. The power consumption gradually increased with the larger constraint values. This means that specific superheating values are needed to achieve higher energy efficiency. This is a similar conclusion made in the previous study by Jensen and Skogestad (2009) for the PRICO single mixed refrigeration LNG process. As seen in Figure 3, the superheating values at the best-known solutions required around 8 K and 14 K for the WMR and the CMR. After 10 K of minimum superheating, the WMR and/or the CMR did not reach the optimal superheating values due to the constraints, and rather settled at the minimum values of the constraints. Thus, constraint values that are higher than the optimal superheating values will lead to sub-optimal solutions, which means larger power consumption of the process.

This can also be observed by the LMTD values of the heat exchangers in Figure 2 (right). After 5 K of minimum superheating, the LMTD value of heat exchanger HE1 increased significantly. The other heat exchangers also experienced a rise in the LMTD values after 10 K of minimum superheating. An increase in the LMTD values means larger temperature difference between warm and cold composite curves in the heat exchangers, which results in larger entropy generation due to increased irreversibilities.

### 4.2 Effect of superheating with maximum heat exchanger area constraints

Minimum temperature difference constraints are widely applied in modeling and optimisation of processes with heat exchangers. By specifying the value of minimum temperature difference, one can manipulate the trade-off between process power consumption and heat exchanger area. Nevertheless, the minimum temperature difference does not optimally utilize the heat exchanger area since it delivers a sub-optimal distribution of temperature driving forces particularly for systems operating below ambient temperature such as LNG processes (Austbø and Gundersen, 2015). The temperature driving forces should be distributed proportional to the temperature level to achieve the optimal use of the area. Thus, in this work, maximum heat exchanger area constraints were tested with the UA value from the best solution obtained by minimum temperature difference constraints in the previous section.

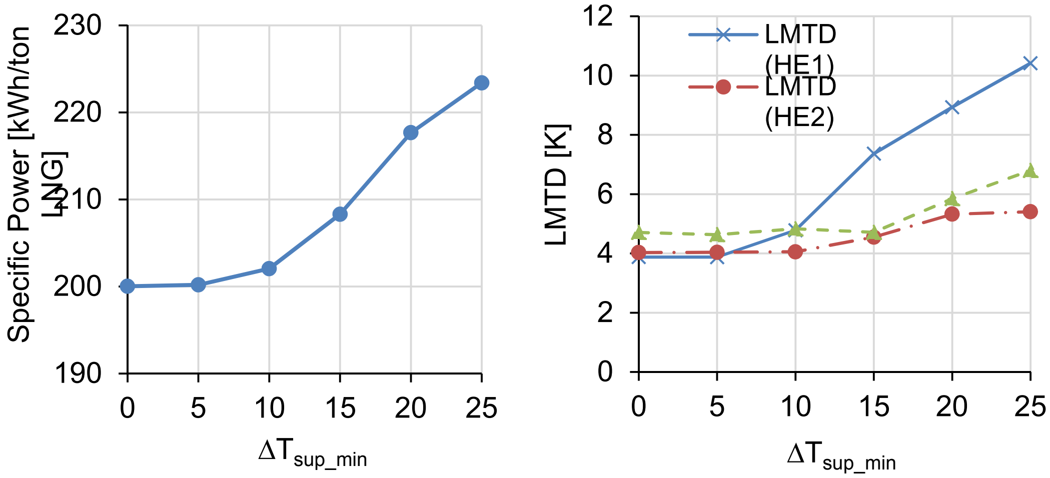

*Figure 2: The variation of specific power consumption (left) and LMTD values of the heat exchangers (right) with minimum superheating requirement in the optimised cases with $\Delta T_{min}$ constraints.*

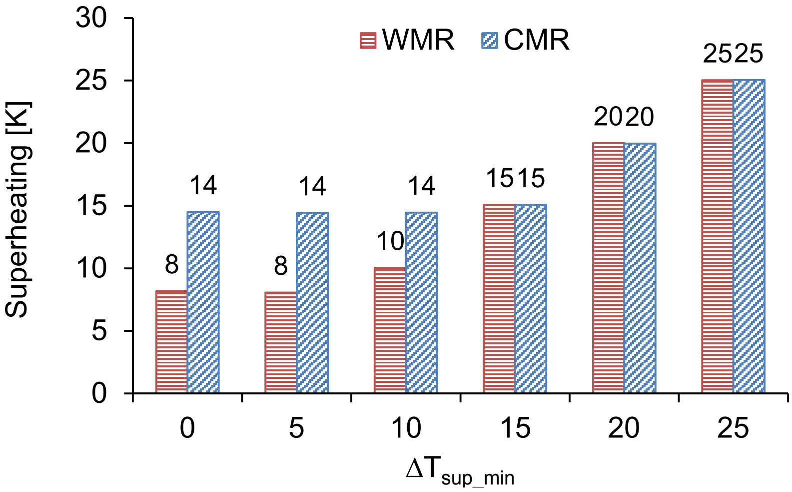

*Figure 3: The variation of superheating values for the WMR and CMR with minimum superheating requirement in the optimised cases with $\Delta T_{min}$ constraints.*

Figure 4 (left) demonstrates that the use of the maximum heat exchanger area constraint also leads to a similar trend in specific power consumption as the use of minimum temperature difference constraints. However, the difference in the specific power consumption between the best and the worst cases was reduced to less than a half, compared to the one with $\Delta T_{min}$ constraints. As expected, the best solution was improved from 200.1 to 196.6 kWh/ton LNG when using the $UA_{max}$ constraint. As illustrated in Figure 5, the optimal superheating values for the WMR and the CMR were 10 K and 12 K correspondingly. Thus, the superheating constraint values less than 15 K had no influence on the specific power consumption. From 15 K and higher superheating constraints, the specific power consumption increased almost proportionally to the difference between the optimal superheating values and the minimum superheating constraints.

The effect of the minimum superheating constraints became less sensitive with the $UA_{max}$ constraints due to the optimal distribution of the temperature driving forces in the heat exchangers. At superheating constraint values, larger than the optimal degree of superheating, the LMTD of heat exchanger HE3 operating at the lowest temperature is reduced, while the others have larger LMTD. The use of maximum heat exchanger area constraints results in smaller driving forces for the heat exchangers operating at lower temperatures and vice versa, which reduces total irreversibilities. This agrees with the results of the previous study about the optimal use of heat exchanger area for the PRICO process (Austbø and Gundersen, 2016). Returning to the optimisation case using $\Delta T_{min}$ constraints, one should notice that the LMTD for HE3 increased more than the LMTD for HE2 for increasing values of the superheating constraint, thus increasing total irreversibilities.

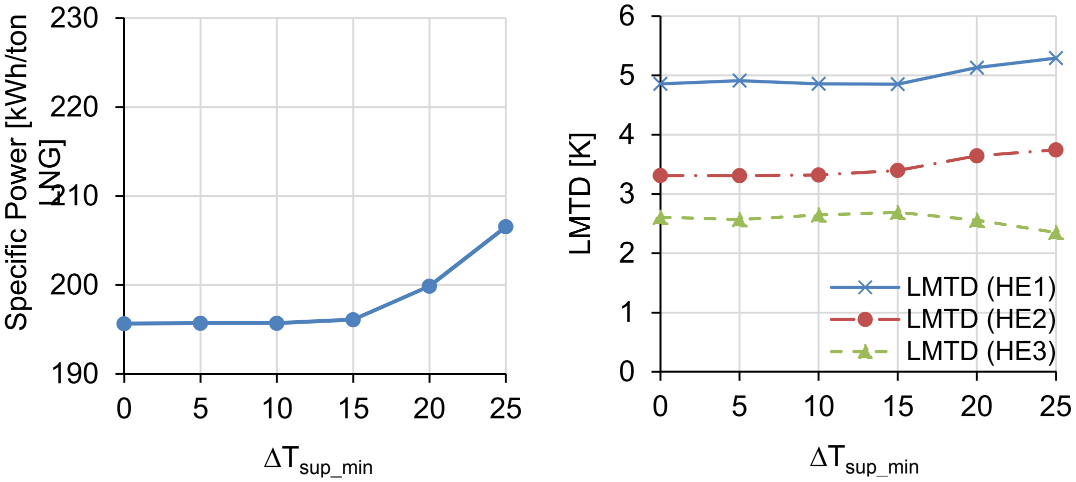

*Figure 4: The variation of specific power consumption (left) and LMTD values of the heat exchangers (right) with minimum superheating requirement in the optimised cases with $UA_{max}$ constraints.*

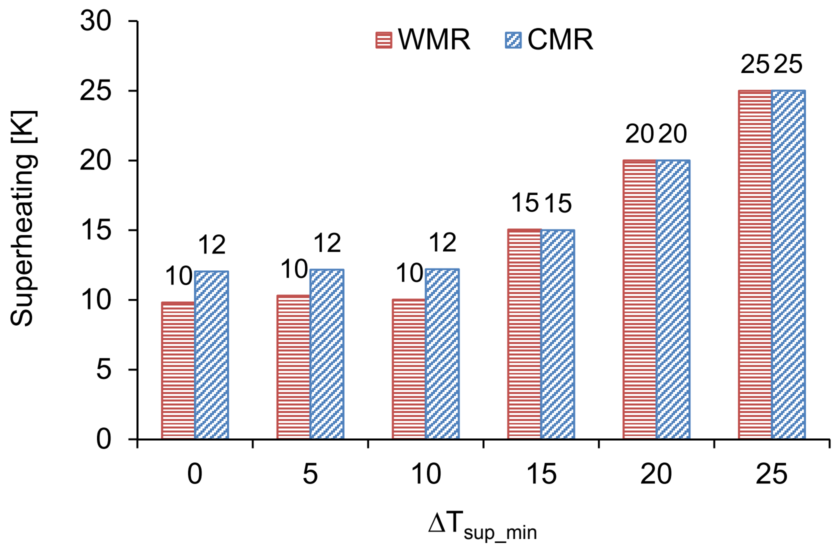

*Figure 5: The variation of superheating values for the WMR and CMR with minimum superheating requirement in the optimised cases with $UA_{max}$ constraints.*

The superiority of the maximum heat exchanger area constraint over the minimum temperature difference constraint can be explained by comparing their best and worst cases. With the same UA value, the $UA_{max}$ constraint reduced power consumption with 2 % points compared to the $\Delta T_{min}$ constraint for the best case, and 8 % points for the worst case.

Figure 6 (left and centre) also illustrates that the maximum heat exchanger area constraint results in reduced $\Delta T_{min}$ and LMTD values for lower operating temperatures for the heat exchangers. The $UA_{max}$ constraint guides the temperature driving forces to be proportional to temperature as explained before. Instead, the constraint of minimum temperature difference results in larger LMTD for colder heat exchangers and smaller LMTD at warmer heat exchangers as illustrated in Figure 6 (centre).

The maximum heat exchanger area constraint also redistributes the cooling duties of the heat exchangers to be proportional to temperature as shown in Figure 6 (right). This means to place less duty on the heat exchangers having larger irreversibilities per unit duty, and irreversibilities are inversely proportional to temperature.

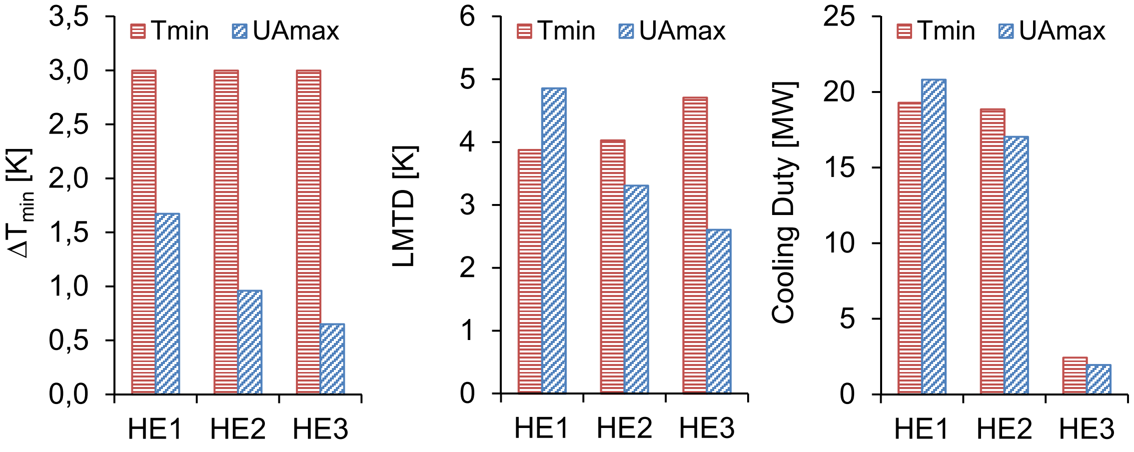

*Figure 6: Comparison of $\Delta T_{min}$ (left), LMTD (centre) and cooling duty (right) in the heat exchangers between the best solution with $\Delta T_{min}$ and $UA_{max}$ constraints.*

## 5. Conclusions

In this paper, the effect of superheating constraints was examined for a dual mixed refrigerant LNG process with different constraints for heat exchangers. Unlike refrigeration processes with pure component refrigerants, the case studies indicate that a certain degree of superheating of the two refrigerants is encouraged. However, a high value of the minimum superheating constraint may lead to sub-optimal solutions since it can miss optimal superheating values.

In addition, for a fixed value of the minimum superheating constraint, the maximum heat exchanger area constraint resulted in higher energy efficiencies than the minimum temperature difference constraint. The penalty of the sub-optimal superheating values was also reduced with the maximum heat exchanger area constraint. The maximum heat exchanger area constraint was superior to the minimum temperature difference constraint due to an optimal distribution of temperature driving forces in the heat exchangers.

### Acknowledgments

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