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Steady-state optimality analysis for investigating the energy optimal operation of representative natural gas liquefaction cycles

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Abstract

This study examined the energy optimal operation of representative natural gas liquefaction cycle processes such as propane precooled mixed refrigerant (C_3MR) process, dual mixed refrigerant (DMR) process, and modified single mixed refrigerant (MSMR) process. Steady-state optimality analysis in dynamic simulation environment was conducted to explore the operational behavior of each cycle. From this analysis, a steady-state optimality map that describes the relation between cost function and decision variable is obtained. By exploring this map a promising optimizing variable is discovered which further can be used to develop an energy optimizing control structure for the liquefaction process. Despite the same basic working principles, the operational behavior of the three cycles is dissimilar. The DMR has the narrowest optimal operation range while in the MSMR cycle the optimum value of cost function spans in relatively wide range of decision variable. The feasible operation of C_3MR and DMR is bounded by the suction temperature of mixed refrigerant compressor while in the MSMR cycle this constraint is inactive. Based on the steady-state optimality analysis the temperature difference between the warm-end inlet and outlet MR streams (TD) were proposed to be a promising optimizing variable for the C_3MR and DMR process while for the MSMR process the optimizing variable is the flow rate ratio of heavy and light mixed refrigerant (HK/LK ratio).

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Keywords: LNG; natural gas liquefaction; steady-state optimality analysis; energy optimizing control; rigorous dynamic simulation; Hysys

1. Introduction

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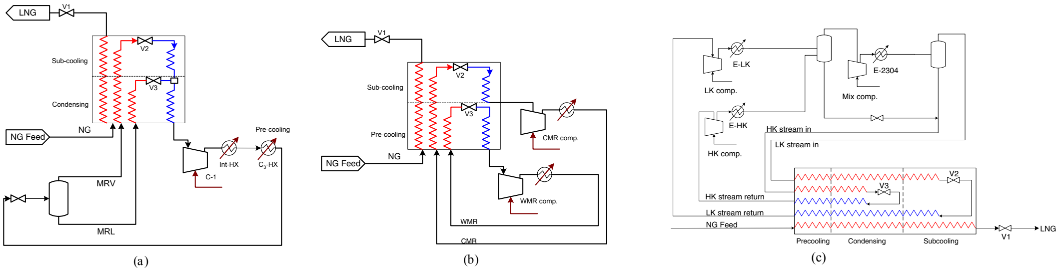
C_3MR process is the basis of many new emerging liquefaction technologies [1]. For instance, DMR process was developed by replacing propane refrigeration with mixed refrigerant (MR) cycle. The recent development of offshore natural gas liquefaction plant creates a demand to find a more compact yet highly efficient process. To answer this challenge, the compact single mixed refrigerant (SMR) process is integrated with the considerably high efficient DMR process which creates MSMR process that satisfies the offshore process requirements [2].

The C_3MR, DMR and MSMR process are constructed with different structure e.g. the structure of MR compression unit. Consequently the conditions that define the optimal operation of each cycle are dissimilar. This study is aimed to investigate the optimal operation space of each process with ultimate purpose is to find the optimizing controlled variable. Steady-state optimality analysis was conducted in the dynamic simulation environment of each process. From this analysis a map that describes the relation between total compressor duty and refrigerant flow rate is plotted. This map provides necessary information to locate a promising optimizing variable which can be used further to develop an energy optimizing operation or control structure.

Based on the steady-state optimality analysis temperature difference between the warm-end inlet and outlet MR streams (TD) were proposed to be a promising optimizing variable for C_3MR and DMR process while for MSMR process the optimizing variable is the flow rate ratio of heavy key (HK) and light key (LK) mixed refrigerant (HK/LK ratio).

2. Process description

Fig 1a outlines the C_3MR process in which after the propane precooling unit (C_3-HX), the single MR is separated into vapour (MRV) and liquid (MRL) stream. MRL condenses the refrigerants and natural gas while MRV subcools natural gas. In the DMR process (Fig 1b) all cooling are done by two mixed refrigerants with different composition. The warm mixed refrigerant (WMR) cycle is operated at lower pressure and refrigeration temperature compared to the cold mixed refrigerant (CMR) cycle. In the MSMR process (Fig 1c) the high pressure mixed refrigerant from 'Mix comp.' is separated into light key (LK) and heavy key (HK) refrigerant streams. LK undergoes a larger pressure drop through adiabatic expansion and departs from liquefaction unit at lower outlet pressure compared to the outlet pressure of HK. This pressure difference necessitates a separate compression of LK and HK stream prior being mixed at same compression unit.



(a) (b) (c)

Fig. 1. Conceptual diagram of: (a) C_3MR cycle, (b) DMR cycle, (c) MSMR cycle

3. Steady-state optimality analysis

The objective of an LNG production plant is mainly to achieve and maintain the LNG temperature at certain range. The value of LNG temperature is the product of complex function of every state variable associated with the liquefaction process. For a given natural gas (NG) flow rate there are infinite possibilities of refrigerant flow rates to meet a specified LNG temperature. However some parameters such as compressor safety operation and process efficiency create a division between feasible and infeasible solutions. Therefore it is important to analyze the optimal operation range that satisfies the safety and efficiency of the liquefaction operation.

Fig 2 summarizes the procedure for conducting the steady-state optimality analysis. This analysis was conducted on each process at fix conditions of NG feed and LNG temperature. Regulatory controllers to maintain all suction pressures and outlet temperatures of after-coolers in compression unit were also arranged. The objective function for each process is expressed through Eq. 1.

$$\min J = W_s/m_{LNG} \tag{1}$$

where W_s and m_{LNG} denote the total compressor duties and NG flow rate, respectively.

For the steady-state optimality analysis purpose, MRV, CMR and LK flow rate are the manipulated variables to control the LNG temperature in the C_3MR, DMR and MSMR process, respectively. The other refrigerant flow rate was used as the source of variation for the step test which was repeated for several different NG flow rates. On each variation of the refrigerant flow rate, several final steady-state data was recorded such as the total compressor duty and the variables that are potential to be the optimizing variable e.g. temperature difference of warm-end outlet of refrigerant and (TD) the flow rate ratio of the two refrigerants in each cycle.

The result of steady-state optimality analysis of each cycle is presented in Fig 3. On each map there are several solid curves that represent different NG flow rates. On each curve there is an optimal point that denotes the minimum compressor duty. The line that connects all the optimum duty points divides the maps into the feasible and infeasible operating conditions. The plots imply that despite the same basic working principles, the operational behavior of the three cycles is dissimilar: the feasible operation of C_3MR and DMR is bounded by the suction temperature of mixed refrigerant compressor while in the MSMR cycle this constraint is inactive.

The lines that represent the constant value of the potential optimizing variables are also drawn on the map. The variable that has constant lines most parallel with optimum duty line is selected as the optimizing controlled variable. For the C_3MR process the constant TD lines are the one that most parallel with optimum duty line while for the DMR and MSMR process the optimizing variable is the flow rate ratio of the two refrigerants (WMR/CMR ratio and HK/LK ratio, respectively).

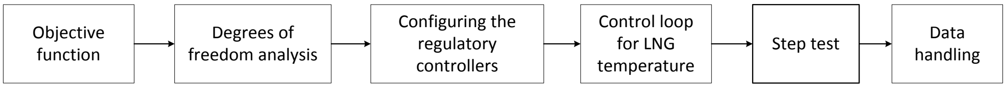


Fig. 2. Procedure of steady-state optimality analysis

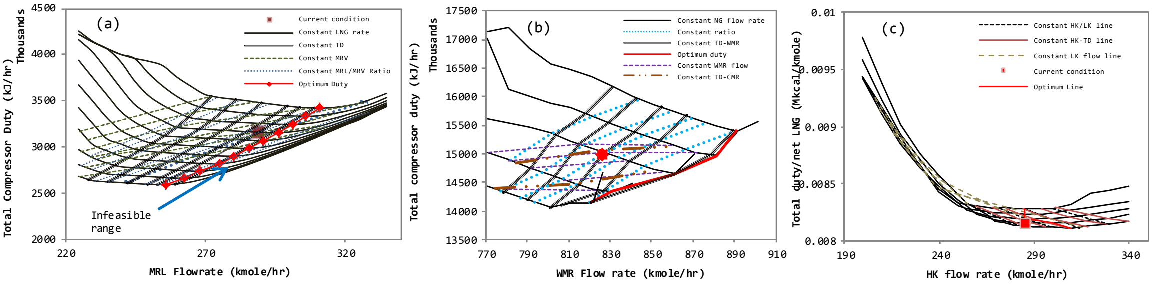


Fig. 3. Steady-state optimality map of: (a) C_3MR cycle, (b) DMR cycle, (c) MSMR cycle

Each point in the steady-state optimality map contains information of a whole steady-state operating condition such as pressures and temperatures of all streams that construct the MR compression unit in respective cycle. The exergy efficiency of each cycle can be analyzed by plotting the temperature vs. entropy (T-S) diagram (Fig 4). Despite the fact that the area under T-S diagram is only meaningful for reversible process, however it can still be used to compare the relative entropy generation among the C_3MR, DMR, and MSMR process. The closed area on each diagram qualitatively shows the property of energy in the cycle. It can be seen that the entropy generation of each cycle is lower as it is operated closer to optimum operating condition. The T-S diagram can be further used as a useful tool to enhance the operational efficiency of each cycle.

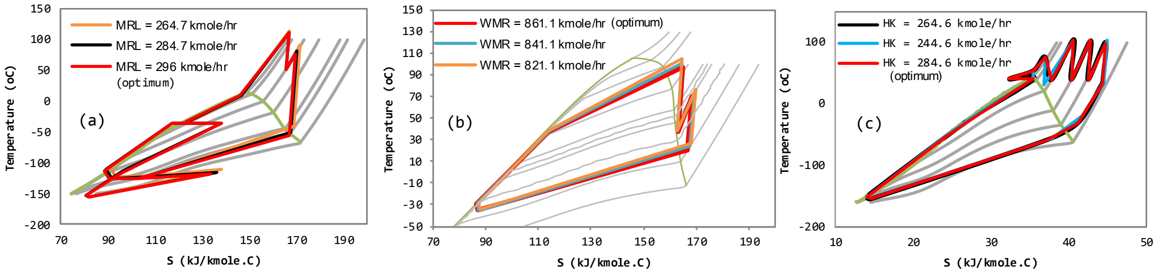


Fig. 4. T-S diagram of (a) C_3MR cycle, (b) DMR cycle, (c) MSMR cycle

4. Conclusions

The steady-state optimality analysis was developed to determine the optimizing controlled variable of three representative liquefaction cycles. Temperature difference of refrigerant in warm-end outlet was observed to be the promising optimizing variable for the C_3MR while for the DMR and MSMR process the optimizing variable was the flow rate ratio of the two refrigerants (WMR/CMR ratio and HK/LK ratio, respectively).

Acknowledgements

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Biography

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Moonyong Lee, PhD currently works a professor at the School of Chemical Engineering at Yeungnam University in South Korea. He had experience working in the area of energy refinery petrochemical plants for 10 years as a design and control specialist. His current areas of specialization include modeling, design and control of chemical processes.