Optimizing control structure for dual mixed refrigerant process*

Yuli Amalia Husnil, Bonggu Choi, Jinho Park, Riezqa Andika and Moonyong Lee

***Abstract*— This study was aimed to investigate the best control structure that provides optimal operation for dual mixed refrigerant (DMR) process. The steady-state operational map that correlates the refrigerant flow rate and the total compressor duty was drawn to locate the region the optimal operation of DMR process. This map also encompasses information of state variables in DMR process that in particular combinations provide the optimum solution.**

The steady-state operational map of DMR process was developed by conducting steady-state behavior analysis in a rigorous dynamic simulation of DMR process built in Aspen Hysys. The resulting steady-state operational map suggests that when the flow rate ratio of the two mixed refrigerants (WMR/CMR ratio) is kept constant, the operational of DMR process will remain within optimum region. From several control tests, the control structure that consists of WMR/CMR ratio loop has better performance on recovering the process after propagated by disturbances

***Keywords*: LNG, optimizing control, steady-state optimality, liquefaction, dynamic simulation**

I. INTRODUCTION

Dual mixed refrigerant (DMR) process became one of the leading technologies in natural gas (NG) liquefaction industry when it was selected as the technology for the Sakhalin LNG project [1]. This process is known to be the more appropriate technology for NG liquefaction plant operated in arctic weather compared to its more famous predecessor technology, propane precooled mixed refrigerant (C_3MR) process [1]. It is also mentioned that DMR cycle has the highest efficiency among all liquefaction cycles [2]. However another study concludes that the performance of C_3MR operated in tropical weather is actually similar with the performance of DMR operated in arctic area [3].

For many years optimal operation and process efficiency has been the main research focus in chemical engineering field including liquefaction process with mixed refrigerant (MR) cycle. Several studies addressed the optimization of MR cycle by incorporating algorithm to define the optimal operating conditions of the respective cycle. Most of them used C_3MR process and single mixed refrigerant (SMR) as the studied process [4], [5], [6]. Also to the authors' knowledge there is only one paper that investigates the optimal operation of DMR process [2].

Most optimization studies on liquefaction process 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 process dynamic stability because there is no guarantee that a steady-state analysis for optimization purposes will also maintain the dynamic performance of the process [7]. Disturbances are frequently propagating to a process and disrupting its stability and product quality as well. The action of controllers on bringing back controlled variables to their set-points can be energy consuming which violates the purpose of optimization. Therefore, a process should be equipped with at least one control loop to optimize the energy consumption during plant operation.

The main objective of this study was to develop a proper control structure for DMR process that can help to maintain the operational optimality of the process and the stability as well. This objective was achieved by adapting the self-optimizing control procedure [8]. In this adapted framework, the control objective is divided into two parts. The first part is related to control structure synthesis for maintaining the stability of LNG production. The second part on the other hand is related to designing the optimizing control structure so that the DMR process can be operated with minimum control cost. The procedure for designing the optimizing control structure of DMR process consists of two steps. The first step is to define the cost function to be minimized i.e. the total compressor duty. The second step is to determine the promising optimizing controlled variables by conducting a steady-state optimality analysis.

From the steady-state optimality analysis there were two candidates that potential to be the optimizing controlled variable, i.e. the ratio between the flow rate of warm mixed refrigerant and cold mixed refrigerant (WMR/CMR ratio) and the temperature difference between inlet and outlet stream of warm mixed refrigerant (WMR). The two candidates were used to build two different optimizing control structures. From several control tests, the structure that includes the WMR/CMR ratio loop has better performance on maintaining the process stability against the predefined disturbances.

II. PROCESS DESCRIPTION

The conceptual process flow diagram of DMR process is illustrated in Fig. 1. The DMR process is operated using two mixed refrigerants with different composition. WMR is a

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Y. A. Husnil Author is with the School of Chemical Engineering, Yeungnam University, Dae-dong, Kyeongsan 214-1, Korea (e-mail: yuli.husnil@gmail.com).

B. Choi Author is with the School of Chemical Engineering, Yeungnam University, Dae-dong, Kyeongsan 214-1, Korea (e-mail: bgwrite@naver.com).

J. Park Author is with the School of Chemical Engineering, Yeungnam University, Dae-dong, Kyeongsan 214-1, Korea (e-mail: Jino2516@nate.com).

R. Andika Author is with the School of Chemical Engineering, Yeungnam University, Dae-dong, Kyeongsan 214-1, Korea (e-mail: rzq_andika@yahoo.co.id).

M. Lee Author is with the School of Chemical Engineering, Yeungnam University, Dae-dong, Kyeongsan 214-1, Korea (corresponding author to provide phone: +82-53-810-2552; fax: +82-53-811-3262; e-mail: mynlee@yu.ac.kr).

mixture of higher boiling point components e.g. propane and butane while cold mixed refrigerant (CMR) is a methane dominant mixture. These two mixed refrigerants are circulated in separate compression units at different working pressure. The box that encircled each compression unit in the figure denotes that the compressors are operated with single speed. The WMR is compressed in two stages compression unit to reach the working pressure of 24 bar. This relatively low pressure consequently gives small pressure drop when WMR is expanded through V3. Therefore WMR has a narrow working temperature where it can only precools the NG and hot CMR from 38°C to -25°C. The CMR is compressed in three stages compression unit and enters the liquefaction unit at 55 bar. This refrigerant is then expanded in V2 in larger pressure drop compared to WMR. This expansion reduces the temperature of CMR to -164°C. The precooled NG is subcooled by the low temperature CMR and discharges from the liquefaction unit at -159°C.

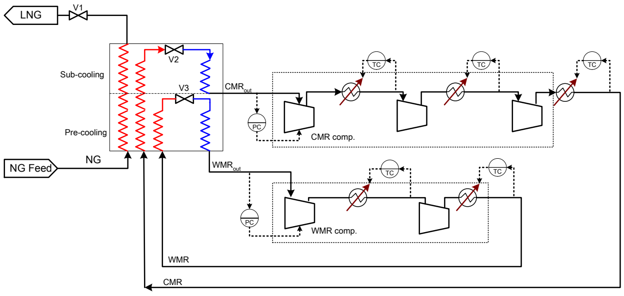


Figure 1. Conceptual process flow diagram of DMR process

In this study, the rigorous dynamic simulation of the DMR process was built in Aspen Hysys^{TM} where the solution was calculated by using the Peng-Robinson equation of state. The base case operating conditions of DMR process are listed in Table I.

TABLE I. THE BASE CASE OPERATING CONDITIONS OF DMR PROCESS

Stream	Variable	Value
NG	Feed temperature	38°C
	Feed pressure	52 bar
	Flow rate	627.2 kmole/hr
	LNG temperature	-159°C
	Composition	
	Nitrogen	0.005
	Methane	0.872
	Ethane	0.067
	Propane	0.035
	i-Butane	0.006
	n-Butane	0.009
	i-Pentane	0.003
	n-Pentane	0.002
	n-Hexane	0.001
WMR	Inlet temperature	38°C
	Inlet pressure	29.78 bar
	Suction temperature	25.31°C
	Suction pressure	3.55 bar
	Composition	
	Nitrogen	0
	Methane	0.008
	Ethane	0.492
	Propane	0.065
	i-Butane	0.159
	n-Butane	0.276
CMR	Inlet temperature	38°C
	Inlet pressure	51.45 bar
	Suction temperature	-29.15°C
	Suction pressure	3.31 bar
	Composition	
	Nitrogen	0.137
	Methane	0.356
	Ethane	0.409
	Propane	0.098

III. Control Objectives and Process Constraints

The control objectives of DMR process are divided into two parts (Fig. 2). The first part of the goal is to produce LNG with a pre-defined temperature under stable operation. The operational stability of DMR process is achieved by keeping WMR and CMR compression unit from violating some constraints. The two important constraints in the operational of compressor are the minimum surge flow and the dew point temperature of the inlet stream to compressor. The surge phenomenon can be prevented by controlling the suction pressure of compressor inlet. The dew point temperature is composition dependent and in DMR process is associated with the exiting temperature WMR or CMR from the liquefaction unit. This exiting temperature should not be controlled because it will limit the heat transfer in liquefaction unit.

The goal in the second part is to optimize the operation of the LNG production by minimizing the control cost. This goal is attained by controlling one or more optimizing controlled variable which will be discovered through the steady-state optimality analysis. The total compressor duty of WMR and CMR compression unit is the control cost (J) that will be minimized. The duty for cooling the compressor outlet streams in intercoolers is much lower than compressor work there for it is excluded from the cost function [9].

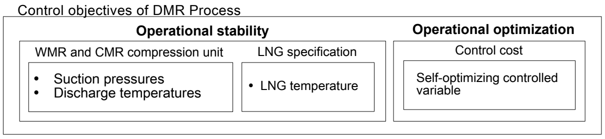


Figure 2. Control objectives of DMR process

IV. Degrees of Freedom (DOF) Analysis

The number of actual degrees of freedom (N_{ss}) can be calculated by using the following (1).

$$N_{ss} = N_{MV} - N_0 \tag{1}$$

where N_{MV} denotes the number of dynamic manipulated variables while N_0 refers to the number of degrees of freedom without steady-state effect. The DMR process used in this study has 10 N_{MV} as follows.

a. Three choke valves: V_1, V_2, and V_3

b. One common speeds for WMR compression unit

c. One common speeds for CMR compression unit

d. Five flow rate of cooling medium for the WMR and CMR compressor coolers

There is no liquid level that needs to be controlled in the recycle loop ($N_0 = 0$), hence $N_{SS} = 10$. A number of variables from N_{SS} can be used as the degrees of freedom for the optimizing controlled variables. Based on the formulation of control objectives, to achieve a stable operation of WMR and CMR compressor unit, all suction pressures and discharge temperatures are subject to control (Fig. 1). Therefore all compressor speeds and flow rate of cooling medium in WMR and CMR compression units cannot be used as the degrees of freedom for optimizing controlled variable. Also spillback valves and release valves are usually closed in normal operation. In this study the NG flow rate is considered to be constant at all situations. Thus, CMR valve (V_2) and WMR valve (V_3) are the only remaining degrees of freedom for operational optimization.

V. OPTIMIZING CONTROLLED VARIABLE

There are several criteria that can be used as a guideline on selecting the proper optimizing controlled variables of a process. First, when its value is held constant the process can always be operated within feasible region at a minimum cost e.g. minimum compressor duty [10]. Second, this variable is insensitive to unmeasured disturbances and third, variations in its set-point will not affect the cost function significantly [11]. Keeping an optimizing controlled variable in its set-point will create coordination in the process where all manipulated variables are optimally adjusted [12].

WMR and CMR flow rate is potential to be an optimizing controlled variable because the movement of each respective control valve will change the suction pressure and consequently the compressor speed as well. WMR/CMR flow rate is also potential to be the optimizing variable. Keeping the refrigerant ratio in an appropriate mixture of high and low boiling point components will result in a high specific refrigeration effect at a relatively low refrigeration temperature [13]. The next candidate is the temperature difference (TD) between the warm-end inlet and outlet of WMR or CMR stream. The difference between the condensation and evaporation temperature in a simple refrigeration cycle is considered as the dominant factor in the relationship between heat transfer and compressor work [14]. Also it was reported that for propane precooled mixed refrigerant (C_3MR) liquefaction process, the difference temperature between inlet and outlet of MR is discovered to be the proper optimizing controlled variable [10].

VI. STEADY-STATE OPTIMALITY ANALYSIS

The steady-state optimality analysis was performed to obtain a map that describes the operational space of DMR process. In this map the relation between total compressor duty and WMR flow rate is plotted. At one particular NG feed condition (pressure, temperature, composition, and flow rate) there are infinite combinations of WMR and CMR state variables to meet a specified LNG temperature. However not all of the combinations are necessarily the optimum solutions where some of combinations might not even feasible. A more advanced function of this map is to use it as a tool to discover the optimizing controlled variable for DMR process.

The steady-state optimality analysis was conducted at a fixed NG feed condition and LNG temperature (-159°C). To keep the LNG temperature, CMR flow rate is used as the manipulated variable. Therefore WMR flow rate is the remaining free variable that can be used as the source of input variations. The resulting map is illustrated in Fig. 3A. In the map, there are five solid curves that represent five different NG flow rate with 10 kmole/hr increment. In each NG flow rate curve there is an optimum point which denotes the minimum compressor duty. This point puts a boundary between feasible and infeasible operating conditions.

Several lines that represent the constant value of the five potentially to be the optimizing controlled variable are drawn on the map. The dashed, dotted, and three-layered lines represent the constant CMR flow rate, WMR/CMR flow rate ratio, and TD_{WMR} lines respectively. From the map it can be seen that lower compressor duty is achieved at lower CMR flow rate, higher WMR flow rate, lower CMR/WMR ratio, and higher TD_{WMR}. However the factor that defines the minimum point of compressor duty in each NG curve is the dew point temperature of the outlet stream of WMR (WMR_{out}). It means that this stream is at its dew point temperature at every point in the minimum duty trajectory.

The correlation between refrigerant flow rates and other state variables to the compressor duty can be explained through the following (2) [15].

$$\text{Compression duty} = NT_1 \frac{K}{K-1}\left[\left(\frac{P_2}{P_1}\right)^{(K-1)/K} -1\right] \qquad (2)$$

where N denotes the number of moles or standard cubic feet per hour (SCFH), T_1 is the suction temperature, K is the ratio of specific heats, P_2 is the discharge pressure and P_1 is the suction pressure. When the flow rate of WMR was increased, the cooling agent that precools NG, warm CMR and also warm WMR was consequently increasing. As a result the temperature of WMR_{out} was decreasing. This temperature was decreasing at bigger deviation compared to the deviation in WMR flow rate. Therefore the duty of WMR compression unit is reducing even though the circulation rate of WMR is increasing.

Another consequence of increasing the WMR flow rate is the temperature of CMR after precooling (CMR_{sub}) was decreasing. Thus the amount of required CMR flow rate to keep the LNG temperature at its set point is also reducing. The exit temperature of CMR from heat exchanger (CMR_{out}) is thus also decreasing due to this situation. Hence because of the lower CMR flow rate and suction temperature, the duty of CMR compression unit is decreasing.

The area after the minimum point of compressor duty refers to the situation where increasing WMR will increase the flow rate of CMR. As the WMR flow rate is getting larger, the cooling duty in this refrigerant is no longer sufficient to reduce the temperature of both WMR and CMR in precooling section. Therefore the required flow rate of CMR to maintain the LNG temperature is increasing. If the flow rate of WMR is continually increased after the optimum duty point, the WMR_{out} will reach the dew point temperature where drops of liquid are started to form. Based on this operating the cryogenic exchanger at the optimum duty line is not recommended. To secure the compressor from any damage due to the liquid drops, the temperature of WMR_{out} needs to be higher that its dew temperature. Therefore the process should be operated a bit distanced from the optimum duty line. Also if the process is kept at the optimum duty line, a small variation in either WMR or CMR flow rate will quickly bring the process to the infeasible area.

To select the proper optimizing variable several hypothetical trajectories are drawn on the map (Fig 3B). These trajectories are the ones that the DMR process will follow when NG flow rate is increased or decreased from the current operating condition (the star point). Variable with trajectory that fulfills most of the criteria listed in previous section is selected as the optimizing variable. When NG flow rate is increased or decreased at constant CMR flow rate or constant TD_{CMR}, the compressor duty is considerably constant compared to the rest variables. However, depending on where the starting operating condition and how much the NG flow rate is increased, keeping either CMR flow rate or TD_{CMR} at constant value will likely bring the process to the infeasible region. Increasing or decreasing NG flow rate at constant WMR/CMR ratio or TD_{WMR} will indeed change compressor duty at bigger deviation however the process will remain within feasible region at any situation.

From Fig 3A it can be seen that the constant WMR/CMR ratio lines, especially the two adjacent lines, are parallel to most parts of the optimum trajectory where each point in these lines has an almost equal distance to the respective optimum point. This distance was adapted to the term process liquefaction efficiency, η, defined by (3).

$$\eta = 1 - \frac{Q_i - Qopt_i}{Q_i} \tag{3}$$

where i corresponds to a point in the constant NG flow rate line. This equation implies that making DMR process to follow constant WMR/CMR ratio can maintain the process liquefaction efficiency. For instance, at every point in the line of WMR/CMR ratio = 1.315, the process will maintain 99% efficiency within a feasible region under NG flow rate variations. The optimum duty line is actually coincide with one of the constant TD_{WMR} line ($TD_{WMR} = 17.7^oC$) which suggests that the process will remain at optimum duty if the TD_{WMR} is kept constant. However, the DMR process should be operated outside the optimum duty line within the feasible region. Based on this observation the WMR/CMR ratio can be a promising controlled variable for optimizing control of the DMR process.

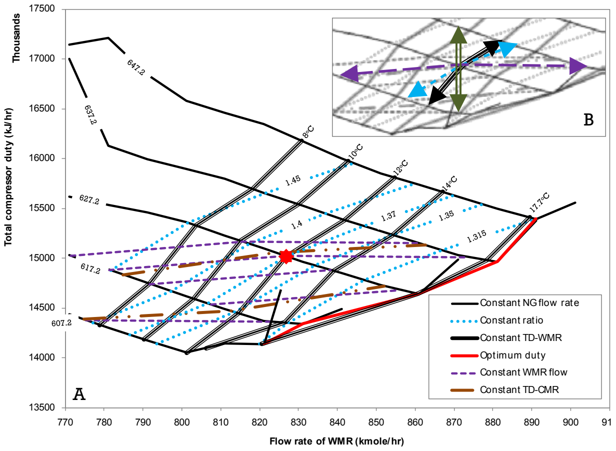
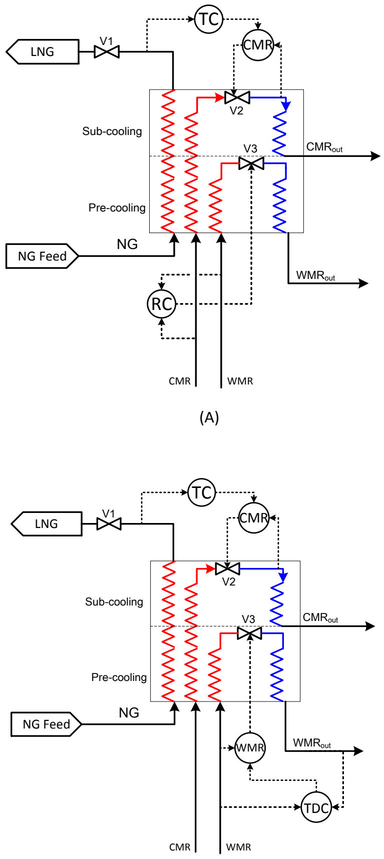


Figure 3. Steady-state optimality map

VII. CONTROL STRUCTURE PERFORMANCE

To validate the conclusion from steady-state optimality analysis, the control performance of DMR process with a WMR/CMR ratio control loop and TD_{WMR} control loop was examined. The arrangement of control structure in DMR liquefaction unit that includes the optimizing control loop is illustrated in Fig. 4.



(A)

(B)

Figure 4. Control structures of DMR process: (A) with WMR/CMR ratio loop, (B) with TDWMR loop

Each control loop is PI controller and was tuned by using the auto-tuning tools in Hysys®. The tuning parameters of all control loops are listed in Table II.

TABLE II. TUNING PARAMETERS

Control loop	Notation	Kc	Ti
LNG temperature	TC	0.3	35.8
CMR flow rate	CMR	0.178	0.006
WMR/CMR ratio	RC	0.5	0.3
TD_{WMR}	TDC	0.3	0.398
WMR flow rate	WMR	0.1	0.05

Six different kinds of disturbance were introduced to each system and the responses of LNG temperature to these disturbances are presented in Figures 6 and 7. D1 refers to a ±1 bar disturbance in the NG feed pressure, D2 is a $\pm 3^oC$ disturbance in the NG feed temperature, and D3 is a ±0.03 disturbance in the NG feed CH_4 mole fraction. For D3, when the CH_4 mole fraction is decreased by 0.03, the mole fractions of C_2H_6 are increased by 0.03. The disturbances were arbitrarily quantified by considering that the selected values are the acceptable range in which the system can still overcome.

DMR process that is optimized by the WMR/CMR ratio control loop qualitatively has better performance compared to the process that is optimized by the TD_{WMR} control loop. The system with WMR/CMR ratio control loop had a smaller overshoot for most of disturbances and reached the settling time faster than the system with TD_{WMR} control loop (Fig. 5).

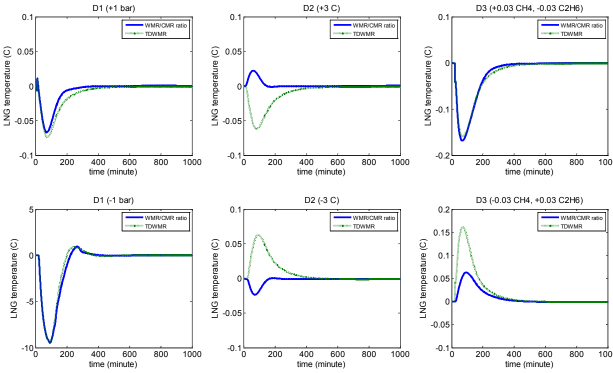


Figure 5. Responses of LNG temperature (in deviation value) after disturbances in NG feed

Quantitatively the system with WMR/CMR ratio control loop is proved to have better performance compared to the system with TD_{WMR} control loop. The *Integral Absolute Errors* (IAE) of the system with WMR/CMR ratio control loop for all types of disturbances is smaller compared to the other structure (Table III). The superiority of WMR/CMR control loop over TD_{WMR} control loop can be explained as follows. For the same disturbance i.e. D2 (+3°C), the deviation of WMR in TD_{WMR} control loop is bigger than the deviation in WMR/CMR control loop. Even though in TD_{WMR} control loop the WMR flow rate can quickly reach a new steady-state value however the big deviation give a greater impact on LNG temperature which reflected in the deeper undershoot (Fig. 5B). A constant WMR/CMR ratio helps to keep the heat transfer in both sections of heat exchanger always balanced. The WMR flow rate only change when there is a variation in CMR flow rate and it will only deviate in proportional value i.e. not more or less than necessary.

TABLE III. IAE VALUES OF THE VARIOUS STRUCTURES AFTER DISTURBANCES

Disturbance	WMR/CMR ratio	TD_{WMR}
D1 (+1 bar)	4.654	7.326
D2 (+3°C)	1.166	6.943
D3 (+0.03 CH_4, -0.03 C_2H_6)	14.539	16.082
D1 (-1 bar)	754.82	717.016
D2 (-3°C)	1.183	6.575
D3 (-0.03 CH_4, +0.03 C_2H_6)	13.83	14.29

In terms of control cost the performance of both systems cannot be compared. As can be seen from Fig. 6, the total compressor duty will increase or decrease depending on the direction of the disturbance. Nevertheless the system with WMR/CMR ratio control loop is preferable considering it has relatively better performance on recovering the system after the propagation of disturbances.

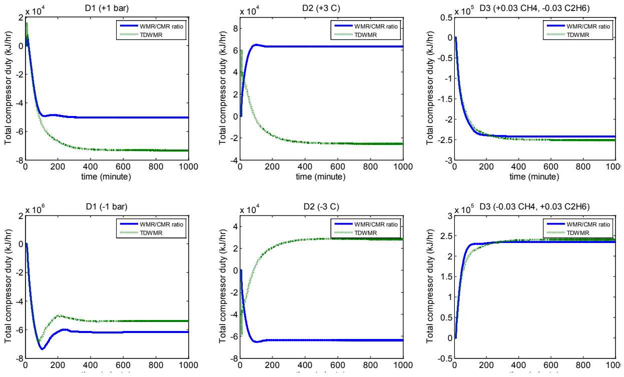


Figure 6. Responses of total compressor duty (in deviation value after disturbances in NG feed conditions

The system with WMR/CMR ratio also showed better performance compared to its opponent when the NG flow rate was increased by 10 kmole/hr. The system with WMR/CMR ratio control loop had smaller offset area (Fig. 7A) and the compressor duty was increasing with lower deviation compared to the system with TD_{WMR} control loop (Fig. 7B). Excellent performance of the system with the WMR/CMR ratio control loop was also observed when the NG flow rate was decreased by 10 kmole/hr (Fig. 7C). The total compressor duty in the system with TD_{WMR} allows decreased with lower deviation (Fig. 7D). However the LNG temperature in this system returned to its original set-point with larger error compared to the system where the WMR/CMR ratio is fixed.

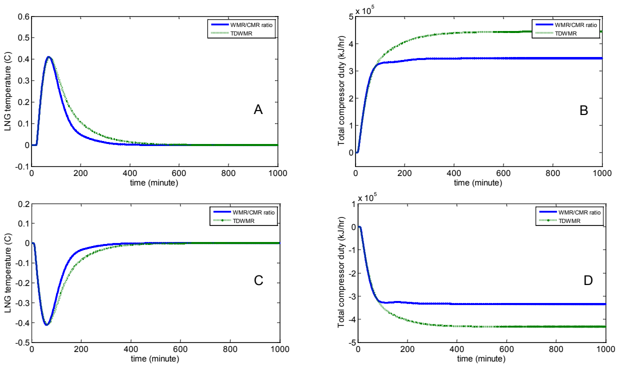


Figure 7. Responses of LNG temperature and compressor duty (both in deviation value) after variations in NG feed flow rate

VIII. CONCLUSION

This paper presented a steady-state optimality analysis to find the optimizing controlled variable of the DMR process. Steady-state optimality analysis showed that the WMR/CMR ratio and TDWMR are the candidates to be the optimizing controlled variable. Keeping WMR/CMR ratio at constant value will allow the DMR liquefaction process to remain within feasible region suppose there is a variation in NG flow rate. On the other hand the optimum compressor duty of the DMR liquefaction process is reached when the temperature of WMR outlet stream is in its dew point temperature. Further analysis to determine the contribution of both variables on maintaining the process stability was conducted. The control structure that keeps the WMR/CMR ratio at constant set-point shown better performance compared to its opponent structure.

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