Evolution and optimization of the dual mixed refrigerant process of natural gas liquefaction

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Abstract

This study unfolds the important developments in the evolution of dual mixed refrigerant (DMR) process of natural gas (NG) liquefaction followed by its optimization. The initial designs of DMR process involve direct intermixing of non-equilibrium streams that causes thermodynamic irreversibility and reduces efficiency. Major developments that improved DMR process efficiency were the use of coil-wind type heat exchangers followed by three stage throttling in NG pre-cooling and direct utilization of cold energy available to the boil-off gas. After enumerating major developments a generic design of DMR process is selected and optimized for specific compression energy (SCE) and overall heat transfer coefficient (UA) using Box methodology and controlled elitist genetic algorithm. Single objective optimization of SCE and UA with Box methodology results in savings of 36% and 15% respectively. There exists a partial trade-off between SCE and UA, thus the savings in SCE are offset by the increase of UA. Consequently a multi-objective optimization is performed that results in a simultaneous decrease of 24% and 3% in the SCE and UA values, compared to the base case.

1. Introduction

A dual mixed refrigerant (DMR) is one of the favored natural gas (NG) liquefaction technologies for on-shore locations as it is known to have the highest efficiency among the liquefaction cycles [1]. Nibbelke et al. [2] compared the propane-pre-cooled MR (C3MR) process with DMR in terms of the LNG and LPG production rates and concluded that the DMR process has 15% more capacity than the C3MR process. Furthermore, Nibbelke et al. [2] concluded that the DMR process has the flexibility of full gas turbine exploitation. Therefore, the DMR process has 11% more exploitable power than the C3MR process. The use of a dual refrigerant loop helps produce LNG more efficiently in DMR process, particularly in remote and colder locations. The cold weather helps the turbine work more efficiently and produces more power. DMR process also takes advantage of the wider range of available temperatures (of low boiling to high boiling refrigerant in MR) and liquefies the NG more effectively. The DMR process is very flexible in operation and can function with both spiral wound and plate frame exchangers to utilize the full power of the installed turbine. The Sakhalin-2 LNG project, which employs the DMR process in cold weather, is considered to be three times more energy efficient than the average LNG plant [3].

The prime objective in the design and operation of an LNG process plant is to minimize energy consumption and maximize LNG production while operating at changing product demand rates and under varying ambient temperature conditions [4]. The sizeable changes in temperature of the available cooling water with the changing seasons or climatic zones impart process inefficiencies that reside in the matching process load of NG to be liquefied against the refrigerant [5]. The use of the DMR process allows for significant degrees of freedom in the variation of the compositions of each low level (operating at low temperatures) and high level (relatively high temperatures than low level) refrigeration cycles both
The DMR process was first designed in 1978 [9], with improvements and modifications followed by the optimization of DMR process [8]. The DMR process model was developed in the commercial process plant simulator Aspen Hysys and the Peng–Robinson equation of state was used for thermodynamic property calculations. Fig. 1 illustrates the DMR process flow diagram that involves two mixed refrigerant cycles: the warm MR (WMR) cycle contains mainly ethane and propane, and the cold MR (CMR) cycle contains nitrogen, methane, ethane, and propane. The WMR is engaged to pre-cool the NG and partially or totally condense CMR, while CMR liquefies and sub-cools the NG. During refrigeration both CMR and WMR absorb the heat of vaporization and reject the atmosphere through water intercoolers. Ambient temperature strongly affects the DMR process efficiency because more work is needed to reject heat at higher temperatures. Thus, two different ambient conditions are used during the simulation for imitating different geographical locations and their respective effects on DMR process efficiency. The first condition (called Condition #1) assumes 25 °C ambient temperature and 30 °C as the intercooler discharge temperature. Condition #2 assumes 38 °C as ambient and intercooler discharge temperature. Table 2 lists the major process conditions used during modeling of DMR process.

3. DMR process modeling and simulation assumptions

The DMR process model was developed in the commercial process plant simulator Aspen Hysys and the Peng–Robinson equation of state was used for thermodynamic property calculations. Fig. 1 illustrates the DMR process flow diagram that involves two mixed refrigerant cycles: the warm MR (W MR) cycle contains mainly ethane and propane, and the cold MR (CMR) cycle contains nitrogen, methane, ethane, and propane. The WMR is engaged to pre-cool the NG and partially or totally condense CMR, while CMR liquefies and sub-cools the NG. During refrigeration both CMR and WMR absorb the heat of vaporization and reject the atmosphere through water intercoolers. Ambient temperature strongly affects the DMR process efficiency because more work is needed to reject heat at higher temperatures. Thus, two different ambient conditions are used during the simulation for imitating different geographical locations and their respective effects on DMR process efficiency. The first condition (called Condition #1) assumes 25 °C ambient temperature and 30 °C as the intercooler discharge temperature. Condition #2 assumes 38 °C as ambient and intercooler discharge temperature. Table 2 lists the major process conditions used during modeling of DMR process.

in the makeup of the refrigerant and variation of the compositions. This feature of the DMR process allows for the re-matching of the liquefaction load without altering the equipment [6]. Hwang et al. [1] reported the optimal operating conditions for the DMR process by considering the compression power requirement as an objective. A hybrid optimization method consisting of SQP and GA was used to find the optimal values of the design variables. The authors placed more emphasis on analytical modeling of the DMR process and in giving the concept of LNG FPSO its configuration, safety, ship motion, etc., while the details of the optimizing methodology were obviated from the manuscript. Husnil and Lee [7] examined the optimal control structure of the DMR process by drawing the steady-state optimality map containing information on the major state variables. Husnil concluded that optimal and stable operation in the DMR process is obtained when the ratio of the flow rates of the working refrigerant is constant. Conclusively there are several studies giving details of the design aspects of DMR process (see Section 2) but neglecting the optimization problem arises out of involved mixed refrigerants in DMR process [8], which help in increasing process efficiency [9]. This gives the motivation for present study that begins by highlighting the major developments during DMR process evolution (Section 2) followed by the optimization of DMR process using box methodology and controlled elitist genetic algorithm [10].

2. Chronological development of the DMR process

This section explains the important developments that took place in the evolution of DMR process. The first design of DMR process was revealed in 1978 [11]. Since then, a number of patents have been granted and Shell, AP C1 and Axens-IP alliance has acquired most of the licensed DMR processes [12]. In the earlier DMR designs no regard was given to the process efficiency when mixing non-equilibrium streams that causes thermodynamic irreversibility, although efforts were made to avoid the intermixing of non-equilibrium streams in the later designs. In earlier designs high temperature level MR is boiled at several different pressure levels (two or three) with inter-stage compression. This boiling requires multiple Hex zones, which leads to multiple vessels, valves and associated piping. This problem was overcome by using efficient flow paths [13,14]. The DMR process design was further enhanced by employing low level refrigerant for sub-cooling and high level refrigerant for NG pre-cooling and low level refrigerant cooling [6] [15–17]. The latest designs of DMR process employ hybrid flow paths and place emphasis on high process safety and efficiency [18–20]. A small number of heat exchangers, three stage throttling in pre-cooling, and direct utilization of cold energy available to the boil-off gas are the main features of the hybrid DMR design and provide ideas of the extent to which the boundary of the dual MR process is stretched [21–25]. The important chronological developments of DMR process are illustrated in informative Table 1 where extracted common attributes are taken to draw an informative matrix.
Most of the conditions are adapted from reference [34] and few are modified from reference [7].

4. Optimization variables, design constraints and objectives

4.1. Optimizing variables in DMR process

Individual component flowrates and operating pressures (suction and discharge) of CMR and WMR are the main optimizing variables in the DMR plant operation [1,7]. This is because of the ease of matching process load with compression load during changing product demand rates and varying ambient temperatures [37]. Individual stage pressures in CMR and WMR loops are not considered as the optimizing variable. Instead the suction and discharge pressures were taken into account and the increase of pressure is evenly distributed among all the compression stages to avoid high compression energy (Table 3).

4.2. DMR process design constraints

The DMR process optimization is constrained by minimum allowed approach temperature inside cryogenic heat exchanger. Operating at a very low approach temperature requires very big size
heat exchanger while high approach temperature needs more compression energy. As a practical approach guided by previous literature [10,38] the minimum approach temperature value is constrained to 3 °C. The compression ratio is constraint to vary between 1.5 and 4 only [39].

### 4.3. Optimization objectives in the DMR process

In the operation of liquefaction cycles, minimization of the total required compression power is the desired objective [40]. Based on the underlying assumption of 75% compressor isentropic efficiency, Lee et al. [41] also considered minimization of the total compression power for the DMR process optimization [42]. In DMR process two loops of refrigerant (CMR and WMR, see Section 3) operate on dedicated compressors and the total compressor energy required for NG liquefaction is given by Eq. (1), while Eqs. (2) and (3) illustrate the individual compressor power as a function of

\[
W_{\text{total}} = \sum (W_{\text{WMR, compressor}} + W_{\text{CMR, compressor}}) \quad (1)
\]

\[
W_{\text{WMR,ij}} = f_{\text{WMR}} \Delta H_{\text{WMR,ij}} \quad (2)
\]

\[
W_{\text{CMR,ij}} = f_{\text{CMR}} \Delta H_{\text{CMR,ij}} \quad (3)
\]

\( f \) is the flowrate of W/CMR and \( \Delta H_{\text{WMR,ij}} \) is specific enthalpy change of WMR/CMR at \( i \)th compression stage. Once the dedicated compressors outlet temperature and pressures are fixed the actual compressor power is calculated based on the compressor efficiency. Eq. (4) illustrates that the SCE can be written as the ratio of total compression energy by the LNG flowrate,

\[
\text{Minimize } \text{SCE} = \frac{W_{\text{total}}}{f_{\text{LNG}}} \quad (4)
\]

However compression energy minimization is not the only objective during early design stages of DMR process. Heat exchanger size is also considered for optimization as a major capital cost element. Although compressors also contribute to the capital cost but they have proprietary design and that their selection depends on the plant capacity, they are not considered within optimization objective. Instead, UA, which is a product of overall heat transfer coefficient and required heat exchanger area, is considered for minimization. The LNG exchanger duty is proportional to the overall log mean temperature difference (LMTD), where UA is the proportionality factor. Thus by definition of convective heat transfer between metal and fluid, UA can be written as Eq. (5) and considered as optimization objective.

\[
\text{Minimize } \text{UA} = \frac{Q_{\text{convective}}}{\Delta T_{\text{LMTD}}} \quad (5)
\]

Product of UA is easily exported to optimization platform and UA is a constant term depending on the material property. Thus minimization of heat exchanger area can be achieved by minimizing UA value, hence consider for optimization. For existing LNG plant UA value is fixed and minimization of the operational cost is one of the preferred options for efficiency improvement. Nevertheless, in the early design stages, both heat exchanger size and operational duty of the plant are considered together for lower annualized cost. During SCE minimization by varying the MR flow rates and pressure levels, compression work decreases to some local optimal point, and beyond this point the compression work decreases at the expense of UA. A higher value of UA entrails higher annualized cost because a large heat exchanger is required for the same heat transfer duty. Alternately when UA is optimized after some local optimal point the compression work increases and compensates for the low UA. A low value of UA results in a smaller sized heat exchanger which requires the LMTD, resulting in exergy and operating cost losses. The upper limit of the UA value is dictated by the minimum size of the compressor requirements, which are sometimes limited, e.g., 1988 MW/tonne-LNG [43]. Therefore, there exists a trade-off between total compression energy and UA value, and a multi-objective approach is needed to ensure minimum energy and cost design.

### 4.4. Objective function dependence on feed variations

The specific compression energy (SCE) of the DMR process decreases with decreasing feed temperature that mostly depends on the ambient conditions, so cold ambient naturally helps in refrigeration and in turn SCE decreases [44]. When the feed pressure is higher, the SCE requirement decreases [45] because expanding NG from a higher pressure provides self-refrigeration and decreases the dependence on external refrigeration. Increase in the feed flowrate increases the refrigeration load unless the liquefaction plant is operating at the sub-optimal state and the surplus flow of refrigerant balances the increase in NG feed flowrate for the same SCE.

### 5. Box optimization technique

The Box optimization technique is based on the Complex method of Box [46]. The optimization idea of the Box methodology was inspired by the downhill simplex algorithm [47]. The Box method is a sequential search technique that finds the near optimal solution to the constrained non-linear optimization problem. This is a gradient-free methodology that handles non-linear objectives and constraints by a direct function evaluation. Given a feasible starting point, the Box methodology generates a complex of \( n + 1 \) points around a centroid or feasible point and evaluates the objective at each point. The worst point in the complex is reflected through the centroid and a one dimension contraction is performed. The method continues until the convergence criteria are met or the maximum number of iterations is reached. Fig. 2 shows the adopted Box algorithm; further details of this method and its successful application can be found in reference [48]. The basic idea of the Box algorithm is that it navigates the search space by reflections, expansions or contractions. First, a simplex which is a polytope in \( n \) dimensions with \( n + 1 \) vertices is created. Than the simple vertex points are rearranged so that \( x_{n+1} \) is the worst point.

\[
f(x_{n+1}) > f(x_2) > f(x_1)
\]

Then generate a trial point \( x_i \) by reflection across the worst point as
\[ x_i = \bar{x} + \alpha (\bar{x} - x_{n+1}) \]

where \( \bar{x} = \left( \sum_{i=1}^{n} x_i \right) / (n + 1) \) is the centroid with \( \alpha > 0 \). After computing \( f(x_i) \), there are three possibilities:

a. If \( f(x_i) > f(x_j) > f(x_k) \) that means \( x_i \) is neither best nor worst, then replace \( x_{n+1} \) with \( x_i \).

b. If \( f(x_k) < f(x_i) \) that means \( x_k \) is the new best point and assumed direction of reflection is good enough to keep looking in the same direction by expansion \( x_k = x_i + \beta (x_k - \bar{x}) \) where \( \beta > 0 \). If \( f(x_k) < f(x_i) \), then replace \( x_{n+1} \) by \( x_k \), otherwise expansion is failed and replace \( x_{n+1} \) by \( x_i \).

c. If \( f(x_j) > f(x_i) \) than the polytope is too large and contraction is performed by \( x_c = \bar{x} + \gamma (x_{n+1} - \bar{x}) \) where \( 0 < \gamma < 1 \) is the

Fig. 2. Box optimization methodology.
contraction coefficient. If \( f(x_i) < f(x_{n+1}) \) then replace \( x_{n+1} \) by \( x_i \), otherwise contract again.

Standard values of \( \alpha = 1 \), \( \beta = 1 \) and \( \gamma = 0.5 \). The above explained algorithm is simplified in Fig. 2.

### 6. DMR process optimization results

The optimization results of the DMR process are compared with the base case using two different feed conditions, i.e., Conditions 1 and 2. The purpose of using different feed conditions is to analyze their effect on DMR process optimality and the relative importance of individual parameters. The other reason for different feed conditions is to mimic different ambient environment and their effect on DMR process efficiency. Condition #1 assumed feed and intercooler discharge temperatures are at 25 °C and 30 °C, respectively, whereas Condition #2 assumed feed and intercooler discharge temperatures both at 38 °C.

#### 6.1. Results comparison for compression energy minimization

Table 4 lists the comparison of optimization results for SCE minimization. The results comparison shows that the box methodology successfully reduced the SCE by 36% in Case 1 and 34% in Case 2. The results further show that the over-specified values of the total MR flow rate are the main cause of the high energy requirement in the base case. The box optimization methodology is successful in locating the minimum within the decision variable space although there is a 24% increase in the UA requirements. This means that the improvement of SCE is partly offset by the gain of UA. This also suggests the interdependence and partial trade-off between UA and SCE values. The trade-off between UA and SCE can be addressed by solving together. Case 3 using condition 1 shows a 45% SCE saving compared to the base case. High savings in Case 3 are due to different feed conditions where low temperature feed naturally helps in refrigeration. Moreover slightly higher pressure also decreases SCE by providing self-refrigeration. This shows that the ambient temperature has a significant effect on the DMR efficiency and arctic efficiencies are always better than the tropical region. The information available in Table 4 was simplified using Fig. 3, where a comparison bar graph illustrates the difference in the SCE requirement. The lowest SCE is achieved in Case 3, i.e., 0.3399 kW/kg-LNG, which is due partially to the low ambient conditions and partially by the box optimization. If the ambient condition of Case 3 is increased to Case 2, the optimized SCE increases to 0.4094 kW/kg-LNG, which is a 17% increase compared to Case 3. The heat absorbed by the MR is rejected to the ambient through the intercoolers. Therefore, the intercooler duty, as shown in Fig. 4, is also an important parameter for making a fair comparison between the optimized and base cases. The result trends of Fig. 4 are similar to those in Fig. 3 because the intercooler duty largely depends on the total circulating MR flowrate and decrease in its value being the same change in SCE.

![Fig. 3. SCE variation in SCE and UA optimization cases.](image-url)
6.2. Results comparison for UA minimization results

Table 5 lists the optimization results for UA with the box methodology and its comparison with different cases. The comparison of base case with Case 1 revealed that box methodology can find the values of the decision variables that reduce the SCE and UA values simultaneously. The Case 1 results in Tables 4 and 5 further show that minimization of the compression energy is successful but the success is offset by the increase in UA value. In contrast, with the result of Table 5 Case 1, the simultaneous decrease in UA and SCE values apparently makes the UA minimization a better objective. The approach temperature and LMTD are also different in case 1 of Tables 4 and 5. The UA minimization objective has a higher approach temperature and LMTD while compression minimization objective has a lower value. The higher value of the LMTD means a higher heat transfer driving force, which requires less exchanger area; hence, Table 5 has low UA values and higher SCE values than Table 4. Case 2 further revealed the superiority of the UA minimization objective over the compression energy minimization with lower UA and SCE values at similar LMTD values. A comparison of Cases 2 and 3 in Table 5 showed that the decrease in UA value is offset by the corresponding increase in LMTD and SCE values. Fig. 5 further shows the results of the specific UA value (UA/kg-LNG) for the compression and UA minimization results. The specific UA values of Cases 1 and 2 are similar but the higher value of Case 2 (even higher than base case) can be explained by the low SCE. The specific UA values are all higher than the base case in the compression minimization objective because the target was to reduce the SCE, which was achieved by minimizing the heat transfer driving force and decreasing the heat transfer approach in the exchanger. This in turn requires a higher heat exchanger area or higher specific UA value.

From the above discussion, it can be concluded that there is no absolute best or worst solution, and it depends on the process requirement and conditions. At the optimized state, the decrease in one objective is always offset by the corresponding increase in the other. This statement is only true when the system is fully optimized and there is no room for improvement except by deteriorating the other objective. For example in Table 5, a comparison of the base

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**Table 5**

UA minimization results.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Base case [7] (0.1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 1 (0.1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 2 (1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 3 (1 MTPA) intercooled @30°C feed @25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy parameters</td>
<td></td>
<td>Condition 2</td>
<td>Condition 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total compression power</td>
<td>kW</td>
<td>7,221.97</td>
<td>6,385.26</td>
<td>43,991.19</td>
<td>65,520.94</td>
</tr>
<tr>
<td>Specific compression power</td>
<td>kW/kg-LNG</td>
<td>0.6195</td>
<td>0.5477</td>
<td>0.3529</td>
<td>0.5256</td>
</tr>
<tr>
<td>Total cooling duty</td>
<td>kW</td>
<td>9,937.88</td>
<td>9,099.28</td>
<td>71,801.61</td>
<td>93,331.27</td>
</tr>
<tr>
<td>Specific cooling duty</td>
<td>kW/kg-LNG</td>
<td>0.8525</td>
<td>0.7806</td>
<td>0.5760</td>
<td>0.7487</td>
</tr>
<tr>
<td>Total UA</td>
<td>MW/°C</td>
<td>0.79</td>
<td>0.6660</td>
<td>12.20</td>
<td>7.45</td>
</tr>
</tbody>
</table>

Cold mixed refrigerant

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Base case [7] (0.1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 1 (0.1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 2 (1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 3 (1 MTPA) intercooled @30°C feed @25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2 flow rate</td>
<td>kg/h</td>
<td>8,218.42</td>
<td>9,230.92</td>
<td>45,636.46</td>
<td>47,000</td>
</tr>
<tr>
<td>C1 Flow rate</td>
<td>kg/h</td>
<td>12,230.42</td>
<td>9,896.04</td>
<td>72,605.61</td>
<td>119,925</td>
</tr>
<tr>
<td>C2 Flow rate</td>
<td>kg/h</td>
<td>26,336.85</td>
<td>15,846.22</td>
<td>97,172.13</td>
<td>118,775</td>
</tr>
<tr>
<td>C3 Flow rate</td>
<td>kg/h</td>
<td>9,254.30</td>
<td>8,860.525</td>
<td>45,636.46</td>
<td>275,850</td>
</tr>
<tr>
<td>Suction pressure</td>
<td>bar</td>
<td>3.31</td>
<td>3.31</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Discharge pressure</td>
<td>bar</td>
<td>55</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>LMTD</td>
<td>°C</td>
<td>17.99</td>
<td>18.38</td>
<td>7.84</td>
<td>17.26</td>
</tr>
<tr>
<td>Min approach</td>
<td>°C</td>
<td>2.99</td>
<td>8.10</td>
<td>2.99</td>
<td>6.66</td>
</tr>
</tbody>
</table>

Warm mixed refrigerant

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Base case [7] (0.1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 1 (0.1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 2 (1 MTPA) intercooled @38°C feed @38°C</th>
<th>Case 3 (1 MTPA) intercooled @30°C feed @25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 flow rate</td>
<td>kg/h</td>
<td>89.39</td>
<td>47.20</td>
<td>1,000</td>
<td>1,994.9219</td>
</tr>
<tr>
<td>C2 flow rate</td>
<td>kg/h</td>
<td>10,304.18</td>
<td>20,597.93</td>
<td>9,500</td>
<td>20,300</td>
</tr>
<tr>
<td>C3 flow rate</td>
<td>kg/h</td>
<td>1,996.35</td>
<td>3,965.10</td>
<td>20,000</td>
<td>39,800</td>
</tr>
<tr>
<td>i-butane flow rate</td>
<td>kg/h</td>
<td>6,436.78</td>
<td>7,111.78</td>
<td>25,000</td>
<td>49,975</td>
</tr>
<tr>
<td>n-butane flow rate</td>
<td>kg/h</td>
<td>1,117,329</td>
<td>10,610.79</td>
<td>25,000</td>
<td>49,975</td>
</tr>
<tr>
<td>Suction pressure</td>
<td>bar</td>
<td>3.5</td>
<td>4.6</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Discharge pressure</td>
<td>bar</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>LMTD</td>
<td>°C</td>
<td>20.69</td>
<td>22.35</td>
<td>24.18</td>
<td>29.08</td>
</tr>
<tr>
<td>Min</td>
<td>°C</td>
<td>12.86</td>
<td>13.0</td>
<td>9.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>
case and case 1 showed that both objectives (UA and SCE) are minimized simultaneously. This is because of the poor engineering judgment and the over specified values of the decision variables in the base case that are optimized by the box methodology. The other approach for design optimization is by considering both objectives together for minimization. Instead of one absolute point, the multi-objective optimization will give a range of solutions. Therefore, multi-objective optimization using controlled elitist genetic algorithm is pursued and detailed in the subsequent section.

7. Multi-objective optimization of UA-total compression energy using controlled elitist genetic algorithm

The single objective optimization problems attempted in Sections 6.1 and 6.2 show that there exists a trade-off between the UA and SCE. Design attempts to minimize one objective worsen the other; hence a multi-objective optimization (MOO) approach is adopted to satisfy these conflicting objectives at once. Evolutionary algorithms, particularly the GA, are suitable candidates for satisfying multiple, possibly conflicting objectives simultaneously [48]. The solution of the MOO problem culminates in the Pareto efficiency [49], which is a state when it is impossible to make any one objective better off without making the other objective worst off. Therefore, the Pareto optimization is a set of choices or solutions that are Pareto efficient, and each satisfies the objective at an acceptable level without being dominated by any other solution. The Pareto-optimal fronts illustrated in Figs. 5 and 6 are generated using the Matlab library function gamultiobj available in the Global Optimization Toolbox [50]. The objectives, UA and compression energy, are coded in Matlab and the state variables are extracted from the Aspen Hysys model by connecting Aspen Hysys with Matlab exploiting Microsoft COM functionality [51].

Fig. 5 presents the Pareto-optimal front for two competing objectives: UA along with the total compression energy for condition 2. The front appears continuous and illustrates a clear trend of a high UA value for a small compression energy and vice-versa. All points located on the Pareto front are the optimal solutions; thus selecting a best solution requires decision making. Ideally, the minimum solution of the problem in Figs. 6 and 7 lies in the origin corner (because of the minimum case in both objectives), which is impossible because of the non-optimal nature of the solution. Nevertheless, the nearest point on Pareto-front from the ideal corner solution was deemed a desirable final solution, where both objectives attain the best possible value simultaneously, as represented by the red arrow in Figs. 6 and 7. (For interpretation of the references to color in this text, the reader is referred to the web version of this article.) The formal description of the ideal point and tracing the minimum using the normalized Pareto frontier can be found in Sayyaadi and Babaelahi [52].

The result from MOO was compared with the single objective optimization in Table 6. For condition 2, the SCE value obtained from MOO lies between the single objectives of the UA and the SCE minimization objective. Compared to the base case, MOO results in a 13% decrease in total compression energy and a 3% decrease in specific UA. Compared to the single objective optimization of SCE, the MOO results are 24% and 17% higher in the SCE for conditions 2 and 1, while the results are 27% and 40% higher for the specific UA requirement. The UA single objective optimization results in a 12% and 17% less specific UA requirement for conditions 2 and 1 compared to MOO at the same time performing poorly by 2% and 20% in the SCE front. These results show that for single objective optimization, the UA minimization must have been the preferred objective compared to the conventional wisdom of minimizing the operational cost alone.

8. Conclusions

The survey of important developments in the evolution of DMR process followed by its single and multiple objective optimization studies is performed. The information obtained from the survey is
illustrated in an informative matrix and shows that the current drift in the DMR process design is toward high process safety and efficiency using the modified flow paths and cold-wind type heat exchanger. A small number of heat exchangers, three stage throttling in pre-cooling, direct utilization of the cold energy available to the boil-off gas are the main features of the recent DMR developments contrary to the earlier designs.

Single and multi-objective optimization of the DMR process was performed considering the SCE and UA minimization as objectives. Single objective optimization of the SCE results in a 36% saving compared to the base case. This saving can be attributed partially to the optimization and partially to the gain of UA. The MOO, however, results in only a 24% SCE saving compared to the base case but the UA value is reduced by only 3%. Single objective optimization of UA results in a 15% decrease in UA value and a further 11% decrease in SCE compared to the base case. This decrease in SCE is contrary to the single objective results of SCE minimization. Although there was a difference between the MOO and UA results, it was not significant. Therefore, UA minimization can be assumed to be the preferred objective in the design stage because it affects both the capital and operating cost. The pressure values in the decision variables remain mostly unmoved during optimization, which may be due to the judicious selection of the pressure values in the base case. Nevertheless, the over specified values of the MR components are the main reason for the sub-optimality in the base case, which was rectified with optimization.

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Nomenclature

Abbreviations
APCI Air Products & Chemical Inc.
CAPEX Capital expenditure

Table 6
Single and MOO results comparison.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Single objective optimum</th>
<th>Multi-objective optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Compression energy minimization</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 2</td>
<td>Condition 1</td>
</tr>
<tr>
<td>Specific compression energy</td>
<td>kW/kg-LNG</td>
<td>0.3962</td>
<td>0.3399</td>
</tr>
<tr>
<td>Total UA</td>
<td>MW/°C</td>
<td>1.05</td>
<td>14.76</td>
</tr>
<tr>
<td>Specific UA</td>
<td>MW/kg LNG-°C</td>
<td>9.00e-5</td>
<td>11.84e-5</td>
</tr>
</tbody>
</table>

Condition 2: warm ambient (38 °C), Condition 1: cold ambient (25 °C).

Fig. 7. Pareto-optimal front for the UA-Total compression energy minimization, Condition #1 (1 MTPA).
C3MR: Propane pre-cooled mixed refrigerant
CMR: Cold mixed refrigerant
DMR: Dual mixed refrigerant
FPSO: Floating production storage and offloading
GA: Genetic algorithm
HCS: Hydrocarbons
Hex: Heat exchanger
LNG: Liquefied natural gas
LPG: Liquefied petroleum gas
LMTD: Log mean temperature difference
MR: Mixed refrigerant
MTPA: Metric ton per annum
MW: Megawatt
MOO: Multi-objective optimization
OPEX: Operating expenditure
NG: Natural gas
SCE: Specific compression energy
SQP: Sequential quadratic programming
UA: Overall heat transfer coefficient
WMR: Warm mixed refrigerant
Wf: Total refrigerant flowrate
Wf,C: Warm mixed refrigerant compressor duty
Wf,f,C: Cold mixed refrigerant compressor duty
AHf,WMR: Specific enthalpy change of warm/cold mixed refrigerant
f,LNG: Flow rate of LNG
Qconvective: Convective heat transfer between refrigerant and natural gas

References

[31] H. Paradowski, D. Leroux. Method and apparatus for cooling and liquefying at least one gas with a low boiling point, such as for example natural gas. 1985, US Patent No. 4545795.