Weed colonization-based performance improvement opportunities in dual-mixed refrigerant natural gas liquefaction process

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Abstract

Dual-mixed refrigerant (DMR) process is a promising candidate for liquefying the natural gas (LNG) at onshore as well as offshore sites, thanks to its higher liquefaction capacity and flexibility in using full gas turbines. DMR involves two mixed refrigerant cycles to perform precooling and subcooling of natural gas (NG), and these refrigerant compositions need constant tweaking to match the ever-changing NG cooling curve, as it is obtained from different gas fields. Mismatching of cooling curves often results in suboptimal operation, which ultimately leads to an increase in the overall energy consumption. Thus, this study is aimed at making DMR liquefaction operation close to optimal using the invasive-weed paradigm. At first, the decision variables for performance improvement were determined using degrees of freedom analysis then through invasive-weed paradigm the best set of parameters that results in minimal overall energy consumption were obtained. For the given set of conditions, it was found that after optimization, the DMR process can produce LNG using 16.2% less compression power compared to the published optimized DMR process. Taking into account the higher sensitivity of the DMR process against NG feed conditions, the IWO approach was also examined to find the multiple optimal solutions corresponding to different sets of feed conditions. The thermodynamic evaluation revealed that the mixed refrigerant involves in NG subcooling and interstage coolers have the highest level of exergy destruction. After successful performance improvement of the DMR process, it is also found that still, 62% improvement potential (based on avoidable/unavoidable exergy destruction analysis) is available in the DMR process that can be attained through either sole optimization or optimal retrofitting/revamping.

Keywords

DMR, exergy destruction, invasive weed, natural gas liquefaction, overall compression power, varying feed conditions
1 | INTRODUCTION

The demand of liquefied natural gas (LNG) is growing rapidly, mainly due to its clean nature as compared to oil and coal. The transportation of natural gas (NG) as an LNG gives a feasible and safe solution for linking NG reserves and consumers that are geographically mismatched and located in unstable political environment. However, LNG is produced through energy-intensive low-temperature processes that normally account for ~40%-50% of the total cost of LNG supply chain. The total annualized cost of LNG plants steadily rely upon liquefaction capacity, environmental conditions (eg, ambient temperature and humidity), and process selection such as single mixed refrigerant (SMR), dual-mixed refrigerant (DMR), propane precooled mixed refrigerant (C3MR), and cascade refrigeration processes.

Among all well-demonstrated LNG processes, the DMR process is considered to be a promising candidate for both offshore and onshore LNG production, primarily due to its relative high-energy efficiency resulting from its better utilization of cooling power, which is distributed in two different mixed refrigerants cycles. The DMR process has higher capacity than the SMR process. Therefore, recently, the DMR-based schemes have also been implemented to integrate the hydrogen and natural gas liquefaction efficiently. However, the operation of the DMR process is much more sensitive than the SMR process, especially under varying feed conditions. The DMR operation is prone to go under suboptimal conditions upon any variation in feed conditions which causes significant fluctuation in compression power. For this reason, the operation of the DMR process near higher efficiency point saves a lot of energy, which ultimately increases its global competitiveness. Due to complex process thermodynamics and interactions among the design variables, energy minimization (compression power) is highly nonlinear. Suboptimal operation of the DMR process leads to high exergy destruction in intercooling, compression, and expansion stages. This exergy destruction (entropy generation) depends greatly on the temperature drops inside the LNG heat exchangers (including precooling and subcooling exchangers). The temperature gradients are highly affected by any small change in the MR flow rates and other operating parameters of the refrigeration loops. Therefore, these MR flow rates, operating pressures, and temperatures must be optimized in order to achieve optimal operation of liquefaction process corresponding to minimum exergy destruction, which will lead to lower overall energy requirement.

Previously published research work primarily focused on to optimize the DMR process for minimization of energy consumption. Hwang et al used a hybrid optimization approach by combining sequential quadratic programming (SQP) and a genetic algorithm (GA). Wang et al used the commercial simulator Aspen Hysys to simulate and optimize the DMR process using Hysys’s built-in optimization method to reduce the specific annual cost and shaft work requirement for LNG production. Fazlollahi et al presented an optimal design of a DMR process with a 73% liquefaction rate using a GA. Khan et al presented a multi-objective study to optimize the DMR process using the box approach by considering specific compression power and total UA and objectives. Lee and Moon proposed an optimal design of a DMR process by applying successive reduced quadratic programming (SRQPD). They maximized the total profit of LNG production by minimizing the total annual cost and total energy of compression. Ghorbani et al have reduced the compression power requirement for DMR process through the optimal integration of absorption refrigeration cycle.

Finding new ways for efficiency improvement through sole optimization and/or process modification has highly incentivized the process industry and rewards are even greater for energy-intensive operations such as liquefaction. Sole optimization has demonstrated its potential to enhance the profitability of the process by reducing the energy requirement without any capital investment. Optimization of the process conditions is an unending job and must be managed continuously to maximize the profit. In this scenario, extraction of optimal points in the whole process becomes an intriguing task owing to varying feed conditions. Taking into account this problem, this research article, therefore, provides an optimization and analysis of the DMR-LNG using a numerical stochastic optimization algorithm called invasive-weed optimization (IWO) algorithm proposed by Mehrabian and Lucas. The tough nature of invasive weeds against any resistance in the environment makes them effective in navigating highly nonlinear search space. Previously, several engineering optimization problems (complex and nonlinear) have been attempted and solved successfully through the IWO approach. After witnessing those applications, IWO is adopted to optimize the DMR process for minimizing the overall energy consumption to liquefy 1 MTPA (million tons per annum) NG. In this study, for the DMR process simulation and analysis, a well-known commercial simulator Aspen Hysys v10 is used. The developed Hysys model of DMR process is coupled with the MATLAB environment through COM functionality to make a rigorous simulation-optimization framework. The IWO approach is also evaluated to find the optimal decision of DMR process for different sets of feed conditions. Finally, the exergy analysis under best optimal variables is also performed. Furthermore, avoidable and unavoidable exergy destructions associated with each equipment of the DMR process are also calculated in order to determine the further potential of improvement in the process.
Natural gas liquefaction plants are usually classified into three primary types: small scale, peak shaving, and base-load liquefaction plants. For small-scale and peak shaving NG liquefaction units, SMR liquefaction process is usually taken into account. In these plants, capital costs are center of interest as compared to operational costs. Considering base-load NG liquefaction plants, high volumes of LNG production accompanied by higher operational costs are counted on. In this regard, on the basis of flexibility and higher efficiency, dual-mixed refrigerant (DMR) LNG process has been utilized. DMR process is associated with high level of flexibility, while on the other hand modeling, simulation, and optimization of DMR are substantially more complex as compared to SMR LNG process.

The DMR process has two different refrigeration loops of mixed refrigerants, providing cooling for natural gas liquefaction. One refrigeration loop precools the feed natural gas while the second refrigeration loop liquefies the natural gas and provides subcooling. Generally, mixed refrigerant circulated in a precooling refrigeration loop is called warm MR (WMR) and mixed refrigerant that is used to produce subcooled LNG is called cold MR (CMR). WMR consists of methane, ethane, propane, isobutane, and n-butane whereas the ingredients of CMR are methane, ethane, nitrogen, and propane. Figure 1 presents the DMR process flow schematic. The main components include:

- **CHX**: Cryogenic heat exchanger
- **E**: Interstage cooler
- **JTV**: Joule-Thomson valve
- **K**: Compressor
- **V**: End flash gas vessel
of the DMR process are LNG exchangers (CHX-01 and CHX-02), expansion devices, and compressors (multi-stage) with after-coolers between each stage. In a traditional DMR process, natural gas (stream-18) and CMR (stream-07) are entered into the precooling heat exchanger (CHX-01). The natural gas (stream-19) exits the precooling heat exchanger with 5%-10% liquid fraction and the CMR (stream-08) is produced having 25%-45% liquid fraction owing to optimal precooling temperature and composition. In the subcooled heat exchanger (CHX-02), the remaining gas fraction of feed NG is converted into subcooled liquid, that is, subcooled LNG. Subsequently, the stream-20 is exited from the CHX-02 and is crossed through JTV-3, where its pressure is reduced to facilitate the safe and economic storage as well as transportation. The stream-21 as a main LNG product is attained with <10.0% end flash gas. The precooling or WMR (stream-12) loop starts from its compression and the CMR starts as stream-1; after expansion, both MRs are restored to a high-pressure (optimal value) state by passing them through compressions units. The stream-16 (high-pressure WMR) enters the precooling LNG heat exchanger CHX-01 and, right after utilizing the JTV-1 to lower its pressure, intertransfers the cold exergy with natural gas (stream-18 and 19) and the CMR (streams 7 and 8). From CHX-01, a superheated vapor stream-12 is exited, which is sent to the compression units of the WMR refrigeration loop for the completion of the WMR refrigeration cycle. Similarly, high-pressure CMR enters the CHX-02 and it turns into a liquid state by cooling from stream-10. This stream-10 appears after the pressure reduction of stream-9 through JTV-2. Finally, stream-11 (superheated vapor) is exited and recycled to accomplish the CMR refrigeration loop.

3 | DMR PROCESS MODEL DEVELOPMENT AND ASSUMPTIONS

A well-know commercial simulator Aspen HYSYS is used as an interational mean of simulation for calculation and design creation of dynamic and state steady processes. In addition, it exhibits the COM interface which permits different programs to set and acquire values of any given process. 23 It is an advanced simulator used for modeling different chemical processes from the level of unit operations to large chemical plants like LNG production units. Aspen HYSYS is used for rigorous calculation of different aspects involved in thermodynamics like mass and heat transfer, energy and mass balances, pressure drops and liquid-vapor equilibrium, etc. It is used on industrial academic level for dynamic and steady-state simulation of LNG processes. 13,24

In this study, a steady-state rigorous model of the DMR process was developed using Aspen Hysys® v10. The Peng-Robinson 25 thermodynamic fluid package with Lee-Kesler 26 enthalpy calculation option was selected. The feed NG temperature, pressure, flowrates, and other simulation assumptions are provided in Table 1 that was adopted from Khan et al 8 to establish a base case for DMR process. To develop a simulation of the base case of DMR process, the following major assumptions were made:

- Heat losses from the exchanger are negligible.
- Loss of heat to the surroundings is negligible.
- A variable speed compressor with 75% isentropic efficiency is used in both refrigeration loops.
- Water as a cooling medium is used for the interstage cooling in the refrigeration cycles.
- Each interstage cooler causes a 0.5 bar pressure loss.
- For 96.3% liquefaction efficiency, the end flash valve pressure is set at 1.1 bar.
- A minimum internal temperature value of 3.0°C is specified for both precooling and subcooling LNG heat exchangers.

### Table 1: DMR process feed conditions and simulation basis 8

| Property                               | Condition        |
|----------------------------------------|------------------|
| Natural gas feed conditions            |                  |
| Flow rate (kg/h)                       | 124 654.33 (1 MTPA) |
| Temperature (°C)                       | 25.0             |
| Pressure (bar)                         | 55.0             |
| Natural gas feed composition          |                  |
| Methane                                | 87.23            |
| Ethane                                 | 6.68             |
| Propane                                | 3.49             |
| n-Butane                               | 0.89             |
| i-Butane                               | 0.59             |
| n-Pentane                              | 0.19             |
| i-Pentane                              | 0.29             |
| Nitrogen                               | 0.49             |
| Intercooler outlet temperature, °C    | 30.0             |
| End flash gas %                        | 3.7              |
| Pressure drops (bar) across LNG heat exchanger (CHX-01) |                  |
| From stream 18 to 19                   | 1.0              |
| From stream 07 to 08                   | 0.5              |
| From stream 15 to 16                   | 0.5              |
| From stream 17 to 12                   | 0.1              |
| Pressure drops (bar) across LNG heat exchanger (CHX-02) |                  |
| From stream 19 to 20                   | 1.0              |
| From stream 08 to 09                   | 1.0              |
| From stream 10 to 11                   | 0.1              |
The invasive-weed optimization (IWO) algorithm is established having base on the simulation of the colonization of invasive weeds in nature. Invasive weeds attack the cropping area by spreading and find their living zones amid the product (crops). Particular attacking weed finds the fresh reserves in the field for its survival, develops into a blooming weed, and produce fresh weeds, independently. Total newly generated weeds rely upon the strength of that blooming weed in the environment. Those weeds having more effective appropriation to the earth and get resources that are more unused grow rapidly and create seeds to a greater extent. The newly born weeds arbitrarily spread over the field and develop into blossoming weeds. When the weeds, reaching to the maximum number, appear in the field, this procedure stops. Like now, just those weeds with greater strength can continue to live and generate the new weeds. This aggressive competition among the weeds makes them become very well adapted and enhanced over time. Each individual agent that occupies the each optimization variable value is termed as a “seed.” Each seed develops into a flowering plant or weed in the environment. Every plant develops after the fitness evaluation of each individual agent. Therefore, the process from seed to plant formation corresponds to the fitness evaluation of each individual agent. The simulation of the colonization of the invasive weeds is described as:

**Defining the solution space:** First, a number of decision variables (N) are selected for optimization. Then, for each variable, a lower and an upper bound must be attributed in the d-dimensional solution space.

**Population initialization:** A determinate number of seeds are spread over the d-dimensional solution space. Shortly after, every seed assumes a random location. Location of each seed is considered as an initial solution comprising values equal to the number of variables of the optimization problem.

**Fitness evaluation:** Every initial seed that develops into a flowering plant is called a fitness function. This function describes the fitness of the solution and assigns fitness values to their relative seeds. The assigned fitness value seed becomes a plant.

**Population ranking and reproduction:** Before the plants produce more seeds (reproduction), population ranking takes place according to the fitness value of each plant. After ranking, they are allowed to produce seeds. In other words, plant reproduction totally depends on the fitness value or its ranking in the colony. That increases production from minimum seed production (S_{min}) to maximum seed production (S_{max}). Those plants that are more adaptive in the colony produce more seeds. This reproduction phenomenon is shown in Figure 2.

In this ranking and reproduction contest, all the plants participate. This is the most important aspect of this algorithm that differentiates it from other algorithms.

**Spatial dispersal:** The newly produced seeds spread randomly over the d-dimensional space with a mean equal to zero, or simply we say that seeds are distributed in such a manner that they are located near their mother or parent plant with changing standard alteration. The typical alteration at the existing time can be formulated as

\[
\sigma_{iter} = \frac{(iter_{max} - iter)^n}{(iter_{max})^n} (\sigma_{initial} - \sigma_{final}) + \sigma_{final},
\]

where iter_{max} represents the maximum number of iterations, n is the index of nonlinear modulation, and \(\sigma_{initial}\) and \(\sigma_{final}\) are the initial and final standard deviations, respectively.

**Competitive exclusion:** When all the seeds occupy their space over the entire space, the new seeds develop into blooming plants and then are grouped with their parents. Now, seeds with less fitness are excluded to attain an ultimate number of plants, that is, \(P_{max}\). In this manner, plants and seeds are grouped and those that have enhanced fitness value are sustained and reproduced. It is obvious that total plants present in the colony are lower than the population density. After that, surviving plants creates new seeds in the colony according to their rating or reputation in the colony. This procedure repeats at the ‘fitness evaluation’ step till the fitness criterion is attained or the maximum number of iterations is accomplished. The working flowchart for the IWO approach is provided as Figure 3.

A comprehensive explanation about the IWO approach can be found in Mehrabian and Lucas, \(^17\) Pal et al, \(^19\) Pourjafari and Mojallali, \(^20\) Rad and Lucas, \(^21\) Zhou et al. \(^22\) Furthermore, the major features of IWO approach on which its performance is superior to other competitive
optimization algorithms (e.g., PSO and GA) have been reported by Karimkashi and Kishk.\textsuperscript{18}

### 4.1 Optimization framework

The individual flow rates of mixed refrigerant (cold and warm) components and suction and discharge pressures were chosen as decision variables, as were considered in other latest DMR optimization studies.\textsuperscript{7,8,27} Accordingly, the energy requirement for the DMR process strongly depends on the refrigerant flow rates, suction pressures, and discharge pressures of both cold and warm MRs. Therefore, this study also uses these variables as the decision variables to minimize the exergy destruction of DMR process to produce the 1 MTPA LNG production. The design variables along with their bounds limits are provided in Table 2.

The total compression power for the WMR loop and the CMR loop has been considered as an objective function in several studies of optimization of LNG processes,\textsuperscript{28} as well as particularly for DMR processes.\textsuperscript{7,8,27} Therefore, the total required shaft work for compression units was also chosen as an objective function to find an optimal value of the selected operational parameters for the optimal operation of the DMR process. The objective function can be presented as follows:

\[
W_{\text{total}} = \left( \sum W_{\text{WMR, compressors}} + W_{\text{CMR, compressors}} \right). \tag{2}
\]

\[
\text{Minimize } f(X) = \text{Min } W_{\text{total}}(X) \tag{3}
\]

subject to

\[
\text{MITA}(X)_{\text{CHX01}} \geq 3.0^\circ\text{C}, \tag{4}
\]

\[
\text{MITA}(X)_{\text{CHX02}} \geq 3.0^\circ\text{C}. \tag{5}
\]
where \( X \) is a decision variable vector and bounded as

\[
X^L_i \leq X_i \leq X^U_i, \quad i = 1, 2, \ldots, n. \tag{6}
\]

The minimization of the overall power requirement (objective function) is constrained by the minimum internal temperature approach (MITA) through the main LNG heat exchanger. The exterior penalty function (EPF) is one of the best possible approaches for handling constraints, especially optimization of liquefaction processes where highly nonlinear constraints are involved.\(^{29,30}\) Using the exterior penalty function approach, the constraints are folded into the objective function, which converts an inequality constraint into an equality constraint. In this paper also, the EPF method was employed to handle the constraint MITA value of 3.0°C inside both heat exchangers associated with the DMR process. Finally, the constraints for both heat exchangers are folded into the objective function as follows:

\[
P(X) = \text{Min} \left( \sum_{i=1}^{k} W_{\text{total}}(X) + r(\max \left\{ 0, (3.0 - \text{MITA}(X)_{\text{CHX01}}) \right\}) + r(\max \left\{ 0, (3.0 - \text{MITA}(X)_{\text{CHX02}}) \right\}) \right),
\]

where \( r \) a positive penalty parameter.

**TABLE 2** Decision variables along with their bounds limits

| Decision variables          | Lower bound | Upper bound |
|----------------------------|-------------|-------------|
| Cold MR (to subcool NG)    |             |             |
| Discharge pressure (stream-11), \( P_{11} \) (bar) | 30.0 | 70.0 |
| Suction pressure (stream-6), \( P_{6} \) (bar) | 2.5 | 7.0 |
| Nitrogen flow rate, \( m_{n2} \) (kg/h) | 30 000.0 | 60 000.0 |
| Methane flow rate, \( m_{c1} \) (kg/h) | 50 000.0 | 90 000.0 |
| Ethane flow rate, \( m_{c2} \) (kg/h) | 80 000.0 | 125 000.0 |
| Propane flow rate, \( m_{c3} \) (kg/h) | 200 000.0 | 350 000.0 |
| Warm MR (to precool NG)    |             |             |
| Discharge pressure (stream-12), \( P_{12} \) (bar) | 15.0 | 28.0 |
| Suction pressure (stream-13), \( P_{13} \) (bar) | 1.2 | 4.0 |
| Methane flow rate, \( m_{c1} \) (kg/h) | 500.0 | 1500.0 |
| Ethane flow rate, \( m_{c2} \) (kg/h) | 7500.0 | 11 000.0 |
| Propane flow rate, \( m_{c3} \) (kg/h) | 15 000.0 | 40 000.0 |
| i-butane flow rate, \( m_{c4} \) (kg/h) | 15 000.0 | 35 000.0 |
| n-butane flow rate, \( m_{c4} \) (kg/h) | 15 000.0 | 35 000.0 |
| Precooling temperature (stream 19 and 16), \( T_p \) (°C) | −28.0 | −15.0 |

**TABLE 3** IWO parameters used to set the optimization framework

| Symbol | Parameter | Value |
|--------|-----------|-------|
| nPop_0 | Initial population size | 10.0 |
| nPop | Maximum population size | 50.0 |
| dim | Optimization problem dimensions | 13.0 |
| S_{\text{min}} | Minimum numbers of seeds | 0.0 |
| S_{\text{max}} | Maximum numbers of seeds | 5.0 |
| e | Variance reduction exponent | 3.0 |
| \sigma_{\text{initial}} | Initial value of standard deviation | 0.5 |
| \sigma_{\text{final}} | Final value of standard deviation | 0.01 |

### 4.2 IWO algorithm parameters

The parameters were fixed during the optimization of the DMR process under different numbers of iterations. The IWO algorithm parameters were chosen after analyzing several optimization studies in which nonlinear optimization problems were solved successfully and efficiently through the IWO strategy.\(^{31}\) The parameters involved to set the optimization framework of the IWO algorithm are provided in Table 3.

### 5 RESULTS AND DISCUSSION

#### 5.1 Process optimization results and analysis

The invasive-weed strategy was successfully applied to the optimization of a 1 MTPA capacity DMR process. According to Figure 1, the details of the temperatures and pressures for all streams of the base case and the IWO-optimized DMR process are given in Supplementary material as Table 4. The decision variables progress during the DMR operation optimization through the IWO approach corresponding to different numbers of iterations are listed in Table 5. Figure 4 presents the convergence of the IWO approach with regard to the minimization of the overall compression power at different numbers of iterations. The change in the objective value from 500 to 1500 is 3%, while the change from 1000 to 1500 is <1% (see Figure 4). Most of the improvement is achieved within 500 iterations, so, if IWO is implemented online, a small drop in performance can be traded for increased speed. Different numbers of iterations were chosen to analyze the
rigorous computational effort against the optimal solution, although the computational effort also depends on the system involved in the simulation-optimization framework.

The difference between suction and discharge pressure is the measure of the compression power invested for liquefaction. Keeping the difference to a minimum directly reduces the compression energy. However, this increases the total refrigerant flow rate, which, in turn, increases the compression power. The same effect is visible in Table 6, where the percent deviations of parameters from the base case are given; any increase of refrigerant flow rate is accompanied by a decrease in the suction/discharge difference and vice versa. Therefore, IWO tries to strike a balance between these two conflicting factors by tuning the individual refrigerant flow rates to mimic the natural gas cooling curve more closely and keeping the approach temperature to a minimum (see Figure 5). The 14% gain in the flow rate of propane in the optimized results (after 500 iterations) indicates that the approach temperature is a strong function of the flow rate of propane in the subcooling cycle, while, in the precooling cycle, the decreases of 27% and 40% in the isobutane and n-butane flow rates make them most sensitive to compression minimization.

After optimizing the operations of the liquefaction process, the energy-saving opportunities can also be illustrated through an analysis of the composite curves within exchangers, that is, CHX-01 and CHX-02. Figure 5A,B shows the TDCC and THCC curves for the CHX-01, respectively, whereas, for the CHX-02, the TDCC and THCC can be seen in Figure 5C,D, respectively.

The TDCC analysis gives information about the MITA value along the length of the heat exchangers. The efficient heat transfer can be obtained when the peak of the TDCC varies between the approach temperature values of 1°C-3°C.29 The TDCC analysis gives the information about the influence of all the decision variables on the overall power consumption to liquefy NG by adopting MR-based refrigeration cycles such as the DMR process. In the precooling LNG exchanger (CHX-01), the TDCC curve peak varies from 3.0°C to 16.0°C, which finally leads to varying temperature gradients through the exchanger and demonstrates the exergy destructions, as shown in Figure 5A,B. This peak of the TDCC curve higher than 3.0°C shows the potential for further improvement by applying a rigorous robust strategy. Furthermore, exergy destructions inside the heat exchangers can also be evaluated by observing the distance between the THCC curves. As presented in Figure 5B, the encircled area exhibits a significant space between hot and cold composite curves, demonstrating that additional improvement can be made possible either through sole optimization or optimal retrofitting.

In the main LNG exchanger (CHX-02), within the range of −153.0°C to −60°C, the TDCC curve follows the constraint, that is, 3.0°C, whereas the TDCC curve peak is ~38.0°C between the temperature ranges of −60°C and 32.0°C. This TDCC curve peak is still substantially higher than that of specified value, that is, 3.0°C, as shown in Figure 5C. The THCC curves for the main LNG exchanger illustrate that the gap between composite curves has been reduced from points A to D, as shown in Figure 5D. However, the triangular area ABC is still showing room for additional distance minimization between the composite curves.

Furthermore, in the proposed study, operational optimization of the DMR process was also performed under different conditions (of temperature and pressure) of the feed natural gas. As shown in Figure 4, the change in minimization of the overall energy consumption value from 500 to 1500 is 3% while the change from 1000 to 1500 is <1%. Hence, most of the improvement was achieved within 500 iterations. Therefore, optimization of the DMR process with feed under different conditions was also performed.

| Stream | $T,$ (°C) | $P,$ (bar) | Stream | $T,$ (°C) | $P,$ (bar) |
|--------|-----------|-----------|--------|-----------|-----------|
| 1      | 13.19     | 3.25      | 1      | 18.51     | 3.0       |
| 2      | 72.48     | 8.344     | 2      | 79.58     | 7.915     |
| 3      | 30.0      | 7.844     | 3      | 30.0      | 7.415     |
| 4      | 96.14     | 21.42     | 4      | 97.79     | 20.88     |
| 5      | 30.0      | 20.92     | 5      | 30.0      | 20.38     |
| 6      | 97.82     | 55.0      | 6      | 99.51     | 55.1      |
| 7      | 30.0      | 54.5      | 7      | 30.0      | 54.6      |
| 8      | 26.54     | 54.0      | 8      | 20.82     | 54.1      |
| 9      | −157.1    | 53.0      | 9      | −157.1    | 53.1      |
| 10     | −160.3    | 3.25      | 10     | −159.4    | 3.1       |
| 11     | 13.19     | 3.25      | 11     | 18.51     | 3.0       |
| 12     | 27.0      | 1.3       | 12     | 27.0      | 3.14      |
| 13     | 103.8     | 24.0      | 13     | 69.21     | 23.0      |
| 14     | 30.0      | 23.5      | 14     | 30.0      | 22.5      |
| 15     | 30.0      | 23.5      | 15     | 30.0      | 22.5      |
| 16     | −24.0     | 23.0      | 16     | −18.0     | 22.0      |
| 17     | −44.93    | 1.4       | 17     | −23.78    | 3.24      |
| 18 (NG)| 25.0      | 55.0      | 18 (NG)| 25.0      | 55.0      |
| 19     | −24.0     | 54.0      | 19     | −18.0     | 54.0      |
| 20     | −157.1    | 53.0      | 20     | −157.1    | 53.0      |
| 21     | −160.0    | 1.1       | 21     | −160.0    | 1.1       |
| 22 (LNG)| −160.0   | 1.1       | 22 (LNG)| −160.0   | 1.1       |

End flash gas

End flash gas

TABLE 4 Thermodynamic data of all streams of the DMR process
using only 500 iterations. The IWO-based optimization results corresponding to different feed natural gas conditions are summarized in Table 7. As expected, an increase in feed pressure decreases the compression power owing to self-refrigeration. However, this trend reverses with feed temperature. High feed temperature adds more energy to the system and compression energy should increase as in the case of condition I feed NG temperature 25°C to condition II feed NG temperature 35°C. However, the changes of other parameters such as the flow rates of methane and propane are more sensitive to compression energy requirement. Therefore, it was seen a net decrease of specific compression power from condition I to II (the same is true for condition III and IV). It indicates that the complex interaction of decision variables in leading optimal solution cannot be intuitively explained taking one parameter at a time without holistically seeing the results. The low-temperature feed eases the compression burden while high temperature adds more energy to the feed, which must be expelled to the ambient surrounding through intercoolers by extra compressor work. It would be interesting to see how compression energy changes with the change in feed composition and intercooler temperatures.

### 5.2 Exergy analysis

The individual equipment contribution in overall exergy destruction or entropy generation can be easily identified through the exergy analysis. In this study, the mathematical relations for the calculation of the exergy destruction through each equipment involved in the DMR process are
provided in Table 8. Figure 6 presents the exergy destructions of the IWO-optimized DMR process in comparison with the base case.  

The exergy analysis in Figure 6 illustrates that the compressors, interstage coolers, and LNG exchangers are the major causes of exergy destruction in the whole process. The maximum exergy destruction occurs in the exchangers (CHX-01 and CHX-02) and compression units. This is due to the fact that in LNG process, compression and heat transfer are always associated with the increment in the entropy, that is the primary cause of the maximum exergy destruction through compression units and LNG heat exchangers. More generation of entropy causes more destruction of exergy. The very three reasons of exergy destructions in the heat exchangers are as follows: transfer of heat between the cold and hot fluids, transfer of heat between the exchanger and environment, and due to fluids’ movement. During the exchange of heat between the fluids, temperature usually drops, that is the primary cause of exergy destructions. This exergy destruction could be minimized to some certain levels, however, it

**FiguRE 4** Convergence of IWO algorithm corresponding to different number of iterations

**TABLE 6** Percentage deviations in parameters of interest from their base values

| Comparison parameter                        | Percentage deviation from base value |
|--------------------------------------------|-------------------------------------|
| Iteration number                           | 500 1000 1500                       |
| Suction/discharge difference (subcooling cycle) | 12.47 −20.44 0.67                   |
| Suction/discharge difference (precooling)   | −13.57 −15.55 −12.51                |
| Total refrigerant flow (subcooling cycle)   | 9.77 14.64 18.31                    |
| Total refrigerant flow (precooling)         | 11.46 33.60 23.11                   |
| Specific power saving                       | 13.40 14.80 16.2                    |

**FIGURE 5** (A) and (C) TDCC and (B) and (D) THCC in the precooling exchanger (CHX-01) and main liquefier exchanger (CHX-02) of the IWO-optimized DMR LNG process, respectively
cannot be extinguished entirely. The lowest level of exergy destruction is through the JT valves, although the exergy de-structions through the JT valves are not negligible and cannot be ignored completely. Therefore, any small improvement in any unit of the refrigeration cycle can enhance the overall performance of the liquefaction process. For example, Qyyum et al.\textsuperscript{36} improved the single mixed refrigerant process by exchanging the JT valves with a cryogenic hydraulic turbine. A similar concept can also be applied to the performance enhancement of the DMR process.

Figure 7 presents the exergy destructions associated with the IWO-optimized DMR process under varying feed conditions. It can be clearly seen that the subcooling MR cycle has the highest exergy destructions in comparison with the precooling MR refrigeration cycle. Furthermore, Figure 7 also shows the exergy destruction through individual pieces of equipment associated with the DMR process. Accordingly, interstage coolers and the subcooling LNG exchanger (CHX-02) suffer the highest exergy destruction among all

\begin{table}[h]
\centering
\caption{IWO-assisted parametric analysis of DMR process with 500.0 iterations under varying feed conditions}
\begin{tabular}{|l|c|c|c|c|}
\hline
Name & IWO optimized & \\
& Condition-1 @25°C & 55 bar & Condition-2 @35°C & 55 bar & Condition-3 @35°C & 65 bar & Condition-4 @25°C & 65 bar \\
\hline
\textbf{Decision variables cold MR} & & & & & & & & & \\
Suction pressure (stream-11), $P_{11}$ (bar) & 4.08 & 3.33 & 3.04 & 2.56 \\
Discharge pressure (stream-6), $P_{6}$ (bar) & 63.20 & 55.49 & 39.14 & 47.74 \\
Nitrogen flow rate, $m_{N}$ (kg/h) & 45 296.0 & 35 645.5 & 31 273.2 & 30 000.0 \\
Methane flow rate, $m_{C1}$ (kg/h) & 65 187.0 & 59 995.8 & 62 970.2 & 55 931.09 \\
Ethane flow rate, $m_{C2}$ (kg/h) & 103 681.0 & 93 588.3 & 80 001.9 & 80 000.0 \\
Propane flow rate, $m_{C3}$ (kg/h) & 200 000.0 & 200 000.0 & 262 799.1 & 214 253.4 \\
\hline
\textbf{Decision variables warm MR} & & & & & & & & & \\
Suction pressure (stream-12), $P_{12}$ (bar) & 2.58 & 3.39 & 2.64 & 1.9 \\
Discharge pressure (stream-13), $P_{13}$ (bar) & 22.2 & 18.16 & 24.23 & 20.6 \\
Methane flow rate, $m_{C1}$ (kg/h) & 756.0 & 1476.0 & 730.8 & 700.0 \\
Ethane flow rate, $m_{C2}$ (kg/h) & 7652.0 & 7528.0 & 7524.0 & 7538.0 \\
Propane flow rate, $m_{C3}$ (kg/h) & 15 623.0 & 37 764.5 & 25 115.04 & 15 288.9 \\
i-butane flow rate, $m_{iC}$ (kg/h) & 35 000.0 & 34 993.9 & 34 887.60 & 34 999.06 \\
n-butane flow rate, $m_{nC}$ (kg/h) & 31 892.0 & 35 000.0 & 34 949.47 & 35 000.0 \\
Precooling temp ($T_p$), °C & −18.0 & −18.0 & −18.85 & −25.53 \\
\hline
\textbf{LNG exchanger constraints} & & & & & & & & & \\
MITA($X_{CHX-01}$) (°C) & 3.7 & 3.05 & 3.27 & 3.01 \\
MITA($X_{CHX-02}$) (°C) & 2.3 & 2.24 & 1.8 & 2.53 \\
\hline
\textbf{Performance parameters} & & & & & & & & & \\
Liquefaction rate (%) & 96.3 & 96.3 & 96.3 & 96.3 \\
Total compression power (kWh) & 36 707.77 & 35 783.18 & 35 764.03 & 36 765.24 \\
Specific comp power (kWh/kg-LNG) & 0.2945 & 0.2871 & 0.2869 & 0.2949 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Mathematical relations for exergy destruction calculation through each piece of DMR equipment}
\begin{tabular}{|l|l|}
\hline
\textbf{Equipment} & \textbf{Exergy destruction (kJ/h)} \\
\hline
Compressor & $E_{\text{dest}} = (\dot{m}) (E_{\text{in}} - E_{\text{out}}) - W$ \\
Pump & $E_{\text{dest}} = (\dot{m}) (E_{\text{in}} - E_{\text{out}}) - W$ \\
After-cooler exchanging heat with ambient & $E_{\text{dest}} = (\dot{m}) (E_{\text{in}} - E_{\text{out}})$ \\
Phase separator & $E_{\text{dest}} = (\dot{m}) (E_{\text{in}} - E_{\text{out}})$ \\
Throttle valve (JT valve) & $E_{\text{dest}} = (\dot{m}) (E_{\text{in}} - E_{\text{out}})$ \\
Multistream LNG heat exchanger & $E_{\text{dest}} = \sum (\dot{m}) E_{\text{in}} - \sum (\dot{m}) E_{\text{out}}$ \\
\hline
\end{tabular}
\end{table}
the equipment. It has been reported in several studies that interstage coolers exhibit the highest exergy destruction because of the significant difference in temperature and pressure of the compressed process stream and the cooling medium (air or water). To date, it is an open issue on how exergy destruction through interstage coolers can be reduced in an energy-efficient, economic manner. For the case of the subcooling LNG heat exchanger, much of the exergy destruction is primarily by virtue of the existence of the high-boiling-point component, that is, propane (−42.0°C), in the CMR. Actually, the major purpose of the CMR is to provide the cold energy for liquefaction and subcooling of natural gas rather than for precooling. Therefore, there is a large temperature gradient in the subcooling LNG exchanger because of the presence of the high-boiling-point component (propane). The large temperature gradient inside the subcooling LNG exchanger can be reduced by removing the propane from the CMR and then applying the optimization again to find optimal flow rates for CMR ingredients (nitrogen, methane, and ethane). Hence, any enhancement to the interstage coolers and subcooling LNG exchanger will lead to a reduction in the overall power consumption for the LNG production process. JT valves associated with the DMR process also contribute a significant portion of exergy destruction because of isenthalpic expansion, which can be replaced with isentropic expansion.

**TABLE 9** Assumptions to deduce unavoidable exergy destruction

| Component       | Operating conditions for $\dot{E}_{UN}$                   |
|-----------------|------------------------------------------------------------|
| Compressor      | 90%                                                        |
| Multistream heat exchanger | $\Delta T_{min} = 0.5^\circ\text{C}, \Delta P = \Delta P_{real}$ |
| Interstage cooler | $\Delta T_{min} = 5^\circ\text{C}, \Delta P = \Delta P_{real}$ |

**FIGURE 6** Exergy analysis of IWO-optimized DMR processes after 1500 iterations

**FIGURE 7** Exergy destruction in each involved component of IWO-optimized DMR processes under varying feed conditions
5.3 Computation of improvement potential regarding exergy destruction

Presence of huge amount of exergy destruction within components derives the importance of potential measurement of improvement. Conventional exergy analysis is not able to determine the origin and nature of generated irreversibilities; so, advanced exergy analysis is utilized for this purpose. In addition, it does not contain the ability to gauge the potential of improvement regarding exergy destructions within concerned component. Therefore, using advanced exergy analysis, total exergy destruction of the system is split up into two following categories, avoidable exergy destruction and unavoidable exergy destruction.

### TABLE 10 Splitting of exergy destruction into avoidable and unavoidable parts (in kW)

| Equipment          | Base case | @500 Iterations | @1000 Iterations | @1500 Iterations |
|--------------------|-----------|-----------------|------------------|------------------|
| K = Compressors    | 100 89    | 3514            | 6575             | 7662             | 2676             | 4986             | 7592             | 2648             | 4943             | 7389             | 2584             | 4805             |
| E = Coolers        | 8586      | 772             | 7814             | 6607             | 1351             | 5256             | 6488             | 614              | 5874             | 6566             | 613              | 5953             |
| CHX = LNG exchangers | 111 81    | 9963            | 1218             | 5673             | 4334             | 1339             | 6129             | 4487             | 1642             | 5322             | 4048             | 1274             |
| P = Pump           | -         | -               | -                | 18               | 10               | 7                | 16               | 10               | 7                | 21               | 12               | 9                |
| Net               | 29 856    | 14 249          | 15 607           | 19 960           | 8372             | 11 588           | 20 225           | 7759             | 12 466           | 19 297           | 7257             | 12 041           |
| % share           | 47.7%     | 52.3%           | 41.9%            | 58.1%            | 38.4%            | 61.6%            | 37.6%            | 62.4%            |

### FIGURE 8 Avoidable exergy destruction and exergy saving opportunity in case (1500 iterations)

### FIGURE 9 Avoidable and unavoidable exergy destruction share in case (1500 iterations)
exergy destruction classification in this case can be observed in Figure 9.

6 | CONCLUSIONS

The proposed study has demonstrated obtaining of the optimal values of operational parameters involved in the DMR-based natural gas liquefaction process. An invasive-weed colonization-inspired approach has been exploited successfully to reduce the overall energy requirement for refrigeration cycles used in the DMR process. Using ActiveX methodology, the invasive-weed approach was linked with a rigorous DMR model that was constructed in the Aspen Hysys simulation environment. The concluding remarks of the proposed study can be summarized as follows:

- The operation of the DMR process was optimized under different numbers of iterations. It was found that the overall compression power can be minimized by up to 16.2% using 1500 iterations at the expense of 17.2 hours of computational cost.
- Under varying feed conditions, LNG can be produced with specific compression powers of 0.2945, 0.2871, 0.2869, and 0.2949 kWh/kg-LNG at condition 1 (25°C and 55 bar), condition 2 (35°C and 55 bar), condition 3 (35°C and 65 bar), and condition 4 (25°C and 65 bar), respectively.
- The highest level of exergy destruction was found for the subcooling LNG exchanger and interstage coolers.
- The case having 1500 iterations was observed most efficient regarding potential of improvement having 62% of avoidable exergy destruction.

7 | FUTURE RECOMMENDATIONS

It was observed that, by adopting the exterior penalty function technique, the invasive-weed optimization approach did not follow the specified constraint value (ie, 3.0°C) for the LNG subcooling (CHX-02) exchanger. However, in the published base case, the specified constraint value for the precooling (CHX-01) exchanger was not followed (ie, 17°C) using the BOX optimization approach. Therefore, evaluating other newly developed single-solution-based or population-based algorithms with rigorous constraint handling methods is needed to find the optimal operational and design parameters for the DMR liquefaction process at a constraint MITA value of 1°C-3.0°C.

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NOMENCLATURE

N2 Nitrogen
C1 Methane
C2 Ethane
C3 Propane
iC4 Isobutane
nC4 n-Butane
iC5 Isopentane
LNG Liquefied natural gas
MR Mixed refrigerant
NG Natural gas
COM Component object model
MTPA Million tons per annum
SMR Single mixed refrigerant
C3MR Propane precooled mixed refrigerant
DMR Dual-mixed refrigerant
IWO Invasive-weed optimization
KBO Knowledge-based optimization
NLP Nonlinear programming
GA Genetic algorithm
PSO Particle swarm optimization
MITA Minimum internal temperature approach
CHX Cryogenic heat exchanger
THDC Temperature difference between composite curves
THCC Temperature-heat flow between composite curves
CHX-01 Warm MR cryogenic heat exchanger
CHX-02 Cold MR cryogenic heat exchanger

CONFLICT OF INTEREST

The authors declare no competing financial interest.

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