Energy efficiency enhancement of a single mixed refrigerant LNG process using a novel hydraulic turbine

Muhammad Abdul Qyyum a, 1, Wahid Ali a, 1, Nguyen Van Duc Long a, Mohd Shariq Khan b, Moonyong Lee a, *  

a School of Chemical Engineering, Yeungnam University, Gyeongsan 712-749, South Korea  
b Department of Chemical Engineering, Dhofar University, Salalah 211, Oman  

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The advancement in hydraulic turbine (HT) technology was exploited for energy and cost benefits in natural gas liquefaction. Replacing the conventional Joule–Thompson (JT) valve with HT has the potential to recover the work input. This research investigated the effect of replacing the JT valve with HT in the energy efficiency enhancement of a single mixed refrigerant (SMR) process. To fully take the potential benefit of the HT, the proposed SMR schemes were optimized by using a modified coordinate descent optimization method, which was implemented in Microsoft Visual Studio environment and linked to the rigorous HYSYS® model. The results showed that the required energy of the proposed HT based SMR process could be saved up to 16.5% in comparison with the conventional SMR process using the JT valves. Utilization of the recovered energy into boosting the natural gas feed pressure could further reduce the energy requirement up to 25.7%. Exergy efficiency analysis also showed that whole exergy efficiency of the enhanced SMR process can be increased by about 11% as compared to the base case. The proposed HT based liquefaction technology can be extended to other natural gas liquefaction processes as an attractive option for enhancing the energy efficiency.  

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1. Introduction  

Natural gas (NG) is the cleanest and aggressively growing fossil fuel often found in remote locations. For transport of NG on long distances, conversion to liquefied natural gas (LNG) is preferred because of economic, technical, safety-related, and political reasons [1]. However, NG liquefaction requires a large amount of energy as well as cost in the present scenario of hydrocarbon processing facilities. It was estimated that the refrigeration and liquefaction processes alone account for 35% of the capital and up to 50% of the operating costs (required energy is 1188 kJ/kg of LNG [1]) for the entire NG liquefaction plant [2]. Any small advancement in their performance corresponding to the energy efficiency will lead to a huge economic benefits.  

Liquefaction cycles using a mixed refrigerant such as propane precooled mixed refrigerant (C3MR), cascade, dual mixed refrigerant (DMR), and single mixed refrigerant (SMR) have been widely employed for NG liquefaction in the LNG plants. Among them, the SMR process, also called as the PRICO (poly refrigerant integrated cycle operation) process, is one of most popular processes for the small-scale LNG production [3]. The SMR process recently receives a lot of attention as a promising candidate for FLNG-FPSO (floating liquefied natural gas-floating production storage and offloading) application with its small capital investment and small spot space requirement [4].  

The SMR process requires a significant amount of energy and improving its energy efficiency can result in substantial cost and energy savings. Modifying the refrigeration cycle by improving and/or replacing and/or adding core units such as compressors, cryogenic heat exchangers, and expansion devices is one of representative approaches to enhance the performance of LNG processes in terms of energy efficiency [5]. An expansion device as one of the core units mainly affects overall energy efficiency in a liquefaction cycle. In a NG liquefaction process, expansion devices are mainly used for two purposes, i.e., to let down the refrigerant pressure for generating the cooling effect for liquefaction and to decrease a LNG stream pressure for making feasible and economic transportation. A Joule-Thompson (JT) throttling valve is a most widely used

* Corresponding author.  
E-mail address: mynlee@yu.ac.kr (M. Lee).  
1 These two authors contributed equally to this work.
expansion device in mixed refrigerant NG refrigeration cycles because of its many practical advantages such as simplicity, low investment, and maintenance cost. However, from thermodynamic point of view, it has an inherent limitation of low expansion efficiency because an expansion process through the JT valve essentially consists of isenthalpic process. It has been reported that refrigeration cycles associated with isenthalpic expansion have lower COP (coefficient of performance, which is defined as the ratio of useful cooling effect to the compression energy supplied) compared with isentropic expansion-based refrigeration cycles.

This inefficiency can also be simply indicated from the well-known Maxwell thermodynamic relation (i.e., $dh = T ds + v dp$).

A turbo-expander might be considered as an alternate of the JT valves for better expansion efficiency and energy recovery. Although the turbo-expander has high expansion efficiency, its use is only limited to gas expansion and not feasible to a two-phase stream containing liquid that is the case in the refrigeration cycles using mixed refrigerant. However, recent technology advancements in cryogenic liquid expansion turbines have enabled the replacement of the JT expansion valve with a cryogenic power recovery turbine (also known as a liquid expander). The hydraulic turbine (HT) realizes near isentropic expansion of high efficiency over 90% [6,10] and generates the energy through the expansion.

Much energy can be wasted due to non-optimal execution of design and operating variables, contributing to process irreversibilities. The energy efficiency of LNG process for a given structure can be largely improved by efficient optimization only [11–13]. Cao et al. [14] carried out a comparative study of SMR and N2–CH4 expander process using Hysys optimizer in the original mode. Lee and Moon [15] optimized the SMR process by using a successive reduced quadratic programming (SRQPD) to minimize the total energy requirement and total annual cost. Morin et al. [16] used an evolutionary search algorithm to minimize the specific compression power required for SMR process. Similarly, Wang et al. [17] have optimized the propane-precooled mixed refrigerant LNG process applying a mixed-integer nonlinear programming (MINLP). He and Ju [18] analyzed the variation in the energy consumption of mixed refrigerant LNG processes upon different disturbances by using dynamic simulation model. To remove or minimize these disturbances, optimization is needed to maintain low energy consumption as much as possible. Replacing a new device while remaining process structure same can also change the optimal condition of a whole liquefaction process. Thus, rigorous optimization has to be essentially followed for any design of a new liquefaction process to fully take its potential benefits by process modification.

In this study, the SMR process was investigated to determine the enhancement of its performance by replacing the JT valves with the HT to improve the energy efficiency of NG liquefaction. To take its potential benefit fully, the proposed SMR process using the HT was optimized by applying the modified coordinate descent (MCD) optimization algorithm [19]. Furthermore, the efficient and economic utilization of recovered energy from the HTs was also investigated.

2. Process description

2.1. Conventional SMR process

Fig. 1 presents a basic schematic diagram of a conventional SMR process. The conventional SMR process mainly consists of a cryogenic exchanger, expansion (or JT) valves, compressors, and coolers (air or water).

In a typical SMR process, NG enters the LNG heat exchanger at an elevated pressure and ambient temperature and exchanges the latent heat of vaporization with the MR. NG leaves the exchanger as a subcooled (stream-6) liquid and is then flashed to a pressure slightly higher than atmospheric pressure through the JT valve, and LNG is obtained in stream-7. In a mixed refrigerant loop, the MR (stream-1) is compressed to a high pressure through multiple compressor stages each equipped with after-coolers. After lowering the pressure through the JT valve, the MR (stream-4) is vaporized inside the LNG heat exchanger and leaves as a superheated (stream-5) vapor for recompression and the cycle is completed.

The major advantage of a JT refrigerator is its simplicity. It consists of a relatively small number of hardware components, with no moving parts in the cold box or heat exchanger. If the heat exchanger is sized accurately, it always works. Meanwhile, the main disadvantage of the JT valve is the relatively high inlet pressure, which requires a high-pressure multistage compressor. Although a turbo-expander has a better expansion efficiency, its use is only limited to gas expansion. The turbine cannot usually work in a two-phase region. When the compressed MR (Fig. 1, points 2–3) in the heat exchanger is precooled, its temperature is just above the saturated liquid point and after expansion in steps 3–4, it is mostly liquefied. Handling a liquid with a turbo-expander is not feasible. The liquid particles in the turbine fly at a velocity close to the sonic velocity (200–300 m/s), which can damage the turbine wheel. Thus, the idea of a turbo-expander is not practical for SMR. Note that for an N2-expander liquefaction cycle, turbo-expanders are employed because the refrigerant remains in gaseous phase all the time.

2.2. Enhanced SMR process using HT

Fig. 2 shows a schematic diagram of the proposed SMR process where the JT valves are replaced with the HTs. In addition to its high isentropic cryogenic liquid expansion efficiencies over 90% [6,10], recovering and utilizing energy generated from expansion process is another important benefit from the HT application. An isenthalpic expansion takes place when a high pressure fluid goes through the JT valve while an isentropic expansion occurs when it expands through the HT. The JT expansion valve associated with refrigeration cycles has a low energy efficiency due to the entropy generation during the isenthalpic expansion as expressed in Eq. (1) from the Maxwell relation [20].

$$dh = T ds + v dp$$

where $h$, $T$, $s$, $v$, and $P$ are specific enthalpy, temperature, specific entropy, specific volume, and pressure, respectively. According to Eq. (1), in the case of JT valve expansion (isenthalpic) process, the increase in the fluid enthalpy is higher than that of HT expansion (isentropic) process. Hence, in the case of a HT expansion based refrigeration cycle, the liquid portion of the fluid (refrigerant) will be higher than that employing the JT valve. It means that, the isentropic expansion will result in higher cooling capacity per unit mass of mixed refrigerant with lower shaft work. Therefore, the energy efficiency of liquefaction cycle can be improved by replacing the JT valves with the HTs. From economic point of view, it has been reported that the installation of HTs in a liquefaction plant can provide a significant cost reduction and a payback time of less than one year [21]. It was reported [22] that the economic payback of installing two liquid turbines, at a retrofit cost of US $10 million, is 125 days. Replacement of an existing unit with a new one will incur capital investment. Thus, the improvement of energy efficiency comes at the expense of capital cost and often has a trade-off.

3. Process optimization

The specific compression power for the enhanced SMR process
towards the minimization was selected as an objective function that was constrained to a minimum internal temperature approach (MITA) value of 3 °C. The flow rate of the individual ingredients of the mixed refrigerant (methane, ethane, propane, and nitrogen), the evaporation, and the condensation pressures of the MR in main cryogenic LNG exchanger have a pronounced effect on the energy requirement more specifically as a compression power (objective function). Therefore, these variables were taken as a design variables in the optimization. The upper and lower range with step interval and sequence of decision variables are listed in Table 1.

The efficiency of HT in terms of the recovered energy and cooling effect upon expansion strongly depends on the discharge pressure of HT. Although a high discharge pressure (pressure of the recycled SMR) will facilitate the reduction of the overall compression power, it will increase the flow rate of the refrigerant to achieve the same cooling at a lower discharge HT pressure. Therefore, the upper limit of the evaporation pressure (i.e., P4) should neither be extremely high nor extremely low (near atmospheric).

Mathematically, the objective function as specific compression power relative to the design variables and constraints will be defined as.

$$\text{Min } f(X) = \text{Min} \left( \sum_{i=1}^{n} W_i / m_{\text{LNG}} \right)$$

Subject to

$$\Delta T_{(\text{min})}(X) \geq 3$$

$$T_3(X) > T_{5, \text{Dew}}(X)$$

$$X_{\text{lb}} < X < X_{\text{ub}}$$

where $X$ is the vector of decision variables; $X = (P_2, P_4, m_{N2}, m_{C1}, m_{C2}, m_{C3})$.

### Table 1

<table>
<thead>
<tr>
<th>Decision variables with lower and upper bounds.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation pressure of MR, $P_2$ (bar)</td>
</tr>
<tr>
<td>Evaporation pressure, $P_4$ (bar)</td>
</tr>
<tr>
<td>Flow rate of nitrogen, $m_{N2}$ (kg/h)</td>
</tr>
<tr>
<td>Flow rate of methane, $m_{C1}$ (kg/h)</td>
</tr>
<tr>
<td>Flow rate of ethane, $m_{C2}$ (kg/h)</td>
</tr>
<tr>
<td>Flow rate of propane, $m_{C3}$ (kg/h)</td>
</tr>
</tbody>
</table>

Fig. 1. Conventional SMR process for NG liquefaction using JT expansion valve.

Fig. 2. Schematic diagram of the enhanced SMR process using HT.
The complex thermodynamics and nonlinear interactions between the design variables and constrained objective function of the SMR process, due to this, optimization of the SMR process is considered as a complex nonlinear, non-convex problem with many local optima [23]. The conventional coordinate descent (CD) algorithm is based on the idea that a multivariable function can be optimized by minimizing the objective function along one coordinate [24]. The significant advantage of MCD over the CD method is its higher efficiency for highly non-linear processes [25]. Its few tuning parameters and ease of implementation are other important advantages. With these advantages, the performance of MCD method for the optimization of complex natural gas processes was already illustrated in several previous work [19,25,26]. Meanwhile, stochastic approaches such as genetic algorithm (GA) and particle swarm optimization (PSO) were also successfully applied for the optimization of LNG processes [13,20]. However, one limitation of these methods which are often observed in the design optimization of a highly non-linear and complex system such as the SMR process is the termination in the infeasible region (i.e., a negative MITA value) before achieving an optimal and/or meaningful solution. The success using stochastic approaches tends to sensitively depend on its tuning parameters.

In this study, the MCD method was chosen for optimization of SMR processes before and after enhancements. The MCD algorithm was coded in Microsoft Visual Studio environment and then linked to the ASPEN HYSYS® V9 by using COM functionality. The schematic diagram of the MCD algorithm is shown in Fig. 3. Details of MCD algorithm is available in Ref. [19].

4. Case study

4.1. Base case

The SMR process shown in Fig. 1, which was used by Khan and Lee [13], was chosen as a base case for this study. The commercial simulator ASPEN HYSYS® was used for modeling. The process simulation basis and feed conditions are summarized in Table 2. The well-known Peng–Robinson equation of state [27] was used to calculate the thermodynamic properties and the Lee–Kesler equation [28] was used to calculate the enthalpies and entropies. To ensure the validity and feasibility of heat transfer through the LNG cryogenic exchanger, the MITA was chosen as 3°C [29]. The isentropic efficiencies of compressor and HT were assumed to be 75% and 90%, respectively [10]. To make an economical compressor system and reduce the irreversibility of the process, the compression ratio for each compressor was kept in the practical range of 1:3 [30]. Finally, the simulation of base case showed that a power of 0.3807 kW is required to liquefy 1 kg of NG.

4.2. Enhanced SMR process

To observe the individual effect of the optimization and the replacement of JT valve with HT, the optimization results were categorized into three cases as follows:

Case I. MCD-based optimization of conventional SMR or optimized SMR.

Case II. Effect of replacing JT valve with HT or enhanced SMR.

Case III. MCD-based optimization of enhanced SMR or optimized enhanced SMR.

Table 3 presents the detailed results of the above three cases in comparison with the base case. For case I, up to 1.9% of the specification ratio for each compressor was kept in the practical range of 1:3 and 90%, respectively [10]. To make an economical compressor system and reduce the irreversibility of the process, the isentropic expansion affects the thermodynamic properties in the main cryogenic exchanger and leads to different temperature difference across the cryogenic turbine and JT valve.

Larger temperature reduction in comparison with JT valve was observed at the exit of both HTs (mixed refrigerant HT and LNG HT), which leads to the increase in the MITA value from 3°C to 5.3°C. This larger temperature reduction is mainly due to the isentropic expansion, as observed in the study on cryogenic turbine efficiencies by Ref. [5] where the exit temperature of HT was decreased by 2°C in comparison with that of JT valve. This higher value of MITA provides an opportunity to further optimize the process at the constraint MITA value of 3°C. By applying again the MCD algorithm, the specific power required for liquefaction could be saved up to 16.5% as compared to the base case.

<table>
<thead>
<tr>
<th>Property</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas (Stream-0)</td>
<td>32</td>
</tr>
<tr>
<td>Temperature ('C)</td>
<td>50</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>1.0</td>
</tr>
<tr>
<td>Flow rate (kg/h)</td>
<td>Mole fraction</td>
</tr>
<tr>
<td>Composition</td>
<td>0.0020</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.9135</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.0536</td>
</tr>
<tr>
<td>Propane</td>
<td>0.0514</td>
</tr>
<tr>
<td>n-butane</td>
<td>0.0046</td>
</tr>
<tr>
<td>i-pentane</td>
<td>0.0047</td>
</tr>
<tr>
<td>n-pentane</td>
<td>0.0001</td>
</tr>
<tr>
<td>Pressure drops across LNG-exchangers</td>
<td>0.0001</td>
</tr>
<tr>
<td>Stream-0 to Stream-6 (bar)</td>
<td>1.0</td>
</tr>
<tr>
<td>Stream-2 to Stream-3 (bar)</td>
<td>0.1</td>
</tr>
<tr>
<td>Stream-4 to Stream-5 (bar)</td>
<td>0.1</td>
</tr>
<tr>
<td>Compressors isentropic efficiency (%)</td>
<td>1.0</td>
</tr>
<tr>
<td>Hydraulic turbine isentropic efficiency (%)</td>
<td>90.0</td>
</tr>
<tr>
<td>After-coolers outlet temperature ('C)</td>
<td>40.0</td>
</tr>
<tr>
<td>LNG (Stream-7) pressure (bar)</td>
<td>1.209</td>
</tr>
<tr>
<td>Boil-off gas (vapor fraction)</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Fig. 3. Modified descent coordinate optimization algorithm.
Note that a simple replacement of JT valves with the HTs does not make a notable improvement of the overall energy efficiency. The process should be properly re-optimized after modification to achieve maximum benefits of enhancement. The condensation pressures of MR in Cases I, II, and III are commonly higher than that of base case. Since the capital cost of a process normally increases as a design pressure increases, this high pressure effect needs to be considered with caution for the evaluation of process economics.

### 4.3. Composite curve analysis

The composite curves matching technique is widely used as a thermodynamic graphical tool to measure the efficiency of any process where cooling and heating are dominantly involved. For an energy efficient liquefaction process with low specific compression energy, each hot and cold composite curve of NG and MR should be located as closely as possible. Fig. 4a shows a plot of the composites curves, while Fig. 4b shows a plot of the temperature difference between the composite curves (TDCC) of the abovementioned case I (MCD optimization of conventional SMR process). There are small gaps between the TDCC curves in the temperature range of $-160$ $^\circ$C to $-70$ $^\circ$C, which indicates that it is difficult to enhance the heat transfer performance. However, there is a high possibility of enhancement in the temperature range of $-60$ $^\circ$C to $40$ $^\circ$C.

For case II, the gap between hot and cold composite curves in Fig. 5a and b in comparison with the above optimized composite curves (Fig. 4a and b) shows the area to further minimize the specific compression power (objective function). By replacing the JT valve with HT, exergy losses were recovered. This opportunity for further optimization was possible because of the isentropic expansion through the HT.

Again, the MCD algorithm was applied for the optimization of the enhanced SMR to minimize the gap between the hot and cold composite curves. The optimized composite curves of the enhanced SMR at the constraint MITA value of 3 $^\circ$C are shown in Fig. 6, which are comparative in contrast to those in Figs. 4 and 5.

### 5. Utilization of the recovered energy

HTs increase the overall LNG process efficiency by minimizing the expansion losses while generating power as an incentive. There are two possible ways to integrate this incentive power within the LNG process to achieve maximum benefits in terms of energy savings: (I) integration with the MR compression cycle and (II) integration into boosting the NG feed (stream-0) pressure.

Integration of the recovered energy from the expander (either gas expander or liquid turbine) is considered a challenging task owing to the rigorous control system and reliability. This difficulty in control system totally depends on the specifically required compression power of individual compressors in the refrigeration loop. If the value of the recovered energy of one expander will exactly match with that of any of the compressors, then it may be easy to integrate with such compressor as compared to that which requires a higher or lower compression power than the recovered energy. In this study, the two approaches mentioned were also applied to analyze the most energy efficient integration approach of the recovered energy within the LNG process.

#### 5.1. Integration with MR compression cycle

The approach on recovered energy utilization first assumes that it can be integrated with the MR compressors to minimize the required energy. At a steady-state SMR process, it is very simple to analyze the efficiency of this approach by subtracting the recovered energy from the total required specific compression power. It is indicated in Table 4 that up to 19.6% of the total compression power can be saved; it means that up to 3.1% of compression power can be further saved by utilizing the recovered energy.

#### 5.2. Integration into boosting the NG feed pressure

The NG feed conditions affect the overall performance of the LNG process. The feed pressure has an impact on the overall compression power as well as on the LNG cryogenic exchanger performance in terms of MITA values, as shown in Fig. 7a and b [23].

Accordingly, it is another option for integrating the recovered energy. As shown in Fig. 7a, boosting the pressure of NG increases the MITA value, which again opens the opportunity to further reduce the overall required compression power. The optimization results show that the overall compression power can be saved up to 25.7%. This high energy saving showed that the integration of recovered energy to boost up the NG feed is one of the best energy utilizations as compared to approach I. The final optimization results with a comparison of the recovered energy utilization approaches are presented in Table 4. Fig. 8 shows the composite curves and TDCC-optimized enhanced SMR process with efficient utilization of the recovered energy.

Fig. 9 shows the enhancement of utilizing the HT and efficient energy utilization. In particular, Fig. 9a shows that the composite curves of the optimized enhanced SMR process with efficient utilization of recovered energy are closer than those of the optimized enhanced SMR process, which are closer than those of the optimized SMR process. Meanwhile, Fig. 9b shows that the TDCC of the optimized enhanced SMR process with efficient utilization of recovered energy is lower than that of the optimized enhanced SMR process, which is lower than that of the optimized SMR process. They all lead to improved performance.

It is important to note that the energy efficiency enhancement of

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**Table 3**

Enhancement and MCD optimization results.

<table>
<thead>
<tr>
<th></th>
<th>Base case</th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation pressure of MR, $P_2$ (bar)</td>
<td>46.50</td>
<td>62.49</td>
<td>62.49</td>
<td>80.87</td>
</tr>
<tr>
<td>Evaporation pressure, $P_4$ (bar)</td>
<td>1.3</td>
<td>2.03</td>
<td>2.03</td>
<td>1.69</td>
</tr>
<tr>
<td>Post-expansion temperature, $T$ ($^\circ$C)</td>
<td>$-152.7^\circ$</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Flow rate of nitrogen, $m_{N_2}$ (kg/h)</td>
<td>0.226</td>
<td>0.259</td>
<td>0.259</td>
<td>0.046</td>
</tr>
<tr>
<td>Flow rate of methane, $m_{CH_4}$ (kg/h)</td>
<td>0.471</td>
<td>0.463</td>
<td>0.463</td>
<td>0.437</td>
</tr>
<tr>
<td>Flow rate of Ethane, $m_{C_2H_6}$ (kg/h)</td>
<td>0.571</td>
<td>0.766</td>
<td>0.766</td>
<td>0.576</td>
</tr>
<tr>
<td>Flow rate of Propane, $m_{C_3H_8}$ (kg/h)</td>
<td>2.769</td>
<td>2.267</td>
<td>2.267</td>
<td>1.736</td>
</tr>
<tr>
<td>Total refrigerant (kg/h)</td>
<td>4.037</td>
<td>3.755</td>
<td>3.755</td>
<td>2.795</td>
</tr>
<tr>
<td>MITA ($^\circ$C)</td>
<td>3.0</td>
<td>3.0</td>
<td>5.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>2.45</td>
<td>2.35</td>
<td>2.35</td>
<td>2.63</td>
</tr>
<tr>
<td>Specific compression power (kW/kg-LNG)</td>
<td>0.3807</td>
<td>0.3734</td>
<td>0.3710</td>
<td>0.3179</td>
</tr>
<tr>
<td>Relative energy saving (%)</td>
<td>–</td>
<td>1.9</td>
<td>2.6</td>
<td>16.5</td>
</tr>
</tbody>
</table>

* Khan and Lee [13] used this temperature as a decision variable i.e., the temperature of stream $-4$ in Fig. 1.
each proposed energy integration technique strongly depends on the recovered energy amount, feed NG initial pressure, and composition. The proposed energy efficiency enhancement technique can be utilized in retrofit projects. Although the hydraulic turbine technology is not fully matured for the expansion of cryogenic fluids such as LNG, its application in the cryogenic industry has been rapidly emerged. Several companies including FLOWSERVE, EBARA intl., and CryoStar etc., have developed cryogenic liquid turbines successfully and trying to retrofit existing cryogenic processes. In this context, FLOWSERVE Company reported that the economic payback of installing two liquid turbines, at a retrofit cost of US $10 million, is 125 days [22]. However, in the comparison between HT-based LNG process and conventional SMR process equipment, capital cost cannot be the same owing to the cryogenic material used in the manufacturing of HT. Furthermore, the economic benefits of HT depend upon the isentropic efficiency as well as the enthalpy reduction. Accordingly, the economic benefits are directly proportional to the enthalpy reduction and isentropic efficiency [21]. Therefore, the maximum isentropic efficiency also offers the maximum economic benefits.

6. Exergy analysis

The exergy analysis offers a common denominator to compare the performance of different refrigeration systems. It also indicates the amount of irreversibility associated with any heat transfer process operating across finite temperature difference. Exergy is not conserved due to irreversibilities. Exergy is the ability of a system to cause a change as it achieves equilibrium with its environment through a hypothetical reversible process [31]. It can be expressed as Eq. (6)
Heat Flow (kW)

0 0.2 0.4 0.6 0.8 1

Temperature (°C)

-160 -140 -120 -100 -80 -60 -40 -20 0 20 40

Hot composite curve
Cold composite curve

Fig. 6. (a) Composite curves and (b) TDCC of case III.

Table 4
Optimization results with recovered energy utilization approaches.

<table>
<thead>
<tr>
<th></th>
<th>Base case</th>
<th>Enhanced SMR w/o utilization of recovered energy</th>
<th>Enhanced SMR (approach I)</th>
<th>Enhanced SMR (approach II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_2$ (bar)</td>
<td>46.50</td>
<td>80.87</td>
<td>80.87</td>
<td>78.90</td>
</tr>
<tr>
<td>$P_4$ (bar)</td>
<td>1.3</td>
<td>1.69</td>
<td>1.69</td>
<td>2.60</td>
</tr>
<tr>
<td>Feed P (bar)</td>
<td>50.0</td>
<td>50.0</td>
<td>50.0</td>
<td>64.8</td>
</tr>
<tr>
<td>$m_{N_2}$ (kg/h)</td>
<td>0.226</td>
<td>0.046</td>
<td>0.046</td>
<td>0.070</td>
</tr>
<tr>
<td>$m_{C_1}$ (kg/h)</td>
<td>0.471</td>
<td>0.437</td>
<td>0.437</td>
<td>0.478</td>
</tr>
<tr>
<td>$m_{C_2}$ (kg/h)</td>
<td>0.571</td>
<td>0.576</td>
<td>0.576</td>
<td>0.511</td>
</tr>
<tr>
<td>$m_{C_3}$ (kg/h)</td>
<td>2.769</td>
<td>1.736</td>
<td>1.736</td>
<td>1.819</td>
</tr>
<tr>
<td>Total refrigerant (kg/h)</td>
<td>4.037</td>
<td>2.795</td>
<td>2.795</td>
<td>2.878</td>
</tr>
<tr>
<td>MITA (°C)</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>2.45</td>
<td>2.63</td>
<td>2.63</td>
<td>2.35</td>
</tr>
<tr>
<td>Required power (kJ/kg-LNG)</td>
<td>0.3807</td>
<td>0.3179</td>
<td>0.3060</td>
<td>0.2830</td>
</tr>
<tr>
<td>Relative energy saving (%)</td>
<td>—</td>
<td>16.5</td>
<td>19.6</td>
<td>25.7</td>
</tr>
</tbody>
</table>

Fig. 7. Effect of the NG feed pressure on the (a) approach temperature and (b) compression power.
Furthermore, when there is no any nuclear effects, magnetic effects, electric effects, and surface tension, molar or mass exergy of a stream of matter $A$ can then be determined by Eq. (7) [32].

$$A = A_K + A_P + A_{phy} + A_{Chem}$$

(7)

where $A_K, A_P, A_{phy}$, and $A_{Chem}$ are the kinetic, potential, physical, and chemical exergy, respectively. However, since chemical reactions are not involved during the natural gas liquefaction, the chemical exergy can be taken as zero. The mechanical exergy due to kinetic and potential energy can also be neglected due to its small contribution compared to the physical exergy.

The physical exergy losses for the compression assembly with inter-stage cooling, LNG cryogenic exchanger, and whole SMR process can be calculated using the following relations, which are presented in Refs. [20, 25, 32, 33].

For the compression assembly with inter-stage cooling:

$$E_{loss} = \sum (m)E_{in} - \sum (m)E_{out} + W$$

(8)

For the LNG cryogenic heat exchanger:

$$E_{loss} = \sum (m)E_{in} - \sum (m)E_{out}$$

(9)

For the whole SMR process:

$$E_{loss} = m(E_{in, LNG}) - m(E_{out, LNG})$$

(10)

The performance of the systems that exchange the heat to and/or from the ambient is strictly related to the environmental conditions, more specifically ambient temperature and pressure. In this context,
an exergy reference, i.e., the environment should be defined for the exergy reference. It is generally assumed the environment to be at $T_0 = 25 \, ^\circ C$ and $P_0 = 1 \, atm$, at these reference conditions, the system is said at dead state and has no potential to do any work. Finally, the exergy efficiency can be determined using Eq. (11)

$$\eta_{EX} = 1 - \frac{\text{Exergy loss in each equipment}}{\text{Actual energy provided}}$$

(11)

Based on the above Eqs. (6)–(11), the exergy efficiency analysis was carried out. Table 5 lists the exergy analysis results. It can be seen that after the SMR process enhancement and recovered energy utilization, the exergy efficiency of compression units (with inter-stage cooling) and LNG cryogenic exchanger increased by 16.07% and 10.74%, respectively, as compared to the base case. Similarly, the exergy efficiency of the whole SMR process improved by 10.95% in comparison with the base case. The exergy efficiency improvement of LNG cryogenic heat exchanger is due to the close matching of hot and cold composite curves in the enhanced SMR case. The compression and cooler assembly has the exergy efficiency of 58.54% in the enhanced SMR case (approach II). Low exergy efficiency of compression and coolers assembly implies the opportunity for further enhancing the exergy efficiency of the enhanced SMR process as a future work.

7. Conclusions

Enhancement of the SMR process was proposed by replacing the JT valve with HT followed by optimization using the MCD scheme. The optimization results showed that the specific compression power can be reduced by improving the expansion step of the NG liquefaction process. The MCD algorithm based optimization successfully saved the compression energy by finding the minimum value within the search domain. In particular, up to 16.5% of the required energy can be saved in comparison with the base case. The recovered energy can also be efficiently utilized to further improve the efficiency of the LNG process and to boost up the NG feed pressure, which is the best feasible option for utilization of the recovered energy. In terms of exergy efficiency, the enhanced SMR process (with integration of recovered energy) has 10.95% higher exergy efficiency as compared to the base case. This study clearly showed the potential of HTs with integrated energy recovery to enhance the refrigeration effect as well as the energy efficiency of industrial gas liquefaction processes.

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